PROCEEDINGS

OF THE

DREDGING SUMMIT & EXPO 2022

July 25-29, 2022

Houston, TX

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FOREWORD

The ***Dredging Summit and Expo 2022*** was held in Houston, TX, on July 25 to 29, 2022. The conference was organized by Mr. Thomas Cappellino, Executive Director of the Western Dredging Association (WEDA), the WEDA Technical Papers Committee, and the WEDA Events Committee. The Technical Papers Committee members were Dr. Shelly Anghera (Chair), Mr. Robert Ramsdell, Ms. Lori Brownell, Mr. Walter Dinicola, Mr. Paul Fuglevand, and Dr. Donald Hayes. Events Committee members were Mrs. Carol Shobrook (Chair), Mr. Mathew Binsfeld, and Mr. Jos Clement.

These proceedings include 70 papers and extended abstracts by a broad spectrum of professionals working in the dredging community. These papers describe successful projects and important research that dredging professionals can rely on to further advance the profession. Readers will find the context of these proceedings wide ranging, covering almost every aspect of dredging, dredged material management, beneficial use, sustainability, equipment innovations, contaminated sediment management, and environmental compliance.

These high-quality manuscripts result from hard work and dedication to excellence by the authors. Their willingness to contribute to the continuing education of dredging professionals by sharing their knowledge and expertise is deeply appreciated. The Western Dredging Association makes these proceedings publicly available as part of its educational mission. We hope they spur more dredging professionals to share their work with others, through future conference proceedings and the Journal of Dredging.

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U.S. BENEFICIAL USE FRAMEWORK PROVIDES NATURE-BASED SOLUTION AND NATURAL INFRASTRUCTURE OPPORTUNITIES

S.L. Goetz[1], V.S. Magar[2], L. Nelis[3], B. Suedel[4], and L. Sittoni[5]

ABSTRACT

Understanding how dredged sediment is regulated and managed by federal and state agencies is necessary to identify beneficial sediment use (BU) opportunities for nature-based solutions (NbS) for flood risk management, coastal resiliency, and restoring ecosystem services. The BU Framework in the U.S. is summarized. The US does not have a federal law mandating beneficial use. Instead, BU has grown out of the policies, guidance documents, and advocacy from the permitting agencies operating within the federal permitting framework. Most dredged material evaluated for BU is "clean (i.e, requires no special handling)," Therefore, it is not managed under regulations for hazardous substances. However, there is a framework for assessing sediment for BU when contamination is present.

The U.S. regulatory framework, permitting processes, and evaluation frameworks are summarized from USEPA and U.S. Army Corps of Engineers' guidance documents. This paper aims to review how to apply U.S. EPA's guidance for the BU of industrial byproducts to dredged sediment. Further, U.S. EPA's risk assessment process allows the determination of "clean" or "contaminated" sediment, and the parallels between the guidance documents are drawn. State and regional guidance documents are also reviewed because there are no federally promulgated sediment quality standards, and few states have promulgated standards. These state and regional examples are incorporated to provide examples of state agency and stakeholder input into the BU decision-making framework.

The BU Framework provides regulators the flexibility to consider how to manage dredged sediment determined to have "acceptable levels of risk." Although, the BU Framework does not solve location-specific variability in "what is clean versus contaminated" or "acceptable." Regulators and project teams can weigh site-specific lines of evidence to determine acceptable uses. In addition to considerations of sediment quality, evaluations may include geotechnical properties (e.g., sediment texture, organic content, strength, compressibility), dewatering properties, treatability of the dredged sediment, how the dredged material may provide treatment as an amendment or cover, the sediment's economic value, or its natural capital value.

The BU Framework allows stakeholders to assess dredged sediment for acceptability and, when it is deemed acceptable, incorporate it into nature-based solutions and natural infrastructure. The use of dredged

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sediment as a resource rather than treating it as waste creates opportunities for sustainable flood risk management, coastal resiliency, and habitat restoration and mitigation.

Keywords: Dredging, beneficial use, nature-based solution, natural infrastructure, risk-based approach.

INTRODUCTION

Beneficial use (BU) of dredged sediment is the use of dredged material for a productive purpose beyond removal and disposal (PIANC 2009) and in harmony to human and natural development (CEDA 2019). BU has grown out of the policies, guidance documents, and advocacy from the permitting agencies operating within the federal permitting framework (USEPA and USACE 2004). The U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency are tasked with permitting dredging projects under the Clean Water Act, the Marine Protection, Research, and Sanctuaries Act, and the National Environmental Policy Act (USEPA and USACE 2007a). There are several examples of Army Corps and Environmental Protection Agency advocating for BU with policy (USACE 2021), guidance documents (USEPA 2016a and 2016b; GLDT 2020), and research publications (Williams et al., 2020; Bridges et al. 2021). However, the state and local coordinating and joint permitting agencies make some determinations during the project permitting process. Therefore, the ease of getting project BU opportunities to align with permitting timeframes and regulations is variable (Searcy Bell et al. 2021).

BU opportunities include NbS for flood-risk mitigation, coastal resiliency, and ecosystem restoration, among other market applications such as geotechnical fill, amended topsoil product, or aggregate (Maher et al. 2013; Bridges et al. 2021). The potential end uses of BU dredged sediment are numerous but generally can be categorized into aquatic or upland placement. The disposition of the sediment (aquatic or upland) will determine the testing and permitting the project requires. Federal sediment quality standards are lacking for projects with aquatic BU applications, and few states have promulgated sediment quality standards; however, several regional frameworks for sediment testing and evaluation exist (Searcy Bell et al. 2021). States typically manage projects with upland BU applications under solid waste regulations. However, they may have placement permitting exemptions for dredged sediment that may be waterbody-specific, dredge quantity-specific, or end-use-specific (GLDT 2020). Although the dredged material quality and desired end use for each BU project varies in complexity, a BU evaluation framework that follows a risk-assessment approach provides a “roadmap” for projects to evaluate sediment quality for the proposed end use (GLDT 2020).

OBJECTIVES

In the U.S., most dredged material evaluated for BU is not managed under regulations for hazardous substances, meaning it is “clean.” Searcy Bell and others (2021) present that of the millions of cubic meters of navigation dredging performed by the U.S. Army Corps during the last 20-years, the amount used beneficially for beach nourishment, wetland creation, habitat construction projects, and shoreline stabilization has consistently ranged between 30% and 50% of the total annual placed quantity. Because as much as anywhere from 50% to 70% of annual navigational dredging is not beneficially used, leveraging these projects provides the greatest opportunity to provide the necessary clean material for NbS or natural infrastructure projects, more so than leveraging sediment from contaminated sites. However, “clean” is relative. Testing and evaluation frameworks are necessary when even relatively low levels of contamination are present. This paper presents a summary of select federal, regional, and state testing and evaluation guidance, regulation, and protocols to provide a context in which to understand the U.S. framework for BU.

FRAMEWORK OVERVIEW

There are federal, regional, and state testing and evaluation frameworks under which dredged material can be evaluated using a risk-based approach for BU applications. This paper presents a general overview of risk-based evaluations and the guidance documents. The reader is referred to source documents for greater

Table 1. BU regulatory framework.

Agency	Permitting Role	Coordinated Federal Regulations
U.S. Army Corps	Issues dredging permit	Clean Water Act ([CWA] 401/404), Marine Protection, Research, and Sanctuaries Act (MPRSA), National Environmental Policy Act (NEPA), Rivers and Harbors Act, Water Resources Reform and Development Act (WRRDA) of 2014 and WRDA 2020
U.S. Environmental Protection Agency	Provides environmental performance criteria, permit review, and concurrence	CWA, MPRSA, NEPA, Clean Air Act, Resource Conservation and Recovery Act (RCRA), Toxic Substances Control Act (TSCA), Surface Mining Control and Reclamation Act (SMCRA)
State/Tribal/Local Governments	Provides disposal authorizations, water quality certifications, and coastal zone consistency	Coastal Zone Management Act, Endangered Species Act, Section 402 Clean Water Act, National Historic Preservation Act, RCRA, TSCA, SMCRA

detail and nuanced information. The summary of federal regulations coordinated between federal and state/local permitting agencies in Table 1 is meant to provide a basic understanding of the regulatory framework under which BU projects are permitted.

Risk-based Approach

The CWA delegates the setting of surface water quality standards to the individual states; therefore, there are no federally promulgated sediment standards except for open ocean disposal (40 CFR §227.13 restricts dredged material placement and 40 CFR § 227.6 prohibited constituents). Instead, there are promulgated surface water quality standards and non-enforcement sediment quality screening levels or toxicity evaluations to support risk evaluations. Some states have established regulatory standards for bulk sediment concentrations, but most do not (ITRC 2011). Some states may regulate sediment the same as dry soil, whether or not it causes a surface water quality violation, or whether or not it exceeds an “acceptable” risk threshold to human health or ecological health (ITRC 2011). In the absence of screening benchmarks, the risk assessment process can be followed to estimate risk (Figure 1).

There are four stages to the risk assessment process (USEPA 2021):

- Hazard Identification stage- the dredging project area should be evaluated for potential sources of contamination, the source(s)’ likelihood of contribution to that contamination, and the duration of that contribution
- Problem Formulation stage- the approach to characterizing the dredged material should be developed to determine what is/are the hazard(s) of concern, how exposures to the contaminant occur, and who is at risk from those exposures
- Analysis stage- samples of the dredged material are collected to evaluate the potential for risk *in situ* and post-removal *ex situ* conditions
- Risk Characterization stage- the health risk to receptors is estimated (calculated) and uncertainties with the estimation are identified.

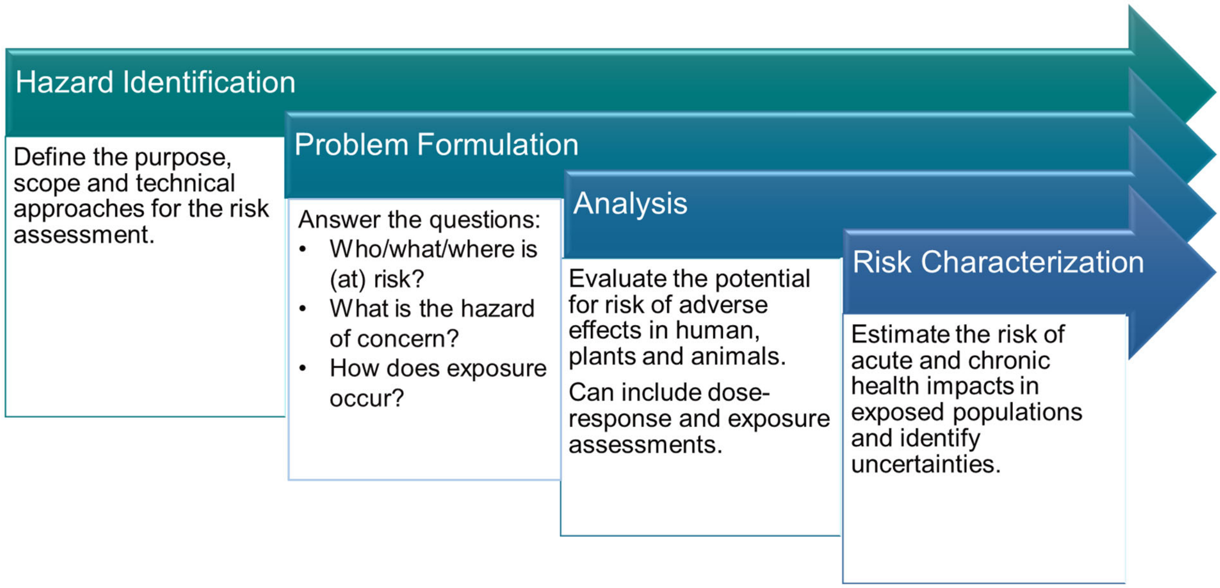

Figure 1. U.S. EPA's risk-assessment framework (Adapted from U.S. EPA 2022).

U.S. Environmental Protection Agency also has developed a risk-based framework for BU of industrial byproducts that can be applied to dredged materials (U.S. EPA 2016a and 2016b), especially if treatment may be needed. This framework was initially developed to manage industrial non-hazardous secondary materials. "Secondary materials" are any materials that are not the primary products from manufacturing and other industrial sectors. Once generated, secondary materials are often sent directly for disposal, but some have the potential to be beneficially used instead. Beneficial use involves substituting these secondary materials, either as generated or following additional processing, for some or all virgin raw materials in a natural or commercial product. An example of a secondary material in manufacturing is foundry sand used in metal manufacturing. The foundry sand may have some metals contamination that can be stabilized, so the foundry sand can be used for another use, like being blended with organic material to make topsoil.

Similarly, dredged material may be evaluated, treated, and beneficially used or marketed if applicable. BU of dredged material may include:

- geotechnical fill - upland backfill, roadway base, or bankline natural infrastructure
- soil cover or cap - brownfield or landfill cap or cover
- habitat creation - beach or marsh nourishment, island creation, emergent aquatic substrate
- creation of marketable goods - bricks or agricultural products such as amended topsoil

The potential BU end use(s) and receptors will determine the type of impact analyses required. Figure 2 summarizes the BU industrial byproduct risk-based framework adapted for dredged material considerations. In addition, the U.S. Environmental Protection Agency guidance document includes a detailed decision flow chart to aid project stakeholders and decision-makers with the BU evaluation methodology (see Figure 1 in USEPA 2016a).

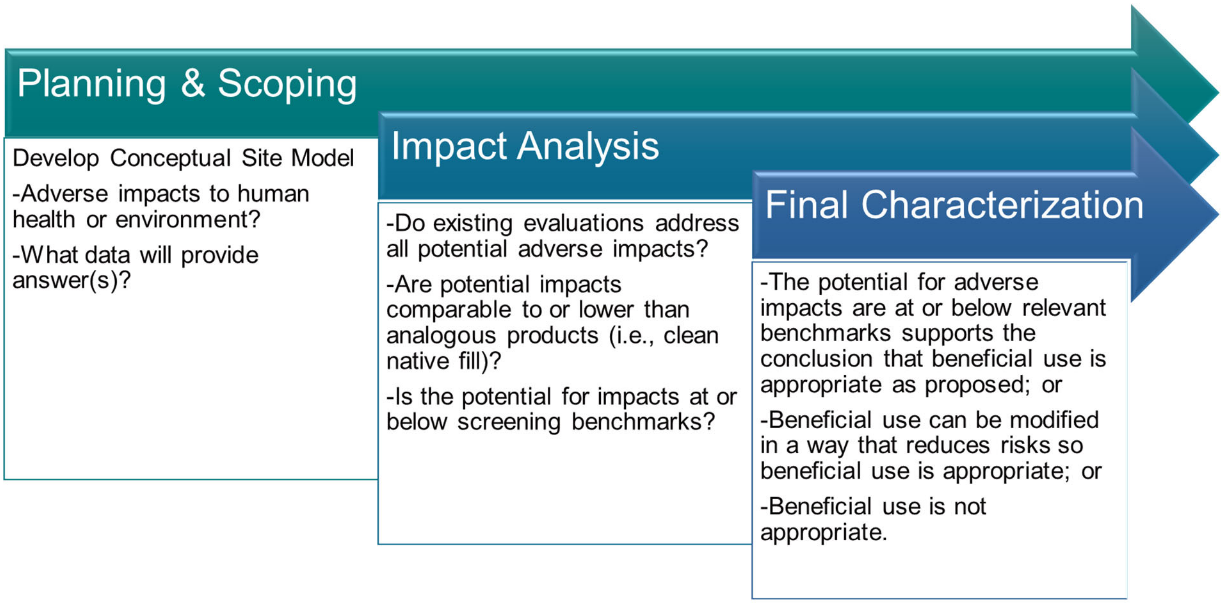

Figure 2. Risk-based evaluation of industrial byproduct BU. (Adapted from USEPA 2016a).

Several regional and state guidance documents incorporate the U.S. Environmental Protection Agency's risk-based approach in their evaluation of dredged material. For example, the Great Lakes Dredging Team (GLDT) presented compendia of state regulatory criteria and screening levels in the 2020 guidance "*Environmental Evaluation and Management of Dredged Material for Beneficial Use*." In addition, state regulatory criteria may incorporate risk in their derivation. Searcy Bell and others (2021) present a review of BU regulations and permitting processes for several states. The following are select examples of guidance documents that have adopted the risk-based approach and that facilitate BU.

- Sediment Evaluation Framework (SEF) (RSET 2016) -- Pacific Northwest region, including the States of Washington, Oregon, and Idaho; The SEF describes procedures for the risk-based sediment assessment of potential contaminant-related environmental impacts of dredging and the aquatic placement of dredged material in inland waters and the disposal of dredged material in ocean waters.

- Dredged Material Evaluation and Disposal Procedures User Manual (USACE et al. 2021) – Washington State; The manual is a framework for characterizing proposed dredged material for unconfined aquatic disposal suitability and characterizing proposed post-dredge surface material for compliance with state regulations. The Washington State Sediment Management Standards (SMS) and Model Toxics Control Act (MTCA) evaluate sediment quality for non-navigation projects.

- Long-Term Management Strategy (LTMS) (USACE et al. 2001) -- San Francisco Bay Region; The LTMS presents long-term dredging, disposal, and beneficial reuse strategy for dredged material placement. Recommended testing follows the "Green Book" for ocean disposal and the "Inland Testing Manual."

- Master Plan for Beneficial Use of Dredged Material (CH2MHill 2011) -- Coastal Mississippi; The guidance identifies priority coastal zone BU areas, outlines permitting regulations, and provides testing guidance.

- Innovative Reuse and Beneficial Use of Dredged Material (MDE 2019) – Maryland; The guidance document includes regulations and permitting requirements for beach nourishment and marsh creation and provides a risk-based framework that incorporates chemical concentrations, exposed populations, exposure duration, and pathway(s) for other beneficial uses for which regulation and permitting requirements are less prescriptive.

- Environmental Evaluation and Management of Dredged Material for Beneficial Use (GLDT 2020) – Great Lakes region; The guidance presents a tiered risk-assessment approach to the testing and evaluation of dredged material, provides example conceptual site models to support project scoping, and discusses operational and engineering controls for different exposure pathways.

Testing and Evaluation Manuals

The U.S. Environmental Protection Agency publishes analytical test methods applied to bulk sediment, pore water, elutriate, or biota tissue samples to evaluate sediment quality for BU applications. The data quality objectives of the sampling program will determine site characterization methods, sample media, analysis methods, and evaluation approach (USEPA 2001 and 2006). Potential BU end-uses will guide the development of the data quality objectives. Region-specific and location-specific considerations (e.g., riparian owners, ecologically sensitive areas, or environmental windows) may be incorporated as sampling programs are formalized. Although there is not a "one size fits all" approach to testing and evaluating dredged material for its environmental suitability for BU, the following manuals are foundational.

- Green Book or Ocean Testing Manual (USEPA and USACE 1991) - evaluation of ocean disposal under the MPRSA
- Inland Testing Manual (USEPA and USACE 1998) - evaluation of placement in U.S. waters under the CWA
- Upland Testing Manual (USACE 2003) - evaluation of dredged material proposed for disposal at confined disposal facilities
- Technical Framework (USEPA and USACE 2004) – evaluation of dredged material placement under MPRSA, CWA, and NEPA, including alternatives considerations for beneficial use

Table 2 is from the Great Lakes Dredge Team Manual (2020), which summarizes a risk-based tiered approach to testing sediment to determine its suitability for aquatic and upland placement, considering potential exposure pathways and receptors. The table presents the testing recommendations from the guidance mentioned above documents that may be used to determine the environmental suitability of BU alternatives. The testing may be completed in a progression, or a lower-tier may be skipped if the conceptual site model (CSM) is well understood. However, any testing program should be clarified with coordinating permitting agencies. Sediment quality/toxicity or elutriate that is below "acceptable" risk thresholds may be considered by project stakeholders to be "clean" and sediment above risk thresholds may be considered "contaminated." The presence of contamination may not preclude BU but treatment or isolation of contamination required, or a placement option that controls pathway exposures considered (GLDT 2020).

Testing may not be limited to the analyses presented in Table 2 and may include a broad suite of physical (e.g., color) and geotechnical parameters to ascertain BU suitability. Geotechnical characteristics may be helpful to match dredged material to potential usages (Maher et al. 2013) and, in the case of Michigan, may somewhat limit the analytical requirements if >90% sand is present (GLDT 2020). Evaluation of the geotechnical properties including sediment texture, organic content, strength, and compressibility will also provide information about the dredged material's dewatering properties and treatability. The geotechnical properties, in combination with tiered evaluation data, may be supportive information for the dredged material to provide treatment as an amendment or cover.

Table 2. Evaluation Tiers for Aquatic and Upland Placement of Dredged Material (GLDT 2020).

TIER	RISK-BASED PROCESS	AQUATIC PATHWAYS		UPLAND PATHWAYS	
		Water column	Benthic exposure	Human Health	Environmental Health
Tier I	Development of project goals and CSM to focus pathways being evaluated	Comparison to placement/ reference site sediment concentrations		Comparison to placement/ reference site soil concentrations	
Tier II	Reliance on chemical analysis of samples, and modeling	Elutriate chemistry and dispersion/ dilution modeling	Theoretical bioaccumulation potential	Comparison to generic soil screening levels	Modeling and/ or further chemical analysis
Tier III	Incorporation of laboratory bioassays and/or additional site-specific exposure assumptions	Elutriate toxicity tests	Sediment toxicity bioaccumulation tests	Site-specific risk-based screening levels and/or modeling or extracts	Bioaccumulation tests
Tier IV	Site-specific evaluations	Site-specific sampling, analysis, and/or evaluations		Site-specific sampling, analysis, and/or evaluations	

Beneficial Use Alternatives

The incorporation of BU into dredging projects provides opportunities to implement Engineering With Nature (EWN)®, a U.S. Army Corps of Engineers collaborative effort to sustainably deliver economic, social, and environmental benefits associated with water resources infrastructure (USACE 2021). BU alternatives developed from a "Working with Nature" (PIANC 2018) perspective consider natural system processes in concert with the project's technical design. This initiative incorporates natural and nature-based features into water infrastructure projects to support sustainable practices (Bridges et al. 2014a; Bridges et al. 2014b). For example, coastal protection EWN projects that leverage BU may realize coastal protection and multiple benefits of ecosystem services (i.e. pollination, climate regulation, water storage and purification, filtering and buffering of pollutants, etc.), in contrast to a conventional engineered solution that only achieves the intended primary engineering objective. Generally, NbS are more cost-effective and require less maintenance than engineered solutions due to their adaptability; however, they may require maintenance, particularly after extreme events (Bridges et al. 2021). Accordingly, the evaluation of BU alternatives for incorporation into these projects should be consistent with the risk-based framework.

The Technical Framework (USEPA and USACE 2004) summarizes that where BU opportunities exist, the alternatives that are developed should consider the nature and needs of the dredging projects and the material to be dredged. Considerations include:

- Physical and chemical characteristics of the dredged material must suit the potential BU alternatives.
- Logistical and management considerations (i.e. technical implementability and cost) for each BU alternative must also fit the dredging project to be retained for consideration during evaluation.
- Environmental considerations (regulatory compliance) must be suitable for an alternative to be retained.

The alternatives screening should weigh multiple lines of evidence and should consider factors such as site availability and site characteristics that may be incompatible with dredged sediment volume or characteristics or the project dredging plant. Legal considerations, regulatory drivers, and permit timing of BU alternatives may also eliminate BU alternatives from consideration or may affect the feasibility. Complex legal coordination may be required depending on the scale of the project and the number of property owners involved (USEPA and USACE 2004). Legal considerations may include riparian access, ownership transfer, or pre- and post- project property valuations. Regulatory considerations may be at play if some contamination is present in the dredged material and treatment or isolation is required before a BU application is possible, or the contamination limits which BU alternatives can be considered, if any (Tables 1 and 2). BU placement may require permitting separately from the dredging project, depending on the coordinating agencies with authority for the desired placement or end use (refer to Table 1). Conflicting alternatives should be removed from consideration as soon as possible and the rationale for removal may include the aforementioned technical feasibility factors, climate resiliency considerations, or economic feasibility, as examples. USEPA Region 5 developed a Dredged Materials Management Tool (DMDT) to evaluate beneficial uses of dredged material management options (Williams et al. 2020). This DMDT tool facilitates stakeholders quantify and weigh the environmental, social and economic aspects of BU alternatives.

Dredged material has economic value and natural capital value, depending on the outcomes of physical, geotechnical, and risk evaluations. The economic value is the market worth of the dredged material as a commodity, whereas the natural capital value includes the monetized and non-monetized worth of the ecosystem services the beneficially used dredged material also provides (HM Treasury 2020; WFNC 2021). Evaluation of a project's natural capital facilitates the comparison of NbS to conventional infrastructure solutions. For example, differences between nature-based and conventional hardened infrastructure can be made based on function (e.g., coastal protection) and materials (e.g., cost of sand versus rip-rap, concrete, or steel), but the anticipated performance and maintenance of the infrastructure during its design life may be more important; in addition, the long-term value of the benefits may outweigh incremental costs (Bridges et al. 2021, Percy et al. 2021, Oerlemans et al. 2021). The degree to which BU may be incorporated into an NbS project solution will vary with the aforementioned factors. Although these factors may limit the appropriateness of some BU alternatives, the application of NbS for coastal and fluvial infrastructure occurs along a continuum (Figure 3, Bridges et al. 2021), which presents creative opportunities for BU.

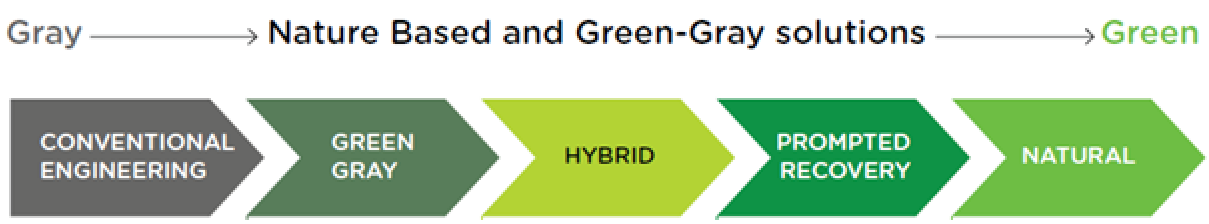

Figure 3. Continuum of NbS Use in Infrastructure. (Adapted from Bridges et al. 2021).

CONCLUSION

As discussed above, there are millions of cubic meters of navigationally dredged sediment that are available for BU each year. This dredged material provides an opportunity to add natural capital to the U.S. waterways each year when beneficially used for natural infrastructure. Dredged material is evaluated for its suitability under a risk-based framework. The risk-based framework for evaluating dredged material for BU:

- is broadly accepted at the federal, regional, and state levels of governance
- provides a standard approach to making site-specific determinations about the suitability of dredged material for BU

- provides testing and evaluation flexibility based on project goals and CSM
- supports progressive testing and BU modification to reduce risk
- uses multiple lines of evidence for decision-making

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DATA AVAILABILITY

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DPWH INNOVATIVE SOLUTIONS FOR NEGLECTED SHORELINES AND FLOOD MITIGATION FOR THE INLAND WATER CHANNELS IN THE PHILIPPINES

T.N.L Ilao[1] and M.C. Tarroza[2]

ABSTRACT

The edges of continents require attention against excessive siltation from both directions: From inland precipitation flowing into rivers, and higher tides from sea level rise. The big budget projects have not prioritized this intersection of land and sea due to high mobilization costs. This is where a new class of efficient, nimble, self-contained, and self-propelled dredgers can be effective in deepening rivers and tributaries which act as buffer zones for floodwater. Otherwise, flooding will occur consistently, and shoreline inhabitants will be forced to move further inland. This is already happening in parts of coastal Florida.

Due to the importance of ports and shipping in the supply chain, emphasis in global dredging has traditionally been on deep-water sediment removal. However, climate change caused unpredictable and sometimes overwhelming rainfall, floods, and erosion of previously stable riverbanks. This causes massive water and silt volume from uplands, ensuing siltation of the rivers, lakes, and dams.

This results in low-lying river mouths with inadequate flushing force from the formation of dunes, causing stagnation of flow. This calls for deepening the network of tributaries, canals, and river mouths to reduce inland flooding and keep the channels and marinas navigable for small to medium-sized vessels.

The enormous accumulation of deltas and shallow water systems necessitates smaller, more efficient machinery. Multi - Purpose Amphibious Dredgers (MPADs), transportable with trailers, fill the void with their self-maneuverability from land to water and back. Sediment and vegetation removal are not limited to bucket/barge/tugboat but can be a continuous operation with pumping of liquified spoils. These MPADs can strengthen riverbanks with wood or steel pilings, among other tasks. Additionally, beneficial reuse is possible by separating silt into reusable sand, gravel, and fines, which could generate income. Therefore, practical, economical MPADs could be a viable solution.

High mobilization costs with multiple machines and a large crew can be replaced by MPADs which can easily and economically access challenging project sites and continuously operate. Investing in MPADs to integrate various solutions for shoreline improvements contribute to environmental health, flood mitigation, and creates economic opportunities.

This paper discusses the introduction of innovation for flood mitigation and shoreline protection based on "Ambidextrous Organization" model[3], with focus on cost and differentiation strategies as a government agency – devoting cost-effective, easy-to-mobilize MPADs to meet the challenges in coastal protection and flood mitigation. Our proposed strategy is built around existing technologies, using technical attachments

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[3] https://hbr.org/2004/04/the-ambidextrous-organization

and innovative processes to link engineers, government authorities, and other resources for project development and investment.

INTRODUCTION

The Department of Public Works and Highways - Bureau of Equipment (DPWH-BOE), is responsible for the management of the water – based equipment fleet of the Department of Public Works and Highways (DPWH) that are for use in the nationwide by - administration dredging projects for flood control of the Philippine Government.

The DPWH-BOE, more than a decade ago, had this dilemma between retaining without refleeting the existing decades old cutter suction dredge or acquiring newer technology dredging equipment adaptable for particular working environments. This is on top of the downsized manpower which greatly affected our capability and impact of climate change. The organization needs to move forward and one of the keys is to innovate, to be an Ambidextrous Organization[4].

In 2013, DPWH began the acquisition of Multipurpose Amphibious Dredge (MPAD) and still continue to date. In its decades of operation, the application of relatively small, self – propelled, highly mobile, and efficient to operate dredgers for the maintenance of rivers channels, river mouth, and smaller tributaries such as canals has been widely adopted by the DPWH as a flood control strategy. This strategy involves the removal of accumulated sediments and other flow - obstructing materials in the waterways which are otherwise impractical or inaccessible to the other types of water - based dredging equipment.

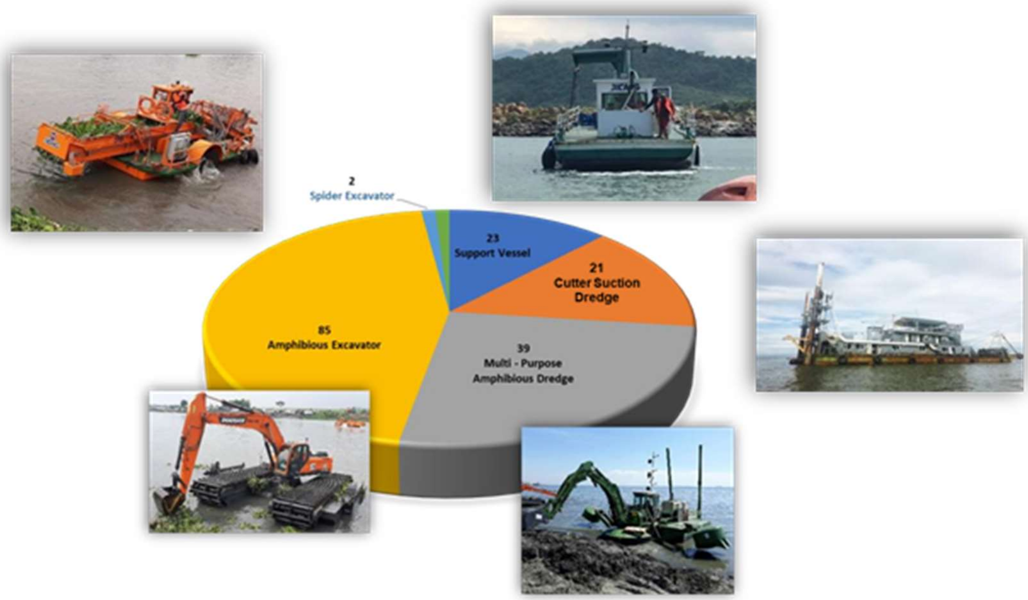

Figure 1. Composition of the DPWH Water – Based Equipment

Currently, the water – based fleet of DPWH consists of eighty – five (85) Amphibious excavators, twenty – one (21) cutter suction dredge, thirty – nine (39) multi – purpose amphibious dredge, and twenty - three (23) support vessels. These equipment are currently deployed to dredging projects in the sixteen (16) Regions of the Philippines. Due to the high diversity of the site conditions that the dredging equipment fleet of the DPWH would have to work with in the conduct of its operations, it is paramount that the most suitable

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[4] Organizational Ambidexterity refers to an organization's ability to be efficient in its management of current's organization and also adaptable for coping with tomorrow's changing demand.

equipment type in terms of dimension, output capacity, economics and safety features be selected for each project to ensure the maximum returns to the stakeholders of the Philippine Government, the Filipino People. With the MPAD consisting about 23% of the one hundred seventy (170) current water - based equipment units in the fleet of the DPWH, it is the second most adapted and preferred unit type for the dredging operations in the Philippines.

In - line with this, this paper has been devised to look into the specifications, capabilities and other feature of the MPAD unit type which may have enabled it to cater to the specific need of the project sites in the Philippines, with basis to the projects registered in the database of the DPWH - BOE.

Transitioning to Ambidextrous Organization

"**Innovation is an essential means by which organizations survive and thrive. As a result, innovation must be managed, but before it can be managed it needs to be understood**."[5]

With impact of Climate Change and increasing demand for flood control all over the Philippines, to be specific – dredging, DPWH-BOE has to move out of its usual mode "focus on what we have now" to "responsive to demand of tomorrow".

Government has to invest in resources to cushion the effects of flooding if not to eliminate. DPWH decided to make a long-term investment by acquiring additions to the fleet, newer technology dredging equipment, and technology to strengthen the undermanned, including capability development. The organization acquired MPAD. Below shows the transition of DPWH-BOE as an Ambidextrous Organization – with focus on Michael Porter's Generic Strategies' on cost and differentiation as a government agency.

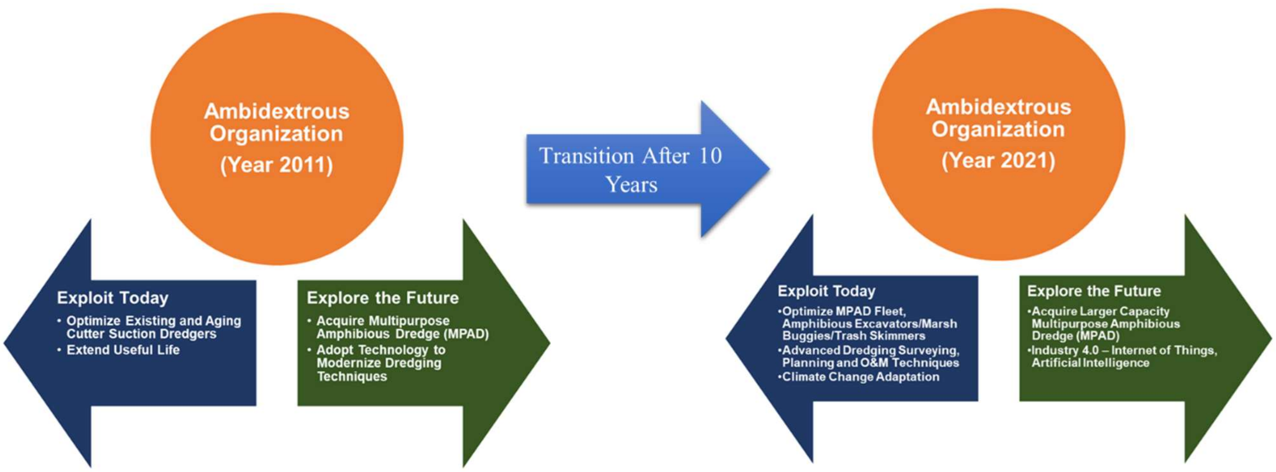


Figure 2. DPWH-BOE as an Ambidextrous Organization

FLOODING MECHANISM ADDRESSED BY THE DPWH DREDGING PROJECTS

The DPWH has been considering the general mechanism behind the transport of run – off water resulting from the inland precipitation, and the silt and other solid materials through the river system in the creation of the dredging plans for its various project sites in the Philippines, from the precipitation source up to the point of discharge to the seas thru the river mouth. While the transport mechanism consists of natural processes, the long – term human activities contributing to climate change, deforestation, urbanization of natural floodplains and other construction/material gathering operations have considerable relationships to

[5] p.1, Dodgson, M., Gann, D., Philipps, N., "The Oxford Handbook of Innovation Management", Oxford University Press, 2015.

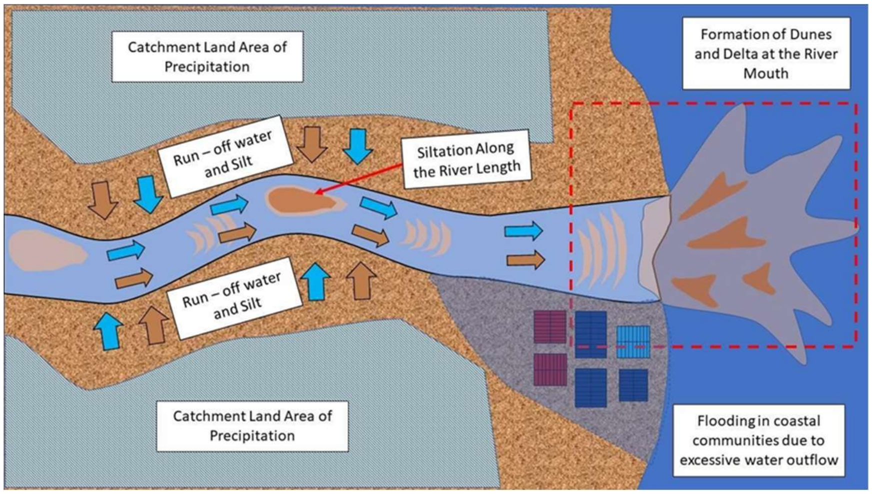


Figure 3. Illustration of the Water – and Silt – Flow Mechanism

this mechanism, which could eventually result to the flooding on human settlements, as well as disruptions to the economic activities within the adjacent communities in the Region.

As shown in the above image, the flow of water from the occurrence of precipitation on the river basin catchment area, with the elevation gradient towards the point of discharge (river mouth) drives the transport of water and sediments along the river channel. *The river channel serves two (2) key functions in this system, firstly, the river channel directs the flow of water and other materials carried by it towards the sea, where it will be discharged*. The maximum volumetric flow of water which the channel can convey before overtopping the channel and flowing through the surrounding areas, which is expressed in cubic meters per second $\left(\frac{m3}{s}\right)$ is dependent on the cross-sectional area of the river channel and the flow velocity which is affected by the channel slope and direction.

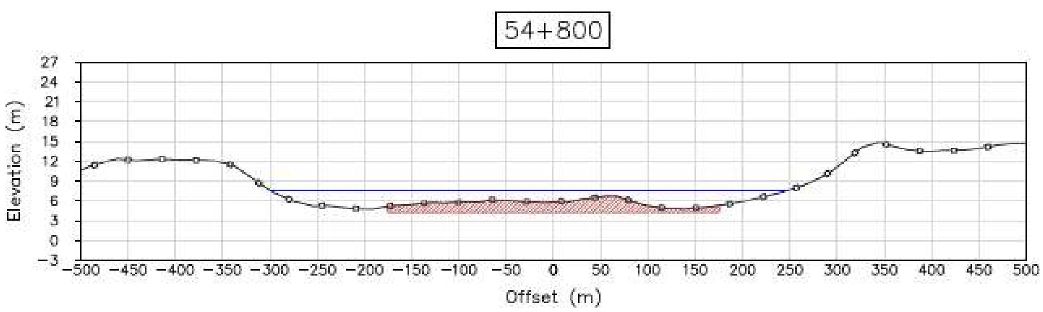


Figure 4. Example of a Channel Cut (in red) Produced in the DPWH Dredging Operation

Secondly, the river channel acts as a containment or buffer zone for the water run – off along the catchment land area. Considering these 2 primary functions of the river channel, the maintenance of sufficient cross – section area for the flow is critical in maximizing the water flow conveyance as well as the water volume retainment of the river, ultimately towards the mitigation of flooding on communities residing along the river channel.

The enumerated mechanism of flow for the rivers can be improved and maintained sustainably towards the protection of communities from flooding by allocating operational resources for the dredging and desilting of the network of small tributaries, canals, and channels in the river system.

PLANNING AND DESIGN FOR DPWH DREDGING PROJECTS

The DPWH - Bureau of Equipment (BOE) has a dedicated Division that manages all of the dredging projects around the country proposed by the administration. Before the planning starts, reconnaissance and field survey will be conducted for the optimal area to be dredged. Communities affected, economic benefit, frequency of flooding, environmental impact, and ease of navigation are some of the parameters that were taken in consideration during the planning period. During planning, the dimensions of the design river channel were determined from hydraulic and hydrologic analysis of the river basin.

Following the DGCS Volume 3 of DPWH, the three processes to be carried out for hydrologic analysis were catchment delineation, design rainfall analysis, and flood design model. These processes were performed using Geographic Information Systems (GIS) software and by using HEC-HMS to determine the design discharge. The peak discharge obtained from hydrologic analysis will then be used for hydraulic analysis of the river to be dredged.

During the analysis, the river channel will be modified to accommodate the design flood discharge by deepening and/or widening of the channel while considering the roughness and natural slope of the river. Using HEC-RAS, the flooding is simulated on both before and after dredging of existing ground surface. The design of the river channel will be modified until the simulated flood level achieves minimal to low flooding in the area. The resulting design channel and simulated flood levels will be used to prepare a dredging plan of the area. The design of the river channel will be subsequently modified to conform with regards to existing flood control infrastructures and to no dredge zone areas.

The main objective of the dredging is to increase the capacity of the river to convey flood water and to minimize the flood levels experienced in the vicinity. Based on previously dredged rivers by the Bureau, the dredging of the rivers helped lessen the occurrence of flooding during stormy seasons and minimize the flood levels experienced within the area.

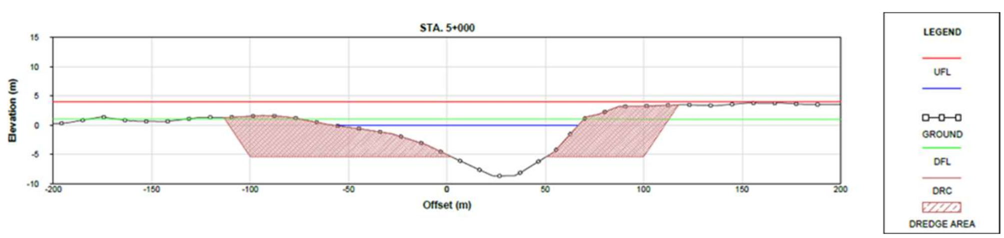
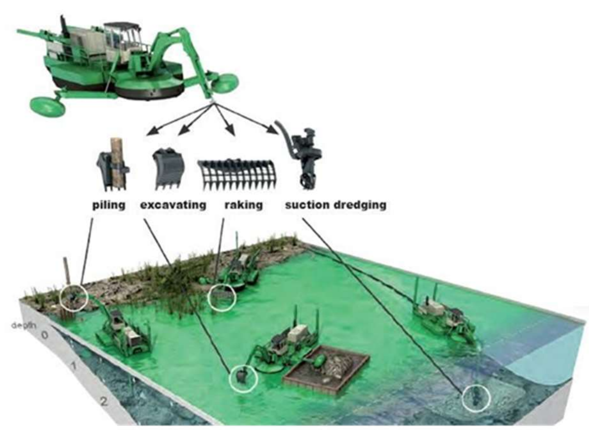


Figure 5. Example of a Channel Cut with simulated Flood Levels (Red line - Flood level before dredging; Green Line-Flood level after dredging)

THE MPAD UNITS DEPLOYED IN THE DPWH OPERATIONS

The design and the corresponding features of the small MPAD makes it highly suitable for dredging small – to medium – sized river channels, given that the site conditions (depth of water, water current velocity, distance to spoil site) are within the specifications of the equipment for both practical and safety considerations.

For example, the MPAD unit – MPAD has a max operational water depth capacity for cutter suction dredging of 6 meters, with its two spud stabilizers which can anchor the unit to the river channel bed for up to 6.7 meters. Beyond this depth, operation is no longer possible. The 3.3 – meter width (*can be extended marginally with the installation of side pontoon*) of the MPAD unit, however, would limit its operational stability when subjected to substantial water currents. This ultimately restricts the unit for use with inland dredging operations.



Max Depth of Operation :	6 meters
Dredging Capacity:	900 cubic meters/hour (sludge) / 300 cubic meters/hour (net for solids)
Discharge Diameter (for cutter suction attachment):	10 inches
Engine Power:	200 kW
Max Discharge Distance:	1.5 km (can be extended with booster pumps)
Mobility:	Self - unloading and loading
	Self - Propelled on Water
Capabilities (Based on Available Attachments):	Excavating (Bucket)
	Cutter - Suction Dredging
	Piling (Pile driver attachment)
	Floating Material Removal (Rake Attachment)
Transport:	
Transport length (with boom):	16 meters
Transport width:	3.3 meters
Transport weight:	19.5 tons

Figure 6. The Applications and Specifications of an MPAD – MPAD

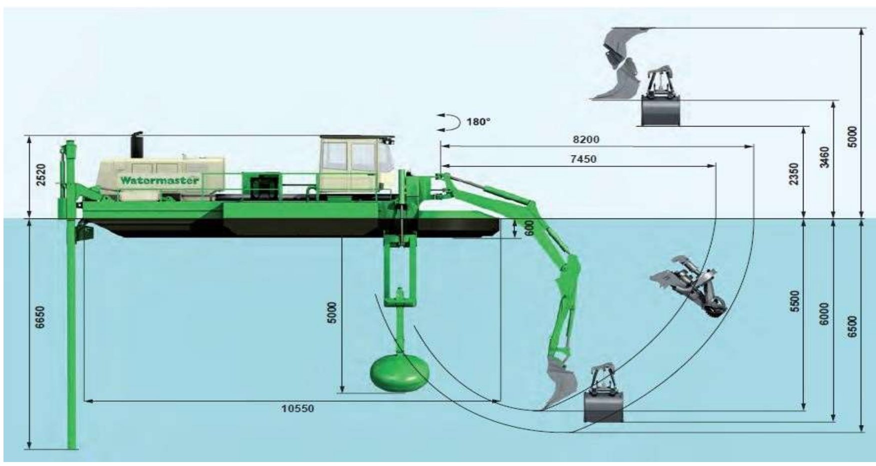


Figure 7. The Operational Dimensions of an MPAD

On the feasibility and economics of operating a small MPAD unit, the self – contained design which already packs all the necessary functions (i.e., engine, hydraulics, electronics, controls, propulsion, spoil transport and discharge) into a single compact unit allows for efficient operations. *In conjunction to what has been mentioned in the abstract, a smaller crew would be required for the operation and maintenance of such a unit due to the said design features*.

The self – loading/unloading and deployment feature of this type of dredger could also yield benefits in lowering the mobilization costs involved. This is especially applicable in cases where there are multiple project sites with relatively short durations of operation, and the units would often have to be transported from site to site. In the right conditions, it will only take a single transport equipment (prime mover with trailer) to haul and deliver the MPAD unit to the sites where they are needed. *Most notably, the small dimensions and the self – propulsion capability of such units makes them ideal with the operations in small river channels.*

While the low – scale, modularity, and flexibility in the design of small MPADs could yield a multitude of benefits which makes them attractive for use, heavy considerations must still be made with respect to the compatibility of the operational specifications of the unit with those of the prospect sites for operation. Therefore, the conduct of on – site surveying/data gathering and using the acquired data for project planning and in determining the most appropriate equipment unit is essential and indispensable.

Common Functions of the MPAD Units in DPWH

1. **Restore Shallow Waterways**

Watermaster can deepen, build, and clean out inland waters in shores. With this multi-purpose technology, the smart approach for various problems can be chosen, so that the work is done cost effectively and properly.

Large-scale shallow water dredging requires large-scale dredging capacity. Traditional big dredgers with limited mobility are poorly suited for inland waters. With a fleet of amphibious multi-purpose watermasters you are equipped to handle all kinds of environments and projects of all sizes.

Figure 8. The Operation of DPWH MPAD K3-26

2. **Flood Prevention and Environmental Clean - up**

Through the effective removal of the materials obstructing the flow and occupying flow areas in the riverbed, the MPAD units have been found by the DPWH to be highly applicable for use in flood prevention. The DPWH have from time to time used these MPAD units in the cleaning of canals and esteros.

The use of the rake and bucket attachment has also enabled the dredging crew of DPWH to remove obstructing vegetation and waste materials in the said small bodies of water which are usually located within urban areas.

Additionally, the rake attachment of an MPAD is most used on a river for removing trash and vegetation (both floating and rooted).

3. **Suction Dredging**

The cutter - suction attachment is the most commonly utilized accessory with the MPADs deployed by the DPWH in its nationwide dredging projects. The submersible pump that comes with this attachment allows working with very shallow waters as well as in dry land. The attachment also includes two cutter crowns which are compatible with different kinds of soils and aggregates located on the riverbed. The cutter - suction attachment is especially applicable in the case that the spoil site is located remotely from the dredging site since it can be used to pump the slurry containing the spoils to a distance of up to 1.5km.

4. **Backhoe Dredging**

The MPAD unit can reliably perform backhoe dredging using the bucket attachment due to its on - board stabilization system which employs independent anchoring with four stabilizers which can work in a depth of up to 6 meters. The most efficient backhoe dredging depth from the experience of the DPWH is 0 to 5 meters.

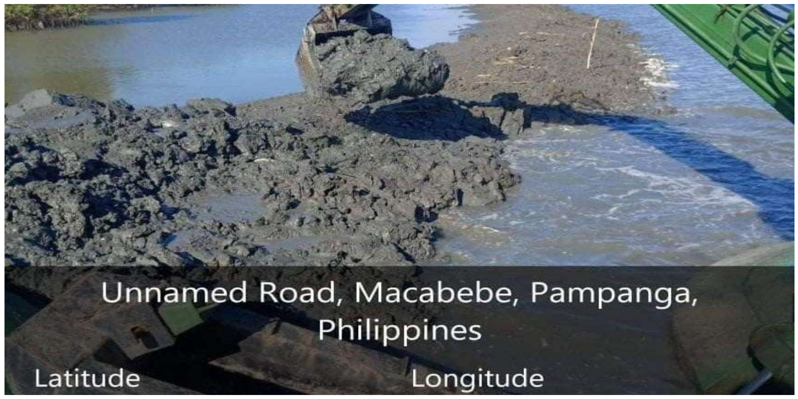


Figure 9. Backhoe Dredging Using the Bucket Attachment of the MPAD

5. The Economics of Operation Utilizing an MPAD Unit

As shown in the Table below is the breakdown of operational cost comparison of MPAD and CSD in a given dredging work in cubic meters. As shown in the table, CSD requires more manpower and crew to operate, hence having a higher Total Labor hourly-rate of one thousand four hundred ten pesos (Php 1410) with a total of fifteen (15) crew members compared to the MPAD of eight hundred fifty-two pesos (Php 852) with seven (7) crew members. CSD also requires more materials to operate such as fuel compared to MPAD.

Dredge Type		Multi-Purpose Amphibious Dredge (MPAD)		Cutter-Suction Dredge (CSD)	
Dredging Works (m^3)		112,500.00		285,606.00	
No. of Hours		2,112.00		1,056.00	
Labor Cost - Hourly Rate (Php)		No. of Personnel	Hourly Rate	No. of Personnel	Hourly Rate
	Dredge Master III	1.00	290.65	1.00	290.65
	Engineer II	1.00	209.90	1.00	209.90
	Dredge Foreman	1.00	95.22	1.00	95.22
	Dredgeman II	-	76.60	2.00	76.60
	Dredgeman I	1.00	67.69	-	67.69
	Laborer	3.00	62.89	5.00	62.89
	Watchman I	-	63.64	2.00	63.64
	Mechanic II	-	67.69	2.00	67.69
	Heavy Equipment Operator II	-	84.36	1.00	84.36
	Total Labor Hourly-Rate		852.13		1,410.44
	Total Labor Cost	1,799,698.56		1,489,424.64	
Material Cost		Qty. (Liters)	Unit Price	Qty. (Liters)	Unit Price
	Fuel (Dredge)	43,532.22	50.00	342,996.00	50.00
	Fuel (Generator)	540.00	60.00	540.00	60.00
	(15% of Fuel Cost)	-	32,649.17		257,247.00
	Total Material Cost	2,241,660.00		17,439,447.00	
Total Cost (Php)		4,041,358.56		18,928,871.64	
Total Cost per Dredging Work (Php/m^3)		**35.92**		**66.28**	

Based on the given data from the table above, MPAD has a lower Operational Cost per cubic meter of dredging work of almost thirty-six pesos per cubic meter (Php 36 / cu. m) compared to CSD of almost sixty-seven pesos per cubic meter (Php 67/ cu. m), making the MPAD more economical in terms of dredging works.

Dry-Docking Repair Cost			
Dredge Type		**Multi-Purpose Amphibious Dredge (MPAD)**	**Cutter-Suction Dredge (CSD)**
Cost (Php)	Electrical Works	-	**10,783,664.00**
	Hydraulic/Pneumatic System Works	3,077,895.00	**825,011.20**
	Hull Repair and Replating Works	-	**7,759,371.20**
	Engine Room Works	180,743.00	**1,597,475.60**
	Dredge Pump Engine	-	**10,099,808.67**
	Hull Preservation Works (Support Vessel)	-	**541,888.35**
	Engine Works (Support Vessel)	-	**2,638,452.40**
	Electrical Works (Support Vessel)	-	**346,037.00**
Total Cost (Php)		**3,258,638.00**	**34,591,708.42**

As shown in the Table above is the breakdown of Dry-docking repairs of MPAD and CSD. CSD cost of Dry-docking repairs is almost ten times more than MPAD. CSD also has a support vessel which also adds to the cost of Dry-docking repairs. MPAD are also relatively new making the Dry- docking repair cost smaller than the CSD which are relatively older in terms of years of service.

DPWH PROJECTS UTILIZING MPAD UNITS

Due to the determined compatibility of the Multi - Purpose Amphibious Dredge Units in certain site conditions relative to their small, faster mobilization/demobilization, nimble form factors and high operational efficiency, this dredging equipment type has been widely deployed by the DPWH in its nationwide dredging projects for flood control. Because of these features, the following are the notable dredging projects that are utilizing MPAD in the Philippines:

1. Cagayan River Dredging Project

Cagayan River is the longest River in the Philippines about 520 kms long. It flows in a northerly direction from its head waters in the Province of Nueva Vizcaya through the Provinces of Quirino, Isabela and Cagayan Valley to its mouth in the Babuyan Channel.[6]

On November 14, 2020, Cagayan Valley experienced the worst flood to hit in 40 years. Floodwater level rose to 13.1 m, higher than the 11 meters that it had risen to in the past. Experts attributed the flooding the swelling of Cagayan River over the course of several weeks brought about by over a month of rain[7].

Immediately, in the same period, prospective dredging projects by the DPWH-BOE identified several choke points along the stretch of Cagayan River, two of which are at the Municipality of Gattaran and

[6] https://asat-edu.com/index.php/2021/01/18/1570/

[7] https://newsinfo.inquirer.net/1360770/what-caused-cagayan-valleys-worst-flood-in-40-years#ixzz7WmaZ7Zno

Municipality of Lal-lo in Cagayan Province. These municipalities are located in the downstream portion of the river. Lal-lo portion of the river is about 55 kilometers to the discharge, which is in the Municipality of Aparri. A fleet of dredging Equipment was deployed in the area, including two (2) Multi-Purpose Amphibious Dredges (MPAD) both with 10-inch discharge diameter.

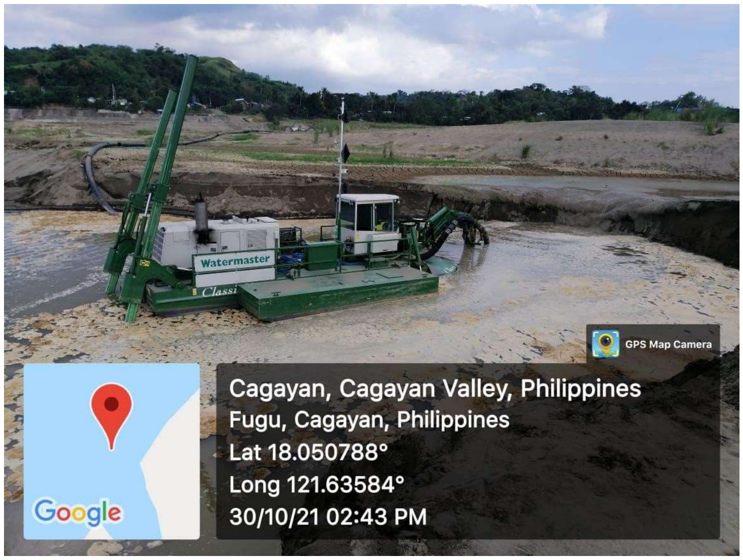


Figure 10. Multi-Purpose Amphibious Dredge (MPAD) during dredging operation in Barangay Fugu, Municipality of Gattaran, Cagayan Province

Table. Samples of weekly dredging output with the MPAD unit at Brgy. Fugu, municipality of Gattaran, Cagayan province

MPAD with Cutter-Suction Dredging Attachment ($165 m^3/hr$)							
Duration	**Equipment Code**	**Qty**	**Effective Dredging Hours**	**Actual Volume Dredged (cu. M)**	**Average Hourly Output (m^3/hr)**	**Efficiency (%)**	**Fuel Consumed (L)**
Sep. 27 – Oct. 03	K3-30 K3-32	2.00	93.00	12,555.00	135.00	82%	**5,755.00**
Nov. 01 – Nov. 07	**K3-30 K3-32**	**2.00**	**53.80**	**7,263.00**	**135.00**	**82%**	**3,346.00**

Presented in the table above is the weekly accomplishment and dredging output of the Department's MPAD for the period of two weeks. The MPADs shows an average dredging output per hour of one- hundred thirty-five cubic meters per hour (135 m^3/hour) with an operational efficiency of eighty- two percent (82%) as compared to the rated dredging output of one-hundred sixty-five cubic meters per hour (165 m^3/hour) for the MPAD unit. This indicates the high – efficiency of these MPAD units, even when utilized in non – ideal operating environments.

The geotextile tubes (Geotubes) are intended as part of the spoil management system in the Cagayan River Dredging Project. It will be used with the dredging and slope protection in the Magapit Narrows section of the Cagayan River in the Municipality of Lal-lo, Cagayan Province. The one thousand two hundred fifty-meter (1250 m) stretch part of the Cagayan River will be dredged as the Geotubes are piled on the side of the river as shown in the figure below.

In addition to the conduct of dredging and spoil stockpiling operations, the MPADs with the cutter – suction attachment are also being used to fill up the Geotextile Tubes during its installation in the determined riverbank in the Cagayan River. Geotextile Tubes, also known as Geotubes are large, tube-shaped bags made of a strong synthetic fabric and filled with a slurry of sediments and spoils. The slurry of spoils will then be dewatered thru filtration by the Geotubes leaving only solid sediments inside.

As part of the installation process, the Geotubes are connected to the discharge pipe of the MPAD which will pump the Sludge inwards as shown in the figure below:

The Geotubes will be piled in the side of the river in a way that it will form an embankment which will prevent the spoils and other sediments from eroding back to the river and will help maintain the dredged area as shown in Figure 11 below.

Figure 11. Geotubes Piles at Magapit Narrow in Lal-lo, Cagayan

Geotubes are also utilized as part of the spoil management system in the Municipality of Appari, Cagayan Province. Geotubes are used to form a river embankment to protect and prevent the erosion of spoils and sediments on Cagayan River and fill the other side of the Geotubes with Spoil from the dredged area of the river as shown in Figures 12 - 16.

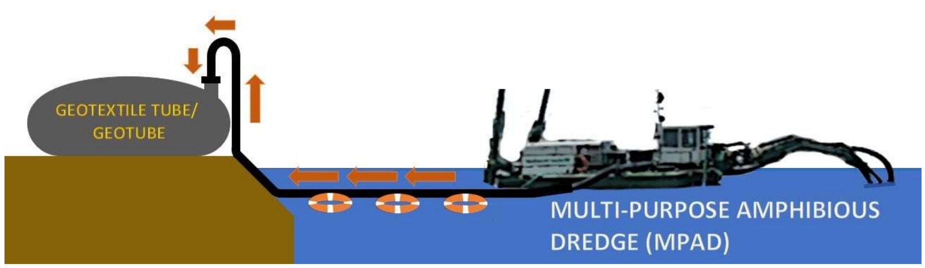


Figure 12. Filling-up of Geotubes

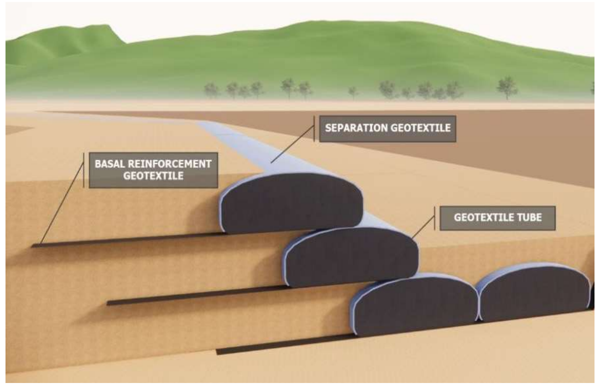


Figure 13. Geotubes Piling Arrangement in Magapit Narrow

Figure 14. Spoil Site Location in the Municipality of Aparri, Cagayan Province.

Figure 15. Area to be Dredged (Yellow Highlight) and Spoil Site to be Filled (Red Highlight) in the Municipality of Aparri, Cagayan Province.

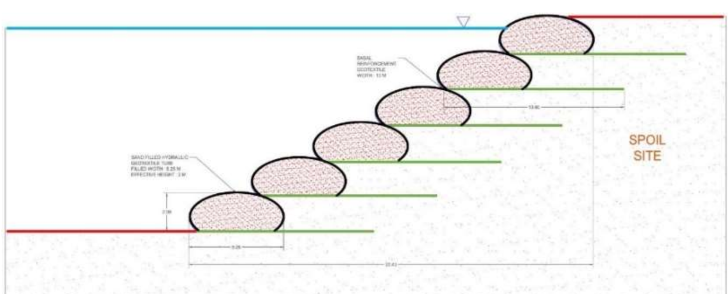


Figure 16. Geotubes Piling Arrangement proposed in the Municipality of Aparri, Cagayan Province.

The use of MPADs in filling up the Geotubes is beneficial to the dredging project as the actual dredging in the site and filling of Geotubes will be done simultaneously, reducing the completion time needed for the project.

2. DPWH Sagip Manila Bay

The Department of Public Works and Highways launched "Sagip Manila Bay" last March 5, 2019 – a massive environmental cleanup initiated by the National Government. The goal of the initiative is make Manila Bay achieve Department of Environment and Natural Resources (DENR) Class SB Water Quality for Marine Waters – fit for primary contact recreation, including swimming.

Two (2) units of Multi-Purpose Amphibious Dredge (Watermaster Classic 5) and four (4) Amphibious Excavators were deployed that offer a combination of mobility and heavy-duty dredging capacity that will make the clean up faster. As of August 2019, the accomplished dredged volume for this project is 48,177 cubic meters of silt that was removed over approximately 1.5 kilometers of Manila Bay from Manila Yacht Club to the United States Embassy in Manila.

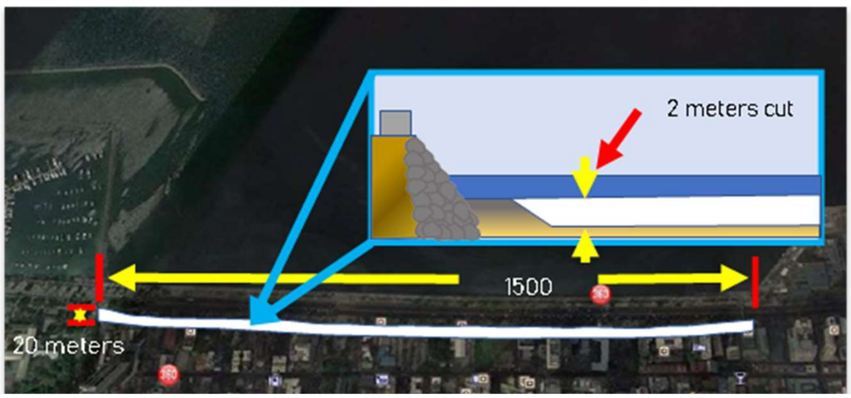


Figure 17. Manila Bay Rehabilitation Plan Map

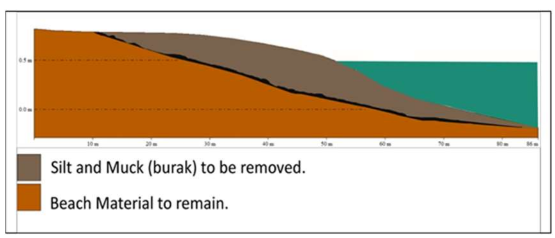


Figure 18. Sample Cross Section View (Seawall to 86m Offshore)

Figure 19. Multi-Purpose Amphibious Dredge (Watermaster) and Amphibious Excavator (left), Set up of the Equipment (right)

The proceeding table shows the total volume dredged by BOE and disposed to Metro Clark Waste Management by DENR.

Week No.	Date	Stockpiled	Hauled
21-22	July 29 – Aug 10	2339	13,320
19-20	July 15 -27	4,380	7,582
18	July 8 - 12	3,166	900
17	July 1 - 6	1,910	1,800
16	June 24 - 29	2,639.7	2,700
15	June 17 - 22	5,384.1	3,780
14	June 15 -10	2,373.6	360
13	June 8 - 3	3,744.7	1,080
1 - 12	March 5 - June 1	22,239.48	16,714.5
Total Volume (m^3)		48,177	48,236
Target Volume (m^3)		48,000	48,000
Percent Completion		**100%**	**100%**

DPWH-BOE, with the assistance of the Metro Manila Development Authority (MMDA) and other Manila LGUs, has been continuously conducting water quality monitoring and bathymetric surveys of the sites to monitor the progress until June 19, 2019, while the DENR did the sediment sampling for toxicity and quality testing.

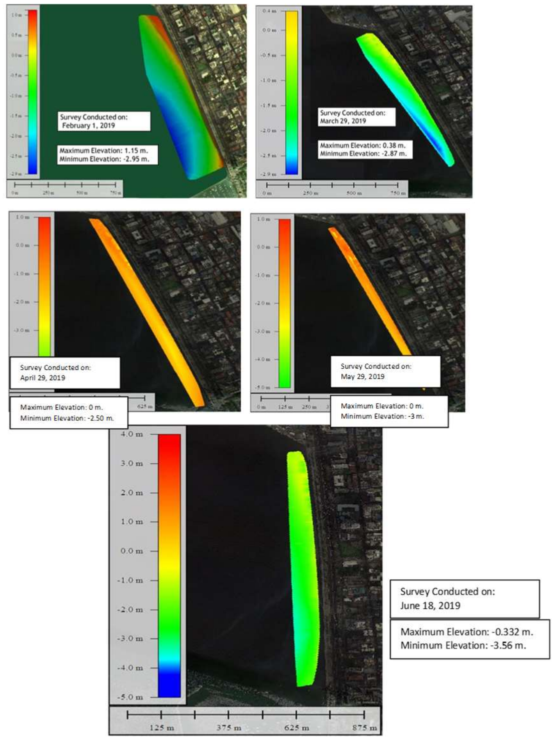


Figure 20. Consolidated Bathymetric Survey Result

CONCLUSIONS

Due to the diverse working environments present, with increasing effect of Climate Change, for the nationwide dredging operations by DPWH-BOE, innovation has to be always considered. Given the competing resources for all agencies, innovation will pave way for cost and differentiation strategies. This means better delivery of public services despite the challenges. In our case, flood control management through dredging. In conjunction with the versatile design, adaptability to medium to small sized channels, and technology attached, the agency acquired MPAD units available in the market and continue to do so.

Further as a cost strategy based on Porter's Generic Strategy, it has been determined in the analysis of the typical project cost samples that the MPAD units are overall more economical in terms of operational cost, cost per dredged volume and the maintenance cost compared to the typical large cutter – suction dredger units. From the experience of the DPWH with the specified projects, the use of MPAD units have been widely successful in removing the riverbed materials as specified in the dredging plan, as these units have registered dredging outputs which are close to those specified as the rated output of the MPAD unit.

Because of this efficiency, as differentiation strategy, the DPWH-BOE have effectively removed the targeted obstructions and enlarged the water conveyance capacity of the water bodies, contributing to the maintenance and restoration of the shorelines and flood mitigation for the communities in the Philippines. This means the agency can continue and sustain dredging by administration.

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CITATION

Ilao, T.N.L. and Tarroza, M.C. "DPWH Innovative Solutions for Neglected Shorelines and Flood Mitigation for the Inland Water Channels In The Philippines", *Proceedings of the Western Dredging Association Dredging Summit & Expo '22, Houston, TX, USA*, July 25-28, 2022.

USCG AND NAVY COLLABORATE TO DEVELOP MULTI-PURPOSE HABITAT FROM REPURPOSED PIER DEMOLITION RUBBLE AND MAINTENANCE DREDGED SAND AT BALLAST POINT, SAN DIEGO, CALIFORNIA

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EXTENDED ABSTRACT

The United States Coast Guard (USCG) Mooring Ballast Point (MBP) station is co-located at the United States Navy (Navy) Naval Base Point Loma (NBPL) in San Diego, California. In 2018, the USCG MBP was in need of critical dredging with mooring docks nearly buried in sand, and USCG vessels touching bottom at low tide. Accelerated permitting was necessary to obtain approvals for dredging and placement of the project sediments.

In the early stages of planning, the Navy approached the USCG to collaborate on an artificial reef and eelgrass restoration project directly adjacent to the dredging site at a Navy beach called Smuggler's Cove. The restoration plan proposed by the Navy recycled materials from the demolition of the P-180 Navy Fueling Pier to build a rocky reef structure, and sediment from the USCG dredging to restore the eroding beach and offshore areas up to a shallower grade, all stabilized by the new reef. After building the reef, eelgrass was planted to further stabilize the beach and increase ecological function and benefit to essential fish habitat (EFH) in San Diego Bay.

The Navy and USCG worked synergistically to obtain complementary project permits and agreements in nearly record time, despite budget driven government shutdowns. Resource and Regulatory Agencies partnered in these efforts due to multiple benefits of the project work, including restoring a recreational beach, stabilizing a seawall, reducing shoreline erosion, creating eelgrass habitat, and adding a rocky reef. The project benefited two Habitat Areas of Particular Concern (HAPCs) under the Pacific Groundfish Fisheries Management Plan and contributed to goals of shoreline softening under the San Diego Bay Integrated Natural Resource Management Plan. The project further enabled the Navy to meet objectives for solid waste diversion while providing recreational benefit to military and their families and research opportunities for local students.

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The USCG objective was to obtain a new 10-year maintenance dredging permit and characterize dredged material rapidly due to sediment shoaling. Permitting and dredge schedule windows were short. The Navy objective was to restore a beach and enhance EFH. A contingency disposal location was necessary in case the beneficial re-use project did not pan out. The Navy offered the USCG a long-term alternative and backup placement location, and the two agencies completed dredging and construction within their respective schedules.

To ensure project success for both parties, the Navy offered a secondary placement site for the duration of the USCG maintenance dredge permit cycle and a USCG sediment stockpile area until artificial reef areas were adequately permitted and constructed. Dredged materials were tested in accordance with agency-approved guidance documents for ocean disposal (USEPA/USACE 1991; USACE/USEPA, 1998). To determine compatibility with the proposed placement sites, reference sediments were collected from the LA-5 Ocean Dredged Material Disposal Site and the two proposed nearshore placement areas. For nearshore placement suitability, grain size envelopes were evaluated for compatibility.

Sediment was characterized in July 2018, but nearshore and ocean disposal suitability for unconfined aquatic disposal (SUAD) determinations and permitting faced delays due to federal government shutdown in late 2017 and early 2018. Although the USCG and other agencies were affected by the shutdown, the project team and agencies that were still working collaborated to streamline determinations and permit issuance as soon as the shutdown ended. For dredging and beach sand stockpiling, Curtin Maritime used a shallow-draft dredge with a pipeline dredge to a shore receiver site that was shaped using excavators. The FeISH reef was designed by Merkel &Associates (M&A) with Moffat & Nichol and constructed using concrete pilings and pier pieces recycled from the demolition of the Pier 180. Once the reef was established with these materials by R.E. Staite, a Navy contractor, it was filled with the stockpiled USCG sand. Then eelgrass was planted by M&A. The success of the reef and its recruitment have been monitored by both M&A and a student at California State University Fullerton (CSUF) as part of an educational outreach effort.

Sediment testing results indicated that the MBP materials were compatible with all Navy-proposed beneficial reuse options. In addition, results of Green Book Tier III and Inland Testing Manual testing (USEPA and USACE 1991; USACE and USEPA, 1998) indicated that because the proposed materials contained low levels of chemicals and posed no potential toxicity or bioaccumulation concerns, the materials were determined to be SUAD at the LA-5 Ocean Dredged Material Disposal Site as a third placement option.

Curtin Maritime performed dredging in March 2019. The following challenges were encountered during dredging: (1) narrow access space and shallowness of the USCG MBP area, which prohibited access for deep-draft dredging equipment; (2) potential to compromise critical pier and side slope integrity; (3) limited environmental windows for in-water work, particularly for the California least tern; (4) delayed permit approvals because of the government shutdown; and (5) need to stockpile sand on the nearby beach to avoid materials sloughing back into the newly dredged USCG mooring area.

Reef construction began in November 2019 using recycled pilings to provide rocky reef structure and the USCG sand. Eelgrass was planted to enhance EFH by creating HAPC in San Diego Bay. The reef will be monitored from 2021 to 2026. The project area currently shows a stable beach and reef, expanding eelgrass habitat, new soft shoreline that is increasingly used by foraging birds, and developing reef communities. In addition, student research studies are developing insights into the processes and sequence of reef community development within an enclosed bay environment.

Since 2021, the reef has been monitored by M&A in collaboration with CSUF as part of an educational outreach effort. To date, the reef and restored eelgrass are maturing well. This project is an example of successful collaboration among agencies (Navy and USCG and other partners) that led to a significant ecological benefit, including maximized beneficial material reuse. The cove, renamed La Playa de Purdue in honor of Mitch Purdue, who spearheaded the project and passed away during construction, provides a legacy recreation area for military personnel and their families to enjoy for years to come.

Keywords: maintenance dredging, beneficial use, essential fish habitat, habitat of particular concern, eelgrass, agency collaboration, dredged material disposal, nearshore placement, ocean disposal, beach replenishment.

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DATA AVAILABILITY

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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UTILIZATION OF A NATURAL AND NATURE-BASED SOLUTION FOR DREDGED MATERIAL MANAGEMENT IN A NAVIGATIONAL DREDGING PROJECT

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ABSTRACT

The Office of Maritime Resources (OMR) of the New Jersey Department of Transportation (NJDOT) is responsible for maintaining 200 nautical miles of shallow draft navigation channels statewide. The Brigantine Channel, Atlantic County, New Jersey, which provides access for recreational and commercial marine traffic including commercial fishing, had not been dredged in decades and was so severely shoaled as to make boat passage impossible. As is true along much of New Jersey's coastline, the bay's densely developed geography had made it very difficult to find suitable locations to manage dredged material. Historically, the dredged material from the channels in this area would have been taken to a nearby beach, however, characterization of the material in the worst shoal was too fine-grained to be used on a public bathing beach and would need to be taken to a Confined Disposal Facility (CDF). Unfortunately, there was no available capacity in CDFs within 5 miles of the site, prompting a search for alternatives. It was decided that the material could be beneficially used to expand existing shallow water habitat adjacent to the channel for the use of wading birds and to reinforce an eroding shoreline. In January 2021, the project team completed the hydraulic dredging and in-water placement of 21,823 cubic yards (yd^3) of clean sediment from approximately 2,050 linear feet of the Brigantine Channel.

This presentation will review strategies used, specific challenges addressed, costs, and how this project could be replicated for other projects in developed areas where traditional management methods are not viable.

Keywords: Intertidal and subtidal shallows, shoreline erosion, beneficial use, subaqueous placement, engineering with nature.

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INTRODUCTION

The Brigantine Channel is a 6-mile (9.7-km) state-maintained navigation channel located along the western side of the barrier island community of Brigantine City, NJ (see Figure 1). The channel provides access to the Absecon Inlet for recreational and commercial marine traffic, including commercial fishing. Due in part to the impacts of Superstorm Sandy in 2012, the Brigantine channel between Sunflower and Boot Island was so severely shoaled with hard packed sand that it was impassable and had been closed to motorized marine traffic. A condition survey conducted in November 2019 indicated that 27,000 yd^3 (20,600 m^3) of sediments needed to be removed from a 2000-foot (ft.) (610-m) reach to reopen the channel.

Figure 1: Brigantine Channel.

As is true along much of New Jersey's coastline, the dense development makes it very difficult to find suitable locations to manage dredged material. Historically, the dredged material from this channel would be used for beach replenishment or placed into a Confined Disposal Facility (CDF). However, based on the sediment characterization, the material was not beach quality sand (>90% coarse) nor were there any CDFs with available capacity in close enough proximity to the project site to be practicable. This prompted a search for alternative dredged material placement locations.

Superstorm Sandy, which devastated the coastal communities of New Jersey in 2012, prompted a shift in thinking in regard to the value of sediment in coastal processes which support habitat and coastal resiliency in the face of sea level rise and climate change. Sediment, rather than being seen as a nuisance that requires careful regulation, is now seen as a resource that is critical to many important coastal processes such as marsh accretion and to mitigate the impacts of increased erosion that weaken shorelines (Douglas et al., 2019). Current thinking is that rather than removing and isolating dredged material, an effort should be made to keep it in the system.

Engineering with Nature (EWN) is a U.S. Army Corps of Engineers (USACE) initiative defined as the intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental and, social benefits through collaborative processes (https://wen.el.erdc.dren.mil/). The NJ Department of Transportation's Office of Maritime Resources (NJDOT/OMR), the agency responsible for dredging the Brigantine Channel, has looked to EWN methods such as shoreline stabilization, thin layer placement and subaqueous placement as ways to manage dredged material while keeping sediment in the system. A number of pilot and demonstration level projects using a variety of techniques have been utilized successfully (Douglas, 2021, Douglas et al., 2022).

These two initiatives encouraged NJDOT/OMR to explore the potential to beneficially use the sediment from this channel in a manner which kept it in the system while benefitting habitat in the immediate area. A viable solution would utilize all of the sediment that needed to be dredged to open the channel to safe navigation at an affordable cost, and in the time allowed for the project (Sept 1 – December 31).

METHODS

Site Selection

While the Brigantine uplands are highly developed, the surrounding marshes and intertidal subtidal shallows are extensive and heavily utilized by birds and other wildlife. Desktop evaluations of the surrounding marshes did not indicate any candidate sites for marsh enhancement, however it was clear that the edges of some marshes were severely eroded. NJDOT/OMR initially proposed using the sand to augment the sand spit on the Boot Island side of the channel, however after consultation with NJ Department of Environmental Protection (NJDEP) resource managers, it was agreed that creating a beach there might attract human visitation that could disturb a nearby heron rookery. It was suggested that placing the material on the Sunflower Island side of the channel might be acceptable, even though historical photographs did not show that this side of the channel had ever had intertidal beaches.

Further evaluation of the shallow water area between the channel and Sunflower Island indicated that sufficient capacity was available, however placement there would impact a larger area. Consultation with resource managers of shellfisheries at NJDEP, the National Marine Fisheries Service (NMFS) and the US Fish and Wildlife Service (USFWS) revealed that the Sunflower Island area was extensively utilized by shellfish and there was concern that the area might contain Submerged Aquatic Vegetation (SAV), a protected resource. An investigation of the area did not indicate the presence of SAV, however there was a large population of attached macroalgae (Lacey, 2020, McKenna et al, 2021). Resource managers suggested that while some placement around Sunflower Island might be allowable, large portions of the identified area was eliminated and placement lower than Mean High Water would not be allowed. This decision effectively reduced the capacity of the area below what was needed for the navigation project.

Evaluation of the surrounding bathymetry revealed that there was a deep scour hole on the south side of Boot Island to the east of the previously proposed beach site. This area averaged 3-5 ft below MLW, too deep to be suitable for SAV. Conversations with local officials indicated that this area had once held a viable shellfishery, but that no clams had been harvested there in many years. A site investigation confirmed that the hole was not heavily utilized by shellfish. Resource managers suggested that partial filling of this hole with the sand from the channel would significantly improve the benthic habitat, perhaps returning shellfish to the area and would also provide foraging habitat for wading birds from the nearby islands.

By combining the reduced capacity on the Sunflower Island side with the capacity in the scour hole on the Boot Island side, there would be sufficient capacity for the dredging project. The sand from the channel could be hydraulically dredged and placed into the two areas. The goal for the Sunflower Island side would be to stabilize the eroded shoreline and reconnect the remaining portions of emergent marsh to the island. The goal for the Boot Island side would be to elevate the bottom to a depth of 1-2 feet below MLW to create subtidal habitat with increased light penetration for the establishment of SAV and foraging habitat for wading birds.

Site evaluation and Monitoring

The sites would be monitored for elevation, re-establishment of marsh grasses and recovery of the benthic communities. Six sediment samples (see Figure 2) were taken in the two placement areas to determine the baseline benthic invertebrate community (Vasslides, 2020). The results suggest a community generally consistent with others found in the region, including the recently studied Barnegat Bay to the north (Taghon et al. 2017). Additional samples will be taken in the summer of 2022 and 2023 to determine if the benthic communities recover post placement. An evaluation of SAV will also be conducted to monitor the post-dredging conditions.

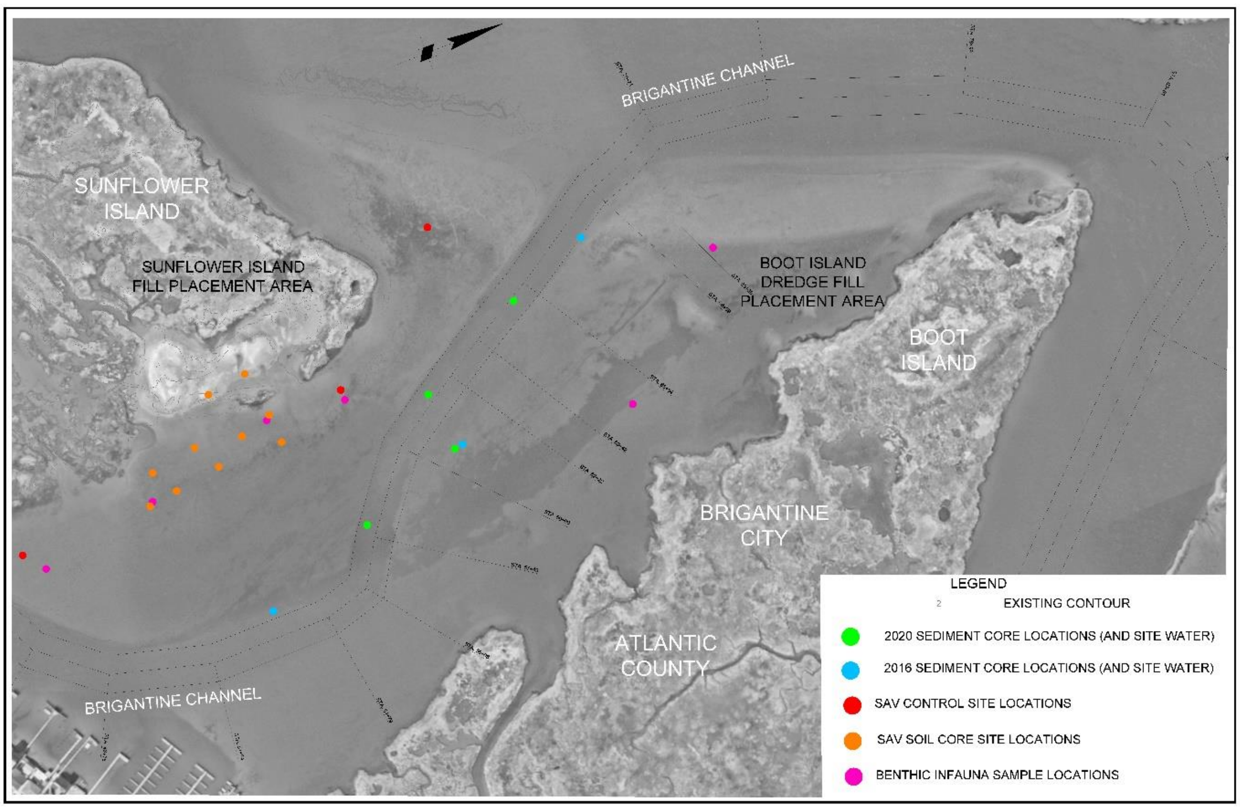

Figure 2. Benthic, SAV, and Sediment Core sample locations.

The material in the dredging area was sampled in five locations to project depth using a Vibracore sampler. Each core was evaluated for grain size (ASTM 422-D), TOC (method) and percent moisture. Samples taken in 2016 were only analyzed for physical parameters, but additional chemistry data were required for permitting the proposed placement strategy. Therefore, additional samples were taken in 2020, specifically targeting areas where finer grained material was expected to be found. A composite of these three additional cores was analyzed for grain size, TOC and bulk sediment chemistry. A sample of site water was used to prepare a modified elutriate sample from the composite and both the site water and elutriate were tested for target analytes in accordance with the NJDEP dredging manual. The physical parameters of all six samples are shown in Table 1. None of the analytes tested exceeded NJDEP ecological criteria in the bulk sediment of the composite and there were no exceedances of NJDEP water quality standards in the prepared elutriate.

Table 1. Physical characteristics of source material in Brigantine Channel.

Sample	Percent Fine	Percent Coarse	Percent Moisture	Total Organic Carbon (ppm)
Core 1 2016	26.7	73.3	55.5	5570
Core 2 2016	17.7	82.3	39.7	4100
Core 1 2020	71.9	28.1	50.23	21,078
Core 2 2020	73.6	26.4	53.93	25,054
Core 3 2020	48.0	52.0	42.02	13,585
Composite 2020	46.2	53.8	41.22	16,806

Two areas were permitted for dredged material placement during the Brigantine dredging operation. The first permitted dredged material placement area was located on Boot Island (located northeast of the channel) where dredge material was to be placed submerged in water no higher than elevation -2 ft MLW. The second permitted dredged material placement area was located on Sunflower Island (located southwest of the channel) to be placed on land up to elevation 5ft (NAVD88).

The capacity at Sunflower Island was estimated to be 4500 yd^3 (m^3), while the capacity at Boot Island was estimated to be 21,000 yd^3 (m^3). Dredging depth was -5 ft MLW with an allowable overdepth of -6ft MLW and 3:1 side slopes. The shoal was to be removed from a 2050 ft (623 m) reach of the 100-ft (30m) wide channel.

Dredging and Placement

Starting in October 2020, dredging operations commenced in the channel. The dredge, owned by Wickberg Marine Contracting of Belford, NJ, was an AMMCO PD-12E 900 hp cutterhead pipeline dredge with a 12in.x12in. GIW 7,500 GPM pump. The dredge hull was 35ft. wide and 75ft. in length with a 43ft. long ladder. Approximately 1,500 LF of 12in. pipeline was used to transport the dredged material to the two placement sites. A scow mounted excavator and marsh excavator were used to position the discharge end of the pipeline and direct the material as needed to achieve the target elevations in the permitted placement areas (see Figure 3).

Approximately 7651 CY (5850 m^3) of sand was placed directly into the open water adjacent to Sunflower Island and integrated into the shoreline using a marsh excavator. The sand stabilized 550 ft (170 m) of shoreline and reintegrated two remnant portions of marsh back into the island. Another 17,192 yd^3 (7,200 m^3) of material was placed into the 21.4-ac (8.7-ha) subtidal depression at Boot Island to achieve a final elevation of 2 ft. to 3 ft. (0.6 to 0.9 m) below MLW.

Figure 3: Sidecast dredging operation places dredge material on Sunflower Island.

Monitoring and Adaptive Management

Both placement areas were surveyed and the perimeters staked prior to the start of dredging. The perimeter stakes around the Sunflower Island placement area were marked with the target elevation of +5 NAVD88. Inspectors monitored the placement of dredged material regularly during all dredging days using visual observation (Sunflower Island) or by taking soundings (Boot Island) with a rod and portable GPS unit according to a pre-established grid of the placement area (See Figure 4). It was noted that a small portion of the material placed at Sunflower Island was being washed out naturally with the currents, tides, and severe weather which resulted in a fan of material spreading into adjacent mudflats. No action was taken to change this occurrence. The Boot Island placement was shifted to the north in order to keep the material farther from the channel edge. Several small high spots were identified during placement at Boot Island (higher than the target of -2 ft MLW). These spots were monitored over the course of the project and eventually were knocked down below target grade by currents, tides, and severe weather. No further action was required.

In compliance with environmental permit conditions, water quality parameters were measured during dredging and placement activities. Using a YSI 6000 multiparameter probe, water quality was assessed at the surface (1ft, 0.3m) and at 3.3 ft (1.0 m) intervals until the bottom was reached on 6 different dates.

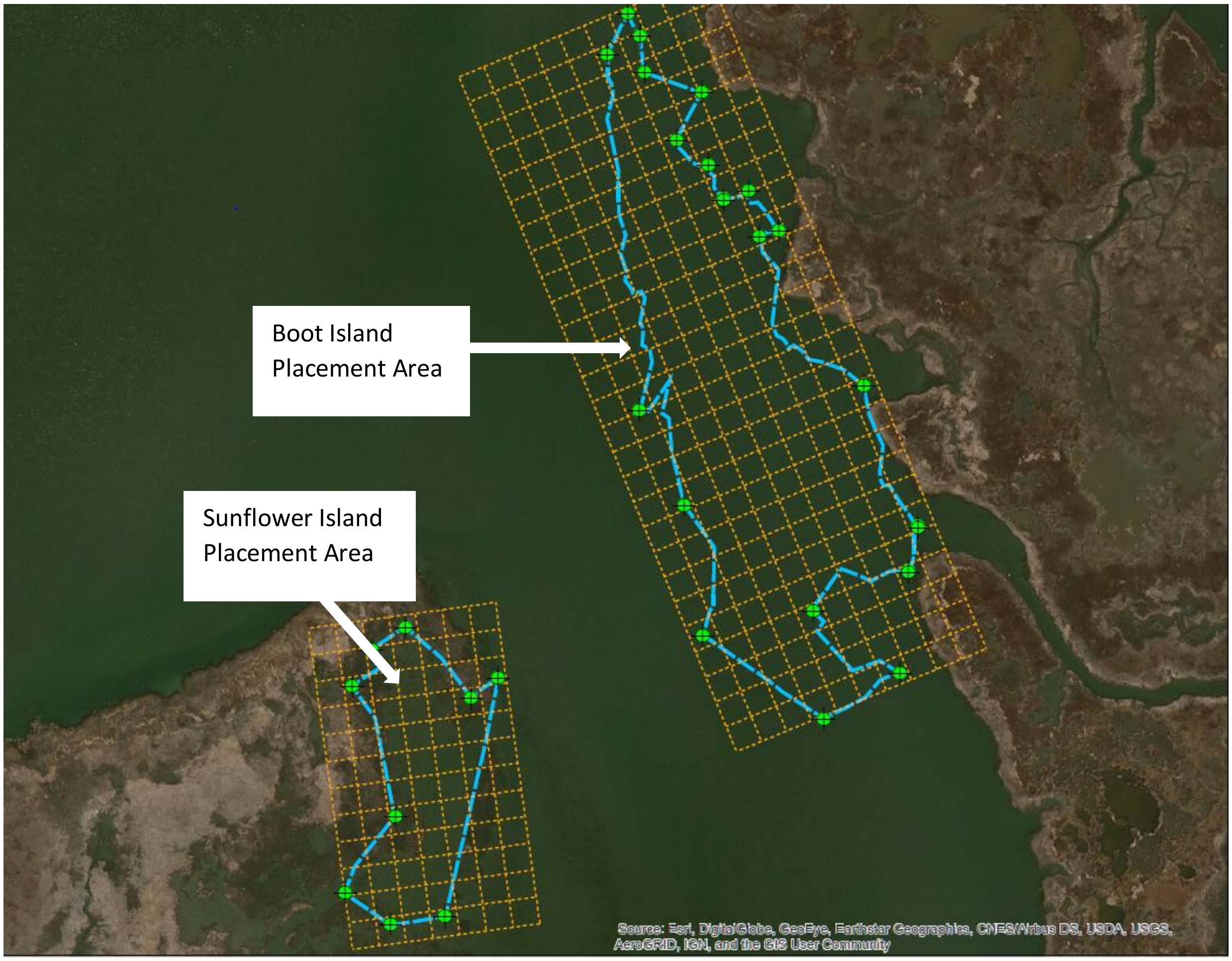

Figure 4: Grid used to help with monitoring of placement of dredge material at Boot Island.

RESULTS

Dredging Summary

In January 2021, the project team completed the hydraulic dredging and in-water placement of 21,823 cubic yards (yd^3) of clean sediment from approximately 2,050 linear feet (623 m) of the Brigantine Channel over 42 dredging days.

Because the channel was impassable prior to dredging, and that the available capacity was close to what was needed, there was concern that the capacity would be exhausted before the entire channel was cleared. Therefore, the dredging was performed in two passes. The first pass was dredged at a width of 80ft and a depth of -4ft. MLW with an allowable over depth of -0.5ft. MLW. WMC cleared 1,696ft (517 m) in 31 dredging days.

After resurveying, additional placement capacity was identified adjacent to the previously identified placement. This, combined with the remaining capacity, assured the project team that sufficient capacity remained to dredge to the authorized width and depth of 100ft at -5 +1ft MLW. During the second pass, WMC cleared 621 ft (189 m) in 11 dredging days. Figures 5 and 6 depict the before dredging and after dredging conditions.

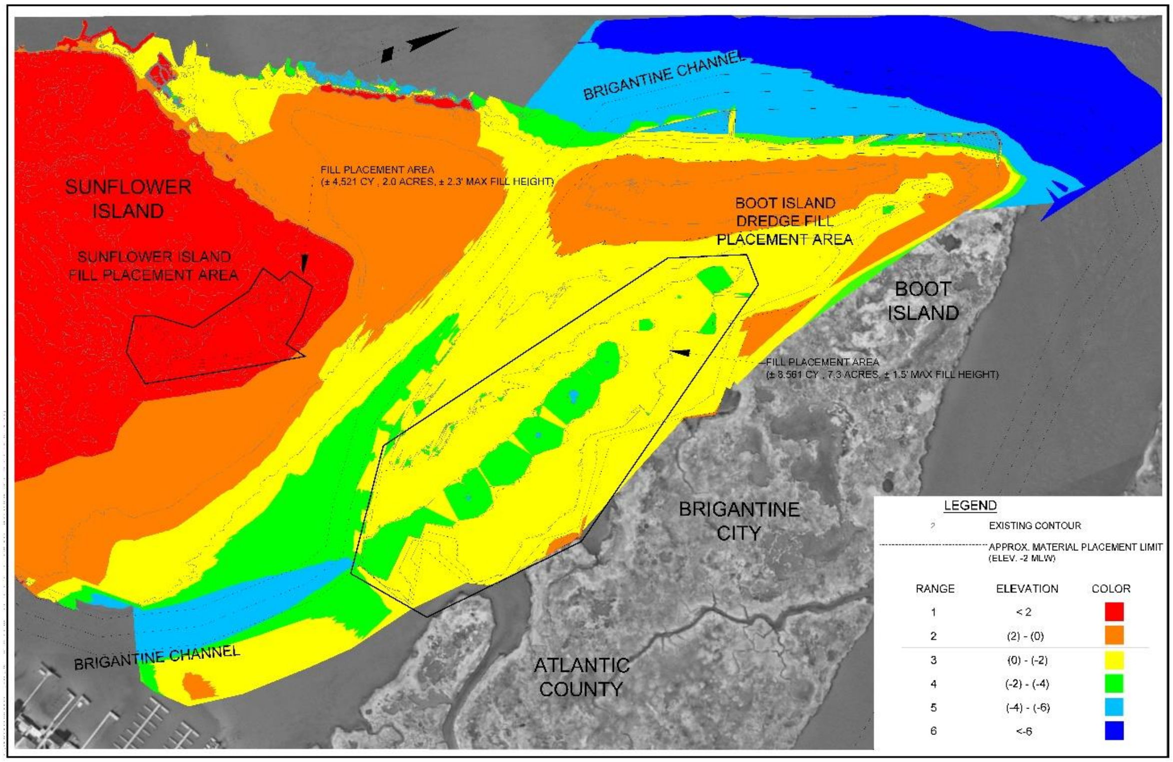

Figure 5: Bathymetry at Brigantine before dredging. Targeted placement areas are outlined.

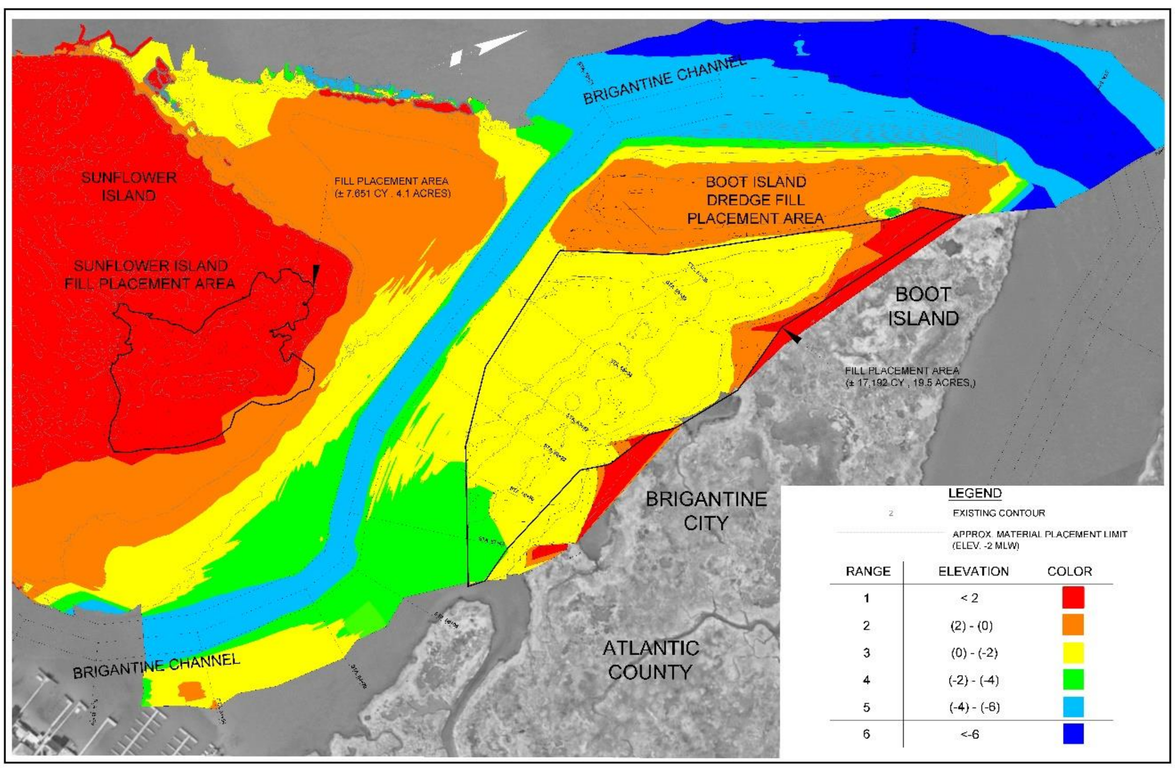

Figure 6: Bathymetry at Brigantine after dredging. Outlines show extent of actual placement.

In total, 21,823 yd^3 (16,685 m^3) were dredged from Brigantine Channel. WMC advanced a total of 2,317 ft. (1,771 m^3) , dredging a volume of 16,909 yd^3 (12,928 m^3) at a template depth of -5ft. MLW, a volume of 2,582 yd^3 (1,974 m^3) at an over depth of -6ft. MLW, and 2,332 yd^3 (1,783 m^3) of material that was out of the template for a total of 21,823 yd^3 (16,685 m^3) over 42 dredging days. WMC averaged 520 yd^3 (398 m^3) per day, advancing an average of 55 ft. (17 m) per day.

Placement Summary

Post placement survey results showed that a total volume of 7,651 yd^3 (5850 m^3) of dredged material was placed into the Sunflower Island Placement Area over a total of 21.5 hydraulic dredging days, and a total volume of 17,192 yd^3 (13,144 m^3) of dredged material was placed into the Boot Island Placement Area over a total of 20.5 hydraulic dredging days. The difference in total volume from the results of the channel surveys and placement area surveys is due to the sediment in the channels becoming disturbed and “fluffed” up during the dredging process. With time the material in the placement areas will consolidate and the disparity in volumes will decrease. Figures 7 and 8 show the Sunflower Island placement area immediately after dredging operations were completed in January 2021, and a year later in February 2022. In total, approximately 23.6 ac (9.6 ha) of habitat was created.

Figure 7: Dredged material placed on Sunflower Island, January 2021.

Figure 8: Dredged material placed on Sunflower Island, February 2022.

Monitoring Summary

Water quality was monitored on six days over the course of the project (Table 2). Temperature, salinity, pH and dissolved oxygen were all within the range expected for the region and there were no differences detected between sampling areas. Turbidity ranged from 6.4 to 155.3 NTU over the course of project, with turbidity in sampling and dredging areas typically higher than background, however the averages observed were still within the NJDEP water quality standard of a 10-day average of 30 NTU. No exceedances of the turbidity standard were observed outside of the placement areas and the plume never extended more than 100 ft (30 m) from the outfall pipe (McKenna et al, 2021).

Table 2. Results of Water Quality Monitoring During Dredging Activities. Mean of all measurements within observed range.

	Temp (°C)	Salinity (ppt)	pH	Dissolved Oxygen (%sat)	Turbidity (NTU)
Background/Control	11.1 (7.22-13.77)	30.7 (29.7-31.1)	7.9 (7.73-7.97)	99.6 (97.3-103.8)	10.2 (6.7-14.2)
Boot Island placement area (within staked perimeter)	10.6 (6.85-12.45)	30.8 (29.97-30.99)	8.0 (7.89-8.04)	104.1 (99.6-108.7)	31.8 (7.3-127.1)
Sunflower Island placement area (within 500 ft)	11.12 (10.-11.49)	30.9 (30.73-31.08)	8.0 (7.82-8.04)	102.4 (99.4-105.3)	14.9 (9.1-30.3)
In Channel	10.8 (6.83 -12.19)	30.8 (30.39-31.05)	7.9 (7.84-8.05)	104.1 (102.3-106.9)	12.3 (6.4-24.8)

DISCUSSION

The Brigantine Channel dredging project, with beneficial reuse of the dredged material as unconfined placement, resulted in the enhancement of 23.6 acres (9.6 ha) of intertidal/ subtidal shallows and the protection of 500 ft (152 m) of shoreline. In total 24,843 yd^3 (18,993 m^3) of dredged material was placed at a cost of \$1.7 million, or \$68 per CY. Of that cost, 77% was associated with the construction operations, 14% was associated with engineering, and 9% was associated with monitoring. This cost is comparable to other beneficial use projects conducted by the NJDOT; more expensive than traditional methods, but less costly than many innovative uses such as marsh enhancement or mechanical dewatering (Douglas et al, 2022).

In addition to the typical challenges of weather and a permit limited window for dredging, several other challenges were encountered. With limited capacity for placement, the dredging was performed in two phases. Initially the channel was cut at a reduced width and depth to ensure that the channel could be reopened if problems were encountered. Fortunately, due in part to consolidation and tidal action, it was apparent that additional capacity was available after the first pass. Therefore, a second pass of dredging was performed to full channel depth and width.

Dredging operations required frequent adjustment of the dredge discharge location while monitoring the placement areas for remaining depth/height. The material placed in Boot Island was discharged below the water surface and did result in some high spots. However, the tidal action eventually levelled the sediment surface to below target elevation. The grid system proved useful for evaluating daily sounding data and managing the placement as the site filled.

Monitoring the placement on Sunflower Island was limited to observing the marked stakes to ensure that target levels were not exceeded, but it was not possible to monitor if the material remained in the target perimeter until after the project was completed. The material placed at Sunflower Island naturally fanned out as the discharge was sprayed into the placement area, however no action was taken to correct this as it was decided that to do so would probably not be effective and would certainly be more disruptive to the benthic community. When placement exceeded the target elevation, a marsh buggy mounted excavator was used to redistribute the material. The as-built survey confirmed that the targeted placement height had not been exceeded.

CONCLUSIONS

EWN can be used to provide innovative beneficial use solutions that are effective for navigation and habitat at an affordable cost. This project was completed on a relatively small scale and proved to demonstrate the effectiveness of in-water placement for habitat enhancement. If used on a larger scale, additional engineering and construction controls may be warranted and could increase costs.

While the project site had not been previously identified as requiring restoration or stabilization, engaging with resource managers early in the process allowed the project team to identify a solution that allowed material to be kept in the system and avoided costly engineering on alternatives that would not be permitted.

Open water placement of coarse-grained material using hydraulic equipment was effective, efficient and protective of the environment. Strategic and frequent monitoring of the placement areas allowed for effective management of the placement. Hydraulic placement techniques can result in initial placement outside of targeted lines and grades, however this can be easily and quickly corrected with standard equipment. While turbidity in excess of standards was occasionally observed around the dredge and at the placement sites, it was localized and did not extend beyond the targeted placement areas, nor did it appear to impact water quality.

Monitoring of the benthic community and SAV will be conducted during 2022 and 2023 growing seasons to evaluate the recovery of the benthic community.

Lessons learned include:

- Engage with resource managers early, during preliminary engineering process to identify habitat areas that could benefit from the addition of managed sediment.
- Establish realistic success criteria that match both navigation and habitat goals.
- Monitor dredging and placement regularly during operations and adjust as needed.
- Have an adaptive management plan in order to be able to adjust to changing site conditions.
- Monitor conditions post placement to demonstrate value of EWN and promote trust.

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DATA AVAILABILITY

All data, models, and code generated or used during the study are included in the manuscript.

SABINE-NECHES WATERWAY: A CASE STUDY OF A COST EFFECTIVE AND TECHNICALLY DEFENSIBLE SAMPLING STRATEGY FOR A 35-MILE-LONG STUDY AREA

E.M. Bourne[1], C.R. Montgomery[2], B.N. Stevens[3], and S.E. Bailey[4]

EXTENDED ABSTRACT

Around the country, US Army Corps of Engineers (USACE) Districts and their non-federal partners (Port Authorities and Navigation Districts) are widening and deepening federally authorized ship channels to accommodate the larger ocean freighters that enter US waters through the improved Panama Canal. These ship channels often stretch for dozens of miles which means channel expansions generate millions of cubic yards of dredged material that require placement or disposal. Whether the dredged materials are placed in upland confined placement areas, used beneficially, or disposed of at an ocean dredged material disposal site (ODMDS), regulations require that these materials be evaluated to ensure: (1) no adverse impacts are created to humans or the environment during dredging and/or disposal; and (2) navigational hazards are not created as a result of open water placement.

New work channel improvement projects present unique challenges, such as the generation and placement of large, one-time quantities of dredged sediments that are produced from ship channels that are dozens of miles long. One such example is the Sabine Neches Waterway (SNWW), a 35-mile-long study area with eight ODMDSs at which placement may occur. This presentation will present the Sabine Pass Channel to Sabine Extension New Work Channel Improvement Project (CIP), SNWW, Texas, as a case study for cost effectively sampling a lengthy study area.

The SNWW CIP is intended to improve the efficiency of the deep-draft navigation system while protecting the area's coastal and estuarine resources. The SNWW CIP has been divided into two segments and eight reaches. This sampling and analysis effort only focused on the Entrance Channel segment and itsfour reaches (i.e., Extension Channel, Sabine Bank Channel, Sabine Pass Outer Bar Channel, and Sabine Pass Jetty Channel), as well as the Inshore Channel segment of the Sabine Pass Channel because sediments from this portion of the ship channel have a high likelihood of being placed in one of the eight ODMDSs. The primary objective was to determine the number of samples it would take to represent the geological formation of the new work sediment to be dredged as part of this work (USACE 2020).

Developing a sampling strategy for such a long project area presented conceptual, technical, and regulatory challenges. To reduce sampling and analytical costs associated with traditional dredged material management units (DMMUs), a technically justifiable Lines-of-Evidence (LOE) approach was used to

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develop the sampling locations for the SNWW CIP. This presentation will show how geotechnical information, sediment characteristics, surrounding land uses and regional spill records were integrated to develop a representative project-specific sampling plan for approximately 50 million cubic yards of dredged sediment the project would generate requiring disposal in designated ODMDSs.

The new work sample locations were based upon geotechnical borings from 2008 (USACE 2011) and were selected to be representative of general subsurface geological composition within the study area. The geotechnical boring logs and locations were evaluated in a stepwise manner to determine similarity in stratification and soil classification for the purposes of grouping the formation in the project area into testing "categories". This approach was project-specific and site-specific to this portion of the SNWW associated with new work widening and deepening. Based upon location and composition of the geotechnical borings, only four sampling locations within the channel were deemed necessary to represent and characterize the dredged material in the channel from the anchorage basin just inside the entrance channel out to the farthest point of the channel extension.

Each channel sample was a geological component of the new work dredge prism in the ship channel and consisted of a composite of three subsamples collected on a channel transect within the dredge prism for the widening and deepening of the ship channel.

This presentation will explain the evaluation and classification process that led to final selection of representative samples and will show how this approach can be adapted to other ship channels across the nation.

Keywords: Dredging, ODMDS, geotechnical borings, dredged sediment placement, representative sampling

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DATA AVAILABILITY

Some or all data or models generated or used during the study are available from the corresponding author by request.

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our non-federal sponsor the Sabine Neches Navigation District and staff at the Ocean Dumping Office at US EPA Region 6.

SABINE-NECHES WATERWAY: INTEGRATING LINES-OF-EVIDENCE TO SUPPORT THE OCEAN DISPOSAL OF NEW WORK CHANNEL EXPANSION DREDGE MATERIALS

B. N. Stevens[1], C. R. Montgomery[2], E. M. Bourne[3] and S. E. Bailey[4]

EXTENDED ABSTRACT

Completion of the Panama Canal Expansion Project has allowed for larger ships to travel through the canal and to ports around the US. These larger ships require the widening and deepening of federally authorized ship channels by US Army Corps of Engineers (USACE) Districts and their non-federal partners (Port Authorities/Navigation Districts). The sediments removed from these channel improvement projects, called new work materials, are generally considered unimpacted by anthropogenic activities. All dredged material that is to be placed at an authorized ocean dredge material disposal site (ODMDS) must be evaluated prior to placement under Section 103 of the Marine Protection, Research, and Sanctuaries Act (MPRSA) to ensure no adverse impacts are created during dredging/placement; new work channel expansion dredge materials are no exception.

This presentation highlights the Sabine Pass Channel to Sabine Extension New Work Channel Improvement Project (CIP), Sabine-Neches Waterway (SNWW), Texas, as a case study to illustrate how MPRSA Section 103 evaluations integrate physical, chemical, and biological testing of dredge materials to provide a lines-of-evidence evaluation for open water disposal. Coordination with regulatory agencies throughout the life of the project allowed for meeting regulatory requirements and obtaining concurrence for ODMDS placement.

Four sediment samples, representative of the five reaches of the SNWW and the new work material to be removed for the CIP, were collected. One sediment sample from each of the three designated reference areas was also collected. Co-located site waters were collected for each sediment sample. These representative samples were evaluated for physical properties including grain size, pH, moisture content, and percent solids. Collected sediments, surface waters, and elutriates were analyzed for concentrations of a site-specific list of chemicals of potential concern (COPC) including polycyclic aromatic hydrocarbons, pentachlorophenol, total polychlorinated biphenyls, pesticides, metals, ammonia, total organic carbon, dissolved organic carbon (water/elutriate only), total petroleum hydrocarbons, and total suspended solids (water/elutriate only). Toxicity testing guidance issued by US Environmental Protection Agency (USEPA)

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and USACE was used for the three different types of tests. Both physical and chemical elutriate toxicity were assessed using *M. beryllina* and *A. bahia*. Direct sediment toxicity was assessed using *L. plumulosus* and *A. bahia*. Bioaccumulation was assessed using *M. nasuta* and *A. virens.*

Site water results were compared to water quality criteria (WQC) specifically USEPA WQC and Texas State WQC. Site water COPCs did not exceed applicable screening criteria except for toxaphene and copper. Results for toxaphene for all samples were below the method detection limit, qualified "U", and reported at the reporting limit (RL); however, the RL exceeded applicable screening criteria. Elutriate sample results for toxaphene were like those for site water.

Sediment results were compared to National Oceanic and Atmospheric Administration SQuiRT Cards ERL/ERM and USEPA Region 6 (R6) criteria which were sourced from the Texas Commission for Environmental Quality saltwater sediment benchmarks. Detected concentrations for arsenic in one sample and nickel in two samples exceeded the NOAA ERL and USEPA R6 criteria. These analytes, and other metals detected above the Target Detection Levels (beryllium, cadmium, total chromium, copper, lead, selenium, and zinc), were analyzed in tissues from the bioaccumulation testing.

The result of the sediment bioassays indicated no acute toxicity. Results from the bioaccumulation studies were compared against Food and Drug Administration (FDA) action levels and Western Gulf of Mexico Background Concentrations (WGOMBC). For analytes selected as bioaccumulation COPCs, FDA action levels were not available; the only analyte to exceed WGOMBC levels was copper (detected in *M. nasuta)*. The copper concentrations were not statistically different than those reported for the reference area. The results of testing and lines-of-evidence analysis indicated no significant contaminant bioaccumulation.

Acute elutriate toxicity was observed in all four representative samples for both *M. beryllina* and *A. bahia*. Two of the samples had ammonia levels above concentrations that are expected to cause acute effects to test organisms. A toxicity reduction evaluation (TRE) was completed on the two elutriate samples with the highest concentrations of ammonia. The results of the TRE indicated that the observed toxicity in both species tested is likely due to ammonia rather than COPCs. The lethal concentration (50% survival) (LC50) is used to determine the limiting permissible concentration (LPC), the concentration that will not result in unreasonable adverse effects. However, some samples did not generate a LC50 and the use of a no observed effects concentration (NOEC) was used as the LPC for instances where the study did not yield a LC50 value. STFATE modeling was subsequently performed to determine if the LPC could be met within the boundaries of the ODMDSs. More information about STFATE modeling will be presented by Bailey et al. (2022).

This presentation will discuss how consultation with regulatory partners regarding innovative project specific refinements produced data that could be integrated into the lines-of-evidence for the MPRSA Section 103 evaluation while still protecting human health and the environment.

Keywords: dredging, MPRSA Section 103, regulatory compliance, toxicity testing, Lines-of-Evidence, open water placement

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Bailey, S.E., Montgomery, C.R., Bourne, E.M., and Stevens, B.N. "Sabine-Neches Waterway: Regulatory Compliance Modeling for Dredged Material Placement in a Ship Channel with Eight Ocean Placement Areas," *Proceedings of the Western Dredging Association Dredging Summit & Expo '22, Houston, TX, USA*, July 25-28, 2022

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DATA AVAILABILITY

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SABINE-NECHES WATERWAY: REGULATORY COMPLIANCE MODELING FOR DREDGE MATERIAL PLACEMENT IN A SHIP CHANNEL WITH EIGHT OCEAN PLACEMENT AREAS

S.E. Bailey[1], C.R. Montgomery[2], E.M. Bourne[3], and B.N. Stevens[4]

EXTENDED ABSTRACT

Millions of cubic yards of dredged material are discharged each year around the country as a result of ship channel widening and deepening. When these dredged materials are disposed of at an ocean dredge material placement site (ODMDS), the materials must be evaluated to ensure no adverse impacts are created during the dredging or placement of these sediments. The potential for impacts to the environment depends in part on the chemistry of the dredged material, but also how the material behaves upon release in the water column with respect to mixing and dilution, which is influenced by site-specific hydrodynamic conditions. Modeling is required to evaluate dilution of the dredged material discharge through space and time to ensure water quality compliance with Section 103 of the Marine Protection Research and Sanctuaries Act (MPRSA).

This presentation will demonstrate application of the Short-Term Fate of Dredged Material Model (STFATE) to evaluate ocean discharges of dredged material from the Sabine-Neches Waterway (SNWW) Channel Improvement Project (CIP). The STFATE model was required to accommodate different disposal schemes that would comply with regulatory requirements for ocean disposal for the portion of the ship channel south of the anchorage basin to the entrance channel extension. Eight ODMDSs located west of the navigation channel are available to receive material. ODMDSs 1, 2, 3 and 4 are irregularly shaped sites along the northern portion of the open-bay channel originally established to receive maintenance material; ODMDSs A, B, C and D are square sites along the southern portion of the open-bay channel, designated for new work material.

Elutriate samples prepared from representative sediments were evaluated for elutriate chemistry and toxicity. Although there were no exceedances of water quality criteria for chemicals of concern, elutriate bioassay testing displayed toxicity in three of the four samples. However, the results were confounded by either the presence of ammonia or insufficient toxicity to calculate an LC50. Given the lack of exposure of the new work material to anthropogenic contaminants, there was no reason to expect toxicity to marine organisms. Considering these factors, coordination with the regulatory agency resulted in an agreed upon approach to determine conservative, yet realistic permissible concentrations for each sediment regime.

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Typically, the limiting permissible concentration (LPC) is determined as the LC50 multiplied by an application factor (1%). Where ammonia was found to be the cause of toxicity, the LPC was calculated using an alternate application factor, 5% of the LC50. For instances where an LC50 could not be calculated due to insufficient toxicity, the no observed effects concentration (NOEC) was applied as the LPC. For the four elutriate samples, the LPCs were determined as 100% (NA), 50%, 10%, and 4.12%, which corresponds to dilution factors of 0, 1, 9 and 23.3, respectively. The dilution factor corresponds to the ratio of receiving water to elutriate volume that mixes to achieve the LPC concentration.

Dredged material discharge results in most of the solid particles falling to the ocean floor, while the fluid fraction mixes with the surrounding receiving water, creating a plume that becomes more dilute as it is carried with the currents toward the ODMDS site boundary. STFATE models the release of dredged material in open water, sediment deposition and transport and mixing of the plume. STFATE modeling was performed to determine the minimum discharge distance (or offset) from the ODMDS boundaries required to achieve sufficient dilution to meet the LPC within the designated site boundaries and buffer zones. Model input parameters were developed for each ODMDS to describe site conditions such as water depths, density and current conditions. For each of the sediment samples, the expected dredged material properties were characterized with respect to the mineral fractions (sand, silt, clay) including clumps and water. Dredged material properties were estimated based on two separate assumptions, one with overflow and one without. Characteristics of the dredge vessel and disposal operation were also provided as input. Model runs were performed based on two possible hopper dredges: the 13,500 cubic yard (CY) capacity Glenn Edwards, and a smaller dredge, Columbia, with a capacity of 4,350 CY.

Initial modeling showed that restrictions would need to be placed on either load size or placement location at most of the sites to achieve dilution at the site boundaries (Bailey and Schroeder 2020). Among the eight available ODMDSs, configurations and hydrodynamic conditions varied, resulting in approximately three hundred individualized STFATE analyses. The maximum distances required from the ODMDS boundary ranged between zero feet (ft.) for the sediment elutriate that did not display toxicity, and 4,800 ft. for the elutriate sample requiring the most dilution.

The evaluation resulted in a matrix of sediment dependent placement zones for each ODMDS. While currents are predominantly in a west-southwesterly direction most of the year, the direction shifts during summer months. Therefore, placement zones were developed to accommodate the predominant currents, where the offset distance is applied from the western boundary, as well as the potential for currents in any direction where the offset distance is applied from all boundaries. To accommodate currents in any direction, the modeled allowable placement zones were significantly narrowed such that material representing sediment sample SNWWNew-04 cannot be placed in ODMDS 1 or ODMDS 4.

This presentation will show how the STFATE modeling tool can be used to evaluate regulatory compliance for placement in the ODMDSs that vary widely in both depth, shape and annual currents. Results were used to develop operational guidance for open water disposal of dredged material from the Sabine-Neches Waterway.

Keywords: Dredging, STFATE, ODMDS, limiting permissible concentration, new work material.

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DATA AVAILABILITY

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SABINE NECHES WATERWAY (SNWW): DEVELOPING OPERATIONAL GUIDANCE FOR THE OCEAN DISPOSAL OF NEW WORK DREDGE MATERIALS

C.R. Montgomery[1], E.M. Bourne[2], B.N. Stevens[3], S.E. Bailey[4]

EXTENDED ABSTRACT

Testing of sediments for ocean placement under Marine Protection Research Sanctuaries Act (MPRSA) Section 103 includes chemical/physical analyses, Tier III biological testing and modeling of open water placement of sediments using STFATE software (Montgomery and Bourne 2020). In accordance with 40 CFR Part 227 and the Green Book (USACE 1991), this information is integrated using a lines-of-evidence approach to make the determination that no adverse impacts will be observed during dredging or placement.

For the SNWW Channel Improvement Project (CIP), initial STFATE modeling showed that the Limiting Permissible Concentration (LPC) would not be met when conservative default parameters were used in the modeling. Site-specific refinements (Bailey and Schroeder, 2020) were used in the second round of calculations. These calculations incorporated site-specific values for dredge load, disposal volume, vessel speed/direction and seasonal water current conditions to determine the areas of the ocean dredged material disposal sites (ODMDSs) that were available for disposal. Even with site-specific parameters, the modeling showed that not all of the area of the designated ODMDSs could be used for placement and that placement restrictions were needed. Such restrictions needed to be considered in advance of construction.

Disposal in open water must also adhere to the site-specific disposal requirements of the Site Management and Monitoring Plan (SMMP) (USACE and USEPA 2022) which stipulates how materials are to be placed in ODMDSs to ensure environmental and navigational hazards do not result from open water disposal. In addition to the testing required by MPRSA Section 103, the SMMP puts a 15-foot mounding restriction on disposal operations and restricts which ODMDSs can be used for sediment placement from the various reaches of the ship channel.

The development of project specific operational guidance incorporated the disposal restrictions of the SMMP with the STFATE calculations. Two approaches were developed: 1) placement of sediments based upon representative sediment composition that accounted for seasonal current variations; and 2) simplification of the field logistics by applying the scenario that used the most restrictive disposal area, as determined by STFATE. Both approaches accounted for the disposal restrictions of the SMMP, which only permits placement of new work materials in specific ODMDSs that align with channel reaches.

Keywords: STFATE, Site Management and Monitoring Plan, SMMP, dredging, ocean placement, MPRSA Section 103

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THE TECHNICAL EVOLUTION OF HYDRAULIC DREDGING

R. Wetta[1] and W. Wetta[2]

ABSTRACT

From its inception in the late 1800's, the hydraulic, or pipeline, dredge has been the dominant machine used for near-shore and in-shore sediment transportation in the United States. These dredges were initially deployed to maintain sufficient channel depths to facilitate river navigation, port access and development. Infrastructure development after World War II created an inland market for sand and gravel mining dredges used in the production of concrete and asphalt. The material dredging market is at least an order of magnitude larger than the navigational dredging market in the US. Other public and consumer concerns, such as environmental remediation and coastal restoration, have created niche dredging strategies and equipment.

Hydraulic dredges have evolved from steam powered, manually controlled devices to sophisticated, energy efficient machines designed to present minimal negative effects on the environment. The equipment being manufactured today incorporates advanced algorithms to predict pipeline lengths, elevations, particle grain size, and required transport velocities. Many of these machines assist the operator in controlling the dredge's navigational path and speed as well as the production rate. In the next several months, several dredges in North America will be deployed with autonomous capabilities that include artificial intelligence and real-time sub-surface imaging and mapping with the primary goal of increased efficiency with less risk. This paper will show the evolution of dredging equipment over the past 100+ years alongside other technologies, discoveries and inventions through the same time periods.

Key words: technology**,** efficiency, computers, development, visualization

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1. INTRODUCTION

As a general understanding for the basis of this paper we should first examine the definitions of discovery and technology. “Merriam-Webster (2021) defines a discovery as an act of finding out or learning of for the first time or something found or learned of for the first time. Alternatively, technology refers to methods, systems, and devices which are the result of scientific knowledge being used for practical purposes. It is the use of science in industry through engineering to invent useful things or to solve problems.” A few examples of discoveries may include a math equation, a new species of crab, land or something as simple as sliced bread. A few examples of technology may include the use of robotics in automobile manufacturing, a smart phone, a navigation application on a smart phone or a calculator to ease the burden of solving that complicated math equation. As many things change with time, so has our ratio of discoveries versus new technologies. While discoveries may have been much more common in the past, improved technologies far outweigh new discoveries today.

So why is technology so important to us today? Just a few examples of what technology can provide us include a better way to solve problems, a more accurate or efficient way of performing a task, short-term and/or long-term reduction in costs, increase in safety, environmental benefits and potentially produce new technologies or discoveries.

We can imagine it all starting off very crudely in the very beginning, where people may have used their hands as tools to dig trenches to allow water access to a hole in the ground as a reservoir or to dig a drainage channel to let water flow out of an undesirable ponding area. Then tools were created to help move the material much faster and more efficiently, maybe such tools as a handheld shovel. “According to Wonkee Donkee Tools (2022) history details that shovels were used during the Neolithic Age as people started farming, developing communities, and bartering with each other.” As simple of a tool as a shovel is to us today, it was technology in the time it was developed. And today we have many types of dredges or mechanical shovels that have made our digging and material placement so much more efficient.

1.1 History of the Dredge

There is ancient mention of harbor dredging by several authors. The seven arms of the Nile were channeled and wharfs built at the time of the pyramids (4000 BC), there was extensive harbor building in the eastern Mediterranean from 1000 BC and the disturbed sediment layers gives evidence of dredging. There is additional recorded history of forms of dredging from the third century BC onwards, the most extensive during the first century AD. The remains of three dredging boats have been unearthed; they were abandoned at the bottom of the harbor during the first and second centuries AD (Morhange, Marriner and Carayon, 2017). During the renaissance, Leonardo da Vinci (Figure 1) drew a design for a mud dredge from 15th to 16th century (Figure 2). More recently, dredges have been used during the construction of the Suez Canal from the late 1800’s to present day expansions and maintenance (Figure 3). The completion of the Panama Canal in 1914 relied extensively on dredging (Figure 4).

Figure 1. Leonardo da Vinci
(Digital Image from Shutterstock.com; accessed 19 January 2022)

Figure 2. Model of da Vinci Mud Dredge
(Digital Image from Alamy.com; accessed 19 January 2022)

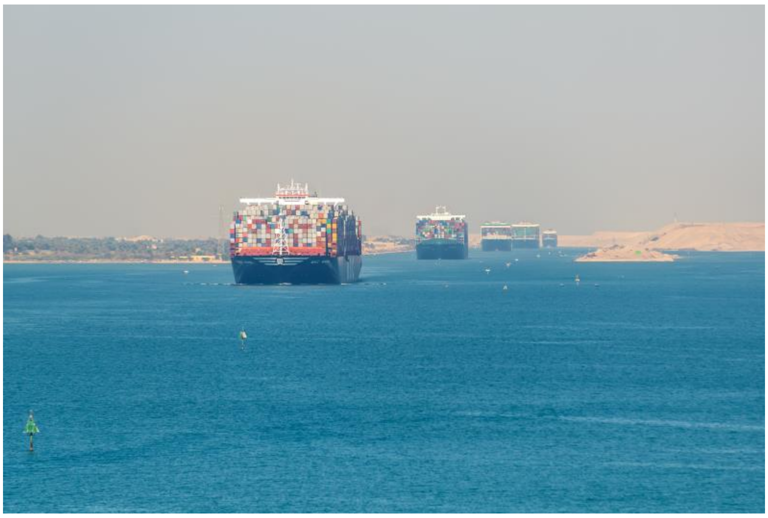

Figure 3. Suez Canal
(Digital image from Shutterstock.com; accessed 19 January 2022)

Figure 4. Panama Canal
(Digital Image from Shutterstock.com; accessed 19 January 2022)

2. WHERE HAVE WE BEEN

This paper will outline some major technologies that haven taken place over the past 100+ years alongside technologies that were being developed in the field of dredging for use in our industry. The examples of new technologies during the timelines are a simple attempt to show how new technologies are being developed and where we stood as the dredging industry with new technology.

2.1 Pre - 1890

The Industrial Revolution provided a time of economic transformation as we moved from a skilled hand craft- based economy to a machine and industry-based manufacturing economy. We began using new materials such as iron and steel. The use of new fuels such as coal, steam, electricity and petroleum, spawned growth in powered equipment such as the internal-combustion engine. New machines were developed to increase efficiency and output with lesser human energy inputs. Factories were developed and specialized labor sectors were created for production. We saw major developments in the transportation sectors including the steam locomotive, steam ships, automobiles and the airplane. Radio and the telegraph are examples of the developments in new communication systems. We began applying science to industry through this period of time and moved towards mass production and distribution of manufactured goods. Figure 5 outlines some of the technologies during this period of technological growth. Of note for the dredging industry is the early development of the swinging ladder dredge near the same time as the invention of the radio.

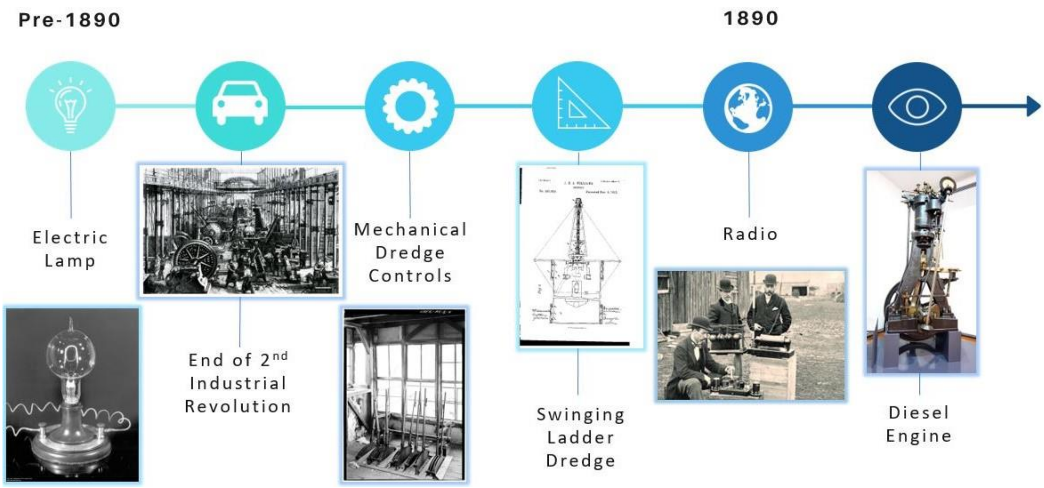

Figure 5. Timeline of pre-1890 technology development

2.2 1890 – 1910

In regard to the timeline of dredging, very early technologies were developed in this time period including tilting spuds, an electrically powered dredge, ball joints, trailing hopper dredge and the cutter suction dredge. It's interesting hearing recent mention by dredge manufacturers of the new technology of a fully electrically powered and environmentally friendly dredge as if this is modern technology. As we can see in Figure 6 below, the first electric powered dredge was developed prior to the 20th century. We can't confuse marketing with true technology. In this time period the dredging industry is holding its own with technological advancements that are happening in other industries.

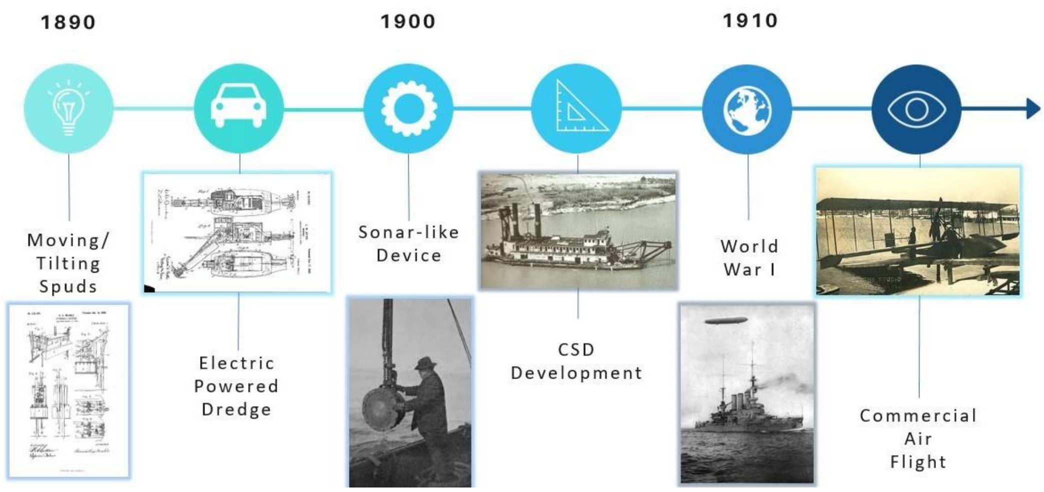

Figure 6. Timeline 1890-1910 technology development

Also notable in this time period is the early development of sonar technology; its primary purpose was detection of icebergs. This is also notable as discussed later in this paper on the current use of sonar technology and also how combining technologies can also lead to new useful technologies.

2.3 1910 - 1930

Again, major technologies and historical events in time begin to surface in the next few decades. The entertainment industry sees the development of talking motion pictures, television and in color movies. The development of radar surfaces with its primary development being conceived from

World War II. Industrial style pneumatic controls for dredges are developed during this time period as well. It is in the authors' opinion that this is the time period where we see other major technologies developing and the dredging industry to begin lagging behind. Maybe other developing industries provided more opportunity for investment than making dredging equipment more efficient? Figure 7 provides an overview of the technologies evolving during this time period.

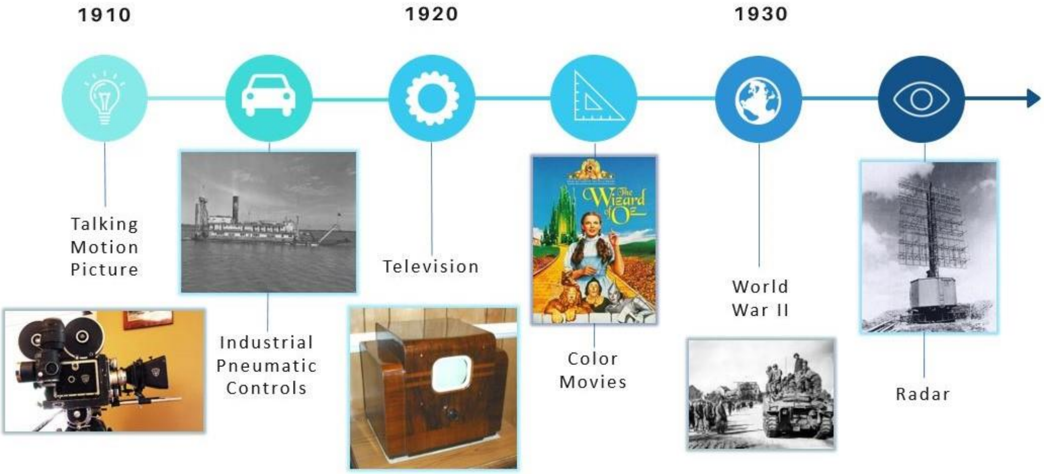

Figure 7. Timeline 1910–1930 technology development

2.4 1930 – 1960

The time period between 1930 – 1960 spawned a lot of technology stemming from the Great Depression to World War II to the Great Flood of 1953. The dredging industry saw the first dustpan dredge, the first diesel powered dredges, the invention of anchor booms, suction relief valves, hydraulic power machinery, laydown spuds and hydraulic dredge controls to name a few. Other developments going on around the world included the development of the Volkswagen Beetle, hydrographic surveys, commercial jet flights, the ball point pen, gas metal arc welding, development of the US Highway system and the credit card. Major developments during this timeframe are illustrated in Figure 8.

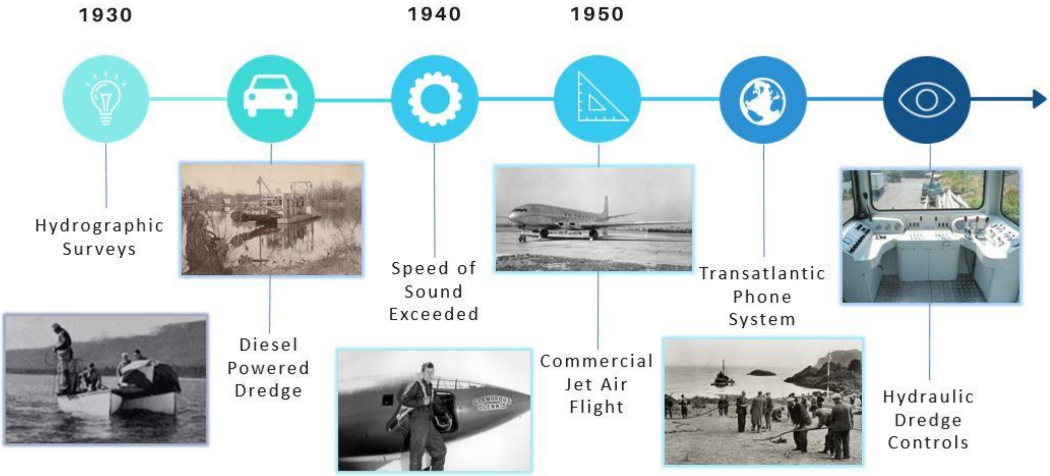

Figure 8. Timeline 1930-1960 technology development

2.5 1960 – 1970

As we enter the next few decades, we again start to see major events and new technology. We enter the time of the Vietnam War, the Cold War and we landed on the moon. As we move into the 1970' we see the first personal computers as well as the creation of the Internet. With the development of new technologies, new thoughts about the health of the Earth also begin to surface as seen with the development of the US Environmental Protection Agency by the establishment of the Clean Air Act in 1970. Our very own World Organization of Dredging Associations (WODA) was formed in a conference held in New York in 1967. During this same period of time many technologies also became available to the dredging industry. The gyrocompass, auger dredges, chain ladder dredges, amphibious dredges, the modern ball joint, industrial velocity meters, industrial densitometers, submerged pumps and polyethylene dredge pipe were all introduced to our industry to help advance dredging technology, efficiency and the accuracy of the dredging work we perform. A timeline of some of the technological advancements is illustrated in Figure 9.

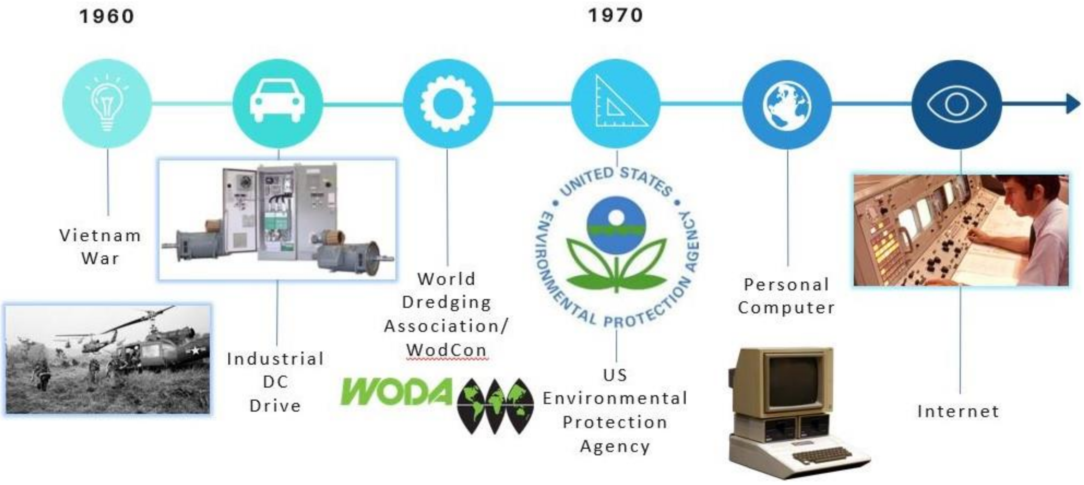

Figure 9. Timeline 1960-1970 technology development

2.6 1980's

As computer technology increased, the 1980's started a boom of other technologies that created efficiencies across the world. The 1980's saw new technologies including the civilian GPS, cell phones, the World Wide Web, Mac and IBM personal computers. The dredging industry introduced technologies including multibeam sonar and small portable dredges. In the US, superfund sites came into existence creating a new mega-market for environmental dredging. Figure 10 illustrates the timeline for these technologies.

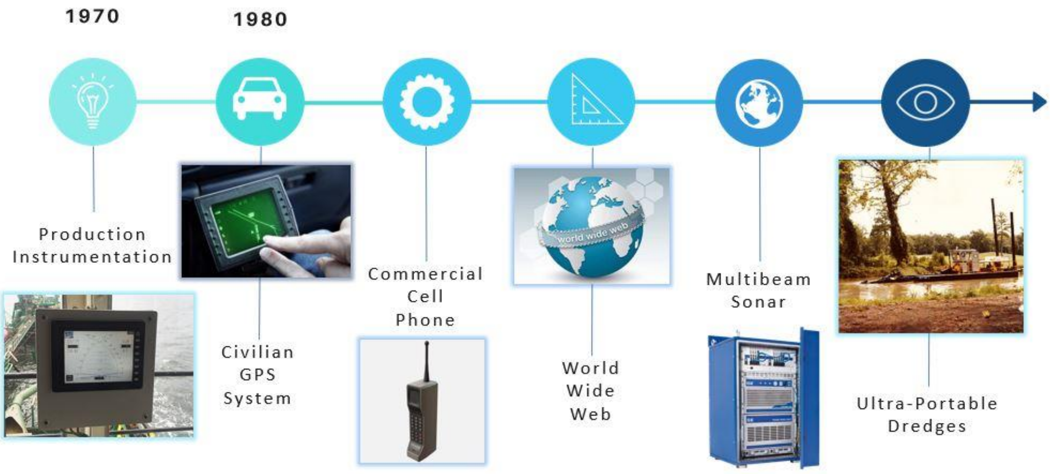

Figure 10. Timeline 1980's technology development

2.7 1990 – 2000's

During this timeframe we continue to see major advancement in computer and processing technology that spawned many new technologies. As a general reference, this time period included the dissolution of the USSR and 911. The technologies being developed include RTK for GNSS systems, notebook computers, USB hardware and connectors, Bluetooth technology, text messaging, DVR's, industrial AC drives, and the iPhone. The dredging industry also saw major technology enhancements and developments that began shaping the industry we know today. Deep mining dredges were being developed, extremely large and powerful dredges were being developed, underwater pumps appeared on swinging ladder dredges, PLC's and PC based operating systems began to be utilized on dredges and a major focus and design of environmental dredges was underway. Figures 11 and 12 illustrate these new developments as we carry these developments from 2010 to the present.

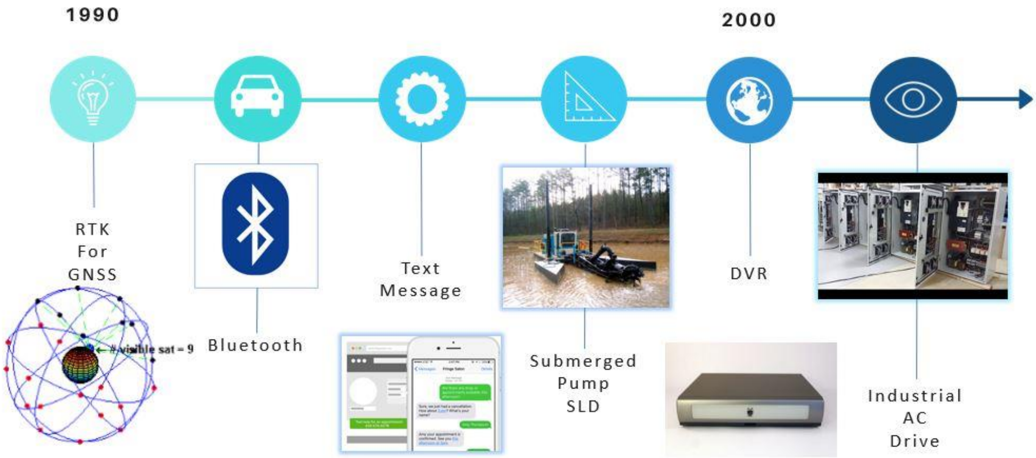

Figure 11. Timeline 1990–2000's technology development

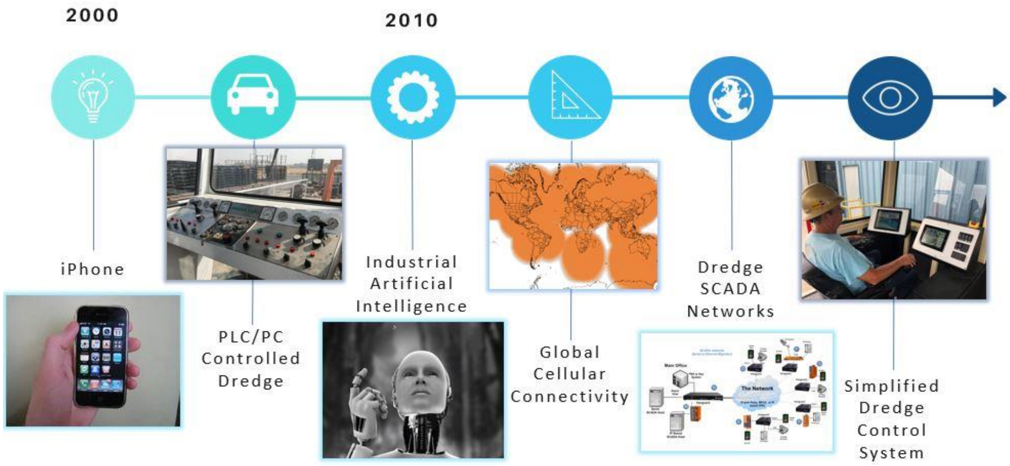

Figure 12. Timeline 2000–2010's technology development

2.8 2010's

This era included major dredging projects including the expansions of the Panama Canal and the Suez Canal to accommodate the increasing and massive size of ships. Climate change has also become a major global concern at this time. The dredging industry puts forth efforts as to how our industry can play a role in helping to address our climate change initiatives. We see the development of the iPad and artificial intelligence (AI) in the use of computers being widely applied to many industries. We enter the world of global cellular connectivity where it has become ever increasingly difficult to be disconnected. In our industry, dredges are using advanced SCADA systems, LNG powered dredges are being developed and dredge control systems are becoming more complex and efficient. Dredging efficiency is becoming increasingly prevalent and we see new patents for inventions such as the wide format swinging ladder dredge and gliding spuds. Towards the end of this decade, new visualization technology is becoming more available as technologies are being merged to create new technologies. Figure 13 illustrates a timeline of some of these events.

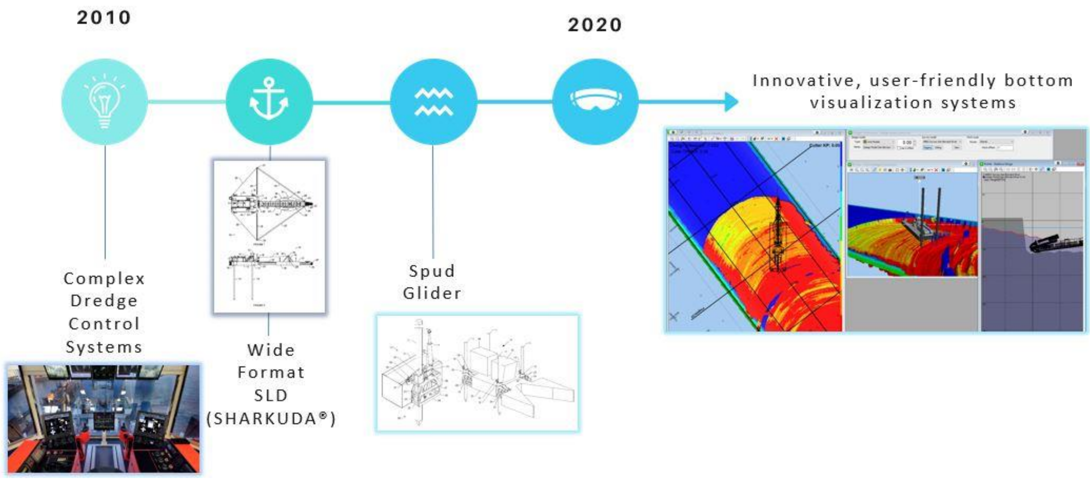

Figure 13. Timeline 2010–2020 technology development

3. THE DEMONSTRATION

We touched on the new visualization technology that is becoming popular today. The simplest form of explaining this new technology is through an example that was demonstrated at DSC Dredge, LLC's offices in the US. We had an employee volunteer to perform some tasks to see the theoretical results of moving from "dredging in the blind" to having a vision, below the water, of the dredging tasks to be achieved. We spread sand on a table to represent a channel in need of maintenance dredging. We put a blindfold on the volunteer, handed them a dust broom and dustpan and explained the task. The task was to remove the sand from the table using the broom and dustpan with no other information provided. The volunteer felt around the table to establish their location and began sweeping up the table. Once the volunteer concluded they completed the task, we observed the sand that was left behind. This first phase of the demonstration illustrated dredging without the use of current technologies such as location. We think of this as dredging with the use of only gauges, no production or location devices are available in phase 1 of the demonstration. While the volunteer was very meticulous and did a good job sweeping up the sand, there was obvious sand left behind that clearly represented under dredging or areas that were missed because of lack of instrumentation to let us know where we have been. The first phase is illustrated by the Figure 14 below noted as Phase 1.

Figure 14. Phase 1 without technology

Phase 2 of the demonstration was similar, but this time we provided verbal guidance to the volunteer. The volunteer remained blind folded. We let them know where to sweep, how well they were doing and when there we areas that needed additional sweeping. This phase of the demonstration represented the use of some existing technology with the use of location. Since the volunteer remained blindfolded but did have the advantage of verbal commands to represent location, this second phase of the demonstration represented technology for simple dredge monitoring. But this technology only knows the location of the excavating device and assumes the material is removed if the excavation was in that known location. Whether or not the material is really being removed could not be confirmed and the volunteer had to assumed that the sand was removed once they swept a location. The volunteer performed the task better that in the previous phase, but we still observed that material was again left behind in many areas. The second phase results are illustrated by the Figure 15 below noted as Phase 2.

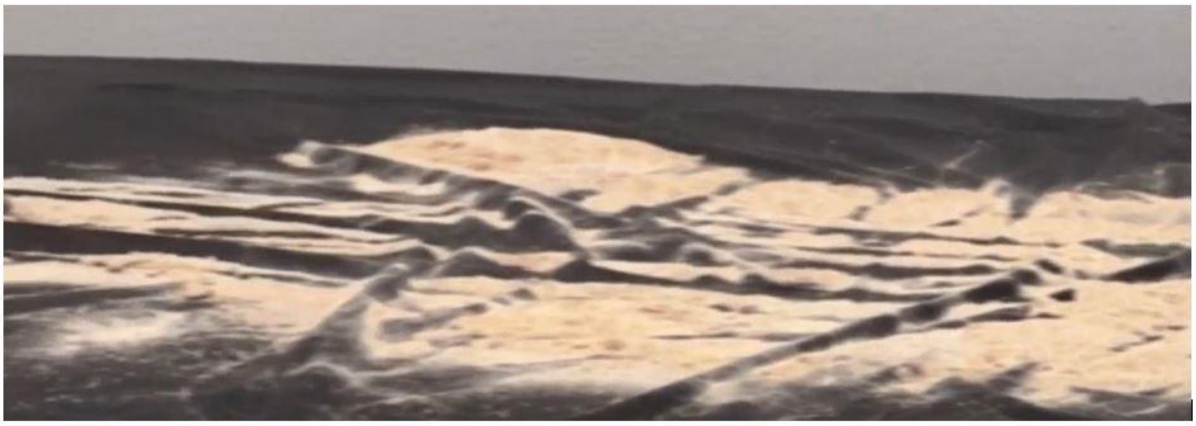

Figure 15. Phase 2 position technology

The final phase of the demonstration was to represent the newest available technology that is currently available to the dredging industry. The table was again set with sand to represent the channel that needed maintenance dredging. We asked the volunteer to remove the blindfold and to sweep the table. This represented devices for location (GNSS) and underwater visualization (sonar) so the volunteer, functioning as a dredge operator, had the tools available for efficient and accurate dredging. We even noticed the volunteer back up to get the sand that was missed on the first sweep demonstrating the attention to minimize under dredging or the quick retreat to capture the "caved-in" material. The results of this phase were as expected with the best results and a task performed both efficiently and accurately. The third phase results are illustrated by the Figure 16 below noted as Phase 3.

Figure 16. Phase 3 advanced technology

4. WHERE WE ARE NOW

Like many other industries, the dredging industry is able to merge different technologies to form new technologies. We can think of some simple examples of technologies being merged to create new technologies, even if the technologies were developed over varying periods in time. According to "Haus of Tool, the invention of the screwdriver is believed to be from the late 15th Century. The oldest artifacts point towards the original screws being flathead type." We know that the screw itself has evolved to have a Philips head and many other types of hex heads, etc., all for different purposes and efficiencies. As electrical power became more common, Black & Decker brought us the corded powered screwdriver in the early 1920's, several hundred years after the invention of the screwdriver. In the early 1960's, Black & Decker also introduced the first cordless power tools which led to the development our battery powered (cordless) screwdrivers that most of us use today.

We are also currently merging technologies in the dredging industry to create new technologies. One of the newer available and affordable technologies is dredge visualization and monitoring systems that was referenced in the third phase of the demonstration above. By combining GNSS navigation systems (location), multibeam sonar (visualization) and remote connectivity (real-time), we can now move away from dredging in the blind to understanding the area we are dredging and to see the work that we do below the water. This includes monitoring the dredging work in real-time, having the capability of viewing it remotely and to capture the data to be used for additional analysis A snapshot of the technological advancements described is illustrated in Figure 17 below.

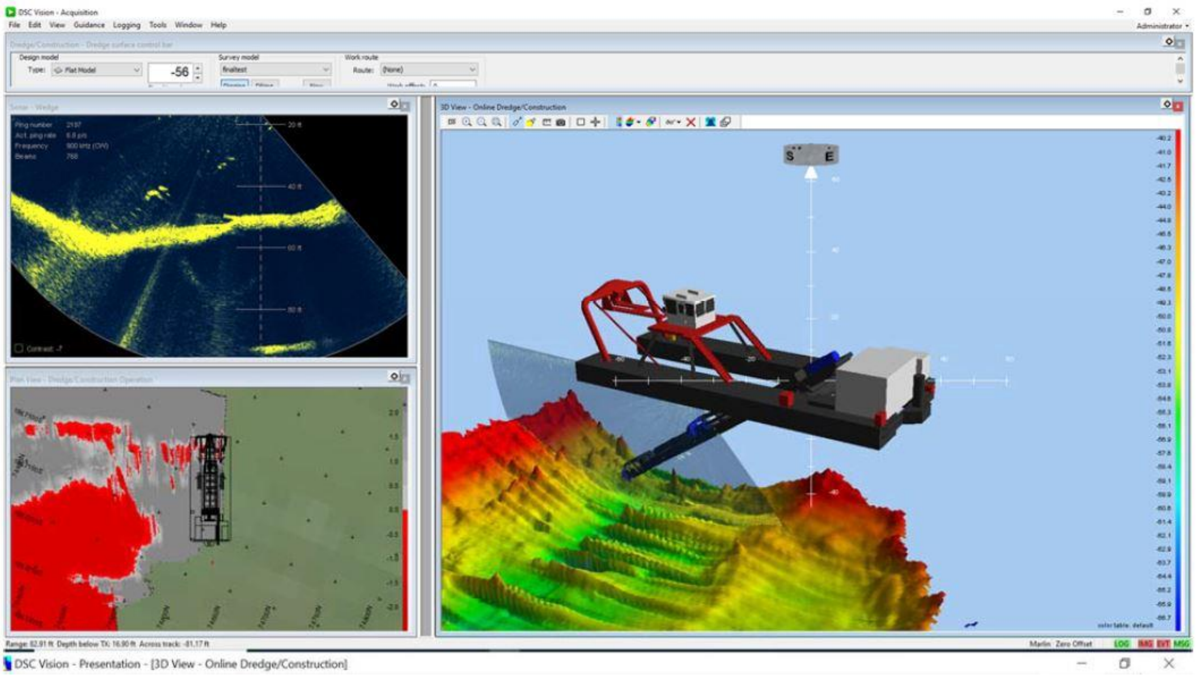

Figure 17. Dredging Visualization

DSC Vision, and several competitive products, are a combination of existing, proven hardware and software technologies that have been integrated onto a dredging vessel for real-time viewing of the dredging process below water. These systems consist of highly accurate global navigation satellite systems with corrections, inertial measurement units, multibeam or imaging sonar systems, computers with integrating software for each device, and remote connectivity to the cloud or other computer networks. Imaging sonar software, traditionally used for forward looking and location tasks, has been modified to produce accurate bathymetric data on dredges due to their slow and repeated movement over targets. Imaging sonars, while not accurate enough yet for navigational dredging, have provided wide adoption into underwater mining operations due to the low capital cost compared to traditional multibeam sonar systems.

Unlike traditional dredge navigation systems that assume bottom removal when an excavator passes over a coordinate, these new systems display the result of the dredging device at the time of excavation, and then resulting changes over time as the sonar beams pass over that coordinate. Because the sonar beams are arranged into a wedge, like a hand fan, engineered placement of the sonar unit allows imaging of the in-situ area in front of the dredge as well as dredged area behind the dredge. The limit on range is controlled by the depth of the bottom, sonar placement, and type of sonar used.

5. WHERE WE ARE GOING

As these new visualization systems become embedded into the dredge operating systems, the use of artificial intelligence will provide dredge operators new tools to increase dredge efficiency and to reduce operating cost. Once the dredge becomes aware of how the bottom reacts to differing swing speeds, cutter speeds, over and under dredging, suction velocity, river current, etc. new or more efficient techniques can be suggested or applied as needed. These systems will also change their solutions as rapidly as the material or job conditions change. It is conceivable that this technology will replace manned dredge operations in non-navigational areas and in areas with high risk to injury or accident.

6. SUMMARY

The authors believe this new visualization technology can provide new possibilities for the dredging industry that will increase efficiency and accuracy, thus lowering project costs. The new technology has a safety component by lessening traffic on the water by eliminating redundant surveys. The efficiency and reduced traffic will also have an environmental component in the reduction of emissions and having an overall positive effect on climate change initiatives. The question is how long will it take our industry to do the research and development of this technology to truly understand and use its benefits? We have the ability to stop dredging in the blind and to enjoy all the benefits that go along with this technology. Will we adopt this technology or lag behind other industries as they make progress?

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INNOVATIVE APPROACH TO PRODUCTION MONITORING AND PROCESS CONTROL WITH ADM NON-NUCLEAR DENSITY METER

J. Peters[1]

ABSTRACT

This paper focuses on the non-nuclear Alia Density Meter (ADM) that takes the disadvantages of traditionally used gamma density gauges away and is also fully compatible with the United Nations Sustainable Development Goals (SDG). The paper explains the working principle and calibration and shows with a practical approach the benefits for production monitoring and process control. It becomes clear that this new instrument provides significant benefits with a fast return on investment.

Keywords: Dredging, density, dredging cycle, dredge production optimization, calibration.

INTRODUCTION

For optimal control of the dredging process, production monitoring with a density and flow meter is indispensable.

Traditionally, density was measured with a gamma density gauge. This was the only sensor that could cope with the abrasive slurry because it could be mounted as a clamp-on system outside the slurry. However, it also has some significant disadvantages. Besides the enormous amount of paperwork, calibration effort and need for an RSO officer, this method is slow and not always accurate.

For a few years, several more or less successful new technologies for non-nuclear density measurement have been developed and tested (Batey 2012, Wei et al. 2019). In the current paper, the working principle of the Alia Density Meter (ADM) is presented to make the specific benefits and requirements clear. Also, factory and field calibration are explained, to demonstrate that this density meter is easy to use. To show its practical use, measurements in comparison to gamma density gauges will be included, and user cases will be described as well.

The strength of the current paper is the combination of a theoretical explanation of the working principle, and a demonstration of the density meter in real life. In our opinion a real innovation does not end on the drawing board but makes end users happy with the new benefits.

WORKING PRINCIPLE OF THE ALIA DENSITY METER

The Alia Density Meter (ADM) provides accurate density measurements of abrasive liquid/solid slurries. To this end, the ADM is positioned inline in the slurry pipeline. The density is measured under dynamic conditions — when the slurry is flowing — but can also be measured for non-flowing, stationary fluids.

The technical working principle is based on basic proven physics, the second law of Newton. Inside the density meter, an actuator exerts a force with a known value and frequency onto the slurry, while a set of accelerometers measures its resulting acceleration. Newton's second law of motion F = m x a relates the

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force F to the acceleration a via the mass m, and this is used to calculate the mass of the slurry. The slurry volume is a known factor inside the measuring tube of the meter. This means that the slurry density, which is the mass per volume unit, is nearly immediate and accurate, regardless of pipe diameter or slurry composition.

The ADM housing has a steel measuring tube inside with an exchangeable rubber wear liner (dark grey in Figure 1) through which the slurry flows. The measuring tube is mounted with a couple of leaf springs which allow it to translate up and down perpendicular to the slurry flow.

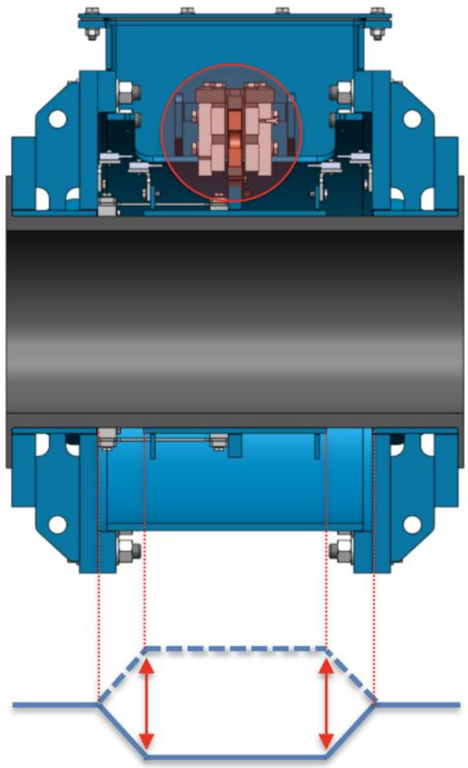

Figure 1. Cross-section of the Alia Density Meter.

A custom actuator (circled in Figure 1) exerts a force on the measuring tube with a hardly noticeable amplitude in the sub-millimeter range with a frequency between 30 and 180 Hz. Two accelerometers, which are positioned on the measuring tube, measure the resulting acceleration of the measuring tube with the slurry flowing through. Two additional accelerometers are positioned on the housing to provide input to compensate for external influences on the measurement.

This simple but fast and accurate working method has been implemented in a robust and simple design. With its basic electronic components and highly sophisticated control software, it is an excellent example of high-tech mechatronics.

Mechanical Model

As a first approach, Newton's second law of motion F = m x a applies to each mass, including the measuring tube with the slurry inside. The actuator exerts the force F onto the measuring tube, the (central) accelerometers measure its resulting acceleration a, and the mass m is calculated as the ratio of both.

When corrected for the mass of the measuring tube itself, the mass of the relevant slurry inside this tube is known. Dividing this mass by the inner volume of the movable part of the measuring tube yields the density of the flowing slurry inside the measuring tube. (Pre-)calibration of the density meter is necessary to fit process parameters to the slurry density.

However, we need to do some adaptation to this simple model. The measuring tube is not an isolated 'standalone' system, and indeed is connected to the rest of the world: via the leaf springs, the measuring tube is suspended inside the density meter.

Figure 2 shows the mechanical model of the suspended measuring tube including slurry flowing through, with mass m_1 and (center of mass) position x_1. L(eft) and R(ight) suspension consists of two springs with stiffness k_L or k_R, and damping d_L or d_R.

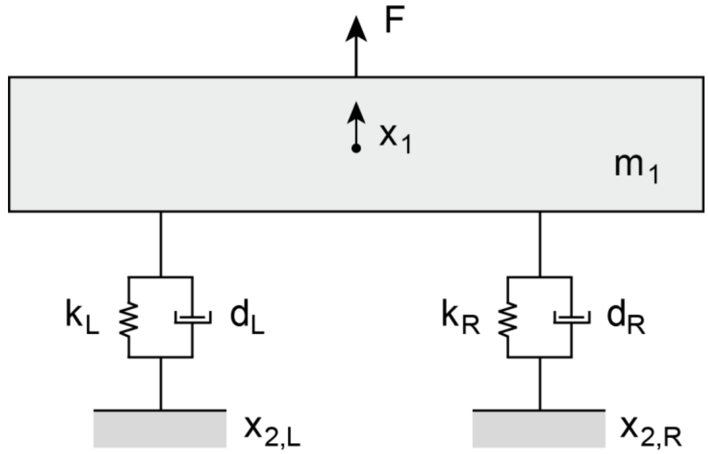

Figure 2: Alia Density Meter mechanical model

Based on the exerted force F and the measured acceleration a, now re-written as x''_1 (the second derivative of the position with respect to time), the mass m_1 of the movable part of the measuring tube including the slurry can be calculated. The equation of motion for this configuration is now:

$$m_1x''_1 = F - k_L(x_1 - x_{2,L}) - k_R(x_1 - x_{2,R}) - d_L(x'_1 - x'_{2,L}) - d_R(x'_1 - x'_{2,R}) \quad (1)$$

where the terms at the right side of F comprise the adaptation of the ‘simple model’ due to the suspension of the tube.

To calculate the mass, the stiffness and damping values need to be known. As these values vary with temperature and pressure, these parameters are continuously updated, i.e., based on the exerted force and the measured acceleration. The mass, stiffness and damping values are jointly calculated.

If the measurement tube vibrates in the way as described here using the actuator, the tube will resonate around its natural frequency which has a typical value of approx. 60 Hz. However, to identify the entire system including the stiffness and damping parameters, a wide excitation bandwidth around the natural frequency needs to be considered. More specifically:

- at frequencies below the natural frequency, the frequency response as measured by the central accelerometers is mainly determined by the stiffness of the system;
- around the natural frequency, the measured frequency response is mainly determined by the damping;
- at frequencies above the natural frequency, the frequency response is mainly determined by the mass.

FACTORY CALIBRATION TESTS

To be sure that the ADM will operate according to specifications, the device is subjected to in-house tests before shipment to the clients. A factory calibration is conducted in-house to determine the system parameters of the device. Here it is checked how accurate and repeatable a slurry density measurement is. To this end, the density meter is filled with media with a known density at a standard pressure of 2 and 8 bars overpressure and room temperature, and it is left there for several hours. By comparing the density measurement values of the ADM as a 'device under test' with the known density of the inserted media, the ADM is calibrated how to calculate the measurement data to the correct slurry density.

In practice, these in-house test media are air, water with an accurately known density of 1.0 kg/dm^3, and glycerine with an accurately known density of 1.26 kg/dm^3. Factory test results are shown in Figures 3 and 4. Water is used for practical purposes and its abundance, and glycerine is used since its density is approaching that of a typical slurry.

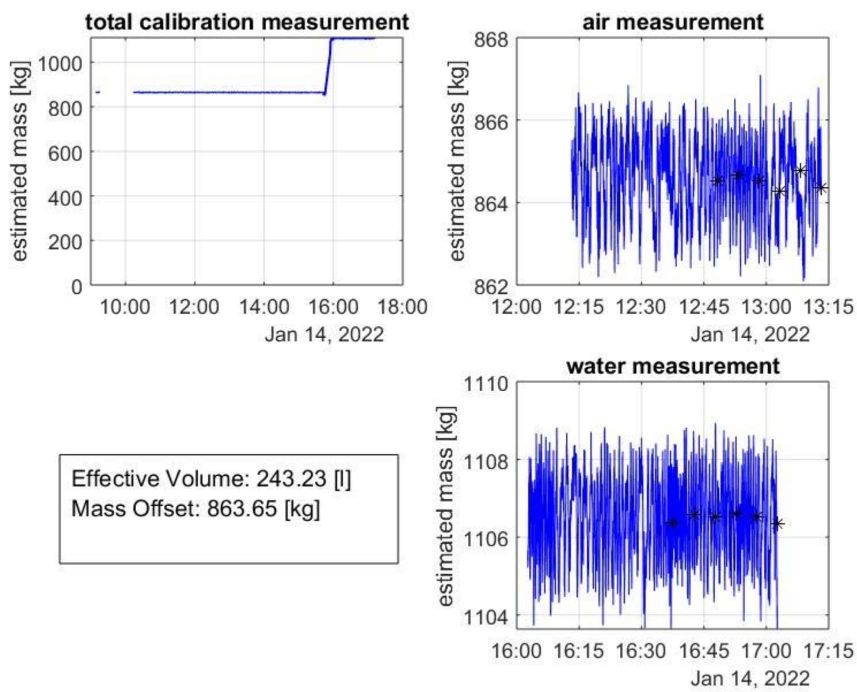

Figure 3. Factory calibration test results with air (both images at the top) and water.

The ADM is only allowed to leave the factory if the accuracy and repeatability are within the required specifications, which is usually in the range of 0.5% of the full scale. Factory default system parameters are stored inside the ADM.

Each ADM is delivered fully factory calibrated to the client. In most cases, the instrument will function plug-and-play or only needs an offset correction. Offset correction can be done very easily by running water (or another slurry) with a known density through the ADM and pushing the calibration button on the local display of the ADM. In some cases, with difficult vibration situations, more sophisticated calibration is needed which can be done by Alia Instruments qualified service engineers. This is often possible via a remote connection.

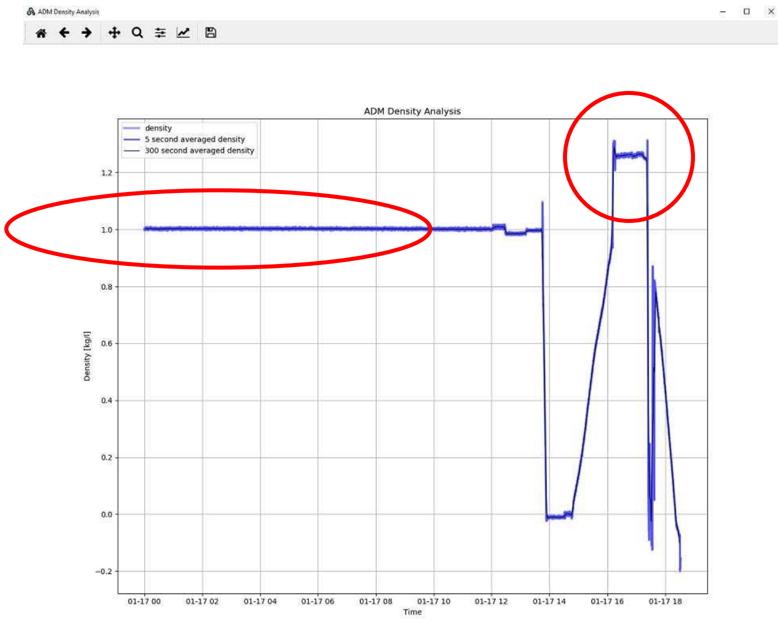

Figure 4. Factory calibration test results with water and glycerine. Density 1.0 kg/dm^3 for water and 1.26 kg/dm^3 for glycerine are indicated by red oval and red circle, respectively.

FIELD MEASUREMENTS

Since nuclear density sensors have been the standard for a long time, it is interesting to compare the ADM against a nuclear sensor. It has to be kept in mind that slurry density measurement using an inline instrument is measuring something else than a clamp-on device. This makes it even more interesting to compare the ADM with a nuclear sensor. Figure 5 shows the measurement results of a slurry after the thickener in a rather stable process inside a mine.

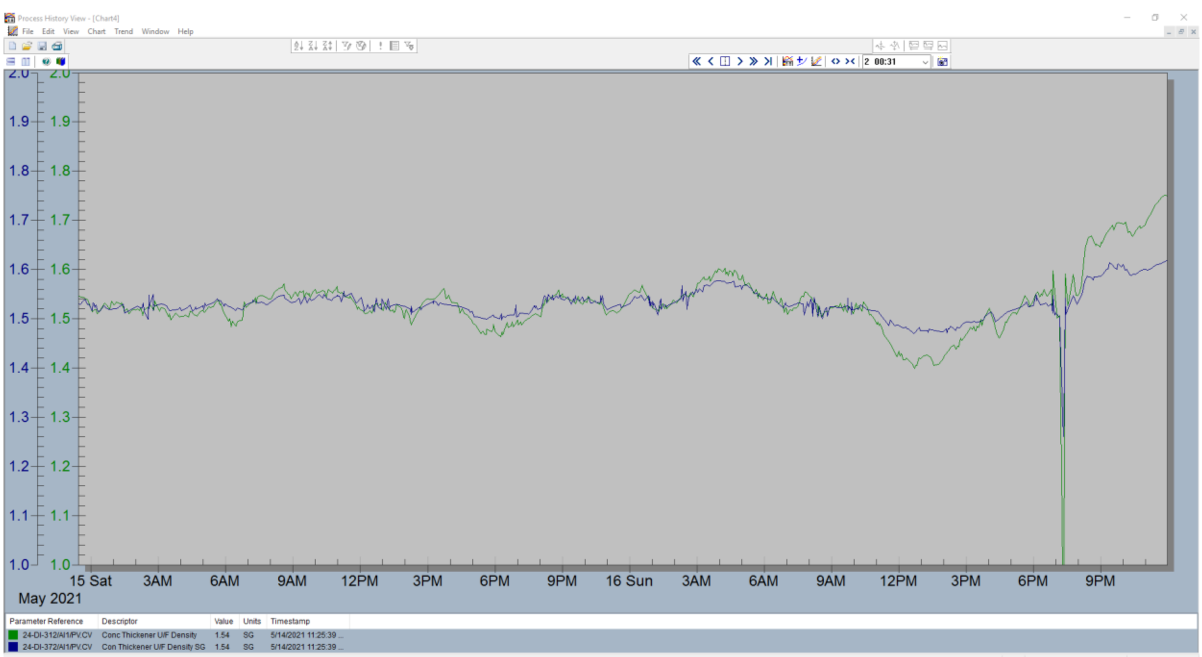

Figure 5. Comparison of nuclear density meter (blue) with ADM (green) in a mining slurry after the thickener.

The measured densities of the nuclear device and the ADM are comparable. However, there are some clear differences: the green line of the ADM in Figure 5 shows more variety in slightly higher or lower measurements. This is a typical situation seen in other measurements where the ADM is compared to a nuclear instrument because the ADM measures the complete volume of the slurry pipeline.

Another important difference that cannot be seen in Figure 5 but becomes very clear in Figure 6 is the fast response of the ADM to density variations. To make this clear, we need to zoom in on ADM measurement data. Looking at the response time of the meter, we should focus on a short time frame. The example in Figure 6 comes from a test where measurements were performed while buckets of sand were thrown at 15:11 and 15:24 in the hopper that fed the pipeline. The response is clearly visible and even the number of buckets can be seen and counted. This shows that this full-volume measurement device gives more exact and especially very fast information.

Figure 6. Test with ADM 100 inserting extra sand buckets in a fine sand slurry.

These results show that the ADM performs comparable to a traditional nuclear meter, and that the fast and accurate measuring results offer interesting opportunities for dredging.

Operational Conditions

To obtain good results from the ADM some basic but important operational conditions need to be mentioned:

1. Proper mounting of the ADM. The ADM should be firmly attached to a fixed structure.
2. Wear liner conditions. The operating pressure should be at least 14 psi to push the rubber wear liner against the wall of the measuring tube. The wear liner condition should be regularly inspected, and the liner should be exchanged in a regular maintenance program.
3. Vibration resistance. Hindering vibrations should be out of reach of the excitation band that ADM is working in. The ADM has sensors positioned on the outer housing to compensate for vibrations. If plant vibrations interfere with the operation of ADM, corrective measures can be taken. Excitation bands can be shifted, if necessary, or a certain disturbing frequency can be isolated.

The following sections provide additional practical information on mounting the ADM and the wear liner.

Mounting ADM

Figure 7 shows an example of a firmly attached ADM. The instrument is connected to the pipeline on both sides and the pipes are fixed to a firm constructional element of the vessel. As can be seen in this figure, there is an inspection hatch behind the ADM to check the condition of the rubber liner.

Figure 7. Firmly attached ADM to bucket dredger by Rohr-Idreco.

Another example of a firmly attached ADM is shown in Figure 8 with the ADM mounted on a skid. The ADM is mounted inline in the pipeline by its flanges and supported by stiff supports that fixate all motion directions. This is an excellent application example of the use of a mobile production platform for long pipelines. The dredger in the background is connected to the skid by a floating pipeline. Adding a flow meter gives complete production information in the long pipeline from dredger to final deposition point.

Figure 8. Firmly attached ADM 450S on a skid at VINCI Construction Maritime et Fluvial for a dredging project in the Rhône River.

Wear Liner

In the ADM shown in Figure 9, the rubber liner was mounted in September 2018 and is still in good order based on visual inspection in September 2021. This is a long time and not representative for other abrasive situations. Alia Instruments advises to exchange the rubber liner at least every year in a planned maintenance program. Another interesting fact about this instrument is that it has been field calibrated in January 2019 and has since then worked properly without recalibration.

Figure 9. ADM 350 on Flevozand (The Netherlands), aggregate dredging.

Table 1 shows the wear liner thicknesses for several ADM types. Especially for dredging applications and medium cutter suction dredgers, the ADM NA 20 and NA 26 have extra liner thickness for long operation time.

Table 1. Wear liner thickness (in inches) for several ADM types.

ADM type	Wear liner thickness (inch)
ADM NA 30	0.85
ADM NA 26	1.24
ADM NA 20	1.85
ADM NA 18	0.85
ADM NA 14	0.66
ADM NA 12	0.73

Since the instrument is placed in a horizontal position, in exceptional cases when a heavy pocket of material is dredged the flow speed can become sub-critical. As the ADM measures the full volume density it also notices any developments in deposition. This can be seen as an advantage by having an early warning for deposition and can prevent downtime. On the other hand, it does not give the expected information for production monitoring since the deposited material is not flowing through the pipe.

Ongoing research shows many examples that concentration in the pipeline is not the same in any position (Miedema 2017). ADM gives a good average, considering the full volume of the pipeline.

In the next application example, an aggregate dredger is described that has the ADM mounted under an angle. This way deposition is prevented. In general, an ADM can be mounted in any position: horizontal, vertical, or under any angle.

APPLICATION EXAMPLES

Production Monitoring for Aggregate Dredging

On the dredger shown in Figure 10, production monitoring has been installed to assist the mainly inexperienced operators to achieve constant production. ADM and flow meter provide the input for the cross-needle meter that is mounted in the cabin (see Figure 11). Big advantage is that a non-nuclear device can be easily installed as an add-on on an existing dredger. The combination of simple installation and calibration makes it easy to upgrade an existing dredger and improve its productivity by better information and visualization for the operators. On this dredger, the ADM has been placed under an angle to prevent deposition since heavy slurries with a lot of gravel can cause deposition.

Figure 10. Alia Density Meter in aggregate dredging application.

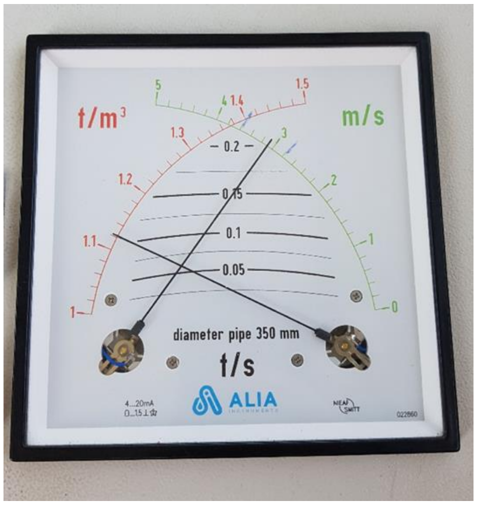

Figure 11. Cross-needle meter for productivity purposes.

Production Optimalisation on Trailing Suction Hopper Dredgers

One of the first prototypes of the ADM was placed on a trailing suction hopper dredger (TSHD), the Shanti Sagar IV owned by Adani Ports and Special Economic Zone Ltd. Recently new instruments have been delivered to replace the old instruments (see Figure 12). The ADM is used by the intelligent automation on board of this vessel.

A very interesting feature of the ADM for production monitoring on board of trailing suction hopper dredgers is of course the fast and accurate density value. This enables the operator to achieve optimal control of the drag head.

But not only the operator. Most advanced dredgers nowadays use the density signal for automation purposes, such as the Poor Mixture Overboard (PMO) function in automation. A fast response time of the ADM saves minutes per dredging cycle.

Figure 12. Alia Density Meter 650 mm on board of TSHD Shanti Sagar IV.

In Table 2 it is demonstrated that the fast response time of the ADM increases efficiency and provides a very short payback time. A typical dredging cycle consists of sailing empty, dredging, sailing full and dumping. During the dredging part efforts are concentrated to fill the hopper with a dense load as fast as possible. In the example below, some assumptions are made to calculate savings made on the dredging part of the cycle. The number of saved minutes per cycle is achieved by replacing a relatively slow nuclear device with the ADM. This very simple example shows that an investment in a non-nuclear solution can be recouped quickly.

Table 2. Savings calculation example by using an ADM.

Number of saved minutes per cycle	1	minute
Average number of dredging cycles per day	8	cycles
Uptime of dredger per year	80	%
Total cost of TSHD per day	50,000	USD
Total savings	81,111	USD

An interesting extra benefit is that if more good mixture gets into the hopper and less is pumped overboard that also saves fine material appearing as a plume after the vessel. Also, if less poor mixture is pumped into the hopper it saves time getting rid of it through the overflow. This also reduces plume, and really helps with sustainable dredging.

CONCLUSIONS

This paper has addressed the working principle, calibration and some application examples of the ADM non-nuclear slurry density meter. In general, the ADM measures comparable values to a nuclear density meter, but with additional benefits. The following conclusions can be drawn:

- ADM technology is based on proven Newton's second law of motion.
- Density measurement is independent of slurry properties (velocity, temperature, etc.) or materials (sand, clay, gravel, magnetic, etc.) because the measurement does not take place in and is not dependent on the slurry (properties).
- The measured density is comparable to that of nuclear meters, with fast response and full volume value as additional benefits.
- The ADM can be easily installed and calibrated in different applications on dredgers
- Benefits provide a quick return on investment.

Current developments will improve the robustness of the instrument for all application conditions.

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CITATION

Peters, J. (2022), "Innovative approach to production monitoring and process control with ADM non-nuclear density meter", *Proceedings of the WEDA Dredging Summit & Expo '22, Houston, TX, USA, July 25-28, 2022*.

DATA AVAILABILITY

Data are proprietary or confidential. These data may be provided upon request and if the original owner gives permission, they can be provided with restrictions on republication and use.

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LARGE SCALE, 4-COMPONENT, SETTLING SLURRY TESTS FOR VALIDATION OF PIPELINE FRICTION LOSS MODELS

R. Visintainer[1], G. McCall II[2], A. Sellgren[3] and V. Matoušek[4]

ABSTRACT

A 4-component model for settling slurry pipe flow has been previously described by Wilson and Sellgren (2001) to predict pipeline friction loss over a range of slurry compositions: from fine to coarse particle size, narrow to broad particle size distribution, and low to high solids concentration. Further development of the model was undertaken by Visintainer et al. (2017, 2021) based on a comprehensive set of laboratory tests in 203 mm (8 inch) and 103 mm (4 inch) pipelines. The goal of the present work is to validate the applicability of the 4-component model to larger pipeline sizes. To that end, a second comprehensive test program, similar to those previously run, has been carried out in a 489 mm (20 inch) pipe loop. In all, 24 tests were performed with particle sizes ranging from minus 40 μm to 25 mm, d_{50} particle sizes from minus 40 μm to 11 mm and delivered solids concentrations from 4% to 40% by volume. Particle size distributions varied from very narrow to very broad, with d_{85}/d_{50} ratios ranging from 1.5 to 320. The resulting data have been compared to the current formulation of the 4-component model in order to assess the applicability of the model for use with larger pipelines.

Keywords: Settling slurry, Pipeline friction models, Pipeline pressure gradient, 4-Component Model, Slurry testing.

INTRODUCTION

The solid-liquid flow of slurry in a pipeline exhibits various regimes according to the mixture velocity, particle size distribution, carrier fluid properties and pipeline geometry. Various schemes have been developed to classify and model these (Shook et al., 2002, Wilson et al., 2006). A 4-component model was originally proposed and further developed by Wilson and Sellgren to predict settling slurry pipeline friction loss over a range of slurry compositions and flow regimes: from fine to coarse particle size, narrow to broad size distribution, and low to high solids concentration (Sellgren et al., 2014). In the 4-component methodology, pipeline friction losses are calculated by a weighted average approach of the standard Newtonian pipe flow model, combined with three established settling slurry models for pseudo-homogenous, heterogeneous and fully stratified flow. The solids are partitioned into four volume fractions or "components" and each is assigned to one of the four sub-models based on the characteristic particle sizes which bound their range of application.

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- **The "Carrier Fluid" fraction, *Xf*** includes all particles <40 μm. These solids are assumed to "combine" with the liquid, altering its density and dynamic viscosity.

- **The "Pseudo-homogeneous" fraction, *Xp*** includes all particles >40 μm, up to a limit of 200 μm.

- **The "Heterogeneous" fraction, *Xh*** includes all particles larger than the upper limit of *Xp* and smaller than the lower limit of *Xs*.

- **The "Stratified" Fraction, *Xs*** includes all particles larger than 0.015 times the pipeline diameter.

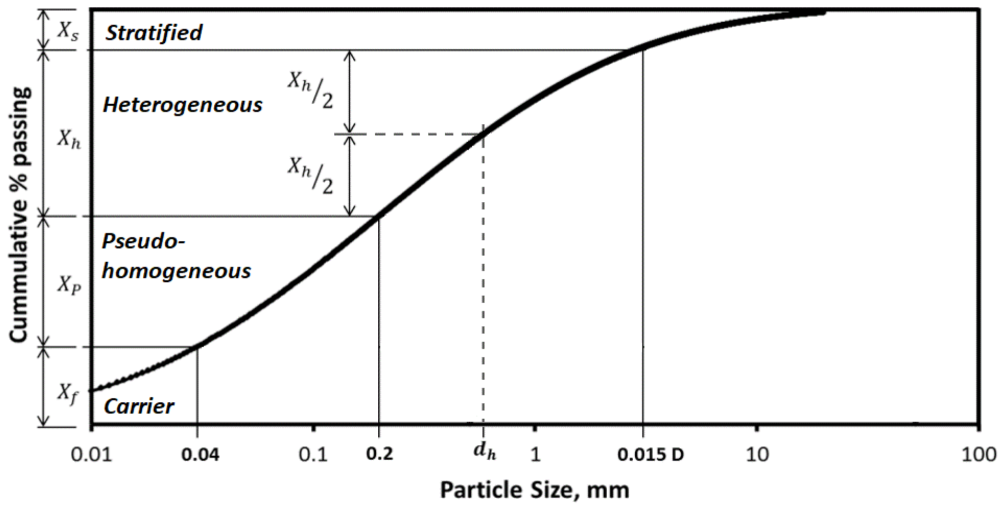


Figure 1. Representation of the 4-component fractions and their particle sizes.

The model was further developed by Visintainer et al. (2017), based on a comprehensive, settling slurry test program performed in 203 mm (8 inch) and 103 mm (4 inch) pipelines, with particle sizes ranging from minus 40 μm to 12.5 mm, and delivered solids concentrations from 4% to 38% by volume. Analysis of the data suggested the introduction of two new empirical parameters to account for the interactions between components. The revised model provided good agreement with the experimental data over the entire range of the test program.

In Visintainer et al. (2021), the 103 mm pipe test program was further extended to higher density solids, consisting of magnetite at a specific gravity S_S = 4.75. Further refinements were proposed, including a variable particle size boundary for the *Xf* fraction depending on S_S, and an expansion of the empirical parameter *A*" used with the pseudo-homogeneous *Xp* fraction.

However, it is recognized that industrial pipeline systems are designed and built at scales considerably larger than the equipment used in the above-mentioned test programs. Furthermore, key variables used in the new empirical parameters are strong functions of pipeline diameter, such as the velocity at the limit of stationary deposition and the threshold velocity at full suspension (i.e., pseudo-homogeneous velocity). Without a similar, comprehensive data set in some larger system, extrapolation of the models beyond the tested 203 mm (8 inch) pipeline size becomes increasingly uncertain. Therefore, a series of tests was undertaken in the GIW Hydraulic Lab using a newly constructed 489 mm (20 inch) pipeline and GIW 24x24 TBC-57 pump.

Detailed descriptions of the 4-component model are given in the references, including an online web page address at which a summary of the latest formulation may be accessed.

DESCRIPTION OF THE EXPERIMENTS

A total of 24 tests were conducted according to a similar methodology, and using a similar range of slurry compositions, as the previous 103 mm and 203 mm tests, albeit on a larger scale. The pump, sump and sampling system are shown in Figure 2, and a portion of the pipe loop in Figure 3.

Figure 2. Pump, sump, and sampling system for the 489 mm (20 inch) pipe loop.

The system was driven by a GIW 24x24 TBC-57 pump with 610 mm suction, 610 mm discharge and 1435 mm impeller. The system volume, including sump, was approximately 60 m^3. Slurry was returned to the top of the sump to maximize the active slurry volume, and thus increase the inventory of available solids and reduce particle degradation during testing. Flow into the sump was positioned below the water line to avoid introducing air into the slurry.

An entrance section of 100 pipe diameters was provided upstream of the friction loss measurement section, which was 50 pipe diameters in length. An additional pressure tap was provided midway in the friction loss section, so that the pressure gradient over the entire section could be compared to the gradients over the first and second half. This was done to identify variations in flow dynamics along the length of the measurement section which might be caused by insufficient entrance length or the development of flow instabilities.

Figure 3. *Top*: 489 mm system showing first half of measurement section (red) and inverted U-loop for SG measurement with magnetic and ultrasonic flow meters.
***Bottom*: 489 mm system entrance section (yellow) and de-aeration stack (purple).**

Slurries were "constructed" by combining four individually sourced silica and granite based products, each with a particle size distribution falling substantially within one of the four component particle size limits, as follows:

- Representing the "Carrier Fluid" fraction ***Xf*:** A silica "rock flour" with approximately 88% passing 40 μm.
- Representing the "Pseudo-homogeneous" fraction ***Xp*:** A silica sand product with approximately 90% falling between 40 μm and 0.2 mm.
- Representing the "Heterogeneous" fraction ***Xh*:** Granite screenings and gravel from a local quarry, with approximately 85% falling between 0.2 and 7.3 mm.
- Representing the "Fully Stratified" fraction ***Xs*:** A screened granite product with approximately 95% larger than 7.3 mm and a top-size of 25 mm.

During testing, these fractions were combined in various “blends” from the narrowly graded individual products, through various combinations of two or three or all four together. Volumetric concentrations of the components were selected to maximize the correlations with previous tests. The target test matrix is shown in Table 1. Each consecutive integer in the test matrix indicates a fresh loading of material. Approximately 475 tonnes of solids were used during these experiments.

Table 1. Test matrix showing target percentages for volumetric concentration.

Test	1a	1b	2	3a	3b	4a	4b	5a	5b	5c	5d	6a	6b	6c	6d	6e	7a	7b	7c	7d	7e	8a	8b	8c
Xf																	10	10	10	10	10			
Xp								5	5	10	10	5	10	10	10	10					5	5	7.5	10
Xh				10	10	20	20	10	10	20	20					10				15	15	10	15	20
Xs	5	10	20		5		10		5	5	10			5	10	10		5	10	10	10	5	7.5	10
Total	5	10	20	10	15	20	30	15	20	35	40	5	10	15	20	30	10	15	20	35	40	20	30	40

The actual concentrations and fraction contents achieved during testing varied from the target values, in some cases significantly, due to uncertainties in the loading procedure and the fact that adjustments were not made during running, in order to minimize run time and solids degradation. Furthermore, even though steps were taken to limit particle degradation, such as loading at velocities below the limit of stationary deposition, particle degradation was significantly higher in the 489 mm pipe loop than seen in the previous 203 mm and 103 mm loop tests. This was due to several factors:

- The loading time was longer due to the larger system volume.
- The relative length of the 489 mm system was shorter and its relative sump volume smaller, compared to previous tests. This was a practical consideration driven by the available space and driver power, and resulted in more frequent recirculation of solids.
- The operating velocities during testing were higher, due to the higher deposition velocities seen in a 489 mm pipe.
- The system was less stable during operation, especially when the coarser *Xs* solids were the dominant fraction, requiring longer run time intervals to stabilize operation between data points, and longer averaging intervals for data collection.

In any case, the actual measured concentrations and particle fraction contents based on samples taken during testing were used in the model calculations and analysis. These are shown in Table 2. Note that all solids concentration values cited in this paper, both measured and modelled, represent delivered (not in-situ) volumetric concentration.

Table 2. Actual measured fraction content and volumetric concentration.

Test	1a	1b	2	3a	3b	4a	4b	5a	5b	5c	5d	6a	6b	6c	6d	6e	7a	7b	7c	7d	7e	8a	8b	8c
Xf	.07	.07	.12	.04	.11	.12	.15	.04	.07	.10	.12	.05	.04	.05	.10	.10	.74	.55	.49	.25	.25	.14	.11	.17
Xp	.06	.04	.03	.10	.17	.12	.13	.35	.24	.36	.32	.82	.83	.42	.33	.18	.17	.14	.12	.14	.23	.12	.11	.15
Xh	.18	.15	.16	.73	.31	.65	.33	.50	.38	.37	.29	.10	.10	.10	.10	.25	.04	.06	.07	.38	.28	.51	.58	.57
Xs	.69	.75	.69	.12	.41	.12	.39	.11	.32	.17	.27	.03	.03	.43	.48	.47	.05	.25	.31	.24	.24	.23	.19	.12
%Cv	5.7	10.5	21.7	9.4	13.9	18.4	26.6	16.8	21.2	34.4	39.1	3.9	7.4	11.0	15.6	22.3	11.5	13.3	18.2	32.3	34.9	21.9	32.8	40.4

Once loaded, the pipeline velocity was increased to approximately 10 m/s, which represented the maximum practical velocity obtainable in this experimental setup, but also a velocity which is greater than typical operating velocities in industrial slurry systems of this size. All tests were run from the maximum velocity downward until stationary deposition was observed, and sometimes slightly beyond. In some cases, the slurry was bedded out in the system and an additional (often coarser) fraction added for another test. In this way, 2 to 5 different tests might be accomplished within a single loading cycle. No cycle was taken through more than 5 loadings before all solids were flushed and the next cycle of tests started with fresh material.

The data collected at each velocity included slurry flowrate (by magnetic induction meter), slurry density (by inverted U-loop as described in Wilson et al., 2006), loss section pressure drops (as described above), and slurry temperature. The data were sampled at 100 Hz and averaged over an interval of 10 to 20 seconds, depending on the stability of the system. Whenever possible, data were taken during steady state operation, the exception being at velocities near deposition where the system was inherently unstable. Unstable points near deposition were taken for reference only and were not used in the evaluation of the model. As mentioned above, the system was also sometimes unstable when large fractions of *Xs* were present, especially when *Xh* and *Xp* solids were largely absent. In these cases, the instabilities were usually cyclic and longer data collection times were used to capture a total average value.

A clear section of piping was installed just downstream of the measurement section to allow observation of the flow dynamics and to identify the velocity at the limit of stationary deposition. Unfortunately, this clear section fractured partway through the test program and was replaced with a piece of steel pipe. However, an alternate indication of deposition was provided by measurement of the temperature differential between heated probes on the top and bottom of the pipe. The onset of a stationary deposit altered the heat transfer rate at the bottom of the pipe and created a sudden, observable change in the magnitude of this temperature differential on the order of 0.10 to 0.15 ^{o}C. This alternate method compared well with the visual observations available during the first part of the test program and was subsequently used for determination of stationary deposition throughout the remainder of the program.

As with previous tests, slurry samples for measurement of the particle size distribution (PSD) were taken using a device specifically designed for these experiments. During sampling, a pneumatic linkage was used to lift the sump inflow pipe above the water line by about 0.5 m. A trapezoidal slurry sampler was then passed through the flow stream, cutting through the entire cross section of the 489 mm inflow. Sample cutter dimensions and velocities are given in Table 3. A picture of the device can be seen in Figure 4, in position for sampling, but with the inflow pipe not yet raised. It can also be seen in Figure 2, positioned immediately beneath the raised inflow pipe. A slurry sample was taken at approximately 7.5 m/s during each of the 24 tests. This velocity was selected on the criteria of being high enough to ensure good mixing of the various particle sizes, but also representative of the interesting range of velocities for industrial applications.

The methodology for processing the PSDs was as follows: All >6.3 mm particles were first cut from the entire sample by a manual wet screening, dried, sieved by size, and weighed. The remaining <6.3 mm solids were dried and weighed in aggregate, then well mixed and split by multiple passes through a sample splitter to produce a representative sub-sample weighing 0.3 to 0.6 kg. This sub-sample was then wet sieved by size down to 40 μm, the individual size fractions dried and weighed, and the total weight for each size fraction calculated based on the ratio of the sub-sample to the total <6.3 mm sample weight. Finally, the <40 μm solids, which were collected in the wet sieve runoff, were captured in a filter press, dried and weighed, and the total sample weight of <40 μm solids calculated as above.

Table 3. Sample cutter details.

Pipe system	opening (mm)	Sampler velocity (m/s)	Slurry velocity (m/s)	Ave. sample volume (litres)
489 mm (20”)	76 x 760	~ 2.0	~ 7.5	~ 22

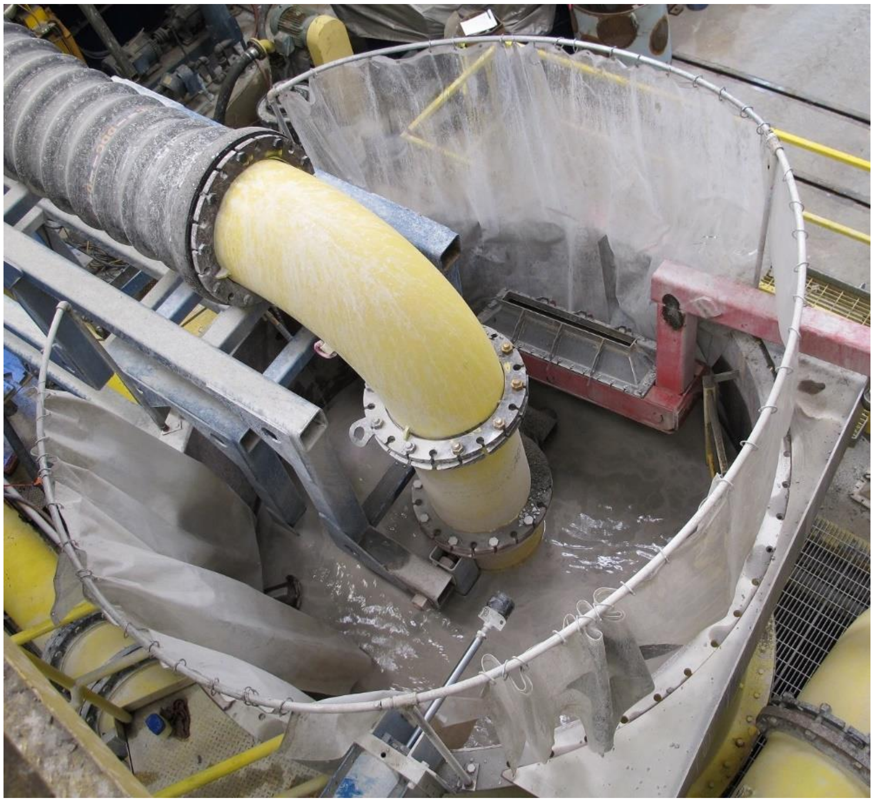


Figure 4. Slurry sampling device in the 489 mm loop.

A number of clear water tests were performed throughout the test program to determine pipe wall roughness, an important parameter for the carrier fluid pressure gradient calculation. Due to the polishing effect of the slurries, this was consistently found to be 0.002 mm.

ANALYSIS OF THE DATA

Figure 5 shows the dimensionless pressure gradient data (i_m), expressed in meters of 1000 kg/m^3 water per meter of pipe, for all 24 tests from the 489 mm loop. This provides a qualitative representation of the scope of the data. Each test is labelled with the dominant particle fractions present and the average total solids concentration during testing at velocities above deposition. The measured PSDs obtained during sampling for these tests are shown in Figure 6.

Due to the nature of closed loop testing, slurry concentration will change slightly with velocity, and slurry temperature will change with time. Therefore, in comparing the measured data to the predictions of the 4-component model, calculations were made using the individual measured values of flow velocity, slurry concentration, and temperature at each data point.

Figure 7 displays the relative error between the measured data and the 4-component model calculation for all data points above stationary deposition. The % error is defined as follows:

$$\% \text{ error} = 100*(i_{m,\,\text{CALCULATED}} - i_{m,\,\text{MEASURED}}) / \; i_{m,\text{MEASURED}} \qquad (1)$$

where i_m is the dimensionless pressure gradient expressed in meters of 1000 kg/m^3 water per meter of pipe.

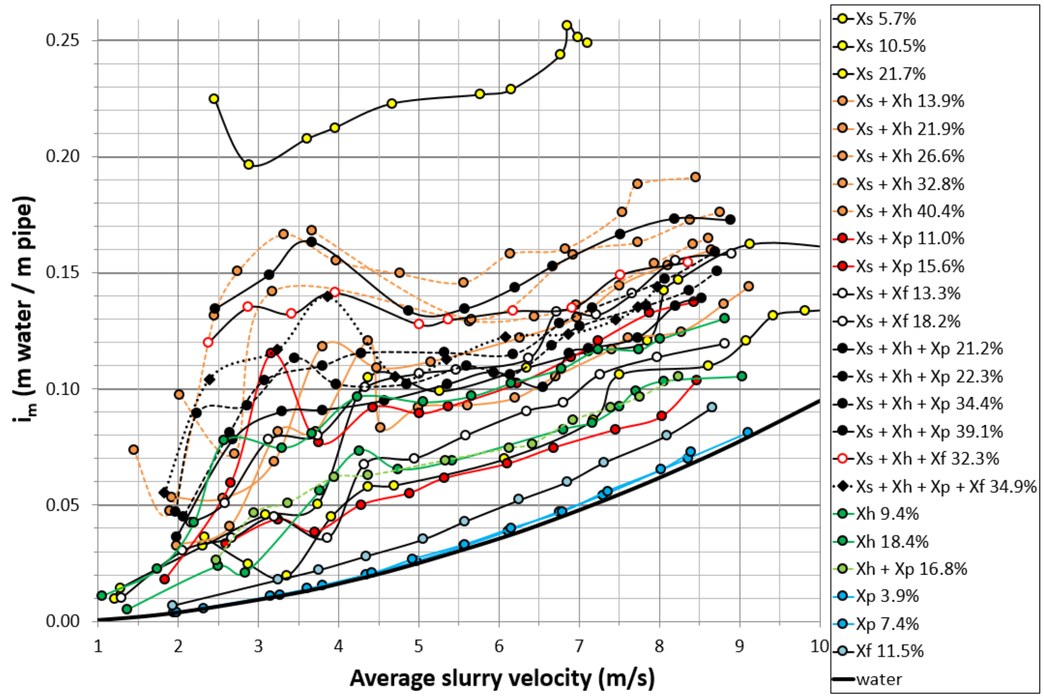


Figure 5. Dimensionless pressure gradient data measured in the 489mm pipe loop.

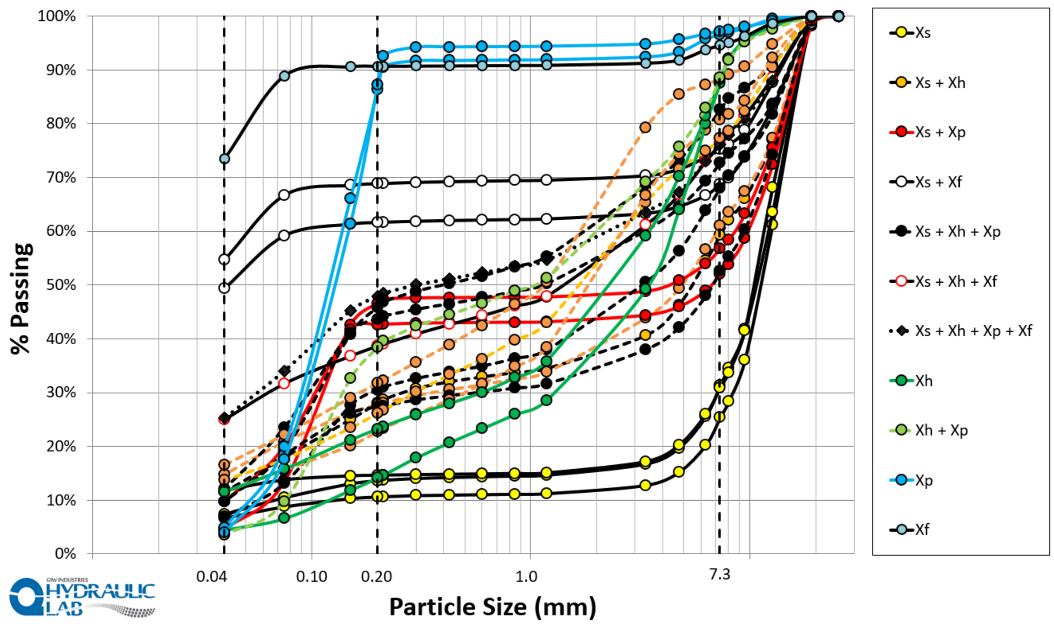


Figure 6. Particle Size Distributions from test samples in the 489 mm loop.

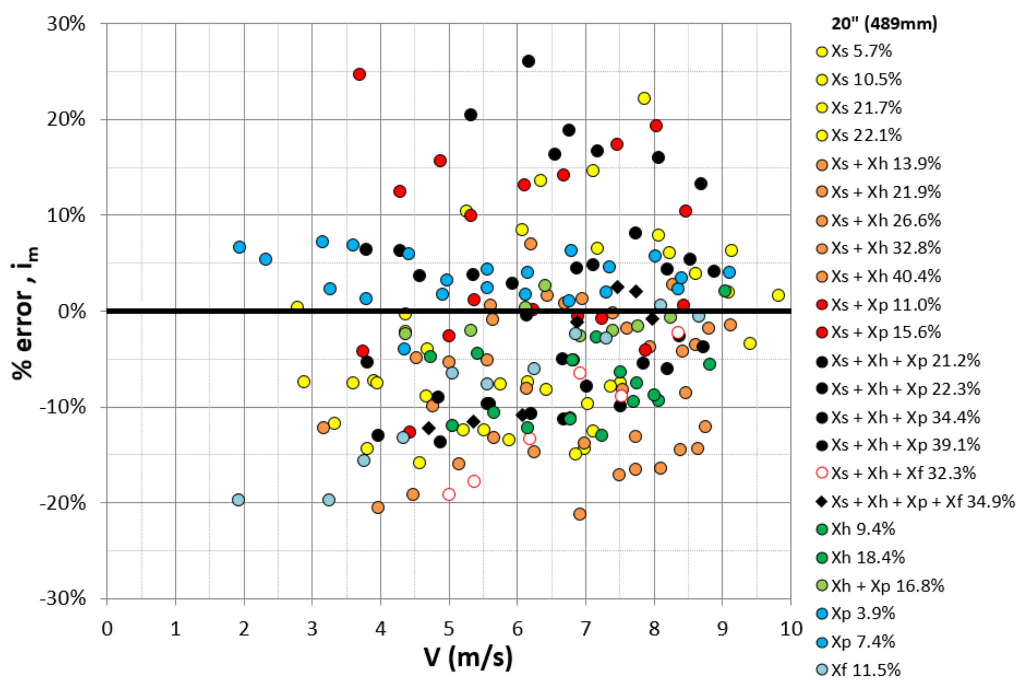


Figure 7. Pressure gradient % error (calculated vs. actual) for the 489 mm pipe.

The spread of error for the 489 mm tests exceeded that seen in previous tests, with an average error of 8.0%, compared to 5.4% and 5.5% for the 203 mm and 103 mm tests respectively, as seen in Figure 8. This may be due to the less stable operation of this larger, closed loop system, as mentioned above. However, since the magnitude of the friction losses are smaller in the larger pipe, the average absolute error in the pressure gradient was similar to previous tests, in the range of 0.010 m H_2O/m pipe. Note that the two *Xs+Xf* tests were omitted from Figure 7 and from the error analysis, as there was doubt concerning their validity. This is covered in more detail in Figure 17.

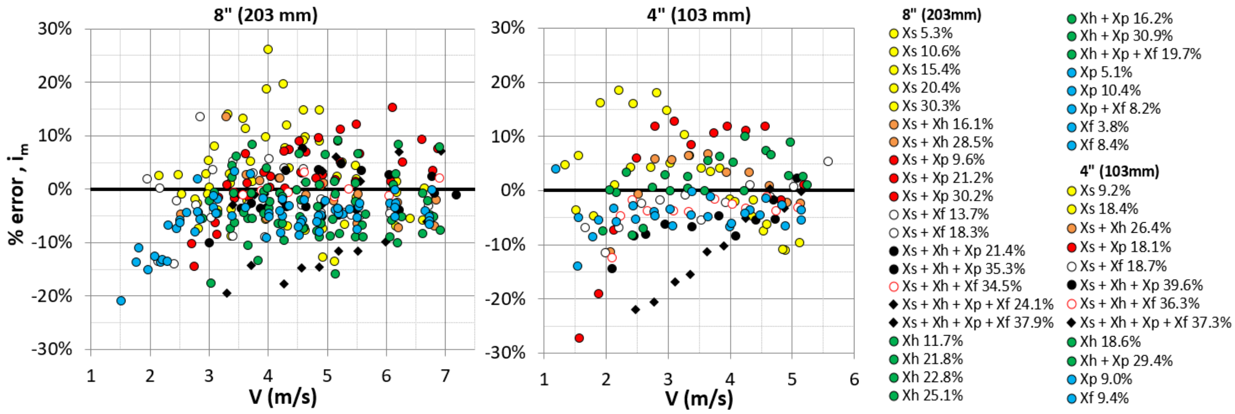
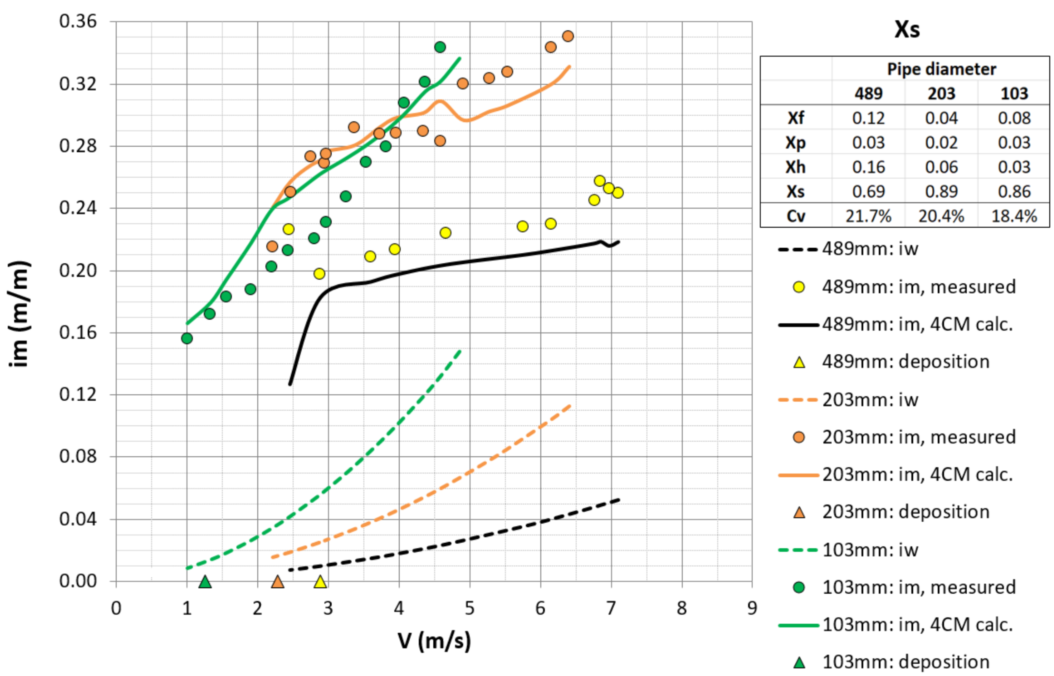


Figure 8. Pressure gradient % error for the previous 203- and 103-mm pipe tests.

The following Figures 9 to 14 provide comparisons of individual test data from the 103 mm, 203 mm, and 489 mm tests with 2.65 S_S solids. Each figure attempts to group tests of similar composition and delivered concentration, however, it should be noted that the correspondence is not exact. Actual component fractions and concentrations are given for each test, together with the measured water, measured slurry and calculated 4-component dimensionless pressure gradients, and as before, the 4-component calculation is made based on the actual conditions measured for each data point.

Figures 9 and 10 show slurries where the single *Xs* or *Xh* components are dominant, resulting in relatively narrow particle size distributions. Volumetric concentrations are near 20%. Note the very visible effect of particle size and pipe size on measured pressure gradient.



	Pipe diameter		
	489	203	103
Xf	0.12	0.04	0.08
Xp	0.03	0.02	0.03
Xh	0.16	0.06	0.03
Xs	0.69	0.89	0.86
Cv	21.7%	20.4%	18.4%

Figure 9. Dimensionless pressure gradient results, actual vs. calculated for 489-, 203- and 103-mm pipe loop tests. *Xs* solids dominant. C_v = 18% to 22%

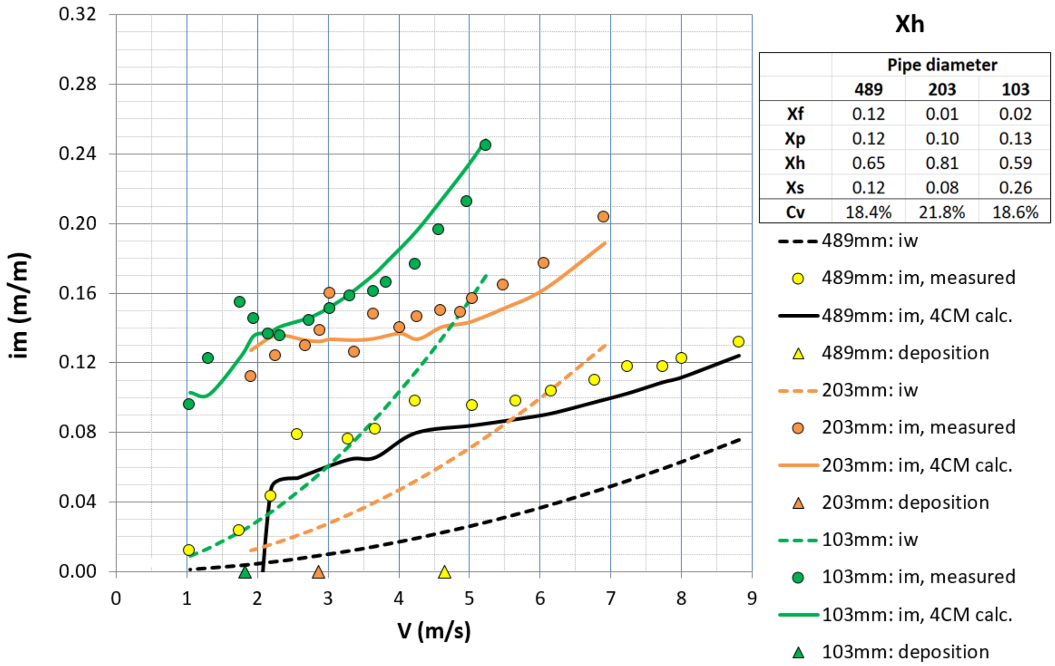


Figure 10. Actual vs. calculated pressure gradient results for 489-, 203- and 103-mm pipe loop tests. *Xh* solids dominant. C_v = 18% to 22%

Figures 11 and 12 show mixtures of stratified *Xs* solids combined with heterogeneous *Xh* and pseudo-homogeneous *Xp* solids respectively. Note that the *Xs* + *Xp* mixtures represent bimodal PSDs, having a relatively small fraction of *Xh* surrounded by larger fractions of *Xs* and *Xp*.

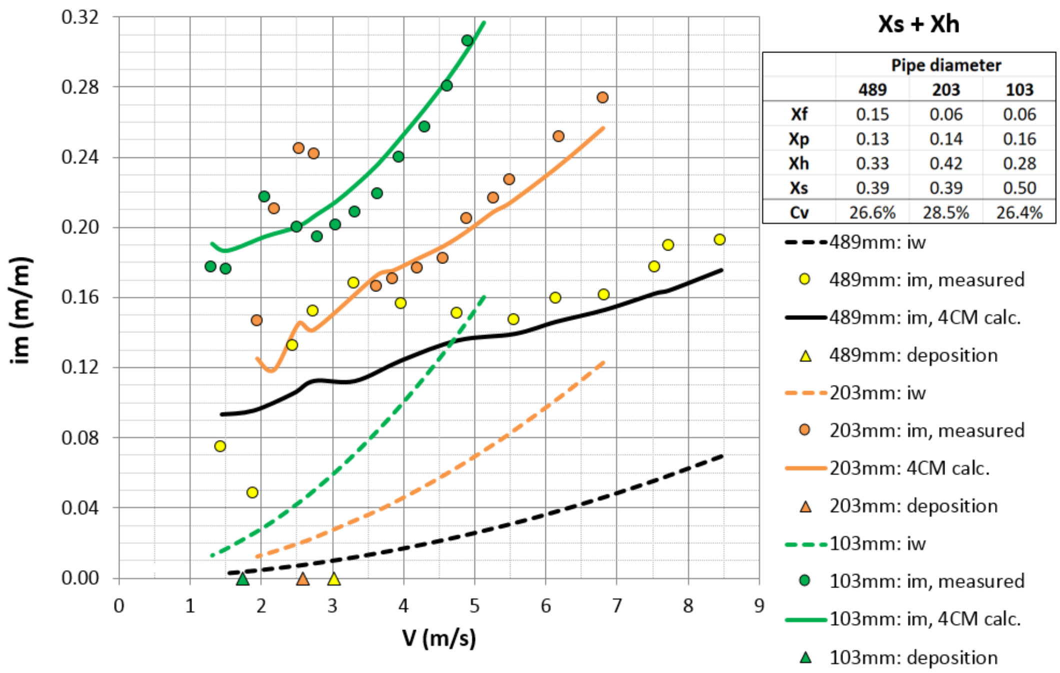


Figure 11. Actual vs. calculated pressure gradient results for 489-, 203- and 103-mm pipe loop tests. *Xs* and *Xh* solids dominant. C_v = 26% to 29%

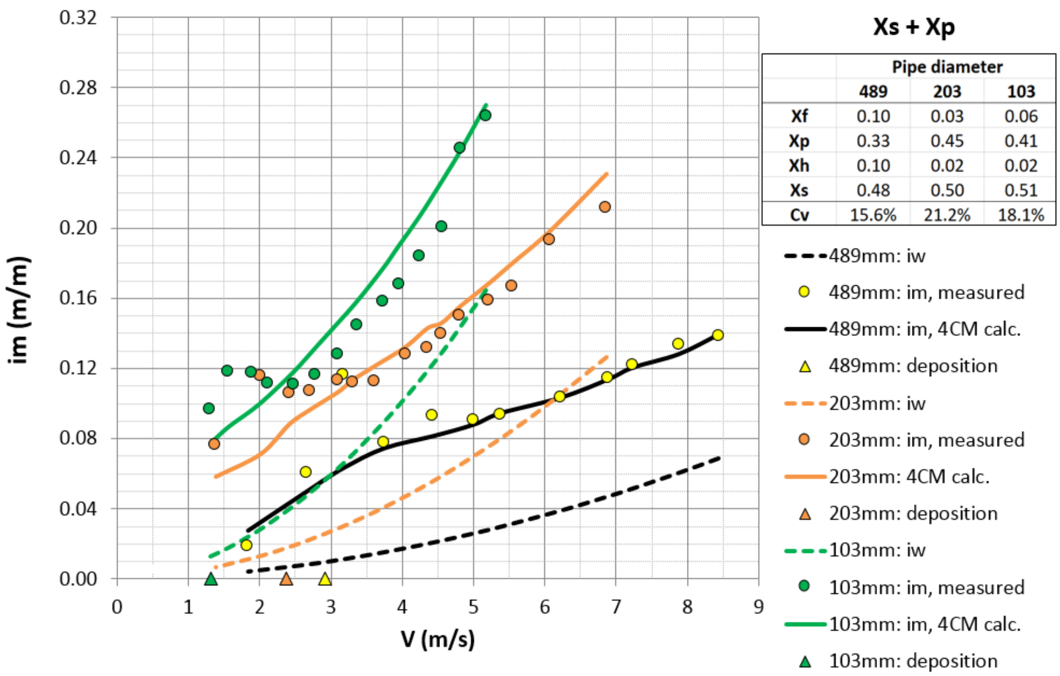


Figure 12. Actual vs. calculated pressure gradient results for 489-, 203- and 103-mm pipe loop tests. *Xs* and *Xp* solids dominant. C_v = 16% to 21%

Figures 13 and 14 show mixtures of three and four components respectively at volumetric concentrations near 35%. These tests represent concentrated slurries with broad particle size distributions. Note that the pressure gradients shown in these figures are comparable to the lower concentration, narrow PSD distributions seen in Figures 9 and 10.

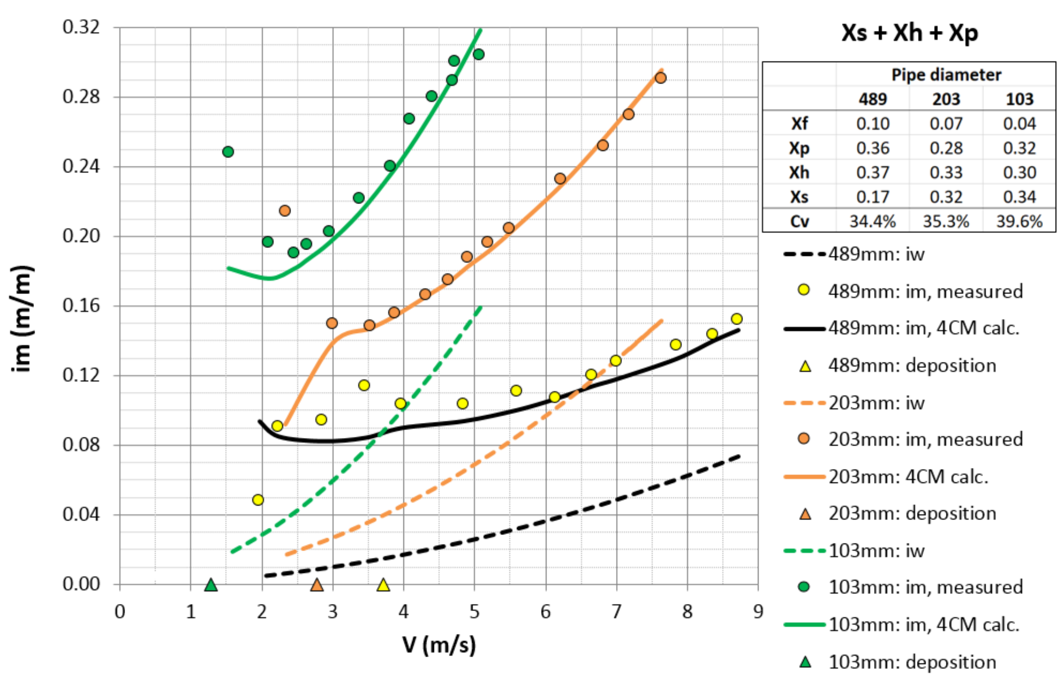


Figure 13. Actual vs. calculated pressure gradient results for 489-, 203- and 103-mm pipe loop tests. *Xs*, *Xh* and *Xp* solids dominant. C_v = 34% to 40%

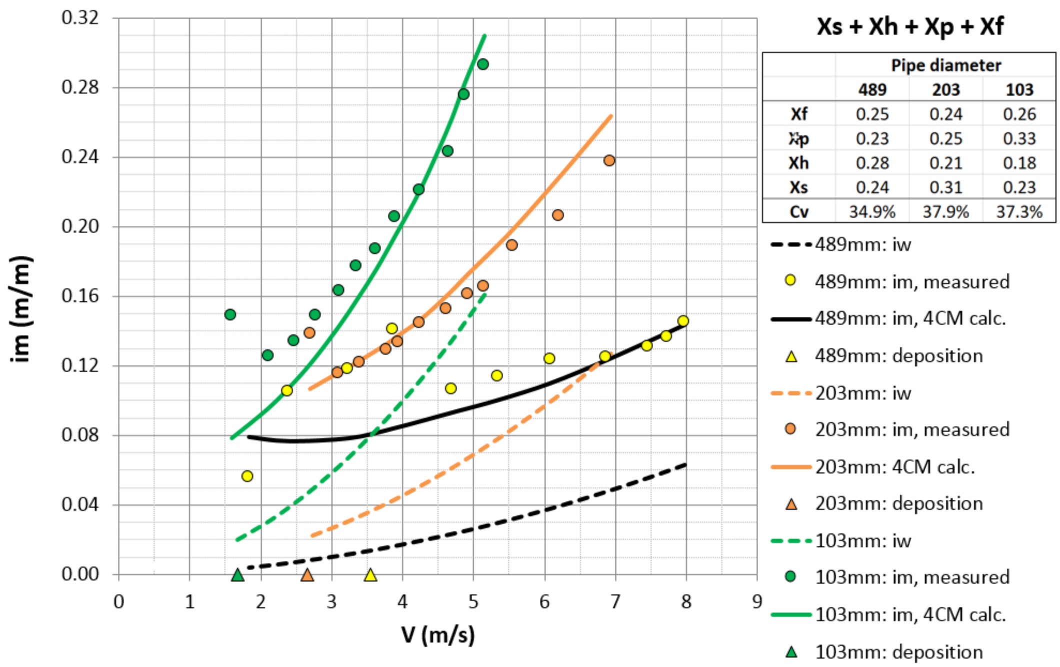


Figure 14. Actual vs. calculated pressure gradient results for 489-, 203- and 103-mm pipe loop tests. All solids components present. C_v = 35% to 38%

Figure 15 compares three tests in the 489 mm pipe loop where the delivered volume concentration of the stratified *Xs* solids is fixed near 10%, while the other fraction concentrations vary, as does the overall solids concentration. In all three tests, the flow contains essentially the same volume of *Xs* grains. In test 6e, the concentration of the heterogeneous *Xh* solids is approximately one half of the *Xs* fraction, and there is also a small fraction of the pseudo-homogeneous *Xp* solids. Test 4b differs from 6e primarily by the higher concentration of *Xh* solids, which has increased by 3.2%. This test displays a slightly higher pressure gradient as shown by the measurements plotted in the figure. In test 5d, the concentration of *Xh* solids is further increased by another 2.5%, however, the pseudo-homogeneous *Xp* solids are also increased by 8.9%. Although the overall solids concentration for this test is increased by 12.5% over 29b, the pressure gradient is essentially unchanged, as the additional friction caused by the higher solids concentration is offset by the friction reducing effects of the *Xp* fraction on the *Xh* and *Xs* solids. Although the correspondence is not exact, the 4-component model successfully predicts this trend.

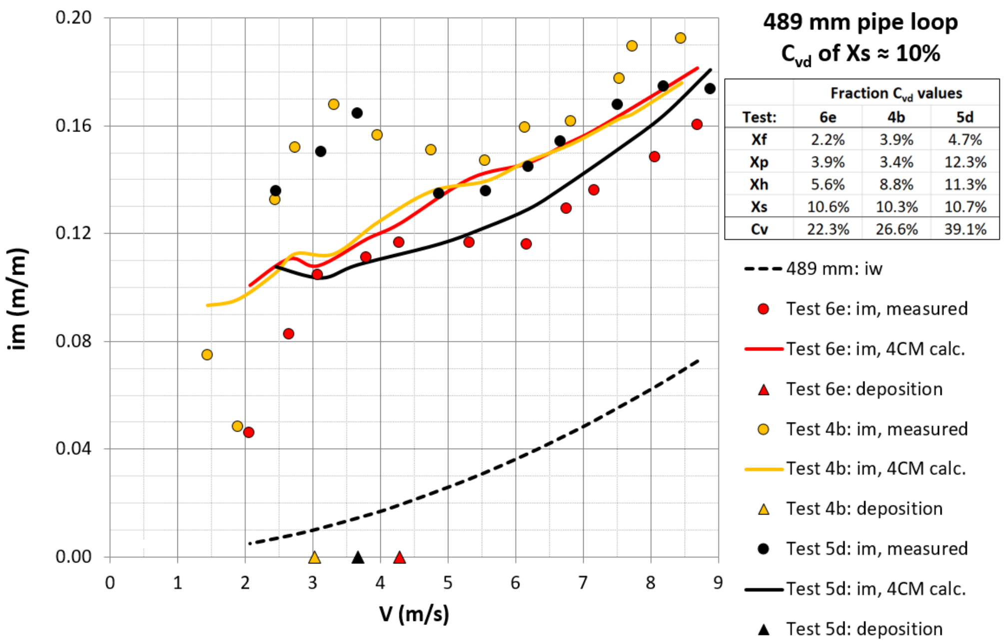


Figure 15. Various 489 mm pipe loop tests where C_v of *Xs* fraction ≈ 10%

Figure 16 compares three other tests in the 489 mm pipe loop where the delivered volume concentration of the heterogeneous *Xh* fraction solids is fixed near 11%, while the other fraction concentrations and overall solids concentration vary. In test 4a, the concentration of the stratified *Xs* solids and pseudo-homogeneous *Xp* solids are both very low. Test 8a differs from 4a primarily by the higher concentration of *Xs* solids, which is more than doubled from 2.2% to 5%. This produces a higher pressure gradient as confirmed by the measurements. In test 5d, the concentration of *Xs* solids is again more than doubled, being now almost 5 times higher than in the first test 4a. However, the concentration of *Xp* solids has also been increased from 2.7% to 12.3%. Due to friction-reducing effect of the *Xp* fraction, the increase in the pressure gradient between tests 5d and 8a is similar to that seen between 8a and 4a, despite the considerably higher concentration of *Xs* solids and significantly higher overall solids concentration, which increased from 21.9% to 39.1%. The 4-component model successfully predicts this trend.

Figure 17 shows results from the *Xs*+*Xf* mixture tests 7b and 7c. These mixtures contained stratified *Xs* solids in an *Xf* fraction carrier, with minimal pseudo-homogeneous *Xp* and heterogeneous *Xh* solids in between. In similar previous 203- and 103-mm tests, the *Xf* solids provided friction reducing support for the *Xs* solids in agreement with the predictions of the 4-component model. However, in the 489 mm tests, these mixtures exhibited a higher than predicted loss with no apparent benefit from the *Xf* solids. In fact, test 1b containing more *Xs* solids that 7c, and having minimal *Xf* solids showed lower pressure gradients than test 7c. It is suspected that the measurements taken for these two tests were faulty, although this could not be proven after the fact. Resolution of this questions awaits future repeat testing. In the meantime, the results of these two tests have been discounted as unreliable.

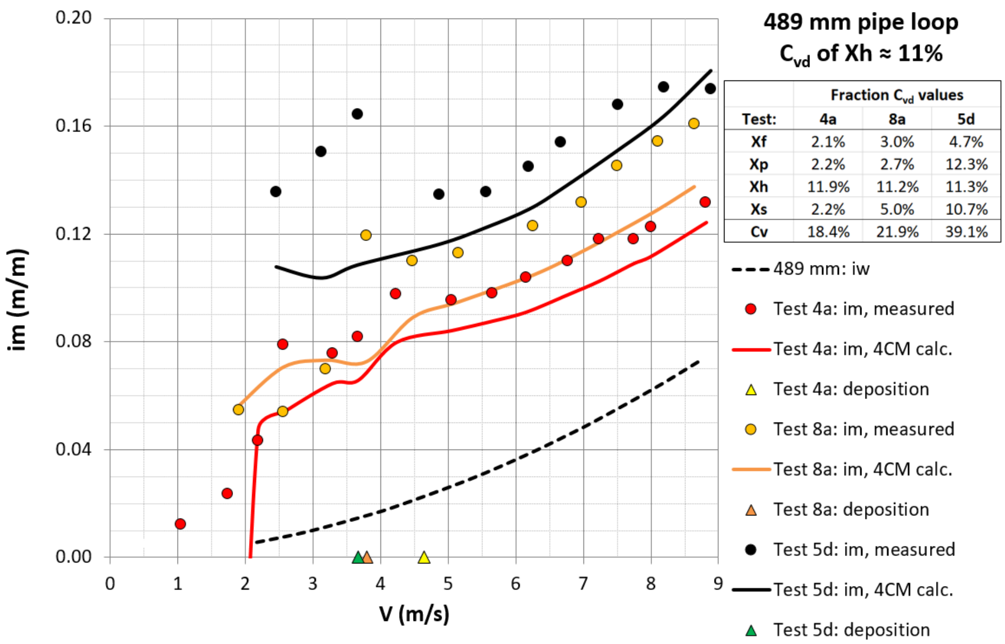


Figure 16. Various 489 mm pipe loop tests where C_v of *Xh* fraction ≈ 11%

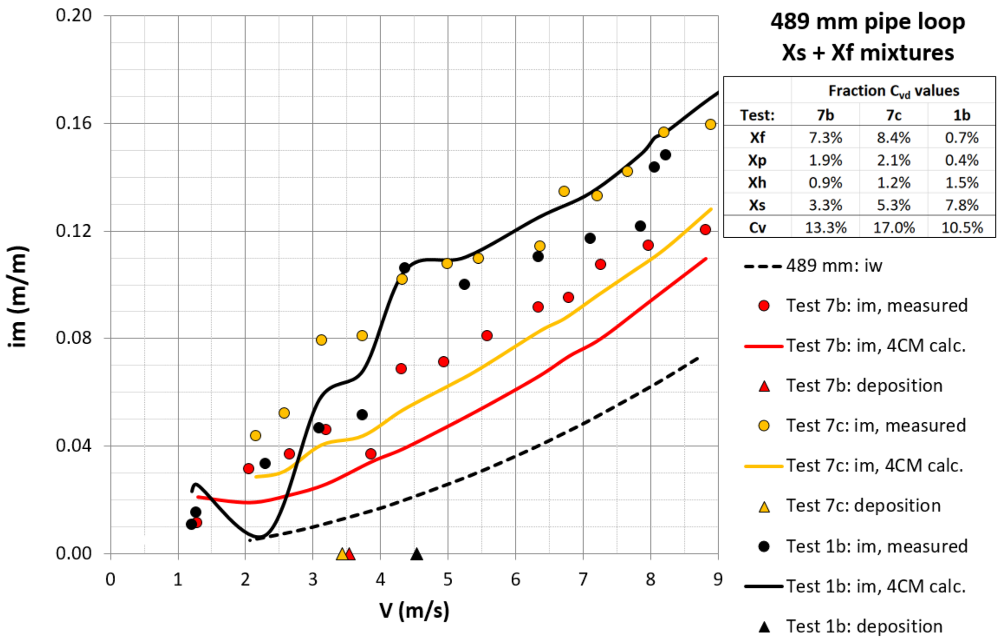


Figure 17. Various 489 mm pipe loop test mixtures of coarse *Xs* in fine *Xf*, with few *Xp* or *Xh* solids.

CONCLUSIONS

A comprehensive data set spanning multiple settling slurry flow regimes in pipelines from 103 to 489 mm has been collected to validate the previously described 4-component model for pipeline friction loss. The model provides reasonable predictions across the range of this test program.

Tests carried out in the 489 mm pipeline experienced higher particle degradation and less operating stability than previous similar tests in smaller pipelines. Two bi-modal tests of stratified *Xs* solids in *Xf* fraction carrier exhibited unexpectedly high friction losses. It could not be determined if this was the result of a faulty measurement, or an unexplained behaviour of the mixture in the larger pipe size. Additional tests will be needed to resolve this question.

Excluding the two tests mentioned above, the average error between measured and calculated values for pressure gradient in the 489 mm pipe loop tests was 8.0%, compared to 5.4% and 5.5% for the previous 203 mm and 103 mm tests. However, since the magnitude of the losses are smaller in the larger pipe, the average absolute error was similar to previous tests, in the range of 0.010 m H_2O/m pipe.

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CITATION

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DATA AVAILABILITY

The dataset generated during the described testing is proprietary to GIW Industries. Inc. The details of the 4-component model are available online at: http://tinyurl.com/4component.

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A LIQUID PISTON PUMP ENGINE FOR DEEP DREDGING

B.E.Abulnaga[1],

ABSTRACT

The accumulation of sediments in reservoirs often occurs at depth in excess of 15 m and sometimes down to 60 m. But in many cases, depths in excess of 60 m require complex equipment. Dredging sediments at these depths is challenging and costly. These sediments often entrap organics that decompose by anoxic fermentation into biomethane leading to emissions 25 folds more potent than carbon dioxide as green house gases. Some projects collect methane for power from lakes such as Kivu Lake in Africa. A similar approach is proposed for dredging and reservoir de-silting.

A new approach was developed for deep dredging based on a submerged internal combustion liquid piston engine pumping dredged sediments in slurry form. The development was funded by a grant from USACE and USBR. Large units can be deployed in permanent caissons near dams, or at the plunge pool to reduce mobilization and demobilization costs and operated at maximum sediment influx.

The submersible slurry piston pump would initially operate on external fuel obtained from natural gas pipelines near reservoirs. As the technology of collectors of methane emissions evolve, the submersible will consume collected emissions as fuel.

Keywords: Deep Dredging, methane emissions of reservoirs, slurry transport, dredged material disposal, internal combustion slurry piston engine

INTRODUCTION

The recent passage of the 21st Century Dam Safety Act illustrates the importance of de-silting reservoirs in the United States. Sediments accumulation in reservoirs diminishes water storage capacity and ability to produce hydropower, but could also be a very beneficial source of topsoil in arid climates once removed from the reservoirs.

Sediments can be found at great depth for example, the Cochiti reservoir has accumulated 41 million cubic metres to a depth of 67 m This reservoir has sand and gravel in the delta and fine silt near the outlet. The Colorado river transports annually 34.5 million cubic metres causing great siltation of Lake Powell and putting the Glen Canyon Dam at risk of failure.

In 2019, the Guardians of Reservoirs formed by the USACE and US Bureau of Land Reclamation organized a competition for new concepts of deep dredging. One topic they identified was dredging at depth of 15 to 60 m beyond the capabilities of suction dredgers. Slushing at these depths usually leads to loss of large quantities of water with concentration at less than 30 g/L. A new liquid piston internal combustion pump for immersion at great depth. It can operate on natural gas fuel, or on the biomethane produced by anoxic

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fermentation of organics entrapped in deposited sediments. This reduces the carbon footprint of reservoirs. The submersible will also benefit from a network of natural gas pipelines near reservoirs.

SEDIMENTATION OF RESERVOIRS

The US Bureau of Land Reclamation in conjunction with the US Army Corps of Engineers manage water reservoirs with a total capacity almost 200 trillion gallons of water ($7.57x10^{11}m^3$) representing half the hydro-electric power capacity of the United States. Some of the reservoirs are over 100 years old. Over time, the accumulation of sediment is threatening the benefits of the nation's reservoirs in the United States (Randle, et al., 2019). Coarse sediments (sand and gravel) tend to deposit at the upstream end of reservoirs forming deltas while fine sediments (clay and silt) tend to deposit farther downstream along the reservoir bottom (Morris and Fan, 1998). The trapping of sediments in reservoirs can cause erosion of the downstream channel impairing aquatic and riparian habitat and streamside infrastructure. A sustainable sediment management practice would be to transport sediments through or around the reservoir to the downstream channel (Randle, et al., 1998).

The National Dam Inventory (USACE 2022) indicates that there are 92,092 dams across the nation (Figure 1), with 61 years average age. Only 3% of the dams produce hydro-electricity.73% are high hazard potentials with EAP.6% of the dams are federally regulated and 70% are state regulated. those dams, 15,500 "could cause fatalities if they failed."(Haas 2020) Of the total dams, 6% are Federally regulated while 70% are State-regulated. California's reservoirs accumulated an estimated 2.1 billion cubic meters of sedimentation through 2008.(USACE(2022)).

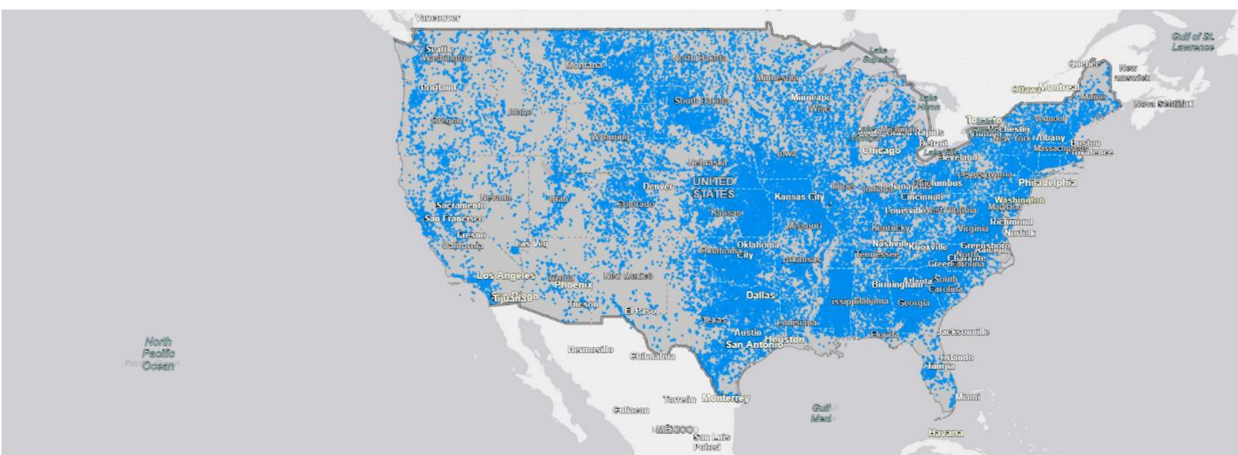

Figure 1. Dams distribution across the United States of America.

For example, Tuttle Creek Reservoir, on the Missouri river is without hydropower at the facility. The reservoir used to have 30 miles of open water but is down to 14 miles now. It is considered to be #1 in need of repair amongst 400 dams in danger across the nation Very fine sediments, silty sand, clays and 90% of the sediments pass through the dam while 10% accumulate in the reservoir. According to KWO (2015) the reservoir has lost 40% of its volume to sedimentation.

Mussetter (2002) estimated that Cochiti Dam traps approximately 1,100 acre-feet (1.356 million m^3) of sediment annually (Davis et al) state that "The upstream sediment loads contain substantial fine materials. The main stem of the Rio Grande usually delivers mostly coarse-grained sediment (i.e., >62.5 µm), while the Rio Chama load can be dominated by fine-grained sediment (i.e., ≤62.5 µm)."

The Hoover dam on the Colorado River. is estimated to have accumulated sediments at a thickness of 60 to 90 ft (18 to 27 m). The dam backs up the waters of the river to form Lake Mead. Lake Mead is the largest man-made lake (reservoir) in the United States, holding almost 29-million-acre feet (35.76 km^3) of water(USBR (2015))

Lake Powell Dam capturing waters from the. Colorado and San Juan Rivers. has lost 7% of its storage capacity since it was built in 1963, due to sedimentation, and a dwindling supply of water. The Colorado river transports on the average 45 million short tons (40.8 million metric tonnes) of sediments/year (Wagen and Gavan,(2018))

Thorne et al (2008) reported on sediments accumulation at the Tarbert Landing on the Lower Mississippi and estimated an annual accumulation of suspended sediment load between 80 and 240 million short tons of which 10 to 25% were considered coarse material.

According to Palmieri, A. (2003). The sedimentation of dams causes a loss in storage capacity at an annual replacement cost of USD 13 billion (Palmieri, 2003) At an average inflation rate of 3%, this would represent $32 billion in 2023. According to Basson (2005), the world may reach 10 billion cubic meters of accumulated sediments by 2030 (Figure 2). This represents 11% loss of the world water storage capacity It does not seem that there are many opportunities to increase water storage capacity beyond 6800 km^3

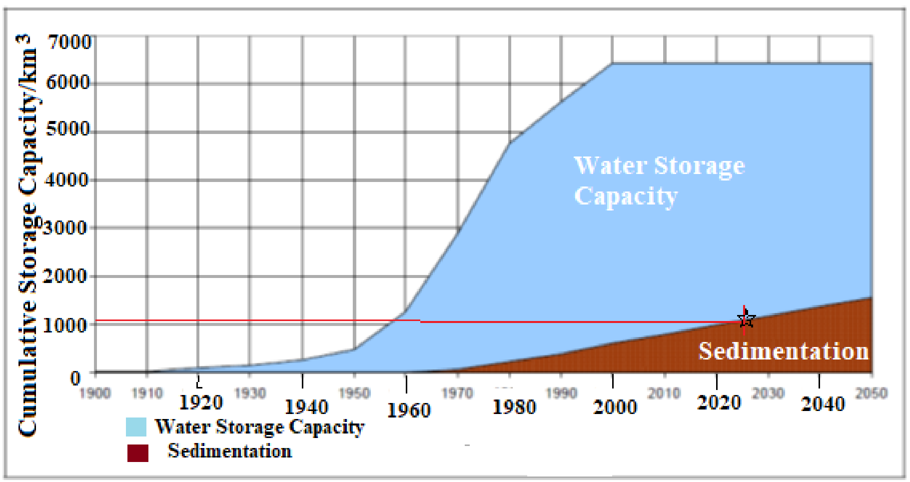

Figure 2. Accumulation of sediments on a world scale – after Basson (2005).

Tullos et al (2019) estimate that the loss of water storage capacity in the USA is between 10% and 35% due to sediment accumulation. Randle et al (2019) estimated that the water capacity per capita in the USA is back to where it was in 1960, due to continuous sedimentation of our reservoirs.

At the International level, the Nile River represents a special case, with an average yearly accumulation of 135 million cubic meters of sediments (Abulnaga and Al-Fadil 2018), since the mid 1960's. Sedimentation is estimated to have accumulated to 8 billion cubic meters. Most of the accumulation is at 500 to 320 km south of the dam and practically in an area where hydropower is too far to use for dredging

When it comes to deep accumulation of sediments, the only alternative consists of flushing. Deep sediment flushing consumes large amounts of water, Espa et al (2019) defined Flushing efficiency (FE) as the ratio between the volume of evacuated sediment and the corresponding volume of water They computed for reservoirs in Italy, the volume of water by including all the freshwater volumes released during the operations with the specific purpose of mitigating downstream impact. The corresponding efficiency of the ten reservoirs ranged between 0.1 and 0.6% .

Morris and Fan (1997) also reported on Flash Efficiency of 2 to 10%. However, there are many cases where the flushing efficiency is much lower The flushing efficiencies were found to be 0.5% and 0.3% for Wlingi and Lodoyo Reservoirs, respectively (Legono et al (2021)). Their simulation showed a maximum "After simulation of different scenarios. They proposed flushing with water rates of 1275 and 800 cubic meters per second containing 30 and 20 g/L concentration and stated" *These values meet the limitation of environmental risk analysis which is 15 g/lit sediment concentration in sensitive reaches of the river with 48 h duration".*

There are however many sites in the world where flushing is not possible. An example is the Aswan High Dam Reservoir (Figure 3). Most of the sedimentation occurs at 500 to 350 km upstream of the dam.(Abulnaga & Abdel Fadil (2008)). The cost of bringing power for dredging in such situations is prohibitive. One alternative consists of capturing the methane emissions of the reservoir, and turning it into fuel for dredging.

As most reservoirs in the United States do not produce hydropower, the conventional dredging for removal of sediments, usually involves producing power on site from diesel fuel to generate electricity and to drive a hydraulic or an electrical submersible pump. The greenhouse gas emissions associated with such an effort, include multiple sources, from trucking diesel fuel from long distance, converting diesel fuel into electricity for dredging, or direct use to operate an engine on a pump. The centrifugal pump by itself has its own hydraulic efficiency. Multiplying all the efficiency factors in the process, such as diesel power at 35% to 50%, centrifugal slurry pump efficiency at 65% to 75%, derating pump performance for solids at 85%, quickly means an overall efficiency <30% with important carbon foot print. Furthermore, with the price of diesel exceeding $5/gallons in 2022, alternative sources of energy for dredging should be explored.

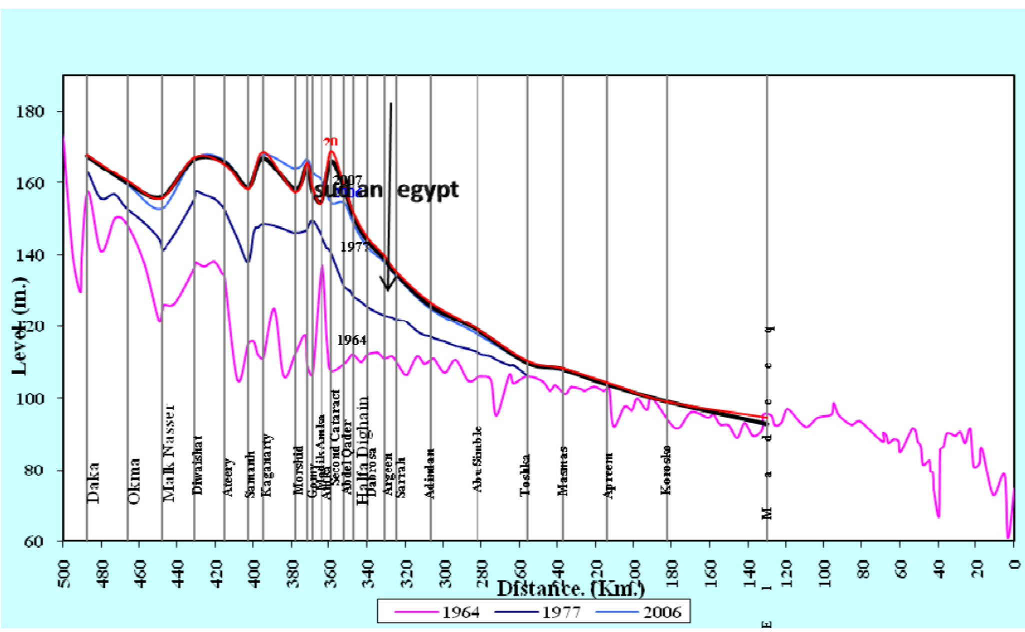

Figure 3. Sedimentation of Lake Nubia and Lake Nasser – Reproduced from Abulnaga and Abdel Fadil (2008).

The United States has a network of natural gas pipelines exceeding 300,000 km. Many reservoirs are however within an acceptable distance of natural gas pipelines (Figure 4) Connecting a dredging operation to a natural gas pipeline, reduces the emissions and inefficiencies associated with transport of diesel fuel. Direct conversion of fuel to pumping power, reduces further emissions while improving overall efficiency.

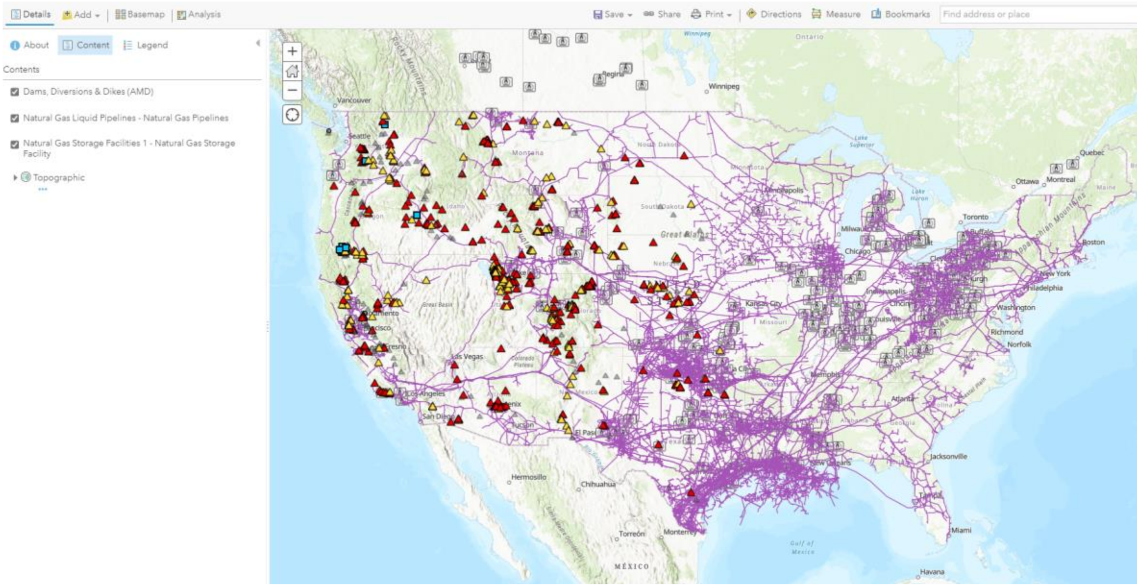

Figure 4. Network of natural gas pipelines vs major water reservoirs (shown as triangles) – courtesy of USACE and USBR (Guardians of Reservoirs).

Lakes and water reservoirs contribute to 20% world emissions of methane. Methane is produced in lakes and reservoirs from degradation of organic matter entrapped in sediments. Methanogenesis is the process of producing methane by microbes known as methanogens. The decomposition occurs in the absence of oxygen using the Carbon in organic matter under anoxic conditions. Archae cells (not to be confused with bacteria) obtain their energy by stoichiometric conversion of substrates such as H_2+CO, formate, acetate, methanol, or methylamines to CH_4 gas.

While most discussions in the past have focused on Carbon Dioxide as the signature of the Green House Gas emissions, the problem of methane emissions is starting to emerge as the most dangerous. (Soraghan (2021)) A quantity of Green House Gas (GHG) is expressed as CO_{2e} by multiplying the amount of the GHG by its global warming potential (GWP) . e.g., if 1kg of methane is emitted, is expressed as 25kg of CO_{2e} (1kg CH_4 * 25 = 25kg CO_{2e}) .

Methane emissions from water surfaces is typically composed of 63% methane and the rest mostly carbon dioxide, Diffusion and ebullition contribute unequally to the total flux of CH_4 from reservoirs to the atmosphere. Although methane has a shorter life span than Carbon Dioxide (about 20 years) its accumulation in the environment contributes more to global warming.

Miller et al (2017) tabulated values of methane emissions from hydropower reservoirs as high as 4234.6 mg m^{-2} d^{-1} of CH_4 for a site in Germany and as low as 0 for another site in French Guyana,. They recommended an average emission factor of 800 mg m^{-2} d^{-1} for CH_4 Deemer et al (2020) measured emissions in a number of dams from Brazil to Quebec and discussed the potential for several alternative pathways such as dam degassing and downstream emissions to contribute significantly to overall emissions. Although prior studies had linked reservoir GHG emissions to reservoir age and latitude, the authors found that factors related to reservoir productivity are better predictors of emission. They estimated global annual emissions from dams and reservoirs to be of the order of 0.8 (between 0.5 and 1.2) billion metric tonnes CO_{2e}.

Published data (Bartosiewicz et al (2021)) on emissions estimated that the annual production of methane in reservoirs, lakes, wetlands and other freshwaters was around 469 and 865 Tg/year. (1 Tg = 1 million metric tonne). The authors suggested that once collected at 75% efficiency, the global production of methane from fresh waters would be equivalent to 50 to 100×10^{11} kWh. By considering that the worldwide production of electricity in 2018 reached 23×10^{12}kWh, they stipulated that there is sufficient methane to cover the electrical energy needs of the world. They suggested different solutions to tap methane emissions including

- Concentration and capture by adsorption on special fluid-solid interfaces
- In-situ adsorption of methane to produce methanol
- Initial separation of methane from water using hydrophobic gas-liquid membrane contactors (GLMC). They would be used as an interfacial barrier between a sorbent and the water retentate, through which only non-polar gas molecules would permeate.
- Some microporous polymer-based membrane technologies are already in industrial application to recover methane from anaerobic effluents in biogas upgrade systems. Some of these systems rely on the hollow fiber technology.
- Membranes are made of polytetrafluoroethylene (PTFE) and polyvinylidene (PVFD) are promising due to their resistance to wetting

Lake Tanganika in Tanzania, has the largest anoxic production of methane in the world that holds 23 Tg of methane. In neighboring country, Rwanda, The Kivu power plant produces 26 MW on a mobile platform 750 m long. The methane is found at a depth of 350 m below layers of salt that prevent it from being released to atmosphere.

THE INTERNAL COMBUSTION SLURRY PUMP DREDGER

The purpose of the submersible internal combustion dredger is to offer an alternative for removing large quantities of sediments at higher concentration than flushing.

Past use of internal combustion liquid piston also called Humphrey pumps showed an ability to move large volume of waters up to 7000 m^3/h (Figure 5). According to McClaughlin (1932), Humphrey developed a liquid piston pump engine for the head of 45 m using a combination of liquid piston and ram effects but found no commercial clients. Smith (1971) describes a 36”cylinder bore engine installed at Cherster, Pensylvania installed in 1927 by the Sun Shipbuilding and Dry Dock Company. It was designed as a 2-stroke engine to operate in a range of head from 20 to 150 ft (6 to 46 m) The engine was installed in a 18ft 6 (5.6 m) diameter and 50 ft (15.25 m) deep steel caisson, about 40 ft below the Delaware river Air was supplied to the engine at this depth through a compressor. The pump supplied the shipyard and underwent endurance tests 8 hrs. a day in 1925 – 27 before switching to 24 hrs. a day with water at head of 150 ft for weeks in 1928.The pump pumped 300,000 US gallons at 70 ft TDH.

The Humphrey pump was never tested on slurry. Our research focuses on the principle of pumping slurry for deep dredging operations. It is also proposed that an internal combustion dredging system be capable of operating on methane emissions collected at the reservoirs, encountered in pockets of sediments, or on natural gas brought externally from a pipeline.

An important part of the cost of dredging is the mobilization and demobilization. Some submersibles can therefore be installed permanently at strategic points and turned during periods of maximum flood.

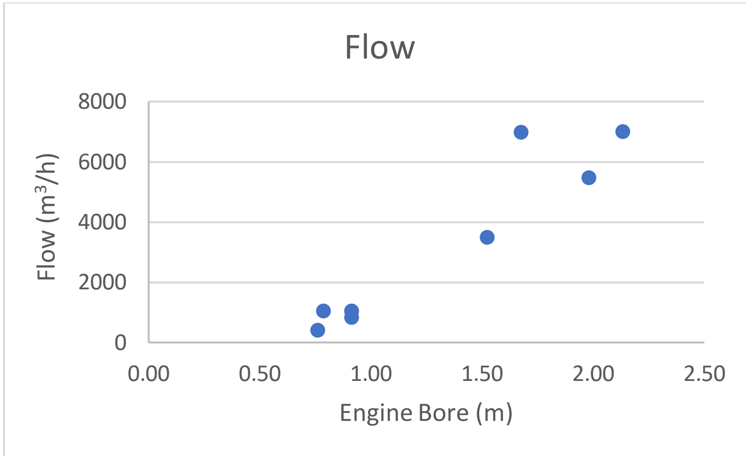

Figure 5. Flow vs Bore Size of IC Liquid Piston Humphrey Pumps.

The Liquid Pump Engine uses gaseous fuel as it is difficult to ignite a liquid fuel in the presence of water. The dredging units are fed with natural gas from the shore (Figure 6).. A compressor on shore will pump air to match the hydrostatic pressure at the depth of immersion.

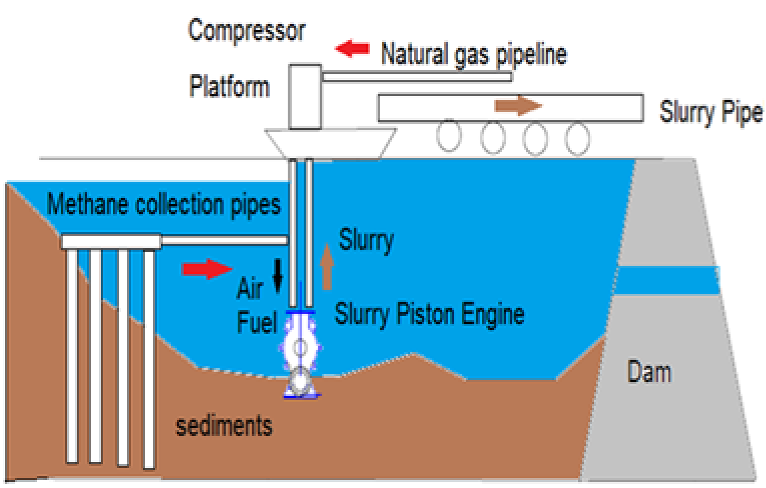

Figure 6. Concept of dredging sediments from reservoirs using collected methane emissions or external natural gas.

One option consists of installing the internal combustion submersible at strategic locations at the root of the dam in caissons or supported from rails and cranes. It can also be supported from a floating bridge or a pontoon or a barge (figure 6) near the pivot point between topset and bottom set sediments or point of plunge (Figure 7).

Referring to Figure (6) Upstream the engine, the pressure is expressed as

$$P_1 = \rho_B g H_B + \rho_U g H_U + \rho_W g H_w \tag{1}$$

Where

H_B	= thickness of the bed layer at the suction (m)
H_U	= thickness of under-current layer(m)
H_w	= thickness of clear water (m)
g	= acceleration due to gravity or 9.81 m/s^2
P_1	= suction pressure (Pa)
ρ_B	= density of the delta topset bed at the suction (kg/m^3)
ρ_U	= density of under-current layer(kg/m^3)
ρ_w	= density of clear water layer(kg/m^3)

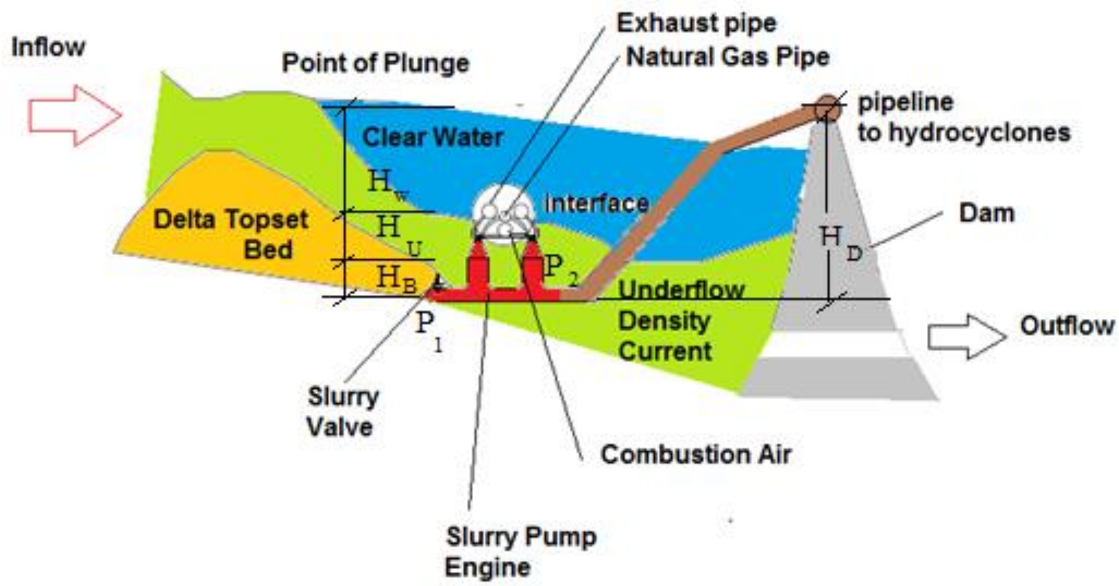

Figure 7. Installation of a submersible slurry piston pump engine under the point of the plunge.

The air pumped from shore must overcome the sum of these pressures. In fact, air is directly injected at the necessary pressure for combustion. We recommend that air be supplied at a minimum of 150 kPa above the magnitude of pressure P_1 to account for losses at the top of the engine head and to maintain space to inject fuel and operate the detonation of fuel and air.

The Internal Combustion Liquid Piston is available in two configurations

- With a cutting jet
- With a cutter

On the discharge side of the engine, the pressure must push the slurry mixture to top of the dam. It must overcome friction losses in the vertical leg as well as friction losses in the horizontal pipe to shore. The explosion of the compressed air and fuel mixture in the engine head must overcome the resistance on the discharge of the engine and must produce sufficient energy to turn the dredging cutter.

The pressure on the discharge is expressed as

$$P_2 = \rho_m g\ H_D + \sum P_f \tag{2}$$

Where

$$H_D = H_B + H_U + H_w + H_s \quad (3)$$

Where

H_D = Total static head on discharge of submersible (m)
H_s = elevation of final discharge relative to top of clear water layer (m)
H_w = thickness of clear water (m)
P_2 = submersible discharge pressure (Pa)
ΣP_f = sum of dynamic pressure losses due to friction and fittings (Pa)
ρ_m = density of the slurry mixture passing through the submersible (kg/m^3)

Abulnaga (1991) modified the Humphrey internal combustion pump engine by adding a turbine between two cylinders. The same principle can be applied to drive a cutter through a turbine under the cylinder of the liquid piston engine.

The power consumed by the turbine is expressed as

$$W_c = T \times \omega \quad (4)$$

W_c = Power to cut through the sediments (Watts)
T = Applied torque at the cutter (Nm)
ω = angular speed of cutter (rad/s)

When a cutting jet is used instead of a cutter , W_c is expressed in terms of flow rate and dynamic pressure of the jet.

The ideal power consumed by the internal combustion submersible dredger must develop is expressed as

$$W_{is} = W_c + Q_s(P_2 - P_1) \quad (5)$$

Where

W_{is} = Ideal Power output of submersible (Watts)
Q_s = Slurry flow rate (m^3/s)

The consumed power on water is expressed in terms of an overall efficiency of combustion, pumping and cutting the dredged sediments

$$W_0 = \frac{1}{\eta_0}\left(W_c + Q_s(P_2 - P_1)\right) \quad (6)$$

Where

W_o = Output Power output of submersible (Watts)
η_o = Overall efficiency (non-dimensional)

The overall efficiency of the system must account for the energy lost to compressing air at the surface, pumping to the engine, as well as pumping the fuel from the surface to the engine.

A further de-rating factor must be applied for the slurry compared to performance on clean water, so the consumed power on slurry is expressed as

$$W_s = \frac{W_o}{E_R} \tag{7}$$

Where

W_s = Derated power on slurry (Watts)
E_R = Derating factor for presence of solids in slurry (non-dimensional)

To avoid any dangers of explosion fuel and air must be supplied from shore in separate pipes. Furthermore, the fuel line can be double contained with leak detection at regular intervals.

The thermodynamics of the Humphrey thermodynamic cycle was studied by Akbari et al (2012), Liu and Akbari (2015), with emphasis to develop space propulsion in a wave engine for NASA, Viktorovich (2014) with detonation engine These authors emphasized that the Humphrey cycle was superior to Otto cycle because full expansion of the products of combustion was possible without the physical restrictions of a fixed movement solid piston

Our thermodynamic cycle is however different as we must supply energy at the compressor on shore similar to a gas turbine in an aircraft propulsion. We also consider that some energy is transferred back to compress the air and fuel mixture with the returning slurry column. We define the efficiency as

$$\eta = \frac{W_i - W_o}{W_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

Where

W_i= is calculated as total inlet power, included terms associated with external compression of air, fuel and energy imparted by returning slurry column

Akbari (2012) defined the ideal thermal efficiency of the Humphrey/Atkinson cycle as

$$\eta_{HA} = \frac{q_i - q_o}{q_i} = \frac{c_v(T_3 - T_2) - c_v(T_4 - T_1)}{c_v(T_3 - T_2)} \tag{8}$$

c_v Heat capacity at constant volume (J/ kg/^{o}K)
c_p Heat capacity at constant pressure (J/ kg/^{o}K)
q_i = Rate of Input Heat (J/s)
q_o = Rate of Output Heat (J/s)
T_1 = Temperature at start of air entry and compression (^{o}K)
T_2 = Temperature at start of ignition at constant volume (^{o}K)
T_3 = Temperature at end of explosion and start of expansion stroke (^{o}K)
T_4 = Temperature at end of expansion stroke (^{o}K)
η_{HA} = Thermal efficiency of Humphrey cycle (non-dimensional)

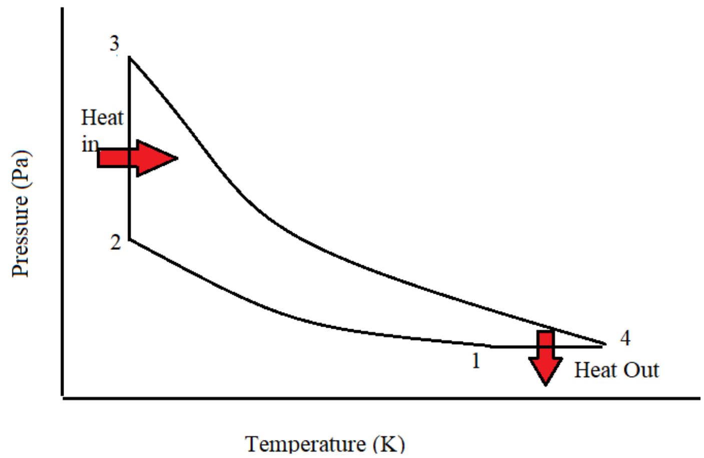

Figure 8. Thermodynamics of the Humphrey cycle (after Akbari (2012), and Viktorovich (2014)).

Expansion occurs between points 3 and 4 and causes the water column to rise in the discharge pipe. However, its sets the column into an oscillation that occurs while heat is being rejected between points 4 and 1 and adds to compression of a fresh mixture of air and fuel between points 2 and 3. The air must be supplied at 1 at a pressure higher than the static head of the column at the suction of the pump engine.

LAB TESTS

A prototype was built for testing in our lab (Figure 9) featuring

- An 8”(200 mm) bore Cylinder
- An engine head with a 2” (50 mm) exhaust and a 2.5” (65 mm) air inlet
- A 20” (510 mm) diameter turbine casing

The engine uses solenoid valves that are operated from a microprocessor. The propane lines and compressed air are separate and the mixing occurs only in the engine head..

The lab unit is a single cylinder prototype with 6-inch discharge. Back pressure is controlled by a globe valve to simulate differential pressure of 15 to 20 psi (100 to 150 kPa) Tests are being conducted with plain water, and with slurry at various volumetric concentration to appreciate the required fuel pressure, scavenging pressure, combustion air pressure, timing for opening and closing of solenoid valves. The solenoid valves and ignition are controlled from a microprocessor.

Samples of the slurry are analyzed using a Macy scale.

The use of a magnetic flow meter proved difficult, because the water column reverses after discharge at the tank, and the pressure wave is similar to water hammer. Flow was measured by the drop of water in the tank at the suction over a fixed period of time.

Figure 9. Prototype of internal combustion slurry piston dredger undergoing tests.

The amount of compressed air entering the engine is controlled through the timing of solenoid valve to expunge products of combustion and admit fresh air. This is critical to maintain a high efficiency without consuming excessive amounts of air.

The discharge of water was observed at the top of the tank after the explosion of the air and propane mixture in the engine (Fig 10).

Figure 10. Discharge of water at top of tank through 10” nozzle.

The lab tests revealed that a jet configuration as shown in Figure (6) provides sufficient force to keep the solids in suspension, instead of a cutter.

CONCLUSIONS

The submersible internal combustion liquid piston engine offers the opportunity to move large quantities of slurry from deep reservoirs as an alternative to flushing reservoirs. Higher concentration of solids can be removed keeping more water in the reservoir.

In view of the current energy crisis, with diesel at $5/gallon, it is recommended to

- Link existing reservoirs that do not produce hydropower to the national grid of natural gas as fuel for dredging
- Encourage the development of methane emissions collectors on reservoirs to collect fuel for deep dredging
- Provide sites for deployment of the internal combustion liquid piston pumps for dredging application
- Promote the technology for deltas at long distance from hydropower dams.

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MANISTEE SEDIMENT REMEDIATION

G. Zellmer[1], E. Dievendorf[2], M. Williams[3], M. Giampaolo[4], N. Gensky[5]

EXTENDED ABSTRACT

The Site is a former manufactured gas plant (MGP) facility located in Manistee, Michigan. Investigations were conducted between 1998 and 2019 to characterize the Site soils and sediment. Upland, shoreline, and in-river in-situ solidification (ISS) were implemented between 2018 and 2019 to address non-aqueous phase liquid (NAPL). The sediment remedy addressed NAPL adjacent to and downstream of the Site in 2020 via mechanical and hydraulic dredging. Work occurred within an active commercial navigation channel, including locations below and near bridges and other structures. This project provides a case study for implementation approaches and lessons learned for combined ISS and dredging remedies, as well as dredging remedies in narrow rivers with in-river structures and active navigation channels.

The ISS portion of the Site consists of medium-grained sands over silty clay. Additional structures present within the ISS area during the work included former piers/pilings, timber retaining walls, cables, and debris. The in-water work area is adjacent to the Site on the Manistee River between Manistee Lake and Lake Michigan. A navigation channel is maintained by the United States Army Corps of Engineers (USACE). The river is narrow with steep banks and the navigation channel occupies most of the river width. Marine traffic includes large commercial vessels and recreational vessels.

The US-31 bascule bridge crosses within the in-water area, with buried cables for controlling the bridge on the northeast side. Other structures located within the in-water area include a large stormwater outfall, docks, and bulkhead structures. The sediment removal area abutted the in-water ISS, which required protection.

Implementation of in-river ISS began with bank excavation in 2018 to remove soils above the water table. In 2019, installation of an outer sheet pile containment wall was completed in the river. Three platform cells were installed along the riverbank to reach the outermost limits of the in-river ISS, which provided support for the crane during in-river ISS mixing. ISS by auger mixing was implemented using a grout mix with a minimum 2.5 percent Portland cement and 4.5 percent blast furnace slag by weight. Approximately 6,450 cubic yards (4,930 cubic meters) of in-river ISS was completed.

More ISS swell material was encountered above the in-river ISS than the minimal amount from upland mixing. The swell was observed when 2019 post-construction survey did not align with the 2020 pre-dredge survey. The swell material was removed using mechanical dredging equipment. Deeper, harder swell material was abraded using a rock wheel attachment on an excavator and removed with the excavator bucket.

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A total of 23,540 cubic yards (17,990 cubic meters) of sediment was removed with a combination of mechanical and hydraulic methods. After initial dredging to the design limits, confirmation observations were collected from surface sediment.

Within the navigation channel, project vessels and equipment were required to move on request to allow vessel traffic through the work area. Coordination efforts included establishing points of contact with local dock operators, identifying vessel schedules, and monitoring marine radio and tracking information. A moon pool system was implemented to allow rapid relocation of the mechanical dredging equipment and resuspension controls. An air bubble curtain was installed downstream of the work area to provide secondary containment. Additionally, traditional turbidity curtains and oil booms were installed outside the navigation channel and a boat patrol crew inspected the area to address visible sheen. Smaller commercial and recreational vessels were able to navigate around the equipment via marine radio or hand signals.

A notice to mariners was submitted to the United States Coast Guard (USCG) with details regarding the work and schedule. Signage and lighting were implemented on construction vessels and within the work area in accordance with USCG regulations. Discussions with recreational dock owners were necessary to coordinate offsets and establish access agreements to dredge around the docks.

In-water work around the railroad bridge was coordinated with the bridge owner. Equipment that required the bridge to be open was moved when vessels were traveling though the opening, to the extent possible. Work was coordinated so that no operations were conducted within the swing radius of the bridge while trains were passing.

Access and requirements for the work within the US-31 bridge area and at bridge openings were coordinated with the Michigan Department of Transportation (MDOT). Based on communications with MDOT, diver-assisted hydraulic dredging was implemented within 25 feet of the buried cables. The implementation of this work was complicated by woody debris. The project team field-revised the approach to maximize removal while limiting work in the areas with heaviest debris.

Structures and infrastructure within and adjacent to the work area were inspected to document pre- and post-construction conditions, including:

- Railroad and US-31 bridges
- Stormwater outfall structure
- Private docks
- Roads associated with construction traffic

Pre- and post-construction conditions, including underwater conditions, were documented. A post-construction inspection was completed, finding no major deficiencies or impacts. Optical monitoring points were installed and surveyed throughout the project. Optical survey points were maintained on the railroad bridge, US-31 bridge, and outfall. No disturbances greater than the notification level were observed during construction.

Riverbank restoration posed several challenges. These included protection of the ISS monolith, meeting the USACE requirement of no fill in the navigation channel, preserving slope stability, and providing shoreline erosion protection. The design was adjusted throughout construction for field conditions. The bank was restored successfully based on post-construction monitoring.

Stakeholder communication was key from investigation through construction completion. This included coordination with the structure and utility owners and the local community. This upfront focus on community relations and frequent contact with commercial shippers, other boaters, and property owners contributed to project success.

Keywords: Environmental dredging, ISS, structural protection, bank restoration, navigational communications, community engagement.

CITATION

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DATA AVAILABILITY

All data and models generated or used during the project are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

ACKNOWLEDGEMENTS

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POST-DREDGING AMENDMENT ENHANCED BACKFILL AND REACTIVE CAPPING – CASE STUDIES

John A. Collins[1]

Background - The use of post-dredging back-fill or ‘reactive’ capping materials over a dredged sediment surface has become increasingly common at contaminated sediment remediation sites. Regulatory acceptance of adsorptive amendments for both of these applications has increased significantly over the recent past and an increasing number of projects are calling for some form of enhancement to backfill or cover layers applied following dredging operations.

Approach/Activities – Amendments or adsorptive materials vary based on the contaminants of concern (COCs), performance and their method and/or relative success in achieving placement objectives. Three case studies will be presented where post-dredging capping or amendment enhanced backfill was performed. Examples will highlight different amendment materials and a range of settings. Information on material properties and evaluation of costs related to the amendments will be provided as well. Sites for presentation will include Passaic River, East Branch of the Grand Calumet River and Potrero Power Plant on the San Francisco Bay.

Summary – This presentation will provide an overview of key issues regarding the use and application of these materials in various settings as well as provide case studies of recent projects. The focus will be on the key issues in material selection and performance. The industry’s understanding and experience in implementation, based on these factors for success has increased significantly over the past five years.

Keywords: Material selection, Passaic River, adsorptive materials, dredge and cap, contaminated sediment.

REFERENCES

None.

DATA AVAILABILITY

Data were provided by third parties for this presentation. Direct requests for these materials may be made to the provider as indicated in the Acknowledgments.

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EVALUATION OF ACTIVATED CARBON FOR ENVIRONMENTAL REMEDIATION APPLICATIONS

A.J. Harris[1]

EXTENDED ABSTRACT

Activated carbon has long been recognized as one of the world's best sorbents for persistent organic pollutants and thus has been widely used in environmental remediation applications. When compared to other sorbent materials evaluated for environmental remediation such as coke, organic-rich soils and sand, activated carbon has been found to exhibit several orders of magnitude higher sorption capacities, providing superior containment of toxic compounds (Murphy et al. 2006). An added benefit of a strong sorbent is that bound contaminants such as polyaromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) have been found to be less bio-available to organisms that may ingest sorbent particles (Millward et al. 2005). The intent of this presentation is to provide a basic overview of the factors that affect the equilibrium loading capacity and kinetics of physical adsorption on activated carbon. The results of a brief study conducted by Calgon to compare the equilibrium loading capacities and adsorption kinetics of a bituminous coal-based activated carbon in granular and powdered forms will be presented.

Evaluating the equilibrium loading capacity is a fundamental step in the design of an amended capping layer or in-situ sediment treatment because it is the mass of contaminant removed per unit mass of sorbent which dictates how much activated carbon will be required for the application. When evaluating the loading capacity, an adequate amount of contact time must occur to ensure that the carbon has become saturated with respect to the background contaminant concentration.

The characteristics of a hydrophobic organic compound that can increase the equilibrium loading capacity for a given activated carbon product include increasing concentration or decreasing solubility (temperature and pH dependent), increasing molar volume (excluding potential effects of molecular sieving), increasing polarizability (i.e., the ease of electron cloud distortion), and the absence of or decreasing concentrations of background organics and other competing adsorbates (Bansal and Goyal 2005). In general, the higher the molecular weight and the more structurally complex a compound, the more easily it will be adsorbed. Adsorbent factors impacting equilibrium loading capacity for a given adsorbate include the base material and the degree of activation; these two factors dictate the distribution of adsorption pore size and energy across the entire adsorption pore volume.

Accurately evaluating the equilibrium loading capacity for the contaminants of concern is important in the process of selecting a sorbent. There are two primary methods for measuring the equilibrium loading capacity of activated carbon: isotherm and column testing. The isotherm method is described in ASTM D 3860. The loading capacity from a column test is simply the total area between the influent and effluent breakthrough curves divided by the mass of carbon. In either case, it is crucial that equilibrium is closely attained to avoid making erroneous conclusions or comparisons. Pulverizing activated carbon to 95% passing 325 mesh is highly recommended to minimize the time required to reach equilibrium, minimize potential bias from microbial degradation and to ensure that different products are tested under the same

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conditions. Alternatively, extending contact times for non-pulverized carbon samples and periodically evaluating for equilibrium is advised (Peel et al. 1980, Randtke et al. 1983)

A certain amount of contact time between the water and the carbon is required to ensure that the contaminants of concern are adsorbed. Adsorption is a molecular diffusion process whereby an adsorbate must diffuse through the bulk phase (e.g., water), through the thin film boundary layer surrounding the carbon particle, through the porous network within the particle and finally attach to an adsorption site (Weber at al. 1996). The total time (or carbon layer thickness consumed) for these diffusion processes to occur in a flow-through process is called the mass transfer zone (MTZ). If the contact time between the adsorbate and the carbon is too short, the adsorbate will break through the carbon layer after only one “bed volume” has been displaced. Characteristics that can increase the rate of adsorption include decreasing carbon particle size, increasing water temperature (decreasing water viscosity), increasing contaminant diffusivity (Khraisheh et al. 2002, Peel et al. 1980, Randtke et al. 1983) and increasing carbon transport pore volume (i.e., pore sizes between 1,000 and 100,000 angstroms) for bulk diffusion limited cases.

The kinetics of adsorption is an important consideration in many applications. However, the effectiveness and efficiency of some applications do not depend on kinetics, such as an amended cap layer that has a contact time (or layer thickness) far exceeding the MTZ within the carbon layer. For column applications, a breakthrough curve can be used to calculate the MTZ length. Contact times in GAC columns for typical water treatment applications range from 10-30 minutes and breakthrough times typically range from 1 month to 1 year depending on the loading. In contrast, contact times in cap designs are typically on the order of a day or more and design breakthrough times are typically greater than 100 years. Thus, it is not practical to conduct pilot column tests to measure the MTZ in cap designs. Activated carbon is typically assumed to be in equilibrium with contaminants in the design of caps at seepage velocities up to 1 cm/day (Murphy et al. 2006, Myers et al. 1991).

Calgon conducted a brief batch adsorption demonstration using an 8 mg/L naphthalene solution and Filtrasorb 300, a bituminous coal-based activated carbon product, to illustrate some of the basic adsorption characteristics previously discussed. Equivalent weights of granular and powdered versions of the activated carbon were mixed into separate flasks of the naphthalene solution, and the naphthalene concentrations were measured periodically for up to 5.9 days. The naphthalene concentrations decreased much more rapidly in the flask with powdered carbon because the average particle size was significantly smaller than the granular carbon. However, as expected the concentrations and loading capacities measured at the end of the test were the same, demonstrating that equilibrium loading capacity is independent of carbon particle size (Peel et al 1980).

In summary, activated carbon is a strong sorbent that has been used extensively in capping applications. The evaluation of the equilibrium loading capacity of an adsorbent is fundamental in the design of an amended cap. Therefore, measuring the capacities of different sorbents requires careful attention to the effects of particle size and contact time. The kinetics of adsorption may be significant for some applications but not necessarily all.

Keywords: Activated carbon, equilibrium adsorption capacity, kinetics of adsorption, amended cap, contaminated sediment.

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All data, models, or code generated or used during the study are available from the corresponding author by request.

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LESSONS LEARNED - DESIGN AND IMPLEMENTATION OF SEDIMENT REMEDIATION PROJECTS

J. Raimondi[1]

EXTENDED ABSTRACT

Sediment remediation projects can push even the best consultants, clients, and regulators out of their comfort zone without knowing they left. After all, what is so difficult about sediment remediation? We collect data, design around a cleanup goal, and implement the design. This sounds exactly like every other remediation project except for one difference, the work is underwater. To further add to the confusion, the differences between navigation dredging and environmental dredging can be significant.

These difference results in an array of new terms, equipment, technology, and other variables that need to be defined, understood, and addressed early in the planning phase of projects. Fortunately, the sediment remediation industry has experienced tremendous growth over recent years. This growth has facilitated the opportunity to implement an array of projects in various environments with differing conditions. Although each project contains unique challenges, there are trends that tend to repeat themselves which have become the basis of this lessons learned discussion. Planning for projects using these lessons learned can help avoid impacts to cost, schedule, and possibly professional reputation during implementation.

The objective of this presentation is to focus on many of the common reoccurring challenges and themes that frequent almost every sediment remediation project. These lessons learned have been developed through a combination of personal experience and discussions with numerous industry professionals. This is not intended to be an all-inclusive list of lessons learned and we will not walk away as experts. However, early review and incorporation of these lessons learned have helped me and other colleagues execute projects in a more successful and predictable pattern.

The lessons learned that will be discussed include, but are not limited to, the falling primary categories:

- Upfront planning and coordination
    - Understanding the team's level of subject specific knowledge and defining key terms;
- Investigation and design
    - Data collection and design/construction requirements; and
- Pre-construction and construction
    - Procurement techniques and construction oversight/management.

These lessons can be applied at any phase within the projects lifecycle but are typically most beneficial and cost effective when integrated early enough to incorporate the site investigation phases of work. Although it is nearly impossible to have even the best design and construction projects implemented without some form of confusion and change, we can use the lessons learned from the past to make our future projects more successful.

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Keywords: Dredging, Capping, Contracting, Cost Estimating, Overdredge, Underdredge, Contaminated Sediment, Client Satisfaction, Dredging Equipment, Schedule, Production Rates.

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DATA AVAILABILITY

No data, models, or code were generated or used during the study.

WATER TREATMENT ASSOCIATED WITH CONTAMINATED SEDIMENT DEWATERING

Randolph J. Pit[1] and Amber G. Wilson[2]

EXTENDED ABSTRACT

Water treatment is a critical step when processing dredged material that is impacted by contaminants. To ensure that contaminants removed from the water body through the dredging process do not make their way back into the water body, they must be captured or otherwise separated from the flow of dredged material and water. Effective, efficient water treatment is necessary for a successful sediment remediation project.

The treatment equipment and processes utilized must be tailored to the contaminants present, as well as the needs of the project, such as: flow (consider both instantaneous rate and total daily volume) of water to be treated, final treated water specifications or discharge requirements, receiving water body, site conditions, volume and type of residual(s) produced by water treatment operations, cost, and not least of all, the experience and qualifications of the staff who will operate the system.

- Water flow to be treated will be determined by the volume of water mixed with the sediment during the dredging process, backwash produced by water treatment operations (residuals), or accumulation of precipitation that has been impacted by contaminated surfaces or stockpiles of material.
- The level of treatment required, as well as the complexity and number of processes, will be driven by the limitations or restrictions on treated water discharge. Those limitations are given in a permit or authorization from the local, state, or federal government.
- Where the treated water is discharged (not always the same waterbody where the dredged material originated) effects the concentration and type of discharge limits that will be imposed. Some receiving waters can accept higher levels of contaminants than others due to mixing zones, higher flow rates and other factors, such as the overall health of the water body. A smaller waterbody with impairments is likely to have more restrictive discharge parameters than a larger waterbody that does not have impairments. If the water is discharged to a sanitary sewer, and will be treated again, discharge flows are likely to be restricted – but contaminant limitations may be higher than those in a General or NPDES permit.
- Space for equipment and the availability of line power can affect the size of the treatment system.
- Treatment systems produce residuals such as backwash waste and settled solids. These residuals must be accounted for and disposed of properly. Removal of residuals takes time and a source of clean water. This must be accounted for in the design of a system, including reduced efficiency when filters are "dirty" (need backwashing) and increased flow to other units while a filter is being backwashed.
- It is key for the design of the plant to match the operator's expertise and training. If an operator is underqualified for the designed plant, operations suffer, and the plant will likely not realize full

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potential. Likewise, an experienced and well-qualified operator will maximize a plant's potential and may even exceed the expectations for the system.

We may classify contaminants based on how they can be removed from water, as well as by their physical and chemical characteristics. The most straightforward type of contaminant to remove from water is suspended solids. Suspended solids are a broad category: the solids may be inert, simply particles of clay or silt – or they may carry organic compounds such as PCBs, or metals such as mercury. Regardless of whether chemicals are present in or on the suspended solid particles, the approaches to treatment are the same: removal by gravity (clarification), or removal by physical straining (filtration). The removal of solids is vitally important in a dredging water treatment application, because if contamination is present, it is going to be found with the solid material. If that were not true, dredging would not be an appropriate method for dealing with the contamination in the first place.

It is critical to attack solids first because they can carry or shield chemical contaminants. Removing solids first also takes out some chemical contamination, as well as making the remaining chemical contaminants easier to remove in subsequent processes.

Clarification or sedimentation uses gravity to settle out suspended solids. This can be accomplished in a tank, or in a lined basin, depending on the flow volume to be treated. Clarification is a relatively uncomplicated process; basic components include detention time to allow solids to settle, a structure to allow clarified water to overflow, and a method for removing settled solids. Clarification may be aided by chemical additives. Flocculants, coagulants, and metal salts are all widely used in water and wastewater treatment to improve clarification.

Often following clarification is a filtration process. There are many different types of filtration, and more than one type may be utilized in series, to achieve better solids removal. Filtration is exactly as it sounds, straining out suspended solids by catching them in media as water flows through it. The filter media can be as simple and ancient as sand, or as modern as straw-like semi-permeable membranes that filter down to a fraction of a micron.

Once suspended solids have been removed, any dissolved contaminants that remain must be addressed. The type of treatment utilized will obviously depend on the type of dissolved contaminants present. Inorganic contaminants like metals can usually be addressed in a simple process of pH adjustment, causing the metals to form insoluble compounds that can be removed through clarification and/or filtration. Dissolved organics, however, can be more difficult to address and are often a contaminant of concern in sediment remediation (substances like PCBs, PFAS/PFOA and PAHs). Dissolved organics are often treated with specialized media or activated carbon, which interact on a molecular level with the dissolved contaminants. These media or carbon products bind the contaminant on their surface, catching it just like a filter would catch a solid particle – except that the organics are dissolved, and they remain so, throughout the binding (or adsorption) process. One example of a specialized media is organoclay. It can also be used ahead of carbon to aid in the removal of oil and grease and preserve the carbon life.

Just like dredging, water treatment is a process that requires professional oversight and control by experienced operators. Water treatment is not a passive process. Water treatment operators must thoroughly understand the design capabilities of the water treatment equipment, the treated water specifications, and the science behind the physical and chemical processes utilized, to maximize efficiency and performance of the overall system, and thereby, the project. The goal is to operate the treatment process, such that it does not negatively impact dredging activities, or violate treated water requirements. This means the water treatment system must keep pace with the volume of impacted water being generated by the project, even as conditions change.

One way to ensure that a treatment system is properly sized and equipped is to conduct treatability testing prior to performance of the project. Treatability testing can range from single bench tests to multiple tests in sequence, involving several chemical and physical process simulations. Treatability test data provides the most benefit to the full-scale project, when it is conducted with an understanding of real-world field conditions, and project constraints. It can develop a body of data that can be used to predict water quality in the field and aid in the design of the treatment system. This data can also be used to support process control decisions during performance of the project; the results of low-stakes testing conducted in the lab, can be used by operators in the field to adjust treatment schemes, lowering the stakes and improving the outcomes of real-time decisions.

Keywords: Remediation, clarification, filtration, carbon adsorption, discharge, NPDES, permit.

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DATA AVAILABILITY

Some or all data generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

COASTAL ENGINEERING SOLUTIONS FOR REMOTE PACIFIC ISLAND COMMUNITIES

S.H. Bettington[1], W. Blank[2] and R.C. Bussey[3]

ABSTRACT

Tuvalu's islands are highly vulnerable to inundation and coastal erosion; issues that are worsening with climate change. These threats were highlighted when large swells associated with Tropical Cyclone Pam in March 2015 pushed high water and waves over the reefs and islands, leading to extensive damage to infrastructure, coastal erosion, and destruction of crops.

The Government of Tuvalu (GoT), undertook coastal adaption works on the remote Islands of Funafuti and Nukufetau to improve resilience to climate change induced erosion and flooding. GoT engaged Hall Contracting, a dredging and civil contractor, supported by designers AECOM, to develop affordable solutions that included seawalls and beach nourishment with groynes on each of the islands.

Being coral atolls, the islands have a lack of rock or other construction materials commonly used for coastal armoring. As a result, armor has historically been imported or won by mining the reef to obtain coral boulders. The only environmentally sustainable construction material that can be exploited on these islands is sand dredged from deeper waters. Recognizing the impact of climate change and budget limitations, large geotextile bags were identified as a suitable qasi-permanent solution. These can provide several decades of protection while longer term climate change adaptation strategies are developed and implemented. The use of this method allowed works to be planned and completed within six months. This approach has the potential to deliver affordable, resilient and attractive protection in areas lacking the resources for more conventional coastal engineering solutions. This paper compares cost and performance of these recent examples with more conventional armor solutions and discusses the application of these technologies on threatened remote islands.

Keywords: Reef, atoll, cay, coastal erosion, seawall, nourishment, groyne, dredging.

INTRODUCTION

Remote tropical islands located on living coral reef platforms, such as coral cays or atolls, are under threat from the combined impacts of coastal erosion and marine flooding. As sea levels rise the future of the communities on these islands is threatened. This paper draws on recent experience with coastal defense projects on remote islands to examine possible solutions that utilize the available resource, namely sand.

Particular reference is made to recent work undertaken on islands in the central Pacific nation of Tuvalu (Figure 1). Tuvalu is made up of a series of low lying inhabited islands, which are highly vulnerable to

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inundation and coastal erosion. The large swells caused by TC Pam in March 2015 resulted in high water and waves over the reefs and islands, which led to extensive damage to infrastructure, coastal erosion, destruction of crops, and loss of amenity. Following this event, the Government of Tuvalu (GoT), supported by the World Bank (ref [1]) and UNDP undertook works to benefit communities, starting with projects on Funafuti and Nukufetau. The works, designed by the authors and built by Hall, included construction of seawalls and groynes using large geobag containers, and beach nourishment utilizing local dredged sand.

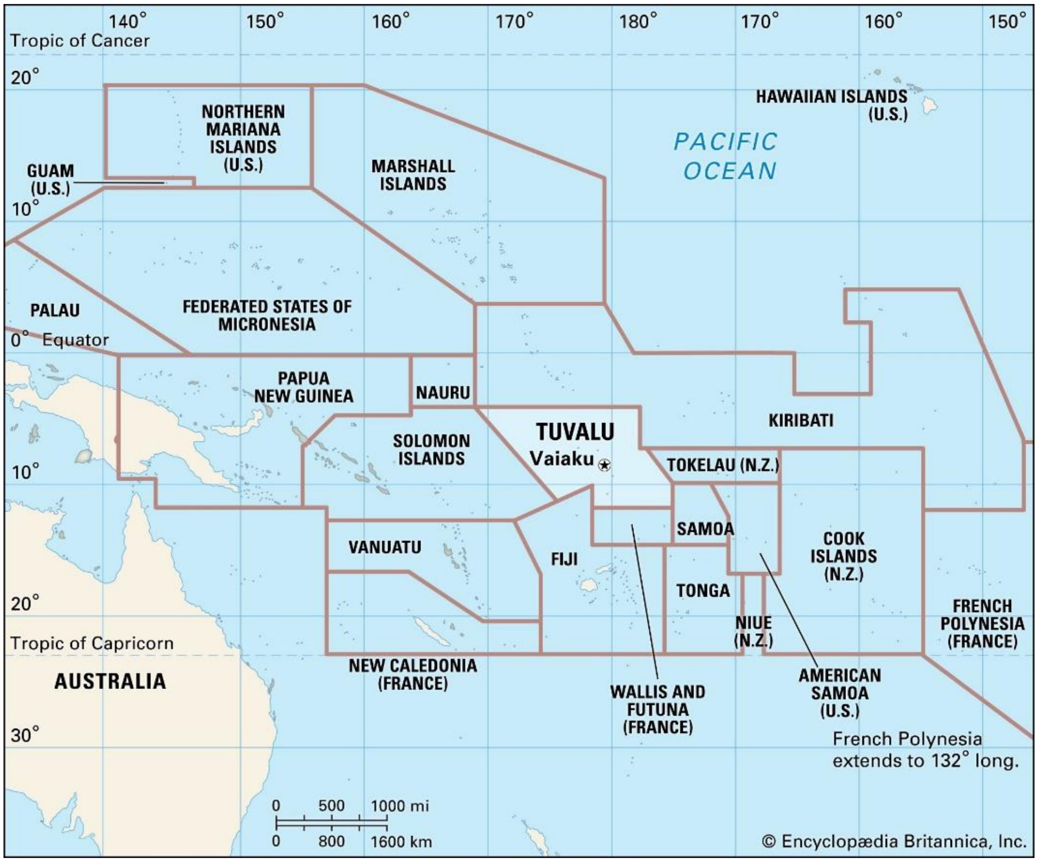

Figure 1. Location of Tuvalu (source Britannica 2022).

REEF TOP ISLAND MORPHOLOGY

The coral cays and atolls are found on coral reef platforms. The islands are created by supply of sediments from the reef and shaped by marine forces. Because sea levels did not arrive at present day levels until approximately 8,000 years ago these islands are geologically young. The process of forming and shaping islands is ongoing and large cyclonic events can provide dramatic step changes in island evolution.

Living coral reef generates approximately 5 kg to 20 kg of sediment, largely sand, per square meter annually (refer Dudley [3]). On the coral platforms this carbonate-based sediment accumulates and is transported around primarily under the influence of currents and waves. Where conditions are right an island form. The shape, size and location of these islands on the reef platform reflect a dynamic stability between the various met-ocean forces driving sediment transport and the sediment supply. The example presented in Figure 2 is in the Torres Strait (off the Northern tip of Cape York in Queensland Australia), where the prevailing weather is a South Easterly trade wind and associated waves, resulting a the islands being formed on the North Western corner of the reef platforms.

Figure 2. Island on NW corner of reef in a climate dominated by Southeast winds and waves.

Because these islands are built up by marine forces, they are low, with typical land levels slightly above normal tidal ranges. During abnormally high-water levels on the reef platform, such as cyclonic events, the islands can be flooded. These events are an integral part of island evolution and act to raise island levels by depositing sediments as seen in Figure 3.

Figure 3. Sediment deposition following TC Pam raising island levels Nui (left) and Vaitupu (right).

THE ISSUES (TROUBLES IN PARADISE)

As discussed previously the islands are created from sand produced by the living reef with marine forces driving the island formation. This makes these reef top islands vulnerable. The amenity and even future existence of these islands is threatened by:

- Direct climate change impacts
  - Rising sea levels
  - Change in prevailing met-ocean conditions
  - Changes to the frequency and intensity of cyclones/hurricanes/typhoons
- Impacts on reef top morphology of anthropogenic actions (climate change, dredged channels, etc.)
- Impacts on coral health and thus sediment supply
  - Warming waters (coral bleaching)
  - Water quality impacts including nutrients, pollutants and turbidity

On the ground these threats are playing out with increased marine flooding and coastal erosion.

Inundation (Marine Flooding)

Because the sand islands are only slightly above normal tidal range during extreme cyclonic events these by islands do experience marine flooding. This flooding is caused primarily by wave setup on the reef top. In March 2015 Tropical Cyclone Pam, a large Category 5 system passed through the northern edge of the South Pacific sending large swell across the region and causing extensive damage where it made landfall.

TC Pam did not impact Tuvalu directly; rather large waves from the cyclone travelled over a thousand kilometres to impact the west facing reefs of Tuvalu. Large waves breaking on the reef edge caused a wave setup on the reef and flooded islands with exposure to the western edge of the reefs as seen in Figure 4 and Figure 5. As is apparent in these figures the hydraulic loads are large and structural damage is wide spread, despite the cyclonic winds not impacting Tuvalu.

Figure 4. Marine flooding swamps over island, caused by TC Pam on Nanumea, Tuvalu.

Figure 5. Sand and modified cube armour blocks deposited through community of Nukulaelae, Tuvalu (Source Public Works Department GoT).

The flooding associated with the cyclonic events is very destructive and frightening for the residents of the islands. Longer term contamination of the water table is a greater threat. Sea level rise is increasing the penetration of seawater into the island water tables. The impact of saline ground water on gardens is presented in Figure 6 where gardens have died after TC Pam flooding.

Figure 6. Gardens destroyed by contaminated ground water on Nukulealea, Tuvalu (Source Public Works Department GoT).

If saline water table impacts gardens or vegetation regularly the future of the island communities will become questionable. The relationship between ground levels and tide levels on Fongafale, the main island of Funafuti, is seen in Figure 7 and clearly shows the vulnerability to this threat.

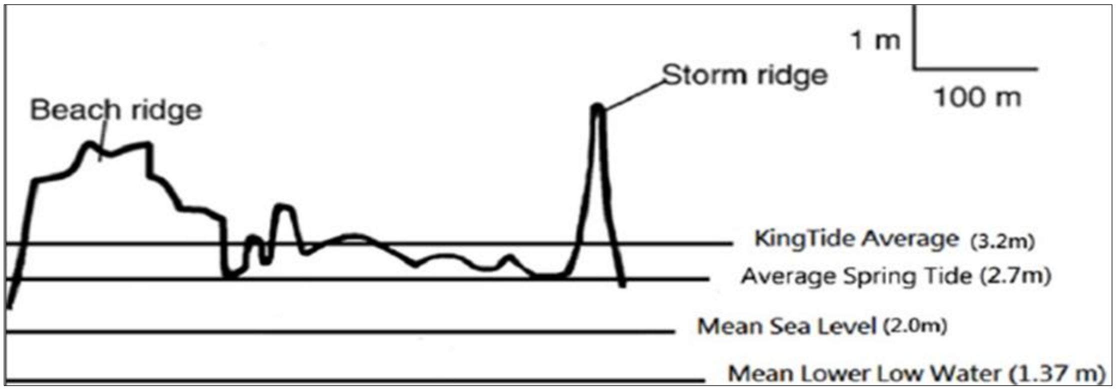

Figure 7. Section through Fongafale, Tuvalu, showing tidal planes and levels. (Source Lin 2014).

Coastal Erosion

The location and shape of coral islands represents a long-term balance between sand supply from the reef and the loss of sand off the reef platform. Changes in this balance are now causing serious erosion issues for the island communities.

<u>Sand Supply Deficit</u>

The supply of sand is dependent on a healthy reef biota. Reductions in reef vigour will reduce the supply of sand. Reasons for loss of reef vigour include:

- Raised nutrient levels – is an issue for islands with large populations where effluent discharges into surface waters.
- Coral bleaching caused by high water temperatures and is becoming an issue in recent times.
- Ocean acidification is forecast to cause issues into the future.

The capital of Tuvalu is located on an atoll known as Funafuti and has a population of 6,000 people. Sewage from this densely populated community discharges via septic tanks into the islands groundwater and then makes its way into the lagoon. This nutrient rich water feeds macro algae and has killed or diminished the reef near along the lagoon foreshore of the island. This loss of reef vigour has resulted in a loss of sand supply leading to erosion on the lagoon side shore as seen in Figure 8.

Figure 8. Degraded foreshore at the site of the recreation area on Funafuti.

Changes in Sand Distribution

The distribution of sand on the reef top represents a balance of the forces, mostly currents and waves. With changes in forcing caused by sea level rise, changes in intensity and frequency of cyclones or the impact of works such as dredged channels the distribution of sand is altered. The dramatic erosion seen on many islands of Tuvalu after TC Pam is evidence of this (Figure 9 and Figure 10).

Sand that is washed off the reef platform is lost to the system and requires healthy coral and lengthy periods of mild conditions to be replenish. Further each time a major system washes over the islands sand is lost to coastal processes as it is deposited on the island, raising it slightly, refer previous chapter on morphology.

Coastal erosion has the dual impacts of reducing the land available on these small islands, and reducing the amenity of the islands, with the loss of sandy beaches.

Figure 9. Erosion and damage caused by waves from TC Pam on western foreshore of Nui, Tuvalu (Source Public Works Department GoT).

Figure 10. Sand and palm trees scattered across reef to edge of reef following TC Pam on Nanumanga, Tuvalu (Source Public Works Department GoT).

RESPONSE

When considering an appropriate response, the circumstance of each community needs to be considered and there is not a one size fits all approach. Typically, budget constraints are very significant along with the realities of the conditions on the ground and community expectations.

Another critical consideration is the life expectancy of the works, and the degree of maintenance required. For remote islands in poor nations this is particularly relevant as it is typically easier to obtain funding for capital works than ongoing maintenance.

Broad Approaches

Broadly the options available to the planners and governments to the issues described can be broadly split into the categories of:

1. Policy response – accepting the natural forces and adapting to the changed conditions with planned retreat, and more resilient communities through betting building design and planning.
2. Soft Engineering (maintenance) – refers to activities such as beach nourishment, sand bypassing and vegetation programs to combat erosion.
3. Defend with hard structures – seawalls and barriers to resists the oceanic forces, commonly reserved for more serious circumstances because of the significant financial contribution required.

In this paper it is assumed that the decision has been made to invest in an engineered solution and that planning, and adaptation responses have already been discounted. Further it is assumed that relying on soft engineering solutions such as sand management has been discounted as a standalone option in recognition of the difficulty in undertaking regular nourishment campaigns on remote islands.

Seawall Options

The decision to build a seawall to defend the coast is usually taken when the existing assets are considered sufficiently valuable to protected from recession and erosion. An advantage of engineered (hard- permanent or quasi-permanent) structures is that the community has a sense of security behind the seawall. Given the very high cost of permanent seawalls and possible detrimental impacts they can have on coastal processes, they should only be adopted where the need is high.

There are a few basic coastal defence structures that have been considered in this paper:

- Rubble seawalls (rock or concrete armour) – sound rock (Figure 11) or concrete armour preferred, coral rock has been used in the past.
- Rigid Seawalls – pattern placed concrete armour such as sea bees or stone pitching (Figure 12).
- Geo-bags – very large, robust sandbags (Figure 13 and Figure 15).

The use of hard engineering structures should not be seen as inconsistent with the use of softer solutions such as vegetation or beach nourishment.

Rubble rock or concrete armor

The conventional rubble mound breakwater is the most common coastal defense structure built around the world, as it is an economic and robust solution. However, on remote islands landing the armor units is a major economic cost, with seawalls of this type costing in the order of US $7,000 to $14,000 per meter.

Traditionally the use of large coral blocks as rock armor is widespread on tropical islands. The coral blocks are commonly a by-product of channel excavation but are not seen as a sustainable source of armor.

Figure 11. Rock armor seawall with concrete head wall on Saibai, Torres Strait.

Rigid light weight seawalls

The use of smaller armor units constructed into a rigid face represents a compromise that requires significantly less material and can utilize local labor. A major issue with light armor solutions is that they rely on interlocking to achieve stability. This makes these seawalls vulnerability to rapid catastrophic failure mechanisms. This was evident on a number of islands in Tuvalu after TC Pam (Figure 5). An example of a more successful rigid or pattern placed seawall, with suitable edge details, is presented in Figure 12. Cost of construction of these labor-intensive seawalls are similar to the conventional rubble structures, though can be cheaper where labor costs are low.

Figure 12. Small pattern placed concrete armor (Seabee) on Boigu, Torres Strait.

Geobag structures

Large geobags have been used for several decades in Australia as a coastal armor unit, however, concerns over the longer-term performance of the bags has limited their application. Experience and testing of the geotextile material from bags after decades in use indicates that the UV degradation rate is not rapid and that the bags would be expected to last for more than 40 years, especially if buried initially to allow impregnation of material with sand. Life of the structure is also impacted by mechanical damage (e.g., vandalism) which needs to be considered, but experience in the field shows that use of more robust vandal resistant material impregnated with sand reduces this risk significantly.

A second issue with the geobags is uncertainty regarding their performance under wave attack. Although there is anecdotal evidence of structural performance under storm conditions there is very limited published data on the appropriate design characteristics. The primary reference relates scaled physical modelling undertaken at the University of New South Wales and published by Coghlan et al in 2009 (refer Coghlan 2009).

The bags are mounted in special frames to be filled with sand, as seen in Figure 13, before being sealed with stitching. The bags need to fill completely to achieve a good performance in the face. A significant advantage of this armor solution is that sand is typically one of the few resources sustainably available on coral islands. Once filled in the purpose-built attachment it is then collected by the excavators to be placed directly form the attachment (refer Figure 14) in a stretcher bond pattern as seen in Figure 15.

Because minimal materials need to be shipped to the islands the construction cost per meter for a geobag seawall is significantly less than conventional armor solutions on most remote sandy islands, with linear rates in the order of US $4,000 to $8,000 per meter. This cost saving needs to be weighed against the limited life expectancy of the bags (40 + years), meaning they offer only a quasi-permanent solution.

Figure 13. Filling 2.5 m^3 Geo-bags using special frame.

Figure 14. Placing 1.0 m^3 Geo-bags with special excavator attachment on Poruma, Torres Strait

Figure 15. 2.5 m^3 (~4 T) Geo-bag seawall corner on Nukufetau, Tuvalu.

EXPERIENCE IN TUVALU

Following the impact of waves from TC Pam the GoT, supported by the World Bank commissioned consulting engineers to examine the coastal hazards and assess options for action (ref. AECOM 2015). At the same time that study was undertaken Hall Pacific were undertaking a land fill project in Funafuti, using sand dredged from the lagoon with a large cutter suction dredge (CSD) to fill borrow pits left after the construction of the airstrip in WWII. The GoT, with funds from the World Bank, saw an opportunity to economically undertake foreshore improvement works utilizing the plant on the island. This was the

Funafuti Recreation Area Project. Separately the UNDP decided to provide support for coastal works on Nukufetau. Again, the logistical and economic advantage of utilizing plant and expertise already in Tuvalu meant that Hall Pacific supported by AECOM were able to propose and deliver an economic solution.

On both projects approvals and detailed design were delivered by Australian based consultants, while Hall Pacific undertook construction. The issues and delivery method were similar, with concerns dredging may impact healthy reef (Figure 16). On both projects dredging was undertaken using a CSD to exploit sand reserves taken from within the lagoon. Dredging with a CSD resulted in minimal plumes at the dredge site in the lagoon with sand taken from depth to avoid direct impact on coastal processes. Onshore the dredged sand slurry was managed with bunds to minimize plumes at the coast, as seen in Figure 18. The sand, once drained, was then used to nourish beaches, reclaim land and fill geobags for seawalls or groynes.

Figure 16. Healthy corals in Nukufetau's lagoon.

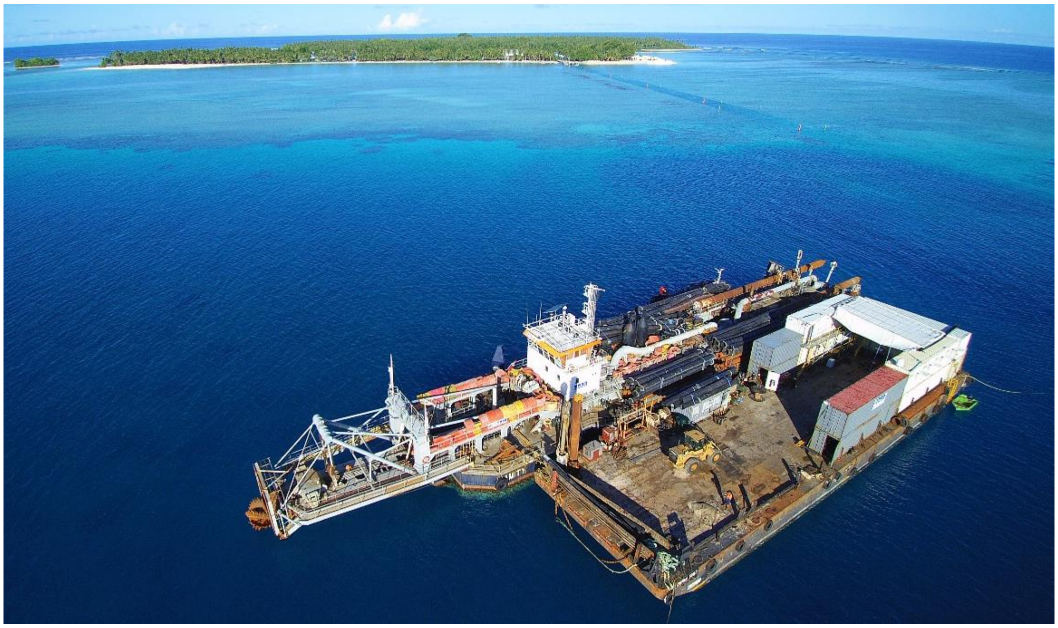

Figure 17. Cutter suction dredge and support barge in the Nukufetau lagoon.

Figure 18. Dredged sand slurry delivered to bunded area for use as beach nourishment and to fill Geobags, Funafuti.

Funafuti Recreation Area Project

The foreshore of the main island of Funafuti has experienced extensive loss of sand since the 1940's due to loss of reef vigor in the lagoon, as described previously. This had left the community with an unattractive lagoon side foreshore that offered little protection from storm conditions as seen in Figure 8. The window of availability between the decision to undertake the project and the Hall Pacific equipment needed to move on was short, and the authors undertook detailed design and the required environmental approvals in just a few months.

Figure 19. Completed Funafuti recreation area contained by groynes plus nourished foreshores.

The adopted design involved:

- Dredge 180,000 m^3 of sand, for reclamation and nourishing 1,500 m of foreshore.
- Construction of two 100 m long groynes utilizing 608 2.5 m^3 geobags to contain reclamation.

The finished product as seen Figure 19 was delivered just 6 months after being initially discussed. The works improve the resilience of the community from lagoon side wave action and flooding and was well received by the 6,000 inhabitants in this land starved community.

Seawalls and beaches for Nukufetau

Nukufetau is a very remote community that was severely impacted by the waves from TC Pam. With no access by air and only a limited marine access the options for affordable solutions was very limited. Based on work undertaken in the broader Tuvalu study (ref AECOM 2015), the authors were able to develop a solution that addressed erosion issues on both the northern and southern ends of the island within the budget expectations. The final solution involved:

- Old damaged seawall buried.
- Construction new seawalls and groynes using 2,020 2.5 m^3 geobags.
- ~20,000 m^3 beach nourishment.
- Recycled coral armor used to repair seawalls.

The finished product as seen in Figure 20 is attractive and was well received by the community. The seawalls address erosion concerns while the beaches improve the immunity of the community to wave attack and flooding.

Figure 20. Finished works on Nukufeau.

SUMMARY

Communities on remote coral atolls and coral cays face ongoing erosion and marine flooding issues. With climate change these issues are worsening and the additional threat of ground water contamination is threating the long-term viability of some of these communities.

The prohibitive cost of constructing conventional seawalls on these remote islands combined with the uncertain future they face leads us to consider alternative solutions. The use of large geobags exploiting either reef top or dredged sand reserves offers a more economical solution. On most of these island's sand is the one resource that can be sustainably exploited. The experience in Tuvalu demonstrated that this approach offers a more affordable solution that, while not as permanent as conventional rock armor structures will give the communities, governments, and agencies time to develop longer term plans to address the threats that future sea level rise will bring.

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DATA AVAILABILITY

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"REMOVAL-TO-REUSE" APPROACH TO DESIGN OF DREDGING AND SEDIMENT PROCESSING ALTERNATIVES – CASE STUDY (GORGE DAM, AKRON, OHIO)

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EXTENDED ABSTRACT

Introduction

Dredging to remove sediment that has accumulated behind dams, often as a precursor to dam removal, is of significant national and global interest. This is a result of heightened attention to aging infrastructure, flood safety issues, recreational demands, and changing priorities in watershed conservation management - in particular, renewed interest in allowing river systems to recover to their natural state. Since 1912, nearly 2,000 dams have been removed in the United States (American Rivers 2022). Over 76% of these dam removals have occurred within the past 25 years, a trend that is expected to continue alongside efforts to address the growing number of high-hazard-potential dams, currently in excess of 15,600 (American Rivers 2022 and ASCE 2021). The removal of contaminated sediment from behind dams is a challenge that proportionally impacts the value engineering design and selection of appropriate dredging and material processing techniques.

The Gorge Dam case study highlights the decision-making approach employed by Federal, State and Stakeholder partners to select the appropriate dredging and placement engineering design for a dam removal and river restoration project, based on a "removal-to-reuse" project perspective. Consideration was given to the ultimate placement and end-use of the dredged material early in the design process, allowing project designers to consider a broader range of innovative dredging and treatment options and ensure connectivity between the front- and back-end components of the design.

Project Background

The Gorge Dam is located on the Cuyahoga River, between the cities of Akron and Cuyahoga Falls, Ohio. Approximately 877,000 cubic yards (yd^3) of soft, contaminated sediment must be removed from the pool behind the Gorge Dam to facilitate dam removal (anticipated 2024) and restoration of the Cuyahoga River

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to a natural, free-flowing channel through the Cuyahoga Gorge. Historical pollution contributed to over a dozen major fires on the river from the mid-1800's to the mid-1900's, eventually spurring the environmental movement in the United States and making the Cuyahoga a symbol of urban riverine degradation.

Concentrations of organic and inorganic chemicals in the sediment behind the Gorge Dam have been observed at or above ecological thresholds, including PAHs, pesticides, PCBs, and heavy metals (Tetra Tech 2015). Dredging prior to dam removal is therefore important to avoid the potential downstream transport of contaminants. Delisting of the Cuyahoga River Area of Concern (AOC) is a key project driver under the Great Lakes Legacy Act (GLLA) funding measures to remediate sediments in the Great Lakes AOCs. The project is being conducted under the auspices of the US Environmental Protection Agency (US EPA) Great Lakes National Program Office (GLNPO) along with project Stakeholders.

Objectives

GLNPO has entered into a GLLA Project Agreement with the Ohio Environmental Protection Agency (Ohio EPA) and the City of Akron, the City of Cuyahoga Falls, and Summit Metro Parks (SMP), collectively referred to as the Stakeholders, to support the successful construction of a remedy that meets the objectives and performance criteria specified in the GLNPO Statement of Work:

- The primary remedial objective is the removal of contaminated sediments from the dam pool area that may pose an unacceptable risk to aquatic and human life.

- The primary restoration goal is to remove remaining soft sediment deposits from the dam pool area and restore the free-flowing natural channel through the Cuyahoga Gorge.

Successful implementation of this sediment removal project and attainment of these goals will increase fish habitat while improving water quality, leading to improved habitat for fish, wildlife, and benthic life and removal of the associated beneficial use impairments (BUIs) in the Cuyahoga River AOC.

Project Considerations and Design Approach

The preferred Remedial Alternative (RA) outlined in the 2015 Feasibility Study (Tetra Tech 2015) included hydraulic dredging during a single construction season, with sediment dewatering and onsite weep water treatment. A 35-acre former landfill along Peck Road in the Chuckery Area of the Cascade Valley Park, adjacent to the Cuyahoga River, was identified as the final dredged material placement site. Dam demolition was proposed to occur during the same season to maintain bank and flow stabilities and avoid complications from spring/fall flood cycles.

Further consideration of a variety of factors, including: (a) the dam removal schedule, (b) the upland placement site construction timeline, (c) the time, space, and operational requirements for geotextile tube dewatering - including water treatment, (d) sediment removal efficiency, (e) operational and placement site space restrictions, and (f) river water levels and access limitations, resulted in the evaluation of alternative approaches to dredging and sediment treatment for beneficial use. As a result, in consultation with US EPA and the primary Stakeholders, three changes to the preferred RA were included in the preliminary design.

Preliminary Design

Stabilization/solidification (S/S) via Pneumatic Flow Tube Mixing (PFTM) has been identified as a viable technology for the treatment, management, and upland beneficial use of Gorge Dam sediments. The preliminary design includes mechanical dredging of sediment, screening, and subsequent transport via high-density polyethylene (HDPE) pipeline to PFTM operations at the upland beneficial use placement site. The sediment will be stabilized with Portland cement (and other additives, as necessary) and managed as a flowable engineered fill upon discharge from the PFTM system.

The preliminary design includes the beneficial use of stabilized Gorge Dam sediment as engineered fill for landscape contouring to restore the designated upland placement site, which will be subsequently planted with native grass and tree species for ecological restoration. Bench-scale testing in support of the preliminary design suggests that there is negligible leaching of contaminants above allowable ecological or human health risk levels. This design also eliminates the management, treatment, and disposal of weep water.

Conclusion

Design engineers and project Stakeholders considered key parameters in pursuit of the Gorge Dam project goals and objectives. As a result, it became clear that historically successful solutions, such as geotextile tube dewatering, would not be sufficient to effectively balance project and Stakeholder needs. Early and up-front consideration of sediment placement and re-use opportunities ("removal-to-reuse" approach) helped to limit the inadvertent disqualification of sediment management and beneficial use alternatives as the design evolved.

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DATA AVAILABILITY

No data, models, or code were generated or used during the study.

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We thank Mary Beth Giancarlo of the US Environmental Protection Agency Great Lakes National Program Office (US EPA GLNPO) who is providing lead project management for the Gorge Dam remediation effort. We also thank the Ohio Environmental Protection Agency which has a shared cooperative project agreement with the US EPA and the City of Akron, and project Stakeholders who are contributing cost-share resources to this project.

IMPLEMENTING A RESLIENT STRUCTURE TO PROTECT COASTAL AND HISTORIC RESOURCES AT BRUNSWICK TOWN/ FORT ANDERSON

Phillip C. Todd[1], Jim McKee[2] and Devon Eulie, PhD[3]

EXTENDED ABSTRACT

The shoreline at the State of North Carolina's historic site, Brunswick Town/ Fort Anderson (BTFA), needed protection from constant tide forces and dynamic wave action. Colonial-era wharves are being destroyed, and precious artifacts from these buried colonial-era wharves are being washed into the Cape Fear River. The Civil War-era batteries are being undermined. Additionally, valuable *Spartina alterniflora* marsh platforms were being eroded. The NC Department of Natural and Cultural Resources (NCDNCR) seeks to halt the shoreline erosion to prevent the destruction of and additional wash of these buried colonial-era wharves, the Civil War-era batteries and the destruction of three other colonial era wharf sites.

The State sought a solution that would be meet the environmental and varying bathymetric challenges at the site. BTFA's waterfront sits along the river's main channel and the passing lane for vessels accessing the Port of Wilmington, NC that enables shipping traffic the ability to speed up and pass other slower moving traffic.

The State had conversations with the Corps of Engineers (USACE) about installing a traditional rock breakwater structure (TRBS). However, the State had concerns about implementing a TRBS, including: 1) maintenance of the TRBS as the site experiences vessel generated wakes (VGW) from vessel traffic accessing the Port of Wilmington, NC; 2) the horizontal challenges of installing wave protection at 'natural' wharfs (deep drop offs into the Cape Fear River without adequate horizontal space for a TRBS); 3) coastal and historic resource impacts resulting from TRBS installation, particularly the wharfs, as a TRBS would fill and cover these resources; 4) adaption for climate change. The State asked a consulting engineering to look at adapting existing technologies and structures to solve the wave attenuation problem at the site. It was quickly identified that passing ship's displacement, based on its tonnage and combined with its speed, was the primary source of the damaging waves.

The engineer identified the Reefmaker (RM), a flow through, pile-based wave attenuation product with ecological benefits, as a potential solution. The product would meet the State's initial concerns, and the engineer and the State quickly realized that the RM could be altered and engineered to dissipate high energy waves. However, the product owner had minimal engineering calculations or construction specifications to ensure that the system could handle a high wave energy environment resulting from vessel traffic in the Cape Fear River.

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The RM concept includes individual ecodisks made of concrete that are stacked on a 12” diameter fiberglass pile. The legs on the ‘water front’ side, or open water/river side of the structure, of the ecodisk tray direct water to the fiberglass piling. The piling speeds up the wave energy speed, and when the water reaches the ‘landward’ side of the structure, then the water exits the structure. The wave energy dissipates because the flow is no longer concentrated, and sediment in the water column drops out, accreting on the shoreline.

The ecodisks utilize fiberglass rebar instead of metal rebar. Fiberglass rebar was used to increase the life expectancy of the structure as metal rebar tends to shrink and swell with cooling and heating, and this tends to lead to cracking of the concrete.

Implementation includes a barge and crane. The excavator was used to pilot the installation of the hollow, 12” fiberglass pile down to depths of 35’ to 40’ as the sub-surface conditions at the site are inconsistent with quaternary surficial deposits, organic loose sands and organic soft clays. The piling was installed with the mechanical support system already attached. After the piling was installed to the correct depth, then the ecodisks were lowered onto the piling.

DNCR staff are very pleased with the results of BTFA shoreline protection. The project is achieving their desired objective: protecting the historic cultural and natural resources from rapid shoreline erosion resulting from constant tidal forces and dynamic wave action. Where the shoreline has been protected, these artifacts are no longer being washed away and lost. Coastal resources have been protected and have benefited from the project’s implementation.

A secondary objective of the project was to have no maintenance costs. Construction for Phase 1 was finalized in July 2017, while implementation of Phase 2 and Phase 3a was completed in August 2018 and May 2021, respectively. Since installation of Phase 1 and 2, the shoreline protection project has been challenged by consistent VGW, such as, from September 13, 2019 to October 15, 2019, there were 37 incidents from 23 port bound and 14 sea bound vessels (RPS 2019. There was several days of high tide storm surge and pounding waves from Hurricane Florence, which crossed over the site, and there was persistent flooding of the structure for many weeks after this storm event. There have been other storm events, including Hurricane Isaias in August 2020 and numerous nor’easters. There has been no damage to the structure, and, DNCR has not expended any funding for maintenance of the implemented shoreline protection.

The project has exceeded the DNCR staff expectations with respect to marsh restoration and marine life utilization of the area. Accretion behind the Phase 1 and 3A structure is restoring the shoreline and marsh and improving water quality as sediment is removed from the water column (CPE 2021). The remanent *Spartina alterniflora* populations are now expanding because the once destructive wave energy from the VGW is being dissipated by the RM (UNCW 2022). Blue crab populations are prevalent at the site, and local fisherman often fish off the property.

Shoreline protection at BTFA has been recognized by other organizations. This includes:

- November 2019, American Council of Engineering Companies – North Carolina presenting the project’s consulting engineering firm with its 2019 Award for Engineering Excellence in the Water and Storm Water/Water Resources/ Special Projects Category.
- April 2021, the USACE (Bridges et al 2021) including BTFA in its Engineering With Nature (EWN) program’s *An Atlas: Volume 2*. BTFA was one of 62 projects that were highlighted from around the world.
- August 2021, the American Shore and Beach Preservation Association 2021 awarding the project as its *Best Restored Shores Award*. (ASBPS undated).

Keywords: Breakwater, Environmental Restoration, Vessel Generated Wakes, Marsh, Accretion, Engineering with Nature

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DATA AVAILABILITY

Some or all data generated or used during the study are available from the corresponding author by request.

RELEVANT STUDIES/ DOCUMENTATION

Todd, P.C, and Eulie, D.O. "Shoreline Protection of Historic and Coastal Resources at Brunswick Town/ Fort Anderson," *Proceedings of the Western Dredging Association Dredging Summit & Expo '19, Chicago, IL, USA*, June 4-7, 2019.

USE OF ROCK REVETMENTS TO PROTECT AN INDUSTRIAL ISLAND FROM NATURAL AND MAN-MADE FORCES

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ABSTRACT

Rock revetments are widely used in areas with important backshore assets subject to severe and ongoing erosion and where it is not cost effective or environmentally acceptable to provide full protection using seawalls. The authors have used rock revetments to protect an industrial facility on an island located along the Savannah River and Atlantic Ocean near Savannah, Georgia, USA. The shoreline has been or continues to be subjected to on-going or instant erosion from natural and man-made forces. This paper discusses the on-going shoreline protection and stabilization efforts at the industrial island within the Savannah River and Savannah Harbor. Lessons learned from this and other two case studies also are discussed.

Keywords: Rock revetments; shore protection; armored systems; shoreline erosion; scouring

INTRODUCTION

Rock revetments are widely used in areas with important backshore assets subject to severe and ongoing erosion where it is not cost effective or environmentally acceptable to provide full protection using seawalls. The function of permeable revetments is to reduce the erosive actions of the waves by means of wave energy dissipation in the interstices of the revetment. Revetments may not prevent on-going shoreline recession unless they are maintained, and, if necessary, extended. If the shoreline continues to erode, the rock revetment may slump downward, becoming less effective as a defensive structure, but usually does not fail completely. Repairs and extensions may be necessary to provide continued backshore protection at the design standard.

The authors have used rock revetments to protect an industrial facility on an island located within the Savannah River upstream of the Atlantic Ocean near Savannah, Georgia, USA. The shoreline has been or continues to be subjected to on-going or instant erosion from natural and man-made forces. This paper discusses the on-going shoreline protection and stabilization efforts at the industrial island within the Savannah River and Savannah Harbor. Lessons learned from this and other two case studies are also discussed in this paper.

FACILITY LOCATION AND DESCRIPTION

Southern LNG Company. LLC (SLNG), a Kinder Morgan Company, owns and operates the Elba Island Liquefied Natural Gas (LNG) Terminal in Savannah Harbor, Georgia. The LNG facility regularly receives

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imported LNG shipments from around the world and serves as a key natural gas supply hub for markets in the southeastern and eastern United States. The LNG facility, previously used only as an import terminal, is now also able to produce LNG for export when it started the commercial operation of newly commissioned liquefaction units in late 2019.

Elba Island is located within part of the Savannah Harbor, approximately five miles [mi] (8 kilometers [km]) east of the City of Savannah, in Chatham County, Georgia, and 8.5 mi (13.6 km) upstream from the mouth of the Savannah River. The island is bounded by the Savannah River and the South Channel, which is part of the Atlantic Intracoastal Waterways (AIWW). Figure 1 shows the project location.

Figure 1. Project Location.

The approximately 840-acre [ac] (336-hectare [ha]) Elba Island includes 225 ac (90 ha) of the existing LNG Terminal (167 ac (66.6 ha) for the plant and 57 ac (22.8 ha) for a ship berthing area (referenced as the ship slip) and two dredged material containment areas (DMCAs) with a combined area of 250 ac (100 ha), designated as DMCA 1 and DMCA 2 as illustrated in Figure 2. A stilling basin for secondary treatment of dredged sediments prior to discharge of the effluent to the Savannah River is also a part of the infrastructure system on Elba Island. Due to heavy traffic of cargo ships passing through the Savannah River to the upstream city facilities, Elba Island's approximately 4,500-linear feet [linear ft] (1370-linear meter [linear m]) shoreline typically experiences severe erosion in addition to natural erosion from the tidal effects in the Savannah River.

Figure 2. Infrastructure system at Elba Island.

IMPACTS FROM NATURAL EROSION AND SHIP TRAFFIC

The authors' experience indicates that most of the severe erosion is caused by the frequency, travel speed, and resulting wave actions of ships passing through the river to the Savannah Harbor in addition to natural erosion from tidal effects from the river (Figures 3 and 4, respectively). Armor stones weighing as much as 2 tons (1.8 tonnes) are routinely displaced by the wave action from ship traffic, which results in the shoreline being exposed to more severe erosion. This erosion becomes expensive to the facility and requires continuous efforts to protect the shoreline. The authors worked with the facility owners to develop measures to control the on-going damage to the shore protection system.

Figure 3. Erosion from ship traffic along the Savannah River.

Figure 4. Natural erosion from tidal effects of the Savannah River.

LONG-RANGE SHORE PROTECTION PLAN

In 2008, the authors developed a long-range protection plan for maintenance of the shoreline due to severe erosion. The plan consists of using a phased approach (Phases I, II and III) whereby the shoreline is broken down into four priority zones (A to D) as defined below. Figure 5 shows the limits of the shore protection plan where Phase 1 is on the southern limit of the island and east of the ship slip and Phases 2 and 3 limits span the western part of the island including the LNG storage tanks and other infrastructure facilities and the DMCAs to the edge of the South Channel. As illustrated on Figure 5, the shoreline is in proximity to these infrastructures and therefore the need to protect them from erosion.

Figure 5. Phased approach for shore protection maintenance.

These areas were subsequently subdivided into zones for the purpose of prioritizing the sequence of maintenance activities and in order to generally classify the type of maintenance activities required. These priority zones are described as follows:

- Priority A: repair for areas of active erosion and areas of on-going loss of shoreline;
- Priority B: repair for areas of recent extensive erosion and areas of imminent loss of shoreline;
- Priority C: repair for areas of moderate erosion and areas of high potential for loss of shoreline; and
- Priority D: repair for areas of limited erosion and areas of moderate potential for loss of shoreline.

SHORE PROTECTION MAINTENANCE DESIGN

An implementation plan was then developed following annual site reconnaissance of the shoreline conditions. Stabilization consists of use of armored systems, comprised of armor stone, riprap underlayer stone, and a gravel bedding layer, to repair areas that have experienced severe erosion. The armor stone weight, size and gradation are generally designed and selected based on the studies performed by the U.S. Army Corps of Engineers (USACE 1984), Ahrens (1981), and the authors' experience. The underlayer stone and gravel bedding layer function as granular graded filter and are generally designed based on the guidelines established by the USACE (1955). The design features of the shore protection system include using armor stones with a median weight of 850 lbs (386 kg) and a median diameter of 2.1 ft (0.64 m) placed between elevations -5 and 13 ft (-1.5 and 3.96 m), Mean Low Water (MLW) to control erosion for the extreme tidal fluctuations and wave action from container ship traffic at speeds approaching 15 knots (8 m/s). Soil backfill consisting primarily of dredged material is also used to backfill areas with severe erosion prior to placing armored system. Figure 6 show typical sections illustrating the shoreline protection stabilization measures utilized for Elba Island.

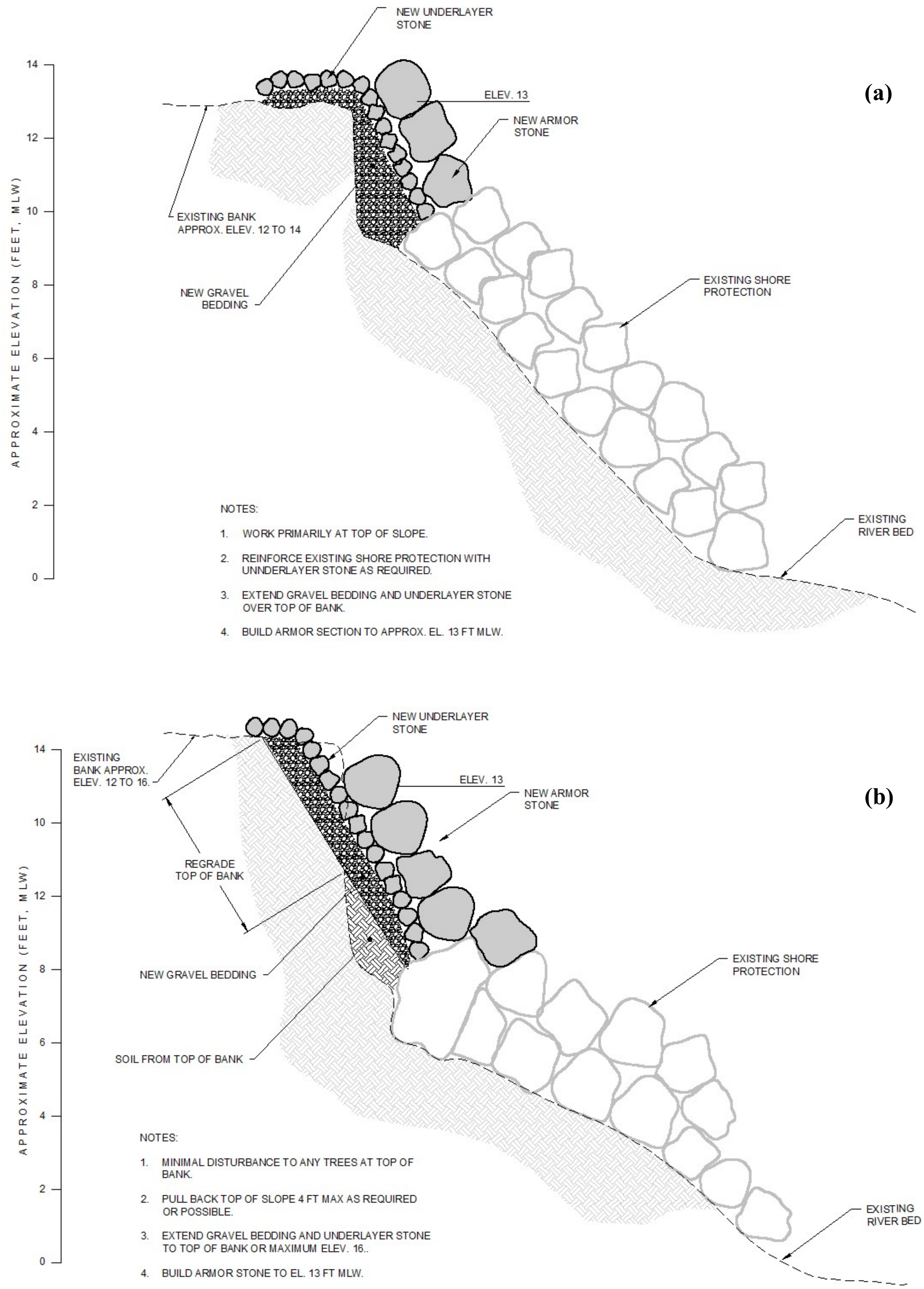
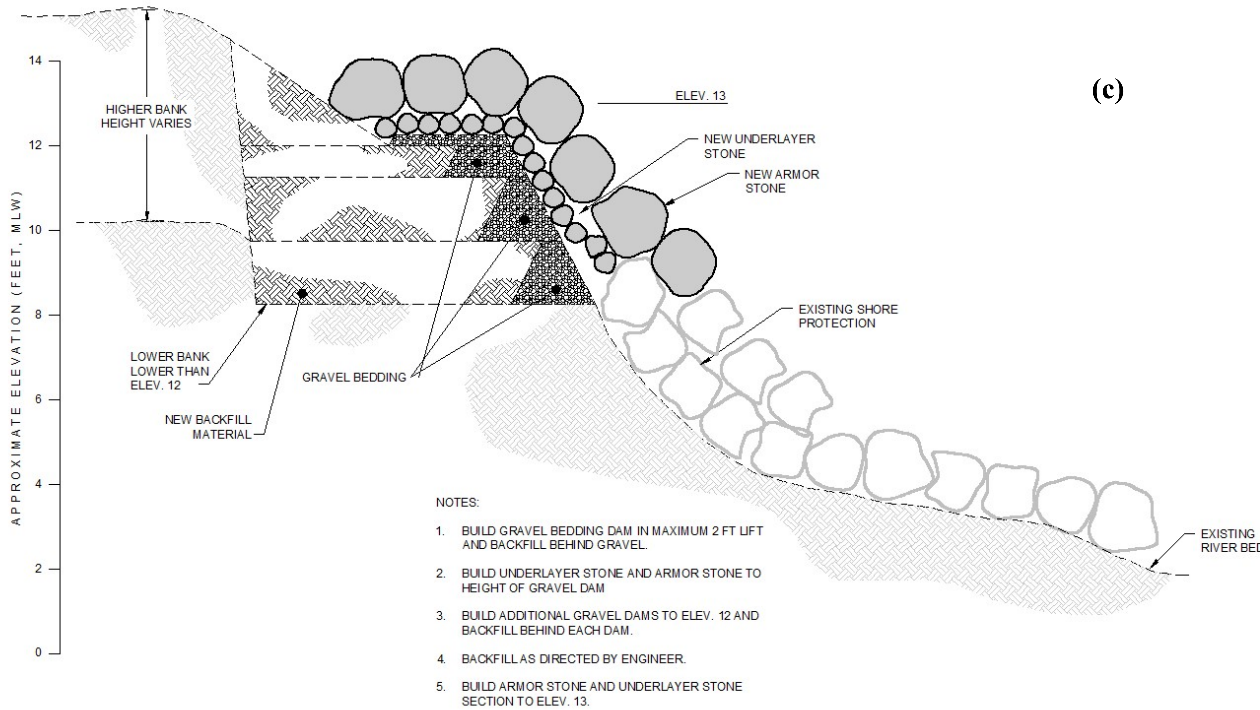


Figure 5. Typical shore protection maintenance at the Savannah River facility: (a) Priority A; (b) Priority B.



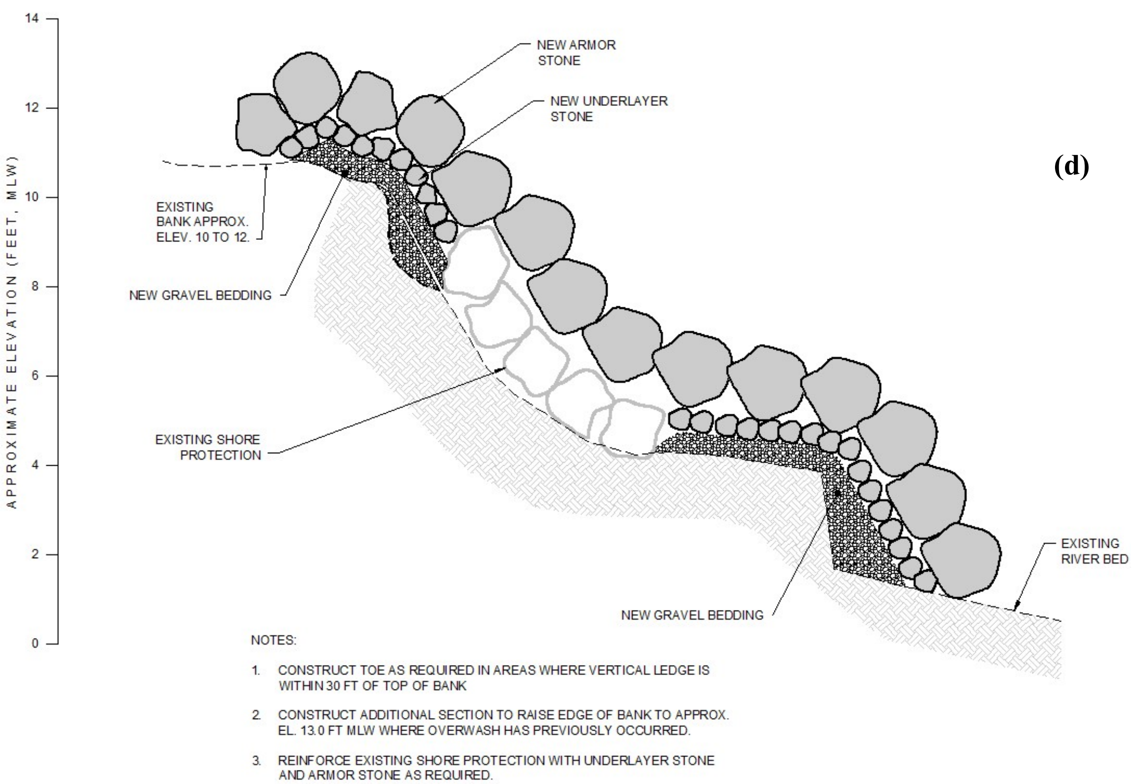


Figure 5 (cont'd). Typical shore protection maintenance at the Savannah River facility: (c) Priority C; and (d) Priority D.

As shown in the above figures, the shore protection maintenance generally consisted of replacing or placing additional armor stones to the crest of the shoreline bank and in some cases to the toe as a result of loss into the river bottom. It is also noted that the authors have preferred to use granular graded filter (gravel bedding and underlayer stone) in lieu of geotextile filter. Even though geotextile filter generally functions in such applications and have been used in previous rehabilitation, it is the authors' experience that depending on the type of geotextile fabric used, they tend to promote or facilitate sliding of the armor stone and are subjected to degradation of its long-term durability and survivability under the semi-tropical conditions of the area.

Implementation Plan

As part of annual maintenance of shore protection systems, the authors regularly provided the facility engineering support services which include: (i) site reconnaissance to delineate area of the shoreline needing repairs; (ii) preparation of construction drawings and technical specifications for each construction season; (iii) contractor procurement support; and (iv) construction oversight and inspection. Following completion of site reconnaissance, construction drawings are prepared, and contractor procurement support is provided to select contractor to implement the maintenance each year. It is noted that since 2008, the facility owner has utilized the same contractor even though bids are solicited from other contractors in some years.

Engineering and Construction Support Services

The authors have provided engineering and construction support services during construction of annual shore protection maintenance on Elba Island. Activities performed included: (i) coordination with regulatory agencies; (ii) review of contractor submittals and tracking of delivered stones; (iii) monitoring of stone placements; (iv) meeting participation; (v) review of contractor invoices; (vi) photographic documentation; and (vii) site restoration.

Coordination with Regulatory Agencies

The authors provide assistance to obtain the necessary permits and approvals from USACE, Savannah District (USACE-SAS) and Georgia Department of Natural Resources (GADNR) Coastal Resource Division (CRD) for the shore protection maintenance construction completed under this project. Since 2018 a blanket permit has been issued by the regulatory agencies since the annual maintenance has become routine for the facility.

Material Source and Requirements

The stone materials generally used for the shore protection maintenance construction project consist of gravel bedding, underlayer stone and barrier stone. All stone materials are required to be composed of granite or granite type rock with a minimum specific gravity of 2.6 (per American Society for Testing and Materials [ASTM] C 127) and maximum 50 percent loss of abrasion (per ASTM C 535). The technical specifications require the gravel bedding material to meet the gradation requirements for American Association of State Highway and Transportation Officials (AASHTO) No. 57 aggregates in accordance with the Georgia Department of Transportation (GADOT) Standard Specifications. A Type 3 stone dump riprap meeting the requirements of Section 805 of the GADOT Standard Specifications is typically specified for the underlayer stone. The barrier stone (also called armor stone) is specified to be either boulders or quarried rock with the following gradation requirements: (i) median stone weight (W_{50}) = 850 lb (386 kg); (ii) maximum stone weight (W_{max}) = 3,400 lb (1542 kg); and (iii) minimum stone weight (W_{min}) = 110 lb (50 kg).

The stone materials are generally obtained from a quarry near Augusta, Georgia. The material certification and test results provided by the supplier are reviewed to confirm compliance with the technical specifications prior to stone being trucked to the site. The authors also monitor the delivery and stockpiling of the various stone materials for each phase of the shore protection maintenance construction project. Truck delivery tickets are collected and summarized in a spreadsheet format for the purpose of invoicing as well as evaluating the actual quantities required for each zone of shore protection maintenance.

Construction Monitoring Activities

The general scope of work for the shore protection maintenance included the following:

- removal of debris along the shoreline that interfered with the placement of shore protection materials;
- placement of gravel bedding to a minimum thickness of 6 in. (15 cm) in eroded areas, as indicated on the construction drawings or as directed by the Engineer;
- placement of stone underlayer on top of the gravel bedding to a minimum thickness of 18 in. (45 cm) in eroded areas, as indicated on the construction drawings or as directed by the Engineer; and
- placement of barrier stone on top of the stone underlayer, as indicated on the construction drawings or as directed by the Engineer.

An excavator with grapple (Figure 6) is typically used for stone placement, especially for placing the armor stone, one at a time, to choke-in (stabilize) the areas as necessary. A rubber-tired front-end loader and an off-road truck are also used for loading and transporting stone materials from the stockpile areas to the construction area for placement.

Figure 6. An excavator with a grapple used for placement of shore protection armor stones.

In general, stone is placed in a manner to produce a reasonably well-graded mass of rock with the minimum practicable percentage of voids and in accordance with the Construction Drawings and Technical Specifications and as directed by the Engineer. Figure 7 shows typical example photographs of before and after shore protection maintenance on Elba Island.

Figure 7. Before and after construction photographic documentation.

Implications of Land-Based Construction Methods

Historically, the repairs have generally involved the use of land-based equipment, whereby repairs are conducted from the bank side of the shoreline as illustrated in the photographs in Figure 6. One of the primary reasons for land-based repairs is that using water-based construction method (i.e., with equipment working from a barge in the river) required marine insurance that would increase the construction costs. Since 2019, the facility has modified operations to include LNG export operations as mentioned earlier. Permitting of this expansion including installation of modular moveable liquefaction system (MMLS) trains required construction of a high sheet-pile surge wall to a constant elevation of 27 ft (8.2 m) mean low water (MLW) around parts of the island as illustrated in Figure 8. This therefore made repairs to the shoreline in those areas challenging and a crane with a long boom was utilized to place armor stones across the surge wall as shown in Figure 9.

Figure 8. Surge wall around parts of Elba Island.

Figure 9. Shore protection maintenance over surge wall.

Implementation Schedule and Costs

Phases I, II, and III components of the long-range plan were implemented from 2008 to 2012 whereby approximately 15,000 linear ft (4,600 linear m) of shoreline were repaired during that period. Since 2013, repairs are conducted at critically eroded areas (i.e., localized repairs) annually following site reconnaissance of the shoreline conditions. The site reconnaissance is conducted along the shoreline in a boat during low tidal conditions to help observe conditions at the toe (Figure 10).

Figure 10. Site reconnaissance during low tidal conditions.

Table 1 shows a summary of the lengths and costs of repairs completed annually with an average unit cost of $250 per linear foot ($76 per linear m). Note that the unit cost for the Phase II localized repairs in 2019-2020 is much greater than the other repairs and average cost because this was the section of the shoreline that repairs were conducted using a long boom crane across the surge wall as discussed above and illustrated in Figure 9.

Figure 11 also shows localized areas within Phases I, II, and III that have undergone multiple repairs since the initial repairs were completed from 2008 to 2012. The authors believe these areas are typically subjected to more or repetitive wave action from ships passing through the Savannah River.

Table 1. Summary of repair lengths and costs

Phase description	Year	Length (ft)	Cost	Unit Cost per Linear Foot
I	2008	2,250	$878,500.00	$390
II	2009	4,075	$571,191.00	$140
III	2010	3,325	$655,386.20	$197
	2011	4,200	$847,135.80	$202
	2012	1,000	$250,000.00	$250
Localized Repairs	2013	1,000	$240,042.00	$240
Localized Repairs	2014	1,020	$259,427.30	$254
Localized Repairs	2015	100	$35,000.00	$350
Localized Repairs	2016	1,000	$299,128.58	$299
Localized Repairs	2017	200	$93,023.59	$465
Localized Repairs	2018	1,100	$362,000.00	$329
Localized Repairs - Phase I	2019	1,200	$385,940.00	$322
Localized Repairs - Phase II	2019-2020	300	$277,913.00	$926
Localized Repairs	2021	400	$140,959.00	$352
Total =	2008 to 2021	21,170	$5,295,646.47	$250

Note: 1 ft = 0.305 m

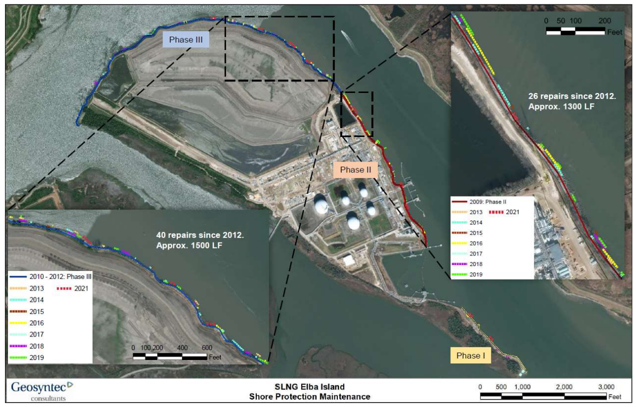


Figure 11. Repaired areas since 2008.

LESSONS LEARNED

The experiences gained from this facility were applied to two other facilities on the Gulf Coast in Mississippi and the St. Johns River and Atlantic Ocean in Jacksonville, Florida, all in the USA (Badu-Tweneboah and Mijares, 2022). The Gulf Coast facility had a storm surge wall (i.e., seawall) that was susceptible to scour due to wave action under normal conditions and during a tropical storm/hurricane event. In 2012, it experienced significant scouring from Hurricane Isaac. The authors designed a seawall scour protection system consisting of rock revetment and provided oversight during construction. In this case the repairs were conducted using water-based construction methods primarily due to the safety concerns associated with the land-based method from inside the facility (Figure 12).

Figure 12. Shore protection maintenance at the Gulf Coast facility.

The third facility located along the St. Johns River experienced severe erosion damage during Hurricane Irma in 2017. Approximately 900 linear ft (270 linear m) of shoreline sustained damage from the hurricane (see Figure 13). The repair design was broken down into three phases from severe and imminent to less severe, similar to the long-range plan for the Savannah River facility, to allow the facility to plan and budget accordingly. Figure 13 also shows the Phase I section that was repaired in 2018.

CONCLUSIONS

The Elba Island's shoreline is continuously being subjected to incoming wind-driven and ship-driven waves along with storm and tidal water depth variations that accelerate the erosion process. The design of the shore protection takes into consideration these factors. The authors were able to develop a long-range shore

Figure 13. Erosion damage from Hurricane Irma and subsequent repairs at the St. Johns River facility

protection maintenance program that categorized various segments of the shoreline as critical areas requiring immediate repairs to non-critical areas needing continued monitoring for future repairs.

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DATA AVAILABILITY

No data, models, or code were generated or used during the study.

CONDITIONS ASSESSMENT TOOL FOR THE TEXAS GULF INTRACOASTAL WATERWAY DREDGE MATERIAL PLACEMENT AREAS

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EXTENDED ABSTRACT

The Texas Gulf Intracoastal Waterways (GIWW-T) main channel is a 379-mile-long, shallow-draft, man-made, protected waterway that connects 16 economically important ports along the Gulf of Mexico from the Sabine River to Brownsville, Texas.

The Texas Department of Transportation – Maritime Division (TxDOT-MRD) undertook a study to inventory and assess the conditions of the GIWW-T Dredged Material Placement Areas (DMPA) by developing a high-risk profile decision support tool to account for each DMPA's functionality, structural integrity, lease life, and costs for rehabilitation and improvements; and subsequently develop plans to extend the service life or navigation safety benefits of the highest at-risk DMPAs by identifying and recommending engineered, beneficial use of dredged material, and/or property acquisition solutions.

A set of criteria was formulated to measure and compare the condition of the inventoried DMPAs, based on collected and compiled data that defined each DMPA's property and physical attributes. Additionally, easily adaptable weighted scores were developed and applied to each criterion to support establishing the risk-profile ranking of each DMPA.

The relational data, attributes, and weighted criteria were structured and networked into an analytical logic tool utilizing the system architecture of MS Access. This weighted ranking tool automated the process to assess the relative condition at each DMPA site for the purpose of determining the sustainability of any

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given DMPA to continue receiving future dredged material, which enabled TxDOT-MRD to quickly forecast when alternative disposal site locations or parcels will need to be acquired, or when future maintenance and capital investments will be required.

The DMPA condition assessment and decision support process started with collecting data related to Property Ownership, Physical Attributes, Frequency of Use, and any other existing data specific to the DMPA parcel, such as the boundary surveys, containment dike surveys, LiDAR, and levee elevation assessments.

Based on the information collected from the physical inventory task, four attributes were identified as criteria for the initial assessment. The four attributes considered for primary scoring were: 1) Property Ownership, 2) Property Lease Life, 3) Functionality, and 4) Condition. Cost of repairs was considered for secondary scoring. Descriptions of the four primary attributes are provided below.

1) Property Ownership. Several attributes such as the owner type (public, private, mixed), the ownership type (owned/leased), ownership duration, agreements of use, and any disputes identifying the potential conflicts associated with the property acquisition were collected as available. Since TxDOT-MRD is responsible for acquiring land, easements, and rights-of-way for the U.S. Army Corps of Engineers to use a DMPA, the ease of land acquisition is an important factor and dependent, in part, on whether the property is owned by a single public owner or multiple different private owners. Therefore, the number of owners was considered a key variable.

2) Property Lease Life. The remaining duration of the DMPA's property lease agreement was determined to be the most critical attribute affecting the risk profile of the DMPA site for this criterion. A lease that is about to expire in the near future indicates that the state of the property ownership is uncertain, and therefore, increases the risk of the operational availability of the DMPA site. Conversely, a remaining long-standing lease agreement suggests clarity on the property ownership and reduces the risk. Therefore, the duration of the current lease was considered a key variable.

3) Functionality. Functionality is defined as the remaining useful life and available storage at a site. The optimal operational life of the DMPA site is defined by the amount of dredge material a DMPA site can accept. The remaining useful life is assessed based on the condition of the DMPA site as determined from the physical inventory and is defined as the number of years remaining during which dredge material can be placed at the DMPA. It is a function of the remaining capacity and the average annual volume of dredge material placed in the DMPA site.

4) Condition. Structural integrity and the ability to use the property for its intended purpose defines the DMPA condition. Using existing survey datasets, the highest and lowest levee elevations were identified for each site. The calculated remaining capacity of each DMPA site was constrained by the lowest levee elevation of the levee system. It was assumed that if the DMPA's levee system is maintained at the highest elevation, that would represent a structurally intact site. However, a degradation or deterioration in the levee system indicates physical defects requiring repair or rehabilitation. Thus, defining and comparing the DMPAs' levee elevations assisted in the evaluation and categorization of the DMPA sites between low- and high-risk categories.

A scoring procedure was established to achieve one score for each DMPA site so that all DMPAs could be compared and ranked to identify the highest at-risk DMPAs. A weighting factor was assigned to each of the 4 main criteria adding up to 100%. Furthermore, each criterion was sub-divided into 1) low, 2) medium, and 3) high sub-criteria, which also were also assigned a weight adding up to 100%.

A MS Access database tool was developed to provide the decision support for performing the Condition Assessment of the DMPA sites, which serves as the data repository. Various queries and forms were developed to review the information and assess the available information integrating the logic for the criteria analysis. Using the attribute data and the user-defined weighting, the MS Access database automatically computed the scores for all the confined DMPA sites considered in this project, which were used to determine the highest at-risk DMPAs for future investments to maintain, rehabilitate, or expand.

In conclusion, this study represented the launching of an effort to improve tracking and evaluation of DMPA's. Creating a database with these key data elements, which can be maintained and expanded, was at the core of the work effort. In addition, an Environmental Systems Research Institute ArcGIS File Geodatabase was populated with the data from the database to visually display information and enhance functionality for the end user.

Keywords: Dredging, criteria, weighting, scoring, relational data.

CITATION

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DATA AVAILABILITY

All data, models, or code generated or used during the study are available from the corresponding author by request.

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The authors would like the U.S. Army Corps of Engineers, Galveston District for providing property, physical, and operational data of the DMPAs. This data was necessary for our team to assess data gaps and to plan for additional data acquisition for the study.

EMISSION PROFILE AND EMISSION REDUCTION FOR TRAILING SUCTION HOPPER DREDGES DURING OPERATION

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ABSTRACT

The largest dredging company in the United States is Great Lakes Dredge and Dock (GLDD). GLDD operates multiple large dredges, including six trailing suction hopper dredges (TSHD). The purpose of this research is to provide an emission model for TSHDs showing an emission profile (CO2, SOx and NOx) per cycle of operations, and present emission reduction methods. Within the emission model there are eight main parts that are connected and create the results. The results are shown per cycle of operation and are calculated per phase. The six main phases of a cycle of operation are: Loading, transit loaded, connecting, discharge, disconnecting and transit empty. The first part of the emission model determines the hull resistance. The second part consist of the trailing resistance. This part is split up into three more detailed segments: the calculations for the cutting force, cutting depth and trailing force. For each job, specific input is required for the calculations. Combining this input and the calculation parts, the emissions, fuel consumption and fuel cost are given per dredged m3. Five methods to reduce the emissions for TSHDs are researched. First, the type of power arrangement is researched. A mechanical power arrangement with a combined drive and a direct drive, an electrical power arrangement and a hybrid power arrangement are investigated. The variations of power arrangements are implemented the Dredge 1. Second, the difference between a fixed (FPP) and controllable pitch propeller (CPP) is researched. Most modern day TSHDs use a CPP, as the efficiency during the wide variation of operating conditions is greater than a FPP. The third method to reduce the emissions is to find the optimal loading speed. The optimal speed is researched for a floating visor and a fixed visor. The most common solutions to comply to the limit of the SOx emission is using ultra low sulfur diesel or installing a scrubber. The fourth reduction method is focussed on the use of scrubbers. The most used types of scrubber are the dry, open loop, closed loop and hybrid scrubber. The last method to reduce the emissions is shutting off the engines when not in use. The trade-off is the wear of the engine. To verify the results of the emission model, the fuel consumption of multiple completed jobs is compared with the predictions of the emission model. The results show that for Dredge 1 a mechanical power arrangement with a combined drive emits the least CO2. With a CPP, the fuel consumption and thus the emissions are reduced. It is found that the optimal loading speed depends on the manually set limit for the penetration depth of the jets. Within the model the optimal speed is 0.70 m/s. The most promising scrubber for TSHDs is a closed loop scrubber which reduces the SOx emission with 96% and reduces the particular matter with 60%. Reviewing one operation of Dredge 1 shows a reduction of 0,5% in fuel with shutting off the main engines when not in use.

Keywords: TSHD, dredge, carbon footprint, emissions, scrubber.

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INTRODUCTION

The International Maritime Organisation (IMO) is a specialized agency responsible for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. Air pollution is one of the contributors. CO_2 emission is recognised as the biggest contributor to the increasing temperature of the Earth. Global warming is a controversial topic and actions are taken to reduce further rising of the temperature on Earth. The IMO has set limits for vessels on the emission of NOx and SOx. Currently, the IMO is negotiating on how to limit the emissions of CO_2 to reach a reduction of 50% in comparison to 2008. The purpose of this research is to provide an emission model for Trailing Suction Hopper Dredges (TSHDs) showing an emission profile (CO_2, SOx, and NOx) per cycle of operations, and present emission reduction methods.

To substantiate the solution the following research question is defined: *What is the total emission profile for trailing suction hopper dredges during operation and what are viable methods to reduce their emissions?*

EMISSION MODEL

This chapter describes the steps that are taken to determine the total energy requirement and the emissions of a TSHD per operation. The basis of the emission model is made with the specifications of Dredge 1. The first sub chapter presents the specifications of this dredge. The description of the model is given in the second sub chapter. The accuracy of the model is tested and verified in the third sub chapter with operations of Dredge 1 that are already completed. A conclusion regarding the emission model is given in the last sub chapter.

Introduction of Dredge 1

The dredge completes multiple jobs yearly, and the power arrangement is relatively simple which makes this dredge a good starting point for developing models. For discharging, dredge 1 can use either bottom dump or discharging by connecting the discharge pump to a pipeline that guides the soil to the dumping area.

On board the dredge there are multiple energy users, energy producers provide energy to supply the users. Five main energy producers can be defined: main engines, generators, pump engines, jet pump engines and the bowthruster engine.

Within each phase, multiple energy producers are necessary to execute the work or in other words, execute actions. The three main actions, providing auxiliary power, providing pumping power and manoeuvring, are powered by energy producers. Table 1 shows in which phase which action is being powered by which energy producer. The auxiliary prime movers consist of two generators (Gen), the pumping prime movers are the jet pump engines (JP) and pump engines (DP). The main engine (ME) is the prime mover for the manoeuvring. To maintain position with (dis)connecting, the bowthruster (BT) is also used which is part of manoeuvring.

Table 1. Actions of the Dredge in Operation.

Phases	Auxiliary	Pumping	Manoeuvring
Loading	Gen	JP & DP	ME
Transit Loaded	Gen		ME
Connection	Gen		ME & BT
Discharge	Gen	JP & DP	ME
Disconnect	Gen		ME & BT
Transit Empty	Gen		ME

Dredge 1 is designed with a mechanical power arrangement with a direct drive. Every pump or propulsor is connected to a single engine. The main engine is connected to a gearbox which takes care of the propulsion. While dredging the dredge engines produce the power for the dredging pump whereas the jet engines produce the power for the jet pumps. The generators are responsible for all the energy to the auxiliary equipment. Lastly, the bowthruster is powered by a similar engine as for the jet pumps.

Total Emission Profile

The purpose of the emission model is to show the amount of CO_2 per dredged volume of soil. On the first page of the model an overview is given where job and dredge specific information can be filled in and results are shown. Choices of the discharge method, visor type, dredge and power arrangement are also made within the overview. Two discharge methods are implemented, discharging with a pipeline and bottom dump. The option of the type of dredging with a visor is given, a fixed visor or a floating visor can be chosen. Multiple dredges can be added to the inventory of the model with their own specifications. The model supports one type of power arrangement which is a mechanical power arrangement with a direct drive.

The other part of the overview shows the power usage, fuel consumption, costs and CO_2 emission per phase per engine. On the left, the time per phase is visible as well as the relevant speed. To determine the results of the emission profile, the calculations are split into eight parts which are presented in the following eight parts of this sub chapter:

1. Hull resistance
2. Trailing resistance
3. Matching propeller and the main engine
4. Fuel consumption
5. Emissions
6. Engine power requirement
7. Pump power requirement
8. Auxiliary power requirement

The hull resistance is calculated with the statistically approach of Holtrop and Mennen (Mennen, 1982) and extended with air and shallow water resistance. The trailing resistance consist of three main parts: (1) the force and moment equilibrium of the dragarm (suction pipes and draghead); (2) the determination of the cutting force and (3) the method to determine the cutting depth.

The force equilibrium is implemented according to the master thesis by Gijs ter Meulen: Drag Analysis and Model for Forces and Production (Meulen, 2018). The cutting forces are implemented according to the book ‘The Delft Sand, Clay and Rock Cutting Model’ by Sape Miedema (Miedema, 2015). The cutting depths are calculated according to the paper Production Estimation of Water Jets in Dragheads by Sape Miedema (Miedema, n.d.). With the known total resistance of the dredge, the matching of the propeller with the main engine is done according to the method published by Hans Klein Woud and Douwe Stapersma in their book Design of Propulsion and Electrical Power Generation Systems (Woud & Stapersma, 2002). The fuel consumption, emission calculations and engine power requirement are also determined according to the book ‘Design of Propulsion and Electrical Power Generation Systems’ by (Woud & Stapersma, 2002). The main document used to determine the pump power requirement is the paper 'The Mathematics of Pumping Water' by Mathew Milnes (Milnes, 2017). To determine the auxiliary power requirement, measurements on board a dredge in operation are personally under supervision executed.

Phases of Operation

There are six main phases to describe one operation of a TSHD. In addition to those, two phases are included. The additional phases are the 'turning time' and 'other time'. When the dredge arrives at the borrowing area, the dragarms are lowered into the water. Once the dragheads touch the bottom, the loading phase starts. The loading phase continues until the hopper is reached maximum capacity or loading weight. At this point, the dragarms are hoisted and the loading phase comes to an end. The dredge accelerates and the 'transit loaded' phase starts. The connecting phase starts when the dredge has arrived at the connector and starts to attain the connection of the connector floating in the water. The connecting phase ends when discharging is possible. When the dredge is connected to the connector, and discharge can begin, the discharge phase starts. Once the hopper is emptied, the discharge phase ends. When the dredging pumps can be shut down as the soil is discharged from the hopper, the disconnecting phase starts. This phase ends when the dredge starts to increase velocity. The dredge now sails to the borrowing area where the cycle of operation can start again till the job is finished. Only the necessary parts of the model are used per phase. For clarification, Table 2 shows which parts of the calculations are used to determine the energy usage per phase. The 'x' represents that the calculation part is used within the corresponding phase. Where no 'x' is present, the corresponding calculation part is not used.

Table 2. Used Calculation Parts per Phase.

Phase	Hull Resistance	Trailing Resistance	Main Engine Matching	Fuels Consumption	Emissions	Engine Power Requirement	Pump Power Requirement	Electrical Load Balance
Loading	x	x	x	x	x	x	x	x
Transit Loaded	x			x	x	x		x
Connecting				x	x	x		x
Discharge				x	x	x	x	x
Disconnecting				x	x	x		x
Transit Empty	x			x	x	x		x

EMISSION REDUCTION METHODS

This chapter covers multiple methods to reduce the emissions of dredges during operation. The design philosophy of the company and the outlook of the emission restriction determine the viability of the methods. These conditions of viability are presented in the first sub chapter. The second sub chapter explains the viable available methods to reduce the emissions.

Conditions of Viability

Companies must consider multiple external and internal factors. These factors narrow down the freedom of designing new dredges. With those factors, conditions of viability of methods to reduce the emissions can be formed. Some conditions are strict and measurable, others are more open for interpretation and are more subjective.

The conditions are defined within this sub chapter. The following conditions are within the scope of this research:

1. The focus of the type of job is beach nourishments
2. All types of costs are neglected
3. The methods are valid for existing and new dredges
4. Mechanical, hybrid or electrical power arrangement are possible
5. The methods must be reasonable to be executed

Methods to Reduce the Emissions

The amount of burned fuel and type of fuel by a combustion engine is related to the emissions emitted. To decrease the emissions, one solution is to reduce the fuel consumption. Within the model, multiple solutions to decrease the fuel consumptions can be found and backed up with the relevant equations. This sub chapter covers five methods to reduce the emissions, the first sub chapter compares different power arrangements. The second explains the advantages of different propellers. The third sub chapter covers the optimal trailing speed while loading. The scrubber is explained in the fourth sub chapter. In the last sub chapter, the reduction method to shut off the engines is discussed.

Power Arrangements

Many power arrangements are available and deciphering which arrangement is most efficient for a particular dredge requires specific research pertaining to that dredge. For each dredge a specific case study must be executed to confirm the most efficient power arrangement. Within this case study, three different power arrangement that can be used in future dredges are approached.

To narrow down the results the following scope is defined:

- This case study is fully focussed on the amount of CO_2 emitted
- The following parameters are not considered:
    - Costs
    - Additional engine room space
    - Retrofit possibilities

Dredge 1 is taken as basis for the calculations. All the specifications of the dredge stay the same except for the power arrangement. The different power arrangements are compared for the phases loading, sailing empty, sailing loaded and discharging. To visualise what power arrangement could be less pollutant, three scenarios are formed. The scenarios differ in loading/discharge and sailing time relatively. Scenario one simulates very short sailing distance where 80% of the time is spent on loading and discharging. Just 20% of the time is spent on sailing (empty and loaded). Scenario two the time is equally divided, 50% of the time the dredge will sail and 50% the dredge will load and discharge. Scenario three simulates that 20% of the time will be loading and discharging and 80% will be sailing. Not all energy consumers are active during each phase, Table 3 shows whether or not in which phase a consumer is active.

Table 3. Activity of Energy Consumers per Phase.

	Loading	**Transit Loading**	**Transit Empty**	**Discharge**
Propulsor	Active	Active	Active	Not Active
Jet Pumps	Active	Not Active	Not Active	Active

Dredge Pumps	Active	Not Active	Not Active	Active
Bowthruster	Active	Not Active	Not Active	Active
Auxiliary	Active	Active	Active	Active

The required amount of power in kilowatt is calculated by taking 80% of the maximum available power (power required) onboard Dredge 1. The 80% load counts for the propulsor, jet pumps and dredge pumps. As the bowthruster is not used continuously during the phases where it is needed, only 20% of its maximum power is taken. The simultaneously factor is hereby considered. The required electrical auxiliary power is taken as the available power as it is constant during each phase. The (prime) movers must generate the power listed under 'total required power'. All engines have a specific fuel consumption. As the total required power is 80% of the total power, the sfc of the engines are taken at a load of 80%.

Mechanical

Two types of mechanical power arrangements are included. The first one is the direct drive where all the energy consumers are directly driven by one energy producer. The second one is the combined drive, where the propulsors and the dredge pumps are driven by each one engine.

Direct Drive. The conventional power arrangement is the mechanical power arrangement. A mechanical power arrangement is a relatively to the other arrangements the simplest arrangement to realize. Each energy consumer is provided by a prime mover.

Within the mechanical power arrangement of Dredge 1 the main engines are from EMD (M.E. small). The total break power of the engines is calculated with the efficiencies of the drive train. The gearbox efficiency is taken as 96%, the shaft efficiency is taken as 99% and the relative rotation efficiency as 98%. The efficiency of the generator to create electrical energy is 97%. Assumed is that all engines have an efficiency of 37%, this means that 37% of the potential energy from the used fuel is converted into mechanical energy available.

To be able to calculate the CO_2 emission in kilograms, the engine efficiency, the specific fuel consumption per engine, the running time and CO_2 content within the fuel must be known. The engine efficiencies and the running time are already known and the content of CO_2 in ULSD is 3.114 kg/kg. The CO_2 emissions are calculated as indicated in Equation (1):

$$\% \text{ run time} * 24 * \text{required power} * \text{s.f.c.} * \text{content } CO_2 \qquad (1)$$

% runtime = hours run per 24hrs (%), required power = engine power (kW), s.f.c = specific fuel consumption (kg/kWh), content CO_2 = CO_2 per kilogram of fuel (Kg)

For each scenario, energy consumer and phase, the CO_2 emissions are determined. The total emitted emission of each power arrangement is then compared.

Combined Drive. The same calculation method for the combined drive is true as for the direct drive. The dredge pump and the propulsor are driven by one engine, which is the only difference with a direct drive. In the loading phase, both the dredge pumps and the propulsor consume energy from the main engine. Within this arrangement the Caterpillar 3612 is used as this engine can generate enough power to provide both consumers.

Hybrid

A hybrid power arrangement consists of a combination of electrical and mechanical driven energy consumers. Two hybrid configurations are used for the case study, they can also be called diesel-electric power arrangements. It is chosen that one of the two largest engines are each mechanically driven as this creates the most impact on energy usage. In the first hybrid arrangement (hybrid 1), the dredge pump is mechanically driven by a combustion engine. All other energy consumers are electrically driven. An electrical drive train brings other efficiencies than a mechanical drive train. Also, more components are required to power the pumps and propellers. To provide for the total required power, three main engines are to be installed within this hybrid arrangement. The efficiencies of the components to convert mechanical energy into useful electrical energy are shown in Table 4.

Table 4. Efficiencies Electrical Components (MAN, n.d.).

Component	Efficiency
Alternator	97,0%
Main Switchboard	99,8%
Frequency Converter	98,5%
Electric Propulsion motor	96,0%

In the second hybrid arrangement (hybrid 2), the propulsor is mechanically driven by a combustion engine. The same efficiencies are used as shown in Table 4 for all pumps that use electrical energy. The drive train calculations for the propulsors are equal to the mechanical power arrangement calculations. Within this power arrangement two main engines are required to provide all the energy besides the energy required by the propulsors.

Electrical

The fully electrical power arrangement is powered by four main engines. The switchboard divides the electrical energy to all the energy users. The used efficiencies are shown in Table 4.

Propulsor Type

Great loss is found in the efficiency of the propeller in loading condition. At trailing speeds of 1 knot, a fixed pitch propeller efficiency is just 11%. This efficiency is according to the results of the calculations of the model of Dredge 1. The difficulty of choosing the best propeller is the variating rotational speed of the propeller and the related vessel speed. In loading condition, the vessel speed is very low due to the additional resistance of excavating. Then, there are the two sailing conditions of which one of them is sailing fully loaded and the other one is sailing empty. A trade-off at the designing stage for the type of propeller must be made where the most efficient propeller must be chosen. The trade-off consists of predicting the amount of time the dredge will execute the three phases to find the optimal efficiency for a certain type of propeller. These days, most TSHDs are equipped with a controllable pitch propeller. Because of the changeable pitch, the overall propeller efficiency increases. Therefore, the ratio of fuel consumption versus the dredged soil will decrease as result of a better overall efficiency. Some other advantages of using a CPP is the better acceleration as the pitch of the propeller can gradually be adjusted. For every load and speed, the most optimal pitch can be used. The rotational speed of the engines can also be influenced as the pitch of the propeller can be adjusted. This enables the engines to run at a more efficient speed.

Loading at Optimal Trailing Speed

The fuel consumption can be optimised by executing the trade-off between the trailing speed of the dredge and a certain cutting depth. As the optimal trailing speeds of the fixed and floated visor differ, this sub chapter is split up into two parts, optimum trailing speed for fixed and for floating visors.

Fixed Visor Optimal Trailing Speed

The optimal trailing speed for the fixed visor is highly dependent on the limit of the jet penetration. This limit can be set manually within the model. At the transition where the jet penetration decreases below the limit and thus the cutting forces of the teeth increase, the optimal trailing speed can be found. The most common visor angle of Dredge 1 of 40 degrees has got a total penetration depth of 0.39 m. The limit of the jet penetration was set at 0.3 m, where it was constant until a trailing speed of 0.7 m/s was reached. Theoretically, until the speed of 0.7 m/s, the jets have enough penetration force to liquify all the saturated sand before the soil ends up in the suction pipe. Until that speed, the only variable that influences the production of the draghead is the trailing speed. With speeds greater than 0.7 m/s, the jet penetration decreased which increases the cutting force and thus the trailing force.

Floating Visor Optimal Trailing Speed

If the angle of the visor is not fixed, the weight of the visor determines the cutting depth. The penetration of the jets clears the way for the floating visor to sink into the ocean floor. With an increasing speed the penetration depth of the floating visor becomes less. This can be due to the angle and the type of the teeth, but also the weight of the visor and the soil characteristics. The power requirement of the floating visor per speed increases less with an increasing speed. The forces on the visor are independent to the jets. The production of the jets differs from the production of the teeth.

Scrubber

As mentioned, a new limit on Sox pollution has been set for the 1st of January 2020. Many shipowners choose to install a scrubber to reduce the Sox content and comply with the restrictions of the IMO. To comply with the sulfur cap, ultra-low sulfur diesel can be bought. For the long term, a scrubber is a better option as the capital expenditure provides returns in fuel cost savings. ULSD is more expensive than MDO, with a scrubber installed, MDO can be used a primary fuel.

Marine scrubbers can be split up into two main types, wet scrubbers and dry scrubbers (Sethi, 2020). The main purpose of scrubbers is to reduce the release of particular matter and SOx from the exhaust gasses. Dry scrubbers in general require a lot of storage space for the scrubbing material. Once the material loses its purpose, new material must be present to continue cleaning the exhaust gasses. The storage space depends on the duration of the travel and availability of the scrubbing material in ports. Wet scrubbers can be split up into three main categories, open loop, hybrid and closed loop scrubbers. What defines a wet scrubber is the usage of alkaline in water.

Engine Shut Off

Depending on the power arrangement, the main engines during the operation are normally kept running. This consumes an unnecessary amount of fuel as the generated energy is not used. The combustion process is very inefficient as there is no load on the engines. The reason the engines are not shut off while not in use for a longer period of time is the increased wear on the engines. This extra wear on the internal engine components is caused by the decrease oil temperature. When the engine is turned off, the oil slowly cools down as well as the internal engine components. An engine is most efficient at a specific operational temperature. Running an engine at lower temperatures than the operational temperature causes increased wear and less efficient combustion cycles.

RESULTS

This chapter shows the results of the accuracy of the emission model in the first part. In the second part the results of the reduction methods are shown.

Emission Model

Dredge 1 is used to validate the results of the emission model. Four completed beach nourishments jobs are chosen. The daily data is registered by field engineers present on the job. The data varies from the amount of fuel used per day to the down time of the dredge. The field engineers send the data to the office employees. All necessary data should be present for the emission model within the daily data. To present an as accurate as possible verification, the average of the daily data is taken for all input. The same setup within the model is used to verify the results. Only the input stated in Chapter 2 was variating depending on the job. The offset of the emissions model with the daily data is shown in **Error! Reference source not found.**. The jobs are shown on the left, followed by the results of the daily data. On the right side the results of the emission model are shown with the offset between the model and the daily data.

Table 5. Offset Fuel Consumption Daily Data versus Results Model.

Job	Offset
Beach 1	+ 0.4%
Beach 2	- 3.7%
Beach 3	- 0.3%
Beach 4	- 4.0%

The four jobs finished by Dredge 1 show that the emission model stays roughly within an offset range of -4% to + 1%. A constant offset within the results is visible which indicates a stable emission model. Dredge 1 is equipped with old engines and the dredge itself is in business for 40 years. To take the age of the dredge into account together with inefficiencies of the propeller, the total resistance of the dredge is increased by 10%. Inefficiencies of the propeller are damage of the blades by cavitation or contact with objects. Due to the age of the dredge the hull can be damaged, or more easily be covered in biofouling. To take the age of the engines into account the specific fuel consumption is also increased by 10%. The fuel consumption depends on the running hours of the engine. One of the reasons is that the rotating parts are subdued to wear. Over time, the piston will be covered with the residue of burned diesel which decreases the cylinder volume slightly. More fuel is needed to generate the same amount power without the residue. Residue of oil and diesel can also attach to the insides of the tubes, this means more power is needed to deliver the same volume of fluid. More factors negatively influence the fuel consumption of the engine with a significant amount of running hours.

Emission Reduction Methods

The results of the five reduction methods are shown within this sub chapter.

Power Arrangement

The results show that in all three scenarios, the mechanical power arrangement with a combined drive emits less CO_2 in comparison with the other power arrangements. The two large main engines are more fuel economic than the smaller engines which gives the combined drive a big advantage. As the combined drive is a mechanical power arrangement, there are less components to transfer the energy to the users. This gives an advantage to the mechanical power arrangements in terms of efficiency. Furthermore, the direct drive become less pollutant than the two types of hybrid power arrangements when the sailing time increases.

The results also show that the hybrid configuration with the mechanically driven propulsors is second less pollutant in all scenarios. The drive train from the main engines to the propulsors are more efficient mechanically driven than electrically driven. An electrical drive brings more inefficiencies as there are more components required to transfer the energy.

For all three scenarios, the difference between the mechanical (DD), electrical and hybrid arrangement is maximum 3 tonnes of CO_2. Within this hybrid power arrangement, the dredge pumps are mechanically driven. The electrical power arrangement emits most CO2 in all scenarios compared to all other power arrangements. This is due the loss in efficiency that is brought by the components to convert mechanical energy into useful electrical energy. The mechanical power arrangement (DD) becomes less pollutant than the hybrid in scenario 2 and 3 where the sailing time increases. The hybrid in these scenarios loses its advantage of mechanically driven dredge pumps as loading and discharge times decrease.

The most important factors of choosing the most efficient power arrangement for a dredge is the fuel consumption of the engines. Within this case study, the fuel consumption of the individual engines has great influence to the results. **Error! Reference source not found.** shows the results of the comparison of the different power arrangements.

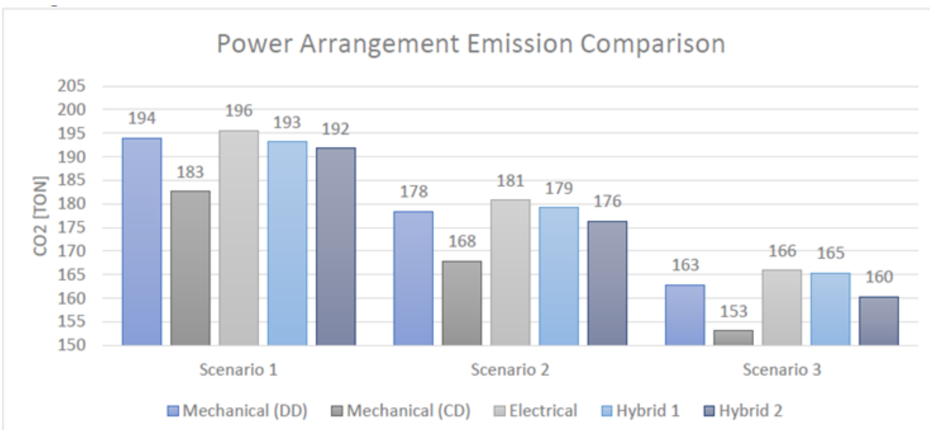

Figure 1. Power Arrangement Emission Comparison.

Loading at Optimal Speed

This part consists of the results of two types of visors, the fixed visor and the floating visor.

Fixed Visor

The jets have a good production rate (m^3/s) and the production versus the trailing speed is high until the jet penetration limit is reached. The produced graphs peak at a speed of 0.7 m/s. The visor is fixed which means the cutting forces increase due to the increasing penetration depth and the trailing speed. The graph of **Error! Reference source not found.** shows the production per kilogram fuel used versus the trailing speed per load. The optimum lies again at 0.7 m/s, after that speed the production per kilogram of fuel slowly decreases.

Floating Visor

Figure 2 shows the production per kilogram of fuel, the optimal trailing speed for a floating visor is at 0.7 m/s just before the penetration depth of the jets start to decrease.

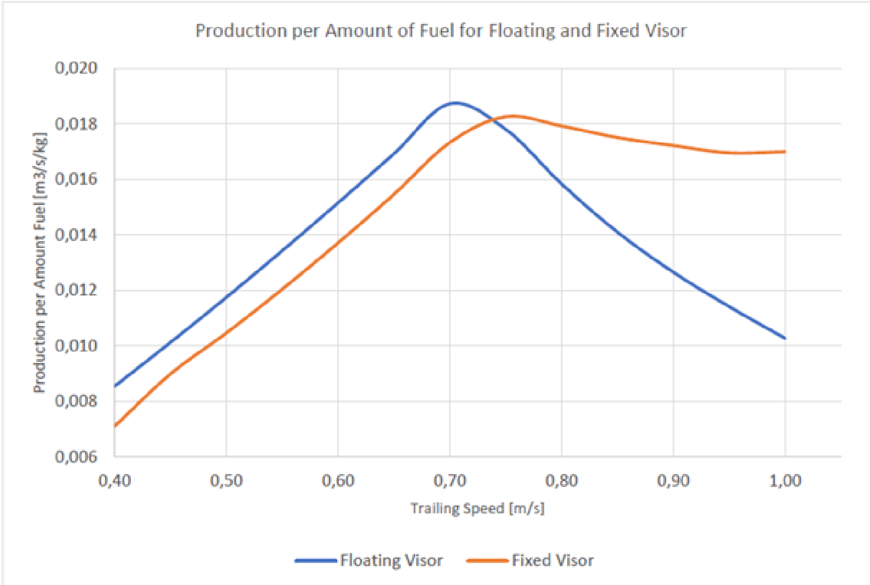

Figure 2. Production per Amount of Fuel versus Trailing Speed.

Propulsor Type

As the efficiency per volume of dredged soil increases, the total emission of CO_2 and SOx also decreases per operation. The NOx emissions are dependent on the rotational speed and the specific fuel consumption of the engine. When the rotational speed can be influenced by a CPP, the NOx emissions can also be reduced by the use of a CPP. The price and additional maintenance for a CPP is the downside of the system in comparison with a FPP. The period to earn back the investment depends on the type and price of the CPP.

Scrubber

Hybrid systems are a combination of open and closed loop scrubbers. As in some areas and ports, open loop scrubbers are prohibited, a hybrid system can switch to a closed loop system to avoid any violation. The primary goal of a scrubber is to remove the toxic SOx content of the exhaust gasses. Depending on the alkalinity of the sea water for open loop scrubbers, the removal rate of SOx is more than 96%. Up to 60% of the particular matter is removed as well (ABS, 2017). TSHDs are mainly used for beach nourishments, which take place within the ECAs. A long-term solution to comply to the stringent SOx regulations is to install a scrubber. For dredges operating along the coasts where the temperatures of the water and the content of alkaline vary, a closed loop or dry scrubber would be the best option. The hybrid solution is too extensive as an open loop system is not effective in the dredging areas. An open loop system would be too inefficient due to the variation of water temperature and in some ports this system is prohibited.

Engine Shut Off

For one of the main engines of Dredge 1 this gives the following. At idling speed (350 rpm) the engine can deliver 228 kW at 100% throttle. The least amount of throttle that can be given is 16%, which gives an available power of 36.5 kW and a fuel consumption of 8.7 kg/h per engine. For the operation Beach 3 in the scenario where the two main engines of Dredge 1 were turned off, the fuel saving would have been 0.55% which results in 0.55% less CO_2 emission.

CONCLUSIONS

The purpose of this research is to provide an emission model and present methods to reduce the emissions of trailing suction hopper dredges during operation. The model can determine the total energy requirement and emission profile for TSHDs for individual jobs. The used power arrangement is mechanical with a direct drive. The discharge method can vary between discharge via a pipeline or splitting the hull. Different TSHDs can be implemented in the database which makes the model independent to one specific TSHD. The type of visor can vary between a floating and a fixed visor. The model gives several different outputs. The main outputs are the amount of the emissions (CO_2, SOx and NOx), the amount of fuel used and the cost of fuel, all per dredged m^3.

Several viable methods to reduce the emissions in accordance with the design philosophy of Great Lakes Dredge and Dock are researched. The design philosophy is formed by internal and external factors. External factors are the availability of knowledge within shipyards to build a modern dredge, the expectations of the market, the available technology, and the height of the building costs. Internal factors are preferably interchangeable parts and the determination of the focus of the market. The philosophy creates viable methods to reduce the emissions of TSHDs.

The first method consisted of determining which type of power arrangement is most emission friendly. Three types of power arrangements are researched, mechanical, electrical and hybrid power arrangements. It is seen that the results are sensitive to multiple factors which can change the outcome of the research. The mechanical power arrangement with a combined drive brought the least emission pollution. The second reduction method considers the propeller type. To increase the efficiency of the propeller in all three phases, controllable pitch propellers form the solution. Besides a multitude of advantages, a controllable pitch propeller reduces the fuel consumption and emissions. The optimization of the excavation depth and the trailing speed is the third method to reduce the fuel consumption and emissions. The optimization was executed for a floating and fixed visor. It was clear that the jet penetration depth is the leading factor to determine the optimal trailing speed. The fourth method to reduce the emissions is the scrubber. The main forms of a marine scrubber are the dry, open loop, closed loop and the hybrid scrubber. For dredges operating at the coast, a dry or a closed loop scrubber would be most efficient in terms of filtering the emissions of the exhaust gasses. Engines running at idle speed are inefficient and the generated power is not used. The fifth method to reduce the emissions is to shut off the engines when not in use for a long time. A disadvantage of shutting off the engines is the increased wear of the engines cause by the reduced temperature.

The basis is made for a model with the capability of predicting the fuel consumption and the emissions for multiple TSHDs with each their unique specifications. By also using the model to optimize dredging characteristics such as trailing speed and penetration depth, fuel consumption and the emissions can be reduced.

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A STUDY OF EMISSIONS AND DREDGING EFFICIENCIES AT VANCOUVER FRASER PORT AUTHORITY

K. Ewert[1] and J. Kerolus[2]

ABSTRACT

Vancouver Fraser Port Authority (VFPA) has undertaken an assessment of current dredging operations in the Fraser River and a forward-looking study of dredging efficiencies, emerging technologies, and alternative fuels to position upcoming dredging contracts in support of the vision for the Port of Vancouver to be the world's most sustainable port. To accomplish this goal, the study Moffatt & Nichol (M&N) is conducting for VFPA has been segmented into six areas of interest: establishment of an emissions baseline, study of California emissions regulations to provide emissions thresholds for dredging activities, recommendations for emissions reductions, modification of dredging and disposal equipment and methods, discussion of alternative fuel sources, and assessment of emerging technologies.

INTRODUCTION

M&N has partnered with Synergy Enterprises, an environmental sustainability firm based in British Columbia, to perform an analysis of current emissions, specifications, historic performance, and new or developmental technologies in the dredging market and form recommendations to provide uplifts in efficiency, performance, and environmental sustainability. Synergy's initial scope of work included comparison of emissions trends of existing dredge equipment to California emissions standards with the goal of recognizing areas of improvement for air and noise emissions. Noise emissions shall be considered, and recommendations will be made to align upcoming dredging activities with VFPA's Underwater Noise Mitigation Plan, established in December 2020. Discussion of emissions standards and recommendations to address areas of exceedance are ongoing and while emissions regulations will be briefly discussed, recommendations for future application will not be addressed in this technical discussion.

M&N has analysed historical dredging production rates and the number of working days during each dredging period to inform a recommendation to VFPA on the minimum and optimal size of hopper dredge unit required. Assessment of the existing specifications, consideration of current and alternative disposal sites, and operational practices forms the basis of recommendations to be made to improve dredge performance efficiency while reducing emissions. To avoid limiting competition, determination of the appropriate size of the dredge to be used on upcoming VFPA contracts will include a survey of existing hopper dredges as well as those that may be newly constructed. Further, the consideration and recommendations for implementation of emerging technologies will also be limited to those that can be installed on existing dredging platforms or integrated into the construction of new hopper dredges. Such recommendations include environmental components to limit turbidity stemming from overflow, draghead selection, and green valves, choices that are supported by their implementation in the European dredging market by industry leaders. Upgrades to existing components may have a significant positive effect on the environmental impact of dredging activities in the Fraser River and neighboring disposal sites. Recommendations have also been included to encourage future VFPA contract winners to take advantage of the innovative automation and visualization tools currently on the market. Operational automation for dredging is an area that may provide some of the greatest gains in improvement of overall efficiency as the

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partnership between hardware sensors and software monitoring allows for adjustments in real time that optimize dredge performance. Similarly, VFPA has indicated an interest in visualization that may be achieved through use of hydrographic survey data collection in real time that informs a model available to the leverman, who can then make adjustments based on available material. Finally, one of the greatest areas of emphasis for upcoming VFPA contracts concerns the use of alternative fuels in support of a global trend away from traditional marine diesel. Research and industry input has led to both short term and possible long-term alternatives for use of LNG, hydrogen, ammonia, and molten carbonates as innovation in the fuel and propulsion spaces continues for the coming decades.

It is M&N's intent to provide VFPA with a comprehensive and strongly supported set of recommendations to achieve efficient, effective, and environmentally conscious dredging programs in service of the Port Authority's goal to become a leading Green Port. All recommendations to be discussed will protect the proprietary information provided by VFPA and its industry partners. Final recommendations to be provided to VFPA will not be included in this discussion in order to avoid limitation of future competition for Port Authority contracts or provide an advantage to contractors seeking work under the Port Authority. Inclusion of systems and components sourced from manufacturers discussed below in proposed dredges will not be considered an advantage for contract award.

ENVIRONMENTAL OBJECTIVES

The VFPA envisions becoming the world's most sustainable port, one that "*delivers economic prosperity through trade, maintains a healthy environment, and enables thriving communities through meaningful dialogue, shared aspirations and collective accountability*" (Port of Vancouver, 2020). The VFPA defines sustainability as "a holistic approach that considers ecological, social, and economical dimensions, recognizing that all must be considered together to find lasting prosperity" (University of Alberta, n.d.). As concerns about climate change and the carbon footprint reduction increase and continue to play an integral role in shaping our world, VFPA has committed to incorporate sustainable practices into strategic plans, to make a positive impact on communities, and to manage resources more efficiently for enhanced energy consumption. The VFPA continues to lead environmental programs and initiatives to protect the nearby environment and ecosystems, and further climate action and responsible practices. Successful existing programs have already been implemented to encourage quieter vessels and manage underwater noise generated from port operations, including in-water construction. For example, the EcoAction Program recognizes and celebrates shipping lines that invest in ship technologies, fuel, and environmental management to meet industry best practices that go beyond regulatory requirements (VFPA, 2021). The EcoAction Program also provides discounted harbor dues to vessels that reduce emissions, underwater noise, and other environmental impacts (Port of Vancouver, 2020). The Enhancing Cetacean Habitat and Observation (ECHO) Program was established to reduce effects of shipping activities on at-risk whales found throughout the southern coastal waters of B.C.

Regulations Applicable to Maintenance Dredging

Active marine vessels must comply with applicable international, national, and local regulations with respect to air emissions. Similar to other in-water construction activities, maintenance dredging must also comply with a number of applicable national and provincial environmental regulations with respect to the potential for adverse impacts on protected species and habitats.

<u>Air Emission Standards, Regulations, Thresholds</u>

International, national, and local regulation compliance for marine vessels focuses on reducing diesel PM, NOx, and reactive organic gases (ROG) emissions from diesel vessel engines. The International Maritime Organization (IMO) mandates fuel requirements for commercial vessels. A sulphur cap was implemented this past January (2020) for most commercial vessel fuels (less than 0.5%) (IMO, 2020). IMO targets for 2030 and 2050 call for additional reductions in air pollutants and GHGs, particularly CO2.

The entire West Coast of Canada and the U.S., including Hawaii, is part of the much more stringent North American Emission Control Area (ECA). While the IMO standard for sulphur is 0.5% as of January 2020, the North American ECA standard is 0.1% since 2015. The ECA also limits NOx emissions by requiring ships constructed on or after January 2011 comply with the ECA Tier II NOx standard and those constructed on or after January 2016 comply with the Tier III NOx standard (IMO, n.d.).

Ships may also need to comply with more stringent regulations at berth. The California Air Resources Board (CARB) requires operators to reduce at-berth emissions from auxiliary engines by 80% while in California Ports (CARB, 2020). Formal emissions regulations specific to British Columbia and other provinces have not been identified at this time. The adoption of future national and/or provincial regulation is likely imminent given this overall trend in other parts of the world. The timing of this adoption is less certain and may depend on population growth and public and industry changes and pressures.

The B.C. Low Carbon Fuel Standard (LCFS) only accounts for diesel and gasoline used in B.C., however, by 2030, its commitments aim to also cover fuels used by the marine industry (Synergy, 2021). Due to increasing carbon emissions, it is likely that marine fuels will be incorporated into the BC-LCFS. To comply with the BC-LCFS, there are two requirements for preliminary incorporation:

(1) Minimum renewable content requirement of 5% annual average renewable content in gasoline and 4% renewable content in diesel; and,

(2) Carbon intensity of a fuel must decrease by 1.09% annually (Synergy, 2021).

A Part 3 Agreement under the Renewable and Low Carbon Fuel Requirements Act allows fuel suppliers to earn credits by taking actions to increase the use of low carbon fuel. (Synergy, 2021).

<u>Noise Standards, Regulations, and Thresholds</u>

There are no present federal laws or standards regulating anthropogenic (human-caused) ocean noise in Canada. The IMO has worked to develop international guidelines to minimize underwater noise, however, these guidelines are voluntary and are not binding in Canada unless adopted into Canadian legislation (World Wildlife Fund-Canada, 2013). For in-water dredging activities, Canada uses approaches to mitigate ocean noise similar to those for seismic air guns. Such measures are applied when marine species may be disturbed from the underwater construction activity, or as required for an environmental assessment. Ocean noise has previously been assessed under the Canadian Environmental Assessment Act (CEAA). Assessment includes the potential effects project-related activities may pose to marine mammals listed in Canada’s federal endangered species law, Species at Risk Act (SARA). The Act prohibits destroying any part of a listed endangered, threatened, or extirpated species’ critical habitat. Acoustic quality is considered a component of a specie’s critical habitat, and must be legally protected (DFO and WWF-Canada, 2013).

A project may be denied approval or have approval postponed if failure to mitigate adverse environmental impacts from project-related activities that produce underwater ocean noise. Dredging vessels, however, have a low sound intensity and do not appear to be strictly regulated with respect to noise. While dredging vessels have low sound intensity, they may still alter behaviour of marine mammals and interfere with their communication, feeding, and breeding (Port of Vancouver, 2020).

While there are presently no comprehensive noise standards, measures must be taken to comply with subsections 34.4(1) and 35(1) of the Federal Fisheries Act. To comply with the Act’s fish and fish habitat protection provisions, measures must be implemented to avoid causing death of fish and/or harmful alteration, or destruction of fish habitat in the dredging area. Additionally, under the Fisheries Act, dredging activity must comply with Section 7 of the Marine Mammal Regulations, which prohibits the disturbance of marine mammals by any activity other than fishing.

PRACTICAL RECOMMENDATIONS TO IMPROVE EFFICIENCIES

Hopper Dredge Sizing

The current dredge performing work under current and previous VFPA contracts has been FRPD 309, a 4,630 m^3 TSHD built in 1983 and owned and operated by Fraser River Pile and Dredge. Analysis of current dredge performance, the most heavily utilized disposal sites, and future efficiencies formed the basis of considerations for determining the optimized TSHD capacity for future work. FRPD 309 has proven capable of meeting project volume demands of approximately 3.5M m^3 removed annually over the past five years with a supplemental 450,000 m removed via Cutter Suction Dredge. Of this volume, 1.6M m^3 has been disposed of at upland sites while the remaining 1.7M m^3 has been disposed of at sea.

Areas of interest for future hopper dredge sizing include draft considerations for all disposal areas, air draft to allow the dredge access to reaches beyond the Pattullo and Skytrain bridges, and load size optimization to allow the dredge to discharge entire loads at a single site. Further, separate dredge material placement needs for other regional projects requiring large quantities of fill material is a consideration for the size of dredge on VFPA contracts. Finally, the optimal dredge size should consider the minimum capacity needed to meet project objectives in the event of a mechanical shutdown that consumes all available schedule float.

The first dredge size to be considered will offer a 4,000 m^3 capacity. The FRPD 309 has a historical haul volume of 70% versus the industry average of 75%, representing approximately 230 m^3 of haul capacity per load that may be gained by a more efficient dredge of the same size. While a 4,000 m^3 TSHD would result in smaller loads than the FRPD 309, a newly constructed dredge would include upgraded systems and components that have been introduced to the market in the forty years since the FRPD 309 was built. A future dredge would be anticipated to perform at a higher level of efficiency, minimizing the difference between existing and anticipated haul volume per load. A smaller hopper dredge may also allow a future dredge to discharge full loads at the smaller upland placement locations, rather than either light loading the hopper or requiring multiple disposal discharges to empty a single load.

The second dredge size to be considered would allow for 6,000 m^3 of hopper capacity. Advantages to a substantially larger hopper would be an increase in the production rate of the dredge as a larger hopper would equate to more material per load and fewer transits to disposal. This may increase the number of available float days in the schedule, providing a buffer against a mechanical shutdown preventing the contractor from completing their obligations to VFPA. Similarly, a larger hopper volume would allow the contractor to supply other regional projects requiring large amounts of fill material. Secondarily, a larger available material volume removed from the Fraser River would be available to supply the local sand market in the months of June to September when shoaling rates are the highest. The material could be transported to fill locations outside of those currently identified for Fraser River dredging contracts. Such material could be placed in support of regional beneficial reuse initiatives and projects.

Specifications Assessment

The basis of recommendations for improvement of operational efficiencies stem from the study of the existing contract specifications with the intent to locate areas of improvement. Project specifications indicate that there are multiple areas of disposal related operations that may be addressed to improve efficiencies.

The specification details that it is the responsibility of the contractor to determine the method of disposal for all material removed from within the dredging limits. The introduction of a structured disposal approach and a greater level of Port control over material disposal destinations may yield an increase in the efficiency of material placement as disposal is completed in a manner that is the most supportive of VFPA goals. On a contract cycle basis, the Port Authority may determine the volume of dredged material that should be placed offshore or upland and make budget decisions accordingly. Existing specification language indicates that approximately 1M cubic metres (m^3) is disposed offshore on an annual basis, however annual averages from 2017 to 2020 result an average of 1.86M m^3 placed offshore each year. Approximately half of the material for offshore disposal is sourced from the furthest reach from the offshore disposal site, Stevenston Cut KM7-12. Alternative placement of material from Stevenston Cut KM7-12 may improve the emissions generated during round trip transit from the dredge prism to the disposal site. Reduction of the extended transit distance to the disposal site may have two additional advantages in the increase in beneficial use of dredged material and an increase in working efficiency due to a reduction in revenue hours dedicated to transit. An alternative placement site for Stevenston Cut KM7-12 would require identification and permitting of a new disposal location, either nearshore or upland that may have beneficial use.

Mainland Sand & Gravel is currently the primary disposal site used for upland material placement and is located near No. 5 Road Reach at KM18. Though this location is situated near the geographical centre of the project, the amount of material placed to the east and west of the Mainland Sand & Gravel site is not equal. Approximately 300,000 m^3 is placed to the east of the Mainland Sand & Gravel site while 900,000 m^3 is placed to the west. An increase in operating efficiency may result from identification and permitting of a new upland disposal site to the west of Mainland Sand & Gravel, allowing for shorter transit distances, sail times, reduced fuel consumption, and increased production. Specifications state that alternative sites have been identified that could be used for future land reclamation or habitat creation. It has not been determined whether any of these sites have been developed or permitted for upland material placement. If the alternative sites previously identified by VFPA to the west of Mainland Sand & Gravel are still viable options for future material placement, an upland site located nearer to the source locations of the majority of upland material may be incorporated into the specifications for upcoming contracts.

Use of in river disposal sites and transfer pits may be an operational area to be adjusted to minimize secondary material handling, specifically in terms of the transfer pits. Specification language indicates that at the transfer pits, material is deposited by the TSHD to be re-dug by the cutter suction dredge (CSD) and pumped to the upland disposal site. It may be advantageous to VFPA to require a single TSHD or CSD that is capable of pumping directly to land rather than involving a second dredge that would increase fuel consumption and emissions generation associated with work at the transfer pits. The final area of possible modification to increase operational efficiency is the identification of those reaches that experience significant monthly shoaling patterns in October through December that may be more effectively addressed through increasing the dredge depth of the dredging prism to allow advanced maintenance digging in August and September to minimize the return efforts required in the last quarter of the year. This solution may require a greater upland site capacity in the months of August and September being attributed to advanced maintenance work with the understanding that the additional material removed under that effort may be offset by the decrease in upland site placement in the months of October through December, opening up capacity for material from other locations.

ALTERNATIVE FUEL CONSIDERATIONS

The purpose of this section is to discuss alternative fuel technologies available for dredge vessels and potential alternatives for application.

LNG Dual Fuel

In the last decade the international dredging industry has begun and develop fuel alternatives that may be more environmentally friendly than Marine Diesel Oil (MDO). At the present, the most feasible solution to replacement of MDO as the primary fuel powering dredge operations is the optimization of dredge equipment to utilize both traditional fuel sources as well as alternatives fuels available at select ports. This dual fuel method has been applied to hopper dredges in the European marketplace.

The European dredging industry leads the market in the application of dual fuel dredging with international dredge companies Van Oord, DEME, Boskalis, and IHC Royal leading this effort. Conversion of existing equipment to incorporate LNG fuel capabilities was pioneered in 2019 by Damen Ship Repair & Conversion with the modification of the hopper dredge Samuel de Champlain. The conversion of the Samuel de Champlain included changes to the dredge’s internal structure to allow for installation of two

LNG tanks and replacement of the diesel engines with dual fuel engines and associated upgrades to electrical and control systems.

The largest obstacle to dual fuel applications on VFPA contracts exists with the infrastructure required to successfully supply dredge equipment with LNG. Currently there are three methodologies for transfer of LNG to vessels, two of which may be more readily available to VFPA. The truck-to-ship transfer option is likely the most frequently employed because of the adaptability of the process of an LNG truck directly connecting to the vessel wharf side. Norway has successful implemented this technique, supplying 61 Norwegian vessels with LNG, a majority of which are coastal ferries and platform supply vessels (Guy & Laribi, 2020). A potentially more flexible option may be the ship-to-ship transfer method, which can be performed both wharf side as well as in coastal waters. The capacity of the LNG vessel would be substantially greater than LNG truck transfer, however LNG vessel size may be limited by existing bathymetry or size limitations of Port locations and geography. This transfer option requires specialized LNG vessels that have high cost and limited availability due to the storage equipment and control systems required to maintain the temperature and pressure necessary to maintain LNG in its fluid state. The final option for fuel transfer is shore-to-ship, the most cost intensive option of the three but also the most stable and suitable for long term use.

The European Alternative Fuels Observatory (EAFO) maintains a register of port facilities reporting LNG bunkering capabilities as well as their bunkering method and start-up year. While shore-to-ship transfer capabilities are among the most common listed, the EAFO does not note which facilities have successfully initiated the transfers. SEA-LNG, a conglomerate of Port Authorities and LNG industry representatives, indicates that as of January 2020, twelve bunkering facilities were in operation with a further twenty-seven in development or ready to be commissioned by the end of 2022 (SEA-LNG, 2020).

As reported by SEA-LNG, Vancouver is currently host to two LNG truck-to-ship locations, both operated by Fortis BC (SEA-LNG Bunker Navigator, 2020). Vancouver has one ship-to-shore and one shore-to-shore location undergoing plan development to be operated by Seaspan. Vancouver also has one bulk LNG bunkering location at the Tilbury LNG Facility with two ship-to-ship vessels in development to be commissioned in 2023 to be operated by Seaspan and Cryopeak LNG Solutions Corporation in partnership with Island Tug & Barge. VFPA is conveniently placed to take advantage of currently available truck-to-ship LNG transfer methods if future dredges are able to utilize both MDO and LNG fuel sources.

Developmental Fuels – Hydrogen Fuels

There are no active marine hydrogen deployments within Canada, however the Hydrogen Strategy for Canada published December 2020 indicates that studies for the application of marine hydrogen are underway in the provinces of Ontario and British Columbia (Ministry of Natural Resources, 2020). Further, the Hydrogen Strategy notes that hydrogen may find its initial marine applications in the supply of shore power and auxiliary power.

Hydrogen fuel is being explored as a feasible alternative to typical marine diesel fuel with blue hydrogen and green hydrogen at the forefront of development. Hydrogen currently used for industrial purposes is grey hydrogen, a derivative of natural gas that has a large CO_2 component for every part of hydrogen created. To improve upon this method, blue hydrogen captures the CO2 generated and either disposes of the CO_2 or uses it beneficially. Green hydrogen utilizes an alternative method to produce hydrogen, electrolyzing water into hydrogen and oxygen components. While green hydrogen is the most environmentally friendly option, especially when water is electrolyzed using a renewable electrical energy source, it is also the most expensive. The International Renewable Energy Agency (IRENA) reports that green hydrogen is two to three times more expensive than blue hydrogen (IRENA, 2020). IRENA predicts that the cost of green hydrogen will decrease through 2050 as alternative electrical energy sources become increasingly available and cost effective.

IHC Royal received an approval in principle to begin early-stage development of a hydrogen powered hopper dredge intended for use a maintenance vessel in the Dutch coastal environment. The Low Energy Adaptive Fuel (LEAF) dredge will be powered by green hydrogen, emitting water vapor as a result of hydrogen-based operation. Design development began in 2019 with the goal of completion in 2024. In 2017, Energy Observer launched a vessel of the same name powered by compressed hydrogen in combination with fuel cells and batteries (Æsøy et al., 2021). Emerging technologies and developments in alternative energy sources primarily consisting of compressed or liquified hydrogen may include a combined application of one or more energy sources to produce an effective result for short range use, such as maintenance dredging.

One of the most significant challenges to be addressed before green hydrogen can be adopted as an effective marine fuel alternative pertains to the storage and transfer of hydrogen fuel. The physical space required to store compressed hydrogen renders it an ineffective option for marine applications. Liquified hydrogen must be stored at approximately -253°C and in low pressure conditions to prevent evaporation of liquified hydrogen (Æsøy et al., 2021), presenting a challenge for storage onboard a vessel. Liquified hydrogen is approximately 2.5 less energy dense than LNG and therefore would require a storage container of increased size (Æsøy et al., 2021). The limited space available within the footprint of a hopper dredge's deck will likely lead to innovation of storage tanks that may be integrated into the structural frame of the hopper dredge to avoid interference with the dredge's split hull capabilities.

The 2020 Hydrogen Strategy for Canada looks beyond the ready availability of green and blue hydrogen as a reliable source of marine fuel and anticipates diversification of hydrogen fuels, including generation of an energy-rich combination of hydrogen and captured atmospheric carbon to create a liquid fuel source to be used in marine vessels (Ministry of Natural Resources, 2020). In the meantime, the arrival of IHC Royal's LEAF hopper dredge in 2024 will mark the first use of hydrogen in powering maintenance dredging activity and a step towards VFPA harnessing hydrogen power sources for use on dredging contracts.

Developmental Fuels - Ammonia

Ammonia can be used as a direct fuel or as a hydrogen carrier (Brown 2018). Current technologies being explored include proton-exchange membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), and internal combustion engines. Proton-exchange membrane fuel cells require ammonia to be stored in a fuel tank and used as a hydrogen carrier (International Chamber of Shipping 2018). The hydrogen then feeds the fuel cell and generates zero carbon power. Solid oxide fuel cells and internal combustion engines use ammonia fuel directly.

In January of 2020 the Viking Energy, a supply vessel, will be modified to be run off a 2 MW direct ammonia fuel cell (Brown, 2020). This is the first ammonia fuelled demonstration vessel proposed and will be operational by 2024. In 2020, Color Line announced an ammonia case study that proposes to convert the world's largest RORO cruise line to ammonia fuel. The RORO cruise ship the 'Color Fantasy' operates in Norway and currently burns 25,000 tons of bunker fuel each year. After conversion, the Color Fantasy will require 60,000 tons of green ammonia annually. There are several other marine vessel ammonia-fuel projects proposed for the coming years.

ENVIRONMENTAL IMPACT CONSIDERATIONS

Environmental Components

<u>Draghead Selection</u>

The work performed by the dredging industry can have significant adverse impacts to the environments being deepened, maintained, or modified. One of the most visible consequences of dredge work are turbidity plumes present in the water column that may have detrimental effects on marine habitats if left uncontrolled. It is understood that work to date under VFPA dredge contracts complies with environmental regulations pertaining to turbidity and environmental mitigation, however there may be room for improvement through the selection and installation of environmentally advantageous “green” dredge components that further lessen the environmental footprint left in the wake of maintenance dredge work.

Research conducted in support of this effort has included communications with dredge industry leaders in the environmental mitigation space. Focusing primarily on improvements that may be made to trailing suction hopper dredges to decrease potential environmental consequences, industry partners have indicated that outside of procedural adjustments such as disposal speed, analysis of material transport and tidal flow, and controlled material disposal in a tightly defined region, two of the most critical component upgrades to be considered should be the draghead design and functionality as well as in-hopper means of reducing sediment released into the water through overflow.

Draghead design selection can be an important feature of dredge production efficiency but the functionality of the draghead can impact the environmental results of dredge operations. By nature, a TSHD draghead functions through injection of water into the material to soften the sediment, allowing a turbulent slurry of water and sediment to be drawn into the pipeline for eventual placement in the hopper. In more compact materials, the jet system in the draghead is a supplement to the use of cutting teeth or blades to excavate bottom material. All dragheads produce some nearbed turbidity that may be transported through the water column to areas outside the dredge footprint. The geometry of the dragheads being used in current and previous maintenance cycles is not known, however it is recommended that a draghead suited to unconsolidated river deposits primarily comprised of silt and coarse to medium sand.

Dragheads under consideration to VFPA include those offered by IHC-Royal, VOSTA LMG, and Holland MT. The IHC type draghead may be well suited to use on maintenance method projects with VFPA because it is the most universal component, capable of removing silt deposits as well as compact sand with some percentage of small rock or gravel present. The IHC-type draghead includes a self-adjusting visor that can also be hydraulically fitted to improve visor control and therefore slurry containment within the draghead, decreasing the external turbidity generated by draghead activity. VOSTA LMG’s universal draghead includes a swell compensation system intended to control the amount of contact the draghead has with the bottom as well as an adjustable water flap that supplies additional flow when digging soft sediments. Dragheads considered for this project from Holland MT are also universal type but with an emphasis placed on replaceable and wear-resistant components that may make Holland MT dragheads an effective choice for long term use in multiple digging environments.

Overflow Control

Turbidity generation as a result of hopper overflow water discharge can be a considerable source of re-suspended sediment in the water column that may result in adverse environmental impacts. It has been an industry practice to recirculate hopper overflow water to be used as draghead jet water through use of “green pipelines”, but the next step is to decrease the amount of sediment that remains suspended in the water standing in the hopper before it is discharged as overflow to make room for more material in the hopper.

Components for consideration under this study may be sourced from IHC Royal and VOSTA LMG. IHC Royal’s Plumigator provides an improved means of capturing and discharging hopper overflow through “airless” characteristics resulting from the absence of hydraulic cylinders causing the entrainment of air and fine sediment in the overflow water to be discharged. To decrease turbidity in the overflow, the Plumigator strives to produce non-turbulent movement of overflow from the hopper through to the discharge. As demonstrated by Figure 2, the Plumigator’s unique design of three stacked inlets, the highest above the waterline and the lower inlets submerged, minimizes turbidity within the hopper through passive flow, allowing suspended material a greater time to settle out of the overflow water before it is removed from the hopper. While the Plumigator is typically installed on new dredges, it can be retrofitted and installed on existing equipment. The Plumigator has been successfully installed on TSHD platforms in the European market with compelling evidence of effectiveness in open water environments.

Figure 1. Comparison between typical overflow systems and the IHC Plumigator design

Lastly, a component of the Plumigator that aids in its reduction of turbulent flow of hopper overflow to be discharged is use of butterfly values, also referred to as "green valves". In a standard overflow system, the turbid movement of water continues down the pipeline and to the discharge. Discharge of an already turbid mixture of water and suspended sediment does not encourage material to more rapidly settle out of the water column when released from the dredge. The Plumigator uses a butterfly valve to keep the overflow pipe full, with a steady, calm flow through to the discharge. Use of the butterfly valve allows the control of overflow velocity, providing suspended material the opportunity to further settle out of the water column.

VOSTA LMG offers their overflow weir with anti-turbidity system which consists of a fixed lower portion and an adjustable upper portion controlled by a hydraulic cylinder that uses continuous positioning to make adjustments to overflow weir height. The option of an additional anti-turbidity system (ATS) including a flap that may be adjusted from the wheelhouse as needed. It is not clear whether VOSTA LMG's overflow weir includes a butterfly valve to decrease turbidity of overflow released from the dredge.

The combination of draghead selection and implementation to an environmentally conscious overflow system will lead to an increased environmental efficiency for dredging work conducted under VFPA through the reduction of visible turbidity plumes, reuse of overflow as jet water which keeps suspended sediments with the dredge system, and reduction of nearbed turbidity plumes that may have harmful effects on marine life.

Equipment Recycling

This study does not assume contracts in the immediate future will include use of a newly constructed dredge. Beyond the immediate contract cycle, the opportunity exists for a newly constructed dredge to be introduced to the VFPA maintenance dredging contract. Construction of new dredge equipment offers the opportunity to encourage environmentally conscious decision making by means of a green passport under IMO Resolution A.962(23), IMO Guidelines on Ship Recycling. A green passport originates with the physical construction of the ship, including an inventory of all materials used during construction, specifically focusing on the amount and location of hazardous or potentially hazardous materials onboard the vessel. The purpose of the green passport is to travel with the dredge throughout its lifecycle to the point of disposal. The information contained in the green passport will be updated with design and equipment changes, allowing all possible materials to be recycled or disposed of through environmentally conscious methods.

This forethought into material selection, identification and documentation of type and location of hazardous materials onboard the dredge, and commitment to global sustainability and recycling initiatives may provide long term means of promoting environmentally conscious dredging practices from vessel construction through to retirement.

CONSIDERATIONS FOR DREDGE AUTOMATION AND CONTROL SYSTEMS

Remote Monitoring

Remote monitoring has emerged in the dredging industry over the last decade as a reliable means of inspecting both mechanical and hydraulic dredging efforts while also enabling remote control and intervention in production software platforms in real time. As a secondary benefit, remote monitoring platforms offer the ability to for IT teams or engineering staff to remotely address software difficulties within production platforms such as DredgePack that might otherwise result in lengthy operational shutdowns and a decrease in overall efficiency.

Considerations for selection of the most appropriate remote monitoring platform are dependent on multiple factors including the level of remote support desired, the purposes of monitoring, and the desired integration of imaging systems. The lowest level of remote monitoring may be most applicable for projects in need of remote technology support while engineering staff is regularly present onboard, and a secondary form of hydrographic survey is readily available. The lowest level of monitoring may be provided by organizations such as BeyondTrust, which allows remote access to the dredge computer and provides access to observe production software platforms to address issues as needed. BeyondTrust access allows both engineering staff and technical support to access the dredge's computer system to upload survey or dredge files or to troubleshoot software related issues impacting dredging performance. BeyondTrust would not require a change in the primary production software platform, DredgePack.

For projects that do not have imaging and engineering support readily available, a more comprehensive form of remote monitoring may be appropriate. DSC Dredge, LLC offers a variety of remote platform systems including complete remote control of operating systems, remote systems management and data logging, and maintenance data collection to aid in calibration and service needs. All DSC Dredge, LLC software offerings include remote viewing of the dredging computer. Such access to a dredge platform during active operations provides the opportunity to make adjustments to real-time operating parameters that may improve efficiency. DSC's maintenance tool specifically may be a useful application for dredging equipment that operates over a prolonged period with short periods of time where maintenance or repairs may be done without interrupting production requirements.

Separately from platforms focused solely on remote access, Teledyne's PDS TSHD platform is specifically oriented to provide industry leading data collection and surface visualization of the dredge surface while also providing operators with a greater level of information on draghead behavior to improve production. The Dredge Terrain Model (DTM) produced by the PDS system clearly shows high and low spots present on the dredge surface that are updated in real-time as the dredge progresses, incorporating new data as soon as it is available to maintain the most accurate representation of the dredge surface possible. This capability may allow operators to specifically target high spots while present in a specific reach rather than waiting for survey confirmation that may require a return to clean-up areas of remaining above grade. Additionally, the hydrographic survey data collected by the PDS system may be used by VFPA to confirm material removal for payment rather than requiring a secondary conditional survey.

It should be noted that BeyondTrust or DSC Dredge, LLC's products may be combined with PDS TSHD for remote access to troubleshoot software difficulties while also supplying visual representations of the dredge surface.

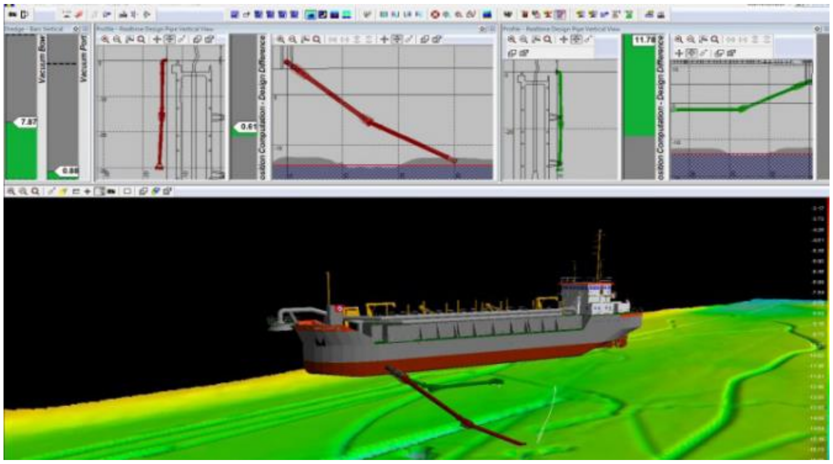

Figure 2. Teledyne PDS Visual Representation

Production Automation

Dredge production automation builds upon the foundation of remote monitoring and expands the operational capabilities to include active control of dredge operations and automation of selected dredge systems and components to improve efficiency. Typical automation systems integrate software and hardware components that work in tandem. Dredge automation systems serve to monitor desired conditions such as draghead jet flow, draghead position, and material flow density to make adjustments that will improve performance and efficiency.

DSC Dredge, LLC offers a platform designed to implement control draghead position, material flow, or full production. DSC Dredge's automation package includes the management, maintenance, and remote access tools previously mentioned with the additional benefits of flow control, comprehensive production monitoring, draghead position control, slurry dilution, material cave-in or slope failure detection, and full production control. Dredge production

IHC Royal's Dredge Control System (DCS) for TSHD and CSD equipment offers a robust and customizable option for implementation of a partial or full automation system onboard a selected dredge. While the DCS is highly customizable to meet the needs of the client, the common areas of monitoring, control, and automated management in terms of active dredge production are found in monitoring and adjusting material density, flow speed, and level of solids and water contained in the hopper. Beyond these areas of control, DCS offers production and operational management through control of overflow ducts, dredge pumps, gantry positioning, and swell compensation to maintain optimal levels of drag head position, suction, material flow through dredge pipelines, and wear on primary dredge components. To achieve this level of management, DCS presents options for control through manual and automatic means as well as implementation of artificial intelligence to produce an efficient and effective outcome.

The platforms considered by this study can be implemented on existing dredge equipment or integrated into the construction of new dredge platforms. Utilization of one or more of the recommended monitoring and automation softwares may require installation of sensors and other associated hardware in a drydock setting.

CONCLUSIONS

Determination of the means and methods that will produce the greatest uplift in operational efficiency, environmental sustainability, and overall performance includes a range of considerations spanning from results of emissions exceedances to the physical components and systems to be installed onboard a TSHD. The areas of analysis performed by M&N have shed light on the ways in which VFPA may position itself and its contracts to support its sustainability initiatives through greater control over specification directives while also seeking recommendations for upgrades to software platforms and system components that will foster greater sustainability through focused areas of improvement. Assessments of alternative fuels and their integration into commercially available dredge systems is likely the most promising means of decreasing the environmental impact of dredging operations in the coming decades. While emerging technologies in the fuel sector may require additional years of development, remote monitoring, visualization, and automation systems that can be installed on new or existing dredges will move the needle towards greater efficiency and thereby less wasted emissions through determination of optimal equipment operating states and identification of specific areas of shoaling or navigational concern that may be targeted rather than captured through larger clean-up efforts.

The study of emissions regulations and recommendations to improvements to areas of current and historical exceedances as compared to California Air Resources Board (CARB) emissions regulations is an ongoing effort that VFPA seeks to understand. M&N's partner Synergy has developed a baseline against which to compare FRPD dredge emissions and performance and emissions regulations and thresholds, providing a clearer picture of the existing landscape and the avenues of focus that VFPA may be interested in pursuing. This assessment of current contract documents and technologies coming into the dredging market are intended to build a foundation of recommendations that may be immediately implemented for the upcoming Fraser River dredging contract cycle.

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DATA AVAILABILITY

No data, models, or code were generated or used during the study.

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EXPLORATION OF THE FACTORS THAT INFLUENCE BOTTOM ROUGHNESS CREATED BY DREDGING PROCESSES

M. Warwick[1] J. Henriksen[2], K. Quinones[3], K. Howell[4], C. Tennant[5], Nathaniel Vazquez[6]

ABSTRACT

An engineering analysis of post dredging Bottom Roughness was conducted in order to investigate the dynamics of dredging equipment in diverse project environments. The engineering analysis utilized survey analysis, Hypack®, dredging theory, Autocad®, and Matlab® software to investigate and quantify the sediment bed roughness after digging. Specific Dredging Equipment in the analysis include clamshell, cutter, and hopper dredging. Results indicate the selection of digging equipment with a specific sediment type will greatly impact bottom roughness.

Keywords: Bottom Roughness, excavation, dredging

INTRODUCTION

Dredging operations provide the fundamental service of maintaining and developing navigable waterways. Post Dredging operations leave behind bottom contours that are characteristic of the dredging process employed. Clamshell, Cutter, and Hopper dredging, each create a unique pattern that are continually influenced by the soil type dredged and the sea state. The accuracy of the dredge's positioning and instrumentation controls the mechanical characteristics of the contours left behind. The amplitude of the contours define the roughness of the surface. Therefore, bottom roughness is a quantitative measure of how uneven the bathymetry is after dredging is complete.

The purpose of this research is to develop a framework by which we can measure and predict the amplitude of bottom roughness in dredging operations. The bottom roughness is influenced by the mechanical characteristics of the dredge, the physical characteristics of the existing bathymetry, material to be removed, sea state, and the accuracy of the measurement dredge's position. The prediction of the amplitude of the bottom roughness should allow the owner and contractor to understand the required material to be removed in order to achieve design grade. This amplitude has financial implications as it indicates the quantity of material removed that may be considered pay and non-pay.

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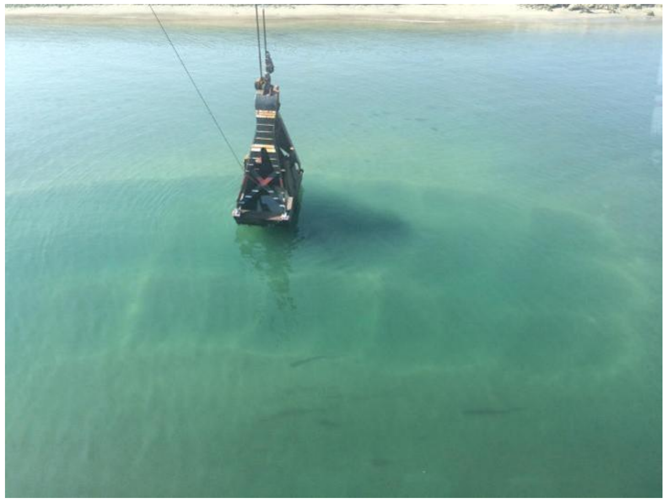

Figure 1. Example of a Mechanical clamshell dredge pattern as can be seen from above the water surface indicating bottom roughness

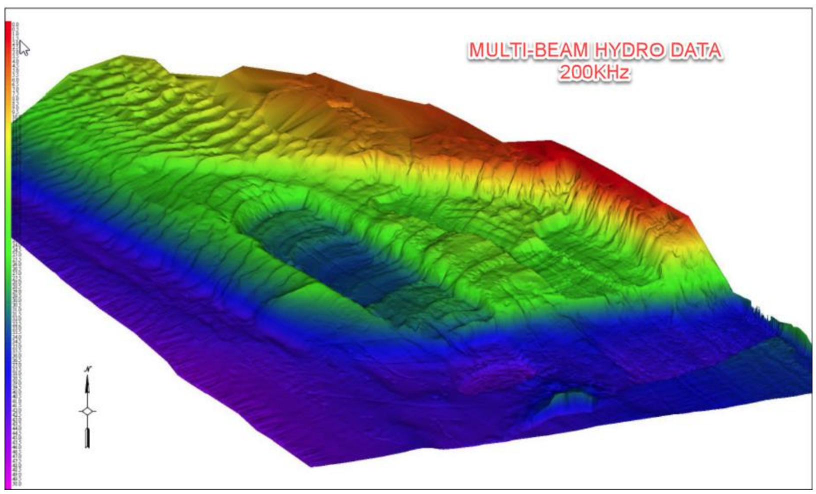

Figure 2. Example of a cutter dredge pattern as can be seen using multi-beam sonar indicating bottom roughness

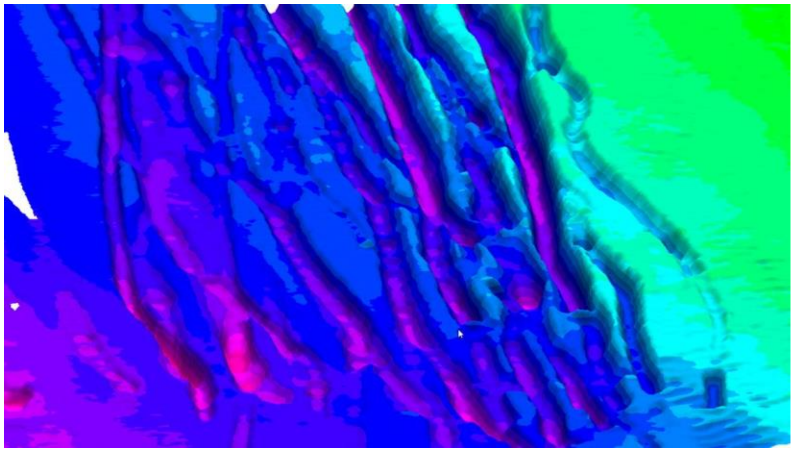

Figure 3. Example of a hopper dredge pattern as can be seen using multi-beam sonar indicating bottom roughness

Bottom Roughness

Figures 1, 2, and 3 visually depict examples of bottom roughness from each dredge type and their corresponding complexity. We will start with a simplified model of bottom roughness. For this model, we will assume that a hopper draghead excavates sand in a rectangular cut. The width of the rectangle is the draghead width and the height is the depth of the cut. Moving the rectangle through the bottom forms a trench. After the dredge has gone by, the sides of the trench slough in and the sides form a slope at the sand's angle of repose. If the draghead cuts are offset parallel to each other, this will lead to a series of long piles of sand on the seafloor. When the dredge is finished the tips of tops of the piles of sand will ideally be at or just below the required dredging template, which is also known as grade. This process is depicted in figure 4. Another way to visualize this pattern is to imagine a raked sand bed, figure 5.

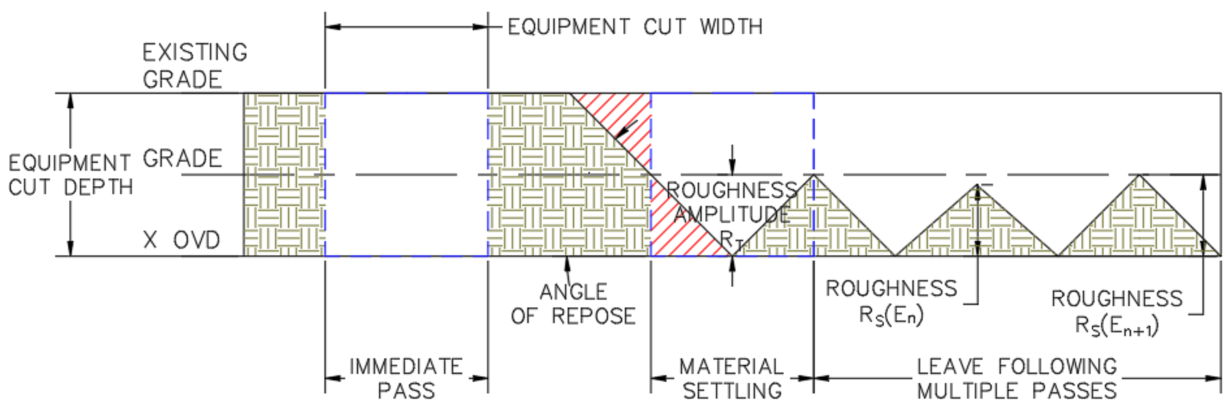

Figure 4. The process of forming the bottom roughness pattern for a hopper dredge in sand

Figure 5. Example of a raked sand bed

Defining and determining bottom roughness is necessary in order to calculate how much soil below the required dredging template must be removed in order to achieve grade. This has financial implications based on contractual payment terms for over depth tolerance or a lack thereof. The bottom roughness allows a contractor and owner to understand how much material will be removed to provide the cleared template. Cost per cubic yard removed is directly affected by the bottom roughness. The bottom roughness also has potential environmental implications, disturbance depth issues, and borrow area design for beneficial reuse of dredged material.

Using this simplified model we can calculate the amount of material removed below grade. This material volume then can be subdivided into paid material or non-paid material based on the arbitrary over depth tolerance specified. Figure 6 depicts this in cross section form with no paid over depth, 1 foot paid over depth, and 2 foot paid over depth.

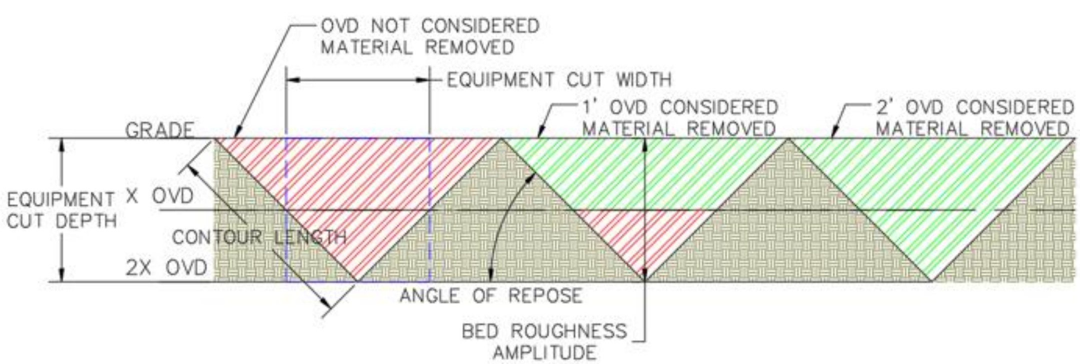

Figure 6. Examples of pay versus non-pay areas by cross section for a given over depth tolerance

The leftmost case in Figure 6 shows there is no over depth. Here there will be no material left in the pay template, therefore the average height of material dredged below the pay template is ½ of the bed roughness amplitude.

The rightmost case in Figure 6 shows the case for when there is an over depth that is equal to the bed roughness amplitude. Here there is no material dredged below the pay template and half of the over depth will be left in the pay template.

The middle case in Figure 6 shows the case when the bed roughness amplitude is greater than the over depth. Here there will some material left in the pay template, some material removed from within the pay template, and lastly some material dredged below the pay template. The pile tip to tip distance is calculated with equation 1 and the average non-pay height is determined by equation 2.

$$\text{Pile tip to pile tip distance} = 2 \cdot \frac{\text{bed roughness amplitude}}{\tan(\text{angle of repose})} \tag{1}$$

$$\text{Average non} - \text{pay height} = \frac{\left(\frac{(\text{bed roughness amplitude} - \text{over depth})^2}{\tan(\text{angle of repose})}\right)}{\text{pile tip to pile tip distance}} \tag{2}$$

Financial Implications

The over depth (O.D.) parameter for dredging contracts is significant to the operational strategy utilized at the jobsite and impacts the paid production derived from the operation. Moreover, the cost implications of this parameter often provide significant variability to the owner and ultimately may produce inflated cost to the tax payer if not approached with the correct strategy and regulatory permits. The appearance is that the unit price is too expensive with contracts that have limited over depth tolerances. The perception is equal to paying 43% more than a contract with 2’ (0.6m) O.D. when looking solely at cubic yard rate. The contractor’s goal is to leave the required grade on the first pass over the dredge area. Over depth improves the chances of being able to accomplish that effort. The anticipated bottom roughness allows the contractor to understand the amount of material that will need to be removed in order to achieve grade. If over depth is allowed, the contractor will be able to utilize the dredging equipment in a manner that will likely leave a higher roughness amplitude, but with likely fewer passes. This is due to the fact the initial mechanical cut can take place deeper than grade. If less over depth or no over depth is allowed the contractor will need to shift the initial mechanical dredge cut higher removing less material with each pass. This will likely provide a lesser bottom roughness amplitude, but the other influences in the bottom roughness calculation will have greater influence i.e. the drag arms on a trailing suction hopper dredge may lift off the sea floor with a rough sea state while attempting to maintain a cut depth at grade than below grade.

Bottom Roughness Framework

As shown in figures 1, 2, and 3, the actual patterns are more complex than the simple model that we depict in Figure 6. The dredge type, soil type, sea state, and dredge positioning accuracy will all affect the resulting bottom left by the dredge. We will discuss each factor in turn and suggest that the bottom roughness is a sum of all of these factors, equation 3, how roughness can be related to the design template, equation 4, and the overall roughness of the material left behind, equation 5. The presented results and considerations focus on a single specific dredge type from the Manson fleet. It is anticipated that the size of the dredge per dredge type will affect the roughness amplitude either making it smaller or larger.

$$\sum \text{Roughness} = \text{Dredge Type} + \text{Soil Type} + \text{Sea State} + \text{Measurement Accuracy} \tag{3}$$

$$f(R_T) = \begin{cases} \text{Dredge Type} \\ \text{Measurement Accuracy} \\ \text{Template Design} \\ \text{Material Type} \\ \text{Sea State} \end{cases} \tag{4}$$

where R_T is the quantitative roughness as related to the design template.

$$f(R_S) = \begin{cases} \text{Dredge Type} \\ \text{Measurement Accuracy} \\ \text{Material Type} \\ \text{Sea State} \end{cases} \tag{5}$$

where R_S is the quantitative roughness as related to the bottom surface.

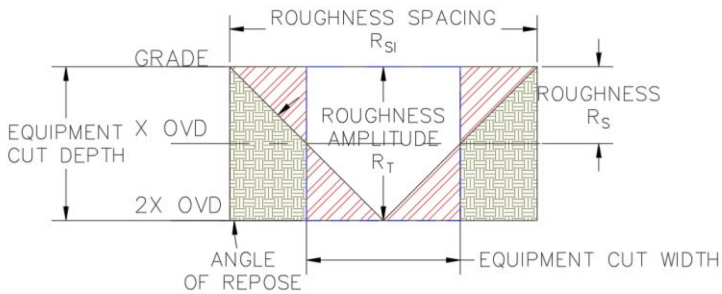

Figure 7. Dredge Cut to provide clear template with generalized contour following material settlement

Figure 7 displays a general schematic of bed roughness parameters. Bed roughness template amplitude (R_T) is the measure of design grade to the bottom of the contours of the remaining bathymetry. This is defined in equations 4 and 9 as R_T. The depth of the mechanical equipment is directly controlled by the dredger with influence from the sea state, material characteristics, accuracy of the position of the equipment, and over depth tolerance. The material left behind will leave a bed roughness that is defined in the region of the initial cut of the material, determined by the geometry of the mechanical means for removing the dredge material. The remaining material will settle into the cut area as determined by the angle of repose of the material. The leave in bed roughness, R_S, is the average measurement of the peaks of the leave in material to the troughs of the bottom, equations 5 and 10. As the mechanical cut is influenced by the all of the elements of the dredging process, the peaks and troughs will fluctuate. Measuring this distance allows for an understanding of the magnitude of the peaks and troughs for the leave in material.

Mechanical Excavation

The mechanical cut of material varies for the dredge type selected. A trailing suction hopper dredge initial cut will leave a rectangular trench along the channel. The cutter suction dredge will leave peaks along the profile of a channel and the peaks will form arcs across the width of the channel. A mechanical clamshell dredge will leave in sloped rectangular depressions dictated by the bucket shape.

Both cutter and clamshell excavation can be calculated by utilizing the excavation path of the dredging tool. The shape of a hopper draghead can also be simplified by utilizing a rectangle. The shape of these cuts can be used to estimate the area of the material removed. Equation 6 provides the calculation for the initial excavation area of cut for a hopper draghead.

$$A_{IC} = EQ_D * EQ_W \tag{6}$$

where EQ_D is the depth of cut and EQ_W is the width of cut.

The remaining material will slough or settle into the initial mechanical dredge cut. The characteristics of the material will influence the sloughing or settling of the material. A sandy material will settle along its angle of repose. For a sandy material, the material from initial dredge cut will slide into the trench left by the dredge. Equation 7 provides the calculation utilized for the angle of repose while Equation 8 represents amplitude of Bed Roughness.

$$\mathbf{A_{LI}} = \frac{\mathbf{EQ_a * \sin(\varphi) * EQ_w}}{\mathbf{2}} \tag{7}$$

where EQ_a is the length of contour and φ is the angle of repose.

$$A = \sin(\varphi) * EQ_a \tag{8}$$

where A is the amplitude the amplitude of the Bottom Roughness.

Sea State

The sea state will influence the position of the mechanical cut of the material. Some variables that influence the sea state are tidal fluctuations, wave height, wind speed, currents, local geology, and past dredging events. While a trailing suction dredge is dredging, the dredge will heave up and down. This causes the drag arms to rise and lower. Systems can be installed on the dredge to help limit the heave action, but heave influences the mechanical cut as it changes the depth of the cut. Similar actions are felt on a cutter suction dredge and mechanical clam shell dredge.

Survey

The operators of dredges rely on the survey data, positioning systems, and sensors in order to maximize the production of the dredge. These tools allow the operator and engineers understand the position of the dredge and what adjustments are necessary for the various physical conditions encountered and the mechanical parameters of the vessel. The accuracy of this equipment is very important to ensure that dredge is operating within the design requirements of the project.

Survey accuracy depends on the system utilized. Single beam surveys typically employ what is known in the industry as a standard high frequency (HF) which is an acoustic frequency of 200 kHz. The benefit of single beam soundings is that they are generally considered the most accurate depth measurement. Most modern high frequency single beam sonars have a worst-case accuracy of 0.1’ + 0.1% (0.03m + 0.1%) of depth. In practical terms, this error would result in potential measurement errors of approximately 0.11’ (0.034m) at a depth of 10’ (3.0m) and 0.15’ (0.05m) at a depth of 50’ (15.2m). Low frequency single beam sonar surveys typically employ the simultaneous use of a high frequency (200 kHz) acoustic pulse and a low frequency (LF) pulse. The specific low frequency to be used is usually specified by the owner and included in the project specifications. Typical low frequencies used in the U.S. are either 28 kHz, 33 kHz, or 40 kHz. The low frequency acoustic energy requires a higher density of material to reflect the acoustic signal. This allows the low frequency to “penetrate” lighter density material, which is commonly referred to as “fluff” that may not need to be dredged. Using a low frequency of 33 kHz as an example, a modern low frequency single beam sonar will have a worst-case accuracy of 0.3’ + 0.1% of depth. In practical terms, this error would result in potential measurement errors of approximately 0.31' at a depth of 10' and 0.35' at a depth of 50'.

The dynamic nature of marine conditions present a significant challenge to the collection of reliable hydrographic survey data. A survey boat, and its compliment of hydro survey equipment, is routinely affected by movement from a variety of sea conditions. This movement (heave, pitch, roll and yaw), if left uncorrected, imparts significant ambiguity in the survey products. For this reason, most modern hydrographic survey vessels engaged in offshore surveys are equipped with state-of-the-art INS (Inertial Navigation Systems). These navigation systems perform highly-precise vessel attitude measurements at rates of up to 50 times per second. As well, these systems can provide horizontal positional accuracies of 10cm or less (using Real-Time Kinematic (RTK) positioning). During post-processing, the distorting effects of motion-related errors imparted unto the data can be diminished, if not completely removed, by applying motion data collected by the INS sensors during the survey. While these systems can be costly, they afford dredging operations with consistent survey data on a day-to-day basis even while sea conditions can vary greatly between survey events.

The dredge positioning system combines the information on the dredge's horizontal location in latitude and longitude or northing and easting with multiple sources for the position of the dredge's equipment. Modern systems provide the horizontal location of the vessel globally using real time kinematic global positioning system (RTK GPS). Older systems may use differential global positioning systems (DGPS), range-range telemetry systems, physical range markers, or even small buoys. Some of these older systems also used a gyrocompass for the dredge's heading. The dredging equipment on board the vessel may have local sensors such as inclinometers, hydrostatic pressure sensors, rotational sensors, and cable counting devices. The vertical position is also adjusted for tidal fluctuations using either a tide gauge using telemetry to the dredge or RTK GPS. RTK GPS eliminates errors from the dredge working a significant distance from a tide gauge. It is important that RTK GPS is used with an INS to remove heave from the vertical tide reading. These can provide the local relative location of the dredging equipment so that operators can know where the equipment is working in relation to the vessel, the existing grade, and the design template. The accuracy of these sensors are dependent on the manufacturers' details. The individual accuracies for each sensor is summed to provide an overall error budget. Depending on the accuracy and number of sensors employed, this error budget can range from +/- 0.33 ft (0.1m) to +/- 16 ft (4.8m).

Roughness Calculation

Each of these elements are to be considered in the Roughness Estimation Calculation. Each parameter influences the contours the dredge leaves following a dredging event and should indicate how a dredge reach will need to be dredged. These variables will define R_T which can be used to provide guidance to over depth considerations. R_S will indicate the final leave in material roughness of the final bathymetry.

Dimensional Roughness Calculation

A Matlab program was generated in order to determine the quantitative roughness predicted from each dredging operation. The Quantitative Roughness in Regards to Template is defined as:

$$R_T = \left(\frac{1}{N}\right) \int_0^N |Z(x) - n| \, dx \tag{9}$$

where R_T is quantitative roughness as related to the design template, N is the number of points along the survey profile, n is the template elevation, and Z is the elevation of each point.

The Quantitative Roughness in Regards to Surface of Cut is defined as:

$$R_S = \left(\frac{1}{N}\right) \int_0^N |Z(x) - Zavg| \, dx \tag{10}$$

where R_S is the quantitative roughness to the surface of the cut, Z*avg* is average cut depth, N is the number of points along the survey profile, and Z is the elevation of each point.

2D Model

An AutoCAD analysis was conducted for clamshell, cutters, and hopper dredging. The geometry utilized for each excavation algorithm is shown in figure 8 for a mechanical clamshell, figure 9 for a cutter suction dredge, and figure 10 for trailing suction hopper dredge displays the general mechanical design utilized to examine the excavation.

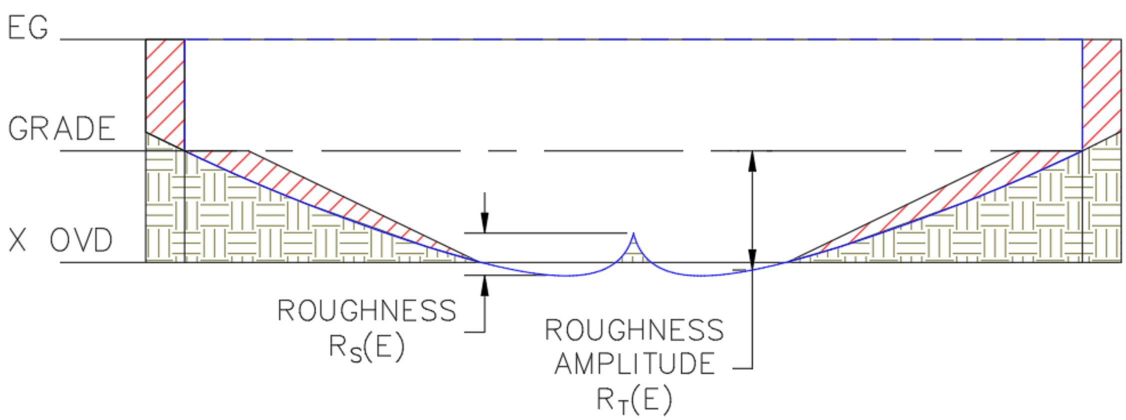

Figure 8. Bottom roughness for a mechanical clam shell

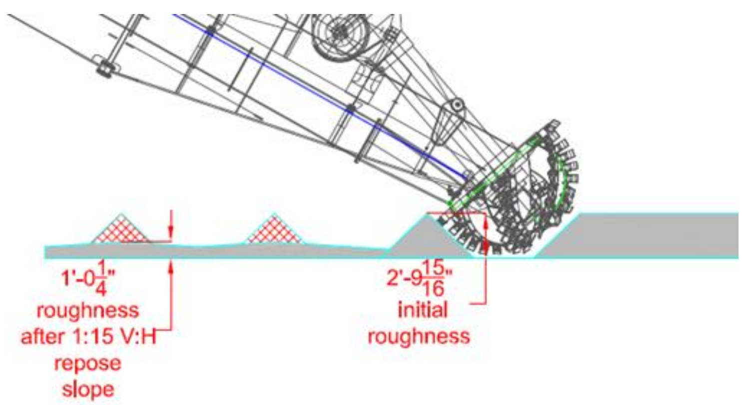

Figure 9. Bottom Roughness for a cutter suction dredge

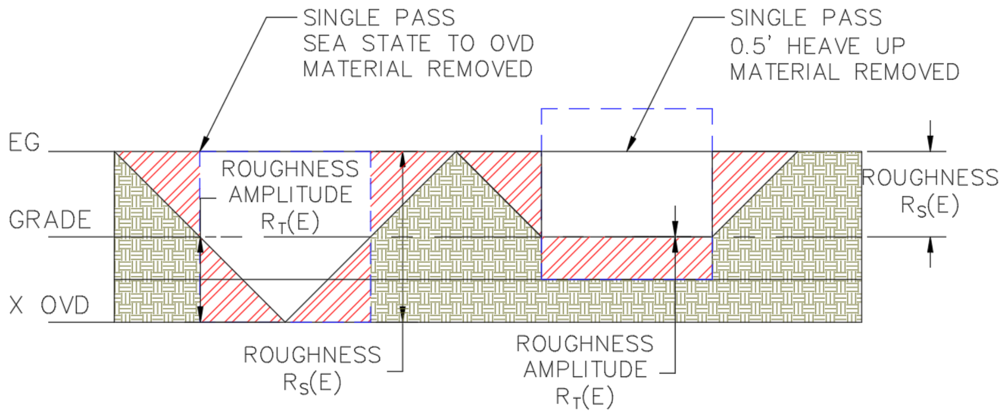

Figure 10. Bottom Roughness for trailing suction hopper dredge

Material Analysis

The material along the sea floor will be disturbed by the actions of dredging. As the material settles into the cut trench it is expected that it should fall along the angle of repose for sands. This settling will influence the final bed roughness amplitude.

Table 1 Angle of Repose for Sands and Silts (Lambe)

Friction Angle		
	Angle of Repose	Slope
Classification	i(°)	Slope (Vert. to Hor.)
Silt (nonplastic)	26	1:2
	30	1:1.75
Uniform fine to medium sand	26	1:1.75
	30	1:2
Well-graded sand	30	1:1.75
	34	1:1.75
Sand and Gravel	32	1:1.60
	36	1:1.40

Survey Analysis

Survey Analysis was completed for specific jobs. This provided actual data on roughness. The jobs compiled included clamshell, cutter, and hopper equipment utilization. The following is a summary of the job locations included in this analysis.

Jacksonville, FL, USA

Figure 11. Clamshell Maintenance Dredging In Jacksonville, FL

Manson Construction performing maintenance dredging at various ship berths in Jacksonville, FL with a mechanical clam shell dredge. The material is generally sands and silts that are deposited in access channels and ship berths. The material type and SPT-N value will dictate the type of bucket utilized.

South Pass, LA, USA

Figure 12. Manson Construction Cutter Section Dredge *R.M. White* dredging in South Pass, LA, USA

Manson Construction's cutter suction dredge, *R.M. White*, performed dredging of shoaled material from South Pass, LA, USA. The project grade is -20' MLG and has a channel width of 300' with material placed at several disposal locations. The *R.M. White* is a 30" delivery pipeline dredge with a 7' diameter cutter.

King's Bay, GA, USA

Figure 13. Manson Construction Trailing Suction Hopper Dredge, *MV Bayport,* Unloading to a beach fill in Fernandina, FL, USA

Manson Construction trailing suction hopper dredge, *MV Bayport*, unloading dredge material to shore for beach fill operations. Material unsuitably for the beach was unloaded offshore at a designated disposal site. The *MV Bayport* is 303ft long with a capacity of 4,800 CY.

Table 2 displays information of the field environment for the jobs discusses as well as the calculated Roughness Values.

Table 2. Jobs, survey parameters, field roughness

Location	Equipment	Material	Wave Height (ft)	Wave Period (s)	Frequency (Hz)	R_s (ft)	R_t (ft)
Jacksonville, FL	Clamshell	Silt	0.5	10	200	0.19	0.8
Jacksonville, FL	Clamshell	Sand	0.5	11	24	0.63	1.86
Southpass, LA	Cutter	Silt	1	Nan	200	0.22	0.94
Southpass, LA	Cutter	Sand	1	Nan	24	0.47	1.57
Kings Bay, GA	Hopper	Silt	3.15	8.11	200	0.88	2.21
Kings Bay, GA	Hopper	Sand	3.15	8.11	24	0.69	0.82

<u>Dimensional Roughness Plots</u>

Figures 14-16 show the roughness calculated for clamshell, cutters, and hoppers. The results show predicted model values for bottom roughness as related to the values shown in Table 2.

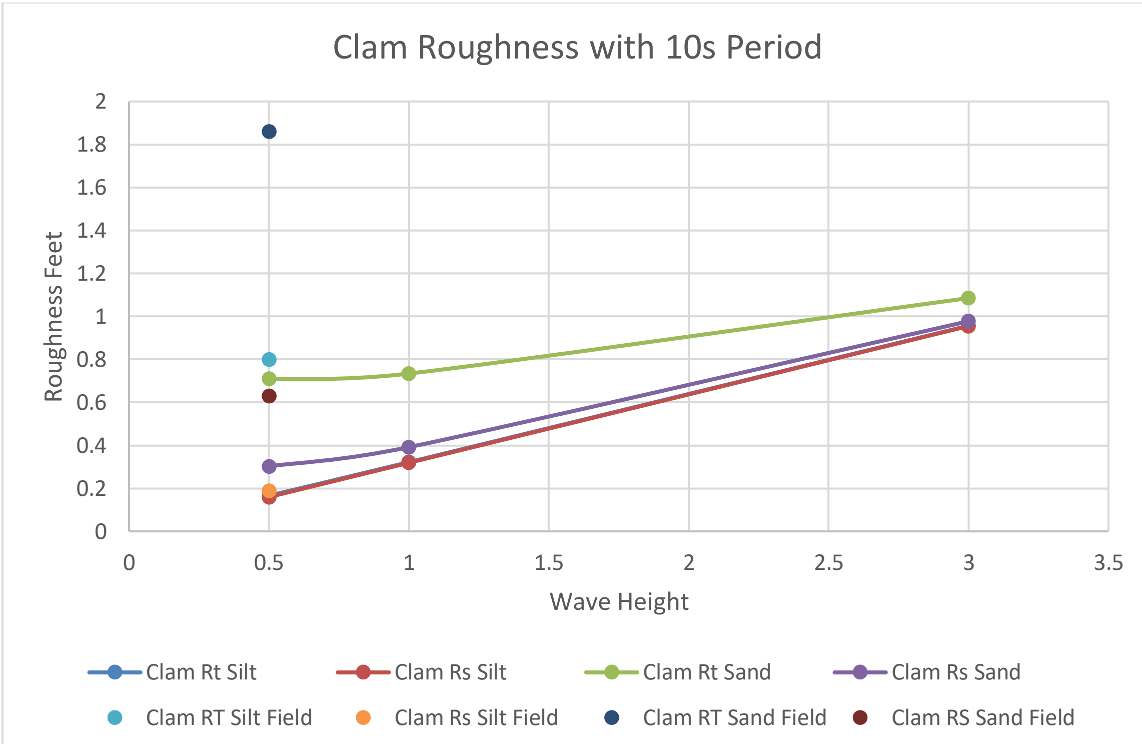

Figure 14. Estimated Clamshell Roughness Results based on field results from Table 2.

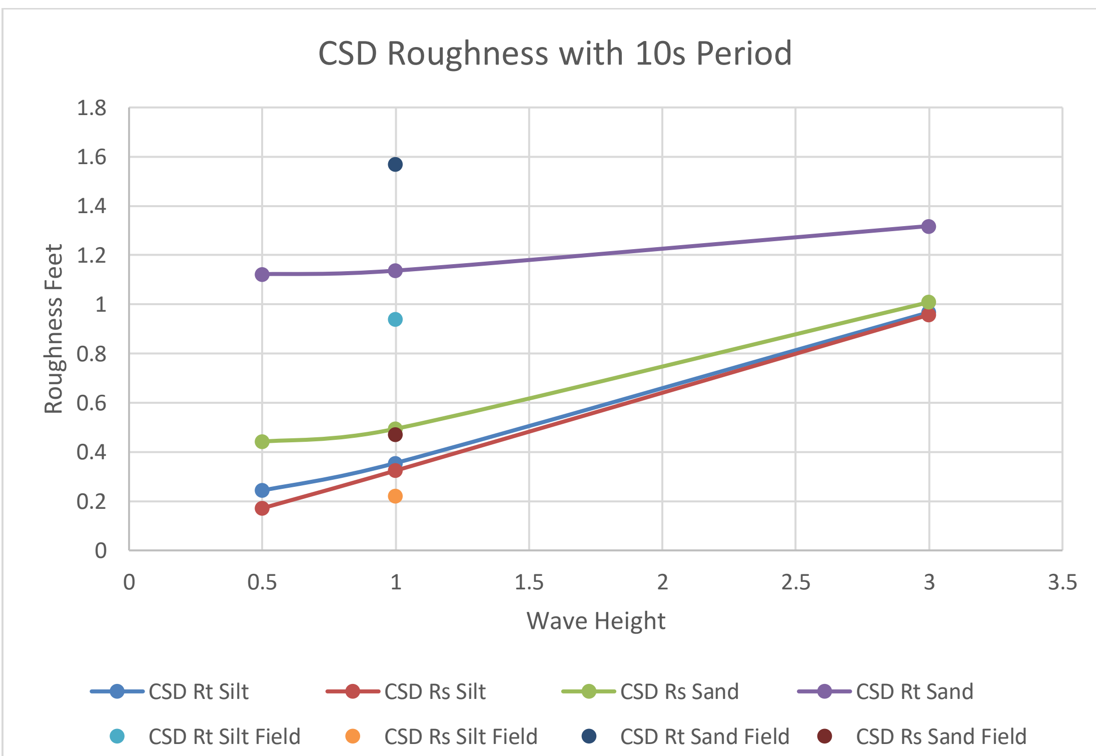

Figure 15. Estimated Cutter Roughness Results based on field results from Table 2.

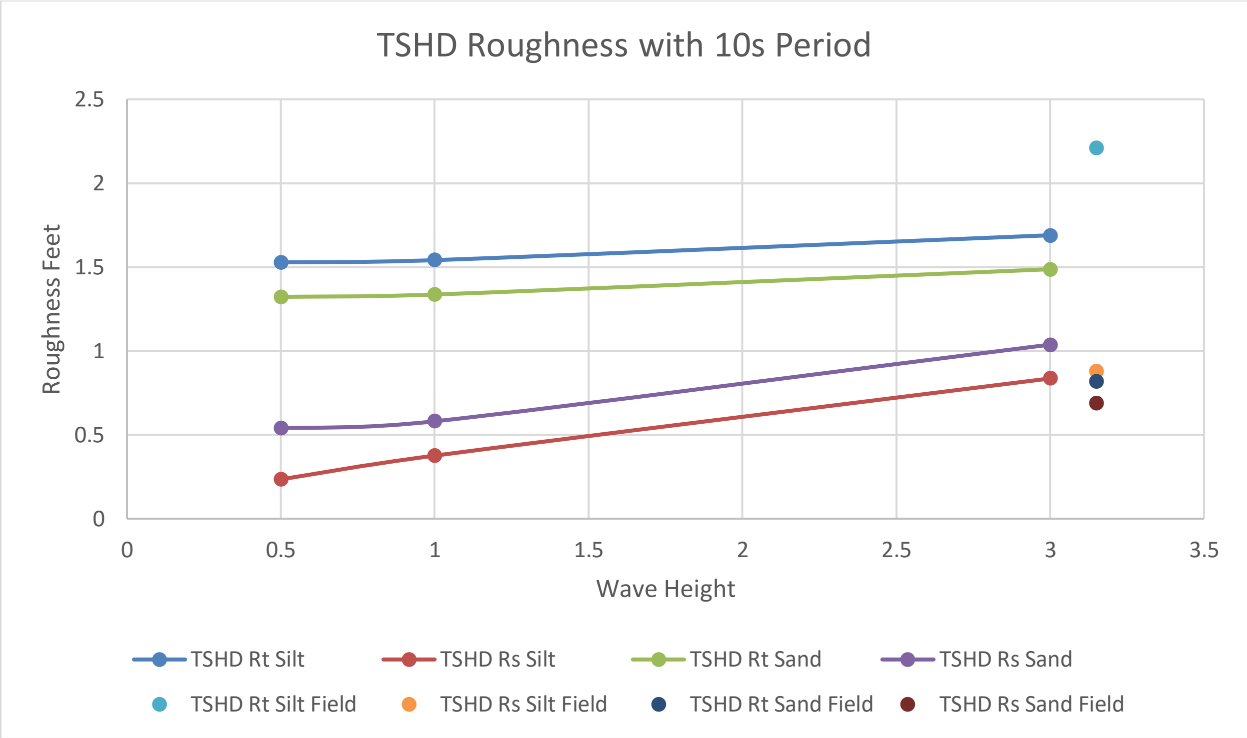

Figure 16. Estimated Hopper Roughness Results on field results from Table 2.

CONCLUSION

Results from this papers show the bed roughness will be specifically effected by both the material type and the wave climate. In particular, a softer sediment will have less roughness in clam and cutter operations, but way have a larger amplitude for trailing suction hopper dredges.

Roughness calculations determined from both field data and computational modeling are specifically correlated to specific dredging operations. It is shown that the bottom roughness is influenced by the dredge type, material type, sea state, and accuracy of positioning. These elements help an owner or designer determine the required over depth needed to clear the dredging template. This will in turn inform the proper characterization depth for soil samples for permitting. It will also inform a dredge operator how to determine their expected non paid material given the prescribed over depth tolerance.

Developing an understanding of the dredging environment and anticipated equipment to complete the dredging efforts, the owner or designer can anticipate the bottom roughness left behind. Bottom roughness should be considered to identify the necessity for over depth material removal. Over depth allows the contractor to complete the dredging efforts more efficiently creating a more cost-effective dredging project benefitting the owner, contractor, and all that use our waterways.

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CITATION

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WATER INJECTION DREDGING IN THE US, CHALLENGES AND SOLUTIONS

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ABSTRACT

Sediment handling and disposal are crucial issues with associated permitting and operational constraints. Once an organization has identified the most efficient, lowest cost alternative with the most flexibility, the next logical step is to seek permits to use the technology. Maritime authorities are continually confronted with the siltation of their waterways. Therefore, regular maintenance dredging is necessary to ensure safe navigation depths. Each year the US Army Corps of Engineers (USACE) and local facilities dredge roughly 250 million cubic yards of material at an estimated $1.3 billion. Water Injection Dredging (WID) is an innovative hydrodynamic dredging technique that is cost-effective, low-impact and environmentally sound. The WID injects large volumes of water at low pressure into the sediment layer, and the resulting fluidized sediment is carried horizontally along the waterway as a density current. The WID process occurs with a minimum of disturbance to the benthic ecosystem. Natural forces (currents, tides, gravity, etc.) facilitate sediment transport, making WID a low-impact dredging technique. Since a WID is highly maneuverable and does not excavate sediment like traditional dredges, there is no need to obtain disposal facilities or transport material, creating cost savings. A WID can operate in places other equipment cannot safely reach, for instance, near jetties and beneath moored vessels. Also, the WID poses less risk of damaging underwater infrastructures, such as pipelines, bulkheads, and dry docks. The WID method has garnered widespread acceptance for maintenance dredging in numerous European ports with continuous shoaling and siltation issues. However, that is not the case within the US. This paper aims to provide an understanding of WID methodology while identifying and evaluating the current challenges related to bringing this type of innovative technology to a maritime facility within the US. The paper proposes means to work within the current challenges and approval system to provide maritime interests the ability to apply innovative technologies to US facilities.

Keywords: Maintenance Dredging, Navigation Channel, Density Current, Water Injection Dredging, North Carolina State Port Authority (NCSPA)

INTRODUCTION

Each year the USACE, ports and maritime facilities allocate a significant portion of their operating cost to maintaining existing channel and harbor depths through maintenance dredging, removing sediments and debris from their harbors and berths by traditional means. Over the last 57 years, the cost to dredge per cubic yard (CY) has increased exponentially, while the total dredging volume has tended to decrease gradually (Figures 1 and 2) (USACE-NDC 2021). The overall reduction in total dredging volume can be attributed to fewer new work dredging, whereas overall maintenance volumes remain roughly the same.

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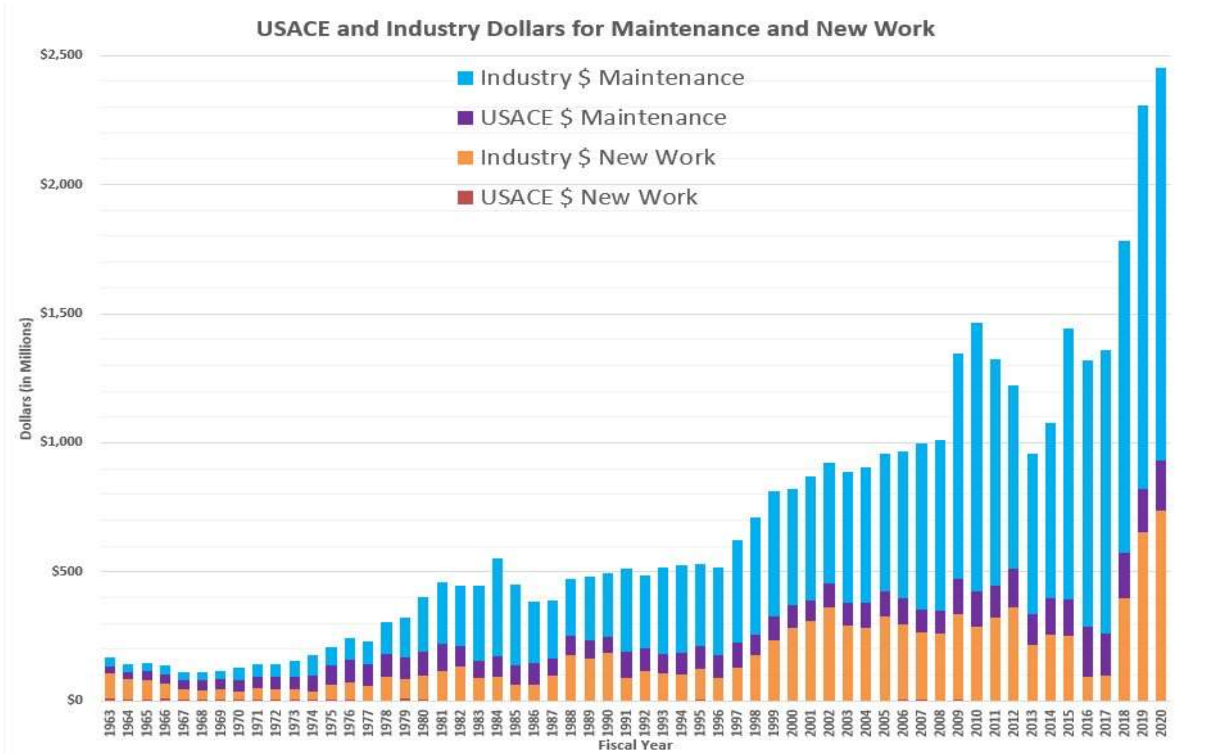


Figure 1. USACE and Industry Dredging Costs from 1963-2020

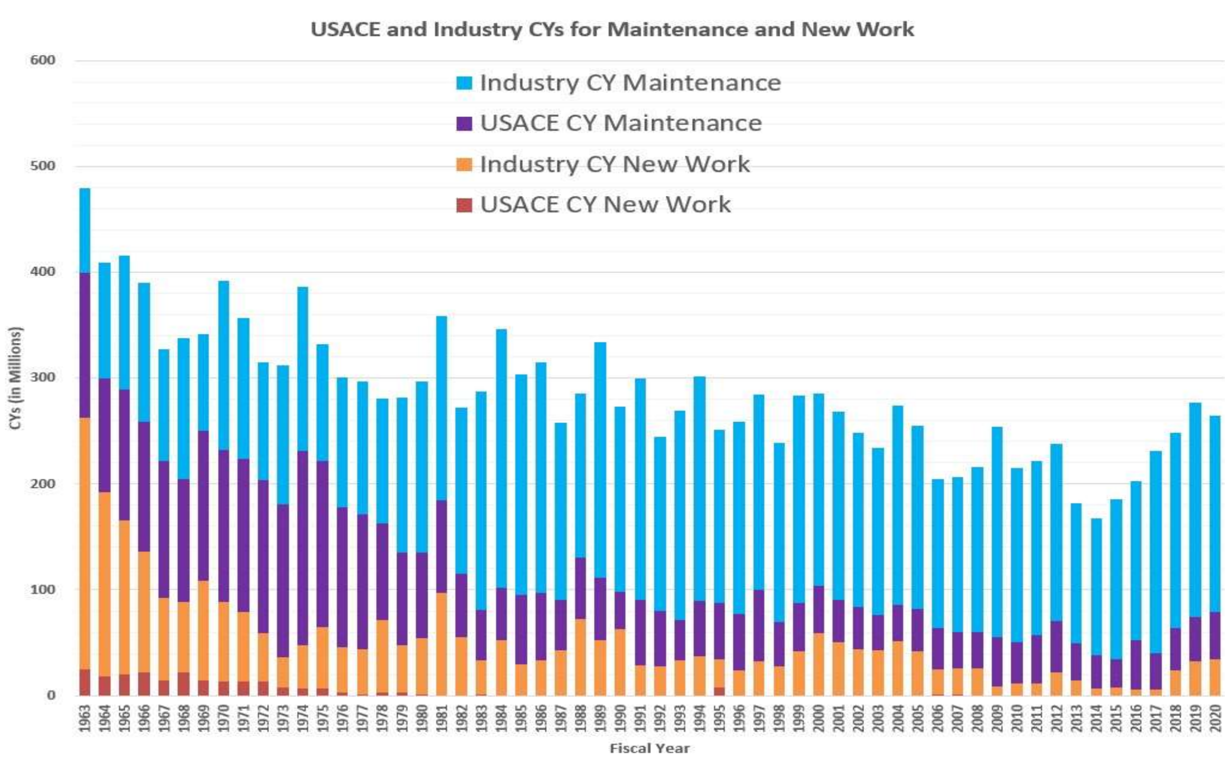


Figure 2. USACE and Industry Dredging Volumes from 1963-2020

It is estimated that maintenance dredging accounted for roughly 60% of all dredging in the 1960s and cost $0.28/CY. In contrast, maintenance dredging accounted for 87% of all dredging in 2020 and cost $7.47/CY. Note that unit prices shown in Figures 1 and 2 have been adjusted for inflation. A key objective of this paper is to demonstrate that innovative dredging methods, such as WID, may be employed to maintain safe navigation channels and harbors more cost-effectively, efficiently, and sustainably.

This paper starts with an overview of the WID theory of operation by describing the vessel and its components, density current dynamics, and site feasibility based on geotechnical characteristics of shoal material. Next, it outlines the capital investment project executed by the North Carolina State Port Authority (NCSPA) to purchase a custom-built WID vessel. It also describes the results of a monitoring and evaluation of WID operations during dredging at Wilmington Harbor, NC, in January 2022.

WATER INJECTION DREDGING OPERATION

WID Vessel

As defined by Uelman (2015), water injection dredge vessels are hydrodynamic dredge vessels with four main components: a water intake, a water pump, a retractable pipeline, and a jet manifold (Figure 3). A low-pressure, high-volume discharge characterizes the water pump. Water from the near-surface is taken into the retractable pipeline and directed toward the seabed, which supplies an injection manifold. The injection manifold has several jet nozzles pointed downward so that the streams of water are injected into the bottom. This dredge type may be self-propelled or maneuvered by a push boat (Wilson 2007).

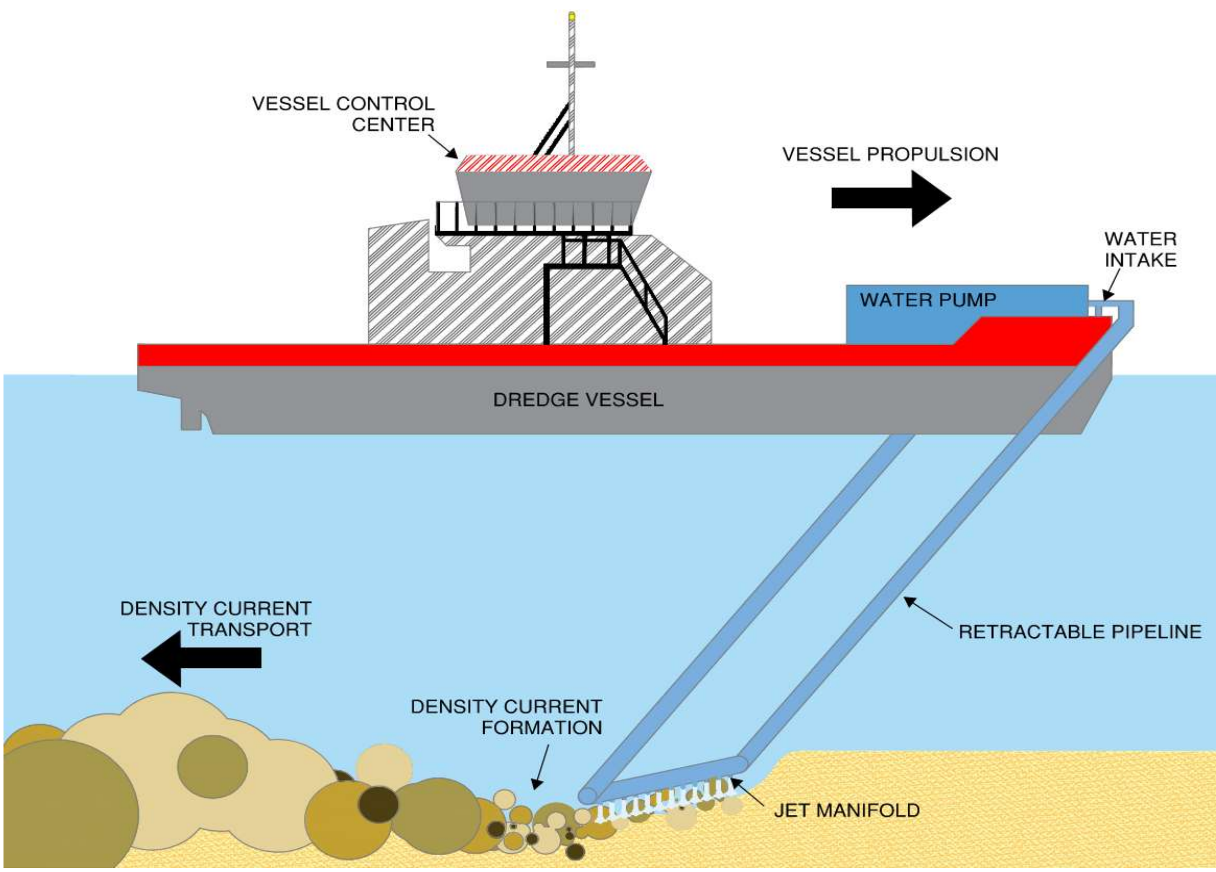


Figure 3. Components and Processes of a WID Vessel

Density Current Formation

The WID vessel is designed and operated to maximize disaggregation, hydraulic lift, and entrainment of bed sediments. Disaggregation occurs when the jetting force exceeds the bed sediment's cohesive shear strength. Alternatively, when the bed sediments are composed of non-cohesive material, disaggregation is achieved when the jetting force exceeds the material's internal friction resistance. The jetting action fluidizes the bed, reduces its solids concentration, and lifts the material into the lower water column.

The result of disaggregation and suspension by the jets is a turbulent slurry entrained by a portion of the water column as it transitions from a supercritical to a subcritical flow. Monitored WID operations have observed an initial density current thickness of 2 ft. (0.61 m) (Knox et al. 1994), 2.2 ft. (0.70 m) (Borst 1994) and 10.8 ft. (3.3 m) (Maushake and Collins 2002).

Density Current Transport

Various factors influence the distance over which a density current will transport sediment, including bed slope, relative densities of the current and the water column, bed roughness, sediment settling velocity and ambient flow conditions. Critically, the type of sediment being dredged affects the propagation of density currents. Silts and clays with low settling velocities will produce density currents that travel farther than sand-sized materials with higher settling velocities. Density currents can propagate down bed slopes as shallow as 1H:1000V (Wilson 2007; Borst 1994). The hydraulic pressure difference between the denser density current and the adjacent water will also drive flow away from the dredging location and in the waterbody's downslope or less dense direction. Bed roughness also influences density current transport, and it can be expected that a rough and morphologically complex bed will hinder transport while a smooth and featureless bed will not. Depending on their magnitude, especially near the bottom, ambient environmental conditions such as tidal and river currents may be primary or secondary transport mechanisms.

Density Current Deposition

Where and when the density current ultimately deposits is determined by the local environmental circumstances, chiefly flow-regime (Welp et al. 2017). Tidal and non-tidal estuarine and riverine flow regimes are typical WID operational areas, but flood control reservoirs are also being investigated and may benefit from WID operations. The density current will disperse and deposit cohesive and non-cohesive sediments in riverine flow regimes with measurable unidirectional near-bottom flow velocities. In tidally dominated flow regimes with the bi-directional flow, cohesive material will preferentially deposit during low near-bottom velocities (high and low tidal peaks). In flood control reservoirs density current dynamics and deposition are influenced by dredging production rate, settling velocity, slope, and the flow-regime.

Sediment Feasibility

Not all sediments are amenable to disaggregation, hydraulic lift, fluidization and thus use of a WID. Determining the applicability of WID to site-specific sediments creates both a logistical and economic problem. In Europe, the feasibility of WID for a given project area is commonly determined by measuring production during a full-scale model. However, this may be cost-prohibitive in the US, given the limited number of commercially available WID plants. Lab-based testing has been deployed to evaluate the response of a range of sediments to fluidization by a water jet simulating a WID. Laboratory testing with this WID simulating device has identified relationships between sediment physical properties and potential for fluidization which can be used to screen sediments as to the likelihood of practical WID application. Additional laboratory testing and field tests of different sediments can provide additional data to refine the screening recommendations.

Sediments that are more liquid (higher water content) and less plastic (sticky) are expected to be more readily diluted or fluidized. Thus, fluidization potential is hypothesized to be a function of liquidity index (LI), which derives from both water content (w) and plasticity:

$$\mathrm{LI} = \frac{(\mathrm{W}-\mathrm{PL})}{\mathrm{PI}} \tag{1}$$

where PL is the Atterberg plastic limit, and PI is the plasticity index.

During testing, sediments with a lower LI tended to merely scour, removing small amounts of sediment, as opposed to sediments with a higher LI, which appeared to fluidize the sediment, causing it to swell and flow as a dense liquid. The minimum LI at which fluidization behavior was noted for each sediment tended to be between 1.4 and 2.0. The amount of sediment removed from the container during testing increased linearly with LI. Based on the fluidization thresholds tested, screening criteria were developed in which sediments with LI between 1.7 and 2.3 would be considered marginally suitable for WID; sediments with LI of 2.3 – 2.9 would likely be suitable; and sediments with LI above 2.9 would be highly suitable for WID.

NORTH CAROLINA STATE PORTS AUTHORITY CASE STUDY

Active Port Facilities and Federal Channels

The federal channel from the Atlantic Ocean to the Port of Wilmington has been expanded incrementally for more than 100 years (NCSPA 2020). To keep pace with navigation demands and open new opportunities, the NCSPA, the non-federal sponsor, and USACE Wilmington District (USACE-SAW) seek to enhance the navigational channel to allow deep-draft vessels to navigate to the Port efficiently. The second NCSPA port is located at Morehead City in Carteret County. The Port of Morehead City is roughly 105 nautical miles from the Port of Wilmington (Figure 4).

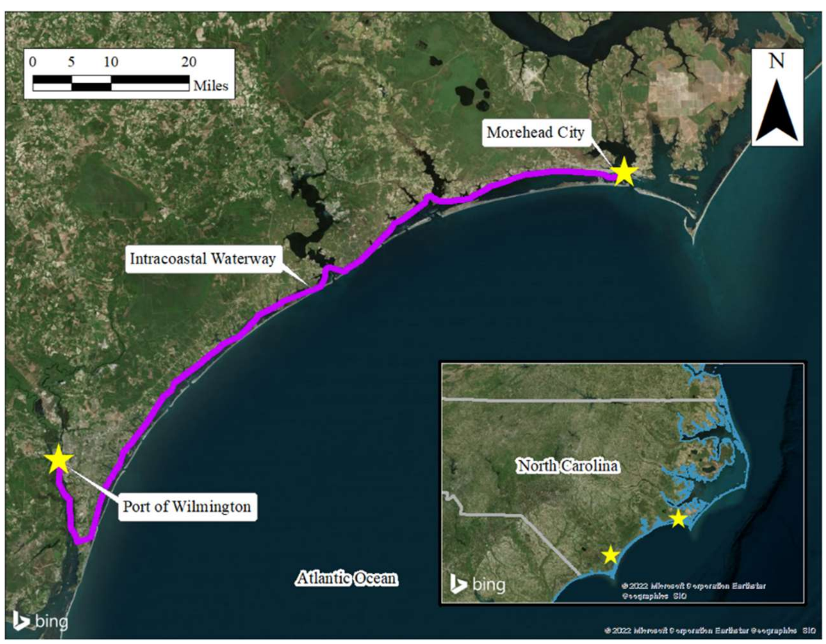


Figure 4. Location of Port of Morehead City with respect to the Port of Wilmington

The Eagle Island confined disposal facility (CDF) historically receives silty material (non-beach quality sediments) from the Wilmington Harbor federal navigation channel upper reaches and port berths. An annual maintenance dredging volume of ~1,250,000 CY/year is generally referenced for this area (NCSPA 2020 and USACE 2007). Giese et al. (1985) calculated that the annual rate of sediment removal outside the upper reaches of the federal navigation project and port berths was ~2,238,000 CY/year (beach quality sands). The resulting total project dredging is ~3,488,000 CY/year. If the Wilmington Harbor deepening plan were to be authorized, the constructed maintenance dredging requirements would be expected to increase by 9.4%

Like Wilmington Harbor, Morehead City Harbor can be segregated into two areas – shoal with beach quality sand and predominantly shoal with non-beach quality sediments (silt and clay). The areas of the federal navigation channel closest to Beaufort Inlet tend to shoal with beach quality material, while the NCSPA Port facility berths and the most seaward reaches of the federal navigation channel tend to shoal with non-beach compatible material (Benedetti et al. 2006 and Bales et al. 2000).

In summary, the widening and slowing of the Cape Fear River in the proximity of the Port of Wilmington results in the need to annually remove ~1,250,000 CY of material from the anchorage/turning basin and adjacent reaches near the Port of Wilmington. Future deepening of the federal navigation channel and the Port's berths is anticipated to increase to ~1,375,000 CY/year. Annually, there is a need to remove ~286,000 CY of material from the anchorage/turning basin and adjacent reaches near the Port of Morehead City inner harbor.

Problem Formulation

The NCSPA seeks to maintain the authorized depths at all berths, channels and turning basins at each port facility year-round. The NCSPA has had to allocate a greater portion of its operating cost to maintaining existing channel and harbor depths through traditional dredging, which has meant removing sediments and debris from their channels and berths by hydraulic or mechanical means.

In the fall of 2016, NCSPA staff contracted a port and maritime consultant to investigate if a better, more efficient process may exist that would allow NCSPA to accomplish the mission of keeping the NCSPA berths, channels and waterways open for commercial navigation, while avoiding creating a new CDF.

Permitting

Soon after the start of preliminary dredging efficiencies discussions, NCSPA staff began modifying the NCSPA's existing regulatory permits to include the use of a WID, although no active WID was operating in the US at the time. Seeking permits for this innovative technology was justified (driven) by the NCSPA's initial review of the possibilities to increase dredging efficiencies, use of modified dredging technology, better planning of dredging projects, use of alternative contractual methods, and NCSPA dredge ownership.

Sediment handling and final disposal are crucial issues associated with permitting and operational constraints. Thus, when it was decided that NCSPA using a WID provided the fastest, most efficient, lowest cost alternative with the most flexibility, the next logical step was to identify the permitting requirements and seek permits for the use of the WID. The permits for using the WID maintained the same general and specific conditions as required for other dredging methods. This included coordination with the National Marine Fisheries Service (NMFS) to address dredging operations during sturgeon and anadromous fish "work windows." Further coordination with NMFS prohibited dredging within the Port of Wilmington and Morehead City from February 01 to July 31 (NCDEQ-CRC 2018a and NCDEQ-CRC. 2018b).

The approved work window is limited to October 01 through January 31. New general and specific conditions were also stipulated at both sites, including the following:

- WID is only to be conducted during outgoing/falling tides. Furthermore, utilizing spring high tides to maximize the velocity of water movement during operations is "encouraged"

- An identified Navigation Point of Contact (POC) must be given seven days "advance notice" of a "planned maintenance dredging event" using WID

- Federal navigation channel hydrographic surveys must be performed no more than 15 days before and within 7 days of completing the WID, at approximately 2,000 feet downstream and 1,000 feet upstream of the point where dredging occurred and covering the entire width of the federal navigation channel

- At the discretion of the USACE District Engineer, any accumulated sediment in the federal channel caused by the WID activities must be removed by NCSPA, if the accumulated sediments are determined to interfere with navigation

Qualitative Opinion of Probable Program Costs

This section discusses capital, fixed, and variable costs that maritime clients would likely incur with purchasing a dredge and associated supporting equipment (e.g., tenders, pipelines, booster pumps, vehicles).

NCSPA initially anticipated using the WID dredging method to supplement the annual dredging performed by the USACE. At the onset of planning, it was anticipated to be used between 10 to 15 times annually during the prescribed environmental dredging windows for both port facilities. The frequency of use and depth of cut would be based on several factors; the values provided are intended only for discussion purposes.

The capital costs associated with purchasing a dredge and dredging equipment vary significantly depending on the type and size of the dredge. The dredge would need to comply with the 1920 Merchant Marine Act (Jones Act), the Foreign Dredge Act of 1906, and the Shipping Act of 1916. NCSPA could have considered purchasing a used dredge. That was not possible in this case. Therefore, the port decided to go with the design-build option - the first WID of its kind in the US.

Fixed costs are incurred over the life cycle of a dredge, regardless of whether the dredge is operating. These costs include but are not limited to:

- Annual dry docking, regular painting to prevent corrosion due to saline environment, pump overhauls, and servicing electric and hydraulic systems

- Dedicated dockage to store and maintain the dredge and supporting equipment

- Depreciation - the reduction of the value of the dredge over time due to wear and tear

- Inspections and certifications - the dredge requires certification and inspection by a qualified person periodically to ensure the dredge conforms with all applicable regulations

- Permanent staff is required due to the size and type of dredge. A full-time crew is required because the crew needs to be familiar with the dredge operation and supervise temporary staff during project operations.

The WID purchased by NCSPA (WID-Osprey) only required two regular crew members and a group of temporary staff that also perform other maintenance duties for NCSPA when not using the WID-Osprey. This dual use of the personnel significantly reduces the overall cost for NCSPA.

Variable costs are also incurred with the dredge's operation on a project-by-project basis. These costs can include, but are not limited to:

- Mobilization/Demobilization - costs to transfer the dredge and supporting equipment from the storage location to the dredge location

- Fuel - fuel consumption is directly proportional to the installed horsepower of the dredge and the number of production hours.

- Oils/lubricants/grease required due to the mechanical nature of the equipment

- Crew costs such as overtime, per diem and travel costs, as applicable

- For hydraulic dredges, there are significant pipeline and booster pump costs. These costs are based on the distance the material must be transported from the cut to the disposal location.

- Mechanical and Hydraulic dredges typically require reciprocal earthmoving equipment for reworking material placed in upland disposal areas

- As regulatory agencies require, environmental monitoring could comprise sea turtle, bird and turbidity monitoring.

Because a WID only needs fuel for propulsion, the water pump, and the winch to power the jet bar, a WID uses significantly less fuel than a typical mechanical or hydraulic dredge operating in similar depths. In addition to not requiring significant pipeline and booster pump costs or transporting and offloading multiple barges, scows, or hoppers, the WID-Osprey does not require energy to fuel offloading dredged material at a disposal area.

A considerable proportion of these costs are time-based unit costs. To make a well-informed decision about dredge ownership, a thorough quantitative economic analysis that considers the total costs of acquisition, operation, and maintenance and an estimated production rate (CY/day) should be directly compared to previous NCSPA jobs to determine if cost savings could be achieved. To date, this detailed analysis has not been provided publicly. However, the consultant's Qualitative Opinion of Probable Program Costs memorandum to the NCSPA estimated that the proposed design-build WID could save the NCSPA annually in the order of $750,000 to $1,000,000 in dredging, handling, and disposal costs.

Few published studies exist on the biogenic, geomorphic, or physiochemical impacts of WID. Pledger et al. (2020) noted that WID is an effective sediment removal technique, although the geomorphic effects of the method can be short-lived, meaning a higher occurrence of dredging may be necessary to maintain channel geometries. The Pledger et al. (2020) study also indicates that the WID method didn't measurably change bed sediment grain-size distributions, and the effects of WID relative to the tide on some water physicochemistry parameters were negligible. However, the environmental impacts may be more significant in other less naturally turbid tidal waters. Notably, the paper indicates a need to better understand the ecological effects of WID across various environmental conditions and management legacies.

Project Approach

After completing the Qualitative Opinion of Probable Program Costs memorandum, the NCSPA engaged a port and maritime consultant to provide WID purchase services for NCSPA's Ports at Morehead City and Wilmington. As part of the consultant's responsibilities, they solicited dredge manufacturers, marine contractors, and naval engineers regarding the NCSPA procurement of a WID. The consultant provided a summary of relevant working conditions and the preliminary schedule for purchasing the WID dredge. Out of the nearly 35 solicited, the 11 responding dredge manufacturers had vast experience with design, manufacturing, and testing industrial dredge vessels on the east coast of the US and were viewed as industry leaders.

The NCSPA was open to purchasing a standardized model WID if the vessel and its appurtenances met the specific needs of the facilities served by the NCSPA. However, because of the limited US WID market, only a custom-built vessel constructed in a US shipyard fully satisfied NCSPA's dredging needs for both ports. As such, NSPA's final selection of the dredge designer/manufacturer was based on a weighted scale (matrix) that considered technical criteria, utility, and economy.

General Research and Dredge Manufacturer Outreach

The WID system was intended to consist of a barge-mounted dredge that would be mobilized and positioned by a tug or a self-contained system with its own propulsion system. The NCSPA required that the purchased WID could be moored or dry-docked at the Port of Wilmington and transported via rail, roadway or the Atlantic Intracoastal Waterway Association (AIWA) to the Port of Morehead City, as needed.

Request for Information & Geotechnical Data Collection

During the bidding process, the NCSPA received requests for information (RFIs) for more detailed in-situ sediment characterization data for the Port of Wilmington and the Port of Morehead City in order to design/build a single WID that could function effectively in both port environments. Providing these characteristics to the dredge manufacturer was critical in value engineering the dredging machinery to provide the performance-based results required in the bid package. Although the in-situ strength characteristics of the accumulated sediment had not been investigated in either port, anticipated characteristics were developed based on background information from past geotechnical investigations at both port facilities, the consultant's knowledge of hydrogeology, USACE dredging information from previous events and other provided information. It was anticipated that the accumulated sediment at the Port of Wilmington facility would consist primarily of fine-grained sediment. Accumulated sediment in the Port of Morehead City was anticipated to consist primarily of fine-grained sediment with some coarse-grained sediment mixed in. To better define the characteristics and respond to the RFIs, testing was completed by NSCPA.

Contracting Summary

The NCSPA conducted a pre-dredging bathymetric survey of the proposed demonstration area before the first proof of concept trial at the Port of Wilmington.
During the seven-day trial period, the consultant's representative was available to monitor the dredging process, document deficiencies or issues, and report findings to the NCSPA. Following the trial period, the NCSPA conducted a post-dredging bathymetric survey, and the consultant evaluated the location and amount of material removed from the demonstration area.

The proof-of-concept trial also included successfully shipping the dredge from the Port of Wilmington to Port Morehead City, where a second seven-day trial occurred. During the trial periods, the dredge manufacturer's responsibility was to train the NCSPA staff in all technical aspects of the equipment, maintenance schedules, mobilizing and demobilizing between port facilities, and storage of the vessel when not in use. Following the roughly one-month-long demonstration and training period, the NCSPA, the consultant, and the dredge manufacturer met to determine if any additional fabrication or alterations were necessary before the NCSPA finalized the purchase of the dredge. That meeting resulted in minor changes to the propulsion systems, which were implemented to provide NCSPA operators with better control when working near bulkheads, piers, and other vertical infrastructure.

NCSPA WID-OSPREY MONITORING (WILMINGTON HARBOR)

The USACE Engineer Research and Development Center (USACE-ERDC) developed and executed a WID monitoring study during the January 2022 WID-Osprey operation at Wilmington Harbor in North Carolina (Tyler et al. 2022). The objectives of the monitoring study included:

1. An evaluation of the production rate of the WID-Osprey

2. Measurement of the hydrodynamic forces generated by the WID-Osprey when operating near harbor structures and moored vessels.

3. Quantifying density current formation, transport, and deposition includes a material balance between the dredging site and deposition site(s) within the navigation channel.

Sediment Feasibility

A WID sediment testing apparatus was developed to simulate the low-pressure, high-velocity jet generated by a WID injection port. The apparatus consists of a jet nozzle connected to a water source with a manifold and pressure regulator. During testing, the jet nozzle is positioned near the surface of a sediment sample in a 1-gallon container fully submerged within a larger tank. The jet operates at 15 psi, with a 1.0 GPM flow rate and jet velocity of 47 fps for 1 minute, potentially fluidizing some, or all, of the sediment. Post testing, the fluidized mass and volume of fluidized sediment fractions are measured. This procedure was conducted for various sediments over a range of water contents, including samples from Wilmington Harbor and Morehead City, NC.

Fluidization tests were performed on two sediment samples from Wilmington Harbor and another from Morehead City at their in-situ water contents. The Wilmington Harbor samples had LI values of 2.09 and 2.53 which would be considered marginally and likely favorable for fluidization, respectively; whereas the Morehead City sample had a LI of 1.14, which was below the typical threshold liquidity for fluidization. The fluidization tests demonstrated that 77 – 83% of the Wilmington Harbor sediments were fluidized and removed during testing, and approximately 20% removed the Morehead City sediments.

Monitoring Instrumentation

A comprehensive approach concerning instrumentation was used in selecting monitoring instrumentation due to the dynamic nature of density current formation, transport, and deposition.

Table 1 summarizes which instrument was used to accomplish the stated objectives of the monitoring study.

Table 1. Summary of Instrumentation Used in Monitoring Study

Instrument	Parameter(s)	Objective(s)
Multibeam and variable-frequency echosounder	Elevation (at variable frequencies), surface and water column backscatter.	1,2,3
Acoustic Doppler Current Profiler (ADCP) – 300 & 600kHz	Current velocity, water column backscatter, turbulence	2,3
Water Quality Sondes	Temperature, Conductivity, Turbidity, Reduced Dissolved Oxygen,	3
Density Meter	Density, Temperature, Yield Strength, Viscosity, Dry Solids	3
Water Depth Sampler	In-situ Density, Total Suspended Solids, Total Dissolved Solids	3
Surficial Sediment Sampler	Grain size distribution, Total Organic Content, Atterberg Limits	1,2,3

Monitoring Scheme

A monitoring scheme was developed for this study using various previously collected data, desktop estimates, and numerical models concerning the fluidization, transport, and deposition of density currents.

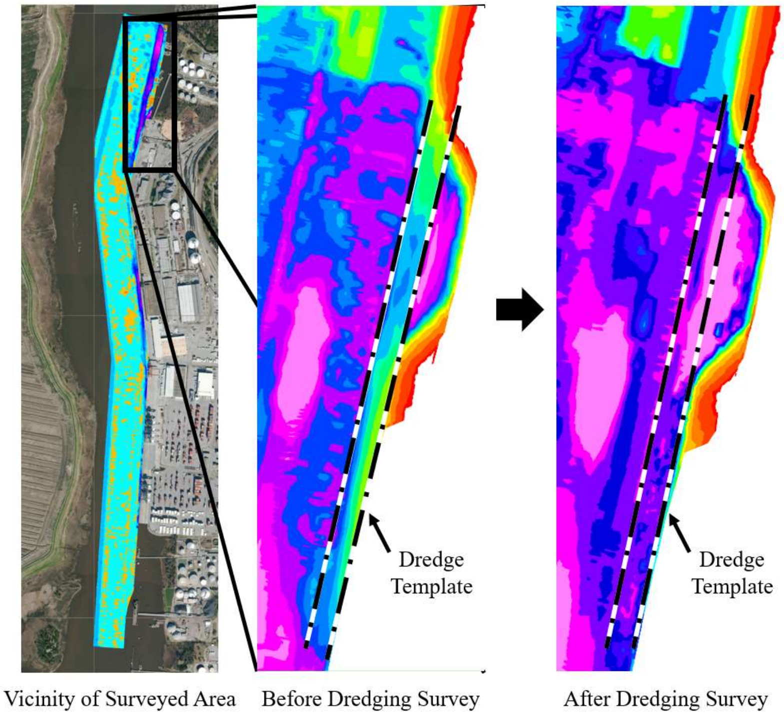
Table 2 provides those estimates of transport distances based on preliminary modeling. Additionally, the Corps Shoaling Analysis Tool (CSAT) and the USACE Hydrographic Surveys (eHydro) were queried to estimate shoaling rates and elevation.

Table 2. Estimates of Sediment Transportation from Preliminary Modeling

Model or Calculation	Model Variables	Transport Distance (ft.)
NOAA CFR Flow Model	Current velocity and direction at various depths	10,000 – 25,000
Displacement Calculation	Dredge material volume and density current concentration, an estimate of density current height, channel dimensions	10,000 – 15,000
Swart (2015) Model	Jet manifold parameters, sediment and water density, cohesion, viscosity, settling velocity, bed slope	In process

Survey Discussion

Before and after dredging surveys were completed by NCSPA on January 11 and January 27 (17 days later), respectively, covering the dredged berth area and approximately 12,000 feet of channel upriver and downriver to measure possible accretion or erosion related to the WID-Osprey operations. USACE-ERDC also completed hydrographic surveys on January 19 and 26 (Tyler et al. 2022). The former used a 33kHz single beam echosounder, while the latter used a multibeam echosounder set to 450 kHz. The complete surveyed area and the before and after 33kHz surveys of the study area are shown in sequence in Figure 5, edited with a dotted line to indicate the bounds of the dredge template. Before WID-Osprey operations, the



BATHYMETRY ELEVATION TABLE		
MIN. ELEVATION (ft)	MAX. ELEVATION (ft)	COLOR
-50.0	-46.0	
-46.0	-45.0	
-45.0	-44.0	
-44.0	-43.0	
-43.0	-42.0	
-42.0	-41.0	
-41.0	-40.0	
-40.0	-39.0	
-39.0	-37.0	
-37.0	-35.0	
-35.0	-33.0	
-33.0	-29.0	
-29.0	-22.0	
-22.0	-15.0	
-15.0	-5.0	
-5.0	-3.0	

Figure 5. Before- and After-Dredging Surveys of the Berth Area

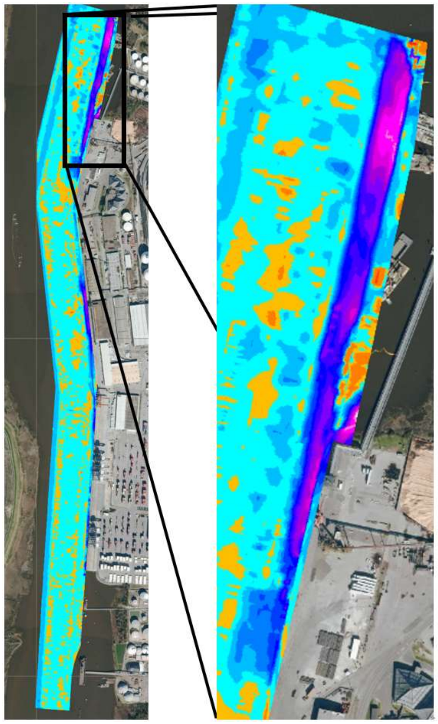
average depths within the berth area ranged between -35 ft MLLW to -42 MLLW. After 29 hours of dredging, after-dredge surveys reveal that the dredged area had not filled back in with accreted material and remained at depths between -44 MLLW to -50 MLLW. A review of the NCSPA surveys indicated that approximately 71,000 CY (54,283 m^3) of material was removed from the dredged berth area.

WID-Osprey Production Rate Results

The first objective of the monitoring study was to estimate the WID-Osprey production rate. The production rate was determined by calculating the volume difference between the before- and after-dredging surveys and dividing the removed volume by the total hours of dredging. The dredge operated for approximately 29 hours, resulting in a production rate of roughly 2,450 CY/h (1,872 m^3/h) from the NCSPA data set. The net difference between before- and after-dredging surveys, which illustrates the amount of material removed or accreted in feet, is depicted in Figure 6 for the entire surveyed area and a close-up of the dredged berth area. The color-coating scheme utilized in Figure 6 organizes the different magnitudes of net material removal or accretion in intervals. Within the berth area, the pink to blue color-coated pixels shows where dredging removed approximately 5 - 10 ft of material. Along the southern side of the berth area, less material was removed during dredging, approximately 2 to 5 ft, as initial bathymetry was deeper. Outside of the berth area, net changes in the surveyed area fluctuate between low amounts of material loss and material accretion, with most areas ranging between -1 ft to +1 ft of material change. This will be further discussed in the section covering material deposition.

Hydrodynamic Forces Generated by the WID-Osprey

The second objective was to measure the WID-Osprey hydrodynamic forces near harbor structures and moored vessels. Two proximity and berth parallel ADCP transects were collected while the WID-Osprey dredged alongside the berths between moored vessels. Figure 7 shows the velocity plots for both transects; for the left plot, the ADCP vessel was outboard of the WID-Osprey, which was very near the berth, while



NET DIFFERENCE ELEVATION TABLE		
MIN. ELEV. (ft)	MAX. ELEV. (ft)	COLOR
-12.0	-11.0	
-11.0	-10.0	
-10.0	-9.0	
-9.0	-8.0	
-8.0	-7.0	
-7.0	-6.0	
-6.0	-5.0	
-5.0	-4.0	
-4.0	-3.0	
-3.0	-2.0	
-2.0	-1.0	
-1.0	0.0	
0.0	1.0	
1.0	5.0	
5.0	10.0	
10.0	20.0	

Figure 6. Net Differences of Before- and After-Dredging Surveys

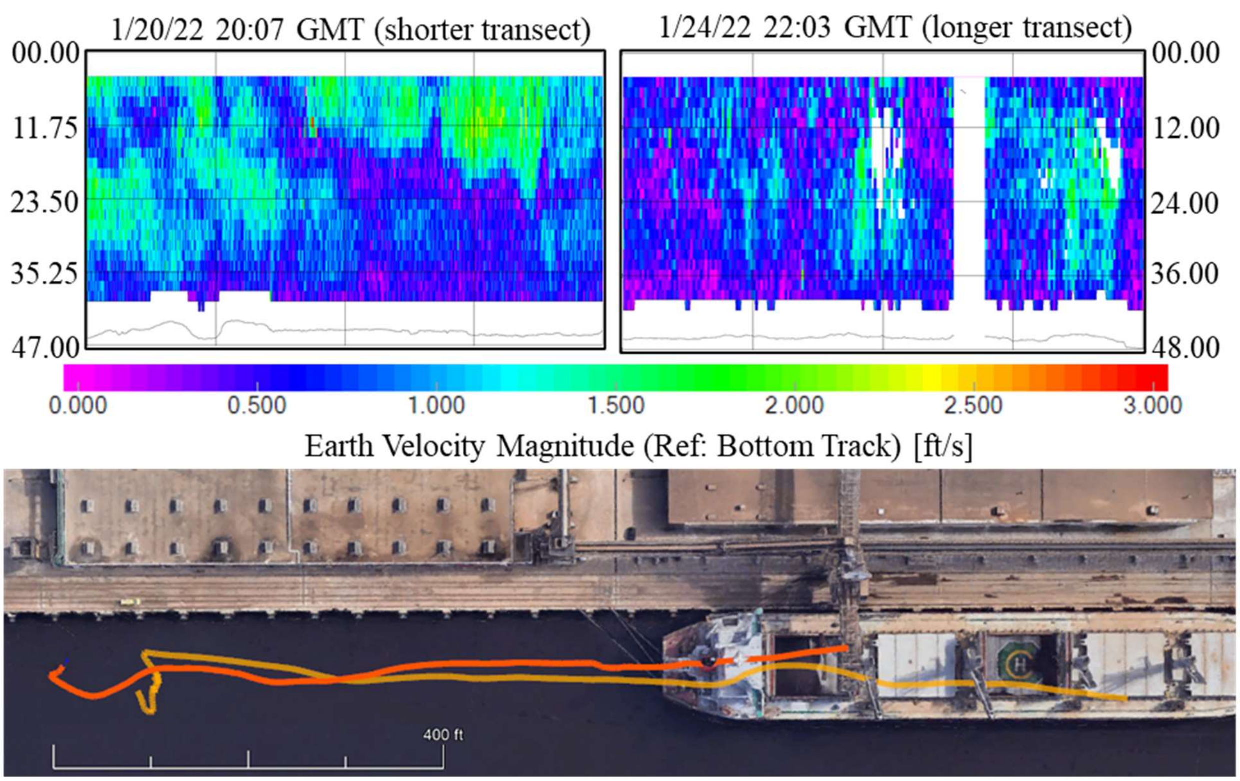


Figure 7. ADCP velocity transects were measured near berths & moored vessels.

for the right plot, the ADCP vessel was between the WID-Osprey and the berth. The transects were collected four days apart, and the WID-Osprey had dredged roughly 1 ft (0.3 m) of additional material in that time. The WID-Osprey induced flow was measured at a maximum of -2.4 ft/s (-0.73 m/s) on the 1/20 transect and -2.2 ft/s (-0.67 m/s) on 1/24. The predicted current velocity at nearby CFR:1610 at 39 ft (12 m) depth was -1.4 ft/s (-0.43 m/s) and -1.1 ft/s (-0.34 m/s) respectively. The measured current direction was about 155°(T), and the CFR:1610 model indicated an ebbing current direction of 147°(T) (Tyler et al. 2022).

Density Current Formation, Transport, and Deposition Results

The third objective of the monitoring study was to analyze if deposition of dredged material occurred within the study area. The volume of the material removed from the permitted dredging area was approximately 71,000 CY (54,283 m^3), as determined from the 33 kHz survey. As mentioned in the previous section on dredge production rates, areas of material removal and accretion outside the dredged berth area can be observed in Figure 6. The different magnitudes of change in channel depths are represented by percentages in Table 3, in which the total area covered by each color-coated interval was compared to the total surveyed area. Within the total surveyed area, not pertaining to the dredged berths, the changes in channel depth are predominately between -3.0 ft to 0.0 ft of removal, making up approximately 78% of the change in the material after dredging and about 17% of 0.0 ft to +1.0 of accretion. These changes in channel depth outside the dredged area are inconclusive in evaluating if and where WID-Osprey dredged material may have been deposited within the survey range. Natural phenomena (i.e., storms, high water levels upriver of the project area, and normal riverine sediment transportation), as well as protentional scouring caused by boat operations that occurred within the study area prior to surveying, could have affected these results.

Table 3. Percent of dredged area relative to the amount of removed material

Change in Depth from WID-Osprey Dredging		Percent of Change in Channel Depth Within Survey area
Lower Range (ft)	Upper Range (ft)	
-12.0	-11.0	0.0%
-11.0	-10.0	0.0%
-10.0	-9.0	0.2%
-9.0	-8.0	0.3%
-8.0	-7.0	0.5%
-7.0	-6.0	0.8%
-6.0	-5.0	1.0%
-5.0	-4.0	0.9%
-4.0	-3.0	1.1%
-3.0	-2.0	2.1%
-2.0	-1.0	14.2%
-1.0	0.0	61.7%
0.0	1.0	16.9%
1.0	5.0	0.4%
5.0	10.0	0.0%
10.0	20.0	0.0%

CONCLUSION

Maritime authorities are continually confronted with the siltation of their waterways, and sediment handling and disposal are crucial issues with associated permitting and operational constraints. WID is an innovative hydrodynamic dredging technique that is cost-effective, low-impact and environmentally sound. The WID injects large volumes of water at low pressure into the sediment layer, and the resulting fluidized sediment is then carried horizontally along the waterway as a density current. Natural forces (currents, tides, gravity, etc.) facilitate sediment transport, making WID a low-impact dredging technique. Since a WID is highly maneuverable and does not excavate sediment like traditional dredges, there is no need to obtain disposal facilities or transport material, creating cost savings. A WID can operate in places other equipment cannot safely reach, for instance, near jetties and beneath moored vessels.

The first objective of the USACE-ERDC monitoring study at the Port of Wilmington was to estimate the WID-Osprey production rate, which was determined to be approximately 2,450 CY/h (1,873 m^3/h) within the dredged berth area.

The second objective was to measure the WID-Osprey hydrodynamic forces near harbor structures and moored vessels. The WID-Osprey did not induce excessive flows in either vicinity.

The third objective was to analyze if deposition of dredged material occurred within the study area. The volume of the material removed from the permitted dredging area was approximately 71,000 CY (54,283 m^3), as determined from the 33 kHz survey. The changes in channel depth outside the dredged area are inconclusive in evaluating if and where dredged material may have been deposited within the survey range. Natural phenomena (i.e., storms, high water levels upriver of the project area, and regular riverine sediment transportation), as well as protentional scouring caused by boat operations that occurred within the study area prior to post-dredging surveying, could have affected these results. However, no notable accumulation of sediments was located within the over two miles of waterway upriver/downriver of the project area.

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CAPSULE PIPELINE TECHNOLOGY FOR DE-SILTING WATER RESERVOIRS

B E. Abulnaga [1]

ABSTRACT

The accumulation of sediments in water reservoirs over the last few decades has exceeded 7000 billion cubic meters on a world scale. Many deltas form at long distance upstream the dam. The de-silting of the reservoirs using conventional dredging pipeline is costly. The hydraulic capsule pipeline was initially developed for mining applications, but once adopted to the dredging industry offers opportunities to transport dredged sediments with very important reduction of volumes of water a, reduced abrasion and reduced power consumption. A dedicated capsule launching system is under development and tested in laboratory environment. The invention is based on the principle of the eductor combined with a rotary capsule feeder.

Keywords: Dredging, hydraulic capsule pipeline, slurry transport, reduction of water for transport, sediments.capsule launcher, pressure losses

INTRODUCTION

The recent passage of the 21st Century Dam Safety Act illustrates the importance of de-silting reservoirs in the United States. Sediments accumulation in reservoirs diminishes water storage capacity, capability to produce hydropower, but could also be a very beneficial source of topsoil in arid climates once removed from the reservoirs.

The conventional slurry pipeline associated with dredging transports solids at low concentration ranging from 5% for very coarse gravel and balls of clays up to 15% with very fine solids, .The volume ratio of water to sediments is often in the range of 5:1 to 6:1, This means that a considerable portion of the power is consumed to transport water.

Encapsulating the sediments in capsules at 80 to 90% of the pipe inner diameter reduces the resistance compared to a sliding bed. At a specific velocity called lift-off velocity, pressure is minimized if the bulk density of the capsule

One fundamental hinderance to the commercialization of the hydraulic capsule pipeline in the past has been the very cumbersome feeding and launching system developed for logs of coal. This system required locks for trains, with opening and closing valves, feed and recirculating pumps. Our team has therefore developed a much simpler system based on the application of the concept of the venturi to a rotary feed. This allows to feed capsules continuously from a conveyor at atmospheric pressure into a pipeline at water pressure.

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DE-SILTING RESERVOIRS WITH LONG DISTANCE TRANSPORT OF SEDIMENTS

According to the U.S. Army Corps of Engineers, the United States has 92,065 dams.(USACE 2022) Of those dams, 15,500 “could cause fatalities if they failed. Of the total dams, 6% are Federally regulated while 70% are State-regulated

WEDA (2021) listed a number of reservoir de-silting projects completed in the last 15 years, with long transport distances, using large cutter suction dredgers (CSD) (>500 mm (20 inch)) such as

- San Jacinto Reservoir, Texas, dredging 2,420,000 yd^3 (1.8 $x10^6$ m^3),(sand and debris) up transported to 50,000ft (15.3 km)
- John Redmond, Kansas, 3,000,000 yd^3,(2,3 $x10^6$ m^3) sediments, transported >30,000 ft (9.2 km)
- Lake Decatur 2nd Phase, Illinois, 10,770,000 yd^3,(8,1 $x10^6$ m^3), silts, clays, sands,>transported 45,000 ft (13.7 km)
- Lake Decatur 1stPhase, Illinois, 1,520,000 yd^3, (1.15x10^6 m^3), silts, clays, sands, transported >18,000 ft(5.5 km)
- Lake Worth, Texas, 1,4990,00 yd^3, (11,3x10^6 m^3), sand/clays/silt, >15,000 ft (4.6 km)
- Loiza (Caraizo), Puerto Rico, 7,800,000 yd^3 (5,9x10^6 m^3), transported up to 35,000 ft(10.7 km)

Medium CSD are considered between 14” and 20” (350 to 500 mm). A number of reservoir de-silting projects listed by WEDA (2021) involving medium CSD included
- Cedar Lake, Iowa, 1,065,000 yd^3 (0.8x10^6 m^3), sediments ,transported <10,000 ft (3 km)
-Lake Mauvaiterre, Illinois, 550,000 yd^3 (0.42x10^6 m^3), sediments ,transported <10,000 ft (3 km)
Strontia Springs, Colorado, 228,000 yd^3 (0.17x10^6 m^3), gravel-based sediments ,transported <10,000 ft (3 km) –

Common commercial dredger (Table 1) require 5 and 6,7 m^3/h of water to move 1 m^3/h of sediments .

Table 1 Performance of commercial cutter dredgers

source	https://www.dredginghoses.com				http://www.hiddredger.net/
model	CSD-8	CSD-10	CSD-12	CSD-14	CSD-18”
size	200 mm	250 mm	300mm	350 mm	450 mm
Water flow (m^3/h)	800 - 1200	1100-1300	1500 – 2000	3000-3500	3500 - 4000
Sediments (m^3/h)	150 -200	200-250	250 - 300	300 - 400	700 – 1000
Discharge distance (m)	800	1000	1200	1500	1500 - 2000
Suction pipe (mm)	250	300	350	400	450 mm
Discharge pipe (mm)	200	250	300	350	450 mm
Volume of water /volume of sediments	6 – 5.3	5.5 – 5.2	5 – 5.55	6.65 – 5.85	5 - 4
Maximum dredging depth (m)	10	12	12	13	13

In the conventional hydraulic dredging, the slurry is then passed through booster pumps in series or placed at specific intervals based on the friction losses and static head of the transport pipeline. In the dredging industry usually, there is no mechanism to increase volume concentration once the sediments enter the pipeline. Subsequent boosters pass the slurry at the same concentration,

Most dredging system try to operate at a pump head of 60 m on light duty, but the ability to transport solids declines as particle size increase due to increased friction in the discharge pipe.
The concept of hydraulic capsule pipelines was originally developed for moving logs pressed out of fine coal (Brown (1987)).When it first appeared in the 1970’s, particularly for research on transport of coal, no-one thought of an application for transport of dredged sediments. In fact, back in the 1970’s sedimentation of reservoirs was thought that it can be dealt by building extra-large reservoirs. Abulnaga (2018, 2021) proposed that the technology be applied to the transport of dredged sediments

THE HYDRAULIC CAPSULE PIPELINE FOR TRANSPORT OF DREDGED SEDIMENTS

There have been numerous academic papers published in the last 50 years on capsule pipelines. The only commercial installations came out of the Soviet Union (Russia) and Japan and have been limited to pneumatic capsule pipelines. Efforts to build hydraulic capsule pipelines were limited to coal logs, but this technology disappeared out of the demise of coal. We will therefore focus in our paper on the practical engineering aspects of transporting sediments in capsule pipelines. Certain simplifications of the proposed solution will be introduced for the sake of clarity.

The technology for long distance transport of dredged sediments, consists of dredging, followed by an intermediary dewatering in a settling pond. The pond is made of individual cells that are dewatered on a daily basis to leave layers of sediments that are excavated and used to fill capsules (Figure 1)The capsules are sent into a hydraulic capsule pipeline (Figure 2). Once the sediments are delivered, the empty capsules are returned with the water back to the source of dredging for re-filling.

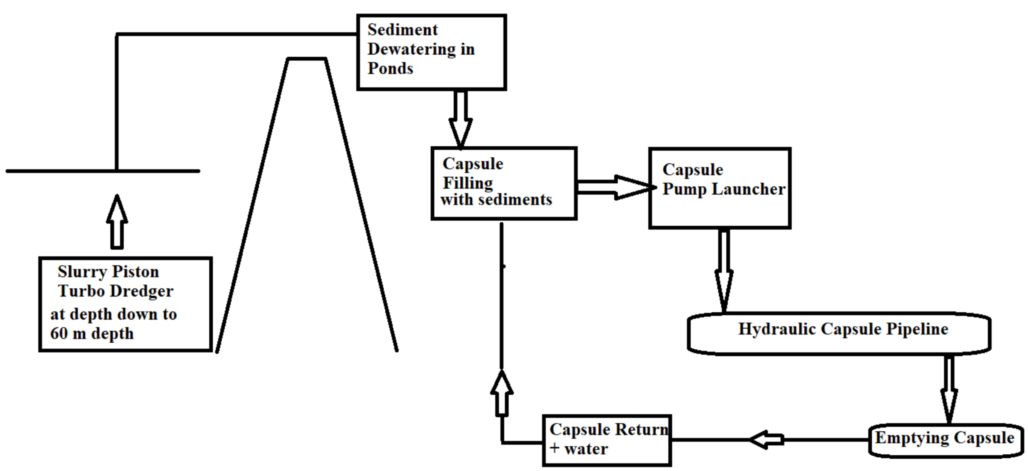

Figure 1. Concept of the hydraulic capsule pipeline for long distance transport of dredged sediments

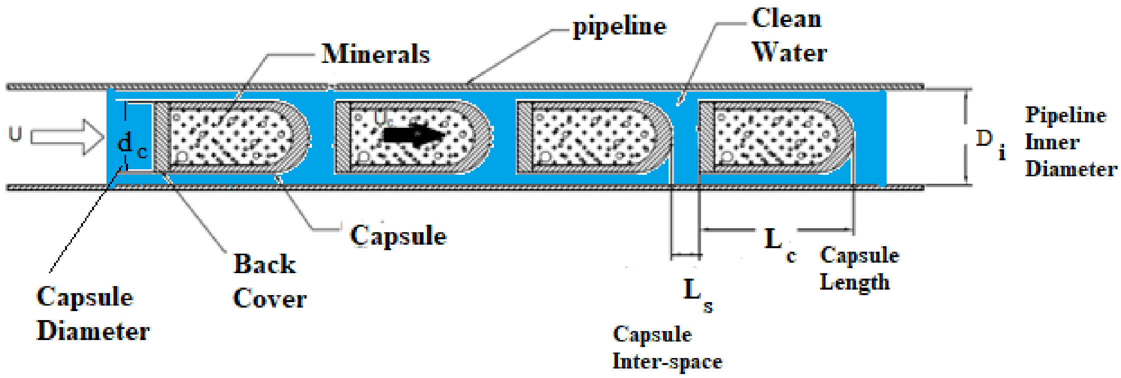

Figure 2. Concept of the hydraulic capsule pipeline for transport of sediments.

Capsules can be fabricated in aluminum or plastics (Figure 3) The plastic capsule is preferrable to reduce the weight and achieve a lower pressure loss. We are contemplating testing a flexible capsule made of thick rubber hose material that can deform when going through valves or bends.

Figure 3. (a) Left -aluminum capsule, (b) Right capsule made of PVC pipe with end caps acting as collars

The commercial capsule must be reliable. It must be manufactured out of a low-density material such as PVC, HDPE, urethane or rubber, The length to diameter ratio is important. A shorter capsule can go through bends. Experience with cleaning polypigs shows that a maximum length to diameter ratio of 2 is used to pass through valves and bends.

The capsule must be suitable for repeated filing at start of pipeline and repeated emptying at discharge. It must be capped or sealed during transport so that surrounding water does not penetrate its walls and mix with the sediments, so water can be preserved and recycled back to the reservoir.

There is currently no commercial capsule in the market for the hydraulic pipeline. Pneumatic pipeline capsules are filled horizontally from the top and are designed on the basis of rotating hopper for quick filling and emptying. This technology would need rotary seals and a hermetic cover to work in a hydraulic pipeline. This adds complexity to the design of the capsule, and we are exploring filling the capsule vertically from a vibrating hopper. It is therefore proposed in this paper that the capsules be manufactured out of HDPE pipe material with suitable caps and end plates.

According to Kruyer (1972) capsules with a bulk density of 750 to 1250 kg/m^3 initially develop a high resistance at zero velocity due to mechanical friction by sliding on the walls of the pipe. As the velocity is increased, pressure is reduced until the curve intersects with an equivalent water resistance curve near the Lift forces add to buoyancy forces to eliminate contact with the walls of the pipeline and mechanical friction. This point is called the low-pressure loss velocity (Figure 4) It depends on the ratio of the capsule diameter to the pipeline inner diameter (k), as well as the bulk density of the capsule.

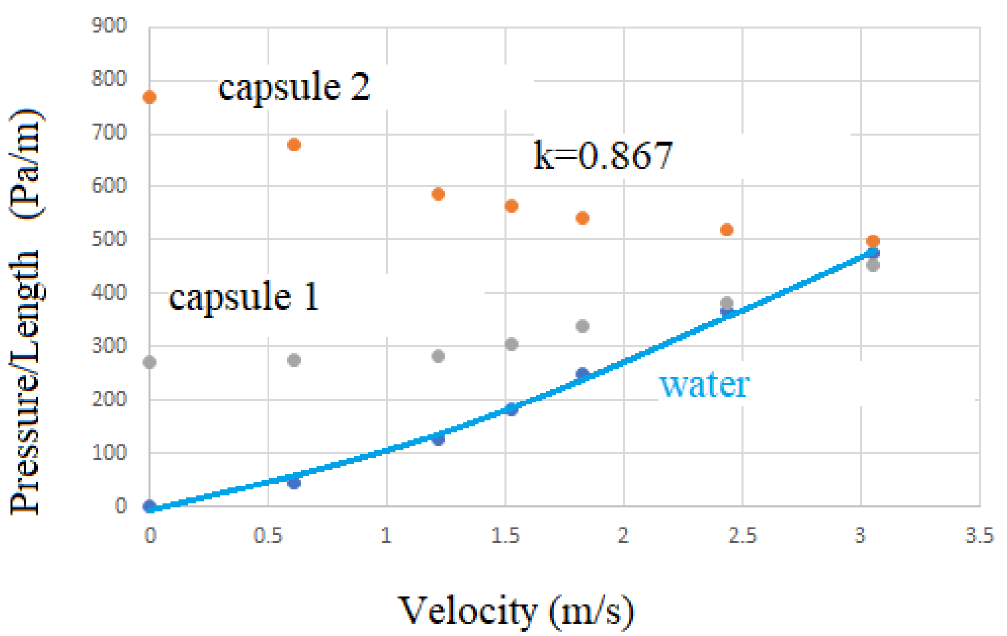

Figure 4. Pressure losses per unit length for capsules with diameter ratio of 0.867. capsule 1 has a density of 1250 kg/m^3, while capsule 2 has a density of 1125 kg/m^3. They start with a high pressure at zero velocity but drop to a value equal to water at a value called the low-pressure velocity around 3 m/s – After Kruyer (1972) for tests in a 4" (100 mm NB) pipe with capsules 24.5 inch (622 mm) long

The bulk density of dry sand used in the concrete industry is between 1520 and 1680 kg/m^3. Wet sand can however a bulk density of 2000 kg/m^3. Laba et al (1963) reported on many cases when the bulk density of sediments is below 1500 kg/m^3.

We have therefore conducted calculations for a family of sizes of capsules made of HDPE DR 7 pipe material. in steel pipes The capsules are usually one diameter smaller than the steel pipe. For example, a 20" steel pipe would correspond to 18" DR 7 capsules. Calculations for capsules fabricated out of HDPE pipe DR7 full of sediments with bulk density of 2000 kg/m^3, result in capsules with bulk density between 1250 and 1400 kg/m^3 (Figure 5).

At a particular water velocity called the lift-off velocity. The capsules are totally water-born. The capsules are then slightly inclined at the front, by analogy with an airplane taking off from ground. The lift-off velocity for a plain cylindrical capsule is calculated using an empirical equation derived by Liu (2003)

$$V_{Lf} = 7.2\sqrt{\left(\frac{\rho_{bc}-\rho_w}{\rho_w}\right)gak(1-k^2)D_i} \qquad (1)$$

V_{Lf} = Lift off velocity (ft/s)
ρ_c = bulk density of capsule (kg/m^3)
ρ_w= bulk density of carrier liquid (water) (kg/m^3)
g = acceleration due to gravity 9.81 m/s^2
a = length to diameter ratio of capsule (non dimensional)
k = ratio of outer diameter of capsule to inner diameter of pipeline (non-dimensional)
D_{if} = pipeline inner diameter (m)

$$a = \frac{L_c}{D_c} \tag{2}$$

And $k = \frac{D_c}{D_i}$ (3)

Where

L_c = length of capsule capsule (m)

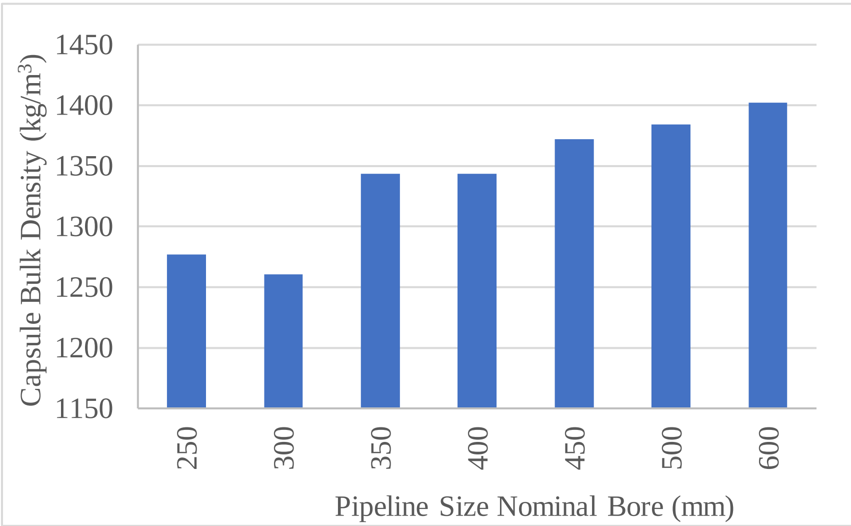

Figure 5. Bulk Density of capsules fabricated from HDPE DR 7 and filled with sand at Specific Gravity 2.0 for use in steel pipes.

The ratio k of capsule outer diameter to pipeline inner diameter is very important for the analysis of capsule dynamics. In the proposed configuration of capsules made of HDPE pipe for a standard steel pipeline, the ratio is between 0.86 and 0.96 (Figure 5)

Liu (2003,(2004)) indicated that hydraulic capsule pipelines can be filled with capsules at a fill ratio of 80%. He defined a line fill ratio as the total length of the pipeline filled with capsules divided by the total length of the pipeline.

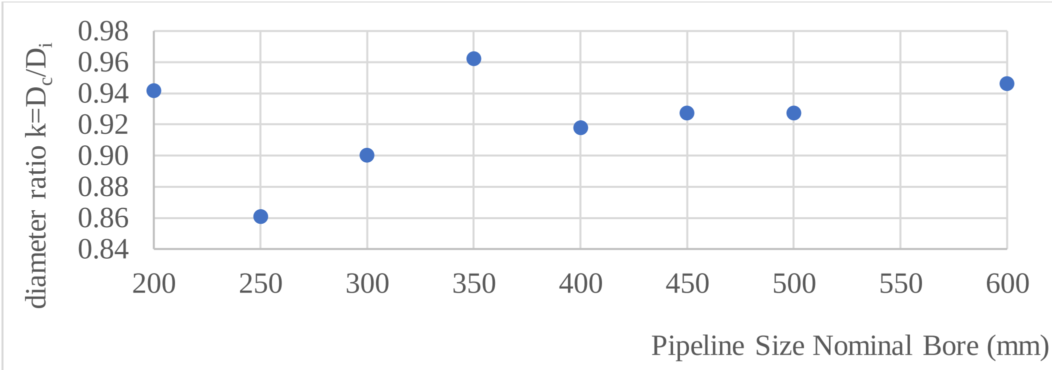

Figure 6. Capsule Diameter to Pipeline Diameter for capsules made of HDPE pipes for a steel pipeline

Applying equation (1) to the capsules discussed in Figure 5and 6 at the capsule length to diameter ratio of 1.5, results in lift-off velocity between 2.5 and 4.0 m/s (Figure 7).

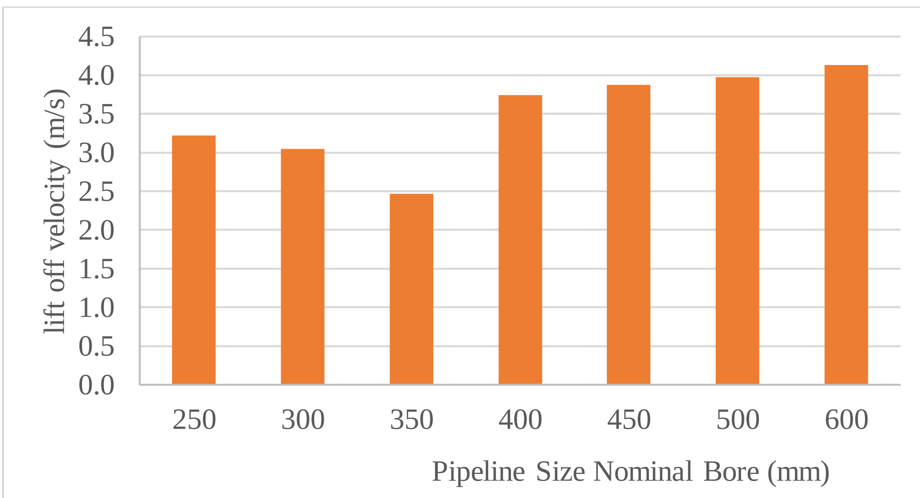

Figure 7. Lift-off velocity for capsules fabricated from HDPE DR 7 with sand at Specific Gravity 2.0 for use in steel pipes.

At the water velocity, called *lift-off velocity*, the capsules move faster than water -It must be noted that Liu had a preference for operation at 90% of V_L for stability of coal logs. Since the capsules will move faster than water they are free of mechanical friction with the walls.

The average flow rate of water in the pipeline is sensitive to friction losses, degree of fill of the pipeline, and slip velocity between pipeline and capsules.

As a first level of iteration,, we assumed that the capsules were operating in a range of bulk density similar to coal logs , and capsule were moving 5% above the lift off velocity, a corresponding average sediment transport flow rate is calculated (Figure 8) with capsule velocity as

$$V_c = (1.05V_L) \tag{4}$$

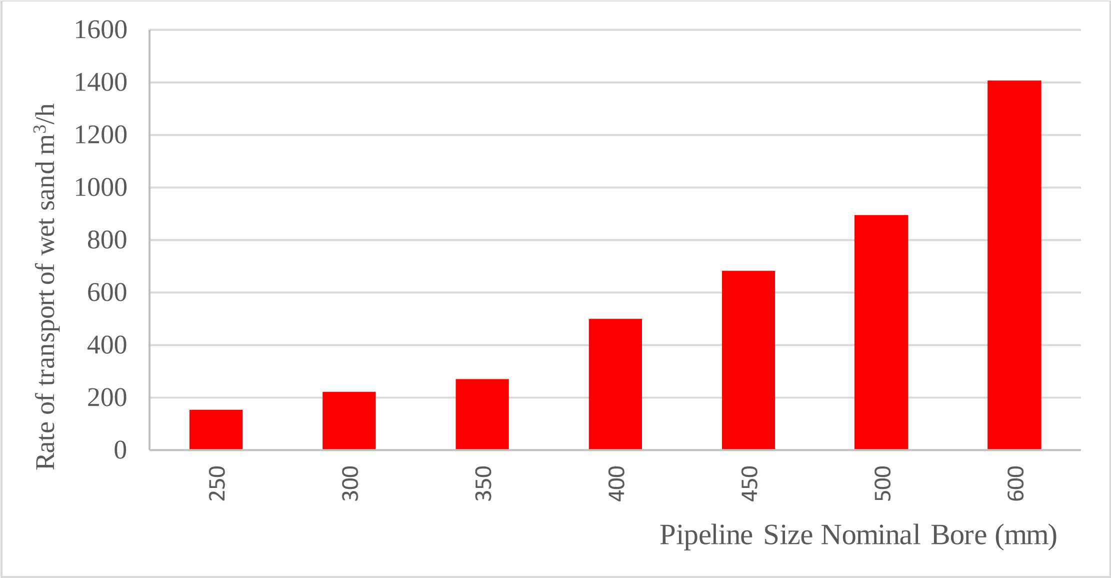

Figure 8. Calculated rate of transport of wet sand with bulk density of 2000 kg/m^3, in HDPE DR7 capsules at lift off velocity, at pipeline fill ratio of 80%

More precisely, the average velocity of water in the pipeline is expressed as

$$V_{bw}A_p = V_c A_c + V_A(A_p - A_c) \quad (5)$$

$$V_A = \frac{V_{bw} - kV_c}{(1-k^2)} \quad (6)$$

Where

A_c	= frontal area of capsule based on its outer diameter (m^2)
V_A	= average velocity of water in the annulus between capsule and wall of pipe (m/s)
A_p	= cross-sectional area of pipe (m^2)
Q_w	= average bulk flow rate of water in the pipeline (m^3/s)
V_c	= capsule velocity (m/s)
V_{bw} =	= average bulk velocity of water in the pipeline between capsules (m/s)

The annulus Reynolds number is defined as

$$Re_A = \frac{\rho_w}{\mu}(D_i - D_c)V_A \quad (7)$$

Re_A	= Reynolds Number based on the annulus
μ	= Viscosity of water in the pipeline (Pa.s)
ρ_w	= density of water (kg/m^3)

Substituting equation (6) into Equation (7) yields:

$$Re_A = \frac{\rho_w}{\mu}(D_i - D_c)\left[\frac{V_{bw} - k^2 V_c}{1-k^2}\right] \quad (8)$$

Kruyer and Ellis (1974), Ellis & Kruyer (1974) proposed that there are two regimes in the annulus surrounding the capsules based on the velocity in the annulus.

Laminar flow when $Re_A \leq 1000$

Turbulent flow when $Re_A > 1000$

When the flow in the annulus is laminar ($Re_A \leq 1000$), whereas the relationship between the fanning friction factor and the Reynolds number is usually expressed as $f_N(Re)=16$, they formulated a new equation for the fanning friction factor

$$f_{NL} = \frac{9.6}{Re_A} \tag{9}$$

the water bulk velocity is then expressed as

$$V_{bw} = kV_c + (1-k^2)\left\{\frac{\left(\frac{dP}{dx}\right)}{19.2\rho_w \mu}\right\}(D_i - D_c) \tag{10}$$

When the flow in the annulus is turbulent($Re_A > 1000$), they formulated the following relationship between the the fanning friction factor and the annulus-based Reynolds Number

$$f_{NT} = \frac{0.07}{{Re_A}^{0.25}} \tag{11}$$

the water bulk velocity is expressed as

$$V_{bw} = kV_c + (1-k^2)\left[\left\{\frac{\left(\frac{dP}{dx}\right)}{0.14{\rho_w}^{0.75}\mu^{0.25}}\right\}(D_i - D_c)^{1.25}\right]^{0.57} \tag{12}$$

dP/dx	= pressure loss per unit length due to friction (Pa/m)
f_{NL}	= fanning friction factor in laminar flow (non-dimensional)
f_{NT}	= fanning friction factor in turbulent flow (non-dimensional)
A_p	= cross-sectional area of pipe (m^2)
Q_w	= average bulk flow rate of water in the pipeline (m^3/s)
V_L	= lift off velocity (m/s)
V_{bw} =	= average bulk velocity of water in the pipeline between capsules (m/s)

The correlation between the average bulk velocity of water V_{bw} and the capsule velocity V_c is expressed in a difference called slip velocity V_s. Liu (2003) reported experiments on coal logs with a bulk density of 1300 kg/m^3 and indicated that the capsule velocity was about 15% faster than surrounding water at the diameter ratio k=0.806 and lift off velocity.

Figure 9 Shows a particular case when the water bulk velocity is at 90% of the lift velocity. When comparing water flow rates from Figure 9 with commercial Cutter Suction Dredgers (CSD) in Table 1, we note a reduction of volume of water per volume of sediments from approximately 5.5:1 to 3:1 –

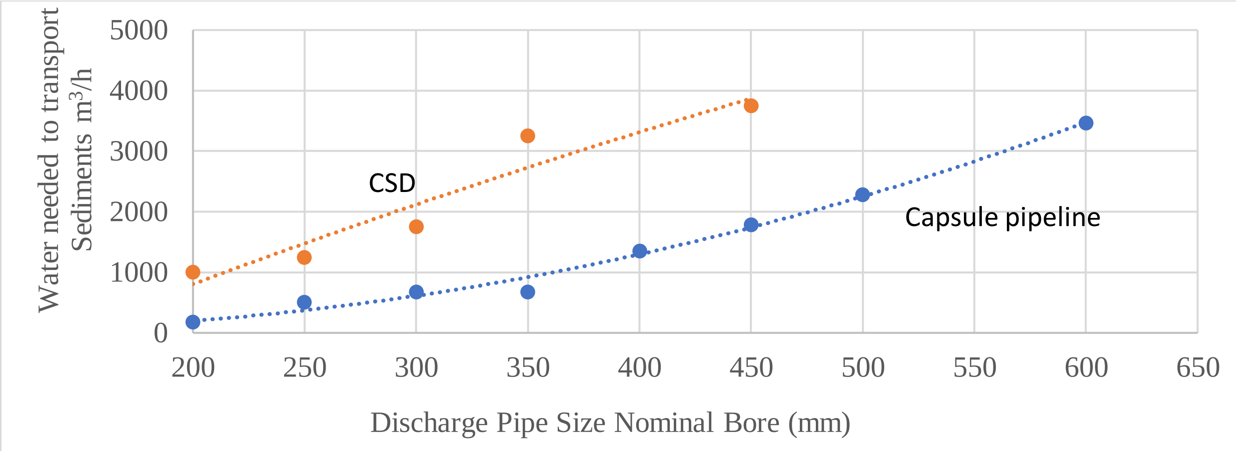

Figure 9. Calculated volume rates of water to transport sediments vs commercial suction dredgers

Further savings are achieved when water is not discharge into the river and is used to return empty capsules in the recycle pipeline(Figure 1). We may assume in this case a 10% loss of carrier water by evaporation at fill and emptying stations This leads to substantial reduction of water consumption for transport of sediments.

There are currently no particular incentives for a dredging contractor to save on water as he is usually paid in delivered volume of sediments, except to reduce his OPEX by reducing the energy due to water used in transport The concept of saving on water is more of an issue for the owner of the reservoir. Offering an incentive to reduce overall water discharge, would justify the construction of a recycle water pipeline for the empty capsules, rather than transporting them by truck or other mean. The current water reserves per capita in the United States is down to where it was in the 1960's due to continuous sedimentation (Randle et al (2019), so reservoir owners should encourage new technologies to save on water.

In the case of a commercial dredger the volume of sediments removed drops with the median particle size In the case of a capsule pipeline, the opposite effect occurs. As the particles get bigger (e.g., gravel), their void ratio increase, and therefore the bulk density of the full capsule decreases.

Ellis & Kruyer (1974) developed the following empirical equations for pressure losses in a pipeline

When $Re_A \leq 1000$ (laminar flow in the annulus)

$$\frac{dP}{dx} = 19.2\mu\frac{(V_{bw}-kV_c)}{(D_i-D_c)(1-k^2)} \tag{13}$$

When $Re_A > 1000$ (turbulent flow in the annulus)

$$\frac{dP}{dx} = 0.14{\rho_w}^{0.75}\mu^{0.25}\left[\frac{V_{bw}-kV_c}{1-k^2}\right]^{1.75}\left(\frac{1}{D_i-D_c}\right)^{1.25} \tag{14}$$

Ellis & Kruyer (1974) extended their analysis and proposed the power needed to transport two teragrammes (2 million metric tonnes)/year of minerals in plastic capsules at a capsule bulk density of 1500 kg./m^3 (S.G. = 1.50) in a 254 mm (10 in.) pipeline would be substantially reduced over slurry systems Based on equation (13), they formulated a power consumption of 7kW/km (15 bhp/mile) with a pressure loss of 172 kPa (25 psi). They proposed that a pump booster be installed at 80 km (50 miles) intervals.

It must be noted that Ellis & Kruyer did not propose the use of HDPE capsules, but rather capsules with 30% air void. The solution proposed in our paper is different and should be confirmed by further lab and field tests.

While most academic papers have focused on the pressure losses on a single capsule, Khalil et al (2008) conducted a computational fluid model of a train of capsules. They showed that the pressure losses were high for the first capsules facing the flow, but subsequent losses depended on the distance between capsules moving in the wake of the first units.

A NEW APPROACH FOR LAUNCHING CAPSULES IN PIPELINES

Past efforts to develop hydraulic capsule pipelines have focused on very complex systems of underwater conveyors with check valves and bypass pumps (Figure 10)

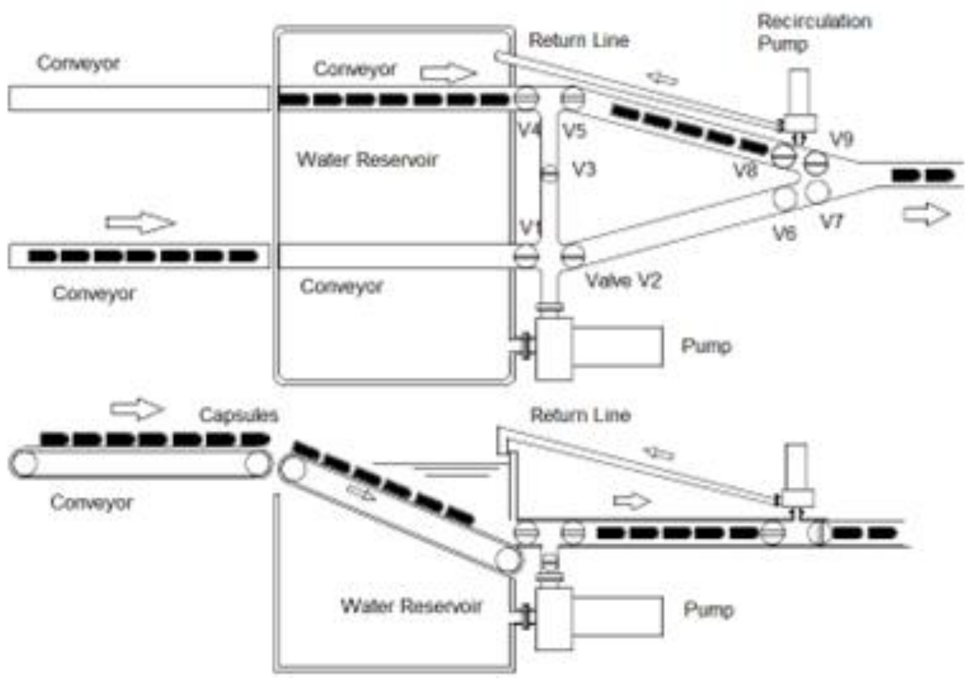

Figure 10. Conventional schemes to feed capsules in pipelines -reproduced from Abulnaga (2021)

In the 1990's appeared new concepts based on Linear Synchronous Motors (LSM) Montgommery et al (2001). The LSM is an interesting concept for dry capsule pipelines but relies on the use of metallic capsules passing through an electromagnetic field. These capsules are supported on wheels. The LSM requires a fixed infrastructure to create magnetic fields at pipeline intervals. This concept is not applicable to the hydraulic capsule pipeline in dredging, as we have demonstrated the need to use light plastic capsules to reduce overall bulk density.

With a grant from the National Science Foundation, we developed a new approach to feed capsules continuously from a dry conveyor into a water pipeline (Abulnaga 2022). The hydrojet concept (Abulnaga 2022) combines the features of a rotary feeder from a conveyor and a vacuum forming inductors. A scale model was built for launching in a 3” (80 mm NB) Figure 11

This new approach is patent pending and results will be presented in a separate paper.

This new invention works on similar principles as a jet pump and has similar limitations in terms of efficiency or pressure.

Figure 11. Capsules are fed continuously into the launcher from a conveyor- Note water does not rise up to the conveyor due to the formation of venturi at the bottom chamber of the launcher - US Patent Application 17/649556 filed on 2/2/2022

As the capsule drops into a special cavity chamber where the jet is applied, it sucks in a small quantity of air. Once the capsule has entered the pipeline and covered a distance, the pressure is increased through removal of air followed by pumping back water.

Principles of the jet pump as discussed by Jumpeter (1986) were modified to develop a correlation between mass flow rate of water , pressure and mass of capsule being launched.

CONCLUSION

The advent of HDPE pipes in diameter to thickness ratio of 7 (DR 7) up to pipeline size of 24 or 600 NB, offers an opportunity to fabricate light capsules in plastics for the transport of dredged sediments. This results in bulk density of 1250 to 1400 kg/m^3 when transporting wet sand at specific gravity of 2.0

The Criterion of low-pressure loss at lift-off velocity becomes possible to satisfy in this combination of light plastic pipe with heavy sediments. Calculations were conducted for a size of pipes from 200 mm (8"0 to 600 mm NB (24"), At the fill ratio of 80% it is possible to match current commercial Cutter Suction Dredging systems.

The corresponding volume flow rate of water to transport sediments is reduced by 40% . The water consumption can be practically reduced to nil when the water is recycled with empty capsules in a separate return pipeline.

There are currently no commercial incentives for dredging contractors to save on water during transport of sediments and they are paid by the cubic yard delivered. Owners of reservoirs, federal and state regulators are encouraged to offer incentives to contractors to reduce water consumption and return the water after dredging to the reservoir. This is possible by using the hydraulic capsule pipeline technology.

The hydrojet capsule pipeline concept offers a new opportunity to feed capsules directly into the pipeline from conveyors. It is simpler than previous lock and pump systems developed in the 1970's.

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DATA AVAILABILITY

Some or all data, models, or code generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use

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ACCELERATING HOUSTON SHIP CHANNEL EXPANSION (PROJECT 11)

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ABSTRACT

The Houston Ship Channel (HSC), including Port Houston's eight public terminals and the more than 200 private and public facilities, are collectively known as the Port of Houston. The Port of Houston is *the No. 1 U.S. Port in waterborne tonnage* — sustains three million U.S. jobs, generates $802 billion in national economic benefits, and provides $38 billion in annual tax revenue. In anticipation of the project construction, an additional $50 billion in capital investments have been made by Port Houston and local industry along the channel to handle increasing exports and imports which are being driven by step change increases over the past decade in industrial production, manufacturing investment and consumer demand from growing populations in Texas. It is critical that the necessary infrastructure be in place to accommodate future economic opportunities. Port Houston is preparing now for the future needs of vessels and businesses, and with U.S. Army Corps of Engineers (USACE), have defined accelerating the HSC expansion as top priority.

Project 11, the eleventh major expansion in the HSC history, is moving forward following the congressional authorization in the Water Resources Development Act of 2020, signing of the Chief of Engineers Report in April 2020 (USACE 2020), 'new start' designation in January 2021, Project Partnership Agreement execution in July 2021, allocation of $142.5 million in the 2022 Infrastructure Bill, and Port Houston's $600 million funding for the design and construction of Galveston Bay portions of the project that connect the Houston Ship Entrance Channel to Port Houston's container terminals, Bayport and Barbours Cut.

Further, between 2015 and 2017, under authorization of the Houston Galveston Navigation Channel (Project 10) and preparation for Project 11, Port Houston accelerated the permitting (via 204[f]/408 agreement), design, and $100 million dollar construction of Bayport and Barbours Cut to widen (from 300 to 350 feet, 91.44 to 106.68 meters in the land cut area and 400 feet, 121.92 meters in Galveston Bay for Bayport) and deepen (from 41 to 46.5 feet MLLW, 12.50 to 14.17 meters) the channels. This sequence of

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events and the record setting timeframes are unprecedented, and the underlying work labeled "a model project for the Nation" by Chief of Engineers General Todd Semonite, (ret).

As the local sponsor of this crucial federal waterway, Port Houston is partnering with the USACE and private industry to accelerate Project 11 (federally identified as the Houston Ship Channel Expansion Channel Improvement Project [ECIP]). The improvements being designed and constructed by Port Houston and USACE seek to ensure that the waterway continues to safely accommodate growth of commerce to the benefit of the many industrial users of the channel as well as the national economy. Achieving this acceleration is due to innovations in how the Port partnered with USACE and redefined the process for progressing nationally significant navigation projects.

Keywords: Port Houston, Project 11, Houston Ship Channel, Expansion Channel Improvement Project, Houston Pilots, navigation safety, dredging, beneficial reuse.

INTRODUCTION

Project 11 (Figure 1) design and construction includes widening the channel by 170 feet (51.82 meters) (from 530 to 700 feet, 161.54 to 213.36 meters) along its Galveston Bay reach, further widening the Bayport and Barbours Cut Channels to 455 feet (138.68 meters), deepening some upstream segments (up to 46.5 feet MLLW, 14.17 meters), making other safety and efficiency improvements, and constructing new environmental features (from the beneficial use of dredged material).

Accelerating this project required two key innovations. The first innovation was Port Houston and U.S. Army Corps of Engineers (USACE) partnership to transform the navigation project "business as usual" case from a largely serial process, where each step of feasibility, design, and construction awaits specific authorizations, project partnership agreements, and appropriations, into a parallel process where design is accelerated and is concurrent with approvals and authorizations. This new approach, combined with advanced funding brought construction at least 4 years forward, and more likely will deliver this project a decade early when considering that traditional funding process of annual appropriations was bypassed, and that the business-as-usual process can take 20 years from authorization to project completion.

To move the project forward — *outside the standard Federal timeline* — Port Houston's next innovation was setting up a three-pronged execution approach of several advocacy, finance, and design steps to deliver the project on an accelerated timeframe:

Advocacy. Partnership, collaboration, and broad support are critical to moving this project forward and implementing these improvements as soon as possible to safely accommodate growth and economic recovery. Therefore, Port Houston is working with the USACE, Congress, and the administration, as well as many local, state, and national technical experts, local partners, and industry stakeholders to expedite the approval and limited federal funding of this project. This required strategically anticipating federal milestones and timelines for budgeting, legislation, and other processes to have needed messages and work products ready as inputs to those processes. Experts in the methods and priorities of the federal Administration, Congress, and USACE headquarters as well as collaboration with government relations representatives and executives in industry, were added to the overall team efforts to navigate this complex political and financial landscape.

Figure 1. Houston Ship Channel Expansion, June 2022.

Finance. Port Houston is implementing various financing strategies to fully fund (both the Federal and local sponsor cost share) Segments 1 and 2. USACE received $142.5 million from the 2022 Infrastructure Investment and Jobs Act for the construction of Segment 3. Segment 4 is pending allocation of Federal funding. Expertise and advisors in finance and bond strategies as well as in project controls and federal work-in-kind accounting were added to the team to ensure all financial strategies were aligned.

Design. Port Houston Commissioners took the arguably unprecedented step of approving funding for detail design work ahead of project authorization, which provided two critical benefits.

First, it avoided a long delay waiting until authorization and appropriations to initiate design. Secondly, this action-maintained momentum and knowledge continuity in the technical team, thus avoiding more delays from loss of subject matter expertise, deteriorating a collaborative shared understanding among partners, and in new teams getting up to speed.

Port Houston appropriated $28 million for the design phase in the fall of 2019, eleven months prior to Water Resources Development Act (WRDA) authorization. The acceleration of the design allowed for the 95% completion to be timed with WRDA and subsequent award of the first construction contract (dredged material site placement preparation) in April 2021 and the first dredging contract in September 2021. The selected design teams — two separate engineering consultants (Joint Venture and HDR) — worked to deliver the $1 billion project at key milestones, performed Value Engineering with the 65% submittal (March 2021), achieved General Air Conformity by December 2020, delivered the final draft ship simulation report through ERDC, SWG, and Joint Venture by January 2021, Environmental Sufficiency clearance by June 2021, and Biddability, Constructability, Operability, Environmental, and Sustainability (BCOES) / Ready to Advertise (RTA) clearance from USACE for all Port-designed packages between July 2021 and February 2022.

Under this accelerated plan, upland site preparation commenced in 2021, dredging commenced in April 2022, and major project components scheduled for completion at the end of 2025. As of June 2022, 82% of the total project is funded; with the remaining portions (Segments 4-6; Packages 8-12) subject to Federal appropriations. Table 1 provides a tentative procurement and construction timeline by package. Although advocacy and finance are instrumental in the project success, the remaining sections of this report focus on the project importance and design overview.

Table 1. Project 11 Tentative Procurement and Construction Timeline.

Package		Segment	Advertisement	Port/USACE	Construction
1	Dollar Reef Oyster Mitigation	1A	Aug 2021	USACE	Jan – Jul 2022
2	Beltway 8 Site Clearing, Grubbing, and Concrete Demolition	4	Feb 2021	Port	Jun 2021 – Jun 2022
3/4A	Bolivar Roads to Redfish	1A	Jul 2021	Port	Mar – Dec 2022
Abandoned Pipeline Removal	Redfish to Bayport	1B, 1C	Aug 2021	Port	Jan – July 2022
4B/5	Redfish to Bayport	1B,1C, 2	Nov 2021	Port	Oct 2022 – Dec 2024
6	Bayport to Morgans Point	1C	Feb 2023	Port	Jul 2023 – Apr 2024

Package		Segment	Advertisement	Port/USACE	Construction
7	Barbours Cut	3	Oct 2022	USACE	Jan 2023 – Mar 2025
8	Beltway 8 and East 2 Clinton DMPA	4	Mar 2023	USACE	Aug 2023 – Nov 2024
9	Boggy Bayou to Sims Bayou	4	Jun 2024	USACE	Nov 2024 – Nov 2025
10	Sims Bayou to IH 610	5	Sep 2024	USACE	Feb 2025 – May 2025
11	IH 610 to Turning Basin	6	Sep 2024	USACE	Feb 2025 – May 2025
12	Sims Bayou to Turning Basin	5, 6	Mar 2024	USACE	May 2025 – Oct 2025

Pending Federal Appropriations

PROJECT IMPORTANCE

The story of Houston is one of entrepreneurial passion, innovation, and unprecedented success. The growth and achievements of this city are tied to many different enterprises, but most of the pathways can be linked to one historic waterway that has propelled the economy of not only our region, but the entire nation. The channel began as the vision of a few foresighted and determined business leaders more than a century ago, who through, "The Houston Plan", would provide future generations with the continued benefits of international commerce. The Houston Plan was the first significant public-private partnership of its kind, with those sectors working together on a common goal — to deliver a project that is arguably the most essential waterway serving our country. Over 100 years later, Project 11 represents the eleventh significant widening and deepening of the Houston Ship Channel (HSC), Figure 2.

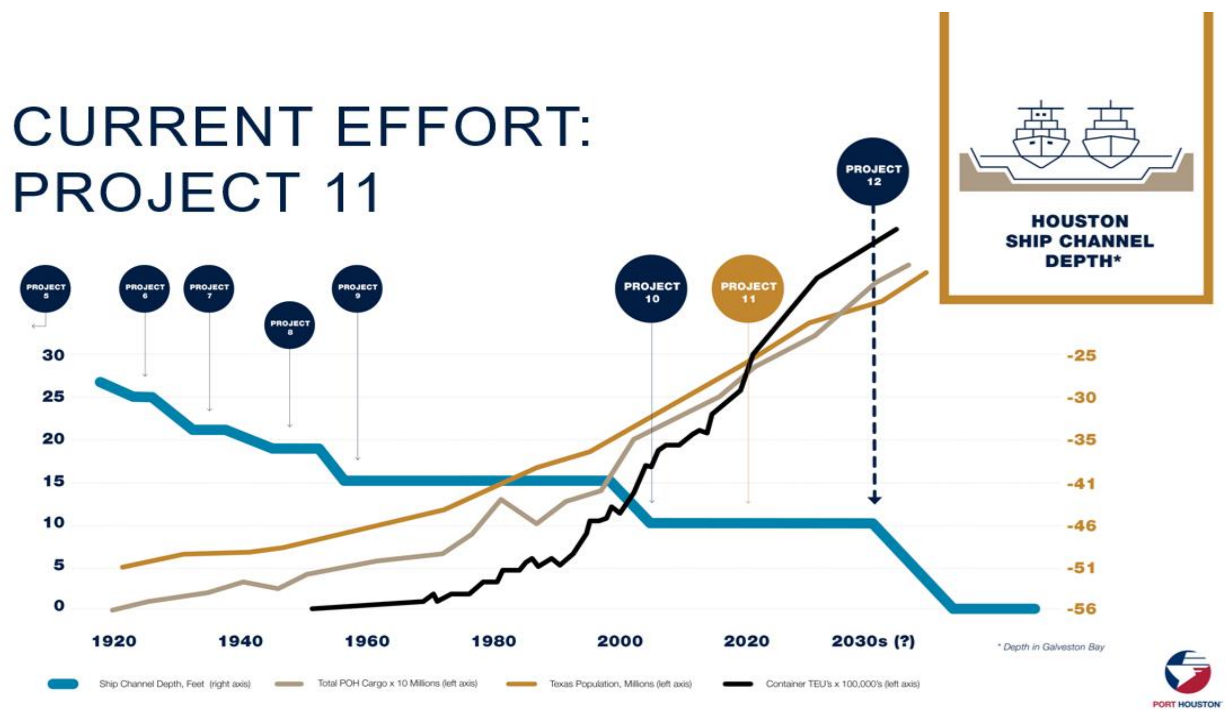

Figure 2. HSC Widening and Deepening Project Timeline.

Renowned economic researcher M. Ray Perryman of The Perryman Group wrote in a June 27, 2022, Houston Chronicle article that the development of a deep-water channel was crucial to Texas becoming a vital hub of global commerce, “The Houston Ship Channel is a cornerstone of the U.S. logistics system, and its economic importance is profound.”

Diversification and Growth

Houston is the home to the largest petrochemical complex in the nation. Carrier services on all major trade lanes link Houston to international markets around the globe. Texas is expected to top five (5) million barrels per day in oil production soon, besting all but one OPEC (Organization of the Petroleum Exporting Countries) nation.

However, Houston is not just an oil port, it is the energy capital of the world with myriad refineries and petrochemical plants, 500 million barrels of liquid storage, thousands of crisscrossing pipelines and deep industry knowledge and expertise, all contributing to an irreplaceable and non-copyable industrial product production and trading center that drives tremendous volumes in ships.

The petrochemical trade cascades to solid cargos in containers by way of plastic resins as well which are produced from derivatives of natural gas, contributing to Port Houston’s position as the largest container port in the U.S. Gulf Coast. Port Houston leads the nation in export of plastic resins with a 58% share of all resins and 73% share of polyethylene resins. Houston is also number one in the nation for steel and project cargo. This includes oil country tubular goods and wind turbines that support energy production. Houston will continue to support energy innovation, as a transition to cleaner fuels and expansion of clean hydrogen support energy exports on ships using the Houston Ship Channel. Agriculture commodities and other cargo manufactured locally are also shipped in containers around the world.

On the other side, Texas has the fastest growing population in the U.S., which is driving imports of consumer goods. Houston also imports and exports cement, grain, petroleum coke (petcoke), and other dry bulk commodities. Together, all this activity generates increasing demand for a safe and expanded Houston Ship Channel, as well as high quality jobs in the region, state, and nation. According to a study conducted by Martin Associates, Houston’s port supports 3.2 million jobs nation-wide and 1.35 million in Texas. It supports $802 billion in annual national economic value.

According to the latest published U.S. Coastal and Inland Navigation System 2020 Transportation Facts & Information (USACE 2020), Houston is ranked the No. 1 U.S. Port by millions of short tons (Figure 3). While down 3.2% from 2019 (284.9 million short tons in 2019 vs. 275.9 million short tons in 2020), new demands resulting from energy and manufacturing growth as well as the expanded Panama Canal are putting pressure on the HSC system today.

The strategic value of the HSC is supported by a recent study (Martin Associates, 2019) that indicates its national impact is more than $800 billion each year, sustaining 3.2 million jobs and providing $38 billion in tax revenue. Houston’s port activity accounts for more than 20% of the gross domestic product (GDP) of Texas. Safe and efficient movement of cargo along the HSC is critical to U.S. energy security, sustaining and growing jobs and local, regional, and national economic growth.

Leading U.S. Ports in 2020

(Millions of Short Tons and Percent Change[1] from 2019)

			Domestic		Foreign		Total	
Rank	Type[3]	Port	Tons	%	Tons	%	Tons	%
1	C	Houston Port Authority, TX	79.2	5.3	196.8	-6.2	275.9	-3.2
2	C	South Louisiana, LA, Port of	112.4	-8.1	112.7	-2.5	225.1	-5.4
3	C	Corpus Christi, TX	25.1	-3.1	125.7	47.1	150.8	35.5
4	C	New York, NY & NJ	40.1	-11.6	83.6	-8.4	123.7	-9.4
5	C	New Orleans, LA	43.2	-10.3	37.8	-14.0	81.1	-12.1
6	C	Port of Long Beach, CA[2]	13.5	46.7	65.7	-7.7	79.2	-1.5
7	C	Port of Greater Baton Rouge, LA	43.4	0.1	28.3	-5.9	71.7	-2.3
8	C	Beaumont, TX[2]	24.8	-19.9	45.8	-26.5	70.6	-24.3
9	C	Port of Los Angeles, CA	4.5	-33.3	55.0	-2.3	59.5	-5.6
10	C	Virginia, VA, Port of	5.0	9.4	53.1	-7.1	58.0	-5.9
11	C	Mobile, AL	18.8	-4.6	34.4	-7.5	53.2	-6.5
12	C	Plaquemines Port District, LA	25.9	-10.6	20.9	-12.3	46.8	-11.4
13	C	Port of Savannah, GA	1.1	22.6	42.3	3.2	43.5	3.6
14	C	Lake Charles Harbor District, LA	20.3	-36.0	22.7	-13.5	43.1	-25.8
15	C	Port Arthur, TX[2]	17.3	11.2	23.9	-2.6	41.2	2.7
16	C	Port Freeport, TX	4.2	7.7	34.6	33.1	38.7	29.8
17	I	Mid-Ohio Valley Port,OH and WV[2]	35.9	-22.5	**	0.0	35.9	-22.5
18	C	Baltimore, MD	4.2	-36.3	31.0	-17.6	35.2	-20.4
19	I	Cincinnati-Northern KY, Ports of	34.5	-5.7	**	0.0	34.5	-5.7
20	C	Texas City, TX	12.5	-24.9	21.2	-14.0	33.7	-18.4

Figure 3. U.S. Ranking of Ports in 2020 by Millions of Short Tons and Percent Change

The Houston Ship Channel and Ship Simulation

The HSC is one of the most difficult waterways in the world to navigate due to its high traffic volume and narrow, shallow, and winding characteristics. In 2021, there were nearly 9,000 vessel calls for a total of over 20,000 commercial ship movements along the Channel, a volume that is equal to the total annual ship calls for the next three largest U.S. ports combined. In addition, the Coast Guard Vessel Traffic Service Houston reported there are over 120,000 tug and barge movements within their area of responsibility in a typical year. In addition to the highest vessel traffic, the 530-foot-wide (161.54 meter) channel is the narrowest relative to vessel beam of all major U.S. Ports. Due to the narrow channel condition, bank forces are the primary hazard.

Given this, a particular focus of the channel improvement is on channel widening (Figure 4) — from 530-foot wide by 46-foot MLLW (161.54 by 14.02 meter) deep channel to 700-foot wide (213.36 meter) channel with relocation of the 230-ft wide by 13-ft deep (70.10 by 3.96 meter) barge lanes in the Galveston Bay reach between Bolivar Roads to Morgans Point. The 32% wider channel will allow for greater ship to bank distances, thereby improving overall navigation safety and efficiency.

As with all coastal jurisdictions, Texas statute requires all foreign flagged vessels to engage a state licensed ship Pilot while in state waters. State licensed Pilots are master mariners with expertise in the specific weather, currents, traffic management, and bottom contours of their respective ship channels. The design team for Project 11 solicited input from Houston Pilots during numerous early design discussions and during full mission bridge simulations of the proposed channel.

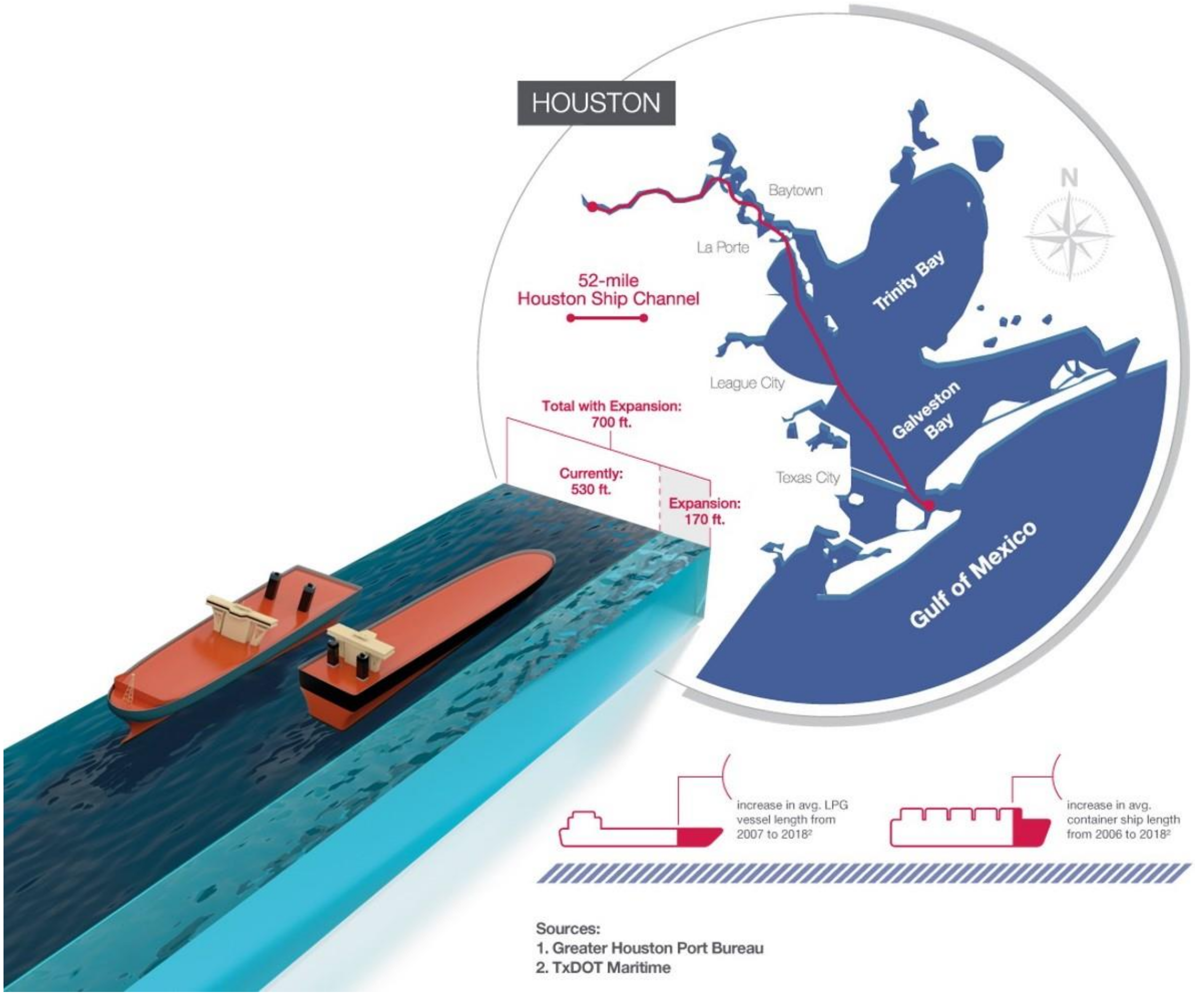

Figure 4. HSC Galveston Bay Widening, Segments 1 and 2.

Based on Houston Pilot experience with large vessels and their participation in extensive full mission bridge simulations sanctioned by ERDC of the improved channel with the proposed design vessels, Houston Pilots forecasted that once construction is completed from Bolivar Roads to Morgans Point, improved channel navigability should allow:

- The combined beam meeting rule below Morgans Point to be increased from 310 to 340 ft (94.50 to 103.63 meters).
- The daylight restriction to be moved 20 nautical miles (37.04 kilometers) upstream from Bolivar Roads to Morgans Point.
- Container vessels over 1,000 feet (304.8 meters) Length Overall (LOA) to transit the HSC 24 hours a day.

PROJECT 11 DESIGN OVERVIEW

The overall Recommended Plan for the HSC ECIP is the Locally Preferred Plan (LPP) as described in the 23 April 2020 Report of the Chief of Engineers (Department of the Army 2020) and summarized in Figure 1. Over the course of 18 months (September 2019 – February 2021), Port Houston designed and submitted a total of nine packages (Segments 1-4; Packages 1-9) to the USACE for review at 65%, 95%, 100%, and BCOES / RTA intervals. Two additional packages — Abandoned Pipeline Removal (to remove up to ten abandoned pipelines in Segments 1B and 1C) and Bayport ATONs, were submitted to the USACE for review and coordination.

The USACE Project Delivery Team (PDT) reviewed the construction packages for general compliance with the following Engineering Manuals and Regulations:

- EM 1110-2-1100 Coastal Engineering Manual
- EM 1110-2-1202 Environmental Engineering for Deep-Draft Navigation Projects
- EM 1110-2-1204 Environmental Engineering for Coastal Shore Protection
- EM 1110-2-1613 Hydraulic Design of Deep Draft Navigation Projects
- EM 1110-2-1614 Design of Coastal Revetments, Seawalls, and Bulkheads
- EM 1110-2-1913 Design and Construction of Levees
- EM 1110-2-5025 Engineering and Design, Dredging and Dredged Material Management
- EM 1110-2-5026 Beneficial Uses of Dredged Material
- EM 1110-2-5027 Confined Disposal of Dredged Material

Once USACE design and legal reviews were completed, USACE issued an RTA memorandum for each Port-led construction package. USACE is designing the remaining Segments 5 and 6 and constructing Packages 1, and 7-12.

Design and Construction Package Summary

The following package descriptions provide a high-level summary (location, description, mitigation, dredged material placement site) for each Port- and USACE-led package.

Package 1. Package 1, designed by Port Houston and constructed by USACE, is for work to construct oyster reef mitigation for HSC Widening Segment 1A Bolivar Roads to Redfish Reef, HSC Bend Easing at Station 28+605 (Part of Segments 1B and 1C), and BSC (Segment 2) and BCC (Segment 3) improvements. The mitigation includes construction of 44.6 acres (18.04 hectare) of rock cultch oyster reef at Dollar Reef Oyster Mitigation site.

Package 2. Package 2, designed and constructed by Port Houston, is for work associated with Segment 4 and includes work for site preparation for the one-time use of Beltway 8 Dredged Material Placement Area (DMPA). Site preparation includes design for site clearing and grubbing, concrete demolition (removal of ammunition bunkers and roadways), pipeline permitting, design, coordination and relocation, and temporary access road design and coordination. The actual design of DMPA features (e.g., dike) for the Beltway 8 DMPA is Package 8.

Package 3/4A. Package 3/4A, designed and constructed by Port Houston, is for new work dredging and placement, and part of the mitigation associated with Segment 1A, to widen the HSC from 530 to 700 feet (161.54 to 213.36 meters) from Bolivar Roads to Redfish Reef (HSC STA 138+369 to 73+476 and Bolivar Roads Channel STA 0+000 to 2+607.32). This package also includes associated relocation of the HSC barge lanes to accommodate the proposed widening. Dredging of new work material would be performed with a (1) hydraulic pipeline dredge with beneficial placement of the into Long Bird Island and (2) mechanical dredging equipment (e.g., bucket and scows) with placement of the remaining material into the existing Offshore Dredged Material Disposal Site (ODMDS). Mitigation work included in this package includes placement of oyster cultch to armor the bird island.

Package 4B/5. Package 4B/5, designed and constructed by Port Houston, is for new work dredging, placement and mitigation associated with Segments 1B, a portion of 1C, and 2 to widen the HSC from 530 to 700 feet (161.54 to 213.36 meters) from Redfish Reef to BSC (HSC STA 78+844to 16+000) and widen BSC from 350/400 to 455 feet (106.68/121.92 to 138.68 meters) (BSC STA 222+75.87 to 42+07.08). This package also includes associated relocation of the HSC barge lanes to accommodate the proposed widening. Dredging of new work material would be performed (1) using a hydraulic pipeline dredge with placement of the new work material used beneficially to construct Three Bird Island Marsh, (2) mechanical dredging (e.g., bucket and scows) with placement of the soft new work material into the existing ODMDS, and (3) mechanical dredging (e.g., bucket and material barges) with placement of material to construct oyster mitigation mounds at San Leon and Dollar Reef mitigation sites. Mitigation work includes placement of oyster cultch to armor the Three Bird Island Marsh and oyster mitigation mounds.

Package 6. Package 6, designed and constructed by Port Houston, is for new work dredging and placement associated with the remainder of Segment 1C to widen the HSC from 530 to 700 feet (161.54 to 213.36 meters) from BSC to BCC (HSC STA 16+000 to -0+003.94 and HSC BAYOU STA 00+00 to 27+48). This package also includes associated relocation of the HSC barge lanes to accommodate the proposed widening. Dredging of new work material would be performed using a hydraulic pipeline dredge with placement of the new work material used beneficially to construct dikes at Atkinson Island Marsh Cell M11and to repair the dikes at M7/8/9 and M10.

Package 7. Package 7, designed by Port Houston (initial)/USACE (final) and constructed by USACE, is for new work dredging and placement associated with Segment 3 to widen the BCC from 400 to 455 feet (121.92 to 138.68 meters) (BCC STA 8+79.4 to 67+10.85) including a new turning basin and flare. Dredging of new work material would be performed using a hydraulic pipeline dredge with placement of the new work material beneficially to create dikes at Atkinson Island Marsh Cell M12. The package also includes design work for the bulkheads along the north shoreline at Spillman Island and southeast shore at Morgans Point and performing a clean sweep of the Cedar Bayou Navigation Channel following completion of the proposed M12 beneficial use site. When USACE issues the construction package for Package 7, USACE will work with the EOR (Engineer of Record) to execute a service contract for bidding and construction phase services as needed.

Package 8. Package 8, designed by Port Houston (initial)/USACE (final) and constructed by USACE, is for construction of the Beltway 8 one-time use DMPA to contain new work material dredged to deepen and widen Segment 4, HSC Boggy Bayou to Hunting Turning Basin (HSC STA 684+03.19 to 930+00) up to 530 feet (161.54 meters) (see Package 9 for scope of channel modifications). This package also includes the construction of a maintenance site at East 2 Clinton DMPA for future USACE use. Initial construction of East 2 Clinton will allow for one maintenance event. East 2 Clinton will then be managed by USACE for future maintenance events. When USACE issues the construction package for Package 8, the USACE will work with the EOR, to execute a service contract for bidding and construction phase services as needed.

Package 9. Package 9, designed by Port Houston (initial)/USACE (final) and constructed by USACE, is for new work dredging and placement associated with Segment 4 to widen the HSC up to 530 feet (161.54

meters) and deepen the HSC to the Hunting Turning Basin up to 46.5 feet MLLW (14.17 meters) (HSC STA 684+03.19 to 930+00). Dredging of new work material would be performed using a hydraulic pipeline dredge with placement of the new work material at East-West Clinton and to beneficially raise the site elevation of the Beltway 8. When USACE issues the construction package for Package 9, USACE will work with the EOR, to execute a service contract for bidding and construction phase services as needed.

Package 10. Package 10, designed and constructed by USACE, is for improvements to the existing Glendale DMPA to contain new work material dredged to deepen the HSC to 41.5 feet MLLW (12.65 meters) (HSC STA 1110+78 to 1266+49). Dredging of the new work material would be performed using a hydraulic pipeline dredge.

Package 11. Package 11, designed and constructed by USACE, is for improvements to the existing Filterbed DMPA to contain new work material dredged to improve the Brady Island Turning Basin to 900-foot (274.62 meter) diameter (HSC STA 00+00 to 30+95). Dredging of the new work material would be performed using a hydraulic pipeline dredge.

Package 12. Package 12, designed and constructed by USACE, is for new work dredging and placement associated with Segment 5, Sims Bayou to I-610 Bridge, and Segment 6, I-610 Bridge to Main Turning Basin, to deepen the HSC up to 41.5 feet (12.65 meter) MLLW and improvement of the Brady Island Turning Basin to 900-foot diameter. Dredging of the new work material would be performed using a hydraulic pipeline dredge.

Outside the preparation of plans, specifications and Design Documentation Report, other PED activities included fieldwork (geotechnical, hydrographic, side-scan sonar, and magnetometer surveys), cultural resource investigation, air quality analysis, ship simulation, ship wake analysis for General Navigation Features, pipeline evaluation, Value Engineering, shoaling analysis (erosion and sediment transport modeling and advance maintenance study, shoaling and countermeasure analysis), and both STFate (supplemental short-term fate) and CDFate (continuous discharge fate) analyses.

Dredged Material Placement Area Plan

Table 2 and Figure 5 provides the Dredged Material Placement Area (DMPA) plan for the project. To the extent possible, all dredged material (with geotechnical value) will be beneficially used to construct oyster reefs, bird islands, and marshes. Material deemed low quality will be placed in the ODMDS. All environmental activities included active outreach and communication with the Beneficial Use Group (BUG) as well as regulatory agencies for transparent coordination.

Table 2. Project 11 Dredged Material Placement Area Plan.

Segment	Feature	Stations	Placement Feature	New Work [3] (KCY)	New Work [3] (KCM)
1A	Widen HSC Bolivar Roads to Redfish Reef to 700 feet (213.36 meters) with Barge Lane Relocation	138+369 - 98+00	Long Bird Island	1,944	1,486
	Bend Easing (3 locations)	98+000 - 73+934	Existing ODMDS	3,038	2,323
1B	Widen HSC Redfish Reef to BSC 700 feet (213.36 meters) with Barge Lane Relocation[1]	78+844 - 16+000	Existing ODMDS[1]	2,474	1,892
			Oyster Mitigation[1]	2,030	1,552
	Bend Easing (NED)		Three Bird Island Marsh[2]	3,181	2,432
2	BSC Widening to 455 feet (138.68 meters)	42+07.80 - 222+75.87		2,108	1,612
1C	Widen HSC BSC to BCC to 700 feet with Barge Lane Relocation and Transition of Widener into Bayou Reach	-3.94 - 16+000	Atkinson Marsh Cell M11[1]	2,800	2,140
			Complete Atkinson Marsh Cell M7/8/9[1]	1,000	765
			Three Bird Island Marsh[2]	1,541	1,178
3	BCC Widening to 455 feet (138.68 meters) BCC Combined Flare/Turning Basin	08+78 - 67+11	Atkinson Marsh Cell M12	2,814	2,151
4	Widen HSC up to 530 feet (161.54 meters)	684+03 - 850+00	Even lift on BW8	1,851	1,415
	Deepen HSC up to 46.5 feet MLLW (14.17 meters)	850+00 - 930+00	East-West Clinton	2,615	1,999
			E2 Clinton Construction for USACE Maintenance	--	--
5	Deepen HSC up to 41.5 feet MLLW (12.65 meters)	1110+78 - 1160+62	Even lift on Glendale	176	135
6	Deepen HSC up to 41.5 feet MLLW (12.65 meters)	1160+62 - 1266+49	Even lift on Glendale	734	561
	Brady Island Turning Basin	00+00 - 30+95	Even lift on Filterbed	267	204

[1] [1] LPP Feature; [2] Partial LPP Feature, [3] Feasibility Quantities shown.

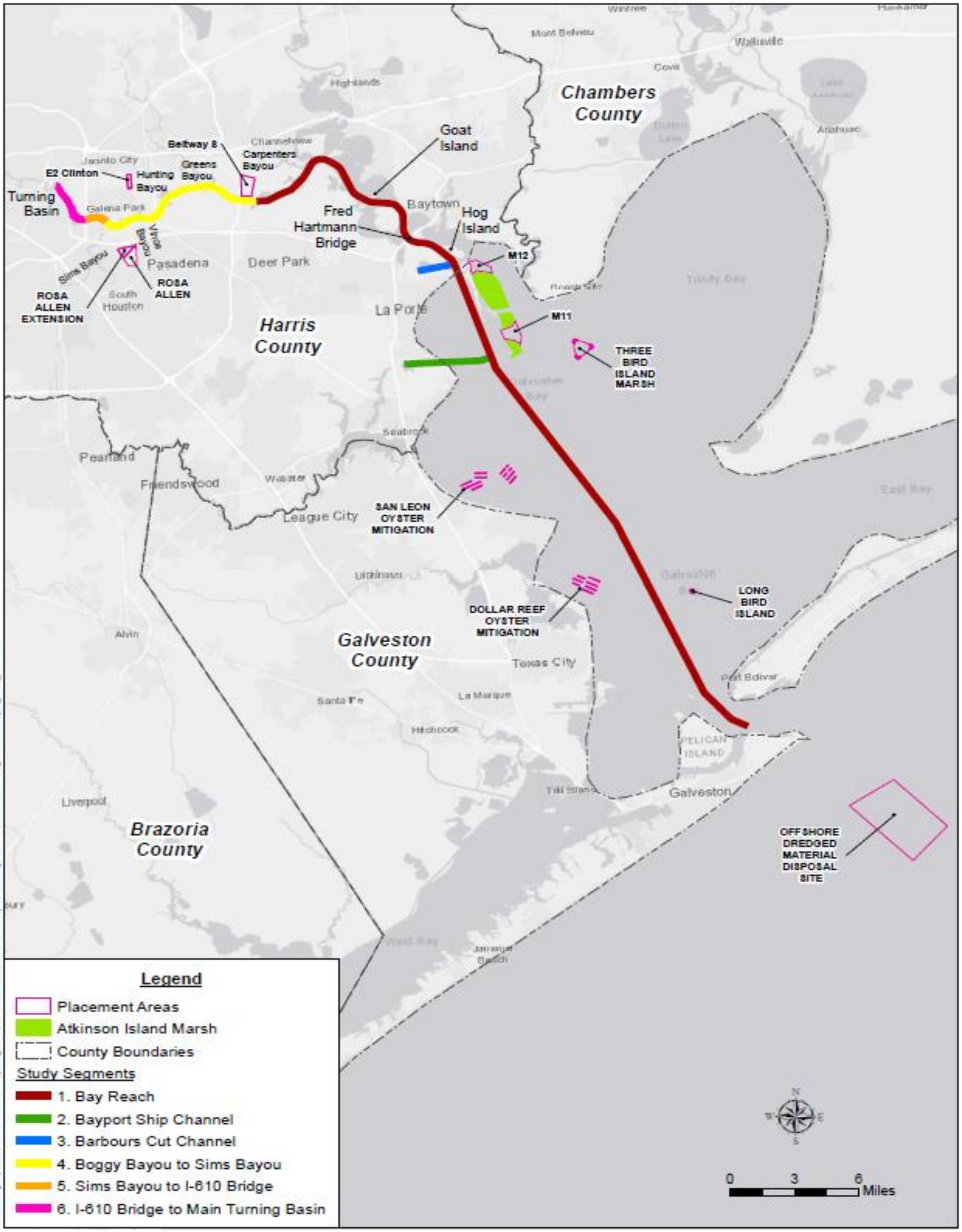

Figure 5. Project 11 Dredged Material Placement Plan.

CONCLUSIONS

Project 11, the eleventh major expansion in the Houston Ship Channel's history, is moving forward following the congressional authorization in the Water Resources Development Act of 2020, signing of the Chief of Engineers Report in April 2020 (USACE 2020), 'new start' designation in January 2021, Project Partnership Agreement execution in July 2021, allocation of $142.5 million in the 2022 Infrastructure Bill, and Port Houston's $600 million funding for the design and construction of Galveston Bay portions of the project that connect the Houston Ship Entrance Channel to Port Houston's container terminals, Bayport and Barbours Cut. Achieving this acceleration is due to innovations in how the Port partnered with USACE and redefined the process for progressing nationally significant navigation projects.

Port Houston, USACE, and the selected design teams — two separate engineering consultants (Joint Venture and HDR) — worked to deliver the $1 billion project at key milestones, performed Value Engineering with the 65% submittal (March 2021), achieved General Air Conformity by December 2020, delivered the final draft ship simulation report through ERDC, SWG, and Joint Venture by January 2021, Environmental Sufficiency clearance by June 2021, and BCOES/RTA clearance from USACE for all Port-designed packages between July 2021 and February 2022.

Under this accelerated plan, upland site preparation commenced in 2021, dredging commenced in April 2022, and major project components scheduled — *subject to Federal appropriations* — for completion at the end of 2025. The improvements being designed and constructed by Port Houston and USACE seek to ensure that the waterway continues to safely accommodate growth of commerce to the benefit of the many industrial users of the channel as well as the national economy.

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DATA AVAILABILITY

Some or all data, models, are available via a in a repository in accordance with data retention policies of Port Houston and may be requested from the corresponding author by request.

ACKNOWLEDGEMENTS

Great appreciation to the USACE Galveston District leadership — *under the direction of Retired Col. Timothy Vail* — and Project Delivery Team, led by USACE Project Manager, Harmon Brown, Ph.D., and the Engineering Research and Development Center (ERDC) for their tremendous, strategic, and collaborative leadership throughout the entire design process. Other federal collaborative partners included Galveston District (Byron Williams, Rob Thomas, Chris Frabotta, Tim Nelson, Shakeel Ahmad, Melinda Fisher, Haley Tucker, John Campbell, Jake Walsdorf, Andrew Cook, Alton Meyer, Patrick Kerr, Thomas West, Belynda Kinman, Trisha Campbell) and ERDC (Jackie Pettway, Keith Martin, Cheryl Montgomery).

Houston Pilots for ship simulation participation, leadership, and proactive communication.

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MARYLAND DEPARTMENT OF TRANSPORTATION MARYLAND PORT ADMINISTRATION'S INNOVATIVE REUSE AND BENEFICIAL USE OF DREDGED MATERIAL PROGRAM

K. Keene [1] W. Dinicola [2]

ABSTRACT

Dredged materials are often viewed as a waste product and referred to as "dredged spoil." Today, with extensive physical, chemical, and geotechnical testing and in conjunction with new guidance from the Maryland Department of the Environment (MDE), dredged material is now recognized as a valuable resource. The Maryland Department of Transportation Maryland Port Administration (MDOT MPA) is providing national leadership on advancing the innovative reuse of dredged material through implementation of demonstration-scale projects and research studies. MDOT MPA has also successfully shown how dredged sediments can be beneficially used to restore aquatic ecosystems and rebuild lost island habitat.

MDOT MPA's long-term goal is to make sustainable innovative reuse and beneficial use (IRBU) programs and projects to address capacity recovery and implement management solution within Maryland's Dredged Material Management Program (DMMP), supporting the long-term success of the Port of Baltimore. Key components of this strategic plan include the advancement of policy, regulatory, technical, educational, stakeholder engagement, and program implementation objectives.

Keywords: dredged material, beneficial use, innovative reuse, dredged material placement, sustainability.

INTRODUCTION

The MDOT MPA DMMP addresses the Port of Baltimore's dredging needs through a rolling 20-year plan. The program is rooted in the Maryland Dredged Material Management Act of 2001 and benefits from the broad participation of citizens, scientific experts, regulatory agencies, and business partners. The DMMP uses a mix of strategies for managing dredged material, including wetland restoration, island recreation, upland placement, construction of carefully engineered containment facilities, and the innovative reuse of dredged material.

The State of Maryland has specific definitions of IRBU of dredged material. The statutory definition of innovative reuse "includes the use of dredged material in the development or manufacturing of commercial, industrial, horticultural, agricultural or other products." The statutory definition of beneficial use "means any of the following uses of dredged material from the Chesapeake Bay and its tributary waters placed into waters or onto bottomland of the Chesapeake Bay or its tidal tributaries, including Baltimore Harbor:

- The restoration of underwater grasses;
- The restoration of islands;

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- The stabilization of eroding shorelines;
- The creation or restoration of wetlands; and
- The creation, restoration, or enhancement of fish or shellfish habitats."

The Innovative Reuse Committee (IRC) is one of ten DMMP advisory committees that provide support and recommendations to the Port of Baltimore (Port) on the management of dredged material. The IRC was created in February 2006 to assist MDOT MPA with the development of a strategy for recycling and reusing dredged material from the Baltimore Harbor.

In 2014, MDOT MPA established the Innovative Reuse and Beneficial Use Strategy (IRBU Strategy), which was approved by the DMMP Executive Committee. The 2014 IRBU Strategy served as the roadmap for MDOT MPA to continue to develop meaningful reuse of dredged material and gain the recognition and support of dredged material as a valuable resource. After 5 years of substantial progress and input from the IRC, as well as other stakeholder groups, such as the DMMP Management Committee, MDOT MPA developed a refined 2020 IRBU Strategy. The 2020 IRBU Strategy outlines a goal to make long-term, sustainable IRBU programs and projects to address capacity recovery an implemented component of the DMMP in Maryland to promote the long-term viability of the Port.

The 2020 IRBU Strategy identifies 12 action items divided into four categories: 1) Policy/Regulatory; 2) Technical; 3) Education and Stakeholder Engagement; and 4) Program Implementation. Since executing the 2020 IRBU Strategy, MDOT MPA has made significant advancements that include successfully engaging regulatory agencies, stakeholders, and partners; establishing an IRBU web tool (https://maryland-dmmp.com/future-solutions/); and continuing to implement a series of the research and development (R&D) contracts aimed at converting Baltimore Harbor sediments into a marketable product.

REGULATORY GUIDANCE DOCUMENT DEVELOPMENT

As part of implementing the 2014 IRBU Strategy, MDOT MPA organized and established an Innovative Reuse Interagency Regulatory Workgroup (Workgroup). The Workgroup consisted of agency partners at MDE, Maryland Department of Natural Resources, MDOT MPA, and Maryland State Highway Administration, as well as the U.S. Army Corps of Engineers, Baltimore District; Maryland Environmental Service; Maryland Geological Survey; and various citizen and stakeholder partners. This Workgroup prepared recommendations on technical screening criteria and regulatory guidance for how to safely reuse dredged material in a manner protective of human health and the environment. From there, the state regulatory agency, MDE, reviewed and approved the recommendations and guidance on the appropriateness of dredged material, including material from Baltimore Harbor shipping channels, for various potential beneficial and innovative uses.

In August 2017, MDE released the *Innovative Reuse and Beneficial Use of Dredged Material Guidance Document* (Guidance Document; MDE 2017), which provides prospective end users a prescriptive method for reusing dredged material in Maryland in a manner that meets environmental and public health standards. The Guidance Document is a living document that allows for updates as needed and establishes a management framework for dredged material reuse that is based on end-use risks evaluating against the U.S. Environmental Protection Agency (USEPA) Regional Screening Levels (RSLs) for chemical concentrations. The Guidance Document guides prospective end users of dredged material through the various steps, permits, and approvals necessary based on the proposed project. It covers the sampling requirements, environmental and public health standards, and long-term management needs. It also describes four categories of risk-based management options for innovative reuse based on the USEPA RSLs. Risks are managed by ensuring that chemical concentrations in fill and dewatered dredged material are below levels that would cause health concerns for people who may come in contact with the material at its final placement location or end use.

In December 2019, MDE issued an updated version of the Guidance Document (MDE 2019). Primary changes involved two components of material management associated with locations where material may be processed for reuse and agricultural lands accepting material.

INNOVATIVE REUSE DEMONSTRATION PROJECTS

Test Nursery at the Cox Creek Dredged Material Containment Facility

MDOT MPA developed an on-site test nursery at the Cox Creek Dredged Material Containment Facility (DMCF) to determine the ability of dredged material to support the growth of grass seed. Seven separate nursery plots, each with varying ratios of dried dredged material, Leafgro (i.e., a local compost product), and lime, as well as a control plot of store brand topsoil, were established. Each plot was planted with the same grass seed mix in early October 2017 (Figure 1). Weekly monitoring occurred throughout the 1-year study. The results of the weekly vegetation monitoring demonstrated that the 100% dredged material and lime plot had the highest percentage of vegetation coverage of all the plots, and the 100% dredged material plot without lime had the second highest percentage of vegetation coverage.

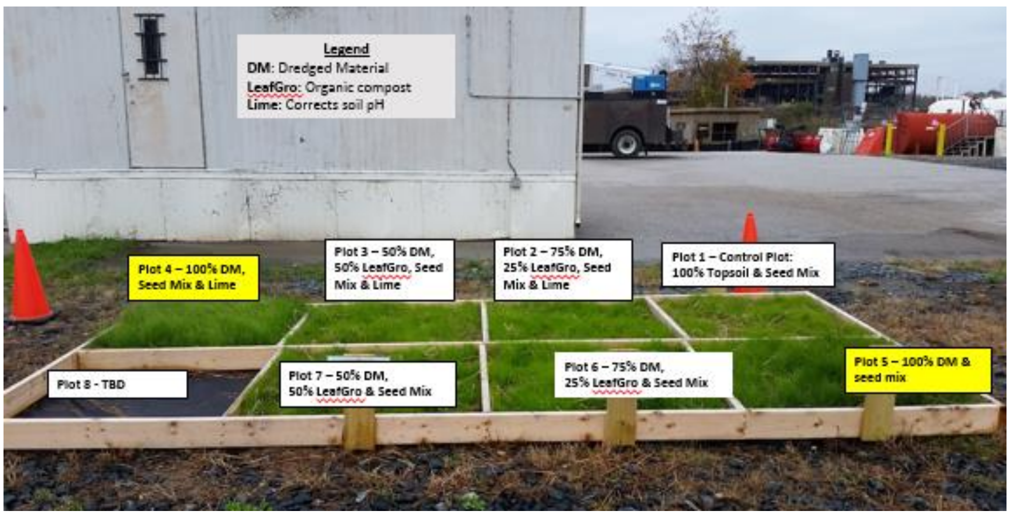

Figure 1. Test nursery at Cox Creek DMCF. Source: MDOT MPA.

Alternative Daily Cover at the Quarantine Road Landfill

MDOT MPA provided approximately 6,000 cubic yards (cy) of dewatered dredged material from the Cox Creek DMCF for use as alternative daily cover at the City of Baltimore-owned Quarantine Road Landfill (QRL) in December 2018 (Figure 2). Based on analytical testing results and landfill operator feedback, MDE provided approval for dredged material to be used as both alternative daily cover and intermediate cover. Although the demonstration project volume was 6,000 cy, the City of Baltimore has indicated that the potential annual cover needs range from 70,000 to 100,000 cy per year.

Figure 2. QRL daily cover. Source: MDOT MPA.

Engineered Fill at the Hawkins Point South Cell

In December 2018, MDOT MPA provided approximately 4,500 cy of dewatered dredged material from the Cox Creek DMCF for use as engineered fill in the development of the Hawkins Point south cell (Figure 3). Public and private sector representatives frequently request dredged material from the Cox Creek DMCF to be used as engineered fill.

Figure 3. Engineered fill at Hawkins Point. Source: MDOT MPA.

Remedial Capping Material at Ridgley's Cove

MDOT MPA used 22,000 cy of blended dredged material from the Cox Creek DMCF to aid in the upland restoration of Ridgley's Cove, a recreational asset adjacent to the middle branch of the Patapsco River, in spring 2021 (Figure 4). Material for the project consisted of 13,800 cy of dredged material from the Cox

Creek DMCF and 8,200 cy of excess fill material from the construction of the Operation & Material Complex at the Cox Creek DMCF. Ridgley's Cove will undergo onshore and offshore remediation in association with the mitigation requirements for Top Golf development in Baltimore City.

Figure 4. Remedial capping material at Ridgley's Cove Recreation Area. Source: MDOT MPA.

IRBU RESEARCH AND DEVELOPMENT REQUEST FOR PROPOSALS

The IRBU R&D Request for Proposals (RFP) was issued in November 2019. The RFP is for applied R&D projects to explore feasible means for reuse of material dredged from Baltimore Harbor channels and placed in the Cox Creek and Masonville DMCFs. These projects will give MDOT MPA an opportunity to better understand the potential for cost-effective capacity recovery of significant volumes within the DMCFs. As a result of contracts issued from this RFP, MDOT MPA will be evaluating lessons learned, adaptive management approaches, and scalability, with an eye on future opportunities to recover capacity in DMCFs. The intent of this program is to award multiple contracts, with each proposal not to exceed $300,000 and a maximum volume of 5,000 cy of dredged material to be allocated per contract. The current list of selected contractors are actively completing their projects and subsequent presentations to the IRC; completion of contracts are expected in 2022 and 2023.

Belden-Eco Products, LLC

Belden-Eco Products, LLC, seeks to transform dredged material from the Cox Creek DMCF into marketable brick and paver products with a patented technology that uses a variety of feedstocks and greatly reduces the energy inputs required for brick production, cost-effectively addressing the MDOT MPA dredged material containment challenge while promoting materials recycling and local manufacturing. They will use dewatered dredged material generated from the Cox Creek DMCF and combine it with other materials, such as Maryland-sourced fly ash, into various mixtures to develop ceramic bricks and permeable pavers. At scale, products could be marketed and sold as a stormwater management solution for the Chesapeake Bay watershed.

Northgate Environmental Management, Inc.

Northgate Environmental Management, Inc., will evaluate and demonstrate the feasibility of using dredged material from the Cox Creek DMCF as a raw material input for two categories of concrete products. Northgate Environmental Management will partner with Lafarge Holcim, a major materials manufacturer, to develop concrete traffic barriers, as well as Natrx, to employ 3D printing technology to manufacture modular shoreline protection structures. This diversity of shapes is expected to serve as evidence that the stable concrete produced can result in many more uses than developed on this specific project, further expanding the commercial viability of MDOT MPA's sediment use program. At scale, products could provide coastal stabilization and support for local transportation projects.

FasTrak Express, Inc.

FasTrak Express, Inc., will demonstrate the feasibility of using dredged material from the Cox Creek DMCF in the development of re-engineered soil for growing sod. FasTrak Express will collaborate with Full Circle Mushroom Compost; Mountain Materials, Inc.; and Central Sod of Maryland to procure dewatered dredged material generated from the Cox Creek DMCF, combine it with mushroom compost and sand, develop a preferred formulation, and apply material to test plots for monitoring. The re-engineered soil will be transported to a sod production farm facility where it will be applied to two 0.5-acre test plots, seeded with a fescue grass seed mixture, and maintained until mature enough to produce sod. A 3-inch layer of re-engineered soil will be spread on the surface of one of the test plots, while the other test plot will have 3 inches of re-engineered soil tilled into the upper 6 inches. The two test plots and control plot will be monitored via aerial imagery for a period to 12 to 18 months.

Susquehanna Concrete Products, Inc.

Susquehanna Concrete Products, Inc.(Suscon Products), will study and demonstrate the feasibility of using dredged material from the Cox Creek DMCF in various concrete mix designs for the production of general use concrete products such as retainer walls and low compression strength blocks. Suscon Products will prepare a number of concrete mix and controlled low strength materials mix designs by integrating different percentages of dredged material aggregates with other ASTM International-certified aggregates. Testing will investigate delayed setting, workability, and compressive strength to determine how the structural integrity and workability of concrete infused with dredged material compares to standardized mix designs.

Harford Industrial Minerals, Inc.

Harford Industrial Minerals, Inc., will evaluate and determine the efficacy of using dredged material as a feedstock to produce lightweight aggregate (LWA) such as lightweight expanded clay aggregate. The LWA produced using dredged material will be compared to existing commercially available LWA options with the goal of producing a comparable or superior and locally produced LWA product. At scale, this effort could provide a locally sourced and produced sustainable alternative to virgin aggregate material typically generated from quarries.

CSI Environmental, LLC

CSI Environmental, LLC (CSIE), is demonstrating the innovative reuse of dredged material to create and enhance coastal resiliency. Sediments from the Masonville DMCF will be hydraulically dredged, pumped as a slurry, and retained in CSIE mini-geotextile tubes. CSIE advanced polymers will be used to expedite dewatering of the dredged material pumped into the CSIE geotextile tubes. Upon achieving the desired degree of dewatering, the geotextile tubes will be loaded onto flatbed trucks and transported to the Baltimore Gas and Electric (BGE) Spring Gardens complex, located along the Middle Branch of the Patapsco River in Baltimore Harbor. Beneficial plant species will be placed directly in the geotextile tubes that form both the upland and shoreline berms. The planting of native plant species directly in the geotextile tubes promotes the desirable habitat and biodiversity consistent with habitat restoration goals associated with the BGE Spring Gardens. It is anticipated that the berms will provide ecological uplift and enhance the resiliency of the subject site.

DEVELOPMENT OF IRBU WEB TOOL

An important component of the 2020 IRBU Strategy involves addressing additional educational and outreach needs related to reuse of dredged material, as well as pursuing new partnerships with other government agencies, businesses, environmental advocacy groups, citizens, and private sector representatives to further the Port's IRBU program, and to develop guidance that will inform prospective end users of the requirements and procedures to obtain dredged material from a MDOT MPA facility. To address these and other needs, MDOT MPA developed an interactive and informative web tool (https://maryland-dmmp.com/future-solutions/) to serve as a one-stop shop for information related to MDOT MPA's IRBU program. The web tool also provides a formal process where prospective end users, can request dredged material, and project dashboard to track active and past IRBU projects (Figure 5).

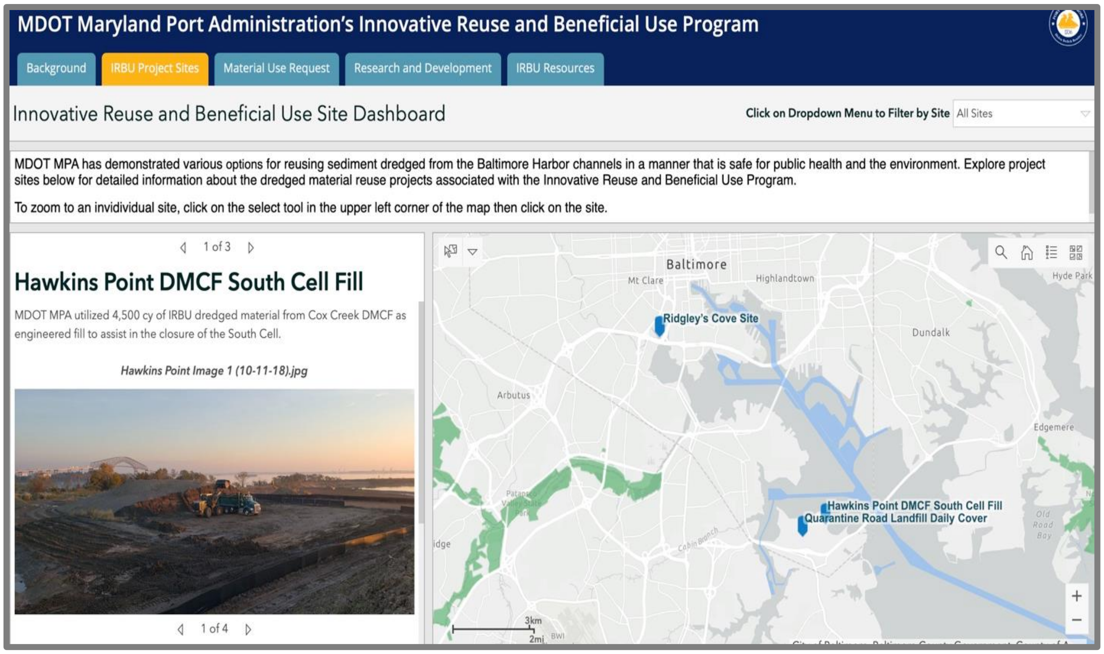

Figure 5. IRBU web tool. Source: MDOT MPA.

CONCLUSION

MDOT MPA's IRBU program is recognized as a national model and one with enormous private sector interest and potential. Reuse of sediment dredged from the channels serving the Port intended to be the future of the DMMP, especially as it relates to the long-term dredging needs within the Baltimore Harbor and opportunities for Port growth.

MDOT MPA is currently seeking to acquire additional property adjacent to the existing Cox Creek facility to advance dredged material reuse efforts and create additional marine terminal space. At the conclusion of the R&D efforts, it is MDOT MPA's goal to have built a foundation of potential private sector partnership, allowing for the competitive advancement of large-scale, long-term innovative reuse of Harbor channel dredged material, assuming additional property in close proximity to the Cox Creek facility is acquired by MDOT MPA. Additionally, MDOT MPA will continue to work with state and federal regulators to identify shared regulatory and technical needs in furtherance of the implementation of the Port's IRBU program.

In summary, a combination of strategic planning, technical implementation and stakeholder engagement has resulted in IRBU becoming a viable and sustainable dredged material management solution for the Port, with strong support from Maryland's Governor and Secretary of Transportation. Through continued implementation of the 2020 IRBU Strategy, MDOT MPA's sediment reuse program will continue to grow, advance, and build a lasting foundation to keep the Port open for business.

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CITATION

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DATA AVAILABILITY

All data generated or used during the study are available from the corresponding author by request.

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THE PORT OF HUENEME DEEPENING–A PROJECT 20 YEARS IN THE MAKING

Christina Birdsey[1], Jack Malone[2], and Steve Cappellino[3]

ABSTRACT

The Port of Hueneme (Port) is owned and operated by the Oxnard Harbor District (OHD), which was created in 1937 as an independent special district of the State of California. Implementation of the Port's deepening project required a long-term commitment from the OHD, the U.S. Army Corps of Engineers (USACE), and the U.S. Navy (USN), as well as unique approaches to overcome technical, operational, and funding challenges. This presentation describes the major engineering, planning, environmental, and funding elements that were required to make the project a success.

USACE's Port of Hueneme Deep Draft Navigation Study (Study) for the project was completed in 1999, but the project was put on hold in 2001 after sediment in multiple parts of the harbor were determined to be unsuitable for beach placement or ocean disposal. Collectively, the unsuitable sediments in the harbor maintained by OHD, USN, and USACE totaled approximately 288,000 cubic yards (cy).

Before the deepening could proceed, this sediment had to be removed from the harbor and disposed of in a cost-effective and environmentally protective manner. A range of options was evaluated, and the construction of a Confined Aquatic Disposal (CAD) site was selected as the best available alternative because it addressed the sediment management needs of all three parties. The CAD site was a cell excavated in beach-suitable sand in the turning basin of the harbor.

Dredging and construction of the CAD site were completed in 2009, addressing the unsuitable sediment so that deepening could proceed. Ten years of monitoring have demonstrated that the CAD site is performing as designed. USACE and OHD executed a Project Partnership Agreement and carried the project forward, and the Federal Channel was deepened in 2021.

OHD's strategic approach to pursuing grants for their berth deepening was successful in securing a U.S. Department of Transportation Maritime Administration (MARAD) Transportation Investment Generating Economic Recovery (TIGER) grant and an Economic Development Agency (EDA) grant that combined, allowed for the deepening of three of their berths. Deepening of two of the berths was completed in 2020, and the third berth will be deepened in 2023.

The Port fuels the U.S. economy through the annual import and export of more than $9.5 billion in ocean-borne freight. The Port serves as a vital niche market port for autos, fresh produce, general cargo, bulk liquids, and fish. It is currently the number one banana import port on the West Coast and the number six

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auto port in the nation. Harbor deepening increases the ability of OHD to meet the changing needs of global shipping and to continue to serve a critical role in the economy.

The significance of this project to Western Dredging Association members is three-fold. First, a long-term commitment among project partners and creative approaches to leveraging available funding sources and developing shared sediment management solutions was critical for project success. Second, a strategic approach to pursuing grant funding for large projects requires a disciplined investment of time and resources to be successful. Third, a CAD site is a cost-effective and environmentally protective sediment management approach.

Keywords: confined aquatic disposal, beneficial use, contaminated sediments, long-term monitoring, local/federal partnership

INTRODUCTION

The Port's deepening project is an example of the importance of long-term commitments of project partners to achieve large-scale transformative infrastructure projects. From concept to completion, the deepening project will have spanned more than 20 years. It required long-term commitment from the OHD, USACE, and USN as well as creative approaches to solve funding and contracting, engineering design, and environmental challenges. The end result is a deepened harbor that improves cargo efficiency, allows the OHD to meet the needs of the global shipping market, and benefits the environment.

HARBOR DEEPENING

Located approximately 60 miles northwest of Los Angeles, the Port is the only deep-water port between Los Angeles and the San Francisco Bay Area and is the U.S. port of entry for California's Central Coast region (Figure 1). The Port is owned and operated by OHD, which was created in 1937 as an independent special district of the State of California. The Port contains berths owned by OHD and USN and a Federal Channel maintained by USACE. All three entities are responsible for maintaining authorized navigation depths in the harbor.

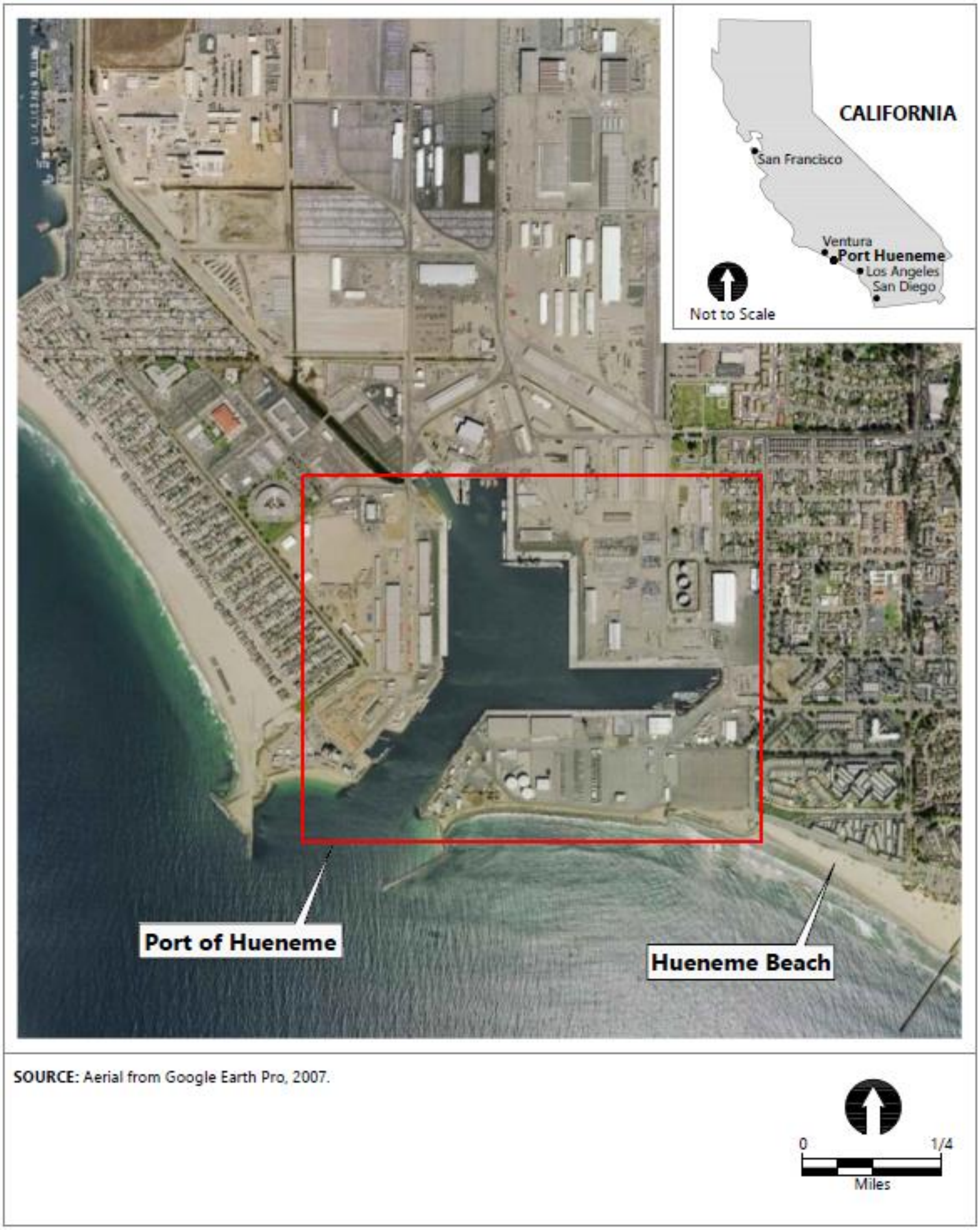


Figure 1. Site location map.

OHD Business Need for Deepening

The Port fuels the U.S. economy through the annual import and export of more than $9.5 billion in ocean-borne freight. The Port's primary exports and imports include automobiles, heavy equipment, bananas, other fruits and vegetables, and bulk liquids (fertilizers). The Port is the West Coast hub for bananas, importing more than 3.3 billion bananas a year and is also the West Coast hub for BMW. Bananas and BMWs imported at the Port are then distributed to 15 western states, creating tens of thousands of jobs along the supply chain throughout each of these states. Some of the bananas and fresh fruit are also then exported by truck or rail to Canada. The Port also handles domestic cargos including wetfish (California Market Squid) and vessel fuel. The Port's strategic location makes it a vital offshore oil support center, servicing platforms located in the Santa Barbara Channel. It is currently the number one banana import port on the West Coast and the number six auto port in the nation. Harbor deepening increases the ability of OHD to meet the changing needs of global shipping and to continue to serve a critical role in the economy.

As an economic engine for Ventura County, the Port makes strategic investments to enhance and improve its existing infrastructure to meet customer needs and increase the economic benefit to the region. Port growth does not happen in isolation. The Port's strategic partnership with the USN, USACE, Ventura County Transportation Commission Cities of Oxnard and Port Hueneme, and the California State Department of Transportation has worked tirelessly in their missions to improve mobility within the region and increase funding to meet transportation needs supporting the intermodal gateway to the Port.

The deepening increases the depth to which vessels can load and still service the Port. Under the current pilot regulations, ships calling the Port's terminals require 3 feet under keel to safely navigate the channel. With this restriction, without deepening, the maximum draft of a vessel calling at the Port's berths is 32 feet (35 feet less 3 feet for under-keel clearance). Deepening enables heavier loaded vessels to use the berths, increasing operational productivity in a time-sensitive market. Deepening the berths to 40 feet thus increases the efficiencies of each vessel. The increased depth will create greater capacity to handle the increases in demand driven by the automobile market. It will reduce bottlenecking in the fresh produce export and import supply chains and will improve economies of scale for private customers that are calling on the Port. The deepening not only addresses the current needs but prepares the Port for future growth as well.

Another benefit of deepening is reduced air emissions. Currently, prior to deepening, certain vessels were required to wait at anchor outside the harbor until high tide. Deeper berths enable these vessels to load with heavier cargo (reducing emissions per pound of cargo) and eliminating the need for them to wait outside the harbor running their engines, therefore reducing air emissions even further.

Evaluation of Sediment Management Alternatives

The USACE completed the Study in 1999 in cooperation with the OHD. The Study concluded that deepening the harbor was feasible and would increase cargo efficiency by allowing deep draft vessels to carry more cargo into the Port rather than "light loading" and berthing only during higher tides. The Study determined that deepening the harbor, including the approach channel, entrance channel, turning basin, and Channel A adjacent to the OHD berths, would require dredging of approximately 634,000 cy of sediment. The dredged material was proposed for beneficial use to nourish Hueneme Beach through direct or nearshore placement.

Following completion of the Study, in 2001 the USACE performed sampling to characterize the sediment to be dredged and determined that a substantial volume of the material was not suitable for beach nourishment. This determination stalled the project because of the lack of a cost-effective placement site for the dredged material.

By 2007 the OHD and USN berths had not been dredged for more than 10 years and had accumulated between 3 and 10 feet of sediment unsuitable for beach nourishment. Several areas within the USACE Federal Channel also contained shoaled sediments unsuitable for beach placement. These sediments were chemically characterized and found to be unsuitable for open-ocean or beach disposal, due in most cases to elevated concentrations of metals, polycyclic aromatic hydrocarbons, polychlorinated biphenyls (PCBs), dichloro-diphenyl-trichloroethane (DDT) and its breakdown products, and organotins, such as tributyltin. Collectively, the unsuitable sediments from the OHD, USN, and USACE areas of Port of Hueneme Harbor total approximately 288,000 cy.

The OHD was determined to develop a sediment management strategy to address the maintenance dredging needs and allow the harbor deepening to move forward. The goal was to remove unsuitable sediments from the berths and Federal Channel areas in the harbor and dispose of this material in a cost-effective yet environmentally protective manner. Because the unsuitable sediments were not appropriate for beach nourishment or open-ocean disposal, the only available off-site disposal location was an upland landfill; however, the costs of dredging, offloading, dewatering, transporting, and disposing of the dredged material at an upland landfill were prohibitive. In addition, transportation of the sediments to an upland disposal site would have resulted in substantial impacts to air quality, traffic, and transportation infrastructure. As a result, two on-site management options and one off-site option were evaluated.

OHD evaluated construction of an on-site confined disposal facility (CDF) or construction of an on-site CAD facility and off-site beneficial use of the sediment as fill material for large terminal development projects at the Ports of Los Angeles and Long Beach. The off-site option was removed from further consideration because the timing of the terminal development projects was uncertain and the distance between the Port and the other ports would have resulted in substantial transportation costs.

The two on-site sediment management alternatives had the benefit of proximity and allowing OHD more control over the project. The OHD evaluated potential locations within the Port to construct a CDF, which is an area designed to confine contaminated sediment to prevent release of contaminants to the environment. A CDF may be constructed on land, in the water, or in the water adjacent to land. Dikes or similar structures are often used to confine the sediment in a CDF. In coordination with USN, OHD evaluated potential locations within the Port to construct a CDF of sufficient size to accommodate the 288,000 cy of unsuitable sediment. Because of the relatively small size of the harbor, the already used upland space, and lack of a large development project requiring fill, construction of an on-site CDF was eliminated from consideration.

Following elimination of the CDF option, the OHD evaluated the feasibility of constructing a CAD site in the harbor. CAD is a containment method in which a natural or human-made subaqueous depression is filled with unsuitable sediment and capped with clean sediment or other materials such as stone or geotextiles. A CAD site is designed to accommodate a specific volume of sediment, and the cap is designed to control the specific contaminants of concern and external forces like scour from vessel traffic or bioturbation from benthic infauna. When OHD and USN evaluated the harbor for potential siting of a CAD, the turning basin was identified as a potentially suitable site. The turning basin provided an area offset from the existing wharves, and unsuitable sediment had not been identified in the potential CAD footprint. To verify the feasibility of constructing a CAD site in the turning basin, deep geotechnical explorations were performed, and the results indicated that the material in the turning basin was beach-suitable sand that could be dredged and beneficially reused for beach nourishment. In addition, the geotechnical properties of the sediment were suitable to support excavation of a large cell to accommodate placement of the unsuitable material and a clean cap. As a result of this evaluation, construction of a CAD facility in the turning basin was selected as the best available alternative.

Construction of a CAD cell provided numerous benefits in addition to being an on-site solution. The benefits included the following:

- It was not tied to other projects like large-scale terminal developments.

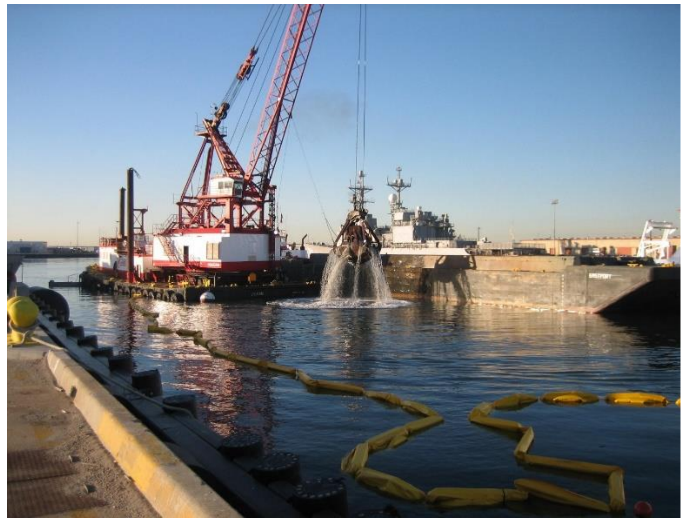
- It provided an environmental protective sediment management approach.
- It provided nourishment of a highly eroded local beach.
- It allowed the harbor deepening project to advance.
- Maintenance dredging restored 100% use of OHD and USN berths.
- It provided a complete solution for the OHD, USN, and USACE.
- It was a cost-effective alternative because the funds and resources of all three parties could be used.

Maintenance Dredging and CAD Project

The maintenance dredging and CAD project consisted of four main components:

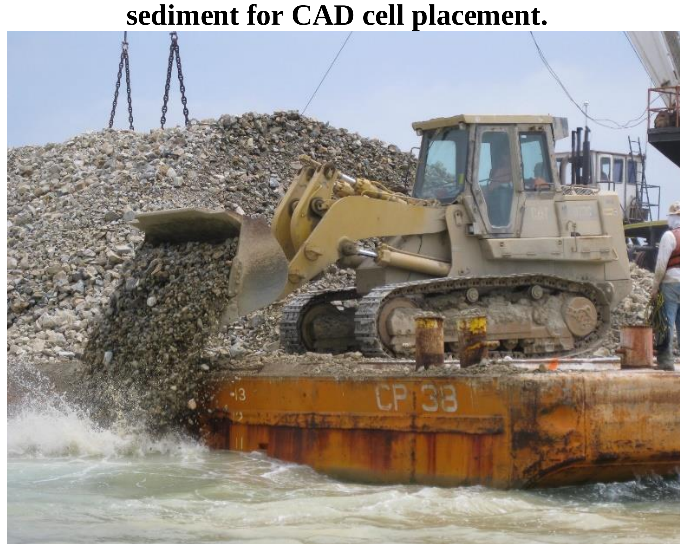
- Hydraulic excavation of the CAD cell with placement of the excavated clean sand on an adjacent beach (Hueneme Beach) that was severely eroded and in need of nourishment (Figure 2, Photograph 1)
- Mechanical dredging of unsuitable sediment with placement of the sediments into the CAD cell (Figure 2, Photographs 2 and 3)
- Capping of the CAD cell, by placing clean operations-and-maintenance- (O&M-) type sediments into the CAD cell
- Placement of armor stone on top of the sand cap to protect the surface from propeller wash erosion (Figure 2, Photograph 4)

Photograph 1. Nourishment of Hueneme Beach.



Photograph 2. Mechanical dredging of unsuitable sediment for CAD cell placement.

Photograph 3. Placement of sediment in the CAD cell.



Photograph 4. Placement of armor stone on the CAD cell.

Figure 2. Maintenance dredging and CAD project components.

Dredging was sequenced to place the unsuitable sediment into the CAD cell followed by "cleanup" dredging of areas adjacent to the CAD cell to remove any residual unsuitable material before placement of the clean cap and armor stone. Dredging and placement were performed while the harbor was in operation so coordination between the OHD, USN, and contractor were critical to maintain vessel traffic and construction. Figure 3 depicts the location of the CAD cell as well as the areas of unsuitable sediment and clean O&M sediments that were placed in the CAD cell. Figure 4 shows a schematic cross section of the completed CAD cell.

Figure 3. CAD project site plan key features.

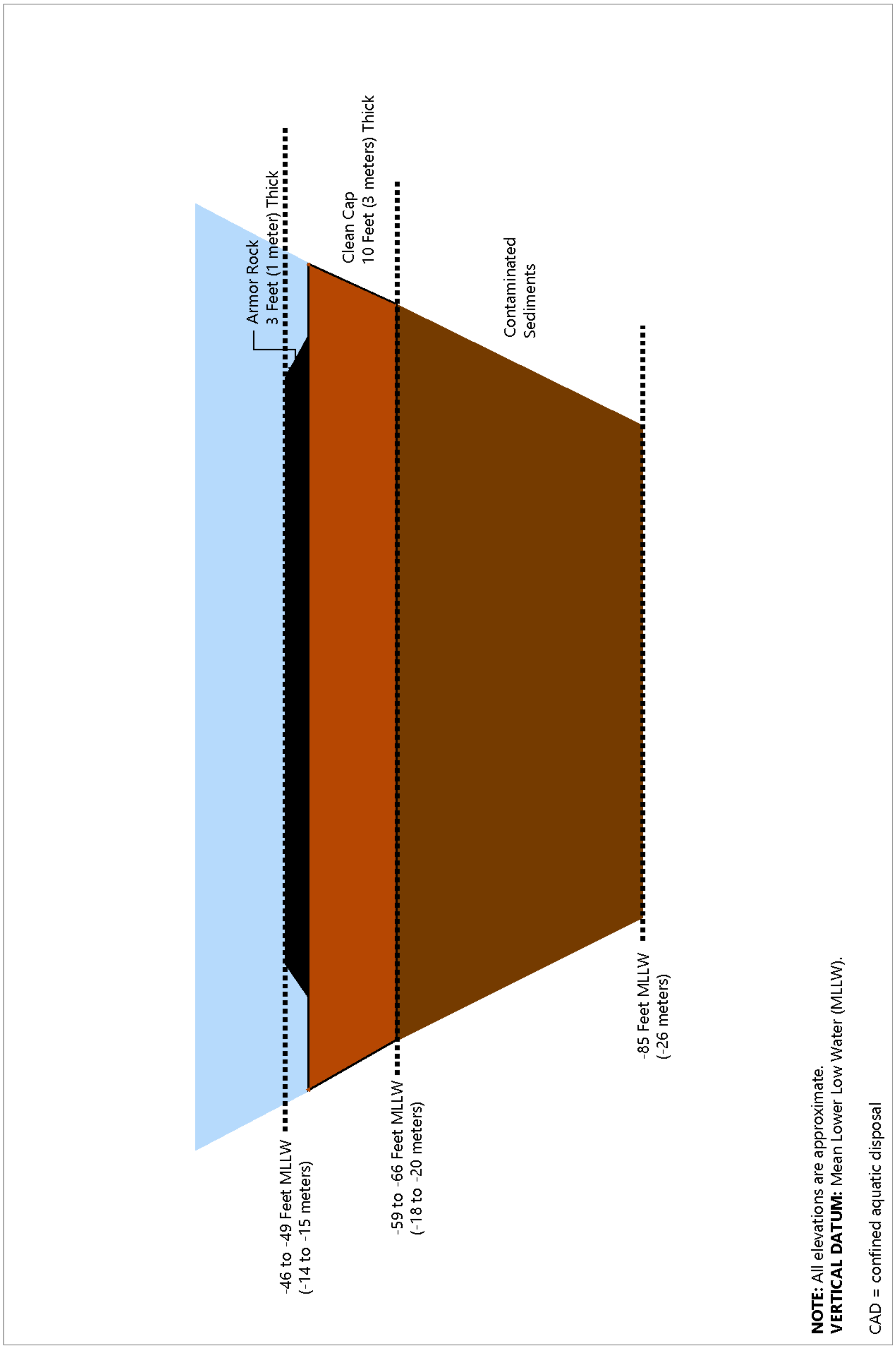


Figure 4. Schematic cross section of completed CAD cell.

Funding and Contracting Strategy

The CAD project required a creative funding strategy to leverage the available funds of all three parties. The primary funding challenges included raising sufficient funds, working within differing budget and funding schedules, and managing contractor negotiations and project scheduling. The parties were able to overcome these challenges because each entity had some funding allocated for dredging, the management and staff were committed to finding effective solutions to make the project work, and there was significant momentum to take advantage of the CAD alternative.

Cost sharing was achieved by dividing the project into isolated work elements and assigning responsibility for costs, as appropriate, to either a single entity (e.g., wharf dredging for the OHD), jointly to two of the three entities (e.g., CAD cell construction for the OHD and USN), or jointly to all three parties (e.g., construction management and environmental monitoring). Table 1 summarizes the allocation of costs among the three parties by project element. The costs were then fine-tuned to accommodate secondary cost-sharing strategies and funding schedules. This approach included balancing the costs to make the project more equitable among all three parties, accounting for unsuitable sediment ownership among the parties, and recognizing existing agreements between the parties.

To meet the requirements of all three parties in the short time frame available, the CAD project required a unique and innovative method of contracting. Agreements were developed between the parties, and existing agreements were used when possible. This approach avoided the need to create complex multi-party agreements that would have required lengthy legal review and approval at high levels within USACE and USN. OHD and USN led the engineering design and permitting effort for the project, while USACE led the contracting and construction effort, which occurred through modification of an existing contract. OHD and USACE signed a cost-sharing agreement for the project, and USN and USACE already had an existing cost-sharing agreement for dredging that was used. OHD and USN signed a cost-sharing agreement for construction and long-term monitoring of the CAD facility. Funds from OHD and USN were transferred to USACE for contracting and management.

Table 1. Summary of cost allocation.

Project Feature	**Responsibility**		
	USACE	**USN**	**OHD**
Project Development			
CEQA/NEPA Permitting		X	X
Engineering Design		X	X
Contracting			
Contract Management	X		
Construction			
Equipment Mobilization	X		
CAD Cell Excavation		X	X
Dredging USN Wharves		X	
Dredging OHD Wharves			X
Dredging “Hot Spots” within O&M Channel	X		
Capping	X		
Placing Rock Armor		X	X
Water Quality Monitoring	X	X	X
Sediment Confirmational Sampling	X	X	X
Construction Management	X	X	X
Post-Construction Activities			
Long-Term Monitoring		X	X

Key Design Elements

Key design considerations for the CAD project focused on construction of the CAD cell and dredging and placement of the unsuitable sediment from around the harbor.

CAD Design and Construction

Approximately 693,000 cy of sand was hydraulically excavated from the harbor's turning basin to create the CAD cell. The excavated sand was pumped directly to the adjacent Hueneme Beach that needed nourishment. The required dimensions of the CAD cell were determined by calculating the amount of unsuitable dredged material expected to be generated from the OHD, USN, and USACE areas, while leaving sufficient space for clean capping material (i.e., USACE O&M sediments). The CAD cell was excavated to a bottom elevation of -85 feet mean lower low water (MLLW), and approximately 288,000 cy of contaminated sediments were placed into the cell to an elevation of -59 feet MLLW.

Cap design and modeling efforts demonstrated that a 3-foot cap thickness would be sufficient for environmental protection and chemical containment. However, to add an additional degree of conservatism to the design, a 10-foot-thick cap layer was ultimately incorporated into the final design. In addition, a 3-foot-thick protective layer of coarse ("armor") stone was added atop a portion of the cap to resist erosive forces produced by propeller wash from military vessels, tugboats, and large commercial vessels in the turning basin.

To form the cap, 130,000 cy of clean sand was placed into the CAD cell, reaching an elevation of -49 feet MLLW. The placement of sand resulted in the top of the CAD cell reaching an elevation of -46 feet MLLW once the armor stone was placed (Figure 4), which accommodated the planned deepening of the harbor by the OHD and USACE.

Cap Chemical Isolation Analyses

A chemical porewater flux model was used to estimate chemical concentrations in the biologically available near-surface layer of the cap (i.e., the bioturbation layer) once long-term equilibrium conditions were achieved. The model predicted steady-state concentrations of sediment or porewater in the surface layer by applying mathematical formulas to represent the upward flow of dissolved contaminants through the cap, and the chemical processes that the sediments are predicted to undergo, including biodegradation and partitioning onto the cap material. The model also evaluated effects of mixing of the surface layer by benthic organisms. The chemical isolation performance of the cap was evaluated by comparing the predicted steady-state surficial concentrations to toxicity guidelines or criteria.

The estimated time to reach steady-state conditions ranged from approximately 2,400 to 277,000 years for a conservatively modeled cap thickness of 3 feet. With the actual cap thickness of 10 feet, approximately 8,000 years would be needed for the most mobile of contaminants present at the site (heptachlor epoxide) to move completely through the cap. These results suggested that the cap would be effective in isolating all contaminants for many thousands of years.

Estimation of Water Quality Impacts from Dredging

The potential for water quality impacts from unsuitable sediment dredging and disposal was estimated using the chemical and physical sediment characteristics and expected placement techniques (split-hull scow). Known sediment chemical concentrations were evaluated to estimate the potential for suspended sediments to contribute dissolved contaminants to the surrounding water column. In addition, the computer model Sediment Resuspension and Contaminant Release by Dredge (DREDGE; developed by USACE) was used to predict short-term water quality impacts at the point of dredging, and the computer model Short-Term Fate of Dredged Material Disposal in Open Water for Predicting Deposition and Water Quality Effects

(STFATE; also developed by USACE) was used to predict water quality impacts at the CAD cell during sediment placement by split-hull scows.

Model results suggested that water quality impacts would not be significant and that movement of suspended sediment from the CAD cell during placement would be minimal. Water quality monitoring during construction confirmed these predictions because no exceedances of water quality standards were observed.

Cap Stability Analyses

Wind waves at the CAD site were expected to be small due to its location within a protected harbor; therefore, the focus of the hydrodynamic analysis was propeller wash forces and scour acting on the surface of the cap. The characteristics of specific vessels using the harbor were applied to a hydrodynamic model to predict the propeller jet velocities. Operational information for typical vessels at the site, including tugboats, automobile vessels, and USN Destroyers, was obtained by interviewing local port pilots. It was determined that the USN Destroyers had the greatest potential to generate significant propeller wash forces and scour on the CAD surface.

The propeller wash model was used to predict the vessel-generated velocities on the surface of the CAD cell, assumed in this modeling to be at a conservative elevation of -42 feet MLLW. The USN Destroyers were predicted to generate a maximum bottom velocity between 9.2 and 12.5 feet per second. The scouring analyses indicate that this propeller-generated velocity would have the potential to generate scour holes in the proposed capping material. Therefore, to protect the cap from these forces, approximately 33,000 tons of armor stone was placed in a 3-foot-thick layer on the southwest portion of the CAD cell, where propeller wash forces were determined to be greatest.

Permitting Strategy

Dredging of the OHD and USN wharves and the USACE Federal Channel, as well as construction of the CAD cell, were subject to both California Environmental Quality Act (CEQA) and National Environmental Policy Act (NEPA) review. OHD acted as the lead CEQA agency, and USN acted as the lead NEPA agency. To meet the project timeline and make efficient use of resources, a joint document combining the CEQA Initial Study and Mitigated Negative Declaration with the NEPA Environmental Assessment was prepared. Because no significant impacts were identified in the environmental analyses, OHD completed the CEQA process by adopting the Mitigated Negative Declaration while USN completed the NEPA process by issuing a Finding of No Significant Impact to accompany the final Environmental Assessment. USACE was also responsible for NEPA compliance for the O&M dredging component of the project and prepared a supplement to its existing Environmental Assessment to analyze placement of sediment into the CAD.

The project also required permits from a number of state and federal agencies. USN and OHD acted as co-applicants to construct the CAD and dredge their respective berths in obtaining permits from the California Coastal Commission, USACE, and Regional Water Quality Control Board. USN acted as the lead federal agency for compliance with key regulatory requirements including the Coastal Zone Management Act, Endangered Species Act, Marine Mammal Protection Act, and National Historic Preservation Act. This approach streamlined the environmental review and permitting process because USN was able to rely on existing studies and baseline information as well as their own resource experts to provide detailed analysis of potential project impacts.

Project Timeline

To meet fiscal timelines and budget constraints of the three parties, the project had to meet an aggressive schedule. Conceptual design work on the project was initiated in January of 2007, permits and design documents were completed in August of 2008, construction began in December of 2008, and construction was completed in July of 2009. The project included more than 1 million cy of dredging and sediment placement.

Project Benefits

The CAD and maintenance dredging project resulted in several key benefits, the most important of which was providing a clear path for the harbor deepening project to proceed as the result of implementing a cost-effective method to manage the unsuitable sediment in the harbor. The project also resulted in beneficial use of sediment to nourish Hueneme Beach, which is a popular recreation area for residents and visitors to the Port. Coastal recreation is an important component of the City of Port Hueneme's economy, and OHD and the USACE look for opportunities to nourish the beach during dredging operations. Within the harbor, the dredging restored the berths and channels to their authorized depths, benefitting navigation and OHD and USN operations. In addition, as part of the cap construction, USACE was able to perform advance deepening of certain parts of the Federal Channel. The project cost was approximately $14 million, but the total project benefits to the region were estimated to exceed $30 million, even without the harbor deepening.

CAD Long-term Monitoring

Following completion of the CAD facility in 2009, a long-term monitoring program was initiated. Monitoring activities included annual bathymetric surveys, periodic collection of sediment cores and porewater from the cap, and testing of the cap sediment and porewater for contaminants of concern. The monitoring activities were successful in meeting the following three goals of the long-term monitoring program over the 10 years since the CAD was constructed:

- Confirming that the CAD cap is maintaining its physical integrity
- Ensuring fractures, erosion, or deposition do not compromise the cap's ability to sequester underlying contaminants
- Determining if contaminants are migrating through the cap at an unacceptable rate

The results of the long-term monitoring program demonstrate that sediments within the CAD continued to remain isolated from the water column and the benthic community (Anchor QEA 2020). The bathymetric surveys and physical and chemical analysis of the cap sediment and porewater provided quantitative evidence that the physical integrity of the cap has not been compromised and that chemical containment has been maintained. These monitoring results are consistent with those from a similar CAD project, the North Energy Island Borrow Pit (NEIBP) CAD Pilot Study, which has also used post-construction monitoring to evaluate cap integrity and sequestration of contaminants (USACE 2007). Sampling of the NEIBP CAD site 12 years post-construction demonstrated that the cap continued to retain its integrity and isolate contaminants from the water column and benthic environment (Anchor QEA and Everest 2014). The NEIBP CAD site 12-year monitoring results suggest that the patterns observed at the end of 10 years of post-construction monitoring are a good predictor of long-term cap integrity and containment of contaminants under typical environmental conditions in Southern California.

Berth Deepening

Completion of the CAD and maintenance dredging project paved the way for deepening of OHD's berths and federal channels to proceed. Berth deepening and the associated wharf improvements have been an objective in the Port's Strategic Action Plan and Capital Improvement Program because of their importance in meeting the OHD's long-term strategic goals. OHD pursued a phased approach to berth deepening to enable them to complete the work as funding became available. The OHD was also responsible for a portion of the cost of federal deepening pursuant to a Project Partnership Agreement with USACE, so local funding was required for the federal deepening as well.

Funding and Grants

OHD operates within a highly competitive global shipping market and must be strategic about infrastructure investments to ensure that they position the Port to be competitive in the future. Projects mandated to comply with environmental regulations, such as installing shoreside power infrastructure, require significant funding, and external events like recessions or global supply chain disruptions also affect the OHD's finances. The OHD has relied on tactical financial tools, such as grants, bond debt, and public-private partnerships, to overcome financial challenges and strategically position the Port to pursue grant opportunities such as the MARAD TIGER and EDA grant programs. OHD was successful in winning both TIGER and EDA grants to fund deepening of all three berths along Wharf 1.

Berth Deepening and Wharf Improvements

OHD prepared a CEQA Initial Study/Mitigated Negative Declaration and obtained permits for deepening of the entire length of Wharf 1, but phased construction to align with funding. The berth deepening entailed dredging from the current authorized depth of -35 feet MLLW to -40 feet MLLW, installing a sheet pile toe wall at the base of the wharf, and replacing the wharf fender system. The wharf improvements modernize the existing wharf to accommodate deeper draft vessels, mitigate the impact of a moderate seismic episode, incorporate existing shore power infrastructure investments, and ultimately increase cargo handling capacity. The improvements also allow greater capacity for heavier crane operations. These improvements support facility resiliency, a critical component of mitigating the effects of climate change within the working waterfront context.

Deepening of Berths 1 and 2 was completed in early 2020 and included dredging and placement of approximately 20,000 cy of sediment in the nearshore of Hueneme Beach for beneficial use for beach nourishment. A sheet pile toe wall and new fender system were constructed along the entire length of Berths 1 and 2, and repairs were made to the existing concrete deck. New bollards and wharf hardware were installed as well. Construction was carefully sequenced to minimize disruptions to vessel calls at the berths, while ensuring that lengths of the wharf were improved prior to dredging those areas so that the structural integrity of the wharf would be maintained. Berth 3 deepening is anticipated to begin in late 2022 or early 2023. Improvements to Berth 3 will continue the same depth and wharf improvements that were implemented for Berths 1 and 2, resulting in a consistent depth of -40 feet MLLW for the entire length of Wharf 1.

Federal Deepening

The federal deepening component of the project is an example of the importance of long-term commitments between project partners to ensure the success of large-scale, transformational projects. Following USACE's 1999 Study and 2001 sediment characterization, OHD, USACE, and USN committed to an innovative CAD project that would allow the harbor-wide deepening to proceed even though at that time there was no guaranteed source of funding for the subsequent phases of the project. OHD aggressively pursued grants to fund their portion of the project while the Los Angeles District USACE's staff and management worked tenaciously to ensure that the project remained active and viable despite the almost 20 years that had passed since the Study. Both OHD and USACE engaged elected officials and effectively communicated the importance of the project regionally and nationally to maintain support over the years.

Deepening of the federal channels was completed in June 2021 and entailed dredging approximately 386,000 cy of sediment, the majority of which (368,000 cy) was beneficially used to nourish Hueneme Beach. The remaining 18,000 cy of sediment were determined to be unsuitable for beach nourishment and were placed on the CAD as additional cap material. The approach channel was dredged to a depth of -44 feet MLLW and the Entrance Channel, Turning Basin, and Channel A (adjacent to the OHD berths) were dredged to a depth of -40 feet MLLW. The federal deepening provides a minimum depth of -40 feet MLLW from outside the harbor to the berths, making a critical connection for the OHD to realize the strategic advantages of harbor-wide deepening.

CONCLUSIONS

The most significant aspect of this project to Western Dredging Association members is that a long-term commitment among project partners is required to achieve large-scale, transformative projects. Without a commitment spanning more than 20 years, this project would not have been possible. A critical part of the partnership was a willingness to develop creative approaches to leveraging available funding and developing shared innovative sediment management solutions. Without that flexibility, the project would not have advanced past the feasibility stage. For projects of this magnitude, a strategic approach to pursuing grant funding requires a disciplined investment of time and resources to be successful.

From a sediment management standpoint, the CAD project demonstrated an innovative approach of combining the resources of OHD, USN, and USACE to create a single, complete solution to sediment management needs while minimizing costs. This solution achieved an efficient means of environmental protection by isolating the contaminated sediment within the harbor while also using clean sand to nourish Hueneme Beach. Construction and implementation of the CAD facility avoided significant adverse effects to air quality, transportation infrastructure, and traffic by eliminating the need to transport the contaminated sediment to an upland disposal facility.

The importance of the deepening project to the region is that through the harbor it enhances global maritime access to an integrated transportation system of railroad and highway routes. This multi-modal network offers shipping choices to manufacturers, growers, and distributors of agricultural and industrial products for both imports and exports. The Port provides connections to various inland means of goods movement so that carriers may reach markets throughout the southwestern U.S. As shippers choose the Port due to its depth and multi-modal capabilities, the region realizes economic advantages including decreased transportation costs, reduced bottlenecks in the import and export supply chains of produce and essential cargo, improved efficiency and reliability in good movements, long-term job creation, and increasing the competitiveness of domestic ports in a global economy.

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CITATION

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DATA AVAILABILITY

DREDGE and STFATE models are available online from the USACE Engineer Research and Development Center Coastal and Hydraulics Laboratory and may be accessed at https://dots.el.erdc.dren.mil/products.cfm?Topic=model&Type=drgmat

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INNOVATIVE APPROACHES FOR ASSESSING POST-DREDGE SEDIMENT DATA AND RESIDUALS MANAGEMENT DECISION MAKING ON THE GRASSE RIVER

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ABSTRACT

This paper describes an innovative approach that was developed to rapidly assess post-dredge surveys and sediment chemistry data to enable timely residuals management decisions on remedial dredging projects. This approach was implemented during remedial dredging on the Grasse River, and the approach is transferable to other similar remedial dredging projects. As is typical for environmental dredging projects, the Grasse River remediation included steps to verify the removal of targeted sediments and achievement of sediment cleanup objectives. The verification process included the collection of post-dredge sediment cores and analytical testing for comparison to cleanup standards. As has been widely demonstrated, post-dredge residuals exceeding cleanup standards often remain following initial dredging. These residuals must be addressed, either through additional dredging or other mitigation measures such as backfilling or capping. Given the cost and pace of remedial construction operations, it is imperative that post-dredge verification and evaluation be completed expeditiously to determine if additional work is necessary to address residuals. For the Grasse River, the project team developed a process to expedite the verification timeline through sample analysis at an on-site laboratory and post-dredge data assessment using custom-designed, automated data processing tools. This process enabled near real-time residuals management decisions. A critical component of the process was the early development and agency approval of a decision tree outlining the project compliance criteria and residuals management requirements. This post-dredge evaluation process resulted in development of consistent and high-quality verification packages that could be efficiently reviewed and acted on by the remedial construction team including the regulatory agencies, owners, design engineers, and construction contractors.

Keywords: Automated data processing, real-time decision making, contaminated sediments, environmental dredging, dredge verification

INTRODUCTION

From 2019 to 2021, the sediment remedial action (RA) for the lower Grasse River was performed, which included remedial dredging and engineered cap placement. To verify the removal of targeted sediments and achievement of sediment cleanup objectives, post-dredge sediment cores were collected and submitted for analytical testing for comparison to cleanup standards. The project team developed a process to expedite

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the dredge verification and enable near real-time residuals management decisions. A summary of the background information for the Grasse River Project, dredge verification requirements, and the tools developed to support dredge verification are described herein.

Grasse River Remediation Project Summary

The Grasse River Study Area (Study Area or site) is located along the northern boundary of New York State in the Town and Village of Massena and includes the lower Grasse River, which is a 7.2-mile stretch of river between the Massena Power Canal and the St. Lawrence River (Figure 1). The Arconic Corp. aluminum fabricating facility is located on the north shore of the lower Grasse River in Massena.

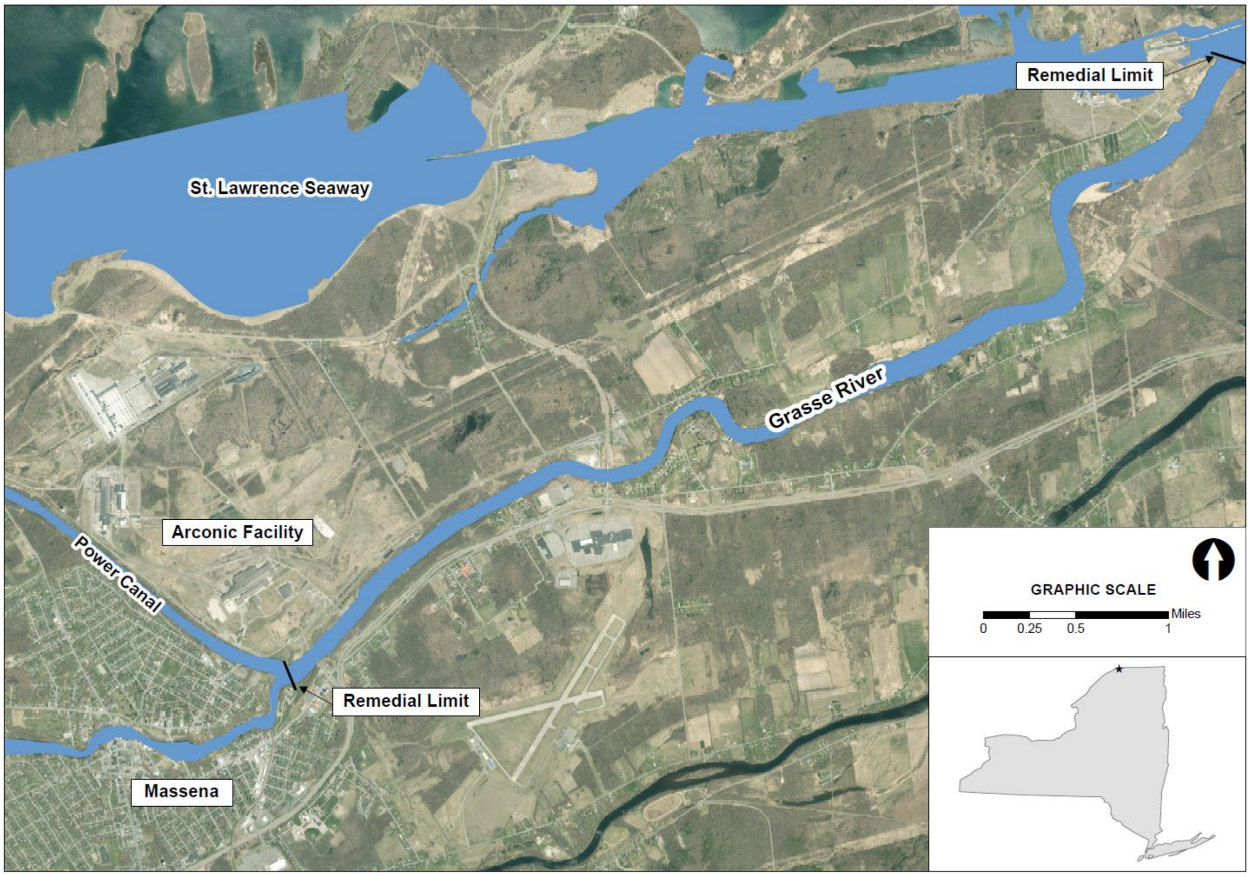

Figure 1. Grasse River Study Area – location map.

The U.S. Environmental Protection Agency (USEPA) selected remedy included the dredging of near shore polychlorinated biphenyl (PCB) impacted sediment, placement of an engineered cap in the main channel, and the dredging of main channel sediments along a navigation channel at the confluence of the Grasse River and Saint Lawrence River. The remedial dredging began in 2019 and was completed in 2021. Near shore dredging and post-dredge backfilling was conducted in 2019. Main channel dredging near the mouth of the river was conducted in 2020 and 2021, with backfill placement in 2021. Engineered cap placement occurred in 2020 and 2021. The Grasse River RA resulted in the removal of approximately 220,000 cubic yards (cy) of material from 48 acres of the river and the construction of a multi-layered engineered cap above 258 acres of PCB impacted sediment.

Dredge Verification Overview

As outlined in the Grasse River Construction Quality Assurance Plan (CQAP; Arconic 2021), a systematic management approach was developed for the planning, implementation, control, and assessment of work to ensure that the end results satisfied the technical, regulatory, and quality objectives for the completion of the RA. The CQAP was developed using the guidelines of *USEPA Requirements for Quality Assurance Project Plans* (USEPA 2001) and included the procedures, responsibilities, and requirements necessary for implementation and assessment of the RA work. Effective implementation of the quality assurance and quality control procedures outlined in the CQAP verified that the completed RA was in compliance with the provisions of project agency-approved plans and specifications. The verification plans and performance criteria for dredging addressed the following objectives:

- Verification that dredging achieved the horizontal and vertical extents required by the design
- Verification that dredging addressed sediments exceeding the project action level in designated dredge areas with appropriate measures for post-dredge residuals

The dredge areas were subdivided into 77 Dredge Management Units (DMUs) based on location and operational considerations to facilitate timely completion of activities within individual work units. In general, the DMUs were developed to target a design dredge volume of about 2,000 to 3,000 cy, which were estimated to require 5 to 8 days dredging based on an average dredge production rate of 375 cy per day per dredge.

To confirm that each DMU had been dredged to the design cutline, post-dredge bathymetric surveys were performed by the remedial contractor and submitted for review and approval by the engineering team. Upon approval, the engineering team provided information to the agencies that documented that the design elevations were met and notified the agencies that post-dredge verification samples would be collected in the DMUs.

Following acceptance of the cutline criteria, sediment cores were collected on a pre-defined grid in each DMU at a sampling density of eight cores per acre. Post-dredge sampling locations were offset from core samples collected as part of the remedial design and pre-design investigation. The sediment cores were advanced to refusal, and the recovered samples were segmented in 6-inch intervals. The core segments from the upper 18 inches (i.e., three segments; depending on core recovery) were analyzed for PCBs, and the underlying segments were archived pending the results of the upper segments.

The approach for interpreting post-dredge sampling results was outlined in the CQAP. Verification was assessed, and follow-up actions were determined based on the average PCB concentration for each 6-inch interval. Additional dredge passes were required when the post-dredge DMU average PCB concentration exceeded the project cleanup criteria. Re-dredge prisms were developed to target the sampling locations causing the exceedance of the project criteria and were delineated using Thiessen polygons. Re-dredging was not required in areas where the previous dredge pass encountered high subgrade (e.g., clay or rock) that prevented the remedial construction contractor from achieving the design dredge elevation. Once the post-dredge PCB levels met the applicable post-dredge verification criteria and USEPA approval was received, dredging in that DMU was considered complete, and backfill was placed, as applicable.

After dredging was completed, certification packages were prepared for each DMU to document that the survey and sampling data achieved the project requirements. The certification packages included checklists to summarize the results of the post-dredge elevation and PCB verification as well as supporting figures and tables. All DMU certification packages for were submitted within the construction year that work was completed and approved by USEPA in the same year.

Data Management

During the remedial design phase, the project team identified the need for innovative ways to efficiently process data during construction to enable near real-time management decisions and support a demanding construction schedule. This included a streamlined approach to collecting, organizing, analyzing, checking, and reporting the significant amount of data generated during construction.

Management of the environmental monitoring and verification data was led by Anchor QEA and included the design and planning of post-dredge sampling locations and techniques, coordination with field sampling crews and analytical laboratories, processing and validation of field and laboratory data, review by the engineering team, and data reporting to the project team and the agency stakeholder team. Anchor QEA used the EarthSoft EQuIS (EQuIS) environmental data management system and customized in-house applications to enable automated data loading, quality review, and reporting. Anchor QEA's data management system was designed to support accelerated turnaround times and rapid decision making based on high-quality data.

Arcadis led the field sampling and environmental monitoring efforts. The field teams used handheld tablets with the EQuIS Data Gathering Engine (EDGE) data collection application for documenting field observations, measurements, and sample information. Anchor QEA customized the EDGE electronic field forms to enable field crews to efficiently enter key sample information during sample collection. Digital field forms controlled data entry and automated sample ID generation so that field data were entered consistently and accurately. Sample labels and chain-of-custody forms were generated with EDGE, eliminating handwritten field documents and minimizing the risk of data transcription errors that could disrupt the timely flow of data from the field and laboratory into EQuIS. Additionally, field information was transmitted directly from EDGE EQuIS, which increased efficiency, quality, and availability of field data.

Pace Analytical Services, LLC (Pace), provided an on-site laboratory to analyze post-dredge sediment and environment monitoring samples. Using the on-site laboratory with dedicated technicians in the field enabled accelerated analytical results, optimized quality controls, and eliminated risks associated with shipping and scheduling conflicts with other projects. Typically, the laboratory was able to begin sample extracts on the same day as sample collection, and results were reported from the laboratory to the project team within 24 to 48 hours. To facilitate laboratory data reporting, Anchor QEA maintained an automated data loading system through which Pace could submit data electronically to EQuIS. This system further increased efficiency by reducing the manual labor required to manage laboratory data and promoted timely availability of laboratory results for analysis and reporting. The data loading system retrieved data packages from emails submitted by Pace and performed quality control checks for accuracy and completeness; automated error messages were emailed to Pace for data packages that were rejected based on these checks. Once loaded, analytical chemistry data underwent a batch-level validation process based on field and laboratory quality control results and were automatically qualified and flagged as validated to USEPA Stage 2A. Once data passed validation, tools developed by Anchor QEA automated data exports and reports to the project team. In general, data could be checked, loaded, validated, and distributed to the project team within roughly 1 hour of receipt when data passed the quality control checks and validation. The data management tools used during Grasse River construction significantly reduced data processing time and were critical to ensuring high-quality data for subsequent analyses and decision making.

Post-Dredge Sediment PCB Analysis

As has been widely demonstrated, even the most state-of-the-art dredging and excavation equipment methods have technical limitations that often result in contaminant residuals left behind that require further management to achieve the desired risk reductions (Bridges et al. 2008). These residuals are typically addressed through additional dredging or other mitigation measures such as backfilling or capping. Given the cost and pace of remedial construction operations, it is imperative that post-dredge verification and evaluation be completed expeditiously to determine if additional work is necessary to address residuals.

From 2019 to 2021, more than 2,000 sediment samples from more than 500 locations were collected, analyzed, and evaluated as part of the Grasse River dredge verification efforts. To enable efficient analysis of the sediment PCB data, Anchor QEA developed a series of tools using Esri ArcGIS (GIS) software coupled with the Python programming language to create a highly automated workflow. As indicated above, automated data exports were generated in EQuIS and distributed to the project team upon receipt and validation of field and laboratory data. These data were processed by the project team using customized Python scripts packaged within ArcGIS toolboxes, which automated the following for each DMU and dredge pass:

- Loading of sample coordinates and observations recorded by the field sampling crew
- Calculation of the area-weighted DMU average PCB concentration for each 6-inch depth interval
- Identification of any depth intervals and verification locations exceeding the project dredge criteria
- Generation of a map showing the sampling locations, PCB concentrations per sample interval, a verification summary table, and target re-dredge extents (based on Thiessen polygons) and depths (where applicable)
- Generation of tabulated summary of the area-weighted PCB concentrations for all sample intervals

Figure 2 provides an example output from the post-dredge PCB processing Python tool.

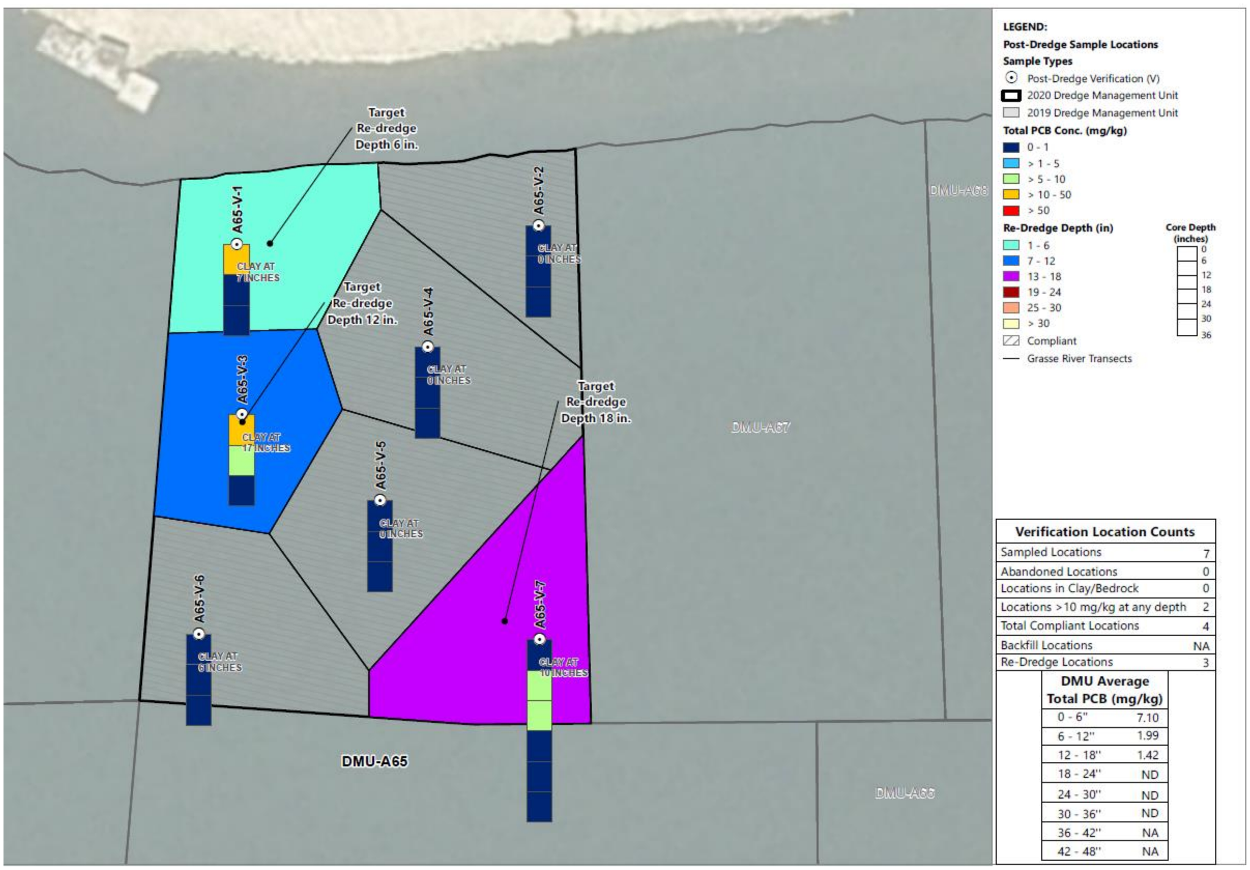

Figure 2. Example post-dredge PCB verification figure.

The PCB concentrations for each core's sample interval are displayed on this figure using stacked boxes. For this example DMU, re-dredging would be required at three locations, and the target re-dredge depths are indicated by the polygon colors and labeled on the figure. DMU verification statistics specific to the dredge pass are populated in the lower right-hand corner of the figure.

In conjunction with the processing of Figure 2, the Python tool also generated a table documenting the calculation of the area-weighted DMU average PCB for each 6-inch interval (see the example shown as Figure 3). Intervals that exceed the project criteria and the individual samples that caused the exceedance were highlighted orange. In this example, re-dredging would be required to target elevated PCB concentrations at locations A65-V-1, A65-V-3, and A65-V-7 within the 0- to 6-inch, 6- to 12-inch, and 12- to 18-inch depth intervals to decrease the DMU average concentration to below the project criteria.

Table A65 - Pass 1 PCB Data
Post-Pass 1 Area-Weighted Average Calculations by Depth Interval

Core ID	Depth	TPCB (mg/kg)	Area (sqft)	TPCB x Area
A65-V-1	0-6"	22	4521	99455
A65-V-2		0.7	4016	2811
A65-V-3		32	4687	149990
A65-V-4		0.04	6167	259
A65-V-5		0.04	5858	240
A65-V-6		0.8	5161	4128
A65-V-7		0.07	5809	378
		Total	36,218	257261
			DMU Average (0-6") (mg/kg)	7.10

Core ID	Depth	TPCB (mg/kg)	Area (sqft)	TPCB x Area
A65-V-1	6-12"	0.04	4,521	190
A65-V-2		0.04	4,016	173
A65-V-3		7.1	4,687	33279
A65-V-4		0.04	6,167	253
A65-V-5		0.04	5,858	240
A65-V-6		0.04	5,161	212
A65-V-7		6.5	5,809	37759
		Total	36,218	72105
			DMU Average (6-12") (mg/kg)	1.99

Core ID	Depth	TPCB (mg/kg)	Area (sqft)	TPCB x Area
A65-V-1	12-18"	0.04	4,521	190
A65-V-2		0.04	4,016	169
A65-V-3		0.30	4,687	1406
A65-V-4		0.04	6,167	259
A65-V-5		0.04	5,858	234
A65-V-6		0.04	5,161	206
A65-V-7		8.4	5,809	48796
		Total	36,218	51261
			DMU Average (12-18") (mg/kg)	1.42

Core ID	Depth	TPCB (mg/kg)	Area (sqft)	TPCB x Area
A65-V-1	18-24"	0.00	4,521	0
A65-V-2		0.00	4,016	0
A65-V-3		0.00	4,687	0
A65-V-4		0.00	6,167	0
A65-V-5		0.00	5,858	0
A65-V-6		0.00	5,161	0
A65-V-7		0.04	5,809	238
		Total	36,218	238
			DMU Average (18-24") (mg/kg)	0.01

Figure 3. Example post-dredge PCB verification table.

The following is a summary of the number of dredge passes conducted and the resulting post-dredge surface PCB concentrations:

- DMUs approved after the first dredge pass: 26 (11.7 acres)
- DMUs approved after two dredge passes: 40 (26.7 acres)
- DMUs approved after three dredge passes: 11 (9.6 acres)

- All 77 DMUs achieved the project criteria
- Post-dredge average PCB concentration in DMUs: 0.6 mg/kg

Individual evaluations of post-dredge PCB data for each DMU and dredge pass occurred a total of 139 times during the dredging portion of the project. The data processing executed by the Python tools in GIS typically ran in approximately 5 minutes or less. Subsequently, where necessary based on quality checks, limited adjustments were applied to data packages to account for the unique characteristics of a particular DMU.

Through the development of these customized tools, the project team was able to significantly reduce processing time and develop consistent and high-quality verification packages. The figures and tables generated by the Python tools were submitted to the project team to provide a clear and concise summary of the PCB results and required next steps. These materials were reviewed and acted on by the remedial construction team including the regulatory agencies, owner, design engineers, and construction contractors, and were critical to establishing agreements in a timely manner to maintain the aggressive construction schedule and minimize downtime.

CONCLUSIONS AND RECOMMENDATIONS

Successful execution of the data management system throughout construction was achieved through early and detailed planning and focused coordination and communication between the project team and laboratories.

The development and use of tools to automate data loading, quality controls, and reporting were critical in the generation of consistent high-quality deliverables, which allowed for near real-time residuals management decisions. Similar tools were developed to automate the processing of post-dredge survey data and cap verification data.

Through the support of these innovative tools, the project team was able to maintain an aggressive construction schedule. From 2019 through 2021, approximately 220,000 cy was dredged at an average rate of 740 cy per day.

Successful on-time completion of the RA would not have been possible without the support and timely reviews by the agency stakeholder team. Close communications with the agency team throughout the design and construction phases were critical in establishing guidelines and achieving efficient decision making.

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CITATION

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DATA AVAILABILITY

- EQuIS environmental data management system is a commercially licensed suite of application. Code developed to automate the loading and processing of data into EQuIS is proprietary.
- Data validation and ArcGIS-Python processing tools developed for the Grasse River Project and the resulting data reports are proprietary.

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MANAGING DEBRIS FOR ENVIRONMENTAL DREDGING PROJECTS

J. Beaver[1], M. Bowman[2], M. Ciarlo[3], M. Palermo[4], and D. Hayes[5]

ABSTRACT

Debris is an important factor in the investigation and project planning phases for environmental dredging projects. An understanding of the characteristics and extent of debris within the dredging footprint is essential to understand potential project cost; identify appropriate means, methods, and required equipment to remove and manage debris; provide environmental protectiveness during construction; and ensure remedy performance after construction. The urgency of effectively investigating and addressing debris issues increases as surface and buried debris volume increases, especially if concentrated debris pockets or zones exist, or if the types and sizes of the debris present specific challenges. Available technical guidelines and resources detail methods for identifying debris, but do not provide definitive guidance for managing debris and minimizing their impact on the 5Rs (Removal, Resuspension, Release, Residuals, and Risk) of environmental dredging. This paper synthesizes available resources on debris considerations, from characterization through remedy construction, to provide a common basis for identifying and evaluating debris issues for environmental dredging projects. The goal is to advance the state of practice for environmental dredging regarding debris-related issues including identification, classification, management, and disposal.

Keywords: Contaminated sediment, sediment remediation, navigation dredging, sediment removal, sediment management, multibeam bathymetry, side-scan sonar, post-dredging residuals.

INTRODUCTION

Defining Debris

Merriam-Webster[6] lists the essential meaning of debris as "the remains of something broken down or destroyed" or "things (such as broken pieces and old objects) that are lying where they fell or that have been left somewhere because they are not wanted." U.S. Army Corps of Engineers (USACE) (2015) described debris as "…large rocks, timbers, trees, trash, and other discarded materials…" and while both may be appropriate, the latter meaning is more appropriate in this context. Experience has shown that debris in waterways and water bodies includes a myriad of items, some uniquely local and others more common. The wide variety of items leads to an even wider variety of shapes, weights, and densities. Consider the differences in gathering 8-foot (2.4-meter) long timber, trees, shopping carts, concrete blocks, wire rope,

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[6] https://www.merriam-webster.com/dictionary/debris, accessed on 26 January 2022.

steel barrels, and 10 feet (3 meters) long steel pipes, for example, embedded in soft sediment, possibly even covered by several feet of sediment. Even abandoned vehicles have been found at some sites.

With that in mind, the authors propose this definition of debris in the context of dredging projects:

> "Non-sediment material(s) of limited intrinsic value scattered or clustered within the sediment matrix, either buried or on its surface, having characteristics such as being sufficiently large and strong as to potentially impact dredging operations intended to remove sediment and/or impact the managing activities of the dredged materials. Debris can range in size from very small objects to large obstructions that require special equipment to remove. Items may range in composition from organic to inorganic materials. Debris typically excludes non-sediment granular materials such as saw dust and spilled raw materials."

Materials such as unexploded ordnance (UXO) and historical artifacts or other items of cultural or archaeological significance are excluded from this definition and are beyond the scope of this paper. Debris is a concern for any dredging project; however, routine dredging that occurs in navigation channels lessens the time during which debris can accumulate. In contrast, environmental dredging projects, especially those at legacy-contaminated sediment sites, often occur in areas that have not been dredged in many years. Further, many environmental dredging sites are in urban or industrial areas with increased debris potential from a variety of sources. Debris in river and lake systems often includes trees and other wood debris transported by floods. Vegetation and root mat can also interfere with dredging and become entrained in the dredge material as debris. Among the challenges presented by debris, it is common for debris to be found buried well below the mudline, complicating identification, characterization, and removal.

Accumulated debris occurring in concentrated debris pockets or zones (also referred to as "dense debris") can be a major issue for environmental dredging projects. This extends beyond the challenges of dredging sediment containing occasional debris. Debris removal operations to address dense debris may require specialized equipment and support vessels. Debris removal operations may increase sediment disturbance, which may warrant supplementary best management practices (BMPs) to protect water quality and control residuals. Finally, the debris itself may be contaminated and require special handling and disposal. Unexpected quantities of debris can impact the project's cost and schedule. Although localized areas of dense debris sometimes exist, especially near public access points, debris is usually scattered throughout the sediment of waterbodies. Widespread distribution further complicates finding debris during the investigation and planning stages. The range of materials dimensions, densities, and weight associated with the debris exacerbates these complications.

Improvements in debris management strategies are needed to mitigate cost increases during construction, reduce project delays, and avoid impacts to environmental protection.

DEBRIS CONSIDERATIONS FOR ENVIRONMENTAL DREDGING

Types of Debris and Key Characteristics

A focused debris characterization system could facilitate improved debris management by providing common terminology that becomes adopted by practitioners. Debris could be described based on a variety of characteristics that relate to how debris affects dredging and sediment handling. For purposes of this paper, a matrix was developed listing commonly encountered debris items and categorizing them by the characteristics most likely to affect dredging (the debris matrix exceeds page requirements for the conference; however, it is available at the following link: http://thedredgingprofessor.com/debris-matrix-table. Key characteristics include the following:

- ***Size***—Physical dimensions of debris determine dredgability and handling needs. Long objects (i.e., pipes, pilings, board, etc.) can prevent bucket closure for mechanical dredging and stop rotating cutters. Wide items such as concrete slab and sheet metal can prevent bucket or cutterhead penetration, occluding access to targeted sediments beneath.
- ***Embeddedness—***Large objects may require removal prior to dredging. As such, their embeddedness in sediment is a key factor in how they affect operations. Pilings, relic seawalls, and abandoned pipelines or cables all present special challenges.
- ***Material Hardness and Density***—Materials such as rotted wood may be soft enough that buckets or cutterheads can shear even large debris into smaller, dredgable pieces ("debris items"). Alternatively, harder debris can cause problems even if debris items are small by preventing bucket penetration, jamming hydraulic screens, causing wear in transport pipes, and jamming pumps. Material that is light or buoyant can become dislodged and pose an obstacle during dredging or add to logistics necessary to manage the floating debris. Concentrated debris pockets or zones may be of such weight that it requires separate equipment for removal or specialized demolition techniques.
- ***Debris Distribution***—Concentrated debris pockets or zones ("dense debris"), as compared to widely distributed debris throughout the removal volume, may have differing logistics for removal. Debris impacts may or may not be similar. For example, significant quantities of medium-sized debris distributed throughout the depths of dredging may be removable by environmental or conventional mechanical dredge buckets (with potentially similar effects on resuspension rates, residuals generation, and dredging production rate), whereas concentrated pockets of medium-sized debris may require supplementary operations for removal. The latter may have some differing considerations for effects on resuspension rates, residuals generation, and dredging production rate.
- ***Environmental Concerns***—Some debris may be a source of chemical release or contain chemicals that require special handling or disposal. This may include creosoted pilings and rail ties, wood that has absorbed chemicals from surrounding sediments, cars or appliances containing oils and hydraulic fluids, and slag or coke containing metals or altered pH. While some of these can sometimes be managed using the same methods as for sediment, others may require special considerations based on the regulatory framework.

Using these characteristics, debris can be classified into common types. Size categories are nominally classified as large, medium, and small. In this effort, large debris is defined as greater than 6 feet in any one dimension, which is larger than the throat of many environmental buckets and sufficient to occlude materials from hydraulic removal. Medium debris is defined as debris between 2 and 6 feet in its largest dimension, and small debris less than 2 feet in all dimensions. The selection of 2 and 6 feet as nominal divisions is based on experience associated with debris management; however, these lengths should not be considered as precise or absolute. They are best described as guidelines.

Common debris materials that differ in hardness and density include: wood; stone and related conglomerates, including rock, concrete, slag, asphalt, or brick; metal (typically iron or steel); machinery, including appliances, cars, vessels, etc.; and other miscellaneous materials such as plastic or foam.

Debris Impacts on Dredging Operations

Debris can significantly impact the effectiveness, implementability, and cost of environmental dredging projects. It can interfere with dredge operations by impeding penetration, movement, and sediment capture, often requiring multiple removal attempts targeting the same sediment. Multiple dredging attempts reduce efficiency and the remolded sediment structure exacerbates impacts associated with the 5Rs of environmental dredging. Figure 1 illustrates the mechanisms of resuspension, release, and residuals as components of the 5Rs given the action of a single mechanical dredging bucket's interaction with the sediment bed. It becomes evident that additional interaction of the bucket and debris, whether dislodging additional sediment or preventing bucket closure, will be contributing to these mechanisms for each bucket cycle involving debris.

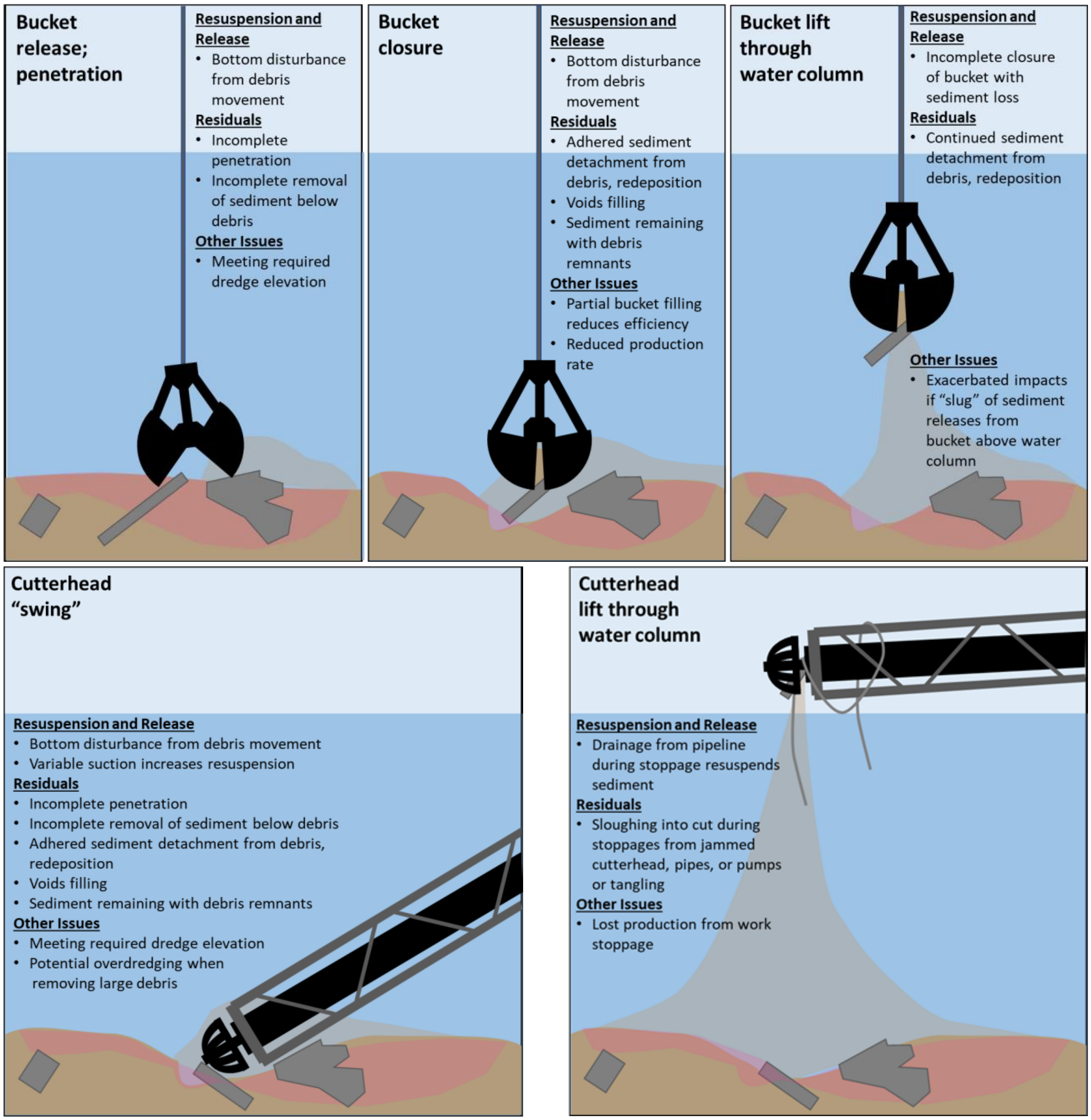

Figure 1. Schematics of debris impacts on environmental dredging operations.

Specific impacts are summarized in Table 1. A section of this paper is devoted to Debris Impacts on the 5Rs of Environmental Dredging.

Project Duration

Debris removal operations and implications on dredging production are discussed separately and are components that impact project duration. Changes to dredging sequencing and redredging are additional impacts to operational efficiency. The amount of redredging required as the result of a single debris item varies. In the best circumstance, the initial dredging attempt moves the debris from the targeted dredging area—either by removing it or pushing it to the side—and the second dredging attempt is fully successful at removing sediment in the area to the required depth. If that were always the case, a relatively straightforward statistical approach could be applied to estimate added construction duration. For example, if debris is expected to be encountered every 100^{th} bucket, then extending the schedule by 1 percent would theoretically cover the additional time required associated with debris.

Table 1. Debris impacts on resuspension, contaminant release, and post-dredging residuals.

Dredge Type	Debris Impact	Sediment Resuspension	Contaminant Release	Post-Dredging Residuals
Mechanical	Incomplete bucket closure	X	X	X
	Incomplete bucket penetration			X
	Unable to remove debris in same pass as dredging		X	
	Disturbance of surrounding sediment when debris is removed	X	X	X
	Disrupts clean cut between target and underlying sediments (loosens/softens for reduced sediment density)	X		X
Hydraulic	Failure to intake sediments			X
	Incomplete penetration			X
	Unable to remove debris in same pass as dredging		X	
	Disturbance of surrounding sediment when debris is removed	X	X	X
	Disrupts clean cut between target and underlying sediments (loosens/softens for reduced sediment density)	X		X

Dredging equipment is typically not designed for debris removal. Therefore, removing or moving the debris out of the dredge area does not routinely occur during the first contact. It may take several attempts for a clamshell bucket to “grab” one debris item sufficiently to raise it to the surface. An environmental bucket designed to provide complete closure to limit loss of sediment and often to provide level cuts for precision removal is relatively lightweight compared to a conventional clamshell bucket and may have difficulty grabbing and moving large or heavy debris. Large, heavy debris may even damage some buckets. Most buckets also have a closure pattern designed to contain soft sediment, which will be ineffective for any debris that is not fully contained within the closing bucket. It has become increasingly common for a separate conventional clamshell bucket or other attachments to be readily available (mobilized and on-hand at the project site) to deploy in the event the environmental bucket cannot effectively remove contaminated sediment with debris; even this approach has limitations when debris is not easily captured and held by the weight of the partially closed bucket. A cutterhead dredge may push debris out of the dredge path; however, the delay can be extensive if it gets caught in the cutter. If that happens, the dredge must shut down, the ladder must be raised, and a contractor must remove the debris from the cutter by hand. Debris may also become lodged in intake screens and dredge pump, pipeline, or sediment processing equipment. Such an operation could easily involve delays that range from a single starting and stopping cycle that slows production rate to a multiple hour event (or events). Such labor-intensive operations can also present significant safety concerns.

Failed dredging attempts can also destroy the sediment structure making it more difficult to remove due to lower density/higher mobility, possibly leading to sediment mobility caused by the dredge equipment disturbances, which may transport these materials from the dredging area. Consider, for example, a clamshell bucket that successfully snags a debris item in the process of capturing a full bucket of sediment that prevents complete bucket closure. It would be typical for most of the captured sediment to remain in the bucket while it is below the water surface. However, as soon as the bucket breaks the water surface, captured sediment will likely flow from the bucket with the water. While most of the sediment mass will likely resettle quickly to the bottom, some sediment liberated (i.e., resuspended) throughout the water column may be transported away from the dredging area by currents. Even if the bucket retains its grip on the debris and successfully removes it from the dredging area, the previously captured sediment now exists in a much lower density. Removing it again may require multiple additional dredging attempts, likely recovering only a percentage of the volume, thus contributing to the need for residual covers or sediment capping to achieve remediation goals.

Schedule delays and project cost increases resulting from debris impacts should be included in the project planning phase[7], or identified to owners as part of risk registers or contingency planning. The effect of multiple removal attempts resulting from the presence of debris on dredging efficiency is obvious; each additional attempt takes time and increases the project duration and cost. Even single digit percentages of increase can represent significant cost. In addition to cost implications, each attempt for debris removal may further impact the accumulating residuals and add resuspension events, which may reduce environmental protectiveness. Unfortunately, a proven method to reliably estimate schedule delays resulting from debris removal and management does not currently exist.

Debris Questionnaire Survey and Results

The authors believe experience-based feedback from practitioners engaged in environmental dredging for contaminated sediment remediation projects is important to fully understand the debris issues and some of its potential solutions. Thus, a survey was prepared to obtain both qualitative descriptions and site-specific details (and data if available) for projects that have included debris as a key factor during project planning or construction. Surveys were distributed to 10 experienced professionals, primarily environmental dredging contractors.

The survey consisted of two parts: four general questions and a project-based questionnaire. The four general questions are included as the numbered questions below along with a summary of the responses. The remainder of the questionnaire that examined additional details specific to individual projects is not provided in the conference paper due to page number requirements; however, this summary provides the primary feedback.

Six survey responses were received. Feedback from the general questions is summarized as follows:

1. In your experience, when projects involve debris as a significant technical and/or constructability consideration, what additional technical guidance and/or procedures are needed to address debris-related issues?

   Responses Summary: Additional technical guidance and/or resources are needed.
   - Technical guidance that provides a common framework for approved approaches to address environmental concerns for debris removal operations is needed. Currently, this can vary significantly among projects in differing regulatory settings. Are turbidity curtains required for pre-dredging debris removal operations? Can debris be placed on barges that allow the water to decant, or will all water in contact with debris require containment in barges and treatment? What means and methods can be identified as acceptable practice irrespective of location?
   - Detailed computations of debris quantity based on site-specific data, considering debris types and sizes, rather than generalized estimates developed during design should be made available to the dredging contractor. This includes characterization and quantification of surface versus buried debris.

[7] The use of the phrase “project planning phase” in this paper generally refers to the stages of the project following the investigation phase (e.g., feasibility study, design, and pre-construction bid support).

- Recognition in the design process that variable characteristics of debris materials should be considered when developing specific requirements and estimating costs, such as these examples:
  - Under the category of debris types, wood versus concrete considerations (removal and management of a disposal unit of wood are significantly different than a disposal unit of concrete).
  - Under the category of debris types, metal cable has special considerations, UXO has safety and handling considerations, historically significant artifacts have federal/state/local agency notification and requirements, and removal and management considerations
- Consistent application of considerations regarding impacts of debris on dredging operations, such as these examples:
  - Acknowledging needs for changes in operations in contract documents, such as provisions that allow alternative buckets to environmental buckets for large debris removal and/or when in areas of dense debris.
  - Additional overdredging allowance when buried debris occurs, especially large debris or concentrated debris pockets or zones.
  - Identification of special removal (pre-removal) and debris handling requirements (grapple) in contract documents.
  - Many others may apply.

2. What are some of the more significant issues you have encountered with debris that could be better mitigated during the investigation and planning phases prior to construction?

   Responses Summary: Significant debris issues that have been encountered on projects may be partially or fully mitigated with debris investigations prior to construction. Examples of significant debris issues or implications were provided.
   - Avoid requirements for contractors to investigate debris during bid period or during construction—insufficient time is available during the bid period and, although during-construction methods such as test pits and diving may be useful, the timing of these approaches is problematic for planning appropriate logistics and, as a result, project costs and schedule may be impacted.
   - Larger-sized debris may necessitate separate removal equipment and crews.
   - Additional BMPs such as bubble curtains and/or supplementary turbidity barriers, increased maintenance and repair activity for BMPs, and additional water quality monitoring may result.

3. With projects involving debris, have you found the challenges are more commonly related to contractual issues (quantity of debris and cost implications, lost production, cost of additional logistics) or the impact debris can have during dredging operations such as water quality impacts, dredge residuals generation? Or is it both? The remainder of the questionnaire can be used to elaborate with examples.

   Responses Summary: Both contractual issues and operations impacts are common when difficult debris conditions are encountered.
   - Projects often transfer risk to the contractor in technical requirements for operations and/or payment structure as lump sum for debris.
   - Achievable production rate and logistics for management and disposal operations may be impacted by debris, which directly involves bid price assumptions that would justify change orders.

4. Have dredging projects you are experienced with required special handling and disposal operations for certain debris(?); if yes, please explain. Additionally, what is the most common handling and disposal processes for dredged debris for your projects?

   Responses Summary: Yes, special handling and disposal requirements are common.
   - Landfills may require special sizing or separation.
   - Special transportation requirements may apply.
   - Archaeological items and UXO require special removal, handling, and final disposition. Significant impacts to project schedule and cost may occur if encountering these items unexpectedly.
   - Metal recycling may be applicable.
   - Local authorities may become involved under certain circumstances (e.g., if recovering automobiles or if debris includes weapons or other materials, additional time for police investigation or inspection may be necessary).

The overall summary of the remaining project-specific viewpoints is as follows:

- Construction project requirements should balance risk between the owner and contractor (e.g., with approach to payment: reduction in added cost for contingency for debris operations may occur by using fixed unit price per ton payment approach, using time and materials, or using a daily rate when significant debris is encountered).
- Investigations for surface and buried debris during design phase are important, using a range of technologies; investigations prior to construction may aid in understanding debris impacts and increasing efficiency and cost-effectiveness of operations.
- Debris impacts production for both mechanical and hydraulic operations, binding cutterheads or clogging dredge pumps/manifolds, sediment losses from buckets requiring additional cycles, etc.
- Debris impacts material handling by posing several challenges (e.g., is there special handling and disposal requiring segregation of certain fraction of debris [metal, artifacts, munitions])?; does debris management require processing such as chipping wood or cutting down large pieces?
- Water quality impacts and increased dredge residuals may occur due to debris; if separate debris removal operations are required, BMPs may be necessary to manage turbidity, etc.

DEBRIS IDENTIFICATION METHODS

Developing a comprehensive understanding of debris quantity, types, and sizes for both surface and buried debris is an important goal during the investigation phase. While debris investigations benefit most projects, they are particularly valuable for projects with known or suspected debris issues or when historical site uses imply a high probability of significant debris item quantities and/or concentrated debris pockets or zones. The appropriate range of equipment types and expected operations for managing both expected and unexpected debris should be considered during the feasibility study to provide a more complete remedial alternative; therefore, the remedial alternative's dredging, material management, and disposal process is more accurately predicted, and a more representative cost estimate may be prepared for comparisons. A more complete understanding of debris from the investigation phase may also influence the selected remedial alternative. The project's selected remedial alternative may then include an additional debris investigation in support of the design, facilitating greater confidence in the estimation of debris removal and management activities that will be required during construction.

Investigation technologies that may provide data to support identification and characterization of debris are listed below. Table 2 provides a summary of debris investigation technologies, the limitations associated with each technology, and the applicability/relevance to specific types of debris or project conditions. Although not included in Table 2, initial research of the site's history can provide considerable insight into potential debris and aid in developing the scope of debris investigations.

Debris investigations are primarily field methods that are commonly phased so the cost of obtaining additional detail can be weighed against the cost of potential debris-related impacts to project costs. Hydrographic surveys provide bathymetric information essential for almost every project. They also provide data that may help identify surface debris. The size and frequency of potential debris identified by hydrographic surveys can be combined with site location and site history information to map suspected debris locations and provide generalized estimates of debris characteristics for further investigation. Project planners can weigh the value of higher resolution surveys to further refine debris characteristics at each specific project phase.

Table 2. Summary of Debris Investigation Technologies

Investigation Method	Description	Interferences or Limitations	Applicability for Debris Identification and/or Characterization
Multibeam Bathymetry (Hydrographic Survey)	Acoustical energy method typical for project investigation phase, which can also be used to identify debris or features suspected as debris. Sonar reflections on the bed of the water body are digitally processed to map the surface.	Shallow water depths may reduce effectiveness. For remediation projects, both single beam and multibeam configurations are suitable for providing bathymetric mapping; however, for debris investigation, the multibeam configuration is necessary for debris identification.	Applicable for surface debris, not buried debris. Debris must be above sediment surface and large enough and/or distinctly shaped to be interpreted from the surrounding sediment surface. Most useful for large and some medium debris sizes. An advantage of using bathymetry for initial debris screening is that given most all projects include this data collection in the early stages of investigations, it provides an opportunity for early identification of large surface debris and may identify debris-like features that warrant further investigation.
Side-Scan Sonar	Acoustical energy method, using active sonar to scan and map bed surface features. Technology can produce a high-resolution image of the bed surface and debris.	Shallow water depths may reduce effectiveness. For some systems, deep water conditions may present challenges with resolution.	Similar to bathymetric survey; however, data density provides a higher resolution of bed features. Large and some medium-sized debris is identifiable if there is a sharp contrast with surrounding sediment. Very precise mapping of surface texture allows for improved identification of debris type and size.
Magnetometer	Local changes in the magnetic field are measured for changes in field strength given presence of ferrous metals.	Significant interferences from sheet pile bulkheads, steel piles, and metal structures may occur if surveying for metal debris in sediment.	May identify anomalies, but likely requires further investigation to confirm and characterize debris. Anomalies without further investigation may be used in the project planning phase, but this may result in unexpected debris conditions during construction.
Electromagnetic Induction	Electrical current transmission to a pipe or wire occurs without direct contact, and a receiver analyzes the signal to determine metal position and depth.	Interferences from metal objects may occur. Pipes without good metal-to-metal connection, broken wires, or breaks in the utility will limit effectiveness. In the coil configuration, can be used to locate ferrous and non-ferrous objects in subsurface (e.g., UXO survey, metal debris, etc.).	May effectively identify utility crossings and allow some estimation of cover depth. Results typically have a range of confidence with data interpretation. Higher confidence interpretations may allow establishment of offsets for dredging. Similar to magnetometer regarding results in terms of anomalies or detections that require further investigation and/or verification.
Sub-bottom Profiling	Acoustical energy reflections from differing sediment (and subsurface geology) densities produce sonar reflections with differing return times to the instrument. High frequency energy may penetrate further than low frequency energy.	Attenuation of energy by sediment may lessen penetration. Gas may leave voids in data. Reefs, rock, or very dense materials may produce a strong return preventing further penetration.	Limited applicability for debris survey. Strong contrasts in density and composition may result in changes in the magnitude of energy reflection occurring in the subsurface. Most often this technology is used to determine distinct geologic layers below soft sediment deposits but may also identify "anomalies" that may signify debris. Further investigation is required to identify and characterize the anomalies. May have limited effectiveness with large-sized buried debris.
Remotely Operated Vehicle Videography and Photography	Controlled vehicle positioned at specific locations or surveyed along transects to record videos or photographs of objects. Light source is provided.	Turbidity in water will impact visibility.	Applicable for surface debris, not buried debris. Ideal as a secondary exploration technology to refine understanding of debris identified using other technologies. Effective for localized investigation, but not practical for use over large areas. If surface debris is encountered and sufficient proportion of the debris is exposed and observable given the orientation of the remotely operated vehicle, the video may provide a relatively high degree of confidence for identification and characterization of the debris. A remotely operated vehicle can combine other remote sensing with videography, etc.

Diver	Certified and experienced dive team may investigate specific features such as near waterfront structures, or further investigate anomalies identified by other technologies to identify and characterize the debris.	Turbidity in water will impact visibility. There are numerous safety considerations for methodology; additionally, environmental suit and specific equipment types are required to isolate diver from sediment and water column for environmental remediation projects.	Applicable for surface debris, not buried debris. Due to potential hazards, only visual inspection may be appropriate, rather than disturbing sediment to attempt a better view of the debris. Effective for localized investigation, but not practical for use over large areas. A clear water box can be used in turbid water to improve visibility of the features. A diver can become the "survey vessel" for high frequency sonar to image structures or debris.
Test Pits	Test pits during in-water work may be accomplished by barge-based excavator or by dredging equipment before production dredging begins; therefore, equipment mobilized by the contractor is used for the investigation.	This method should be employed after other debris investigations have occurred during the project planning phase, at the start of the construction phase if cost-effective. Resulting data provides distribution of debris in sediment; also, allows direct observation of debris types and sizes.	Effective investigation method for refining contractor means and methods; however, the focus of the investigation at the construction stage of the project would be for improving efficiencies or, for example, verifying anomalies from other investigations (to confirm or adjust debris removal and material management activities). This should not be the primary method for debris investigation.

Figure 2 is an example of large debris identifiable by multibeam bathymetry. The automobiles are evident given both the debris size and the technology's ability to scan the entire surface of the sediment bed at high resolution. An additional technology that can be coupled with hydrographic surveys is side scan sonar, which provides even more of a three-dimensional perspective of the sediment bed surface, contributing to identification of debris and some characterization of type, size, and quantity of the debris. A more complete understanding of surface debris conditions may improve predictions of buried debris conditions, but this should not be expected to provide accurate quantity estimates. Methods such as side scan sonar and sub-bottom profiling may identify some fraction of the buried debris, leaving the potential for significant unexpected debris to be discovered during construction.

Quantifying approximate locations, sizes, and characteristics (e.g., density) of debris leads to cost-savings for many projects by leading to the development of the efficient logistics for debris removal, management, and disposal. In addition to facilitating contractor selection of the appropriate equipment, etc., more significant changes to typical dredging operations such as adding pre-dredging debris removal of large debris items or concentrated debris pockets or zones can be included among expected project costs. Despite adding to project costs, this separate operation may provide overall cost-efficiencies for dredging. Even if pre-dredging debris removal does not occur, plans can be developed in advance for removal and management of known debris during the dredging operation.

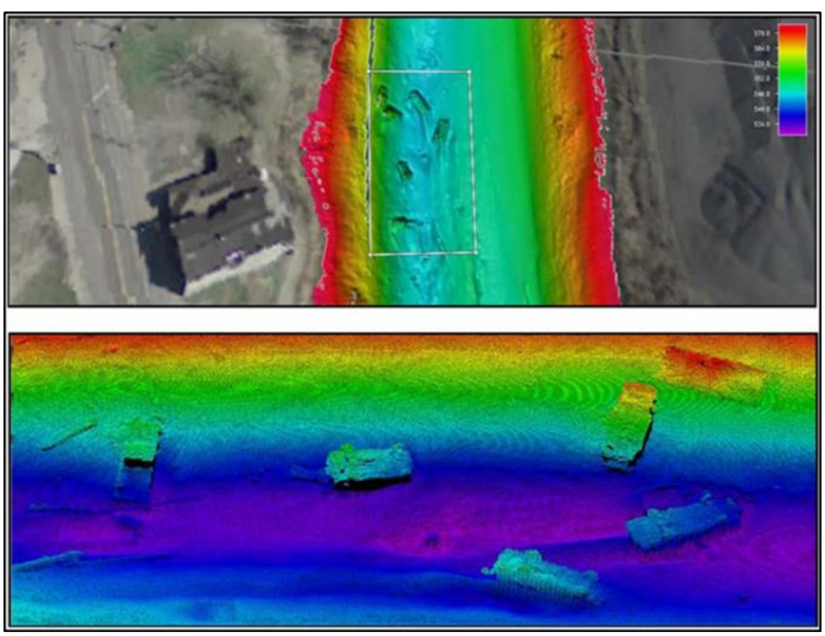

Figure 2. Images from high-resolution multi-beam sonar showing debris.

However, it is unrealistic to expect technologies to precisely locate, identify, and characterize all debris using current methods. Buried debris is particularly challenging. Thus, most environmental dredging operations will encounter some amount of "unexpected debris" that must also be managed, and this debris quantity is unlikely to be addressed during pre-dredging debris removal operations.

PRE-DREDGING DEBRIS REMOVAL AND MANAGING DEBRIS DURING DREDGING

Removal Equipment and Strategy

The primary considerations for the approach and timing of debris removal are the physical characteristics of the debris and its final disposition. Requirements for debris separation from sediment and processing for disposal/recycling/reuse are significant drivers for determining the most appropriate means and methods employed for debris removal. While a detailed discussion of sediment processing approaches is beyond the scope of this paper, it is important to note that a thorough understanding of the extent and type of debris management operations that are necessary, such as debris washing, screening, shredding, crushing, and grinding, is paramount for determining effective means and methods for debris removal.

Equipment and Methods for Removal

Common equipment attachments used for debris removal on dredging projects include excavator buckets, thumb attachments, fork/tine grapples, orange-peel grapples, and clam shell buckets on excavators or cranes deployed on platform barges. Examples of debris removal equipment are provided in Figures 3 through 5. This equipment is readily available to the contractor and effective for the removal of a variety of small to medium-sized debris types. Environmental buckets (excavator bucket with an actuating lid) frequently used for mechanical environmental dredging are capable of picking and removing some light debris materials; if this is successful, it may reduce the need for separate debris removal equipment, thereby avoiding the loss in efficiency associated with changing attachments on the dredge equipment. It should be noted, though, the efficiency of using an environmental bucket for debris removal diminishes quickly with increasing debris weight, size, quantity, occurrence of concentrated debris pockets or zones, as well as shapes of debris incompatible with typical removal equipment.

Less common attachments for debris removal include weed rakes or skeleton baskets that are sometimes used for cobbles, rocks, and vegetation. Hydraulic shear attachments may be used to cut root mass, stumps, and trunks of trees embedded in the banks (or submerged in the dredge area) to minimize waste generation, maintain bank integrity, and size debris. Vibratory pile pullers are employed for removing wooden and steel structures and piles. Contractor have been innovative developing site-specific debris removal approaches. For example, Sevenson Environmental Services, Inc. (Sevenson) designed and developed a rotating screen bucket (pictured, Figure 3) to separate cobbles from sediment during dredging. Ultimately, the equipment and attachments used will depend on the range of debris characteristics, sizes, burial depths, and distribution expected to be encountered at the project site. Specific to hydraulic dredging equipment, cutterhead baskets and chain ladders cutterheads have been used to reject and move large debris away from the pumping zone (USACE 2001). In some instances, debris removal operations can occur from the bank of the water body (particularly along rivers where debris naturally accumulates at the water's edge) using conventional heavy equipment (e.g., excavators). This approach can be advantageous in shallow areas where access may be limited to barges until dredging has commenced. Divers may also be used to facilitate debris removal by cutting embedded debris or rigging large debris such as cars and boats that are sometimes found in the bottom of urban waterways. Although this approach is costly, resource-intensive, and has significant health and safety considerations, in certain conditions it may be necessary.

Debris removal does pose risks for the generation of resuspended sediment materials in the water column. While this risk depends significantly on the debris type, physical characteristics of the sediment, and the hydraulics of the water body, the debris removal equipment used and the approach taken may significantly influence the level of resuspension that occurs. The dredge team should carefully consider the equipment and approach anticipated to be used for debris removal to minimize resuspended materials.

Figures 3. Rotating screen for cobble materials (courtesy of Sevenson); debris scow mechanical offloading operation (courtesy of Sevenson); grapple for debris removal operation (courtesy of Mack Manufacturing).

Effective Sequencing of Debris Removal Operations

Pre-dredge debris removal operations, or sometimes known as debris sweeps, are conducted to remove known debris within the dredge area to facilitate effective and efficient dredging. Whether debris removal is conducted as an operation before dredging or is conducted as concurrent operation will be primarily a function of the type of dredging (hydraulic versus mechanical) as well as the quantity, density, size, and distribution of debris. While hydraulic dredging equipment has some limited capacity to manage rock and wood debris by passing or casting this material from the intake, this operation is at greater risk of potential downtime and maintenance challenges due to debris. Cable and wire debris can be particularly troublesome for hydraulic dredging equipment. Normally, hydraulic dredging requires separate equipment to address medium and large debris (materials size or type too large or potentially damaging to the intake of the dredge) if expected in the dredge area. Gatlin plates, hardened steel plates welded at the intake of the dredge, are used to limit the potential of drawing in debris that could clog or damage the dredge impeller or subsequent processing equipment and piping. Gatlin plates vary in size and are intended to be large enough to exclude the expected debris at the site but minimize the impact to production rate from the reduced cross section of the intake from the steel plate. For dredging efforts that rely on hydraulic dredging or sites that have significant quantities of buried debris that cannot be removed as a part of a pre-dredge debris removal event, debris removal equipment may be mobilized and maintained at the dredging site to conduct debris removal as the items are located. Some contractors find improved efficiency by assigning debris removal crews (which are not typically needed full-time) other work responsibilities such as maintaining turbidity controls.

Alternatively, mechanical dredging equipment is generally capable of removing and managing small and medium-sized debris during dredging operations reducing the need for pre-dredge removal operations or the need for debris sweeps during dredging. Grapples, buckets, and other attachments can be changed during operations to allow debris removal periodically throughout the dredging sequence. As mentioned earlier, depending on the size and character of the debris, environmental dredging buckets can be used to remove some debris eliminating the necessity of switching attachments during dredging.

DEBRIS REMOVAL IMPACTS ON 5RS

Environmental dredging guidelines place emphasis on the primary factors that influence the effectiveness of dredging for environmental protectiveness of the sediment remediation project. These factors are known as the 5Rs of environmental dredging and are increasingly incorporated into evaluations during the planning phase of projects (Palermo et al. 2008; Bridges et al. 2010). Following investigations to provide physical properties of sediment and chemical concentrations for extent of contamination, insights will be available to better understand the relative importance of these factors during dredging operations. Figure 4 shows the 5Rs as a widely referenced schematic of how these factors interact during a mechanical bucket cycle; similar effects are applicable to the swing of a hydraulic dredge ladder.

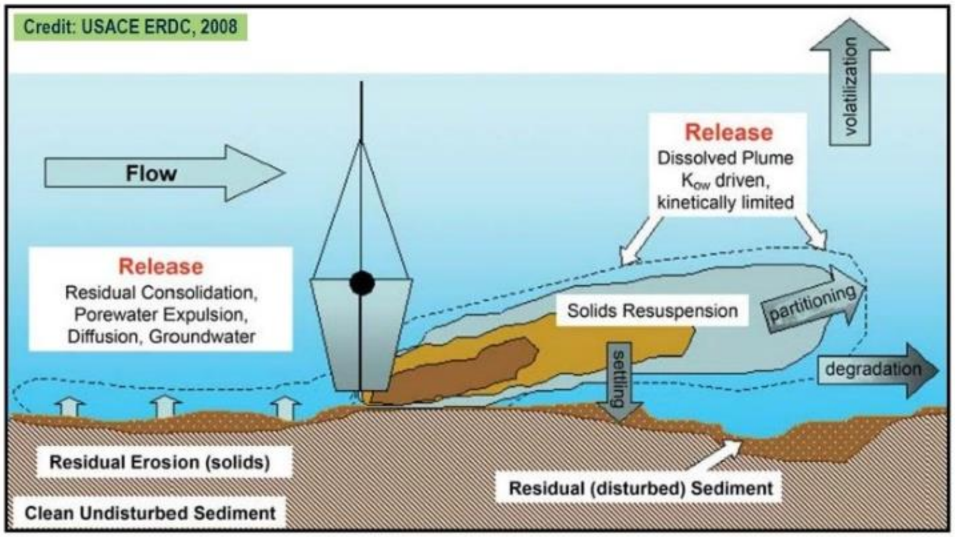

Figure 4. Schematic of contaminant release sources and mechanisms associated with contaminated sediment removal or disturbance (USACE 2008).

The challenges these factors present for projects can be difficult to overcome even when debris is not present in significant quantities at a project site. When debris is present at sufficient percentage of the removal volume, it makes goals to control resuspension, limit dredge residuals generation and mobility, and maintain cost-effective dredging production rates even more difficult.

The impact of debris on the 5Rs is related to how debris limits the ability of the dredge to remove sediment to the desired cut elevation without causing high levels of sediment resuspension. The mechanics of both mechanical dredges and hydraulic pipeline dredges are impacted by debris somewhat differently. The mechanics of each type of dredge are discussed in more detail.

Mechanical Operations

- Debris that is dislodged is loosening and dislodging sediment surrounding the debris items. Disturbances are occurring as the shifting debris is extracted from the sediment. As debris items are lifted, disturbances continue; and, if this debris is partially dislodged (and not fully grabbed by the bucket), it may be dropped and disturb the sediment surface due to the momentum.
- Dislodged debris may create irregular voids that cause sloughing of adjacent sidewalls of the cut, loosening and creating resuspension and residuals in the process.
- Voids from debris removal may remain when in proximity to the dredge prism removal limits, which may collect other resuspended sediment as a sedimentation feature.
- Sediment falling through the water column from partially closed buckets may encounter the sediment bed and alter the density of the sediment locally increasing the mobility of the sediment and/or the erodibility.

Hydraulic Operations

- Debris accumulating in cutters may add to disturbances of the sediment bed, increasing resuspension and residuals.
- Large and medium debris, and some small debris, cannot enter the intake of the dredge pipe; therefore, the dredge may strike the debris items while dredging near it, and increasing the sediment disturbances would be expected to increase resuspension and residuals.
- Large debris items may be dredged around (avoided by the dredge) to allow extraction by a grapple or separate debris removal operation. Voids may be created below the debris, causing surrounding sediment to slough into the voids, likely contributing to residuals.

The potential impacts of debris on each of the 5Rs can be summarized as follows, referencing Figure 4 for the respective illustrations:

- ***Removal***—The process by which sediments are dislodged from the sediment bed and lifted or transported out of the dredge cut. Removal is also related to the ability of the dredge to remove targeted sediment to a defined elevation, or Depth of Contamination (DOC), and the ability to accomplish sediment removal at an acceptable rate such that production targets and timelines for project completion can be met. Depending on the nature and extent of debris, a dedicated debris-removal operation may be required. Such an operation directly increases the timeline for project completion. If a debris removal operation is not required, debris may have potential impacts on the ability to reach the desired DOC, slowing the operation or potentially requiring changes in buckets, or other measures to mitigate the problem. With incomplete bucket closure, repeat attempts may be required for sediment removal and would reduce overall production rates. In addition, increased levels of resuspension and residuals may require increased monitoring and the possibility of requirements to slow or modify operations, or introduce engineered control measures for turbidity (e.g., silt curtains) to reduce water quality impacts.
- ***Resuspension***—The process whereby bedded sediments are dislodged and dispersed in the water column by the dredging operation. Most practitioners have seen the classic example of debris lodged in a mechanical bucket that has prevented it from closing. As the bucket is lifted above the water surface, the sediment fraction leaks from the bucket as it moved to the scow barge, leaving a visible turbidity plume when done. If sediment is cohesive enough to persist as a semi-coherent mass falling through the water column, resuspension would be expected when the rapidly sinking material encounters the sediment bed. As mentioned earlier, debris can affect bucket closure, resulting in increased losses of sediment during operations. Dedicated debris-removal operations call for the use of grapple, conventional dredging bucket, or other technologies to remove debris before production dredging. This equipment is not designed to minimize resuspension, and holds the potential for higher rates of resuspension, release, and residuals. Any debris-removal operation potentially creates turbidity conditions that must be managed by engineered control measures or other BMPs.
- ***Release***—The process by which the dredging operation results in the loss of contaminants from the pore water of the sediment bed or from contaminants adsorbed to resuspended sediment into the water column or air. With increased sediment resuspension, the potential for release of contaminants to the dissolved phase also increases, potentially impacting the ability to meet water quality standards.
- ***Residuals***—Contaminated sediments remaining in or adjacent to the dredging footprint after completion of the removal/dredging operation. The same issues related to resuspension also apply to residuals. Incomplete bucket closure due to debris results in increased “fallback” from bucket leakage as the bucket is raised, contributing to increased residuals. Similarly, the resuspended sediment that redeposits as generated residuals does so with a reduced sediment density from mixing and water entrainment. These materials are potentially fluidized (behaving

more like a fluid than a loosely deposited sediment until sufficient self-weight consolidation occurs). The resulting generated residuals are therefore less efficient to remove with subsequent dredge passes. Higher residuals may trigger the need for additional dredging passes at reduced efficiency or imposition of increased controls such as post-dredging residuals covers or caps. Higher residuals also would potentially impact the ability to meet water quality standards due to additional releases to the dissolved phase as the residual layers self-consolidate.

- ***Risk***—Refers to the likelihood for an adverse environmental consequence or outcome. Each of the potential impacts related to resuspension, release, and residuals translates to a potential increase in the risk associated with the presence of debris. Any impacts to the production rate for the operation increase the duration of potential impacts due to exposure times for resuspension, release, and residuals, leading to the possibility that the post-dredging ecological/human health risk conditions may be affected, or debris may create unanticipated costs to achieve the goals (i.e., increased use of dredge residuals covers).

The descriptions above apply to the effects of sediment released from a single bucket with debris preventing complete bucket closure. If the incomplete bucket closure were occurring every other bucket, or every fifth bucket, the cumulative effects for the project may be significant. As explained, other impacts may occur due to the debris directly interacting with sediment during removal. The net result may be increased resuspension and residuals during construction, exceeding what has been anticipated in design and, therefore, expected by regulatory agencies and permitting authorities; further, the added complication of changes to the dredging operations and/or increases in engineered control measures and other BMPs (i.e., turbidity barriers of different types or multiple barriers) may become relevant.

Recent studies have shown that sediment characteristics such as in situ dry density can be used to estimate the post-dredging residuals conditions following environmental dredging (Patmont et al. 2018). Sediment density changes would also be expected in the process of removing individual debris items. Consequently, this would be expected to directly impact the tendency for residuals generation in the sediment associated with medium- and large-sized debris for significant debris quantities. For example, sediment with physical properties lending to relatively lower dry density conditions will be disturbed to a greater degree during debris removal than sediment with relatively higher dry density conditions. Based on discussions with Mr. Patmont (Patmont 2021), a challenge for understanding these issues specific to debris contributions is the limited available peer-reviewed data sets for environmental dredging projects in general and, therefore, most certainly, limited available data for the subset of these projects that involve significant debris quantities. In addition to debris quantities and the range of types and sizes of debris removed for the project by area, the data sets would ideally include measurements of residual thickness, post-dredging physical and chemical properties of sediment compared to in situ conditions for these same measurement locations, and any sampling and analyses of water quality performed in the vicinity of the dredging operations (the latter of which would not be typically measured and in general is of less urgency as post-dredging debris-related residuals data).

This paper is a call to practitioners to collect additional data to better understand the impacts of debris. With additional data, predictions can be improved. Sediment resuspension is often not measured directly at the removal location where the impact of debris would be more evident; therefore, this paper places the emphasis on post-dredge residuals data collection. Consider the measurement of residuals thickness using sediment profile imaging and from post-dredging cores, as well as sampling and testing of physical and chemical properties of the residuals following dredging for representative dredging units. Applying the sampling and analysis activity to areas directly affected by debris removal as compared to other locations in the same dredging unit may allow prediction of a percentage increase in expected residuals that may correlate to the quantity of debris for that dredging unit, representing the sediment substrate’s physical properties for that project. The goal of this expanded data collection and analysis from the construction phase would be to establish a sufficient database over time that can be used in the project planning phase.

This, combined with improved debris quantities from the project planning phases, occurring because of more complete characterization of the types and sizes of debris that are developed from the investigation phase, may lend to greater cost efficiency in dredging operations and improved environmental protectiveness of environmental dredging as a remedial technology for projects that involve significant quantities of debris.

SUMMARY AND CONCLUSIONS

The following summary and conclusions apply regarding managing debris for environmental dredging projects:

- Debris impacts to dredging operations are an aspect of the practice that has not received sufficient attention to establish guidance for investigations and planning. As a result, a wide range of construction contracting approaches are used that may not properly balance the debris-related risks between owner and contractor during construction.
- A debris definition is offered in the paper, along with debris classification, as well as relationships for the ranges of types and sizes of debris with dredging operations and debris removal technologies in the form of a debris matrix included as a link. The debris matrix is intended as tool to support project planning phases but requires site-specific surface and buried debris investigations to be effective. In fact, the authors emphasize the importance of applying an appropriate array of technologies specific to site conditions during investigations to provide usable debris characterization.
- Further research is needed to better understand the direct impacts of debris removal for each major category of dredging operations (pre-dredging debris removal, mechanical dredging operations, and hydraulic dredging operations). Additional data collection for post-dredging residuals during construction may lead to improved project estimates of debris impacts for these issues. Based on operations, post-dredging residuals thickness and comparative physical and chemical properties of the sediment are more likely candidates for consistency in procedures for a given project than resuspension.
- A vast array of equipment has been developed for providing debris removal and management. Preparation of a remedial design that allows the contractor to have the appropriate equipment available for efficient operations is a challenge, especially due to the common problem of "unexpected debris."

The authors hope this paper encourages further study of debris and development of more detailed technical guidelines that can be applied consistently from project to project, leading to greater efficiencies when debris is an important factor for environmental dredging projects.

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BED LEVELING AND DRAG HEAD MOTION TRACKING THROUGH THE USE OF A SMART PHONE'S BUILT IN FEATURES

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ABSTRACT

Bed leveling operations is a method used to grade the seabed, remove scour marks, and maximize pay material removal by dragging a beam along the sea floor. An experiment was conducted with the use of a gyroscope and accelerometer sensor found in a smart phone to determine the motions of a "V" shape drag bar and a straight beam drag bar while performing bed leveling activities. The experiment included dragging beams with the shapes as prescribed by Army Corps of Engineers contracts on land followed by a proof of concept of the technology with the drag head of the trailing suction hopper dredge *MV Glenn Edwards*. In-situ tests occurred with a "V" shape drag bar during the Thimble Shoal Channel, Maintenance Dredging, Hampton Roads, VA, Hopper Dredging, FY19 project and a straight beam during Galveston Harbor, Galveston Harbor and Channel and Houston Ship Channel, Entrance and Bolivar to Redfish, Galveston, TX, Hopper Dredging, FY21 project. A description of the test, testing methodology, an analysis of the bar motions, and recommendations for future testing and analysis are provided. Crew interviews and observations were recorded to determine the operational advantages and disadvantages, with a focus on safety and ease of use, of the drag bar shapes during bed leveling activities. Through the use of readily available technology and communication with crew, a better understanding of bed leveling tools and activities is established.

Keywords: Motion, Tracking, Drag Bar, Drag Head, Bed Leveling, Smart Phone, Data Collection, Dredging

INTRODUCTION

Bed leveling operations are a useful means to compliment a variety of dredging operations. Bed-levelers mechanically loosen material by being dragged along the seafloor. Encountered high mounds of material are typically redistributed into deeper locations through dragging operations. (USACoE 2015) Bed-levelers can be a variety of rigid steel shapes such as box beams, spud beams, rakes, bladed plows, etc. A bar is typically towed or pushed with a support barge and tug boat ranging in power from 1200 HP to 1800 HP (895 kW to 1342 kW). The beans are lowered to design template grade by winches with support structure

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on the barge. The bar is dragged at 1 to 3 knots (1.85 to 5.56 km/h) for the duration of the activity. (Rau 2008)

The bar shapes are generally selected by the contractor, but can be controlled by contract specifications. Drag bars utilized by Manson Construction Co. have included straight H-beams, repurposed tractor tillers, and a ‘V’ shape bar. The ‘V’ shape was first utilized by Manson Construction Co. at Thimble Shoals Virginia, figure 12, as required by the owner. A straight H-beam arrangement was utilized in Galveston Harbor, Galveston Harbor and Channel and Houston Ship Channel, Entrance and Bolivar to Redfish, Galveston, TX, Hopper Dredging, FY21 project. These two drag beam shapes effectively leveled the seafloor, but had different operational results. The ‘V’ shape had greater dynamic movements while deployed. As the ‘V’ bar came into contact with mounds on the seafloor, the bar would twist as it as it pushed through the material leading to tension building in the outside rigging (furthest from the material) with slackening in the inside rigging (closest to the material). Once the material was pushed into deeper locations and not providing resistance on the bar, the tension in the rigging would cause the bar to swing violently to a straight heading causing the barge to heave and roll. The straight drag beam did not twist as it contacted mounds of material within the template. The straight bar’s rigging shared a more distributed load from the material. The tug and barge felt the effects when contacting the material, but did not have any violent reaction of a swinging bar.

In order to help better understand how the bars performed from an operational stand point, a tracking experiment was developed and implemented using readily available technology. A typical smartphone has built in sensors that can measure linear acceleration and angular velocity that can provide the phone’s body orientation. Through the use of a 3rd party app, this information can be recorded to data files to be processed once collected. Placing the phone on the different drag types and recording the bars movement should indicate the operational differences between the bars. This motion data was recorded for scaled drag beams on land, a drag head during trailing suction hopper dredging operations, a “V” drag beam, and a straight drag beam.

DATA COLLECTION

Utilizing the microelectromechanical systems (MEMS) technology found in a typical smartphone (Manon Kok 2017) the motion data from the drag bars and a drag head (not presented) was recorded. An application called Physics Toolbox Suite utilizes the built in gyroscope and accelerometer to record the motions of the phone. These measurements can be used for position and orientation estimation. The magnitude of these motions are considered in this document.

A gyroscope is a tool that is free to revolve around one or two axes that are perpendicular to one another and spins along an axis that allows the user to measure the angular velocity of a moving object. Gyroscopes measure the rate of change of the sensor’s orientation. Gyroscopes can be found in many common applications such as inertial navigation systems, gyrocompasses for detecting true north, or stability systems on vessels. For the experiment’s application it allows for the measurement of roll, pitch, and yaw. (Manon Kok 2017)

External forces acting on a body can be measured with an accelerometer. The forces considered are the linear accelerations along a plane and the earth’s gravity. The acceleration indicates the rate of change of the instantaneous velocity. Integration allows the user to determine the velocity and distance traveled, equation 1 and the relationship is plotted in figure 1. This gives an idea of the motion the bar is undergoing while underway. (Manon Kok 2017)

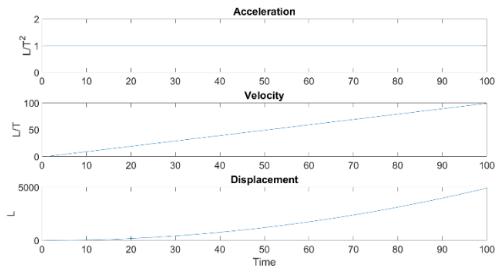

Figure 1. Relationship of constant acceleration with velocity and displacement with respect to time

$$x(t) = \int v(t)dt = \iint a(t)dt \quad (1)$$

where x is displacement with respect to time, v is velocity with respect to time, and a is acceleration with respect to time.

The combination of angular and linear acceleration can provide estimated position and orientation. The estimation of position and orientation can be improved when other sources of information are considered such as magnetometer data or known position information. The data set can be filtered and through the use of probabilistic analysis a relative orientation and position can be determined. This analysis is not performed here, but a presentation of the data collected and indication of the difference in magnitude of the measured data.

Cell Phone – Samsung S7

Samsung S7, figure 2, smartphones recorded angular velocity and linear accelerations for each testing scenario. Any smart phone with a gyro sensor and accelerometer can be used. The linear accelerometer can record at 209Hz and the gyro sensor records at 401Hz, table 1 and table 2. The accelerometer provides accelerations for x, y, and z-directions and the gyro sensor registers angular accelerations with respect to the x-, y-, and z-direction. (Samsung)

Figure 2. Samsung S7 smart phone

Table 1. Samsung S7 Specifications

Samsung S7 Specifications	
Processor CPU Speed (GHz)	2.3, 1.6
CPU Type	Octa-Core
RAM Size (GB)	4
Internal Memory (GB)	24.5
Dimensions (mm)	142.4 x 69.6 x 7.9
Weight (g)	152
Battery Life (hrs)	Up to 15

Table 2. Samsung S7 Built in Sensors

Samsung S7 Built in Sensors	
Accelerometer	Barometer
Fingerprint Sensor	Gryo Sensor
Geomagnetic Sensor	Hall Sensor
HR Sensor	Proximity Sensor
RGB Light Sensor	

Figure 3. Scuba Choice Scuba Diving Dive Waterproof Dry Box Case Container

The case used to protect the smart phone was the Scuba Choice diving water proof dry box, figure 3. It is an off the shelf consumer water tight case advertised for depths up to 100ft (30m), is cushioned on the inside, and is positively buoyant. The case was deployed to approximately 42ft (12.8m) to 52ft (15.25 m) during data logging. Velcro was used to hold the phone in place within the container. By securing the phone within the case, it maintains the body orientation of the sensors. During testing, the case did not leak even when damaged by a rocking floating sheave, when lost at sea for approximately 48 hours in Thimble Shoals, VA, or through wave action in Galveston, TX. Labeling and including a business card in the case allowed for the return of the system when discovered by good Samaritans.

Table 3. Scuba Choice Scuba Diving Dive Waterproof Dry Box Case Container Specifications

Waterproof Orange Dry Box Case		
Description	Metric	English
Inside Dimensions	158mm x 90mm x 35mm	6.22in x 3.54in x 1.38in
Outside Dimensions	186mm x 117mm x 44m	7.32in x 4.60in x 1.73in
Depth Rating	30m	98.43ft

Mounting Options

A mounting plate, figure 4, was designed and built by the Manson Construction Co. Survey Department. The plate was made from a 20in x 20in x 1/8in (50.8cm x 50.8cm x 0.3175cm) steel plate. Four ½ in

(1.27cm) bolt holes were placed in the corner. Slots were drilled in the plate to allow for hose clamps to pass through the plate and over the water proof case.

Figure 4. Mounting bracket and magnet option

A second option used magnets epoxied to the back of the water proof case. Tests indicated that the magnets did not interfere with the readings from the accelerometer or gyroscope. The case and magnet should be scoured prior to applying epoxy for best results.

Physics Toolbox Suite

Physics Toolbox Suite application exports data from internal device sensors to comma separated files. This data is recorded in real time and can be displayed while recording, figure 5. The multi record feature allows for 2 sensors to run and record simultaneously. The application outputs in metric units. (https://www.vieyrasoftware.net/)

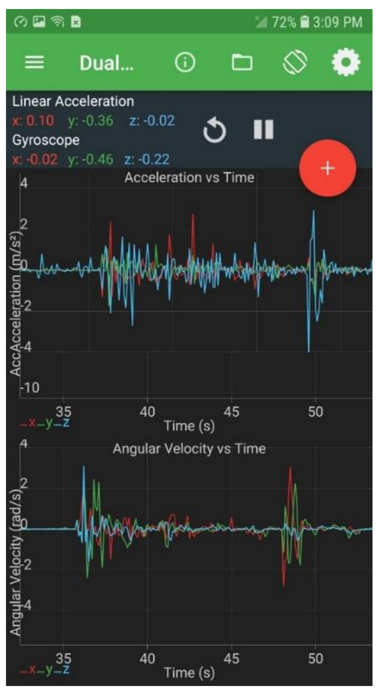

Figure 5. Physics Toolbox Suite Application screen shot of dual sensor recording

TEST PROCEDURE AND OBSERVATIONS

Manson Construction Co. Yard Facility, Jacksonville, FL

Two scaled drag bars were built in by Manson Construction Co. crew members. The drag bars are approximately ¼ the size of the full size bar, figure 6. These scaled replicas were used to represent the actions of a full size horizontal bar and the "V" shape bar.

Figure 6. Scaled "V" and horizontal bar for bed levelling test

The drag bars utilized the similar rigging arrangements as during dredging operations. The "V" shape bar uses 3 vertical lines while the horizontal bar utilizes two vertical lines and two lines whose angle change based on operation depth. The "V" shape rigging tries to maintain the same length of rigging to each support pad eye. The horizontal vertical rigging controls the depth of the bar and the angled rigging controls the port to starboard orientation of the bar.

The bars were dragged along an unpaved surface with a coarse base at Manson Construction's Jacksonville lay down facility with telehandler capable of lifting 5,500lb (24.5kN). The surface was uneven due to ruts caused by use of heavy equipment and drainage. The beams were dragged approximately 500' and then performed a gradual 180° to return to the start line. The operator maintained a fixed height with the telehandler forks keeping tension within the rigging.

As the "V" shape bar contacted mounds of material, the bar would begin to push into the lower areas, figure 7. However, the bar would begin to twist as the rigging did not limit the bar from twisting to port or starboard. This twisting action would cause slack on the inside rigging and tension to build in the other two lines. As the mound of material diminished in the path of the bar, this tension would cause the bar to abruptly swing to port or starboard and oscillate until the tension equalized between all three rigging lines.

Figure 7. Dragging scaled "V" bar with rigging

The horizontal drag bar followed a parallel path of the “V” shape bar. The horizontal bar distributed the mounds of material across the length of the beam, figure 8. The bar would start to twist, but the rigging arrangement prevented the bar twisting too far port to starboard. The beam was easier to control for the operator and did not have any sudden or violent movements.

Figure 8. Dragging scaled straight bar with rigging

TSHD *Glenn Edwards* – Drag Head

Figure 9. TSHD *Glenn Edwards*

Table 4. TSHD *Glenn Edwards* Vessel Information

Length	390 ft	118.9 m
Beam	76 ft	23.16 m
Light Draft	15 ft	4.57 m
Loaded Draft	28 ft	8.53 m
Suction Diameter	38 in	965 mm
Discharge Diameter	38 in	965 mm

Two proof tests of the mounting arrangements and waterproof case was executed on TSHD *Glenn Edwards*’ starboard drag head, figure 9 and table 4. The goal was to show that case would remain water tight in a dredging environment, record data for the duration of the test, and allow for the case and data recovery.

The system was secured with the mounting bracket and then the magnet on the upper portion of the drag head near the suction pipe connection, figure 10. This position remains above the seafloor, is accessible for the crew, and is rigid. The epoxy failed on the magnet and the case floated away leaving the magnet still attached to the drag head. It is thought that buoyant force from the case lifted the box from the magnet. The case and phone were later found and returned by a recreational fisherman.

The Physics Toolbox Suite Application was initiated and began logging data 15 minutes prior to dredging operations. The linear acceleration and angular acceleration was recorded with the dual sensor feature in the Physics Toolbox. The phone's screen was set to a dim setting to maximize battery life. Each test was conducted through a loading cycle.

Figure 10. TSHD *Glenn Edwards* with water proof case installed

"V" Drag Bar – Thimble Shoal Channel, Hampton Roads, VA, Hopper Dredging, FY19

A "V" style drag bar, figure 12, was required to be used during the Thimble Shoal Channel, Maintenance Dredging, Hampton Roads, VA, Hopper Dredging, FY19, figure 11. This presented an opportunity for an in-situ test for measuring the movements of the drag bar with the underwater case and cell phone. The case was secured to the beam with the magnet methodology and the phone recorded information during the activity.

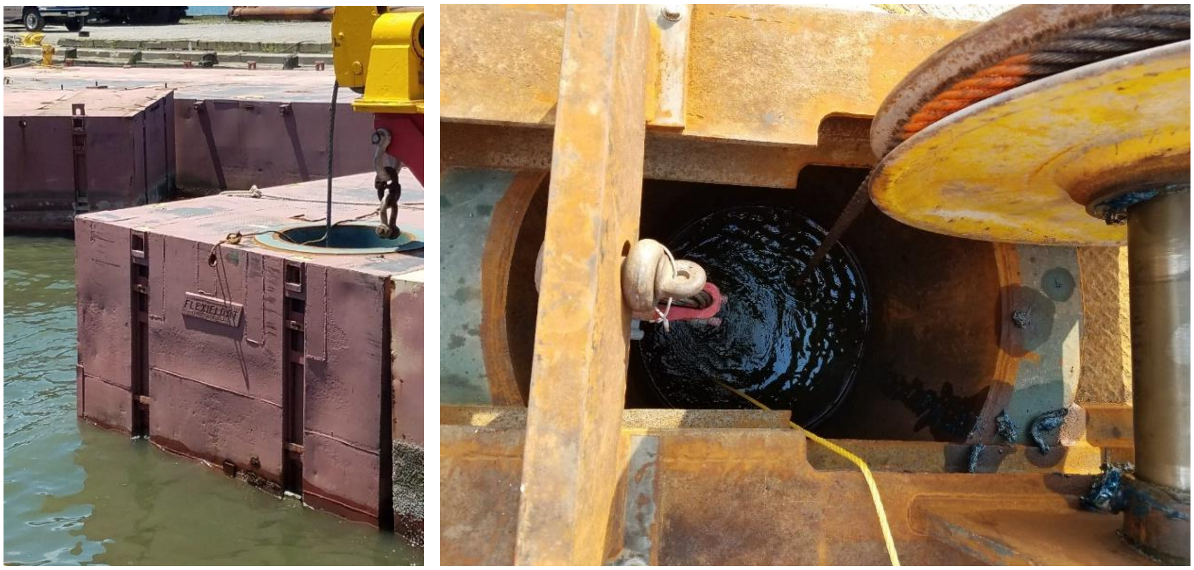

Figure 11. Section of Manson Construction Co. flexi-float barge with moon pool

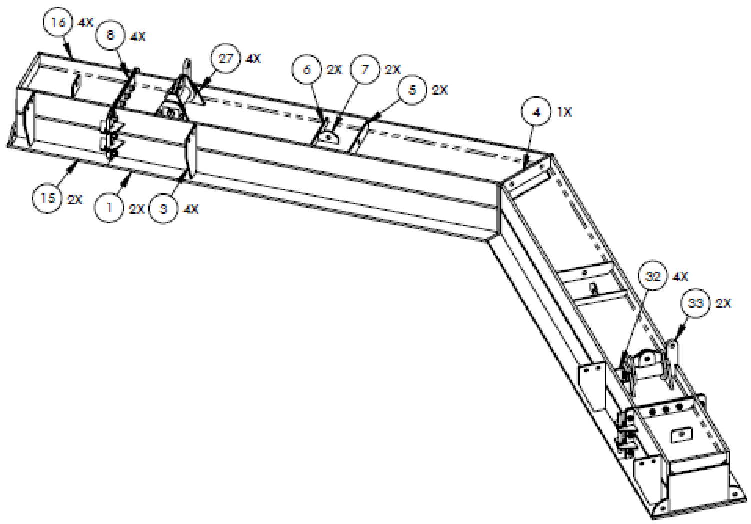

Figure 12. Isometric reference of the 'V' shape drag bar, length overall 47ft (14.24m)

While towing the drag bar in this orientation, a winch man had to maintain control of the three lines through the three moon pools. The wires were mounted on floating sheaves. As the bar passed over mounds of material, the wire and floating sheaves would be pulled to the outside limits of the moon pool. The inside edge to the material would slack, until there was no more allowable movement in the sheaves. The bar would swing back to a center position causing the barge to pitch and roll. This required the winchman to adjust the line tension continuously and made piloting the tug difficult.

Horizontal Drag Bar – Galveston Harbor, Galveston Harbor and Channel and Houston Ship Channel, Entrance and Bolivar to Redfish, Galveston, TX, Hopper Dredging, FY21

Manson utilized a horizontal (straight) box beam for dragging operations in support of the hopper dredge *MV Bayport* during the Galveston Harbor, Galveston Harbor and Channel and Houston Ship Channel, Entrance and Bolivar to Redfish, Galveston, TX, Hopper Dredging, FY21. This beam was supported by barge with an A-frame that was pushed the tug *Gulf Dawn*, figure 13. The drag bar was supported by a vertical line to control the depth of the bar and a horizontal line to maintain the orientation of the beam along the port and starboard line.

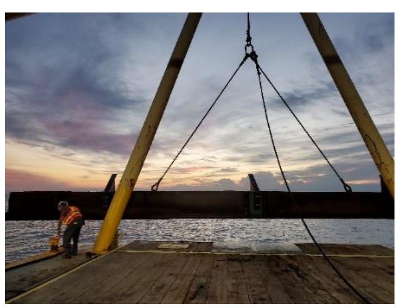

Figure 13. Straight bar A-Frame barge *Manson-80*

TEST RESULTS

The scaled tests indicate that the V bar acts more dynamically than the horizontal bar. The V bar would catch high mounds of material and twist while pushing the material. The V bar would then oscillate back to a center position once there was not more material twisting the bar. The oscillating motion made maneuvering with the bar difficult. The range of changing degrees, figure 15, and acceleration, figure 14, for the V bar is higher than the horizontal bar.

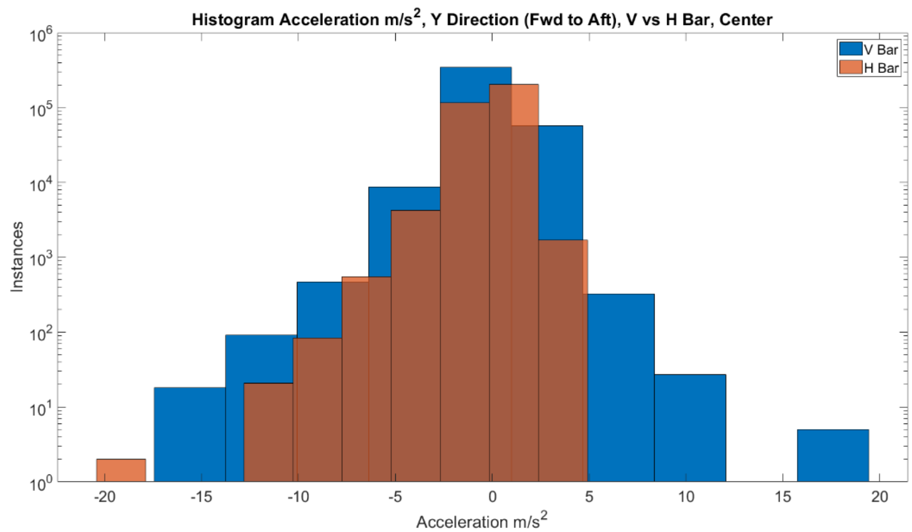

Figure 14. Histogram of acceleration along Y-Axis V-Beam vs H-Beam drag bar scaled test

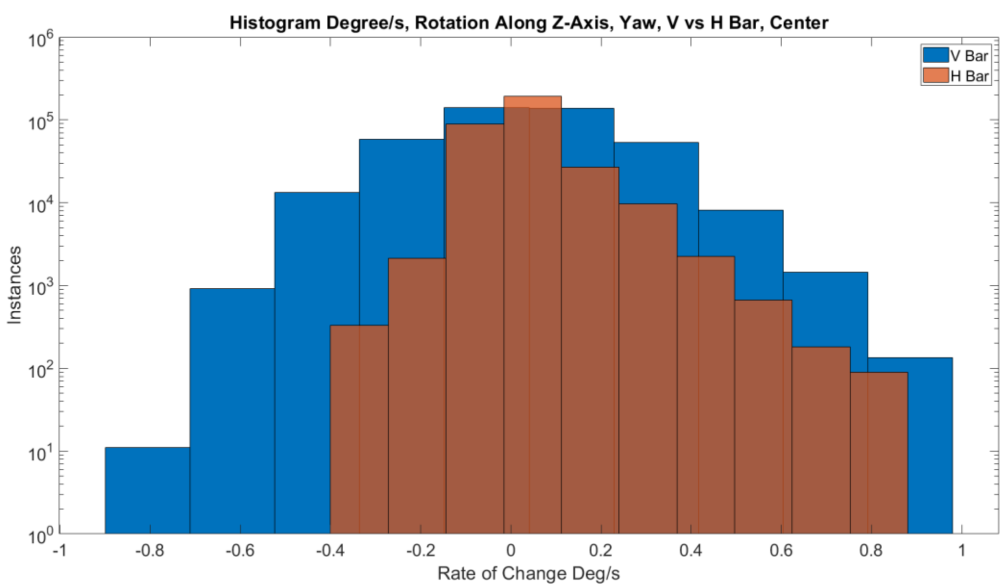

Figure 15. Histogram of rate of change of Yaw V-Beam vs. H-Beam drag bar scaled test

The V utilized in Thimble Shoals had more dynamic actions than the horizontal bar utilized in Galveston, TX which is reflected in the collected data. The V bar had higher accelerations, figure 16, when returning to a steady center position after pushing through material. The V bar also rotated of greater angles, figure 17, than the horizontal bar.

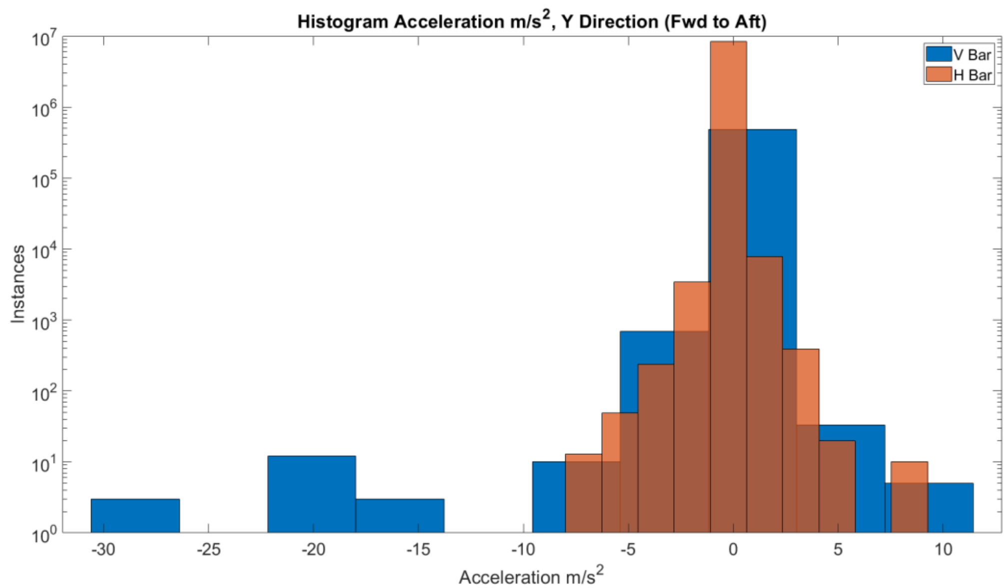

Figure 16. Histogram of acceleration along Y-Axis V-Beam vs H-Beam drag bar operations

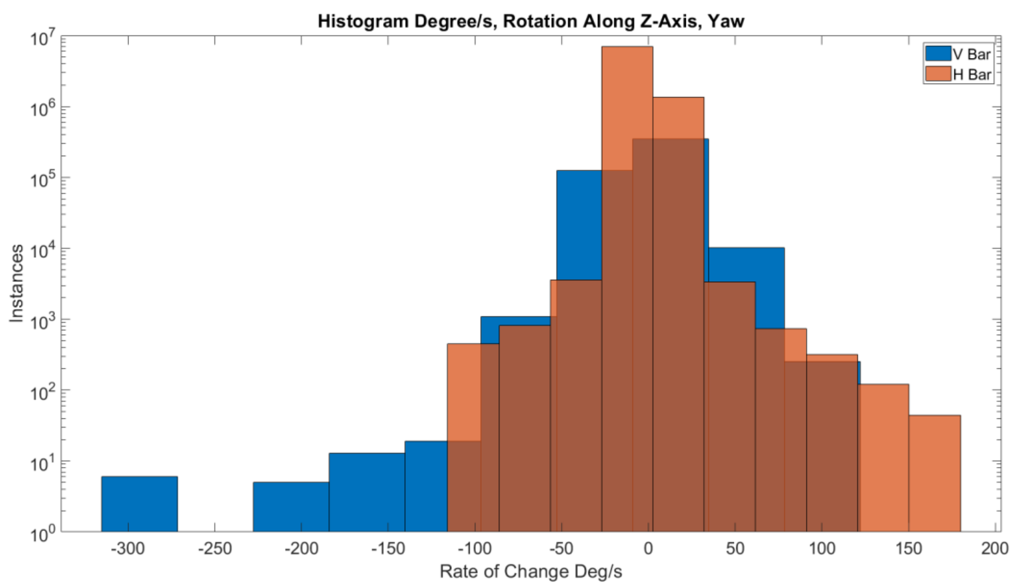

Figure 17. Histogram of rate of change of Yaw V-Beam vs. H-Beam drag bar operations

Future testing should consider incorporating other sensors to help determine the motions of the bar. The use of a magnetometer or GPS recordings from the tug in combination with a sensor on the bar could help identify the true heading of bar. A differential between the heading of the bar and the towing vessel could help identify the track line of the bar while further demonstrating that the V shape bar dynamics is greater than those of a straight beam.

CONCLUSIONS

Using the built in sensors of a smart phone has proven to be a successful, affordable, and approachable means to collect data on dragging operations. It is a convenient and quickly executable tool that is familiar to office personnel through deck hands.

The scaled drag bar testing indicated that a V shape bar is more dynamic than a straight beam. This was verified during recording of dragging operations at Thimble Shoals in Norfolk, VA with a V shape bar and in Galveston, TX with a straight beam. The V shape bar rotated along the Z-axis over a greater range and at higher accelerations. This wide swath of movements makes operations with this bar more difficult to control while underway. The winchman needs to continuously adjust the tension in the lines supporting the drag bar and the tug pilot needs to monitor the barge movements more closely when encountering high mounds along the sea floor. While both drag beams are effective at moving material that is above the template grade, the horizontal beam acts more predictably making it operationally safer and easier to use.

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CITATION

Tennant, C., Henriksen, J., Anderson, W., and Beltran, J. "Dredging Apparatus Motion Tracking through Use of Cell Phone: Drag Bars and Drag Heads," *Proceedings of the Western Dredging Association Dredging Summit & Expo '22, Houston, TX*, USA, July 25-28, 2022.

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The project teams and crews of the *Glenn Edwards* and drag bar crews for discussing the topic and assisting in the installation of test hardware and running of the test at Thimble Shoals. The project team in Galveston, Texas for installing the hardware and recording the data for the horizontal beam. The recreational fisherman for returning the initially lost box. The Jacksonville Yard Crew, William Henry, Freddy Harrel, and Anand Sammy for their help building the scaled bars and performing the test.

INTERACTIVE DESIGN PLATFORM

M. Dijkman[1]

EXTENDED ABSTRACT

C-Job has introduced a unique, online interactive design platform that empowers its customers to adjust, optimize and compare various vessel designs, all via a user interface. As such, it replaces the conventional, paper-based reference and feasibility studies generally used by naval architects.

The platform allows the user to input values for a wide range of design variations along with the details of the vessels' proposed operational scenarios. The various design / mission combinations are then analyzed simultaneously by the platform, generating multiple design parameter studies. These can then be reviewed with the objective of identifying the optimal vessel configuration for each scenario.

The platform's first project has been the optimizing of dredger designs. The inputs are therefore based on a description of the expected operations that the vessel will undertake and varied to see the resulting production outputs. These included the dredging materials, dredging depths, sailing distances between dredging and discharge sites, and the discharge methods. These are collectively referred to as Operational Scenarios.

Multiple scenarios in each run

Multiple operational scenarios can be assessed concurrently, with the platform calculating for each design variation the expected costs per volume of dredged material per operational scenario. By multiplying the operational scenario with the rate of occurrence an overall weighted unit rate is determined. The design variation with the overall lowest weighted unit rate is considered optimal.

For dredgers, this would be measured by the estimated costs per cubic meter (CCM) of dredged material. Different runs would then be made to determine how a change in the constraints (for example draught or type of fuel) effects the optimal variation and so the CCM of the intended operational deployment.

Another critical variable that needs to be assessed is the energy source. Comparing a dredger using conventional fuel versus the same design using renewable fuels is today an essential requirement. The unit rate will show what effect price differences in each fuel has on the optimal design. Where in the past dredgers were often designed to be very full and rather wide, the platform has demonstrated that longer vessels due to their lower required propulsion power become optimal at a certain price level. This was to be expected, but with the tool C-Job can demonstrate exactly where the tipping point occurs.

With the platform being fully interactive, instead of receiving a static report with the outcomes of the reference study the client can manipulate the input values and other requirements to assess their impacts and so finally reach their optimal design. That said, they do still receive a report compiled by C-Job analyzing the results and their implications. The expert view still lies at the core of the design process, but the interactive tool is an added service that greatly speeds up the analytical process.

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C-Job also offers its clients the option of a market study. The selected design variation is compared with other vessels, either operated by the same owner or its competitors, based on the same operational deployment. This delivers direct insights into how competitive a new design will be in the real world and for what operations they offer the most advantage.

The design variations can include any physical parameters. Referencing dredgers once again, this could include the dredging system and other installed equipment characteristics. Other factors that the platform can factor into the analytical process include production cost characteristics and operational variables such as estimates of build (CAPEX) and running (OPEX) costs, maintenance hours and utilization rates. The platform also allows the analysis and comparison of a complete range of propulsion systems and their impacts on the optimal design and its overall cost.

190,000 reference vessels

Previously, between five and ten reference vessels would be selected for a study, with varying estimates of their weights and propulsion systems being applied to calculate the principal dimensions for each combination. With the digital design platform, C-Job designers follow the same process but the weight and power output of each of the reference vessels is now calculated by the algorithm. This allows users to include more reference vessels, and C-Job has a database that contains over 190,000 reference vessels along with their detailed information. This resource means that C-Job always has reference vessels that are close to the design being assessed, making the results more precise.

The platform's first project included C-Job's base fleet of TSHDs. This was made up of nine models, three covering each of the three main classes of dredgers. Hopper capacities were 20-40,000m³ for capital dredging, 5-15,000m³ for multi-purpose dredging and 1.5-7,000m³ for maintenance dredging. Three initial designs, one in each class, had already been defined, from 3,000 to 14,000m³. Others will be available in the future. And that is just the beginning, the platform can be adapted for any class of vessel, using any set of variables. The possibilities are unlimited.

Addressing a gap

By developing this functionality using a data driven, interactive model, C-Job is addressing the gap between standard and one-off custom-tailored vessels in a way that allows clients to independently experiment with different configurations to see the resulting changes in the overall costs.

In addition to its speed and flexibility, the platform also enables its users to present to third parties detailed insights into how a particular configuration was selected. This is done via the design parameter reports generated as part of the analytical process. These are valuable tools for those presenting to senior decision makers, providing evidence that a full range of alternative configurations were considered prior to a recommendation being made.

The introduction of this new analytical platform places C-Job at the forefront of automated vessel design analysis and it can be extended to cover all vessel types. It delivers better quality, more control and more flexibility than traditional methods, as well as empowering clients to take control of the design decision making with C-Job providing support and validating the analyses throughout.

Keywords: feasibility studies, reference studies, optimizing design, multiple operational scenario assessment.

CITATION

Dijkman, M.A., "Interactive Design Platform." *Proceedings of the Western Dredging Association Dredging Summit & Expo '22, Houston, TX, USA*, July 25-28, 2022.

DATA AVAILABILITY

All data, models, or code generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

"BUILDING THE FUTURE OF DREDGING"
A GEOPHYSICAL UNDERSTANDING OF THE SUBSURFACE

J.F. Sawyer[1], P.B Sawyer[2], P.M. Brabers[3], and S. K. Patel[4]

EXTENDED ABSTRACT

A lack of understanding of the geological conditions on many dredging projects tends to be the major cause of cost overruns, time overruns and claims. Arc Surveying & Mapping, Inc. (Arc) is presenting a combination of technologies enabling a more advanced approach to soil investigations using 1) a more advanced geophysical technology "Arc/Aquares" to scan the subsurface in combination with and 2) an interactive presentation technology integrating all available geological information into a 3D digital geological twin of the subsurface. The backbone of this digital twin is a 3D data cloud consisting of subsurface resistivity values provided by the Arc/Aquares technology.

This new soil investigation methodology, as verified on various recent dredging projects, has been proven to increase dredge productivity, reduce the number of geotechnical borings previously necessary to describe the subsurface and significantly reduce or even eliminate the occurrence of changed and/or differing site conditions.

The geological models described below integrate a large variety of information including bathymetry, side scan sonar, seismic reflection information, magnetic information, chemical analyses, borings, geotechnical information (e.g. SPT blow counts) all visualized and linked together in a 3D data cloud of resistivity values.

The main principles of this new soil investigation technology and the 3D integrated digital ground model hosting project data is demonstrated using Arc's presentation of three (3) sample projects, each with a different need for advanced geophysics.

- **Indian River Lagoon, Brevard County, Florida:** Locating muck deposits causing algae blooms in the IRL. Identifying the interface between contaminated and non-contaminated sediments permitting surgical excavation.
- **Port Canaveral, Brevard County, Florida** (Canaveral Port Authority & Jacobs Engineering Group): Port deepening, widening and new berth construction. New perspectives of the port's geology after 30 years of inconclusive boring campaigns.
- **Jacksonville Harbor, Duval County, Florida** (Great Lakes Dredge & Dock): Accurate mapping of hard and soft geological structures in a highly variable geology. Geologically and economically justified selection and positioning of excavation equipment types, i.e. bucket, cutter suction, backhoe, etc.

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This presentation introduces an innovative and proven method of viewing and mapping the vertical and horizontal extent of the subsurface including the quality of rock and sediment structures on marine construction projects. Many years of research, testing and improvement of this survey technology has resulted in a service that is currently in use worldwide in a large variety of field conditions using the configuration illustrated in Figure 1.

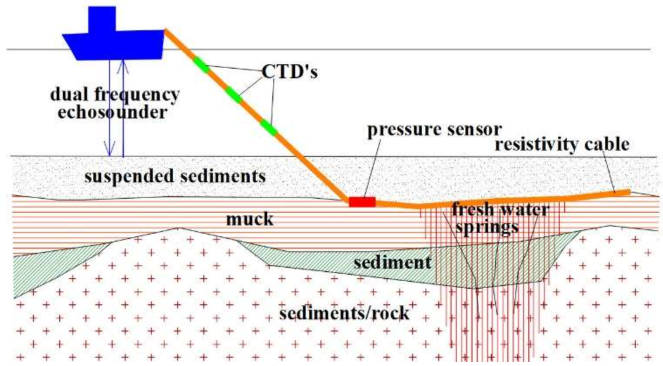

Figure 1. Subsurface Surveying System

The survey vessels utilized for geophysical surveys are configured as shown in Figure 1. and equipped to provide the most accurate bathymetric and subsurface results in the most challenging surface and subsurface conditions.

Data collection profiles are established to assure maximum detail of geophysical structures. On rock dredging projects, 50 ft profile line spacing may be selected whereas for large scale sand search projects line spacing may vary from 500 to 1000 ft. For environmental restoration (muck removal) or diamond exploration projects 50 ft line spacing may be reduced to 25 ft depending on expected lateral variations and economical value of the increased detail. During each survey real-time data are monitored permitting adjustments.

INDIAN RIVER LAGOON, BREVARD COUNTY, FLORIDA

The purpose of this survey was to map muck deposits causing algae blooms in the IRL. The accurate identification of the interface between contaminated and non-contaminated sediments permits surgical excavation.

Figure 2 from top to bottom:

- Blue (very low resistivity value): muck
- Green (intermediate resistivity values): sand
- Brown (high resistivity values): silt
- Blue (low resistivity value): peaty sediments
- Brown (very high resistivity values): clay

Due to the gaseous nature of muck, sub-bottom sonar profiling surveys by others, failed to penetrate the contaminated sediments and a manual hand probing campaign proved to be time consuming and questionable regarding the depth and extent of the muck. The Arc/Aquares survey identified the contaminated and non-contaminated interface for the entire project subsurface and to a depth of 40 feet below existing bottom in one (1) day.

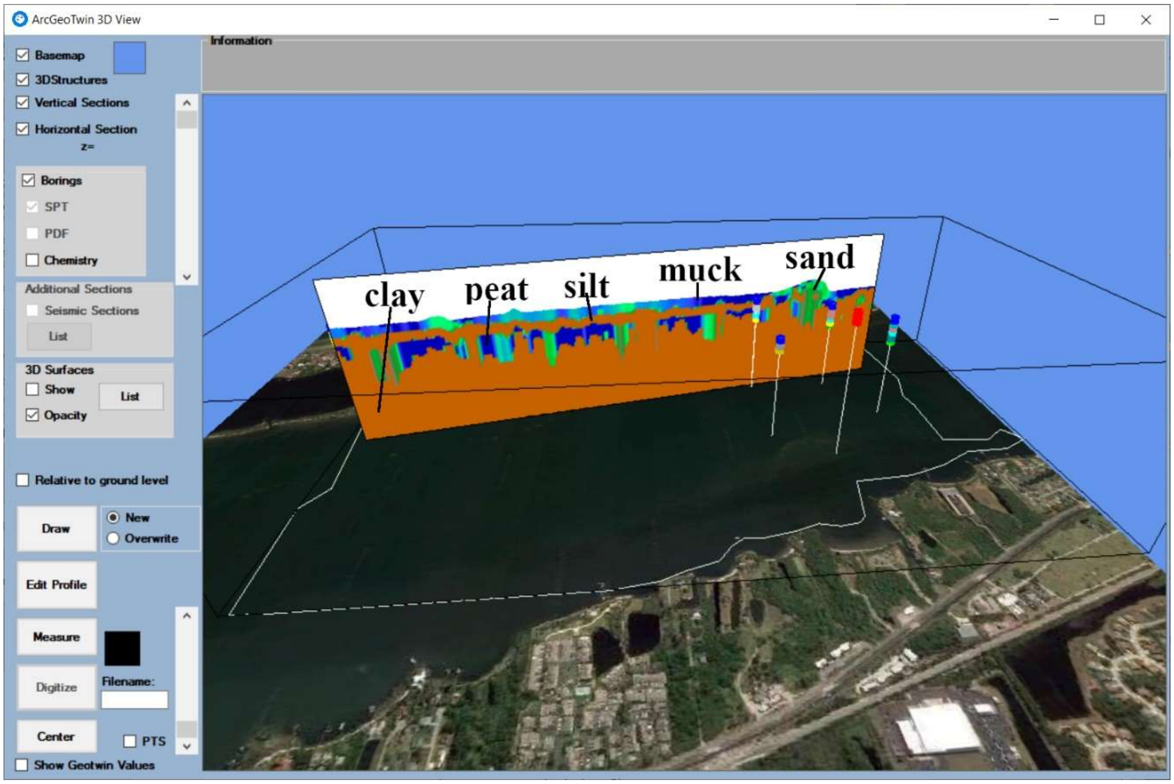

Figure 2. Geophysical profile presented on the ArcGeoTwin platform

Figure 3 illustrates the horizontal position of muck deposits (gray) at 1’, 3’ and 8 ft below the seabed surface. At 8 ft below the seabed surface there is barely any muck remaining.

The information presented in the vertical and horizontal sections, as shown in figures 2a and 2b, allows a very accurate delineation of the muck deposits, permitting the accuracy required for surgical dredging. Only contaminated sediments are excavated minimizing the space required in contaminated sediment remediation areas.

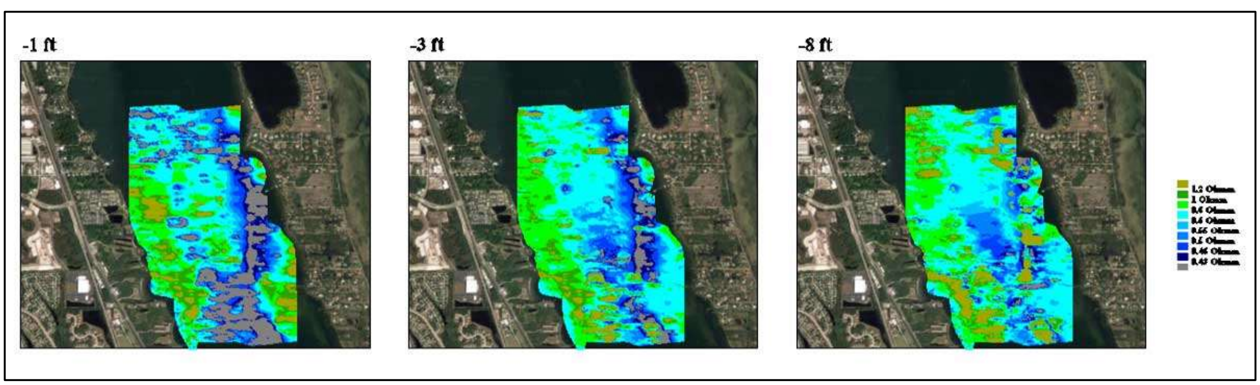

Figure 3. Geophysical horizontal sections

PORT CANAVERAL, BREVARD COUNTY, FLORIDA
GLAUCONITE SAND AND ARTESIAN WATER

Port deepening, widening and new berth construction. New perspectives of the port’s geology after 30 years of inconclusive boring campaigns.

An initial geophysical test survey carried out at Port Canaveral immediately after a dredging campaign provided the highly irregular resistivity structures visible in Figure 4. These very irregular, unusually high resistivity structures (red) viewed in the geophysical campaign didn’t appear to match well with the low resistivity values normally associated with the soft sediments described in the borings. A subsequent geophysical campaign performed several months later in the access channel that hadn’t been dredged showed similar high resistivity structures, however this time more continuous in soft sandy sediments covered with a low resistivity clay layer.

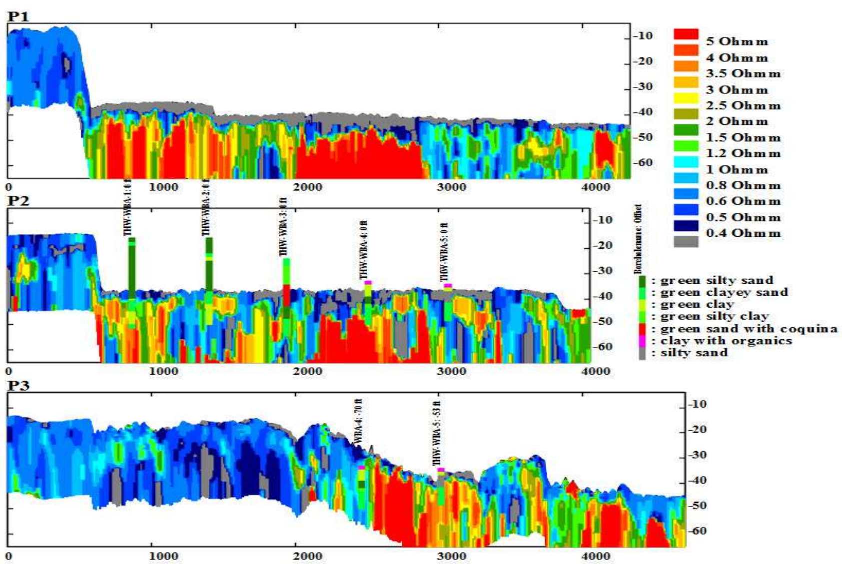

Figure 4. Vertical resistivity sections shortly after a dredging campaign

After researching volumes of geotechnical data, summarizing 30 years of boring campaigns at Port Canaveral, unexplainable observations were made involving completely differing results of borings, some acquired at the same location within a year’s time difference: whereas the first boring described firm sand, the second boring at the same location a year later described soft clay. Similar confusing observations were made during berth construction piling driving operations. At some locations when piling was considered to be completed at refusal, it was discovered that a few weeks later the same pile could be driven deeper, beyond the refusal level experienced a few weeks earlier. It appeared that the geology was changing in the course of time. As there was no indication for the existence of rock in this area, this could only be explained by fresh pore water sediments separated from the seawater above by an impervious clay layer on top of them. In areas where the impermeable clay layer was missing we found high resistivity values in the sediments at shallower levels marking the area of artesian water leaching from the seabed.

Delving more into the detail and results of the numerous historical boring campaigns, a large variety of sediment descriptions are seen going from green sand, green silty sand, green clayey sand, green silty, clayey sand, green silt, green clayey silt, green silty clay to green soft clay, the common denominator being the word “green”. There are not many minerals capable of generating such a green color, but a very common one in the state of Florida is “glauconite” a deceiving mineral that appears to be green sand but easily degrades into soft clay when exposed to an oxygen rich environment (such as seawater). (Figure 5)

Figure 5. Port Canaveral Geophysical vertical section in the access channel

The logical explanation for the unexplainable observations described above is the following.
By interaction of the glauconite sands with oxygen rich seawater, the glauconite mineral is transformed in clay forming an impermeable layer on top of the glauconite sand. Artesian water filling the sand pores is trapped underneath this clay layer and marks the sand with high resistivity values. However, as soon as the clay seal in broken – by dredging activities or piling operations – seawater can enter again in the sediments and continue the transformation process of the glauconite into clay until the seal is restored again (Figure 6). After 30 years of repeated boring campaigns, thanks to these new geophysical technologies, a plausible explanation is finally found for the geological processes active at Port Canaveral.

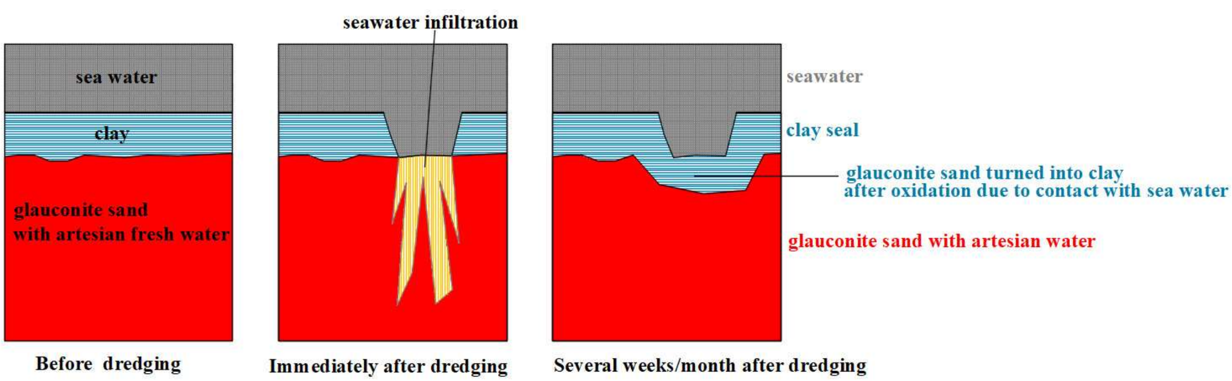

Figure 6: Schematic interpretation of the geological processes at Port Canaveral

The value of the Port Canaveral survey and its contribution to future dredging and waterside construction, is obvious as it emphasizes the need for geophysical surveys prior to a boring campaign, for environmental foresight and as a means of identifying sediment layering and material type quantities for subsequent projects.

JACKSONVILLE HARBOR, DUVAL COUNTY, FLORIDA

The geology in the St Johns River in Jacksonville Harbor is marked by a rapidly varying mixture of soft sediments and harder cemented sediments described as limestone with varying degrees of hardness. These harder spots are very discontinuous which makes it very difficult or even impossible to map them using borings (Figure 7).

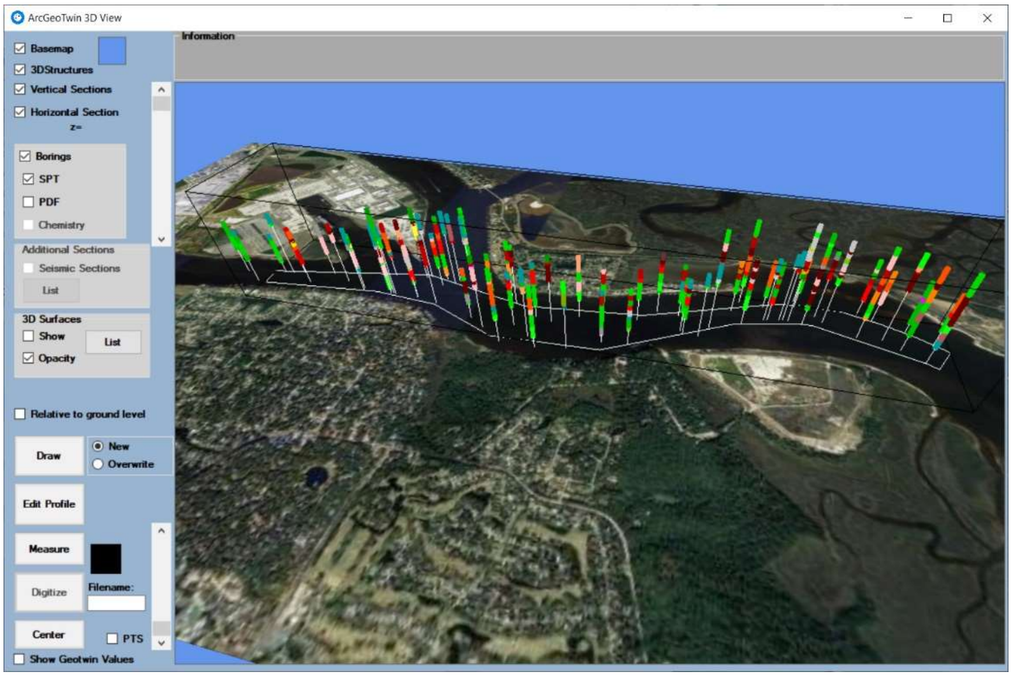

Figure 7. High density of borings on the St Johns River with yellow and green colors for soft sediments and red colors for cemented sediments and limestone.

Figure 8 illustrates the value of a geophysical survey prior to developing a geotechnical boring campaign. Geotechnical changes in the subsurface at this deepening and widening project are impossible to describe by a boring campaign due to the rapid changes in geology. Resistivity values on this project range from 0.4 Ohmm (Gray) soft sediments to 1.2-2 Ohmm (green) slightly cemented sediments and to 5.0 Ohmm (Red) limestone. Prior to the advent of the Arc/Aquares geophysical survey system and ArcGeoTwin 3D interactive model, the Jacksonville District US Army Corps of Engineers performed numerous boring campaigns to identify the subsurface at the Jacksonville Harbor deepening and widening project. By observing the dates and locations of each boring campaign in the 3D model, Figure 4a. it is obvious that rapid changes in geology prompted the need for additional borings as rapid changes in the subsurface were observed after each boring campaign. As a result of the detailed geophysical surveying and mapping of these varying structures, the dredging contractor was able to optimize the use of their different excavation types (bucket dredge, cutter suction dredge, backhoe) in an economically justified way.

CONCLUSIONS

The three examples given show the potential of this new geophysical technology to better understand and map the geology of any dredging project. Arc/Aquares technology and its associated interactive 3D presentation tool are expected to represent a drastic change on the dredging market generating (1) lower explorations costs related to a smaller number of well-selected boring locations, (2) optimizations in dredging strategies and the selection of adequate dredging equipment and (3) a decrease in claims related to adverse geological conditions.

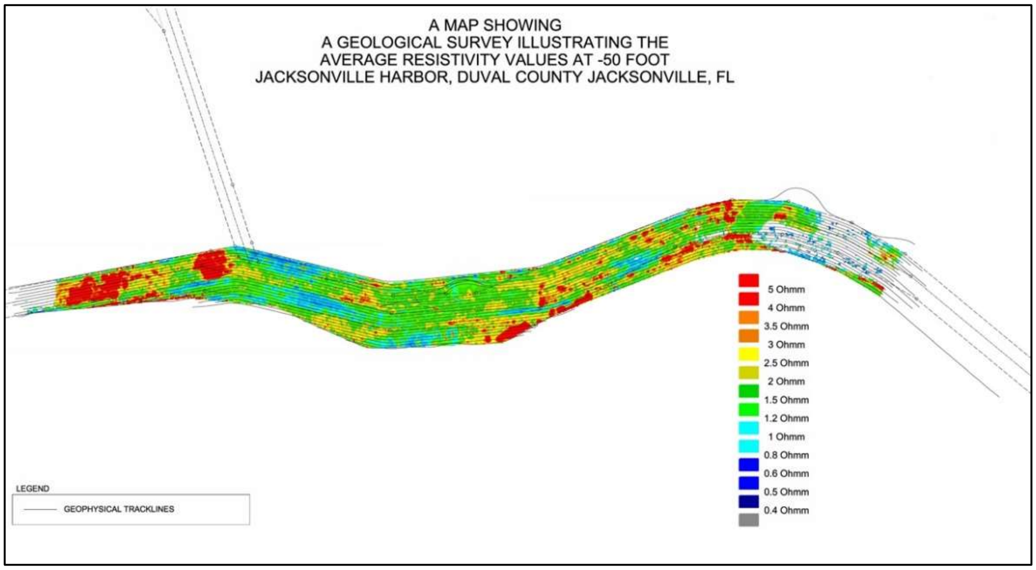

Figure 8. Average resistivity values above grade

Keywords: Dredging, geophysics, Arc/Aquares, 3D model, contaminated sediment, rock

CITATION

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USACE EXPANDED USE OF ARCHIVAL DREDGING DATA

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ABSTRACT

The US Army Engineer Research and Development Center (ERDC) is undertaking efforts to mine archival dredging data from the Resident Management System (RMS), an enterprise database of contracts issued by the U. S. Army Corps of Engineers (USACE) that can be used for advanced data analytics and improved cost engineering practices. The RMS houses daily dredge production records that offer in-depth granularity for many aspects of dredging operations. These include but are not limited to daily production totals, haul distances/pipeline lengths, cycle times, weather conditions, fuel usage, effective working times, and miscellaneous delays. Use of RMS production records on a broad scale will allow USACE to provide meaningful trends through time for relevant quantities such as duration of hauling runs to/from hopper placement sites, relative magnitudes of production time lost due to moving out of the way of ship traffic, and more realistic projections for the actual duration of dredging contracts and the resulting implications for regional contract vehicles. These data mining efforts provide USACE with a better understanding of weather and seasonal delays and how these might influence the scheduling of contracts. In addition, having a better understanding of daily production parameters will assist USACE efforts with federal and state resource agencies for permitting and lead to better coordination with port stakeholders for contract scheduling.

It is common practice for USACE Cost Engineers to use past performance records as a supplement to the USACE Cost Engineering Dredge Estimating Program (CEDEP) when creating the independent government estimates (IGEs) for dredging contracts, though the availability of these past performance records varies widely across Districts. Understanding the factors that affect overall productivity for each project is essential in creating a fair and reasonable estimate, and past performance records are the best indicator of future results for certain metrics. Dredge cycle times serve as one of the more important factors in determining overall duration of any dredging project. For larger jobs that require more than five hundred cycles, a cycle time miscalculation of a few minutes per cycle can noticeably impact the accuracy of the total estimated job duration. By using nationwide past performance datasets that include the entire dredging fleet, USACE can be more precise on cycle times in one specific location and look at broad scale trends on dredge cycle duration in relation to a myriad of variables. Similar analysis of past non-effective working times can be used to track delay trends for specific projects, providing cost engineers with logical assumptions for anticipated recurring delays to productivity. When looking at this data nationally rather than locally, it can be used for better and more accurate scheduling of USACE dredging projects. It may also show seasonal delays for a given region due to traffic variability, weather, tides/currents, etc. Use of these and similar analytics towards creation of a searchable and filterable historic dredge production database will allow USACE to provide in-depth analysis to the factors that affect productivity nationally and refine estimation and scheduling practices. This work discovers high-level productivity trends by

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dredge type, size, and region, serving as a proof-of-concept of some of the contributions and benefits that could be realized through systematic mining of the historic RMS dredge production database.

Keywords: Dredging operations, productivity, data mining, Resident Management System (RMS)

INTRODUCTION

With over 150 dredging contracts awarded annually, the US Army Corps of Engineers (USACE) has a vast portfolio of maintained waterways requiring a wide variety of dredge types and applications (USACE, 2022) (USACE, 2022). This includes deep and shallow draft channels and harbors, coastal and inland waterways, in-channel, and upland placement of dredged material, as well as specialized beneficial use practices (Wilkens, Suedel, & Mitchell, 2019) (McFall, Brutsché, Priestas, & Krafft, 2021). Dredge performance can change significantly for each differing dredge type and the nature of the work to be completed. With such a diverse portfolio of dredging applications it can be difficult to accurately cost and schedule these projects without a true understanding of the constraints that are inherent to each type of project, and/or each individual project (Nachtmann, Mitchell, Rainwater, Gedik, & Pohl, 2014). Historic dredging production data gives the best insight into these constraints and is used heavily by the USACE when creating anticipated schedules and government estimates (Loney, Cotterman, Brown, & Mitchell, 2019). While the USACE Cost Engineering Dredge Estimating Program (CEDEP) is the tool used by the Corps for creating all Independent Government Estimates (IGE) for dredging contracts (USACE, 2017), past production data is often used to verify, and if needed, adjust the CEDEP output. These past performance dredging records offer insight into the daily production values and the outside influences that may affect performance. In some of the larger ports and harbors across the nation, dredging production can be slowed greatly due to marine traffic using the channel. Dredging operations can also be slowed or even shutdown due to weather, tides, and water currents. Past performance records show the average "non-effective" time for any given project as well as the cause of that non-effective time. By studying these records for a given project, a cost engineer will have a better understanding of normal traffic and weather delays and can adjust the effective working time within the estimate accordingly. Similarly, cost engineers rely on past performance data to verify and/or update the total estimated cycle time for operation of a hopper dredge or scow (USACE, 2021). Operations and Maintenance (O&M) dredging projects typically use recurring placement sites (USACE, 2012), making past dredging data a very strong indicator or how long a cycle may take. As previously noted, use of these historic records on a district level for dredge scheduling and estimation is common practice, though apart from this application, historic records are seldom utilized other than to track broad cost and productivity trends. This work mines and analyzes historical dredge production data from the Resident Management System (RMS), to contribute to the general understanding of maintenance dredging effective time and production. The analysis is made with data collected from major dredges (hoppers and cutterheads), between 2010-2020, and aggregated at both daily and project level. This work serves as a proof-of-concept on the type of analysis that could be done with RMS data, and its applications.

RESIDENT MANAGEMENT SYSTEM (RMS) DREDGING DATA

The Resident Management System (RMS) is used by the USACE for construction oversight and contract execution for all types of construction projects (USACE, 2021). In particular, dredging contracts are administered using the RMS daily production worksheets that contain project specific information and productivity entered by the contractor, which are reviewed by USACE quality assurance personnel for progress payments. These daily production worksheets contain a multitude of data points ranging from specific cycle time activities and non-effective time breakouts to length of discharge pipeline, daily quantities removed, which dredge and placement areas are being used, weather, and fuel usage, just to name a few. The RMS program itself creates dredge production summary reports which pull information from selected fields from each daily report. The RMS dredge production summaries are used as the basis for the information presented in this report. While the RMS data is disaggregated to allow for highly detailed production analysis, the confidential nature of the data limits this publication to contain high-level aggregate results. Nevertheless, the analysis shown in this paper contributes to the general understanding of maintenance dredging effective time and production U.S.-wide. The main limitation of the RMS data for the purpose of this work is the heterogeneity in reporting templates and formats on historical data of select USACE districts.

DREDGING DATA APPLICATIONS

Cost Estimating

Recently, the ERDC has undertaken several initiatives using historic dredge production records in differing ways. This includes work for the Cost Engineering Community of Practice (CoP), the Navigation CoP, and ERDC internal data analysis (USACE, n.d.). For these efforts, the RMS data has been the main source of historic dredging production data (CEDEP validation, Dredge Schedule Optimization, Dredge Production Analysis). The RMS daily performance forms provide in-depth granularity for dredging operation for each day dredged. While each USACE District generally has its own dredge production files, the majority of USACE is using the RMS for tracking daily performance. Although the RMS is familiar to contractors working on USACE projects, the vast amount of data contained within in the RMS has rarely been used on a broad scale. As such, the ERDC Coastal and Hydraulics Laboratory (CHL) has downloaded available RMS dredging records for advanced data analysis. This dataset will allow districts to review dredging production records from around the country, filtered by defined parameters, such as pipeline length, haul distances, dredge size, etc. This information will allow cost engineers to compare the aspects of their dredging projects with similar type projects from the surrounding regions, providing critical insight to production and the factors that affect it. These national dredging records become especially useful for districts with smaller dredging programs, who may see changing contractors/dredges in their respective regions. Rather than relying solely on past production data from a class of dredges that may no longer be working in that area, the district can evaluate regional dredging efforts with differing sized dredges and placement distances to find the best fit for their intended project. Specifically, this data will allow cost engineers to compare average sailing speeds, duration of specific cycle time activities, and duration of pipeline activities over differing classes of dredges. This type of information is critical for reflecting actual field activities in the estimates. Further, with more regional type contracts being used by USACE, an analysis of daily production data will assist cost engineers in understanding project limitations in adjacent districts and ensure quality estimates for regional contracts.

The ERDC has obtained RMS data for over 450 unique dredging (hopper/cutterhead) contracts with daily production information that is currently being applied to several differing initiatives and trend analyses (USACE, 2017). As mentioned, the CEDEP is the official dredge estimating program for the USACE. By USACE policy CEDEP needs to be periodically validated to ensure that the assumptions and equations being used by the program are accurate (USACE, 2016). Cost engineers from the Jacksonville District (SAJ), Portland District (NWP), and USACE Cost Engineering Center of Expertise located in Walla Walla District (NWW), have joined CHL in performing a validation study for the production and unit cost output of the CEDEP by using historical RMS dredge data.

Scheduling Optimization

In recent years, the USACE has been working across district and division boundaries to optimize scheduling of USACE dredging projects to maximize the industry dredging fleet (Loney, Cotterman, Brown, & Mitchell, 2019; Mitchell, Wang, & Khodakarami, 2013).. If similar dredging projects can be sequenced into one regional contract, that provides longer working durations for the winning contractor, reduces the amount of "back and forth" mobilization and demobilization, and lowers cost allowing USACE to perform more dredging operations (Dunkin & Mitchell, 2015). Supplementing dredge scheduling optimization with daily production records from varying sized dredges in unique projects, improves understanding of the non-effective working times and cycle times that typically add to the duration of a given project. Additional trends seen from daily RMS production data analysis such as recurring seasonal delays (weather/traffic), productivity versus placement distance, percent Effective Work Time (EWT) versus dredge size, can also help inform the optimization model to provide an accurate scheduling output given known parameters such as dredges available for work.

RMS DATA SAMPLE

CHL has compiled over 450 RMS individual dredging (hopper and cutterhead) contract production summary reports from across the nation from 2010-present. As compared to the number of contracts within the Dredging Information System (DIS) (USACE, 2022), this represents roughly 30.42% of the dredging projects; specifically, 44.14% of Hopper dredging projects and 26.13% of cutterhead projects. Figures 1 and 2 illustrate the total number of contracts sampled and the total amount of daily records by region and dredge type. The West Coast and Great Lakes regions were not included in this evaluation due to small data representation.

The regional groupings for this effort include projects located in the Gulf, North Atlantic, and South Atlantic (Figure 3). The North Atlantic is comprised of the New England, New York, Baltimore, Philadelphia, and Norfolk USACE Districts. The South Atlantic is comprised of the Wilmington, Charleston, Savannah, and Jacksonville USACE Districts, and the Gulf is represented by the Mobile and Galveston Districts. New Orleans District (MVN) daily dredge production summaries were not used for this effort due to the non-standard report structure. While several dredging operations take place every year in MVN, their data is being aligned with the other districts for inclusion into future versions of this effort.

Cutterhead dredges have been categorized by size. The definitions of size bin classifications and the total number of records for each category from the RMS sample are shown in Table 1. A very small portion of projects (and daily records) does not contain information on cutterhead diameter size. Such records were still used for analysis that did not consider diameter size.

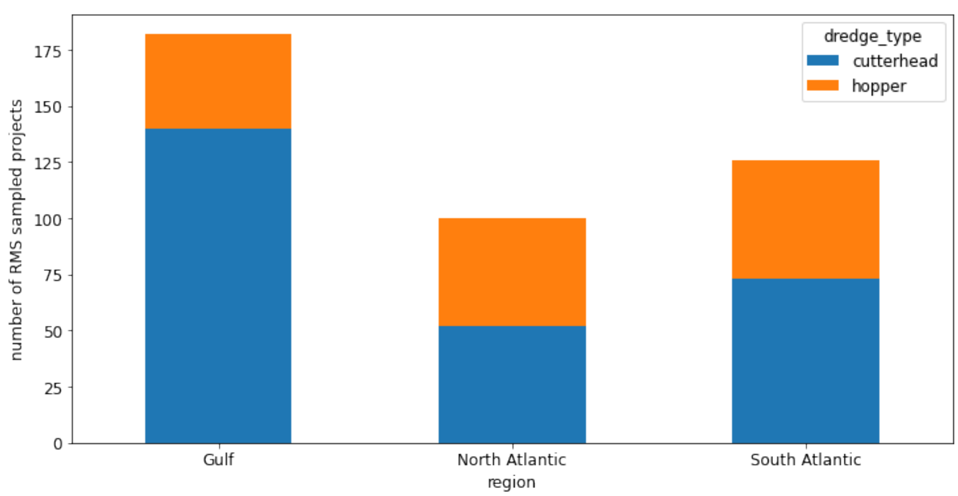

Figure 1. Number of RMS sampled projects, by region and dredge type

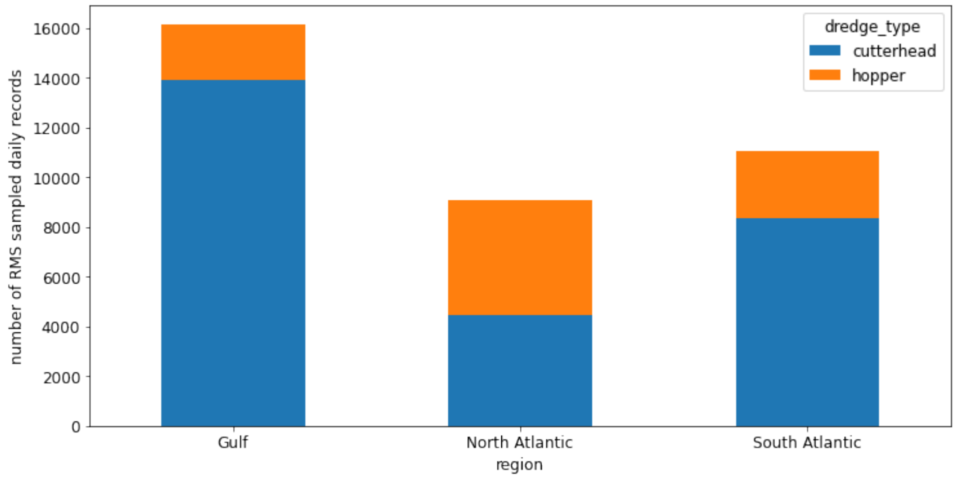

Figure 2. Number of RMS sampled daily records, by region and dredge type

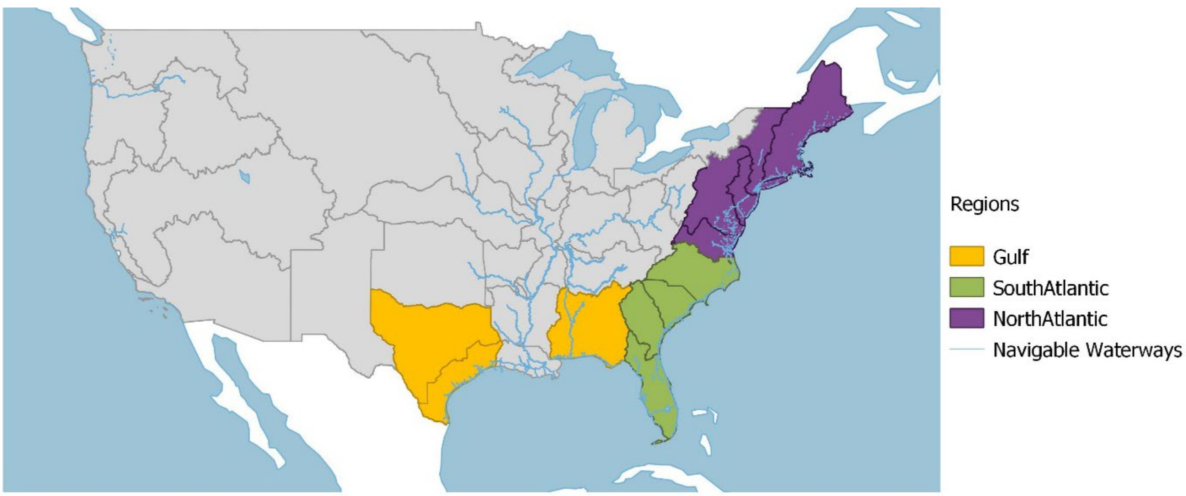

Figure 3. Geographic regions

Table 1. Sample number of projects and daily records by cutterhead size and region

Cutterhead Size	Number of projects				Number of daily records			
	North Atlantic	South Atlantic	Gulf	Subtotal projects in all regions	North Atlantic	South Atlantic	Gulf	Subtotal daily records in all regions
Small (diameter <18in)	12	10	9	31	1270	819	989	3078
Medium (diameter between [18-26in])	14	48	96	158	1346	5666	9730	16742
Large (diameter >26in)	25	12	31	68	1782	1504	2781	6067
Unknown	1	3	4	8	50	338	404	792
Total	52	73	140	265	4448	8327	13904	26679

DREDGE PRODUCTION DATA ANALYSIS

CHL has been using the dredge production summary reports obtained from RMS to compare dredge performance on a national and regional level with varying inputs. The material presented below has been regionalized to increase data groupings and reduce singling out districts, vessels, or contractors. This high-level analysis is intended to be used as a proof of concept for informing dredge cost engineering and scheduling optimization efforts. The following set of figures show some of the early comparisons and results regarding cycle time and productivity for hoppers and cutterhead dredges by region and dredge size.

RMS Cycle Time and Variables Analyzed

The RMS generates a dredge production summary report for each dredging contract using information from individual daily production worksheets. Each production summary report includes information on the time spent by the dredge in each part of the dredging cycle. RMS production summary reports and the variables analyzed in this work vary per type of dredge.

Hopper Dredge Variables Used

The paragraphs below explain a typical dredging cycle for hopper dredges and show the relationship between the different variables used in this work. A brief description of these variables is presented in Table 2.

For Hopper dredges, the following are the daily dredging cycle time activities in RMS, measured in time-spans (hh:mm):

Dredging time = operating time + non-effective time + lost time (1)

The operating time (i.e. "effective time") is further detailed in RMS as follows:

Operating time = pumping time + turning time + time to dump + dumping time + time to cut + connect time + disconnect time (2)

Using the above information, the daily dredging cycle time was broken down into activities that allowed for an analysis of time spent in pumping material out of the channel bottom, versus the time spent in transporting the extracted material to and from the disposal sites:

Dredging time = Effective time "Dredging" + Effective Time "Transporting material" + Non-effective time + Lost time (3)

The following variables were derived, calculated as a time percentage of total daily cycle dredging activities:

Effective time "Dredging" = 100 x pumping time / dredging time (4)

Effective Time "Transporting material" = 100 x (turning time + time to dump + dumping time + time to cut + connect time + disconnect time) / dredging time (5)

Non-effective time = 100 x non-effective time / dredging time (6)

Lost time = 100 x lost time / dredging time (7)

Table 2. Variables used for production analysis of hopper dredges (USACE, 2010)

Variable name	Units	Description	Time measure
Dredging time	hh:mm	Total hopper cycle time, i.e. time when actual production is taking place plus allowable downtime.	Daily
Operating time	hh:mm	Portion of the hopper cycle time spent by the dredge in "effective" work, when actual production is taking place, such as pumping material out of the channel bottom or transporting material to/from disposal sites. (USACE, 2008)	Daily
Non-effective time (hh:mm)	hh:mm	Portion of the hopper cycle time when the dredge is operational but no production is taking place, such as making changes to pipelines, cleaning trash from the suction head, minor operating repairs, and moving between locations. (USACE, 2008)	Daily
Lost time (hh:mm)	hh:mm	Portion of the hopper cycle time when the dredge is not operational, normally due to a lack of required crew, major repairs and alterations, drydocking, cessation, and collisions (USACE, 2008).	Daily
pumping time	hh:mm	Portion of the hopper cycle time spent pumping material out of the channel bottom.	Daily
turning time	hh:mm	Portion of the hopper cycle time spent between finishing pumping material out of the channel bottom, and starting to travel towards the placement site.	Daily
time to dump	hh:mm	Portion of the hopper cycle time spent traveling towards the placement site.	Daily
dumping time	hh:mm	Portion of the hopper cycle time spent disposing the material on the disposal or placement site.	Daily
time to cut	hh:mm	Portion of the hopper cycle time spent transiting to the dredge cut from the placement site	Daily
connect time	hh:mm	Portion of the hopper cycle time spent connecting to pipeline for hopper pumpout	Daily
disconnect time	hh:mm	Portion of the hopper cycle time spent disconnecting from pipeline after hopper pumpout	Daily
Effective time "Dredging"	% of dredging time	Percentage of the hopper cycle time spent pumping material out of the channel bottom.	Daily
Effective Time "Transporting material"	% of dredging time	Percentage of the hopper cycle time spent in all activities pertaining the disposal of material.	Daily
Non-effective time (percent)	% of dredging time	Percentage of the hopper cycle time when the dredge is operational, but no production is taking place, such as making changes to pipelines, cleaning trash from the suction head, minor operating repairs, and moving between locations. (USACE, 2008)	Daily
Lost time (percent)	% of dredging time	Percentage of the hopper cycle time when the dredge is not operational, normally due to a lack of required crew, major repairs and alterations, drydocking, cessation, and collisions (USACE, 2008).	Daily
Average gross production	cy/day	Volume of material dredged per day, in average, during a given contract.	Contract average
Average travel time to/from dumping site	minutes/load	Time spent in all activities pertaining the disposal of material per load, in average, during a given contract.	Contract average

Other RMS hopper dredging variables used for this effort are the Average gross production (measured in cy/day), and the Average travel time to/from dumping site (measured in minutes per load). These variables are calculated per contract by averaging daily records.

Average travel time to/from dumping site (minutes/load) = (8)
Average turning time (minutes/load) +
Average hauling time (minutes/load) +
Average time-to-cut (minutes/load) +
Average connect/disconnect(minutes/load) +
Average dumpling time (minutes/load)

Cutterhead Dredge Variables Used

RMS cutterhead production summary reports contain a total dredging cycle time comprised of variables measured as time-spans (hh:mm) shown in equation (9). A brief definition of variables used in this work is provided in Table 3. The following equations show the relationship of variables used.

Dredging time = pumping time + handling pipelines + handling anchor lines + (9)
clearing pump and pump lines + clearing cutter or suction head +
changing location of plant or job + loss due to natural elements +
moving out of way of traffic + shoreline and shore work +
minor repairs + miscellaneous + lost time

To allow for the production analysis the daily cutterhead dredging cycle time activities were grouped as follows:

Dredging time = Percent of Effective Time (EWT) + changing location + (10)
avoiding ship traffic + work on lines and cutter/suction head +
maintenance and weather delays + other

The following variables were calculated as a time percentage of total daily cycle dredging activities:

Percent of Effective Time (EWT) (“Dredging”) = 100 x pumping time / dredging time (11)

Changing location = 100 x changing location of plant or job / dredging time (12)

Avoiding ship traffic = 100 x moving out of way of traffic / dredging time (13)

Work on lines and cutter/suction head = 100 x (handling pipelines + handling anchor lines + clearing pump and pump lines + clearing cutter or suction head) / dredging time (14)

Maintenance/weather delays = 100 x (minor repairs + loss due to natural elements) / dredging time (15)

Other = 100 x (shoreline and shore work + miscellaneous + lost time) / dredging time (16)

Lastly, this work considers the average gross production (measured in cy/day) per contract and the length of the discharge pipe (ft) used each day by each dredge.

Table 3. Variables used for production analysis of cutterhead dredges *(USACE, 2010)*

Variable name	Units	Description	Time measure
Dredging time	hh:mm	Total cutterhead cycle time, i.e. time when actual production is taking place plus allowable downtime.	Daily
pumping time	hh:mm	Portion of the cutterhead cycle time spent by the dredge in “effective” work, when actual production is taking place, such as pumping material out of the channel bottom or transporting material to/from disposal sites. (USACE, 2008)	Daily
handling pipelines	hh:mm	Portion of the cutterhead cycle time spent due to handling pipelines.	Daily
handling anchor lines	hh:mm	Portion of the cutterhead cycle spent due to handling anchor lines.	Daily
clearing pump and pump lines	hh:mm	Portion of the cutterhead cycle time spent due to clearing pump and pump lines.	Daily
clearing cutter or suction head	hh:mm	Portion of the cutterhead cycle time spent due to clearing cutter or suction head.	Daily
changing location of plant or job	hh:mm	Portion of the cutterhead cycle time spent due to changing plant location.	Daily
loss due to natural elements	hh:mm	Portion of the cutterhead cycle time loss due to natural elements.	Daily
moving out of way of traffic	hh:mm	Portion of the cutterhead cycle time spent due to moving out of way to vessel traffic.	Daily
shoreline and shore work	hh:mm	Portion of the cutterhead cycle time spent due to shoreline and shore work.	Daily
minor repairs	hh:mm	Portion of the cutterhead cycle time spent due to minor plant repairs.	Daily
miscellaneous	hh:mm	Portion of the cutterhead cycle time spent due to miscellaneous work.	Daily
lost time	hh:mm	Portion of the cutterhead cycle time when the dredge is not operational, normally due to a lack of required crew, major repairs and alterations, drydocking, cessation, and collisions (USACE, 2008).	Daily
Percent of Effective Time (EWT)	% of dredging time	Percentage of the cutterhead cycle time spent in removing material out of the channel bottom.	Daily
changing location	% of dredging time	Percentage of the cutterhead cycle time spent due to changing plant location.	Daily
avoiding ship traffic	% of dredging time	Percentage of the cutterhead cycle time spent due to moving out of way to vessel traffic.	Daily
work on lines and cutter/suction head	% of dredging time	Percentage of the cutterhead cycle time spent due to handling pipe and anchor lines, clearing pump and pump lines, and clearing cutter or suction head.	Daily
maintenance/weather delays	% of dredging time	Percentage of the cutterhead cycle time loss due to minor repairs and natural elements	Daily
other	% of dredging time	Percentage of the cutterhead cycle time spent due to shore work, miscellaneous, and lost time (normally due to a lack of required crew, major repairs and alterations, drydocking, cessation, and collisions) (USACE, 2008)	Daily
average gross production	cy/day	Volume of material dredged per day, in average, during a given contract.	Contract average
discharge pipe length	ft	Length of the discharge pipe connecting the dredge with the disposal site.	Daily

Production Analysis

The following paragraphs contain the high-level dredging data analysis from RMS. First, average production statistics per project (CY/day) are compared across regions and dredge types. Next, the analysis focuses on hoppers highlighting daily cycle time activity percentages by region and changes in productivity as a function of travel time to/from material dumping sites. Lastly, for cutterheads, cycle time activity percentages are observed by region and by cutterhead size concluding with notes on productivity versus discharge pipe length.

Figure 4 contains boxplots of the average gross daily production (cy/day) obtained by dredge type and region. These show not only the average production rate but also the range of production rates achieved by each type of dredge. The South Atlantic and Gulf, hopper dredges achieve a noticeably higher production than cutterheads, yet in the North Atlantic the average productivity between hoppers and cutterheads is almost identical. Further, the higher end productivity realized by the cutterheads in the North Atlantic is higher than the hopper dredges. Higher production rates for cutterheads in the North Atlantic is likely tied to the fact that the placement sites, especially the offshore sites in the North Atlantic region are a greater distance from the digging area than in the other regions forcing hoppers to spend longer travel times to/from placement sites at the expense of pumping material out of the channel bottom[4]. In contrast, the Gulf region, which shows the highest productivity by hopper dredges generally has shorter placement site distances. Figure 5 shows the time percentages of the hopper dredging cycle by region.

Hopper Dredge Production Analysis

This section analyzes the percentage of time spent in different cycle time activities by hopper dredges in different regions. In Figure 5, note the dark green "Effective Time: transport to/from placement" in the North Atlantic as compared to the Gulf and South Atlantic. While hopper dredges in the Gulf and South Atlantic spend 36.1% and 41.9%, respectively, of the cycle time hauling material, hopper dredges in the

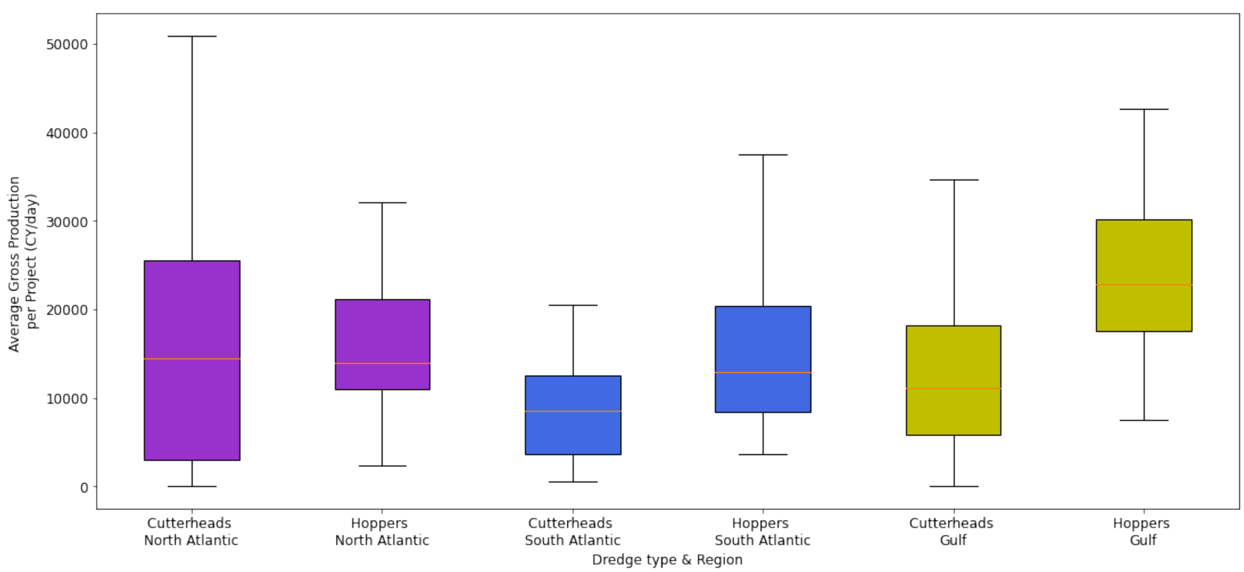

Figure 4. Production (cubic yards dredged per day), by dredge type and region. Production averages calculated form project-level data.

[4] Cutterhead dredging operations are inherently different than the hopper dredges. Hopper dredges pump material into the vessel and traverse the waterway to the placement site, cutterhead dredges stay on the dredging location and continuously pump material through pipeline to a selected discharge location.

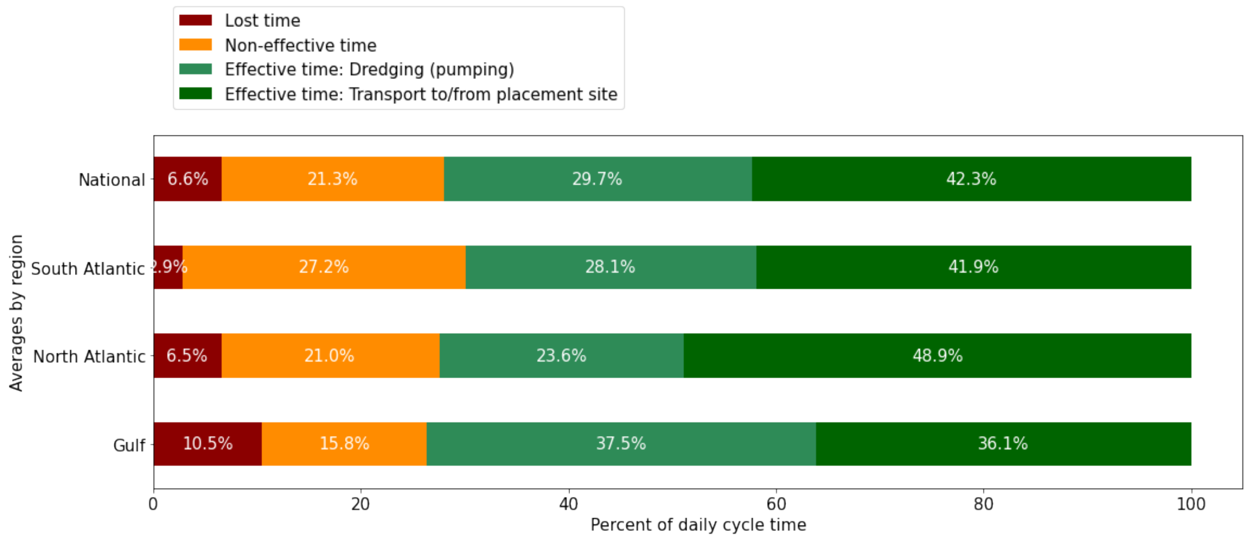

Figure 5. Hopper dredging cycle time percentages, by region. Activity and region averages are calculated from daily production data.

North Atlantic spend 48.7% of cycle time transporting to and from the placement site. This additional time spent transporting material is reflected directly as a shorter dredging portion of the effective time. The Gulf region inversely, has the highest percentage of dredging time with the lowest in transporting time. Notably, hopper dredges in the Gulf region lost a higher percentage of cycle time than in the South and North Atlantic regions. Lost time may be due to a lack of required crew, major repairs and alterations, drydocking, cessation, and collisions.

Next, the authors analyze hopper's average daily production as a function of travel time to and from placement site (Figure 6). Each point of Figure 6 corresponds to a project in RMS. The vertical axle represents the projects' average daily volume of material dredged per day (measure in cubic yards/day), and the horizontal axis represents the travel time to and from the dumping site in minutes per load. Since the distance to placement sites (in miles) is not directly available in RMS, the travel time to and from the disposal site is used as a proxy. Figure 6 shows that the distance to placement sites in minutes) in North Atlantic is longer than in other regions and up to 500 minutes per load. It is intuitive that a longer travel distance to place material for each cycle results in a longer travel time and less productivity per day. This trend is confirmed by the data in Figure 6 for all regions. The daily production data shows that for the projects in the North Atlantic region, the reduction in production as function of the distance to dumping sites is less pronounced than in other regions. Contractors may be implementing practices to compensate for lower daily production from longer distance to dumping sites in North Atlantic such as traveling at relatively higher speeds at the expense of higher fuel consumption. Considering the trendline at National level, 10 minutes of additional travel time to/from placement sites cause an average reduction of productivity in the order of 660 cy/day. Over a several month duration, this variance in productivity becomes significant. This information is important as a deciding factor to allocate disposal sites to projects (USACE, 2012; Wilkens, Suedel, & Mitchell, 2019).

The range of production values per day are much lower within the North Atlantic (35,234 cy/day) than in the Gulf (57,052 cy/day) or in South Atlantic (55,132 cy/day) (Figure 6). This could be attributed to the inherent difference in sediment types in each region, the size of hopper vessel being used, and/or the distance to placement site.

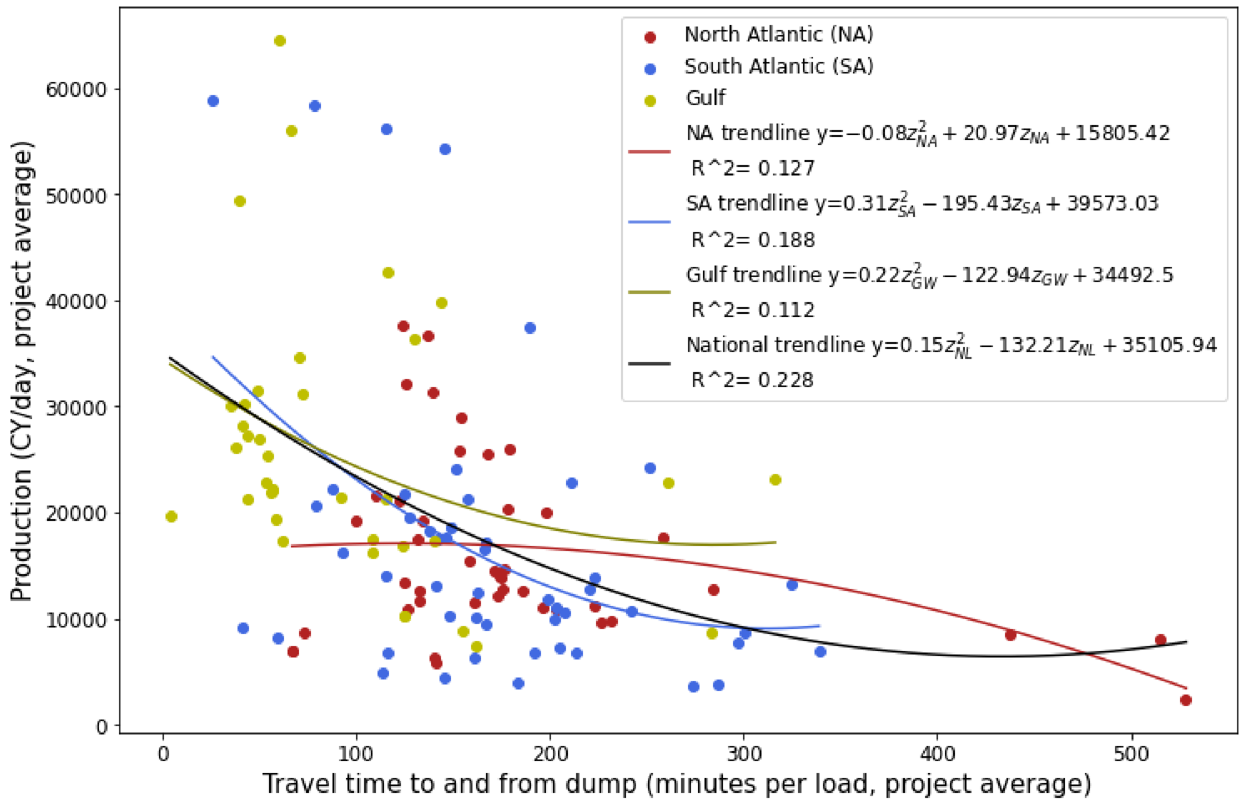

Figure 6. Production (cubic yards dredged per day) versus distance to dump site, by region. Since the distance between the dredging and dumping sites is not available in RMS, the travel time between those sites is used as proxy (in minutes per load). Project-average data displayed.

Figure 7 shows the frequency of occurrences for total travel times to and from placement sites. Based on the data included in this report, the vast majority of USACE hopper dredging projects rely on placement sites within 150 minutes round trip. The project shown to the far right had a vessel that took over 750 minutes (12.5 hours) to make one cycle to and from the placement site.

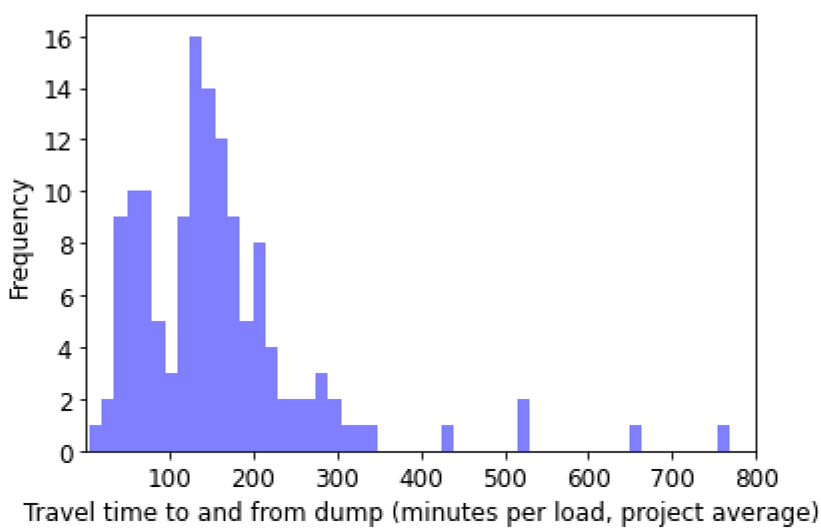

Figure 7. Histogram of distance to dumping/placement site, measures as travel time (minutes)

Cutterhead Dredge Production Analysis

Cutterhead dredging operations are inherently different than the hopper dredges. Hopper dredges pump material into the vessel and traverse the waterway to the placement site. Cutterhead dredges stay on the dredging location and pump material through pipeline to a selected discharge location. As such, there are different activities that are tracked for cutterhead performance Pipeline dredge production can be impacted from needing to move off the dredging location in the channel for transiting vessel traffic (Welp, n.d.). The North Atlantic region has the least amount of traffic interference (Figure 8). This could indicate that more vessels are traversing the Gulf and South Atlantic waterways during dredging season than in the North Atlantic, or it could simply mean that vessels have more space to pass without impacting dredge operations. This could be explored in the future by using Automatic Identification System (AIS) vessel counts in conjunction with dredging dates and locations. While many factors need to be considered when scheduling dredging operations (Nachtmann, Mitchell, Rainwater, Gedik, & Pohl, 2014), reducing the time dedicated to move out of the way of traffic by scheduling dredging operations during seasons of lower traffic would be beneficial for the dredge operation and the impacted vessel traffic. A seasonal analysis needs to be performed but is out of the scope of this work.

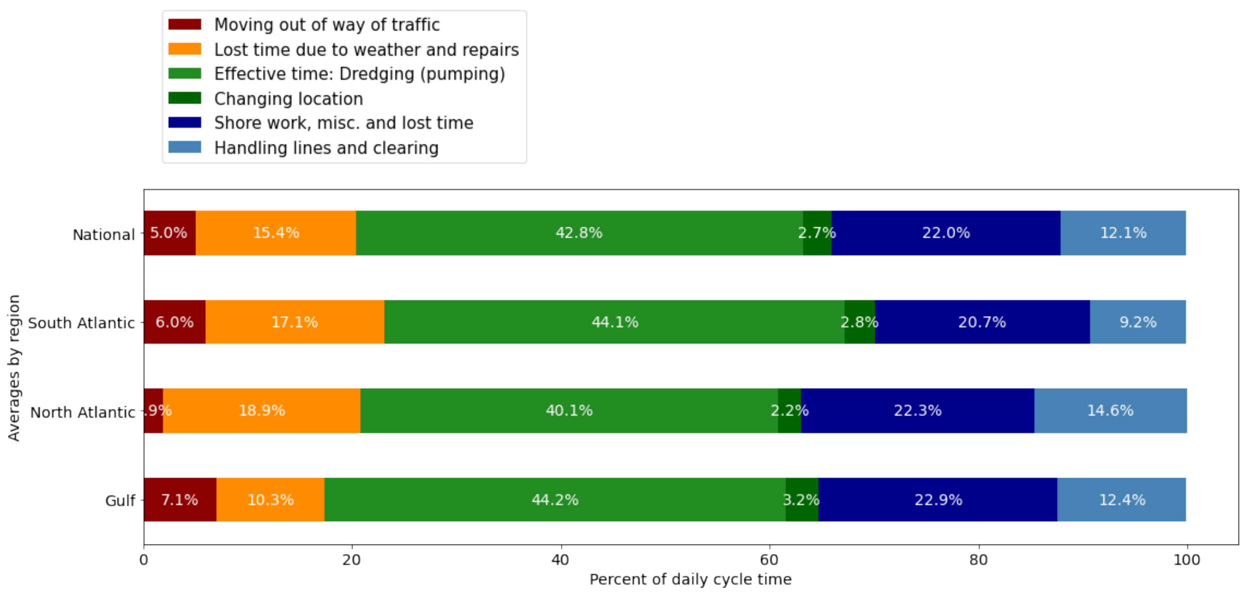

Figure 8. Cutterheads' dredging cycle time percentages, by region. Activity and region averages are calculated from daily production data.

Cycle time activities by cutterhead dredge size are presented in Figure 9 expressed as percentage of total dredging time. It is unclear why the lost time due to weather and repairs (orange portion of the horizontal bars) is higher for large dredges then the small and medium dredges. With all regions and dredge sizes being used at similar times of the calendar year, it is expected that weather delays by dredge size are similar. If so, then the observed lost time reflects higher repair needs on site with larger cutterhead dredges. The small dredges spent the most time handling and clearing pipeline. It is unknown whether this is from pipeline being plugged and needing assistance, or just reworking them for placement changes. From Figure 9, medium size dredges are the most efficient in the cutterhead fleet.

An analysis of the number of days that USACE projects used differing lengths of discharge pipeline by dredge size follows (Figure 10). The pipeline length can be used as a proxy for the distance between the digging location and the placement site. The majority of USACE projects require less than 15,000 linear feet of pipeline, though there are several jobs requiring well over 40,000 linear feet (7.5 miles). The medium

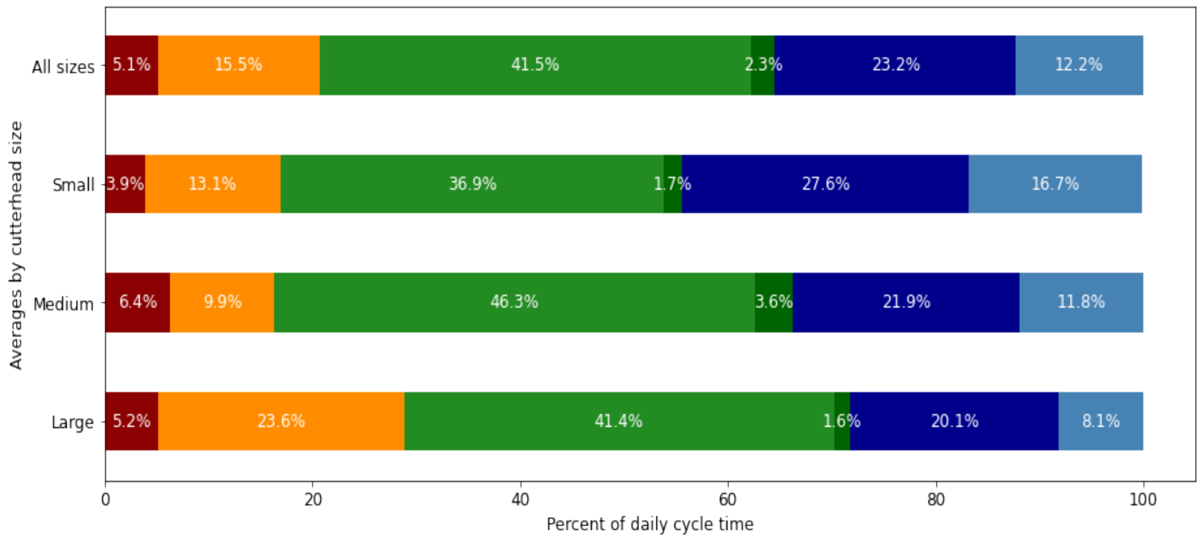

Figure 9. Dredging cycle time percentages, by cutterhead size. Activity and size averages are calculated from daily production data.

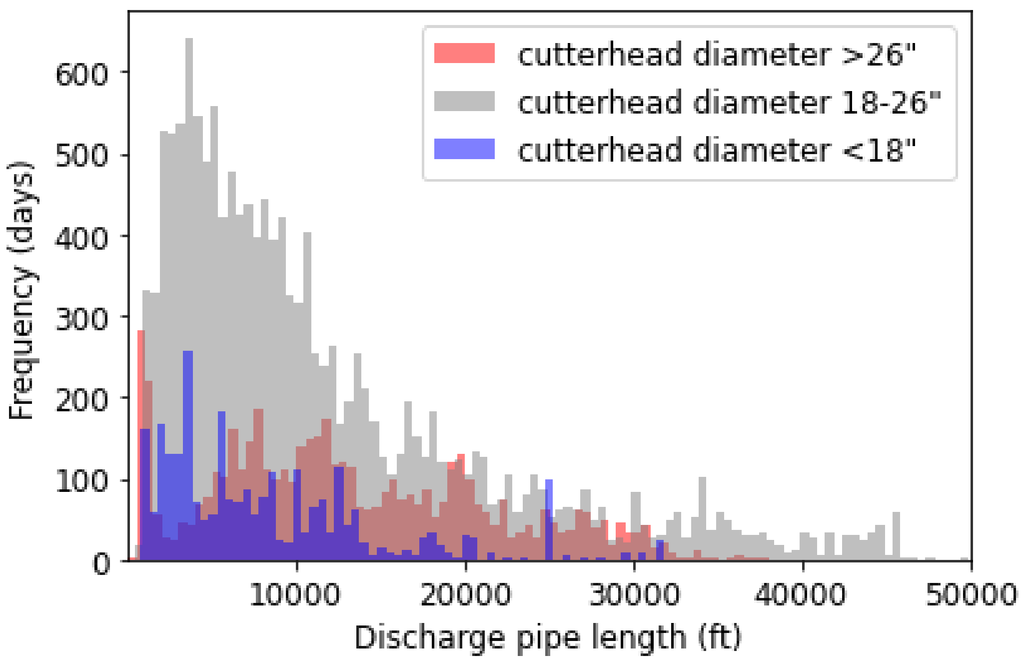

Figure 10. Histogram of discharge pipe length (feet), by cutterhead size. Daily data displayed.

class of cutterheads are generally pumping the longest distances. Production in cy/day was evaluated as a function of pipeline length. The main findings of such effort were that production trendlines were relatively flat for all cutterhead size groupings. The average production by cutterhead size is 24,412 cy/day for large dredges, 11,318 cy/day for medium dredges, and 3,142 cy/day for small dredges.

Lastly, an analysis of percent effective time (EWT) for cutterhead dredges is shown in Figure 11. Each boxplot in Figure 11 shows basic statistics (average, minimum, maximum, and interquartile range) for each group of cutterheads, categorized by region and size. The most interesting data point may be the green box at the right end of Figure 11, evidencing the difference in percent effective time of the large dredges in the Gulf compared to the large dredges in other regions. The small and medium dredges generally maintain percent effective working time over each region. Moreover, the small dredges working on the Gulf region present the lowest minimum and average percent effective time. Figure 11 indicates that the mobilization of larger cutterhead plant to the Gulf region results in a better use of the cutterhead fleet in terms of percent effective time compared to other regions. It is currently unknown why this discrepancy in effective time for large dredges in the Gulf exists.

CONCLUSION

This work provides an overview of the on-going efforts by the USACE in mining, analyzing, and using historic dredge production from the RMS. Hopper and cutterhead dredge production data is analyzed by region (Gulf, South Atlantic, and North Atlantic) and cutterhead size, with more than 36,000 daily records from over 400 projects contracted by the USACE to the private industry across 10 years. This work focuses on the relative percentual time spent by dredges in each of the activities of their production cycles. Highlights of this analysis are that hopper dredges in the North Atlantic spend in average 48.7% of cycle time transporting to and from the placement site, more than dredges in other regions, due to longer distance to disposal sites and at the expense of a reduced pumping time. The analysis explores productivity changes

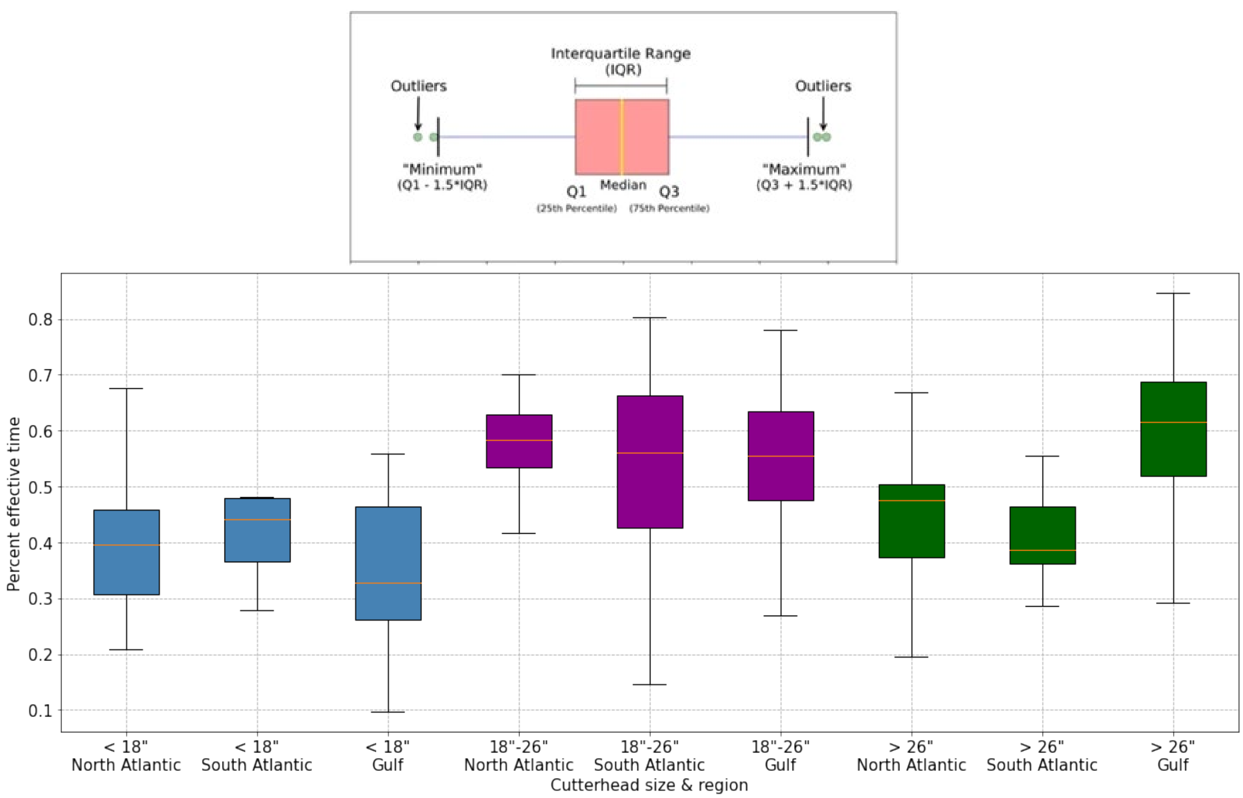

Figure 11. Boxplots showing Percent effective time (time spent pumping material from the channel bottom, as a percentage of the total daily dredging cycle time), by cutterhead size and region. Averages are calculated from daily production data.

(in terms of average volume dredged per day) as a function of distance to disposal sites. For hoppers, the data confirms theoretical assumptions, indicating that hopper dredge production declines as a function of distance to the placement site while cutterhead production remains consistent. The data evidences that the majority of USACE cutterhead projects require less than 15,000 linear feet of pipeline, though there are jobs requiring over 40,000 linear feet (7.5 miles). In addition, for cutterheads, this work evidences and compares percent effective time by cutterhead size and region. The large cutterheads are most effective in the Gulf region.

In the future, seasonality analysis may be made in regard to traffic and weather trends, and how they affect dredging production data from MVN, the West, and Great Lakes divisions where several dredging contracts take place each year will be incorporated into the analysis. RMS data informs future dredge schedule optimization, cost engineering, and regional contracting efforts.

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CONSTANT COMMUNICATION BRINGS A COMPLEX PROJECT TO FRUITION AT AN ACCELERATED PACE

R. Ruchhoeft[1]

ABSTRACT

The United States' busiest Port is at a crossroad of opportunity to catapult itself into the second half of the 21st century. Before the feasibility study could be completed, it became apparent that the normal federal process of construction implementation would be insufficient to address unprecedented industrial growth and associated degradation of safe vessel operations.

Port Houston, the non-Federal Sponsor to the Houston Ship Channel, has been working with its Federal and non-Federal partners to accelerate implementation of the study results through several initiatives spanning public outreach, finances, public and private outreach, and significant technical design acceleration.

This paper discusses the challenges and opportunities resulting from the owner's desire to accelerate the implementation of the deepening and widening of the Federal Houston Ship Channel.

As the program started, the project became engrained across the organization and required the attention of consulting teams to develop plans and specs in a short period, data collection of bathymetric surveys, geotechnical borings, federally certified ship simulations during a pandemic, additional environmental modeling, and quality control evaluation.

The program progression highlighted the need to implement specific milestones across the design, review, and construction implementation spectrum, assuring seamless progress among multiple projects, while assuring completeness across each individual project. Additional hurdles included working with various industrial partners to relocated pipelines and production wells, federal and state agencies, and public citizens to reduce their respective concerns while working on mechanisms that will sustain the Port's capability to serve its other obligations in the future.

Coordinating the sheer number of inputs from the numerous stakeholders, facilitating design challenges, and coordinated solutions, and maintaining an accelerated schedule presented the team with unique challenges that afforded exceptional project executions.

As the first projects near completion, lessons from their execution are being incorporated in the lagging projects adding to the effectiveness of the project.

Keywords: Channel Deepening, Channel Widening, Ship Simulation, Upland Confined Placement Area, Houston Ship Channel, Beneficial Use

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INTRODUCTION

The Port of Houston is home to one of the busiest waterways in the United States with over 9,000 deep-draft and 200,000 barge transits per year. Through a series of improvements first funded in 1853 for $46,000, the Houston Ship Channel (HSC) has been continuously improved through its last major deepening to a 45-foot draft channel in 2005. Even before completion of this deepening, the stakeholders along the channel realized the need for additional improvements. With Congressional authorization in 2014 and an exemption to funding and schedule by the Assistant Secretary of the Army, Port Houston (as the local, non-federal sponsor) and the U.S. Army Corps of Engineers (USACE) Galveston District embarked on a $10M, 4-year feasibility study on 13 November 2015 resulting in a 9 December 2019 Feasibility Study Report and a 23 April 2020 Chiefs Report for the HSC Expansion Channel Improvement Project (HSC ECIP), also known as Project 11.

The $10M budget and 4-year timeframe were chosen to minimize study risks while understanding that certain features and aspects of the with-project condition would require additional study, traditionally performed during feasibility, during the Pre-Construction Engineering & Design (PED) phases of the project. Most of the proposed improvements to the HSC were similar to past practices and allowed the feasibility project development team (PDT) to focus its resources on those activities thought to have the most risk to the viability of the project. A significant portion of the feasibility study resources were dedicated to sediment testing to assure compliance with USACE policies and regulations, State and Federal regulations, and integration to “U.S. Army Corps of Engineers SMART Planning Feasibility Studies” (USACE 2015). Though a critical path activity during feasibility, the fact that the environmental testing activities were performed during the feasibility phase would allow design implementation to occur at an increased rate. While the major components to environmental compliance were covered by NEPA, detailed analysis for complete implementation was deferred for PED level analysis.

FEASIBILITY ASSUMPTIONS

With the complexity of the HSC study limits, the PDT established six separable segments, with Segment 1 further subdivided into three pieces for constructability purposes. While the exact boundaries between the bay and bayou vary by season, Segments 1 through 3 are within the bay reach while segments 4 through 6 are within the bayou reach (See Figure 1). Most of the industrial partners of the HSC are located within the bayou reach, except for Port Houston’s public container terminals and some industrial users located on the Bayport Ship Channel (Segment 2) and Barbours Cut Ship Channel (Segment 3). Although there are no users located directly on Segment 1, all vessel traffic entering and exiting the HSC must transit along this segment making it one of the busiest waterways in the United States (U.S.) with over 9,000 deep-draft and 200,000 barge transit per year.

During the study it became apparent that a major risk factor for a successful project implementation was establishing the authorized channel width within the bay reach. The USACE Engineering Manual (EM 1110-2-1613) originally indicated a need for a channel at least 900 feet (274 meters) in width within Galveston Bay to accommodate existing and anticipated future vessel traffic. This represented an almost doubling of the existing channel width of 530 feet (160 meters) and presented an opportunity for piloted ship simulations to be conducted. A feasibility level ship simulation indicated the need to widen the HSC within Galveston Bay to a minimum of 700 feet (213 meters) to accommodate existing and near future vessel traffic. A more detailed analysis was proposed to be conducted during PED to refine the feasibility level analysis.

Before the feasibility study could be completed, HSC stakeholders established that implementing the proposed recommendations under the established Federal Government processes would cause undue risk to Galveston Bay. The standard system required the feasibility study to be fully approved and authorized by Congress before it could be funded, designed, and constructed. To reduce the timeline, Port Houston created a path to accelerate the process. Using its ability to accelerate funding, Port Houston funded design for four of the identified segments with an emphasis on the systems' most critical segments to widen Galveston Bay (Segment 1) and deepen the HSC from Boggy Bayou to Hunting Bayou (Segment 4). It became apparent the Port maintain a regimented project management plan that allowed flexibility to accommodate inevitable changes on the complex project at hand. The pace and resources would dictate the effectiveness of the project execution.

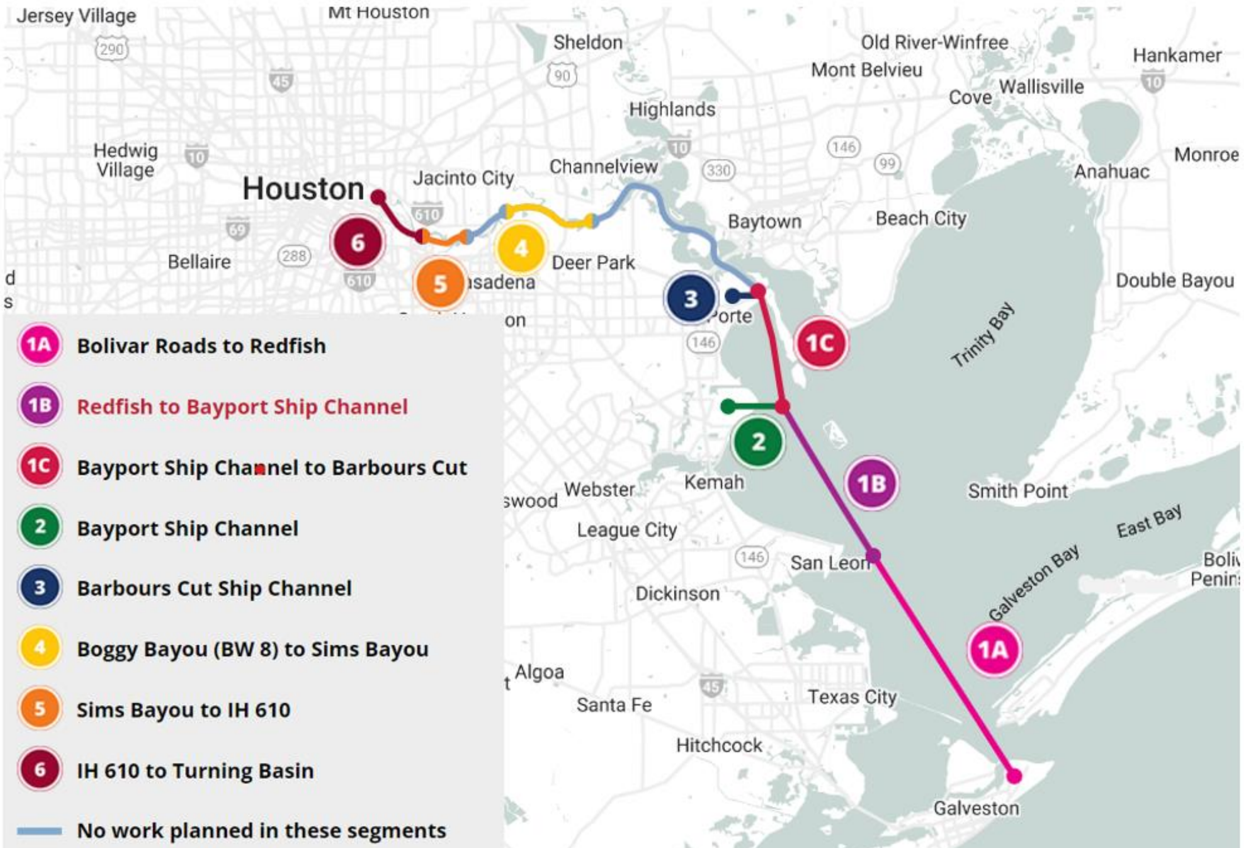

Figure 1. The Houston Ship Channel with Study Segments.

PROJECT IMPLEMENTATION

Port Houston leadership responded to the stakeholders needs by elevating the status of the project as an organizational priority that would become engrained across the organization. The Port implementation team developed an approach to implement the project on a three-legged stool of advocacy, finance, and technical implementation. While still in draft form in mid-2019, the feasibility study highlighted the need for the project implementation. The early challenges revolved around the fact that the project had yet to be authorized by Congress, which would allow federal participation on the project.

Though much of this paper highlights the challenges of the technical teams to develop plans and specs in a short period, all three teams had to ensure coordination of the various concurrent activities and used frequent meetings and milestones to measure progress and assure an accelerated implementation of the project.

The advocacy team went into high gear as the feasibility PDT wound down submitting their final report on 9 December 2019. The team reached out to USACE headquarters to ensure an efficient review of the submitted feasibility report. At the same time, the advocacy team engaged with Congress to ensure their awareness of the project with the proposed passing of the 2020 WRDA bill. The team also reached out to the remaining stakeholders with the implementation of a website providing all stakeholders with updates on the feasibility study and later design and construction updates.

The finance team started the process of ensuring that the project would have adequate funding. The team identified funding sources and prepared the necessary documentation to provide stakeholders with a proper understanding of the project benefits. The Port was able to leverage its strong financial balance sheet to encourage its partners to support the project.

Port Houston was able to effectively use its Request for Qualifications (RFQ) process to award design contracts to two consulting teams. The synergies of selecting the two teams allowed the Port to accelerate the project design. Based on the feasibility results, the four Segments slated for Port implementation were divided into nine construction contracts. The Joint Venture, JV (AECOM, Inc. and Gahagan & Bryant Associates) was selected to perform design for packages associated with Galveston Bay and the Bayport Ship Channel (Packages 1, 3, 4, 5, and 6). HDR, Inc. was selected to perform design related to Barbours Cut and the Bayou reach of the HSC (Packages 2, 7, 8, and 9). Table 1 provides a summary of the HSC ECIP Design Packages by Segment. The remaining two segments to the Congressionally authorized project are planned to be completed once the first nine packages have been completed.

Table 1. HSC ECIP Design Packages by Segment

Construction Package	Segment Number	Project Description	Design Features	Designer of Record
Package 1	1A	Construct Dollar Reef Oyster beds	• Construct reef for mitigation	JV
Package 2	4	Prepare Beltway 8 Site	• Clear and grub site for future placement area construction	HDR
Package 3/4A	1A	Bolivar Roads to Redfish	• Dredge HSC to 700 feet (213 meters) • Construct bird Island (skimmer bird habitat)	JV
Package 4	*Package 4 was split between Package 3 and Package 5			
Package 4B/5	1B/2	Redfish to Bayport and Bayport Ship Channel	• Dredge HSC to 700 feet (213 meters) • Dredge Bayport Ship Channel to 455 feet (139 meters) wide • Construct Port owned wharves • Construct bird island and marsh complex	JV
Package 6	1C	Bayport to Morgans Point	• Dredge HSC to 700 feet (213 meters) • Construct marsh (M11)	JV
Package 7	3	Barbours Cut Ship Channel	• Dredge Barbours Cut Ship Channel to 455 feet (139 meters) wide • Construct bulkhead walls • Construct marsh (M12)	HDR

Construction Package	Segment Number	Project Description	Design Features	Designer of Record
Package 8	4	Construct Beltway 8 and East-East Clinton placement areas	• Construct containment dike for one-time use Beltway 8 placement area • Construct containment dike for East-East Clinton placement area	HDR
Package 9	4	Boggy Bayou to Hunting Bayou Turning Basin Dredging	• Dredge Boggy Bayou to Greens Bayou to 46.5 feet (14.2 meters) MLLW and 530 feet (162 meters) wide • Dredge Greens Bayou to Hunting Bayou to 46.5 feet (14.2 meters) MLLW	HDR

To further accelerate design implementation, geotechnical soil sampling, hazard surveys, and hydrographic surveys were collected under separate contract prior to negotiation of the design contracts.

HVJ Inc. and their subconsultants, through the JV, was tasked to collect geotechnical data and analyze the information via an USACE-approved laboratory. During the winter months, weather conditions within Galveston Bay limited the ability to effectively collect this data. The team planned to use a combination of pontoon barges for protected water shallow borings, spud barges along the bayou reach, and a jack-up barge within the open waters of Galveston Bay. A more detailed scope of services is presented in Table 2.

Table 2. Geotechnical Scope of Work

Construction Package	Segment	Project Feature	Scope of Work
1	1A	Oyster pad	6 Borings at 20 feet (6.1 meters) below mudline
2	4	Clearing and grubbing	Not applicable
3	1A	Bird Islands	9 Borings at 40 feet (12.2 meters) below mudline
		Channel Dredging	10 Borings at -60 feet (18.3 meters) MLLW
4	1A/1B	Channel Dredging	15 Borings at -60 feet (18.3 meters) MLLW
5	1B/2	Bird Island Marsh	21 Borings at 40 feet (12.2 meters) below mudline
		Oyster pad	8 Borings at 20 feet (6.1 meters) below mudline
		Channel Dredging	21 Borings at -60 feet (18.3 meters) MLLW
6	1C	Marsh	12 Borings at 30 feet (9.1 meters) below mudline
		Oyster pad	6 Borings at 20 feet (6.1 meters) below mudline
		Channel Dredging	7 Borings at -60 feet (18.3 meters) MLLW
7	3	Marsh	15 Borings at 50 feet (15.2 meters) below mudline
		Channel Dredging	12 Borings at -60 feet (18.3 meters) MLLW
8	4	Placement area berm	45 Borings at 40 feet (12.2 meters)
9	4	Channel Dredging	25 Borings at -60 feet (18.3 meters) MLLW

Hazard surveys and hydrographic surveys were conducted at the same time as the geotechnical investigation through the JV and its subcontractors to provide baseline data along the channel and at the proposed marsh and island sites. Much of this data collection was dependent on weather conditions affecting the vessels in use.

While the feasibility level design was entirely dependent on existing data, the design teams understood the importance of having an effective level of geotechnical samples and survey maps for their designs to be constructed. At the same time, the teams were willing to initiate their designs with limited data that would require future rework as additional information became available with minor changes to the feasibility level features expected during the design process.

Geotechnical Analysis causes changes to Environmental Features

As the geotechnical data became available, it became apparent that certain assumptions made during the feasibility had been incorrect and design modifications became necessary. Within Segment 1A (Package 3), the quantity of usable dredged material was significantly lower than anticipated. The design team recommended deleting one of two bird islands. The BUG in coordination with the USACE modified the feasibility study results and agreed to remove the 8-acre (32,000 m^2) bird island construction from the project requirement so that full implementation of a skimmer bird island could be achieved. With concurrence by the Federal agencies, the design team finalized the design and established the design details necessary for construction.

Additionally, constructability issues threatened the viability of the Three Bird Island Marsh (BIM) feature. The existing bay bottom soil at the location established during feasibility study was significantly softer than anticipated. Though the study steered away from documented areas of historical oyster mining, the team quickly discovered the preferred location to be unsuitable for construction. To save the viability of the feature, the BIM was moved to a new location avoiding a tangle of pipelines within Galveston Bay. Although the new location's soil substrate was more conducive for construction, the water column was significantly higher and further from the dredged material source, requiring additional dredged material for construction. The implementation plan was revised, including reducing the size of the BIM and including material originally destined for another planned marsh facility.

While the lower bay reach indicated a quantity deficiency, geotechnical investigations of the Barbours Cut Ship Channel indicated stiffer than expected clays, which in turn resulted in a smaller than anticipated material degradation and loss during hydraulic dredging operations. After the exterior perimeter has been completed, to accommodate the additional expected material, the interior of the marsh will be completed during initial construction. The new work material is not expected to consolidate as much maintenance material, so HDR has carefully prescribed discharge operations to minimize the potential of overfilling the marsh area.

The Port to fully engaged all federal stakeholders in all requirements and changes. A schedule with milestones was developed to help guide the process. The Port conducted weekly meetings with its designers to review the risk profile of any proposed changes from the feasibility level design. The Port initiated a peer review of the design packages by engaging Atkins, a member of the SNC-Lavalin Group. The comments provided by the third party reduced the Port's exposure during construction. The changes in the technical project execution were determined minor and only required a sufficiency notice to move the project forward.

Additional Data allows for Physical Channel Modifications

Widening of the Bayport and Barbours Cut Ship Channels encumbered additional uplands. Using EM 1110-2-1613, the channel width recommendation during feasibility was 455 feet (139 meters).

Bayport Ship Channel

The existing Bayport Ship Channel was 400 feet (122 meters) within the bay, transitioning to 350 feet (110 meters) in the land cut area. During feasibility, the PDT determined that a recently constructed maritime college at the local San Jacinto College would need to be protected by a substantial bulkhead. The college became concerned by the proposed construction timeline immediately adjacent to their facility. The design team also discovered that the bulkhead size had been underestimated by the feasibility team as the college's foundation system would not allow it to act independently from the bulkhead. This would be exacerbated during future HSC improvements. While the team prepared contingencies to facilitate the widening, the team also discovered that a berth supporting the economics of the channel had been permitted and was under construction that only considered a partial the widening of the Bayport Channel to match the dimensions in the bay. With the hurdles presented, the team thought outside the box and considered modifying the channel width to facilitate the existing college and berth structures without modification. With verification through ship simulation, the modification was validated and removed a significant cost impact to the system. Figure 2 provides a side-by-side comparison of the Feasibility versus Design Bayport Ship Channel layout. The non-structural change required significant coordination by the Port. As outlined in the Design Documentation Report (Hedderman 2021) for this segment, the primary concern was the safe transit of the design vessels in the Turning Basin. A piloted ship simulation needed to be performed. USACE needed to agree to the template change, and the change needed to make economic sense. The elimination of a substantial bulkhead was evaluated by the technical team while the other teams received an exemption.

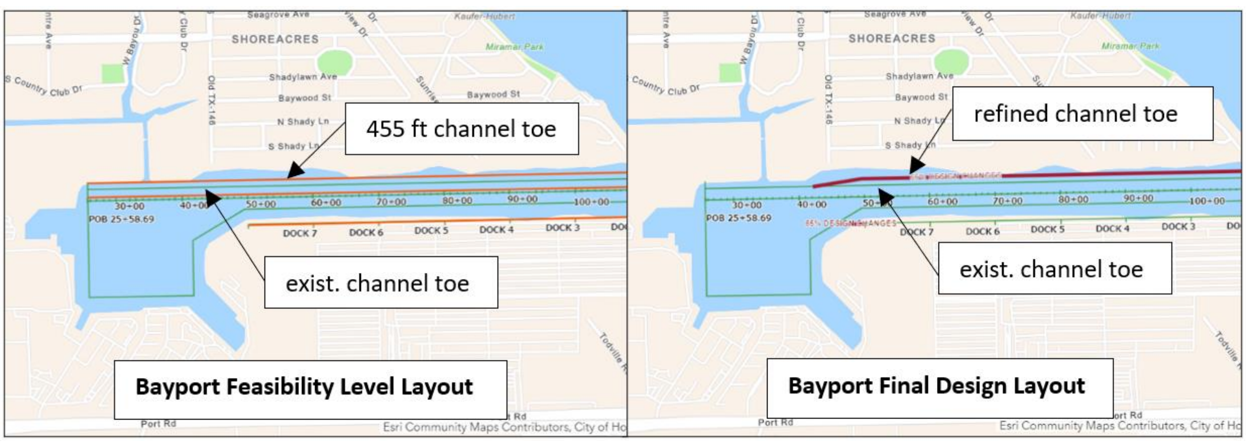

Figure 2. Bayport Ship Channel Feasibility versus Design Layout

Barbours Cut Ship Channel

The Barbours Cut Ship Channel presented itself with its own challenges. During feasibility, it became apparent that a turning basin was necessary at the intersection of the Barbours Cut Ship Channel and the HSC as depicted in Figure 3. The study's tabletop evaluation indicated an opportunity to place the basin towards the Barbours Cut Container Terminal. The Houston Pilots, becoming more familiar with the larger vessels through their simulation practices, noticed that transits would require a more central turning basin location.

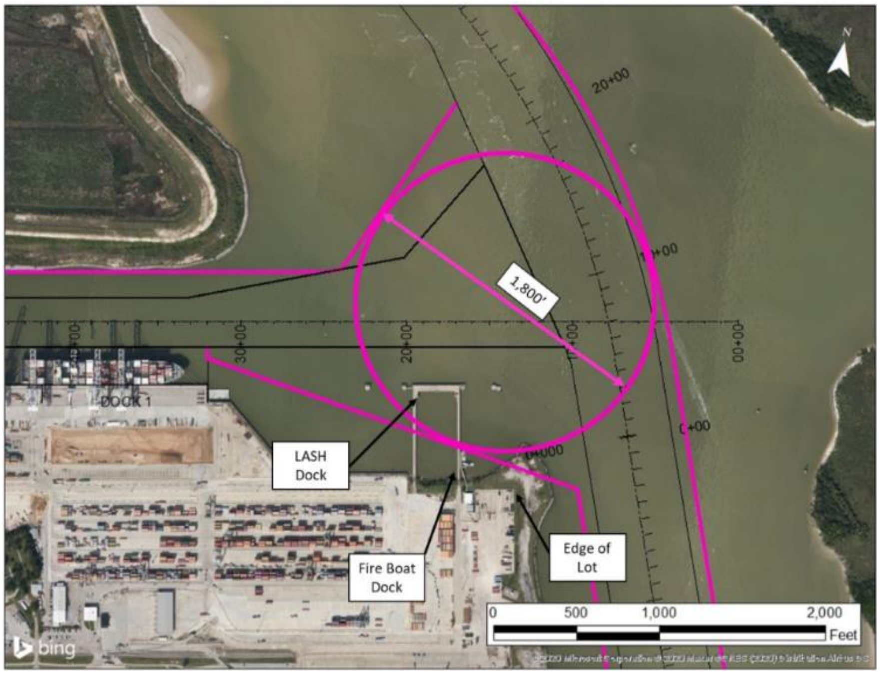

Figure 3. Feasibility Level Turning Basin at the Barbours Cut Ship Channel.

While this change appears to introduce a schedule slip, the need for this change was discovered early in the project when the critical path was Congressional approval of the project. HDR evaluated cost impacts prior to recommending new turning basin locations for piloted ship simulations. The final agreed upon location is presented in Figure 4.

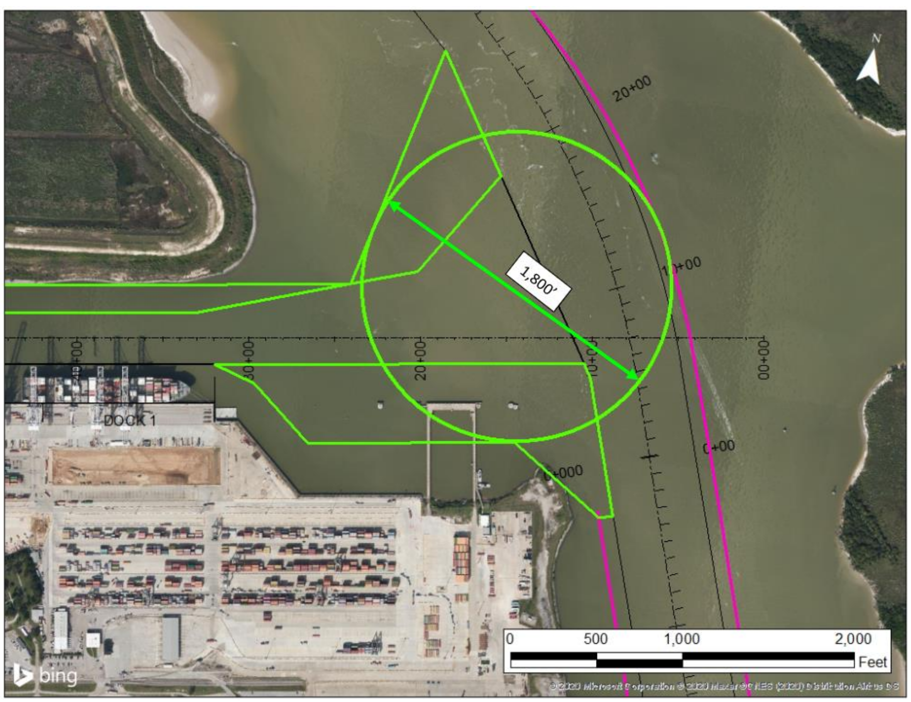

Figure 4. Final Turning Basin Design at the Barbours Cut Ship Channel.

Additional geotechnical investigations revealed that a bulkhead between the HSC and Barbours Cut Container Terminal could be eliminated during this project implementation. The longest of the bulkheads was designed to eliminate the slip plane failure that was produced by modifying the dike footprint of the adjacent Spilman dredged material disposal site.

One bulkhead wall had to be added during design. A pipeline parallel to the Barbours Cut Ship Channel had been constructed outside its proposed limits after the feasibility study had begun. Therefore, the alignment had not been reviewed during feasibility. On behalf of the Port, the design team worked with the pipeline company and its engineer to develop a plan that eliminated a complicated bulkhead system with a multi-faceted construction sequence while dredging the Barbours Cut Ship Channel. The Port found itself coordinating the proposed construction implication and developing a legal agreement between the pipeline user, the Port, and USACE.

Previous Decisions on Pipeline Alignments Impact the Present

While the feasibility study focused on identifying potential pipeline conflicts along the HSC using as-built drawings, HDR Inc. began the process of identifying all potential pipeline conflicts within the HSC as well as placement areas, marshes, and bird islands. While Port Houston licenses pipelines crossing the HSC in Harris County, the pipelines within Chambers and Galveston Counties presented greater risk of being missed by the design team.

Various abandoned pipelines became navigation hazards when the channel was widened from 530 feet (160 meters) to 700 feet (213 meters) became their own removal construction package. To reduce the risk of uncovering abandoned pipelines during dredging operations, the Port coordinated and procured a pipeline removal contract in Galveston Bay. This contract is expected to reduce construction costs by the dredgers as their risk of construction delays are reduced.

Although the Port identified the need to relocate various pipelines within Segment 4, the relocation has become a critical path item potentially needing risk mitigations in the future. Within a pipeline corridor servicing multiple pipelines, six pipelines were identified for a need to be relocated. To reduce the timeline needed to implement the relocation, the Port encouraged the six companies to coordinate their installation and removal. While progress has been hampered by the pandemic, progress is being made with the first permits being issued and construction to begin the second half of 2022 and completion expected late 2024.

Ship Simulations in a COVID-19 World

Much of the final design decisions were highly dependent on the results of ship simulations. U.S. Army Engineer Research and Development Center (ERDC) validation to any variance to EM 1110-2-1613 was required to assure the adequacy of the 700-foot (213 meter) bay reach navigation channel, various bends, turning basins and new channel alignments. As the project had yet to be authorized by Congress and receive first start funding, the Corps was unable to participate in any evaluations, while the design teams were highly dependent on the findings to complete their designs. The Port provided advance funding to the Corps to allow the ship simulations to occur. During this timeframe, the Nation shut down due to the impacts of COVID-19. Travel became restricted. The team devised a plan that would allow the project to proceed. The Houston Pilots ship simulator at the Maritime College of San Jacinto College was employed to provide the simulation venue. While all team members coordinated the number of various simulations needed via email, Webex calls, and phone calls, other team members prepared the necessary precautions within a closed building to reduce the risk to the team members contracting the virus. Team members were brought virtually to the simulations using Webex video feeds and near instantaneous results of the individual runs. In the end, 163 runs allowed the team to maximize navigation safety and establish the primary channel width and alignments within the system. The ERDC published report, "Houston Ship Channel Expansion Improvement Project – Navigation Channel Improvement Study: Ship Simulation Results" (USACE 2021) includes results for the entire HSC downstream of Hunting Bayou and the Bayport and Barbours Cut Ship Channels.

CONCLUSION

Constant communication is key to success of a project of this size and complexity. While the feasibility level design set the character of the project and provided the community stakeholders with certain assurances of the general project implementation, the ability of the team to question details provides a better product for the future.

The driving forces for full implementation were advocacy, finance, and technical implementation. Each worked together ensuring continued successes. As the project progressed, the critical path shifted between the forces, with each team ensuring their piece brought value to the system. Allowing the technical implementation of the project (design) to deviate from the original plan allowed for better value, faster implementation, and a more robust system to be constructed.

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CITATION

Ruchhoeft, R. "Constant Communication Brings a Complex Project to Fruition at an Accelerated Pace," Proceedings of the Western Dredging Association Dredging Summit & Expo '22, Houston, TX, USA, July 25-28, 2022.

DATA AVAILABILITY

Some data or models generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

PROJECT 11: SEGMENTS 1 AND 2 – WIDENING THE HOUSTON SHIP CHANNEL AND BAYPORT SHIP CHANNEL

A. Judith[1], C. Hedderman[2], D. Cheney[3], and R. Ruchhoeft[4]

ABSTRACT

The Houston Ship Channel (HSC) Expansion Channel Improvement Project (ECIP) Final Integrated Feasibility Report and Environmental Impact Statement (FIFR-EIS) was completed in December 2019. To evaluate Federal interest in alternative plans for reducing transportation costs and addressing navigation safety issues, the HSC system was divided into six segments:

- Segment 1: HSC Bay Reach from Bolivar Roads to Morgans Point
- Segment 2: Bayport Ship Channel (BSC)
- Segment 3: Barbours Cut Channel (BCC)
- Segment 4: HSC Bayou Reach from Boggy Bayou to Sims Bayou
- Segment 5: HSC Bayou Reach from Sims Bayou to I-610 Bridge
- Segment 6: HSC Bayou Reach from I-610 Bridge to Main Turning Basin

Port Houston (PHA), U.S. Army Corps of Engineers, and resource agencies collaborated during planning to develop viable options for the beneficial use of dredged material and incorporated them in a plan that would accommodate the project needs for new work material during initial construction and maintenance material throughout the 50-year life of the project. The project builds upon the successes of the last Federal project (Houston-Galveston Navigation Channel [Project 10] constructed between 1995 and 2008) and the beneficial use of dredged materials to create placement capacity and ecosystem value.

Once the HSC ECIP Feasibility Study phase was concluded, the Preconstruction, Engineering, and Design Phase (PED) phase began to further refine the project elements within these six segments with PHA) accelerating the design and construction of some portions of the project. This resulted in nine separate design packages referred to as Project 11. This paper will provide an overview of the project elements identified and included in Segments 1 and 2, which innovatively uses dredged material to build a combination bird island with marsh features, bathymetric relief for oyster reef mitigation, and a variety of placement area dike repairs and raises.

Keywords: Dredging, Beneficial Reuse of Dredged Sediments, Navigation Channel Design, Port Deepening Program Updates.

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INTRODUCTION

The Houston Ship Channel (HSC) Expansion Channel Improvement Project (ECIP) Final Integrated Feasibility Report and Environmental Impact Statement (FIFR-EIS) was completed in December 2019 (USACE 2019).

To evaluate Federal interest in alternative plans for reducing transportation costs and addressing navigation safety issues, the HSC System was divided into the following six segments within the HSC System:

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- Segment 6: HSC Bayou Reach from I-610 Bridge to Main Turning Basin

Once the HSC ECIP Feasibility Study phase was concluded, the Preconstruction, Engineering, and Design Phase (PED) phase began to further refine the project elements within these six segments with Port Houston (PHA) accelerating the design and construction of some portions of the project. This resulted in nine separate design packages referred to as Project 11. This paper will provide an overview of the project elements identified and included in Segments 1 and 2 which innovatively uses dredged material to build a combination bird island with marsh features, bathymetric relief for oyster reef mitigation, and a variety of placement area dike repairs and raises.

BACKGROUND

As summarized below, Segments 1 and 2 consist of channel modifications to widen the HSC and Bayport Ship Channel (BSC), ease channel bends, expand existing turning basins, and construct new ones. The widening through Galveston Bay, Segment 1, is also divided lengthwise into the three straight segments (1a, 1b, 1c) of the existing HSC alignment.

- Segment 1 – HSC Bay Reach
  - (1a) Lower Bay – Extends from approximate Station 138+369 near Buoy 18 to Station 78+844 at Redfish Light 1 referred to as Bolivar Roads to Redfish.
  - (1b) Mid Bay – Extends from Station 78+844 to Beacon 75/76 at Station 28+605, referred to as Redfish to BSC.
  - (1c) Upper Bay – Extends from Station 28+605 to Morgans Point at approximate Station 0+00, referred to as BSC to BCC.
- Segment 2 – Bayport Ship Channel

<u>Design Packages</u>

The project elements within Segments 1 and 2 were originally designed under four separate [dredging] packages (Packages 3, 4, 5, and 6 to separate methods of dredging by packages). The work originally included within Package 4 was later divided between Packages 3 and 5 to conform with Federal requirements for separable elements. The revised dredging packages are now referred to as Packages 3/4a, 4b/5, and 6.

Additionally, Package 1 is associated with Segment 1, but pertains to a standalone oyster mitigation project that was designed by PHA but procured and administrated by the U.S. Army Corps of Engineers (USACE).

A project overview of the four packages is shown in Figure 1 and summarized in Table 1.

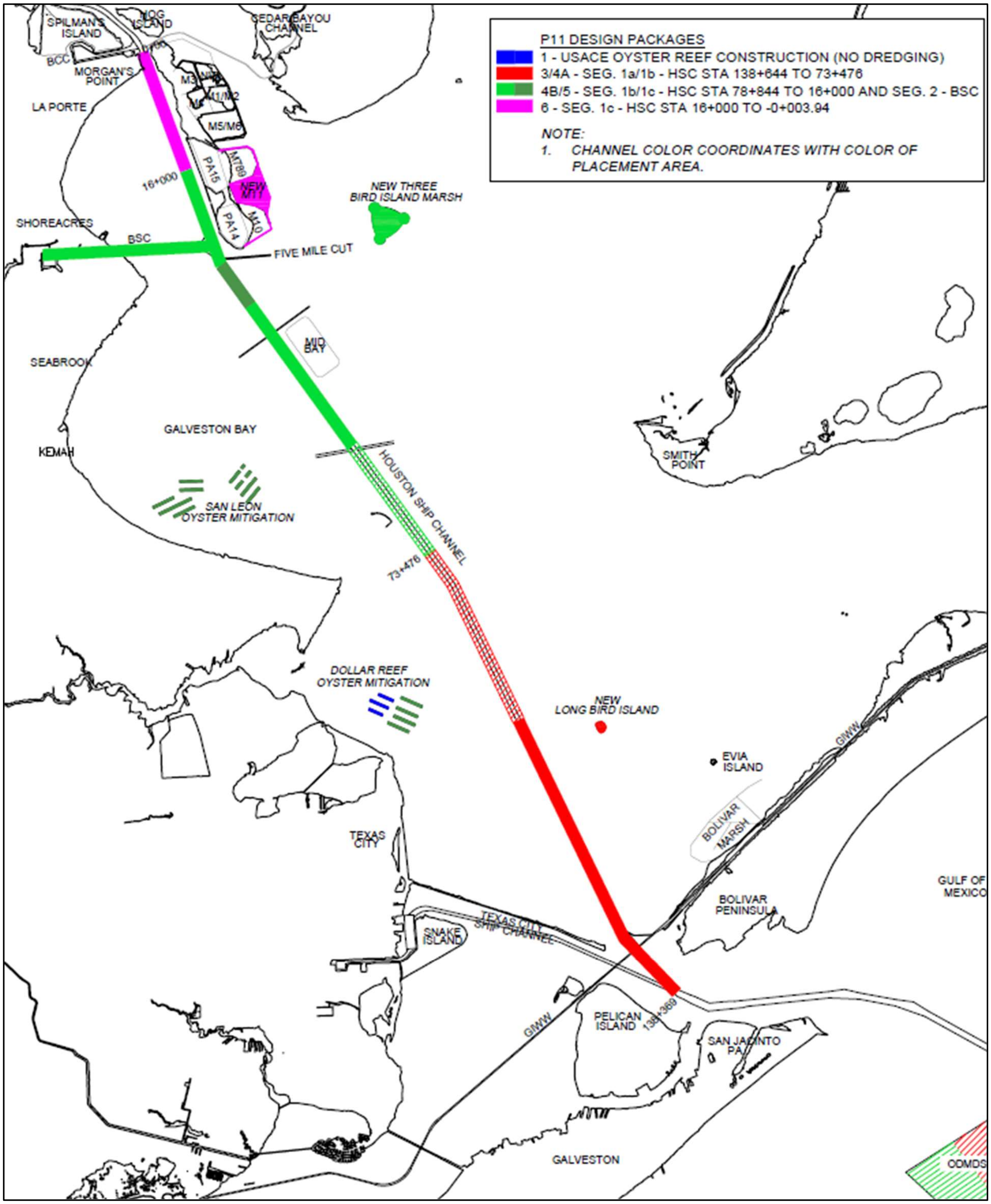

Figure 1. Project Overview of Project 11 Design Packages 1, 3/4a, 4b/5, and 6

Table 1. Project Description Summary of Project 11 Dredge Packages 1, 3/4a, 4b/5, and 6.

Project Number	Project Name	Dredging	Existing PA	New PA
W912HY21C0025	Dollar Reef Oyster Mitigation	--	--	Dollar Reef Oyster Mitigation (DRM)
C90-D13-P11-003/4a	Bolivar Roads to Redfish HSC Station 138+369 to HSC Station 73+476	Widen existing HSC from 530 feet (161.5 meters) to 700 feet (213.4 meters) from approximate Station 138+369 to 73+476. The channel transitions from 700 feet (213.4 meters) back to 530 feet (161.5 meters) between Station 78+844 and 73+476	Ocean Dredge Material Disposal Site (ODMDS)	Long Bird Island (LBI)
C90-D13-P11-004b/5	Redfish to Bayport HSC Station 78+844 to 15+500 & BSC Station 238+37 to 42+00	• Widen existing HSC from 530 feet (161.5 meters) to 700 feet (213.4 meters) from approximate Station 78+844 to 15+500. The channel will resume widening the remains of the channel from 530 feet (161.5 meters) to 700 feet (213.4 meters) between Station 78+844 to 73+476 • Advanced Maintenance of an additional 3 feet (0.9 meters) of new work material between HSC Station 24+000 – 31+000 between existing 530-foot (161.5 meters) and 700-foot (213.4-meter) HSC • Additional Advanced 3 feet (0.9 meters) of maintenance between HSC Station 24+000 – 31+000 within existing 530-foot (161.5 meters) HSC • Adjust BSC Flare transition to the HSC to align with 700-foot (213.4-meter) HSC widening from approximate BSC Station 234+36.61 to 239+22.31. • Widen existing 350/400-foot (106.7/121.9-meter) BSC to 455 feet (138.7 meters) from approximate Station 42+07.80 to 222+75.87 Dredging of BSC Dock 7 (BSC Station 48+19.51 to 60+00) and Dock 1 (BSC Station 110+00 to 122+31.79) • Advanced Maintenance of an additional 5 feet (1.5 meters) of new work material in the southern portion of the BSC Flare Easting between the historic 3,000-foot radius to the 4,000-foot radius. • Additional Advanced 5 feet (1.5 meters) of maintenance of the historic BSC Flare previously mined	ODMDS	Three Bird Island Marsh (TBIM) San Leon Oyster Mitigation (SLM) Dollar Reef Oyster Mitigation (DRM)
C90-D13-P11-006	Bayport to Morgans Point HSC Station 15+500 to -0+003.94	Widen existing 530-foot HSC to 700 feet (213.4 meters) from approximate HSC Station 15+500 to HSC Bayou Station 27+48.18.	Dike Rehabilitation of M7/8/9 & M10	M11

Project Datums

The horizontal datum for the project is based on the Texas State Plane Coordinate System, South Central Zone 4204, North American Datum of 1983 (NAD83). The vertical datum is referenced to Mean Lower Low Water (MLLW).

All prior projects in the Galveston District have used the USACE vertical datum Mean Low Tide (MLT). The USACE has completed the process of converting the channel templates for all navigation projects from MLT to MLLW (USACE, 2015a).

CHANNEL DESIGN

Channel design features and dimensions described in the HSC ECIP FIFR-EIS were further evaluated through:

- Ship simulation
- Templates were verified and/or revised through geotechnical analysis and evaluation
- Coordination with the USACE Galveston District and stakeholders

Houston Ship Channel

The existing HSC from Station 138+369 at Bolivar Roads to Station -0+003.94 at Morgans Point is generally 530 feet (161.5 meters) wide with 235 feet (71.6 meters) of navigable barge space on either side of the channel. The 235 feet (71.6 meters) of navigable barge space begins at the toe boundary of the 530-foot deep draft channel and extends to the -13 feet (-3.9 meters) MLLW contour to the outer toe of the barge lane channel. The channel will be widened to 700 feet (213.4 meters) with associated in-kind relocation of barge lanes. There are four cut-off bends in this section of the channel that will be eased and widened at approximate Stations 138+369, 128+731, 78+844, and 28+605. The 700-foot (213.4-meter) channel will transition back to the existing 530-foot channel between Station -0+003.94 (HSC Bayou Station 00+00) and HSC Bayou Station 27+48.18. The current authorized depth of the channel is -46 feet (-14.0 meters) MLLW from Station 138+369 to 31+059.92 (Bolivar Roads to BSC), and -46.5 feet (-14.2 meters) MLLW from Station 31+059.92 to -0+003.94 (BSC to Morgans Point).

The channel will be widened to a width of 700 feet (213.4 meters) with 3H:1V slopes to a required depth of -48 feet (-14.6 meters) MLLW, with a box cut to the allowable overdepth of -50 feet (-15.2 meters) MLLW. From Station 78+000 to 56+000 the channel slope will be 4H:1V, but maintain the same channel width and depths, due to the engineering/geotechnical properties of the material requiring a lesser slope to remain stable. Barge lanes will be relocated to maintain their existing dimensions with the outside barge lane 235 feet (71.6 meters) 4from the HSC toe at a depth of -13 feet (-3.9 meters) MLLW and the allowable overdepth of one foot to -14 feet (-4.2 meters) MLLW. A typical cross section is provided in Figure 2.

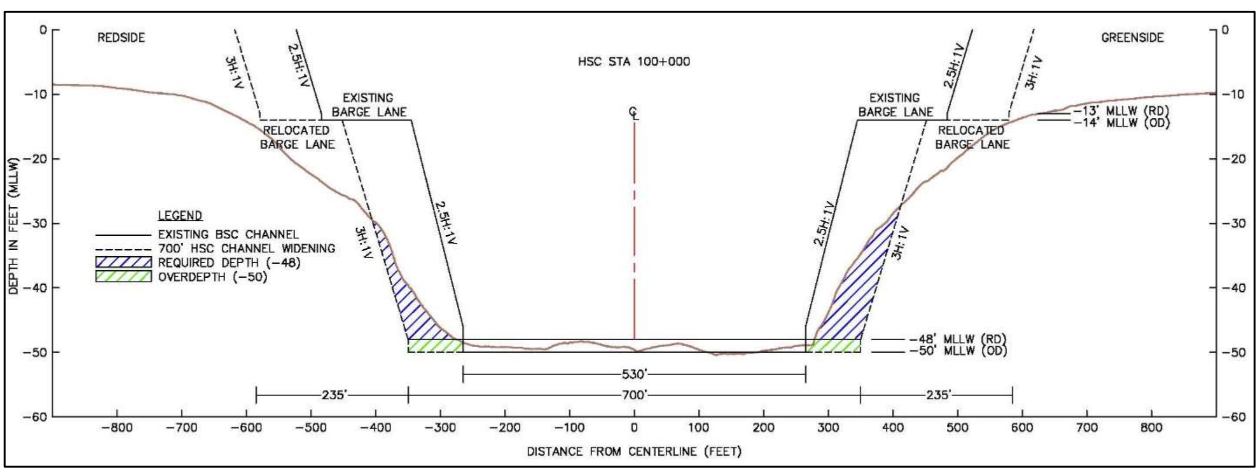

Figure 2. Typical HSC Cross Section.

Materials will be hydraulically and mechanically dredged from the HSC and BSC with placement at BU sites across Galveston Bay including Long Bird Island (LBI), Three Bird Island Marsh (TBIM), oyster reef restoration at Dollar Reef Mitigation (DRM) and San Leon Mitigation (SLM) sites, Atkinson Island Marsh Cells M11 for the rehabilitation of existing and construction of new dikes, and the Ocean Dredge Material Disposal Site (ODMDS). Placement areas are detailed below.

Bayport Ship Channel

The existing 4.1-mile BSC is currently 350 feet (106.7 meters) wide within the land cut from Station 25+58.69 to 115+00, then transitions to 400 feet (121.9 meters) wide at Station 135+00 through the bay cut ending at the flare at Station 221+19. The channel will be widened on the north side to a constant width of 455 feet (138.7 meters) with 3H:1V slopes to a required depth of -48.5 feet (-14.8 meters) MLLW.

Design Considerations and Coordination

The BSC 455-foot (138.7-meter) channel will be created by widening the existing channel to the north from Station 222+75.87 to 42+07.80. Widening within the bay cut by 55 feet (16.8 meters between Station 222+75.87 and 135+00, transitioning to a widening of 105 feet (32 meters) at Station 115+00 within the land cut. The 455-foot (138.7-meter) channel widening will end at Station 49+61.30 and transition to the existing channel toe in the BSC Turning Basin at Station 42+07.80. A typical cross section is provided in **Error! Reference source not found.**.

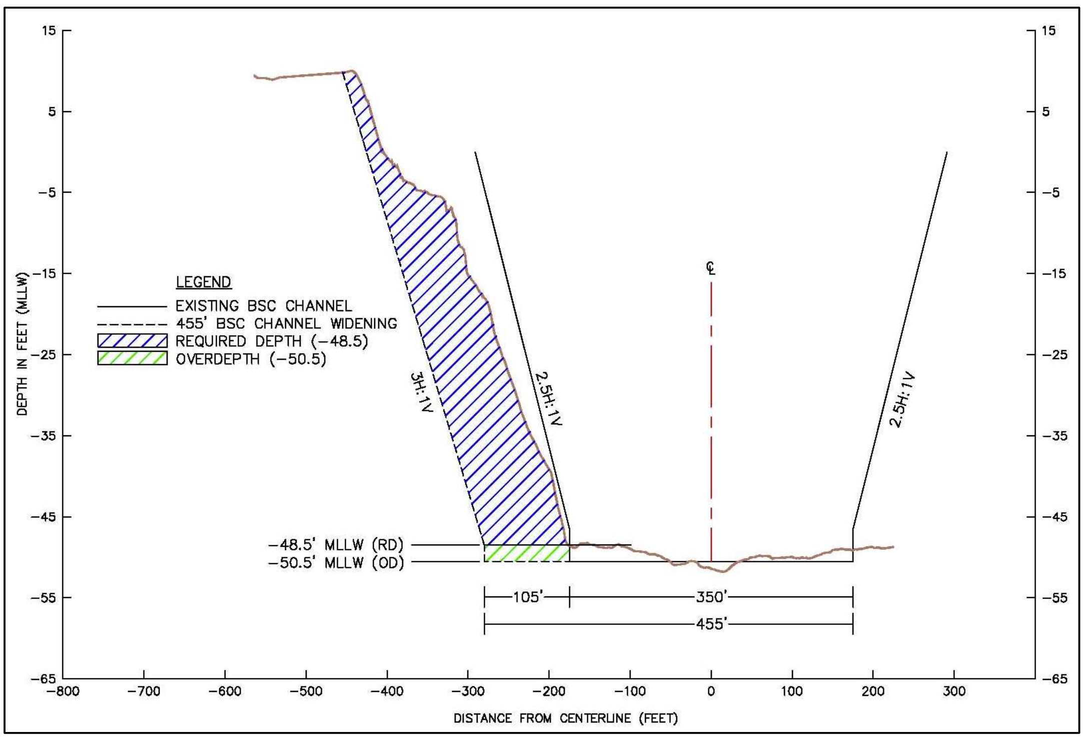

Figure 3. Typical Section of 455-foot (138.7-meter) BSC Widening.

The 455-foot (138.7-meter) BSC was originally evaluated in the HSC ECIP FIFR-EIS to extend the full length of the channel to Station 25+58.

At the western end of the BSC, adjacent to the San Jacinto Community College (SJCC) Maritime Campus, the HSC ECIP FIFR-EIS considered the construction and installation of sheet pile bulkhead walls to protect existing features from potentially being undermined by the BSC widening. During the PED phase, it was determined that the channel slope would encroach into existing shoreside structures in this area unless the proposed channel template was modified. Following a detailed evaluation, the proposed channel template was amended in this location to eliminate these impacts.

The current design calls for 2 feet (0.6 meters) of advanced maintenance with 2 feet (0.6 meters) of allowable overdepth for all of Segment 2 outside of the existing Flare. Materials will be hydraulically dredged and placed at TBIM, as described later.

Areas of the existing BSC north shoreline between approximate BSC Stations 61+80 to 110+90 lay within the BSC new work widening dredge template. The existing riprap shore protection in conflict within these limits will be removed prior to new work dredging, stockpiled in locations approved by the PHA and reinstalled upon completion of the BSC widening. The shore protection will be replaced in-kind to the original shore protection design templates

Some areas of the shoreline have already had the shore protection removed. This occurred during the 2015-2016 BSC Improvements Project. These areas are located between approximate BSC Stations 65+00 – 70+00 and 83+00 – 86+00 and currently remain unarmored. The stone removed from these areas is currently stockpiled on site, adjacent to where it was removed. This material will be re-used during the new project as part of the shore protection reinstallation. However, as not all the necessary material was able to be quantified at the site from the stockpiles due to accessibility, it was assumed that additional shore protection will be required to account for potential losses during the removal and stockpiling of stone. Additional stone will conform to the same design template, but will only include armor stone, due to the small quantity required.

Bayport Ship Channel Flare

The existing 4,000-foot (1219.2-meter) southern BSC Flare toe currently intersects the existing 530-foot (161.5-meter) HSC toe at Station 28+605. The previous 3,000-foot (914.4-meter) radius Flare was mined to -55.5 feet (-16.9 meters) MLLW and later modified in 2018 under a Deferred Environmental Restoration (DER) contract to the current 4,000-foot (1219.2-meter) radius and dredged to a depth of -50.5 feet (-15.4 meters) MLLW.

The BSC Flare will be extended by 85 feet (25.9 meters) at the intersection with the HSC at Station 28+605. The 85-foot (25.9-meter) extended Flare will tie in to the existing 4,000-foot (1219.2-meter) radius Flare at BSC Station 234+36.61 and end at BSC Station 239+22.31.

During the HSC ECIP FIFR-EIS a 5,375-foot (1638.3-meter) radius Flare widening was evaluated. It was determined through ship simulation that the existing 4,000-foot radius (1219.2-meter) Flare was sufficient as long as the adjacent HSC was widened to 700 feet (213.4 meters). During additional simulation and refinement during PED, the 85-foot adjustment to the Flare was developed to intersect the new 700-foot (213.4-meter) HSC and connect the two channels.

Therefore, the historic Flare can be maintained to -55.5 feet (-16.9 meters) MLLW inclusive of allowable overdepth without new construction. The construction of the BSC improvements by PHA will include the additional advanced maintenance over the DER footprint (area between previous 3,000-foot (914.4-meter) radius Flare and the current 4,000-foot (1219.2-meter) radius Flare) to match the historic advance maintenance depths. These construction materials will be used to supplement the materials used to construct the features of TBIM, and they are not anticipated to adversely affect project capacity.

PLACEMENT AREA DESIGN

Conceptual site configurations were estimated and evaluated based on best practices employed on previous HSC projects and as described in the HSC ECIP FIFR-EIS. Following field investigations and engineering design, the placement area sizes and locations were updated to address the criteria of site foundational characteristics, available materials, stakeholder interests, and the wind-wave climate that will be acting on the sites.

Each of the placement area designs was reviewed and coordinated with the Beneficial Uses Group (BUG). The BUG includes a multitude of state and Federal resource agencies including USACE, U.S. Fish and Wildlife Service, U.S. Environmental Protection Agency, Department of Agriculture Natural Resources Conservation Service, National Marine Fisheries Service, Texas Parks and Wildlife Department, Texas General Land Office, and PHA. By leveraging input from resources agencies throughout the PED phase of the project, the placement area sizes, elevations, and features were optimized to restore or create valuable habitat in Galveston Bay.

The following sections outline the placement areas relevant to dredging in Segments 1 and 2.

Long Bird Island

LBI is a BU site for bird habitat that will be constructed in Lower Galveston Bay using hydraulic fill. The site includes a dike along the channel side of the island to protect against wind driven waves and ship wake impacts, with an oyster reef wave trip built along the back side for protection from wind driven wave impacts from the east. The design of LBI is driven by habitat creation more than any other factor, and specific features include an upland un-vegetated habitat with a veneer of crushed limestone to mimic shell hash for nesting birds.

Sizing of LBI dimensions and elevations is a balance of meeting the goals of the project with the available materials. The island will generally remain emergent, but not so high as to perpetually avoid saltwater spray from surface winds and waves or overtopping from large storm events. This is to discourage vegetation growth on the island and maintain the desired environment for nesting birds. Conversely, the island design elevation will allow for it to remain emergent during normal high tide levels so that bird eggs are not washed away from their nests. The selected design elevation is +7.5 feet (+2.3 meters) MLLW at the crown of the island but will include a ridge down the long axis to maintain positive drainage.

LBI is not designed to withstand a major storm event, as that is not economical given the intent and purpose of the site, and therefore, site maintenance following a major storm event is anticipated. The island will be monitored for erosion following larger storm events, and repairs will be made as needed through grading or addition of material. As part of adaptive management and maintenance and monitoring, the island could be renourished from time to time as are planned for the surrounding BU sites.

The oyster reef wave trip is a design feature intended to provide oyster reef habitat, while providing shore protection along the eastern side the island. The dredged material is placed on the bay bottom to provide elevation relief, then a 30-inch (76.2 centimeters) layer of small diameter limestone cultch is placed on top for a final top elevation of -1.0 feet (-0.3 meter) MLLW. The wave trip is designed at an elevation such that it will be fully submerged to promote oyster habitat development while providing a reduced wave state between the wave trip and bird island. The wave trip will have a 100-foot (30.5-meter) wide crown covered with the cultch. Once the reef has been established, the feature should behave like a large homogenous mass, creating a resilient structure.

The final resulting LBI complex is envisioned to be a protected structure with a living shoreline providing multiple environmental benefits. Total emergent island acreage is estimated at approximately 8 acres (3.2 hectares). The area of the oyster reef wave trip is estimated at approximately 3.2 acres (1.3 hectares).

Three Bird Island Marsh

TBIM is a BU that will provide capacity for maintenance material while simultaneously providing environmental value including emergent bird island habitat, wading, and foraging bird habitat, oyster reef, and marsh creation. It is located in Trinity Bay along the Mid Bay Reach of the HSC. The design includes three bird islands, approximately 2-acres (0.8 hectares) in size, positioned in a triangle. The islands will be connected by curved armored dikes that will be approximately 3,850 feet (1173.5 meters) in length each. An oyster reef wave trip will be created outside of the bird islands to provide protection from wind driven waves while simultaneously providing wading habitat for birds and new oyster reef creation. The interior of TBIM will be used for dredge material maintenance capacity for the HSC and to establish a new marsh complex. It will be filled until the target marsh grade is achieved.

Initial concept designs were vetted to develop the current configuration, which resulted in bowing out of the interconnecting dikes to create a more rounded structure versus straight line segments between the islands. Additional considerations involve the design interior future marsh grade. However, environmental direction received was to develop the marsh elevation based on updated surveys of existing thriving marshes in the vicinity, and adjust this target as needed.

Sizing of TBIM dimensions and elevations is a balance of meeting the goals of the project (beneficial use with channel maintenance material capacity) with the available new work materials. Based upon the available materials and through the iterative process of dike configuration and stability analyses, coupled with the dredging template volumes and estimated material retainages, the site was sized for an initial constructed elevation of +10.7 feet (+3.26 meters) MLLW, and to provide approximately 240 acres (97.1 hectares) of containment for marsh fill.

Specific design considerations for the bird islands are that they are to remain emergent and not be inundated by bay water under normal weather conditions, so that common species of marsh vegetation may thrive. Therefore, it was designed above normal high-water levels and should be resilient against the most frequently occurring storm conditions. The dikes are designed to match the height of the island for a constant elevation around the perimeter. Available materials govern the design elevations and final sizing. TBIM is not being designed to withstand a major storm event, as that is not economical given the intent and purpose of the site. Site maintenance following a major storm event should be anticipated.

The bird islands will be constructed with hydraulic fill. Island interiors will be shaped to drain towards the exteriors. While each island is measured at approximately 2 acres (0.8 hectares)at the crown edge, this equates to an emergent acreage of approximately 3.8 acres (1.5 hectares) above Mean High Water.

The oyster reef wave trips are a design feature intended to provide oyster reef habitat, while providing shore protection along the edges of the bird islands at the vertices of the TBIM complex by serving as a wide flat submerged breakwater. A pad will be hydraulically constructed to an elevation of -3.5 feet (-1.1 meters) MLLW. On top of this will be placed a 30-inch (76.2 centimeters) thick by 100-foot (30.5-meter) wide pad of crushed limestone with an approximate 3-inch (7.6 centimeters) gradation (i.e., cultch). The surrounding oyster reef wave trips on the exterior sides are located 367 feet (111.9 meters) outward (crown edge to crown edge) from the islands with a top elevation of -1 feet (-0.m meters) MLLW. This feature will remain predominantly just below the water surface where it will recruit oyster development. The function of the structure will be to trip attacking wind driven waves to protect the islands while simultaneously providing significant ecological benefit. Once the reef has been established, the feature should behave like a large homogenous mass, creating a resilient structure. Each wave trip will provide approximately 5.4 acres (2.2 hectares) of oyster reef habitat.

Dollar Reef Oyster Mitigation

DRM is located just northeast of Dollar Reef in Galveston Bay and is a composite of seven oyster mitigation pad sites. There are four 20-acre (8.1-hectare) pads (DRM pads B-1 through B-4), one 13-acre (5.3-hectare) pad (DRM pad A-1), one 17.4-acre (7.0-hectare) pad (DRM pad A-2), one 6.7-acre (2.7-hectare) pad (DRM Pad A-3) with a 1.0-acre (8.1-hectare) extension (Option 1 at DRM pad A-3), and 6.5-acre (2.7-hectare) extension (Option 2 at DRM pad A-3). The 20-acre (8.1-hectare) pads are each 2,904 feet (885.1 meters) by 300 feet (91.4 meters). The 13-acre (5.3-hectare) pad is 1,887.6 feet (575.3 meters) by 300 feet (91.4 meters). The 17.4-acre (7.0-hectare) pad is 2,531.3 feet (771.5 meters) by 300 feet (91.4 meters). The 6.7-acre (2.7-hectare) pad is 972.8 feet (296.5 meters) by 300 feet (91.4 meters). The 1.0-acre (0.4-hectare) extension is 145.2 feet (44.3 meters) by 300 feet (91.4 meters). The 6.5-acre (2.6-hectare) extension is 941.4 feet (286.9 meters) by 300 feet (91.4 meters). Refer to Figure 1 for the location of DRM.

DRM will be constructed in two parts. The first part will occur in a standalone contract using traditional design and construction techniques (under Package 1 procured by USACE) for DRM pads A-1 through A-3, and the second part pads B-1 through B-4 will be built as part of dredging Package 4b/5.

For the pads at DRM to be built under Package 4b/5, materials from the HSC dredging will be mechanically dredged, transported, and placed over each of the areas to create foundation surfaces. Following this, a 6-inch (15.2 centimeters) veneer of cultch will be installed over the top of the filled pads. The combination of the mechanical fill and cultch veneer will provide an 18-inch (45.7 centimeters) relief above the bay bottom to meet the intended goals. Refer to Figure 4 below.

San Leon Oyster Reef Mitigation

The 179.8-acre (72.8-hectare) SLM is located just north of Eagle Point in Galveston Bay and is to be constructed during Package 4b/5 like those at DRM. Following the previously discussed reconfigurations and mitigation acreage requirements, SLM is now a composite of eleven proposed oyster mitigation pad sites of varying sizes. The proposed pads are listed below in Table 2.

SLM pad sites will be constructed like the pads at DRM, using mechanically dredged and placed materials and covered by an approximate 6-inch (15.2 centimeters) veneer of cultch as shown in Figure 4.

The design of SLM and corresponding coordination occurred in conjunction with the DRM location. During the coordination, one of the 20-acre (8.1 hectare) pad sites from DRM was moved to SLM. Additionally, due to an area of steeper than anticipated slopes, the SLM pad configuration was adjusted to move into areas of relatively flatter bay bottom while maintaining offsets from pipelines and avoid potential obstructions found during site investigations. Refer to Figure 1 for the SLM location.

Table 2. SLM Pad Sizes and Dimensions.

SLM Pad No.	Area (acres)	Area (Hectare)	Dimensions (feet by feet)	Dimensions (meter by meter)
S-1	20.0	8.1	2,904.0 x 300	885.1 x 91.4
S-2	31.0	12.5	4,506.0 x 300	1373.4 x 91.4
S-3	20.0	8.1	2,904.0 x 300	885.1 x 91.4
S-4	20.0	8.1	2,904.0 x 300	885.1 x 91.4
S-5	20.0	8.1	2,904.0 x 300	885.1 x 91.4
S-6	17.2	7.0	2,490.1 x 300	758.9 x 91.4
S-7	20.0	8.1	2,904.0 x 300	885.1 x 91.4
S-8	6.0	2.4	871.2 x 300	265.5 x 91.4
S-9	9.0	3.6	1,306.8 x 300	398.3 x 91.4
S-10	3.4	1.4	500.0 x 300	152.4 x 91.4
S-11	13.2	5.3	1,916.6 x 300	584.2 x 91.4

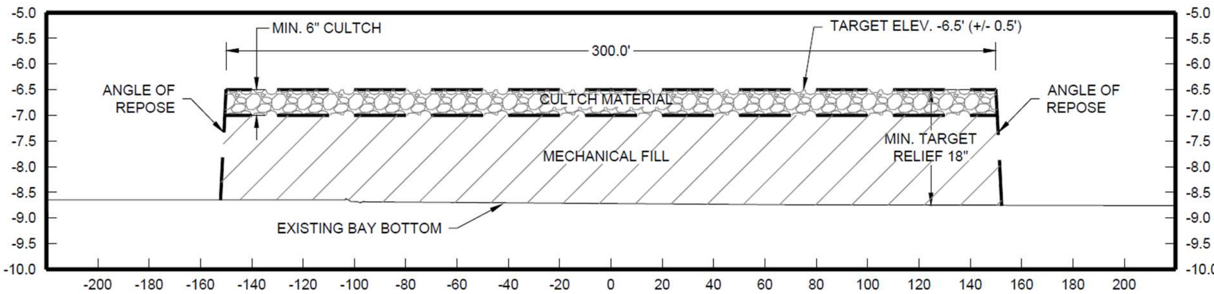

Figure 4. Mechanical Fill Oyster Pad Typical Section

Ocean Dredge Material Disposal Site

The ODMDS is an existing permitted 5,560-acre (2250-hectare) dredged material placement area located offshore of Galveston Island, southwest of the Galveston Entrance Channel. The use of available placement locations within the ODMDS are regulated by the USACE with concurrence from the EPA. Management and monitoring strategies for the placement of suitable dredged material from the greater Houston-Galveston Area are outlined in the 2016 Site Management and Monitoring Plan (SMMP) (USEPA/USACE 2016). Provisions in the SMMP are requirements for all dredged material disposal activities at the site and intended to protect the marine environment, document placement activities and compliance, and preserve the site as a viable option for future projects.

In addition to the ODMDS buffer zone and boundaries for maintenance and new work materials published in the SMMP, another 1110-foot buffer was included in the design as a result of modeling conducted by USACE Engineering Research and Development Center (USACE, 2020) to confirm that environmental criteria are met during placement of dredged material. An overview of the ODMDS layout and summary of site coordinate sources are provided in Figure 5.

Material from the HSC that are not suitable for construction purposes, will be mechanically dredged, transported, and placed offshore within the ODMDS. Coordination with the USACE Galveston District was required to determine the best zones for each Design Package. Throughout construction, regular hydrographic surveys will be conducted for compliance with the objectives of the SMMP.

M11

Located adjacent to Atkinson Island, the M11 marsh cell will expand upon the existing Atkinson Marsh BU complex at Atkinson Island. M11 will be created through the construction of an approximate 1.3-mile dike connecting existing marsh cells M7/8/9 and M10. The BU addition will create approximately 368-acres (148.9-hectare) of added marsh (as measured from the dike centerline). M11 is one of the last marsh cells to be constructed as part of the Atkinson Marsh complex. Additional work for Atkinson Marsh includes the rehabilitation and armoring of existing cells M7/8/9 and portions of M10.

The site will be used for dredged material maintenance capacity for the HSC and will be filled until the target marsh grades are achieved. Design considerations for M11 include tying into existing marsh cells M7/8/9 and M10. Coordination with the BUG has been ongoing through regularly scheduled meetings. The greater Atkinson Marsh BU complex has been planned since 1995 (with Project 10) and will ultimately be completed under this project.

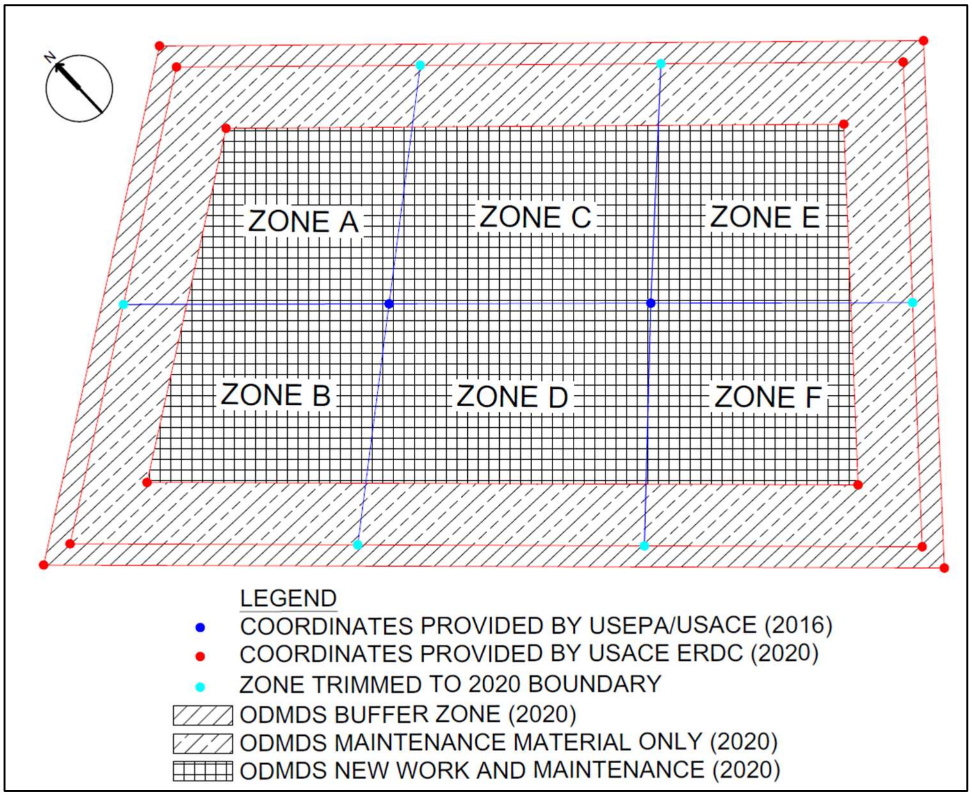

Figure 5. ODMDS Layout.

Of primary concern for M11 construction is the existence of known utility infrastructure that includes gathering platforms, oil and gas wells, service lines, and various other subsurface utilities in the vicinity of the site. Extensive coordination with the utility owners is ongoing to provide for a safe construction effort. Preliminary coordination included ascertaining owners and locations of lines and structures, required clearances, and if needed, implementation of relocation, removal, or abandonment.

Additional considerations involve the design elevations for the future interior marsh. The historic target marsh elevation range fell between +0.6 to +1.1 feet (+0.2 to +0.7 meters) MLLW. However, environmental direction received was to fill the site based on updated surveys of existing thriving marshes in the vicinity, and adjust this target as needed. This work is ongoing.

The portions of M10 and M7/8/9 which require rehabilitation will have material hydraulically pumped over the remaining in-place dike materials. This will repair the eastern and northern facing sides of M7/8/9 and part of the eastern side of M10. The final component is that most of the perimeter will be armored. The armoring will extend around the north and east sides of M7/8/9, continue along the new M11 dike, connecting with the eastern dike of M10, and then extend just until the armor wraps around the southeast corner of M10. There will be an option to extend the armoring along the remainder of M10, if ultimately determined to be needed. The result of this effort will be a large area of fully contained marsh cells, partially or fully armored to protect the site until such time as they can be filled, and a marsh established.

CONCLUSION

Project 11 was a 4-year, $10 million Feasibility Study investigating channel modifications for improving deep draft navigation efficiency to accommodate current and future, larger vessels; evaluate ways to reduce vessel traffic; increase channel safety; plan dredged material placement for the 50-year period of analysis;

and establish environmentally suitable placement areas for dredged materials. With the Feasibility Study finalized and Congressionally authorized in 2020, Project 11 is nearing completion of the design phase with construction of the with first dredging contract commencing in Spring 2022.

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DATA AVAILABILITY

Some data generated or used during the study is available from the corresponding author by request. Some data generated or used during the study is proprietary or confidential. This data may be provided upon request with restrictions on republication and use.

SEGMENT 3 - BARBOURS CUT CHANNEL IMPROVEMENTS

M.C. Perry[1] and D.R. Broyles[2]

EXTENDED ABSTRACT

Port Houston and the U.S. Army Corps of Engineers (USACE) are working together on the Houston Ship Channel (HSC) Expansion Channel Improvement Project (ECIP), also known as Project 11. The focus of the improvements in Barbours Cut Channel (BCC) is to widen the channel and increase the diameter of the turning basin at the intersection of BCC and the HSC to improve maneuverability into and out of the channel. Successfully developing the designs for the channel improvement required very close coordination between PHA, USACE, multiple design disciplines including coastal, dredging, structural, and geotechnical design teams, as well as third-party subconsultants.

A detailed construction sequencing plan is required to complete the project on schedule while providing coordinated access for different construction operations. Prior to dredging operations along Spilman Island and Morgan's Point, work will include existing shoreline protection removal, demolition of an existing pier, debris removal, site demolition, bulkhead wall installation, and grading. Lastly, a pipeline within the dredge template at Spilman Island will need to be relocated and coordinated with the pipeline owners.

Barbours Cut Channel will be widened by 155 ft (47 m) providing a total width of 455 ft (139 m). The diameter of the turning basin at the intersection of BCC and HSC will be increased to 1,800 ft (549 m). The Authorized Dredge depth for BCC and the turning basin is -46.5 ft (-15.2 m) MLLW plus 2 ft (0.6 m) of Advance Maintenance and 2 ft (0.6 m) of Allowable Overdredge. Dredging of 2.8 million cubic yards (y^3) (2.1 million m^3) will be performed and material will be used to create containment berms for a beneficial use marsh site M12. Remaining material will be placed within M12 as upland and marsh fill. Shoreline protection will also be placed along Spilman Island, Morgan's Point, and M12 shorelines.

This project was developed on a fast-paced schedule that had to incorporate numerous unique challenges. HDR completed the project on time and included value added revisions to bulkhead and channel dredge alignments that will save approximately $10MM for wall construction at Morgan's Point. The Federal appropriation for this work is $142.5MM.

The expansion of the channel will require dredging into uplands along Spilman Island Dredged Material Placement Area (DMPA) on the north side of the BCC channel, and into Morgan's Point to the south. These upland cuts will create unstable conditions when considering existing soil properties, dredge templates, and the need to contain future dredged material within the DMPA. Bulkhead walls will be provided to create stable slopes and protect assets of existing features within Segment 3.

The bulkheads for this segment are designed for a future deepening of the channels to -56.5 ft (-17.2 m) MLLW plus Advanced Maintenance and Allowable Overdredge as described above.

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The bulkhead wall at Spilman Island serves primarily as a berm cut-off wall for slope stability, is approximately 3,900 ft (1189 m) long, and is a cantilevered 48-inch (1.2 m) pipe combi steel pile wall system with a portion of the wall being anchored by use of batter piles. The wall types chosen considered the potential for scour, flood zones with wave action based on FEMA flood maps, and potential long term passive soil strength reduction (soil softening) due to the potential for saturated soils.

In addition to the bulkhead wall, significant earthwork is required for the berm reconstruction around the Spilman Island DMPA. The earthwork requires appropriate construction sequencing to ensure a stable system prior to starting dredging work. The wall design team worked closely with the geotechnical and civil engineering team to consider slope stability for the construction phase and permanent performance. Design and analyses were performed with general conformance to USACE design guidelines for Usual, Unusual and Extreme loading conditions. The geotechnical and structural loading limitations are provided on the design documents.

The bulkhead wall at Morgan's Point is 400 ft (122 m) long and primarily consists of an anchored NZ38 steel sheet pile wall system with a concrete cap. Since the wall alignment was near an existing sloped grade and the area to perform the work was relatively narrow, battered the H-pile anchor piles were designed and embedded into the concrete cap for force transfer. The wall design also required a high sour allowance due to the presence of upper sandy soils after the dredging work is completed. Further, the proximity of the wall to the turning basin increased the potential for scour and erosion. This site at Morgan's Point also consisted of existing structures and utilities that required additional subsurface investigations to better understand the existing features within the area of the proposed wall. The data was gathered, and geometry studies were executed to understand potential impacts to the wall design either due to removal of the features or from physical clashing with structural elements.

At Morgan's Point, design adjustments were made to the turning basin position at intersection of HSC and BCC that resulted in bulkhead cost savings and reduced the potential risk for long term slope stability issues.

The presence of pipelines was a major design challenge that required investigation and coordination for potential construction options to address the issue. During conceptual design, two options were considered to address the pipeline conflict with the dredging template. The first option was to design and construct a permanent pipeline protection wall that consisted of a 60-in (1.5 m) diameter pipe combi wall with steel sheet piles and a battered 30 in (0.76 m) pipe pile to provide an anchored wall system. The second option (which is the final design direction) was to have pipeline owner excavate and tie-in to relocate a portion of the pipeline where the pipeline clashed with the future dredge template. Coordination with the asset owner is still on going to be prepared for various work items from the HSC ECIP contractor and the Pipeline contractor which will hopefully reduce the risk for schedule and safety impacts.

Keywords: Dredging, beneficial uses, slurry transport, dredged material disposal, contaminated sediment, bulkhead, batter pile, pipeline, demolition, shoreline protection.

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DATA AVAILABILITY

- Some data, models, or code used during the study were provided by a third party. Direct requests for these materials may be made to the provider as indicated in the Acknowledgments.
- Some data, models, or code generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

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HVJ – Geotechnical Subconsultant

Fugro – Surveying Subconsultant

SEGMENT 4 – BOGGY BAYOU TO SIMS BAYOU CHANNEL IMPROVEMENTS – NAVIGATION

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ABSTRACT

The Houston Ship Channel (HSC) is the longest major navigation channel in the overall system of navigation channels of the Galveston Bay region, located in Harris, Chambers, and Galveston Counties, Texas. This channel system is currently experiencing navigation inefficiencies due to its channel alignment, width, and depth. These inefficiencies are contributing to congestion along the waterway, especially with the high volume of barge traffic and increasingly larger international deep-draft vessels. Segment 4 of the HSC improvement project consists of channel deepening, selective widening, and turning basin deepening. Five feet of channel deepening (from -41.5 ft (-12.7 m) MLLW to -46.5 ft (-14.7 m) MLLW) will be performed along approximately 4.8 miles (7.7 km) of HSC from Boggy Bayou through the Hunting Turning Basin up to Cotton Patch Bayou. Channel widening from 300 ft (91.5 m) to 530 ft (161.6 m) will be performed along approximately 2.6 miles (4.2 km) of this reach between Boggy Bayou to Greens Bayou. These improvements will help alleviate current traffic restrictions for both draft and beam widths to accommodate increased Aframax and Suezmax traffic. No work will be performed from Cotton Patch Bayou to Sims Bayou due to the Washburn Tunnel below the channel, a nationally registered historic place. Approximately 4.7 million yd^3 (mcy) (3.6 million m^3) will be dredged from the channel in Segment 4. The dredged material is designated for two upland confined placement areas (PAs): Beltway 8 and East/West Clinton (E/W Clinton). Beltway 8 will be a new dredged material PA constructed for one-time placement of new work materials from the channel improvements. Covering 446 acres (1.8 km^2), the Beltway 8 site is owned by Port Houston (Port) and is bounded on the north by Jacintoport Blvd and on the south by the HSC. Beltway 8 is slated to receive 1.8 mcy (1.4 million m^3) of material to facilitate future site development. E/W Clinton is an existing PA which will receive the remaining 2.9 mcy (2.2 million m^3) of new work material. The East East Clinton (E2 Clinton) PA was initially designed to receive the 2.9 mcy (2.2 million m^3) balance of new work material from Segment 4. In collaboration with the U.S. Army Corps of Engineers, it was decided that the proposed E2 Clinton PA is better suited for future maintenance dredging materials. The E2 Clinton PA will replace the capacity lost at E/W Clinton during the new work dredging.

Keywords: Channel Deepening, Channel Widening, Ship Simulation, Upland Confined Placement Area, Houston Ship Channel

INTRODUCTION

The Houston Ship Channel (HSC) is the longest major navigation channel in the overall system of navigation channels of the Galveston Bay Area, located in Harris, Chambers, and Galveston Counties, Texas. This channel system is currently experiencing navigation inefficiencies due to its channel alignment, width, and depth. The existing configuration constrains the channel to smaller vessels within the

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international fleet and causes draft restrictions in the upper channel. These inefficiencies also contribute to congestion along the waterway, especially with the high volume of barge traffic and increasingly larger deep-draft vessels in the international fleet. Approximately 8 miles (12.9 km) long in an east-west orientation, Segment 4 extends westward from Boggy Bayou (Station 677+52) to Sims Bayou (Station 1110+77) (Figure 1).

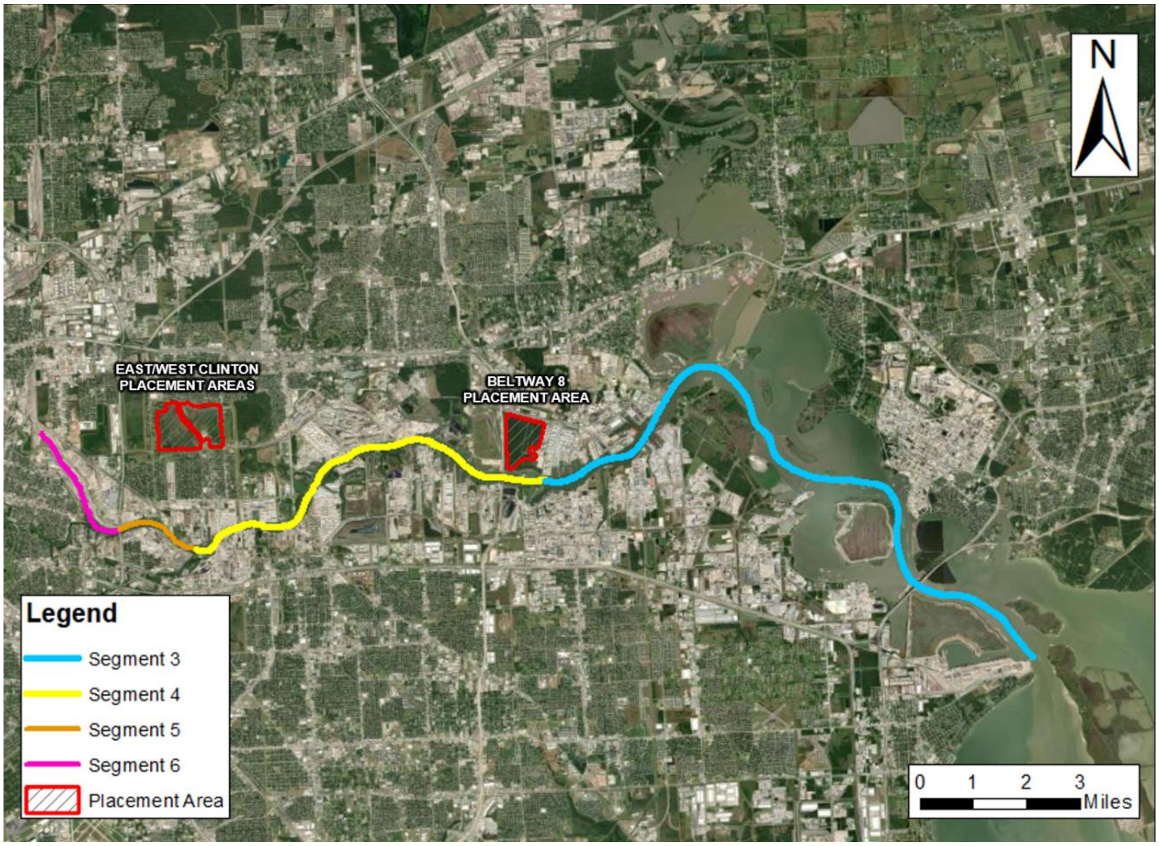

Figure 1. Project Location Map.

This segment is highly industrialized and closely bordered on both sides by berths, docking facilities, and other Port Houston (Port) infrastructure. The channel improvements will help alleviate current traffic restrictions for both draft and beam widths and accommodate increased Aframax and Suezmax traffic in this region. The HSC between Cotton Patch Bayou and Sims Bayou will remain unmodified due to the presence of the Washburn Tunnel below the channel bottom, a nationally registered historic place, in addition to numerous existing pipelines crossing the channel.

Segment 4 of the HSC improvement project consists of channel deepening, selective widening, and turning basin deepening. Five feet of channel deepening (from -41.5 ft (-12.7 m) MLLW to -46.5 ft (-14.2 m) MLLW) will be performed along approximately 4.8 miles (7.7 km) of HSC from Boggy Bayou through the Hunting Turning Basin up to Cotton Patch Bayou. In accordance with a federal Feasibility Study (USACE 2019b) completed for this project, the total channel depth will be -46.5 ft (-14.2 m) MLLW, plus 2 ft of advance maintenance and 1-ft for allowable overdepth (Table 1).

Table 1. Future O&M Dredging Template from USACE (2019b).

Station	To	Station	Authorized Depth, ft (MLLW)	Advance Maintenance, ft (MLLW)	Allowable Overdepth, ft (MLLW)
677+52	**--**	930+00	-46.5	-48.5	-49.5

Channel widening from 300 ft (91.5 m) to 530 ft (161.6 m) will be performed along approximately 2.6 miles (4.2 km) of this reach, extending from Boggy Bayou to Greens Bayou. The channel width will not be increased from Greens Bayou to Hunting Turning Basin due to the highly developed shoreline, and the current channel vessel beam restriction of 116 ft (35.4 m) will not be removed for that reach. Therefore, Panamax vessels will continue to be the largest vessels transiting the channel beyond Greens Bayou. The width of Hunting Turning Basin will also not be increased, as part of the current project, based on engineering evaluations.

GEOTECHNICAL BORINGS

An updated geotechnical study was performed by HVJ Associates (HVJ). HVJ explored the subsurface soil conditions in Segment 4 by drilling twenty-two (22) nearshore soil borings to depths of approximately -60 ft (-18.3 m) MLLW (HVJ 2021a). The recent borings revealed that the Segment 4 new work material is variable and mostly includes shallow soft clays underlain by firm to stiff clay, loose to dense silty sands and clayey sands. Zones of very dense sand, cemented sand, and hard clay were encountered within the proposed dredge depths at many of the borings. Table 2 provides a summary of the percentage of the general soil types encountered in the borings from the mudline down to the proposed total dredge depth of Segment 4, with approximately 48% of the material being firm to stiff clay.

Table 2. Segment 4 Subsurface Sediment Characteristics.

Material Type	% of Total
Loose to Dense Sands and Silts	15%
Very Dense Sands and Silts	6%
Very Soft to Soft Clay	26%
Firm to Stiff Clay	48%
Hard Clay	5%

SHIP SIMULATIONS

As part of the feasibility study, vessel maneuvering simulations were conducted to determine the feasible dimensions of the channel. Final channel dimensions were confirmed through more in-depth ship simulations completed in June 2020 (USACE 2020). Three vessels were considered during ship simulation efforts performed for Segment 4:

- Tanker Aframax, with a length overall of 850 ft (259 m), a beam width of 138 ft (42 m), and a draft of 54 ft (16.5 m).
- Bulk Carrier Panamax, with a length overall of 810 ft (247 m), a beam width of 106 ft (32 m), and a draft of 44 ft (13.4 m).
- Suezmax class vessels with a length overall of 900 ft (274), a beam of 164 ft (50 m), and a draft of 44 ft (13.4 m).

SITE SURVEYS

Topographic, hydrographic, and hazard surveys were performed by Hydrographic Technologies, Inc. (HTI) in December 2019 and Fugro USA Land, Inc. (Fugro) in January 2020 to better define the quantity of materials to be dredged, the location of potential underground pipelines and utilities, and potential sub/surface debris. Surveys performed included multi-beam (acoustic sweep) and single-beam bathymetric surveys, side scan sonar surveys, magnetometer surveys, sub-bottom seismic profiler surveys, and a land-based radio detection survey.

The geophysical surveys not only identified debris in the channel but were used to estimate that up to 100 tons (91 metric tons) of rock, tires, piles, and other submerged debris material will need to be removed from the channel footprint during dredging. Additionally, up to 3,000 tons (2,700 metric tons) of shoreline debris at a private terminal formerly associated with the Port Houston Iron Works shipyard, abandoned after 1962, will also be removed which includes a relic bulkhead, concrete blocks and slabs (Figures 2 and 3).

Figure 2. Concrete slab.

Figure 3. Concrete debris and concrete beam behind relic bulkhead.

PIPELINES

The approximate locations of the pipeline were determined from an existing database provided by the Port, One-Call inquiry to identify pipeline owners, research results from the Texas General Land Office and the Texas Railroad Commission, individual pipeline coordination mtgs, HDR's right-of-way group research, and field investigations by Fugro. Based on information obtained, 43 utility lines cross the HSC within the dredging limits for Segment 4. Utility lines that conflict with the dredging project will be removed prior to dredging.

O&M AND NEW WORK TEMPLATES

The new work template will vary by location based on soil properties. Recent USACE Galveston District (SWG) policy (USACE 2019a) requires new work dredging templates to be constructed deeper than their associated long-term O&M template to completely remove hard material from the O&M template. This guidance was applied to develop the new work dredging templates for Segment 4 (Figure 4 and Table 3), except that overdepth was not included on the side slopes in accordance with a waiver approved by USACE (2021). From Station 677+52 to Station 755+00, where the soil is not as hard, the new work template has a required depth of -48.5 ft MLLW plus 2 ft for allowable overdepth, bringing the total depth to -50.5 ft (-15.4 m) MLLW (Figure 5). Beyond Station 755+00, where the soil is harder, the new work template has a required depth of -49.5 ft (-15.1 m) MLLW plus 1 ft (0.3 m) for allowable overdepth, bringing the total depth to -50.5 ft (-15.4 m) MLLW (Figure 6).

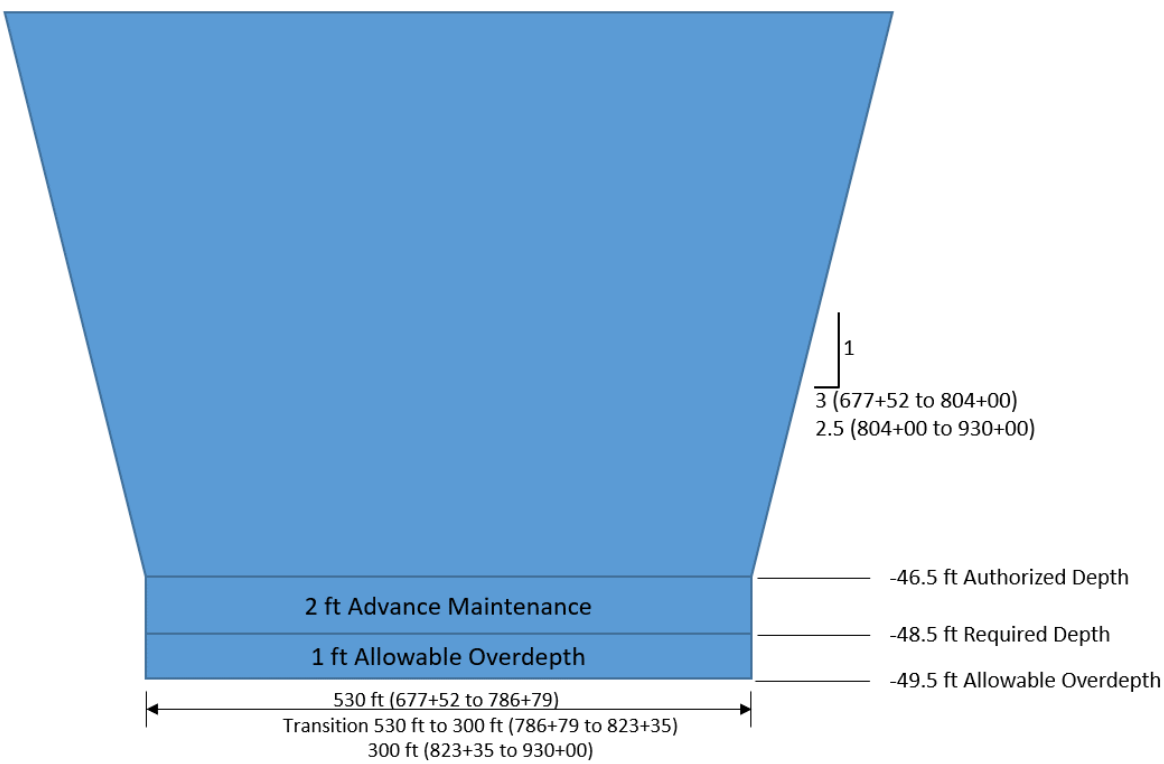

Figure 2. Authorized Template (O&M Template) for Segment 4.

Table 3. New Work Dredging Template.

Station	To	Station	Required Depth, ft (MLLW)	Allowable Overdepth, ft (MLLW)
677+52	--	755+00	-48.5	-50.5
755+00		930+00	-49.5	-50.5

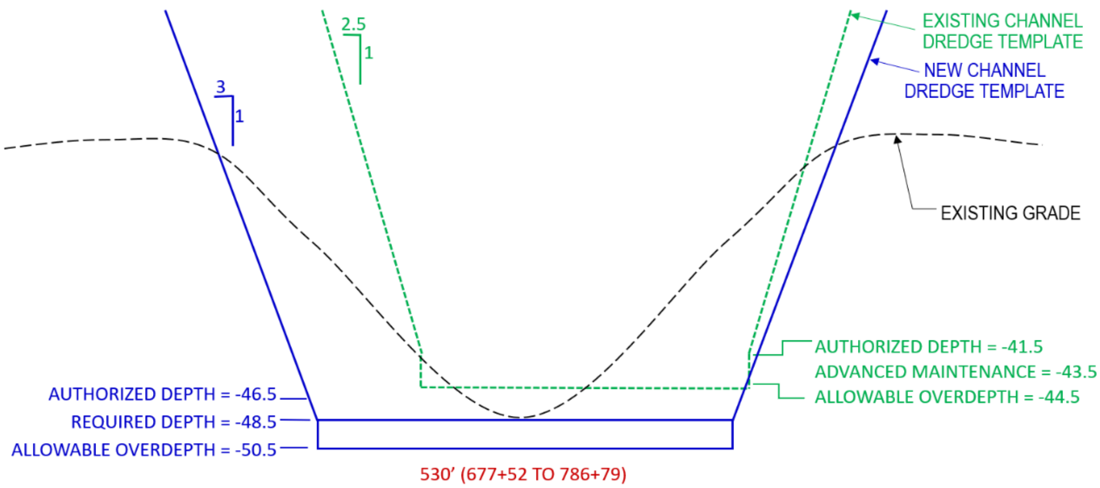

Figure 3. New Work Template for Segment 4 (Sta. 677+52 to 755+00).

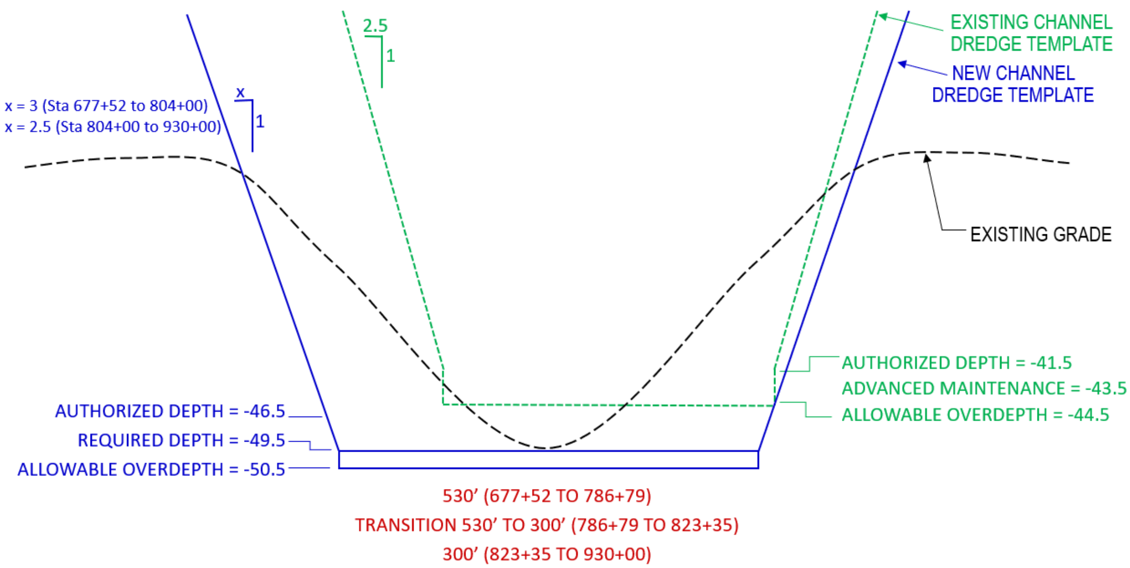

Figure 4. New Work Template for Segment 4 (Sta. 755+00 to 930+00).

The geotechnical analysis performed by HVJ (2021b) indicated 3:1 side slopes were needed from Station 677+52 to 804+00 in order to satisfy slope stability requirements. HVJ's analysis indicated 2.5:1 slopes, as assumed in the Feasibility Study, will be stable from Station 804+00 to 930+00.

The top of the channel template is projected to extend through emergent land at four locations: the north pylon of the Beltway 8 Bridge, which is slated for replacement; in a private terminal ship basin that requires dredging; in a private facility that requires a quarry stone revetment for shoreline protection; and a private facility that may require debris removal. As shown in Figure 7, the channel will overlap the north pylon of the existing Beltway 8 Bridge. This bridge is scheduled to be demolished and replaced within the next 2 to 5 years by the Harris County Toll Road Authority. Dredging around the north pylon will therefore be completed in phases as needed for coordination with the planned bridge replacement project. The pylons for the new bridge will be located on dry land and will not present a dredging or navigation obstruction.

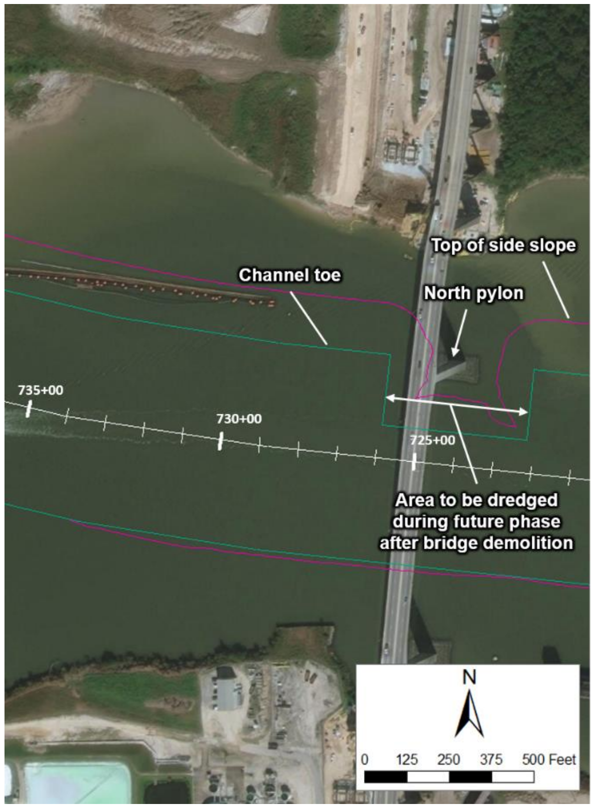

Figure Error! No text of specified style in document.**5. Conflicting feature (north pylon of Beltway 8 Bridge).**

DREDGING VOLUMES

Dredging volumes were calculated using digital surface models developed with Civil3D and AutoCAD software. Required dredging will include new work dredging for the planned channel improvements and maintenance dredging to clear material from the existing channel. Approximately 4.7 mcy (3.6 million m^3) is expected to be dredged from the channel in Segment 4 as shown in Table 4. For the purposes of PA capacity analysis, a 50,000 yd^3 (38,000 m^3) allowance for non-pay volume was added to the pay volume, increasing the total estimated dredging volume from 4.7 mcy (3.6 million m^3) to 4.75 mcy (3.63 million m^3).

Table 4. Dredging Volumes (Pay Volume).

Item	Volume, yd^3
Maintenance (Incl Allowance for Shoaling)	234,000
New Work Material	3,956,000
Allowable Overdepth	510,000
Total Dredging Volume	4,700,000
Note: This summary does not include non-pay volume dredged from outside of the allowable dredging tolerances.	

The dredged material from Segment 4 is currently planned to be placed into two existing PAs (E/W Clinton) and one of the new PAs (BW8) as shown in Table 5. The other new PA, East East Clinton (E2 Clinton), will still be constructed, but the site will not receive new work material from Segment 4. Originally, the E2 Clinton PA was designed to receive the 2.873 mcy (2.197 million m^3) of new work material from Segment 4. In collaboration with USACE it was jointly decided that the proposed E2 Clinton PA is better suited for periodic placement of future maintenance dredging materials to replace the E/W Clinton reduced capacity resulting from the channel new work improvements.

Table 5. Summary of DMPAs.

Placement Area	Bulked Volume Site Capacity (CY)	In-Situ Dredging Volume Planned for Placement (CY)
Beltway 8 PA	3,491,000	1,877,000
West Clinton PA	2,400,000	1,790,000
East Clinton PA	4,700,000	1,083,000
Total:	10,590,000	4,749,000

Beltway 8 is a new dredged material PA that is being constructed for a one-time placement of new work materials from the channel improvements. Owned by the Port, the Beltway 8 site is bounded on the north by Jacintoport Blvd, on the west by Beltway 8, and on the south by the Houston Ship Channel (Figures 8 and 9). With 10 ft (3 m) high dikes, the Beltway 8 DMPA covers 338 acres and is slated to receive 1.877 mcy (1.435 million m^3) of material only during the channel deepening. The limit on dredged material being placed at Beltway 8 is to facilitate future site development.

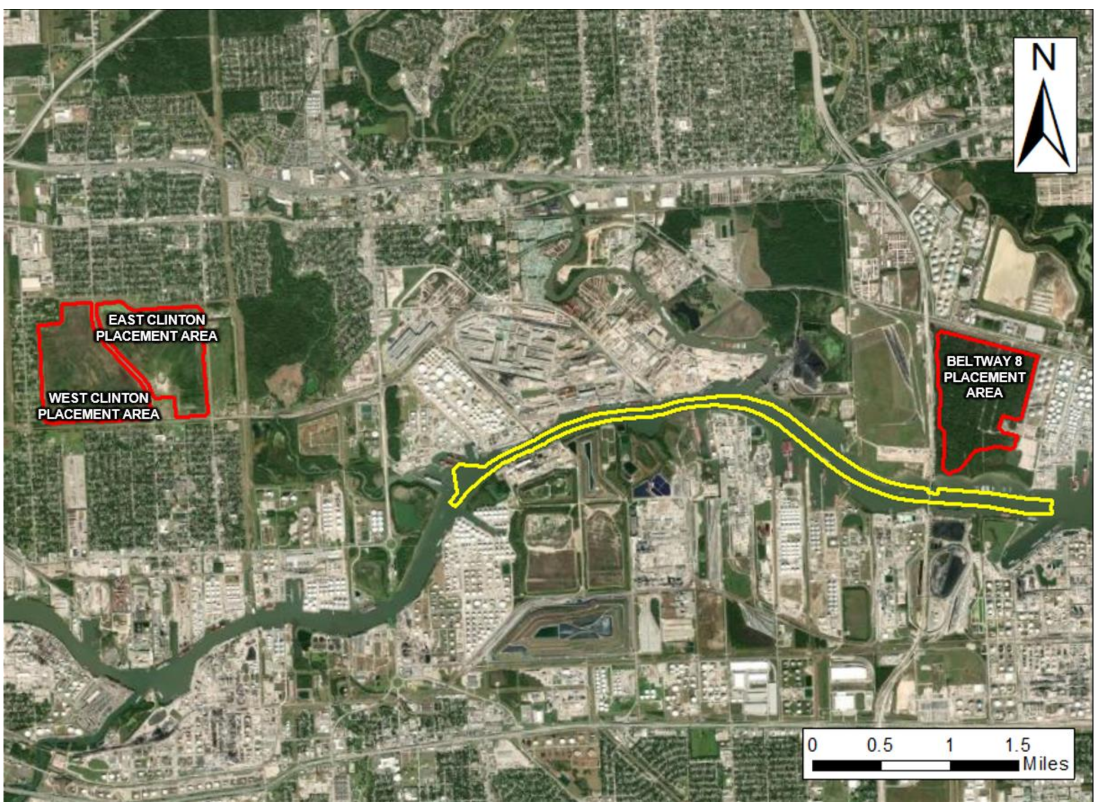

Figure 8. Placement Area Location Map.

Figure 9. Beltway 8 Placement Area.

E/W Clinton is an existing PA (Figure 10) which will receive the remaining 2.873 mcy (2.197 million m^3) of new work. The dredged material will be distributed between the east and west cells such that the layer thickness will be approximately 5 ft (1.5 m) in each cell for short-term bulking and 4 ft (1.2 m) for long-term bulking. An existing pipeline route extends just north of the railroad at Hunting Bayou to the PAs, which will be used to pipe dredged material from the channel to the PAs.

Figure 10. East/West Clinton Placement Areas.

DREDGING OPERATIONS

The dredging will be performed with a pipeline dredge or with a mechanical dredge and a hydraulic unloader. There are known utilities or pipelines within the required dredging limits, as well as adjacent environmental sensitive habitat areas. For a dredging volume of 4.7 mcy (3.6 million m^3), the construction duration is estimated to be approximately 14 months. This duration assumes approximately one month for mobilization, one month for multiple pipeline setups (two weeks at each of the two DMPAs), and two weeks for demobilization. This schedule also assumes that debris removal will progress ahead of the dredging. The dredging production rate was estimated to be approximately 12,000 to 15,000 yd^3/day (9,200 m^3/day to 11,500 m^3/day), assuming a 27 to 30-inch (69 to 76-cm) pipeline dredge.

With the exception of any large debris that may be encountered within the dredging template, all material can be excavated with hydraulic pipeline cutterhead dredging as planned for this project. As noted by HVJ (2021b), cemented sand and hard clay were encountered in six borings below about -41 ft (12.5 m) MLLW. These harder soils will likely significantly decrease dredging production rates and may not be dredgable with improperly selected or operated dredges. The dredging contractor will be required to avoid federally listed species (i.e., sea turtles and West Indian manatee) in the project or active work area in case they are encountered. In addition, the Port Houston has agreed to the implementation of the NMFS's Sea Turtle and Smalltooth Sawfish Construction Conditions. In accordance with these conditions, the dredging contractor shall cease operation of any moving equipment immediately if ESA-listed species are seen within a 50-ft (15.2-m) radius of the equipment and activities may not resume until the protected species has departed the project area of its own volition.

Potential impacts from dredged material return water discharged from Beltway 8 and E/W Clinton in Segment 4 was modeled by the USACE Engineering Research and Development Center (ERDC) using a CDFate model (Montgomery et al, 2021). The model expanded previous studies for HSC by evaluating chemistry, toxicity, and local mixing zone parameters for proposed discharges by refining the model results to be more site specific. CDFate modeling showed that both acute and chronic criteria for chemistry and toxicity dilution conditions are met for the discharge of effluent from BW-8 PA into Buffalo Bayou/HSC. Although CDFate modeling showed that the dilution factor under currently anticipated discharge conditions was insufficient to attain Texas Water Quality Standards (WQS) for both acute and chronic criteria for either the discharge from E2 Clinton into Turkey Run Gully or into Hunting Bayou at the confluence with Turkey Run Gully, these dilutions were found to be mitigated with a Lines of Evidence (LOE) evaluation. Six principle LOE mitigating conditions supported a conclusion of no significant adverse effects resulting from discharges at E2 Clinton PA from the dewatering of dredged new work ECIP sediments from Segment 4 of the HSC. Because the existing discharge from E/W Clinton into Turkey Run Gully is immediately upstream of the proposed discharge from E2 Clinton, findings of no significant adverse impacts are also applicable to discharge from E/W Clinton. ERDC found that based upon evaluation of the CDFate modeling results and further consideration of site-specific lines of evidence, no significant adverse effects are anticipated from the discharge of dewatering effluent from either BW-8 PA or E2-Clinton PA for the new work dredged materials associated with Segment 4 of the HSC ECIP.

CONCLUSIONS

Channel improvements along the HSC from Boggy Bayou through Hunting Turning Basin will be performed as Segment 4 of the overall HSC ECIP. No work will be performed from Cotton Patch Bayou to Sims Bayou due to the presence of the Washburn Tunnel Crossing, a nationally registered historic place. Channel deepening will occur from Boggy Bayou through Hunting Turning Basin. In accordance with the Feasibility Study the O&M dredging template will be deepened to -46.5 ft (-14.2 m) MLLW, plus 2 ft (0.6 m) of advance maintenance and 1 ft (0.3 m) for allowable overdepth. The new work dredging template will be deeper than the O&M template to comply with SWG policy. In addition to deepening, channel widening will occur from Boggy Bayou to Greens Bayou. The channel will be widened from 300 ft to 530 ft (91.5 m to 161.6 m) from Sta. 677+52 to Sta. 786+79. The channel will transition from 530 ft to 300 ft (161.6 m to 91.5 m) from Sta. 786+79 to Sta. 823+35.

Approximately 4.7 mcy (3.6 million m^3) of dredged material will be extracted by pipeline dredge or by mechanical dredge with a hydraulic unloader and placed within upland confined placement areas. New work material will be placed in E/W Clinton and BW8. E/W Clinton are existing placement areas, and BW8 will be created for one-time placement of new work materials from the Federal Channel. Required dredging will include new work dredging for the planned channel improvements as well as maintenance dredging to clear material from the existing channel. Approximately 1.877 mcy (1.435 million m^3) of the dredged material will be placed in BW8. The remaining 2.873 mcy (2.197 million m^3) will be placed in E/W Clinton.

With the exception of any large debris that may be encountered within the dredging template, all material can be excavated with hydraulic pipeline cutterhead dredging as planned for this project. As noted by HVJ (2021b), cemented sand and hard clay were encountered in some of the borings below about -41 ft (-12.5 m) MLLW. These harder soils will likely significantly decrease dredging production rates and may not be dredgable with improperly selected or operated dredges.

The approximate locations of pipelines were determined from as-built plans as provided through the Port, a One-Call inquiry, and a field investigation performed by Fugro. There are 43 pipelines located in Segment 4 from Boggy Bayou through Hunting Turning Basin to Cotton Patch Bayou. Project construction will require approximately 14 months.

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CITATION

Lowe, C., Heilman, D., and Pennison, G. "Segment 4 - Boggy Bayou to Sims Bayou Channel Improvements – Navigation," Proceedings of the Western Dredging Association Dredging Summit & Expo '22, Houston, TX, USA, July 25-28, 2022.

DATA AVAILABILITY

All data generated or used during this study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

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The work described in the manuscript was performed by HDR Engineering, Inc. under contract with Port Houston, the non-federal sponsor for this project. Direction on the scope for this study, as well as coordination with USACE, was provided by Ms. Lori Brownell and Mr. Richard Ruchhoeft at Port Houston.

SEGMENT 4 - BOGGY BAYOU TO SIMS BAYOU CHANNEL IMPROVEMENTS – BELTWAY 8 DMPA

C. Lowe[1]

ABSTRACT

The Beltway 8 site represents development of an overgrown forest into a Dredged Material Placement Area (DMPA) to receive new work dredged material from Segment 4 of the Houston Ship Channel (HSC) Expansion Channel Improvement Project (ECIP), Project 11 (Boggy Bayou to Sims Bayou). Covering 446 acres (180.5 hectares), the Beltway 8 site is owned by Port Houston and is bounded on the north by Jacintoport Boulevard and on the south by the HSC. Beltway 8 is slated to receive 1.8 million cubic yards (1.38 million cubic meters) of material only during the channel deepening and widening dredging. The limit on dredged material being placed at Beltway 8 is to facilitate future site development. Clearing the site meant far more than removing vegetation due to the site's history as part of the San Jacinto Ordnance Depot, a munitions storage facility. More than 50 bunkers had to be removed in addition to foxholes, roads, and pads. The potential for unexploded ordnance (UXO) was explored with project requirements developed to mitigate the UXO risk throughout construction. Demolition of depot remnants in addition to clearing and grubbing has been completed in advance of the DMPA construction. Design of the Beltway 8 DMPA faced many challenges due to the largely unknown nature of the site. Site explorations included geotechnical boreholes, LiDAR survey, and a magnetometer survey. Geotechnical engineering played an important role in the design of stable berms due to localized soft soils and active gas pipelines that bisect the site and will remain in place. An additional geotechnical and hydraulic issue involved rerouting two drainages that bisect the Beltway 8 DMPA. Environmental and cultural considerations addressed during the design process included 24 acres (9.7 hectares) of wetlands, migratory birds, and a cemetery. An additional design challenge was site access due to the industrial nature of the surrounding parcels, combined with the reconstruction of the Beltway 8 bridge at the site's western boundary. The result was a temporary access road over 3,300 feet (1,005.8 meters) long that must be restored at the end of construction. The temporary access road required negotiations with an active railroad, Harris County Toll Road Authority, multiple utilities, and pipeline companies, some of which imposed specific terms and restrictions for the Contractor's operations.

Keywords: Dredged Material Placement Area, San Jacinto Ordnance Depot, UXO, Beltway 8, demolition.

INTRODUCTION

The Beltway 8 site represents development of an overgrown forest into a Dredged Material Placement Area (DMPA) to receive new work dredged material from Segment 4 of the Houston Ship Channel (HSC) Expansion Channel Improvement Project (ECIP), Project 11 (Boggy Bayou to Sims Bayou). Owned by Port Houston, the Beltway 8 site is slated to receive 1.877 million cubic yards (1.44 million cubic meters) of material only during the channel deepening and widening dredging. The limit on dredged material being placed at Beltway 8 is to facilitate future site development. Designing the Beltway 8 DMPA faced many challenges due to the largely unknown nature of the site in combination with the site's history. The proposed Beltway 8 DMPA will occupy approximately 338 acres (136.8 hectares) on the 446-acre (180.5 hectares)

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site. Formerly heavily wooded, the site has been cleared and grubbed, and on-site structures were demolished under a construction contract that was separate from the DMPA construction work.

Located in a highly industrial/urban area, the Beltway 8 site is bordered by Beltway 8 on the west, an existing storage tank area on the east, and the HSC on the south. The Beltway 8 site contains a pipeline corridor with more than 15 active pipes and railroad tracks extending along the northern boundary, parallel to Jacintoport Boulevard. Figure 1 provides an overview of the Beltway 8 site.

Figure 1. Beltway 8 site.

SITE HISTORY

Clearing the site meant far more than simply removing vegetation, due primarily to the site's history as part of the San Jacinto Ordnance Depot, a 4,800-acre (1,942.5-hectare) munitions storage facility that was first constructed for use during World War I and largely abandoned after World War II. Between 1942 and 1960, depot activities included storage and out-loading of ammunition, production of anhydrous ammonia, and demilitarization of ammunition. Records also indicate that chemical weapons (phosgene and mustard-gas-filled bombs) were managed at the site in 1946. Potential activities included burial of both conventional and chemical ordnance. The site was decommissioned, environmentally remediated, and sold in 1960 with a “surface use only” caveat.

Remnants of the depot that required removal included 52 bunkers, two building foundations, roadways, and 40 pads. Removal of the mostly underground bunkers was made more interesting by the overgrown vegetation, which effectively disguised the sheer size of the 18-foot (5.5-meter)-tall bunkers. The building plans for the bunkers set the length of each bunker at 82 feet (25 meters), while the width of each bunker tapers from 60 feet (18.3 meters) at the entrance to 30 feet (9.1 meters) at the back. Figure 2 and Figure 3 show front and side views, respectively, of a bunker at Beltway 8.

Figure 2. Beltway 8 – front view of a bunker.

Figure 3. Beltway 8 – side view of a bunker.

In 2019, the Texas Commission on Environmental Quality (TCEQ) issued a final certificate of completion for cleanup at the site, stating that the site had been cleaned up to commercial/industrial land use standards (TCEQ 2019). Further discussion with TCEQ indicated that dredged material placement on the site would not affect the existing groundwater and the site could be developed as a DMPA.

UNEXPLODED ORDNANCE

The potential for unexploded ordnance (UXO) was explored with project requirements developed to mitigate UXO risk throughout construction. In 2005, the Beltway 8 site underwent a Formerly Used Defense Site investigation, which concluded that the possibility of chemical munitions continuing to be present on site could not be ruled out.

Five bunkers were sampled for explosive residue, total petroleum hydrocarbons (TPH), and metals by collecting surface soil and explosives wipes from inside the bunkers (HDR 2020). No explosives were detected in the tests on four bunkers; however, all of the explosives tested for were detected in the fifth bunker. The test results were validated, which indicated that explosives residue was present on the fifth bunker's floor and could be present at other bunkers. The levels detected in the fifth bunker were determined to not pose a major risk during demolition, and no additional testing or cleanup was performed.

A magnetometer survey was performed to detect buried metal objects such as UXO and pipelines (Fugro 2020). However, the survey was of limited capability so close to the bunkers. As such, the possibility for UXO could not be completely eliminated.

To mitigate UXO risk during construction, one UXO Technician III/II is required on site during the entire duration of earthwork activities, which include clearing, grubbing, foundation removal, and DMPA construction. A UXO Technician III/II must meet the qualifications stated in Department of Defense Explosives Safety Board (DDESB) Technical Paper 18 (DDESB 2020). If UXO is located, the Contractor must stop work and notify the Port Authority immediately. A 30-minute, site-specific UXO awareness/safety training (addressing "recognize, retreat, and report") is mandatory for all field personnel and all authorized visitors.

DMPA DESIGN CONSIDERATIONS

Covering 338 acres (136.8 hectares), the Beltway 8 DMPA will be an upland confined placement area with water discharged via controlled spillways to an outfall channel. The perimeter containment dikes will be constructed mechanically with a crest elevation of +32 feet (9.8 meters) North American Vertical Datum of 1988 (NAVD88) using material excavated from within the DMPA interior above the groundwater level and outside of a 50-foot (15.2-meter)-wide interior stability berm, measured from the interior toe. The borrow material for the dike may need to be dried and stabilized with an estimated 4% to 8% of lime in order to be suitable for use as fill. The amount of lime needed will vary based on construction geotechnical testing for borrow material (HVJ 2021).

A drop outlet structure and outfall channel will be constructed in the southern portion of the Beltway 8 DMPA to allow decant water to discharge from the DMPA into an existing drainage channel that flows into Buffalo Bayou and the HSC.

Topsoil stripped from the site will be applied to finish graded dike slopes before hydroseeding and used as fill for the area between the DMPA and HSC. The balance of the stripped topsoil will be left within the DMPA. The 10-foot (3.0-meter)-high dikes will be sufficient for the DMPA to contain the planned 1,877,000 cubic yards (1.44 million cubic meters) of *in situ* (unbulked) dredged material. The capacity includes allowances for bulking and a total freeboard height of 3 feet (0.9 meters), which accounts for 2 feet (0.6 meters) of ponding above the sediment level plus 1 foot (0.3 meter) of freeboard above full pond level. Following placement of new work materials at Beltway 8, no additional dredged material would be placed at the site to facilitate future development.

The construction duration for the Beltway 8 dike embankment and drop outlet structure is estimated at approximately 6 months, assuming typical weather conditions during summer months when drying conditions are optimum. Construction could require 12 months for final completion without optimum conditions. The estimated timeframe for complete construction is approximately 12 to 18 months.

GEOTECHNICAL CONSIDERATIONS

Geotechnical engineering played an important role in designing stable berms due to localized soft soils and active gas pipelines that bisect the site and will remain in place. HVJ Associates (HVJ) performed an updated geotechnical study and provided recommendations (HVJ 2021).

SITE EXPLORATION

HVJ explored the subsurface soil conditions for the Beltway 8 DMPA by drilling 31 soil borings along the proposed embankment to a depth of approximately 40 feet (12.2 meters) below existing grade (HVJ 2020). In general, firm to hard cohesive soils were observed throughout the boring depths, with occasional loose to medium dense silts below 28 feet (8.5 meters). At most locations, the groundwater depth varied between 18 and 39 feet (5.5 to 11.9 meters); however, groundwater was encountered at 11 to 12 feet (3.4 to 3.7 meters) in the northwest corner of the site.

Two borings in the southwest corner of the site near ground elevations of +30 feet (9.1 meters) NAVD encountered very loose to loose silty sand or silt in the upper 10 to 12 feet (3.0 to 3.7 meters) with groundwater encountered at 6 to 8 feet (1.8 to 2.4 meters). A surficial layer of 2-foot (0.6-meter)-thick very loose silt or sand was observed in four other borings, and a 4-foot (1.2-meter)-thick sand layer was encountered in another boring.

Slope stability of the perimeter dikes was calculated using the guidelines presented in U.S. Army Corps of Engineers (USACE) EM 1110-2-5025 (2015). Dike stability analyses were performed to determine achievable heights (i.e., dike heights that satisfy the USACE required factors of safety) using conventional construction techniques, maintaining the outside toe and slope of the dike, and placing and compacting fill on 3H:1V (horizontal:vertical) and 6H:1V slopes (HVJ 2021). To achieve stable dikes in the areas with weaker soils, the side slopes are set to 6H:1V across much of the southern portion of the DMPA. The short-term bulking factor for material planned for placement at Beltway 8 is 1.86 due to the new work clay properties (HVJ 2021).

PIPELINES

Six shallow pipelines bisect the southern portion of the Beltway 8 site within the future placement area footprint. The DMPA berms cross three gas pipelines in the southeastern part of the site, and HVJ designed the berms to be constructed over the active pipelines. Dredged material will also be deposited over three pipelines. Coordination with owners of known pipeline has occurred, and the Contractor will be directed to avoid excavation within 25 feet (7.6 meters) of the pipelines.

Pipeline companies indicated that three pipelines within the site would be removed prior to site development; however, the three pipelines were still in place when the clearing, grubbing, and demolition was set to begin. In short order, Letters of No Objection (LONOs) access agreements were obtained from the pipeline companies that required matting or air bridges for the construction equipment to travel over the shallow pipelines and avoid damaging active gas pipelines.

SITE DRAINAGE

To facilitate surface drainage around Beltway 8, a drainage swale, requiring a 30-foot (9.1-meter)-wide easement, will extend around the DMPA perimeter. Rock filter dams are proposed along the perimeter swale to control flow velocities. The drainage swale will direct site drainage into existing culverts and storm drain systems, except for the southern portion where the discharges are directed into the HSC.

An additional geotechnical and hydraulic issue involved rerouting two drainages that bisect the Beltway 8 site. One drainage channel originates in the site interior and crosses the eastern boundary. The channel drains most of the site’s eastern side and flows through Enterprise’s tank farms and then south to the HSC. The perimeter drainage swale will connect to the creek’s channel at the site boundary and retain the creek flows downstream.

The second creek flows across the southwestern corner of the site into the HSC, and the creek will be realigned into two 72-inch (1.8-meter) high-density polyethylene (HDPE) culverts along the western property boundary. Riprap will be placed at both of the culverts’ inlets and outlets. Outside of the Beltway 8 DMPA, the downstream end of the existing creek—including its connection with the HSC—will be left intact to receive discharges from the drop outlet structure via the outfall channel.

ENVIRONMENTAL AND CULTURAL CONSIDERATIONS

Primary environmental and cultural considerations at the Beltway 8 site addressed during the design process included 24 acres (9.7 hectares) of wetlands, migratory birds, and a cemetery. To ensure that the resources were adequately protected, the Contractor was required to develop an Environmental Protection Plan.

The Beltway 8 site contains 24 acres (9.7 hectares) of forested wetlands that are overgrown with mostly invasive Chinese tallow trees along with a few other tree species and shrubs. Approximately 128 wetland locations are scattered throughout the northern two-thirds of the tract; however, only 5 of the wetland sites are larger than 1 acre (0.4 hectare). The Beltway 8 wetlands appear to be associated with disturbance to the site, lack of landscape management, and lack of adequate drainage of existing drainage ditches. Wetland impacts are addressed under the USACE feasibility/federal authorization and will be mitigated at an appropriate mitigation bank (USACE 2019).

To comply with the Migratory Bird Treaty Act of 1918, a migratory bird nest and water bird rookery survey was completed for the entire 446-acre (180.5-hectare) site before trees and woody vegetation were removed. The Contractor was not allowed to disturb bird nests, but if an active nest was encountered, the Contractor was to avoid disturbing the nest and consult with the Texas Parks and Wildlife Department (TPWD). TPWD recommended that vegetation removal and ground-disturbing activities be phased to occur outside of the nesting season and that impacts to spring and fall migrants be avoided.

Despite its past as part of the San Jacinto Ordnance Depot, the site was determined to not be eligible for inclusion on the National Register of Historic Places; however, a small unnamed cemetery exists in the southeastern portion of the Beltway 8 site, as shown on Figure 4. The cemetery was designated as a no-work, off-limits zone that the Contractor must not traverse or disturb. No investigation of the cemetery was performed, as details were lacking on the number of grave sites. The cemetery is presently surrounded by a chain-link fence and a border of trees. The site received additional protection by a Contractor-installed temporary fence around the perimeter of existing chain-link fence, which establishes a 100-foot (30.5-meter) buffer between construction activities and the cemetery.

Figure 4. Beltway 8 DMPA and cemetery.

TEMPORARY ACCESS ROAD

An additional design challenge was site access due to the industrial nature of the surrounding parcels, combined with the reconstruction of the Beltway 8 bridge at the site's western boundary. Four potential temporary access routes were evaluated, and the result was a temporary access road more than 3,300 feet (1,005.8 meters) long that must be restored at the end of construction.

From Penn City Road, the temporary access road utilizes an existing driveway just south of the railroad tracks and travels east 3,350 feet (1,021.1 meters) to the northwest corner of the Beltway 8 site. Without geotechnical boreholes or subsurface soils information, the Contractor was required to make the necessary ground improvements, repairs, and maintenance.

The temporary access road required LONOs with an active railroad, Harris County Toll Road Authority (HCTRA), multiple utilities, and pipeline companies, some of which imposed specific terms and restrictions on the Contractor's operations. HCTRA is operating the Beltway 8 bridge construction, and while the Contractor may cross HCTRA's site, HCTRA retains control of site access and may close the temporary access road at times.

The Union Pacific Railroad LONO requires the following: (1) submittal of detailed plans and specifications for the road crossing for prior review and approval and (2) railroad flagmen on site at any time a person or equipment is within 25 feet (7.6 meters) of any track. The flagging requirement affects construction, operation, and demolition/restoration of the temporary access road.

CONCLUSIONS

The demolition of depot remnants in addition to clearing and grubbing has been accelerated in advance of DMPA construction. The clearing, grubbing, and demolition work began in June 2021 and was substantially completed by June 9, 2022. Hundreds of dump-truck trips removed bunkers, depot roads, debris, and vegetation.

The work progressed relatively smoothly, with two noteworthy instances. The Contractor unearthed six concrete foxholes during the vegetation removal (Figure 5) that were not included in the bid estimate. The foxholes had been shown on historic maps, but pre-construction site visits had not located any structures due to the thick vegetation and difficult site access.

Shipping constraints also affected the project, as the Contractor experienced difficulties removing the cleared vegetation in a timely manner. Consequently, large piles of cleared vegetation sat on site longer than anticipated, and one composting vegetation pile caught fire. The Contractor extinguished the fire by smothering it with dirt, but heavy equipment had to remain on site until all piles were removed.

After clearing, hydromulching was completed to stabilize the site until construction of the DMPA, which is planned for mid- to late-2023, pending federal appropriations.

Figure 1. Beltway 8 foxhole.

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DATA AVAILABILITY

The data and models generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

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PROCUREMENT STRATEGY FOR BENEFICIAL REUSE CONSTRUCTION - RESTORING FORMER MARSHES IN SAN FRANCISCO BAY

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EXTENDED ABSTRACT

Federal and private navigation projects annually maintenance dredge over 2½ million cubic yards in the San Francisco Bay region. The region is also home to a significant amount of subsided former marshlands that are behind flood protection levees. Beneficial reuse of dredged material has been identified to be very desirable for reversal of subsidence of these former marshes, to address sea-level rise, to reduce turbidity in the Bay, and to create broad upland transition zones. The dredging community in the region has successfully partnered with restoration agencies over the past 20 years and made significant strides in beneficially reusing material dredged from these projects. Major restoration projects have been constructed using the dredged material, which otherwise would not have been possible without beneficial reuse.

However, much of the beneficial reuse has been linked to capital improvement (deepening) projects, and a substantial amount of maintenance dredged material is still being disposed at in-water aquatic disposal sites. Despite the annual availability of a substantial amount of material suitable for restoration, the region's experience has been that only a small portion of that material is being reused because of significant constraints. The two biggest constraints are location of potential reuse site (fronted by mudflats that do not provide navigation depths for conventional barges/scows) and high initial costs to mobilize the equipment for material delivery and placement (offloader, power needs, and pipeline).

A Feasibility Study was commissioned by the California State Coastal Conservancy to identify a procurement strategy that would allow for reuse of the material to restore former salt ponds in the South Bay, serve as a template for other potential restoration sites, and reduce costs for beneficial reuse such that it could be competitive with other disposal methods.

Work included a detailed review of existing maintenance dredging costs, estimating disposal capacity for the ponds and wetlands, identifying required infrastructure improvements for the reuse, identifying priority locations for placement of dredged material, assessing construction feasibility in terms of dredged material transport, offloading, and placement, identifying pilot projects, and providing recommendations for implementation, environmental compliance, and permitting. Two different contracting mechanisms were identified to accommodate the constraints in procurement strategies under the Federal O&M Dredging Program while allowing local sponsor contributions from restoration agencies.

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Keywords: Maintenance dredging, beneficial reuse, slurry transport, dredged material disposal, marsh restoration, San Francisco Bay.

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DATA AVAILABILITY

Some or all data, models, or code generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

DREDGING TO ACHIEVE ONE OF THE LARGEST COASTAL WETLAND RESTORATION PROJECTS IN THE UNITED STATES: THE BAHIA GRANDE HYDROLOGIC RESTORATION PROJECT

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ABSTRACT

Along the Western Coast of the Gulf of Mexico, the Bahia Grande, or "Big Bay", was historically a large and fertile coastal wetland connected to the Lower Laguna Madre Bay System. It was heavily influenced by the tides, providing the necessary circulation within the ecosystem that is important to the prosperity of native wildlife and vegetation. However, in the 1930's and 1950's, expanding urbanization led to the severing of all tidal flow into the Bahia Grande. The once flourishing ecosystem was subject to ecological degradation and became a source of dust storms and large fish kills. In 2000, the Laguna Atascosa National Wildlife Refuge acquired the 22,000-acre Bahia Grande Unit and, in 2005, a Pilot Channel was dredged, connecting the Brownsville Ship Channel to the Bahia to reflood the basin. While the project successfully mitigated the dust storms, it did not provide enough circulation to the system to significantly improve the ecosystem. Mott MacDonald, in collaboration with the Texas General Land Office and the Port of Brownsville, took on the challenge of designing and constructing channel improvements to lower salinity levels and restore wildlife and habitat. The objective of the analysis and design was to maximize natural tidal circulation into and out of the bay complex, while providing scour protection to the Highway 48 bridge abutment and pile bents. Salinity and hydrodynamic modeling were used to test a variety of deepening and widening alternatives against existing conditions. The Bahia Grande Hydrologic Restoration Project began the construction phase in May 2021. The total quantity of material within the dredge template was less than 100,000 CY, a relatively small amount of volume with tremendous ecological benefits, aiding in the restoration of approximately 10,000 acres of vital wetland and shallow water habitat for local wildlife and fisheries making it one of the largest coastal wetland restoration projects in the United States.

Keywords: dredging, marine mattress scour protection, dredged material disposal, restoration

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INTRODUCTION

The Bahia Grande is located in south Texas between Brownsville and Port Isabel and immediately north of the Brownsville Ship Channel. Around 1951, Highway 48 was constructed on an embankment along the southern shoreline of the Bahia Grande. The Bahia Grande system was heavily tidally influenced, however, the construction of the elevated roadway effectively cut off all tidal connection. This resulted in the Bahia Grande drying up except after large rain or tropical events which flooded the basin. Strong, frequent coastal winds blew salty, clay dust that damaged the local vegetation and caused health problems, clogged air conditioners, shorted power lines, and restricted visibility on State Highway 48 and 100 (Ocean Trust, 2009). In 1982, a small channel was dug from Brownsville Ship Channel to Bahia Grande and the basin was re-flooded, but the owners of the adjacent ranchland took legal action to have the channel filled (Ocean Trust, 2009). In 1999-2000, the U.S. Fish and Wildlife Service (USFWS) acquired 21,762 acres of land surrounding the Bahia Grande, incorporated it into Laguna Atascosa National Wildlife Refuge (LANWR), and developed a wetland restoration plan. An initial hydraulic analysis on the feasibility of opening a channel connecting the Brownsville Ship Channel and Bahia Grande was undertaken by Van Valkenburg and Edge (2003) and H&H Resources (HHR, 2004). Van Valkenburg and Edge computed a 16% tidal exchange for a rectangular 200 ft wide and 12 ft deep channel based on a 600 million ft^3 capacity for Bahia Grande during high tidal ranges or 32% tidal exchange based on 360 million ft^3 capacity during typical tidal ranges. HHR analyzed a trapezoidal channel with side slopes of 4H:1V with a bottom width of 150 ft and depth of 9 ft and computed the tidal exchange as 32% of the maximum flood volume achieved in Bahia Grande during a normal tidal cycle (360 million ft^3 capacity). In July 2005, an approximately 2,200 ft long trapezoidal Pilot Channel was opened between Brownsville Ship Channel and Bahia Grande. The Pilot Channel was constructed with a bottom width of 15 ft, a bottom elevation of -3.3 ft North American Vertical Datum of 1988 (NAVD88) and side slopes of 2H:1V. The Pilot Channel eliminated the persistent dust from the main basin but provided only 2 million ft^3 of water exchange in a tidal cycle, as the connection between the Pilot Channel and Bahia Grande at Highway 48 was constricted by three culverts (two 30” and one 45” diameter). The construction of the 2005 Pilot Channel mitigated the dust storms but did not provide enough circulation to the system and salinities frequently spiked above 40-50 parts per thousand (ppt). Figure 1 shows a location map of the project site.

Figure 1. Bahia Grande project location map.

During 2006 – 2007, internal channels connecting the Bahia Grande, Laguna Larga, and Little Laguna Madre were constructed at approximately 60 ft wide with depths of -2 ft NAVD88. In 2007, construction of a bridge on Highway 48 over the Pilot Channel was completed by Texas Department of Transportation (TXDOT) and the culverts were replaced by a trapezoidal channel under the bridge with a bottom width of 150 ft, top width of approximately 220 ft, depth of -9 ft NAVD88, and side slopes of 4H:1V.

For the present study, Mott MacDonald (MM) was retained by the Texas General Land Office (TXGLO) to design channel improvements to maximize tidal flow into and out of the Bahia Grande along the alignment of the existing Pilot Channel within the available project funding. The overall goal of the construction of the Bahia Grande Restoration Channel for the TXGLO, USFWS, and other project partners are to restore Bahia Grande and LANWR as much as possible to its natural state, including wetland habitat, bird nesting habitat, and upland habitat, through the increase of tidal exchange into the system. Future goals with project partners include providing safe public access to LANWR and the expanded Bahia Grande Channel.

PAST ANALYSIS

A coastal engineering analysis was performed in 2011 (Mott MacDonald, 2011) to analyze the processes controlling flow into and out of Bahia Grande. The coastal processes analysis included the analysis of local geotechnical conditions, wind, water levels, shoreline change, currents, and sediment transport. The project site morphology analysis showed that since opening of the Pilot Channel, the Pilot Channel has been eroding (increasing in area), and most of the sediment eroded from the channel is being deposited inside the Bahia Grande. The area under the Highway 48 Bridge was dredged wider and deeper than the Pilot Channel, resulting in sedimentation. Figure 2 shows the shoreline position change of the Bahia Grande.

Figure 2. Shoreline position change of the Bahia Grande.

Hydrodynamic modeling was performed on a bay-wide scale to develop an understanding of the hydrodynamics in the project vicinity using MORPHO (Kivva et al, 2007; a proprietary model developed by MM). MORPHO is a 2-Dimensional depth-averaged finite volume numerical model that simulates tidally driven water elevation and current velocity. The MORPHO modeling procedure includes construction of the finite element modeling domain, development of boundary and input parameters, model calibration, model verification, simulation of modeling scenarios and analysis of results. The developed model was calibrated using local measured data. The channel configurations were modeled under seasonal wind conditions for both the flood and ebb tidal conditions. Current patterns around the project site during maximum flood and ebb tides without winds, with summer winds, and with winter winds conditions are shown in Figure 3.

The hydrodynamic modeling of the pre-construction condition indicates that the flow rate through the Pilot Channel was approximately 35 million ft^3 of water on a half-tidal cycle which provides a tidal exchange of approximately 9.7%. The tidal exchange has naturally increased to 9.7% from 1.7%, as measured from the 2007 conditions when the Pilot Channel was initially opened, and the Highway 48 Bridge was constructed. This increase in flow rate indicates a natural tendency of the inlet to open.

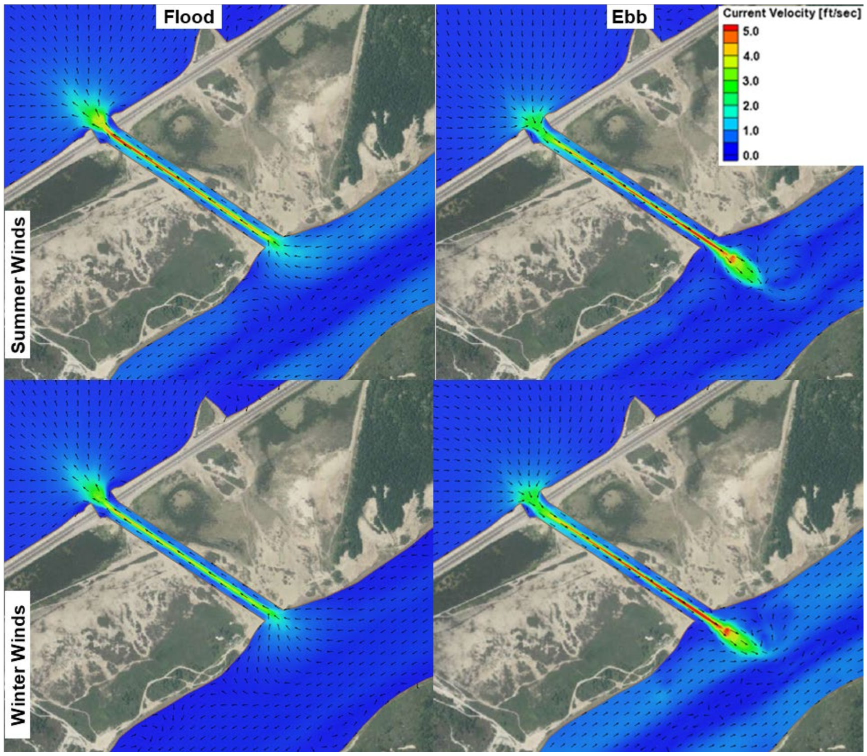

Figure 3. Modeled current velocities in the existing Bahia Grande Pilot Channel.

The observed natural opening of the channel is well explained by the inlet stability analysis performed. The classic paper by Escoffier (1940) provided a hydraulic relationship between the cross-sectional area and the maximum velocity within a channel as a function of tidal prism, friction characteristics, and channel area. Inlet stability was evaluated using an Escoffier type stability curve developed with numerical modeling results of the hydrodynamic model MORPHO. Based on this analysis, the channel was expected to continue to naturally increase in cross-sectional area from its pre-construction area of approximately 280 ft^2 to 860 ft^2. In addition, the inlet stability analysis showed that a maximum stable cross-sectional area of approximately 1880 ft^2 could be maintained by the system, resulting in a maximum possible average volume of approximately 90 million ft^3 of water on a half-tidal cycle or 25% of the maximum possible tidal exchange. Figure 4 shows the stability curve developed using modeled results for various modeled channel configurations.

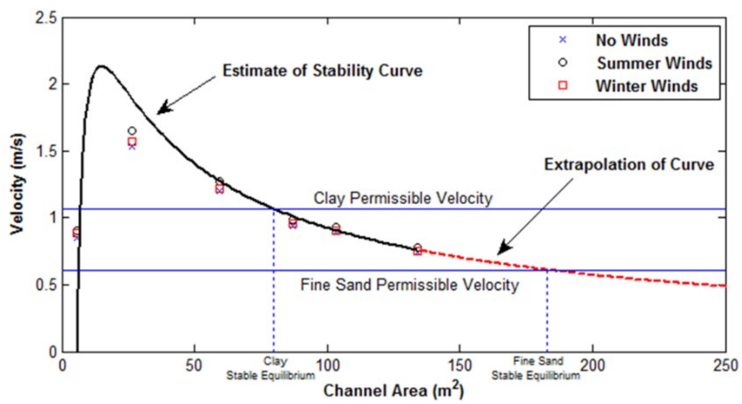

Figure 4. Stability curve created using modeling results for various channel configurations.

The salinity levels in Bahia Grande basin govern the growth and expansion of existing habitat and therefore salinity modeling was performed in 2013 to quantify benefits to the Bahia Grande ecosystem (Mott MacDonald 2013). A synthetic 2-year time period of input conditions were developed to simulate a dry and a wet year and capture the overall range of salinities for existing conditions. Two alternatives were also investigated in the salinity model, the deepest and the shallowest designed channels, to represent the upper and lower bounds of possible channel size. The alternative channel configurations' effect on salinity was simulated during the 2-year synthetic period. It was determined that the dredging of the proposed channel is expected to increase the flow exchange between Brownsville Ship Channel and Bahia Grande thereby altering the salinity levels inside the Bahia Grande basin. In addition, the salinity levels resulting from dredging the channel were analyzed to determine the potential benefits to the habitat. The tested channel templates were oriented along the Pilot Channel with a bend under the Highway 48 bridge to keep the channel orientation perpendicular to the bridge. The channel bottom width varies depending on the dredge depth. The channel side slope is 4H:1V and the channel exit is designed as a radial channel to achieve the maximum flow rates. Figure 5 shows the channel improvements tested in the salinity model.

Figure 5. Channel improvements tested in the salinity model.

Salinity levels in Bahia Grande for existing conditions and two depth varying alternatives for the preferred layout were computed for the top and bottom 5% and the 25-75% Probability of Non-Exceedance (PNE). The results show that the deepest (alternative 1) and shallowest (alternative 2) channel alternatives perform similarly and on average push lower salinity levels farther into the Bahia Grande basin from the mouth of the dredged channel, as shown in Figure 6. Areas currently observed to foster favorable habitats (marsh grass and oyster beds) were correlated to modeled existing conditions of salinity. These areas corresponded to average salinities of less than 35 ppt. The area for the existing conditions less than 35 ppt on average were computed and compared to the same average salinity contour for the alternative conditions. It was determined that the alternatives increased the area below the 35 ppt salinity level by almost 2.5 times (880 and 840 acres for alternatives 1 and 2 v/s 330 acres for existing conditions). These results therefore show that the alternatives have the potential to dramatically increase the available area for future growth of marine habitat by increasing the area where salinity is lower than the 35 ppt average contour.

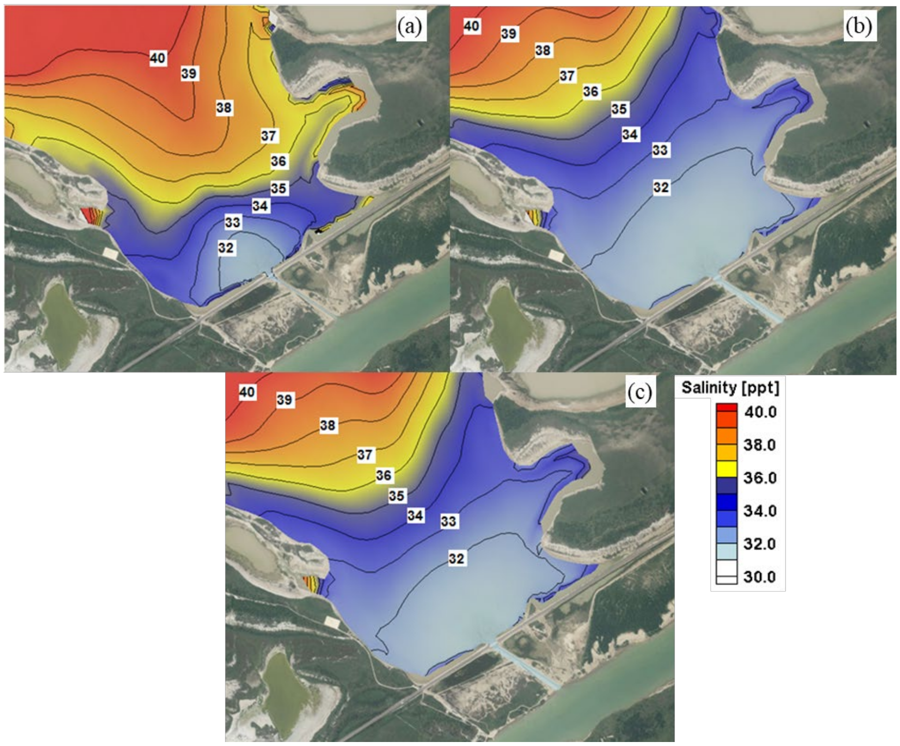

Figure 6. Average salinities (represented by the 25-75% PNE) for the (a) Existing, (b) Alternative 1, and (c) Alternative 2 conditions in lower Bahia Grande Basin.

THE BAHIA GRANDE HYDROLOGIC RESTORATION PROJECT

Design

Three different dredge template layout alternatives were proposed and analyzed to determine which alternative provides the maximum flow rates into and out of the Bahia Grande. Since maximum dredging depth of the channel is dictated by the cost associated with delivery of the material to the placement area, four variations of channel bottom depth and width were analyzed for the preferred channel layout. The final chosen dredge template consisted of the maximum possible cross-section of 1680 ft^2 (150 ft wide bottom dredged to -9 ft NAVD88 with 4H:1V side slopes) and a radial exit transition into Bahia Grande. Figure 7 shows the final designed dredge template along the channel centerline (top) and perpendicular to the centerline (bottom).

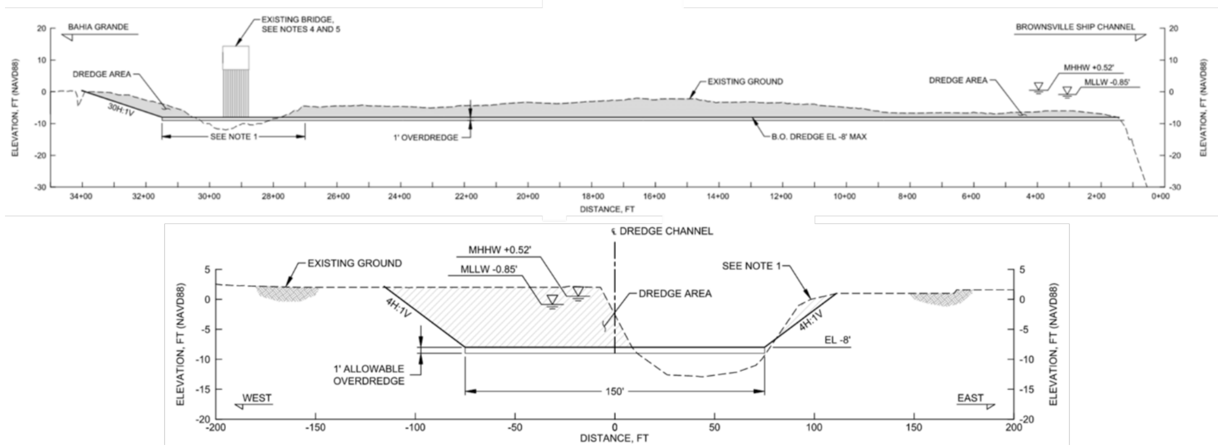

Figure 7. Preferred alternative solution for maximizing flow into and out of the Bahia Grande.

Different dredged material placement options were developed; the placement configuration impacts overall construction price. Placement options included locations directly adjacent to the dredged channel template, along a peninsula inside Bahia Grande, at a USACE-managed dredge material placement area (DMPA) across the Brownsville Ship Channel, and combinations of these options. The preferred option was determined to be the USACE-managed DMPA.

Three robust scour protection alternatives were designed for the increased channel flow velocities of the preferred alternative. The main goal was to protect the existing TXDOT Highway 48 bridge from scour induced damages from the increased flow underneath the bridge. Armor stone, articulated concrete block mattresses and stone filled marine mattress options were designed to give contractors the opportunity to bid the option that best suited their capabilities and make the bidding process more competitive. The scour protection design templates interfaced with the existing bridge abutment scour protection. Figure 8 shows an example of the designed scour protection template for Marine Mattress Alternative.

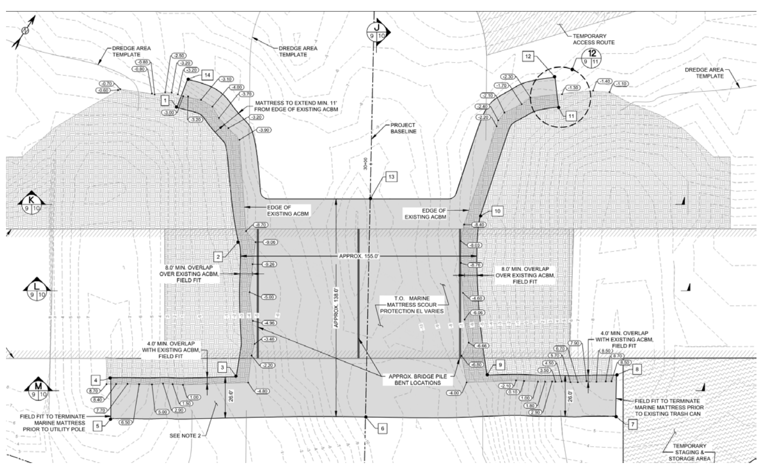

Figure 8. Marine mattress scour protection template.

Construction Phase I

Construction Phase I of this project began in May 2021 and concluded in January 2022. This phase involved the dredging and dredged material placement of approx. 83,000 CY. Phase I endured challenges including an abandoned vehicle found within the dredge template, active USACE maintenance dredging activities within the Brownsville Ship Channel, and active USACE placement activities from a separate hydraulic dredging project within the USACE-managed DMPA. After thoughtful and exceptional coordination with the Port of Brownsville and the USACE, the dredging and dredged material placement for the Bahia Grande Hydrological Restoration Project was successfully completed without conflict from the USACE maintenance dredging projects. During pre-construction activities, local news covered a story about a vehicular accident occurring at the Highway 48 bridge, but it was unclear where the vehicle was located. During pre-construction surveying efforts, the contractor believed to have located the vehicle. TXDOT was notified of the vehicle since it was near the bridge pilings, potentially putting the structure at risk. TXDOT mobilized a crane mounted vehicle to the site, located the submerged vehicle with divers and successfully extracted it from the channel.

Dredging

The dredging for this project included dredging of the Bahia Grande Restoration Channel and fan area of the Bahia Grande that lies north of Highway 48. Dredging the Bahia Grande Restoration Channel was accomplished by using two dredge excavators mounted on a spud barge to simultaneously dredge and load material onto a material transport barge, as shown in Figure 9. A hazard survey was performed within the dredge template footprint during pre-construction activities and an abandoned broken pipeline was identified within the Pilot Channel. A buffer distance was established at the pipeline location and the contractor was directed to be extra cautious while dredging in the area to not damage the pipeline or put the crew at risk. Figure 10 shows the comparison of the 2005 Pilot Channel to the 2021 Bahia Grande Restoration Channel.

Figure 9. Pilot Channel dredging setup.

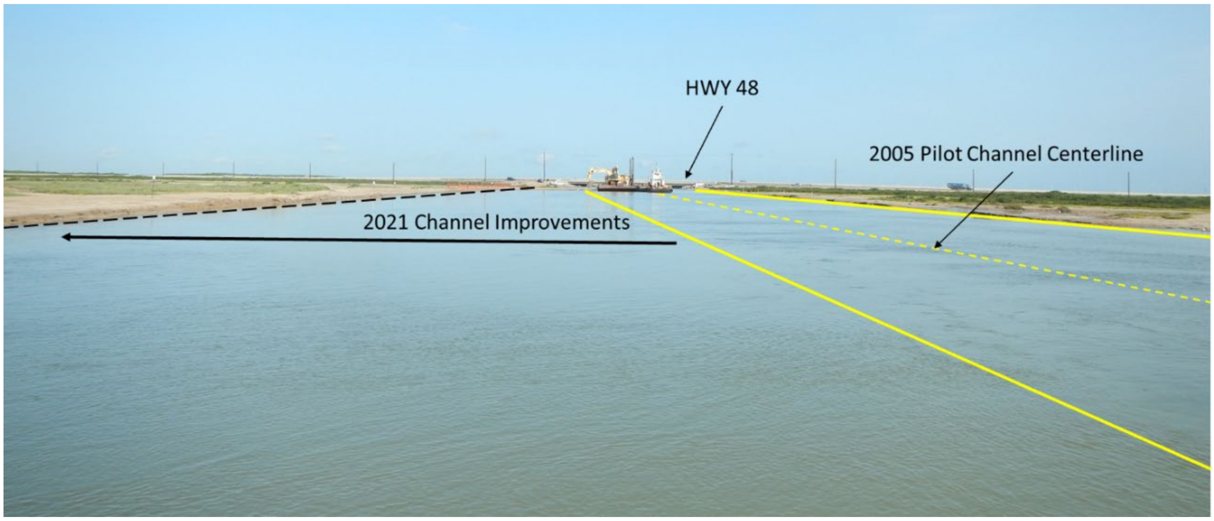

Figure 10. 2021 Channel Improvements versus 2005 Pilot Channel.

Next, the contractor shifted over to the Highway 48 bridge, to dredge underneath the roadway. The focus was on material covering the existing articulated concrete block mattresses that protect the existing bridge abutment from scour. A hydraulic dredging technique was used to remove the material in a safe manner and not damage the existing scour protection. With the Bahia Grande Restoration Channel at full template width, water moved very rapidly during a change of tide, especially at the choke point of the template which was at the bridge. The contractor used a low-profile barge equipped with an "A" frame to hoist a submersible pump to pump dredged material into a hopper barge. The material was then hauled to the placement area where another pump transported the slurry to a designated location with the USACE-managed DMPA. Figure 11 shows the dredging equipment utilized underneath the Highway 48 bridge, where access was very limited and working hours depended heavily on the tidal conditions.

Figure 11. Dredging equipment utilized underneath the Highway 48 bridge.

Signage and fencing were installed as a safety precaution once dredging operations neared the Highway 48 bridge abutments, a popular fishing spot. Furthermore, media postings were made to notify the public of dredging operations and encourage pedestrian and vehicular traffic to avoid fenced off areas.

Once dredging of the Pilot channel and bridge area was complete, dredging of the northern fan area of the Bahia Grande commenced with a marsh excavator, as shown in Figure 12. Elevations in the fan area proved to be much deeper than anticipated. While the marsh excavator floats, the excavator's arm needs to contact the ground to position or move the excavator. To access and grade material in deeper water, material was pushed into a pile for the excavator's arm to make contact with.

Figure 12. Marsh excavator dredging north of the Highway 48 bridge.

Figure 13 shows the comparison of the pre-construction conditions to the 2022 Bahia Grande Restoration Channel.

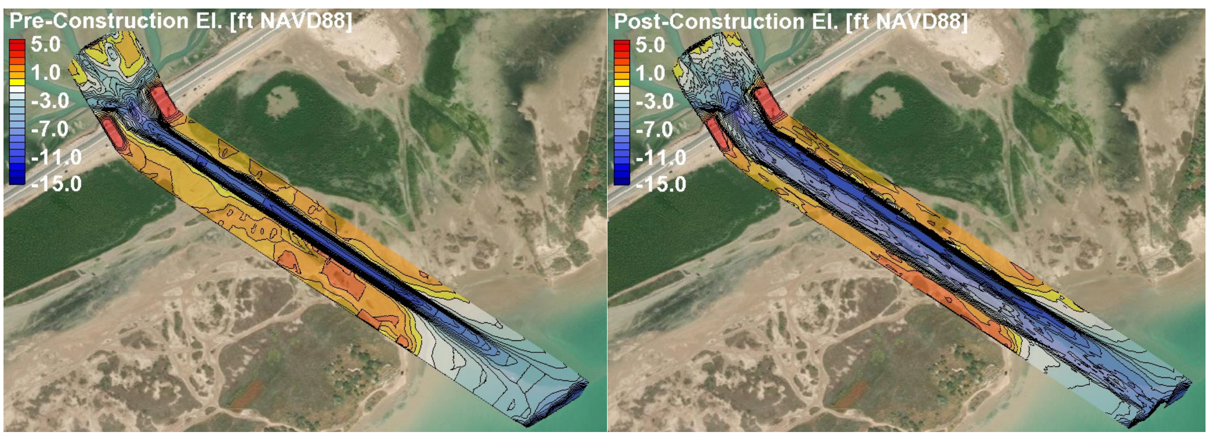

Figure 13. May 2021 Pre-Construction Elevations (left); January 2022 Post-Construction Elevations (right)

Material Disposal

Once the material transport barge was full, a tugboat would transfer the barge to the offloading area at the USACE maintained DMPA, as shown in Figure 14. A long reach excavator staged on a spud barge near the shoreline offloaded dredged material from the material transport barge and onto material transport vehicles.

Figure 14. Dredged material offloading operations at the DMPA.

The material transport vehicles would place the material in the DMPA where an excavator would grade and spread the material, as shown in Figure 15. All material placed in the DMPA was graded to gently slope towards the interior. Dry, dense clay from the dredged material was used to repair low spots in the haul route and outer slope of the DMPA levees. Close coordination with ongoing USACE maintenance dredging projects, occurring simultaneously at the DMPA, led to the successful placement of material for both projects. No delays due to the adjacent USACE maintenance dredging and placement activities occurred.

Figure 15. Dredged material placement operations in the DMPA.

Construction Phase II

Construction Phase II of this project began in January 2022 and is expected to finish in May 2022. This final phase covers the fabrication and installation of marine mattresses and geotextile rock bags as scour protection for the Highway 48 bridge abutments and pile bents. The main difficulties experienced in Phase II involve the low clearances of the Highway 48 bridge, very dynamic flow conditions with the template, and limited working area on land for the contractor to stage heavy equipment. The contractor installed new scour protection utilizing low profile barges and a unique marine mattress laying technique with a fabricated ramp to lower mattresses into the design template in an orderly fashion. The contractor had to be very aware of the tidal conditions, not only to fit their equipment under the bridge but to ensure they were always in control of their barges and equipment with the increased flow due to the channel expansion. The contractor will also utilize a crane to place mattresses in areas of the template that the barges cannot access, north of the Highway 48 bridge. Close coordination with TXDOT is currently underway for approval of a traffic control plan in order to block traffic in one lane of the highway to stage the crane for operation.

Scour Protection Fabrication

At the contractor's leased yard, along the Brownsville Ship Channel, geotextile rock bags and marine mattresses were constructed. The geotextile bags were filled by loading stone into a hopper using a skid steer. The stone was then released onto a conveyer belt below the hopper and poured into the bags. Once filled, the bags were stapled shut with hog rings using a hog ring gun. Figure 16 shows the rock bag filling technique.

Figure 16. The hopper and conveyor belt system used to fill geotextile bags.

The marine mattress scour protection consists of 6-inch thick, 6.5-foot-wide mattresses of various lengths, from 12 to 20 feet long. The mattresses had a geotextile layer pre-affixed to the bottom of each mattress. The mattresses were filled with stone using a skid steer and a hydraulic filling frame. Each of the approximately 2-foot wide diaphragms were sewn shut with HDPE braid materials as they were filled, as shown in Figure 17. Each marine mattress took approximately 10 minutes to construct and stage.

Figure 17. Marine mattresses being filled using the hydraulic filling frame and a skid steer.

The completed scour protection components were staged near the shoreline of the leased property with the geotextile rock bags stacked on pallets of 20-30 bags per pallet and marine mattresses stacked in piles. Figure 18 shows the staged scour protection material post-fabrication.

Figure 18. Completed geotextile rock bags and marine mattresses.

Scour Protection Installation

As of March 2022, marine mattresses and geotextile rock bags are currently being installed within the designed scour protection template. Marine mattresses were transferred from the staging area onto a material transport barge by using an excavator and spreader bar, as shown in Figure 19.

Figure 19. The excavator and spreader bar loading mattresses onto the material transport barge.

To install the marine mattresses, low-profile barges were positioned underneath the Highway 48 bridge using a tugboat and an excavator staged on a spud barge positioned on the south side of the bridge on the low-profile barge. Mattresses were brought onto the front of the low-profile barge and hydraulic ramp using a winch and pull bars, then adjacent mattresses were tied together. The mattresses were lowered off the hydraulic ramp into place, as shown in Figure 20.

Figure 20. Installation of marine mattresses under the Highway 48 bridge.

CONCLUSIONS

MM, in collaboration with the TXGLO and the Port of Brownsville, took on the challenge of designing and constructing the Bahia Grande Restoration Channel to lower salinity levels and restore wildlife and habitat within the Bahia Grande system. Previous analysis was utilized in the final design to maximize natural tidal circulation of the bay complex, meanwhile providing protection to the Highway 48 bridge from scour. A numerical model was used for the salinity and hydrodynamic modeling to test a variety of deepening and widening alternatives against existing conditions. The preferred alternative was taken to a 100 percent design level and the project was bid out to local contractors. The Bahia Grande Hydrologic Restoration Project began the construction phase in May 2021 presenting new challenges to overcome including variable weather conditions, a very dynamic flow environment, as well as adjacent USACE maintenance dredging projects within the Brownsville Ship Channel. Currently the dredging phase of the project is completed but the scour protection installation is underway and anticipated to be completed by May 2022. The total amount of material removed from the dredge template was approximately 83,000 CY of material, a relatively small amount to dredge resulting in tremendous ecological benefits.

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DATA AVAILABILITY

Some data and models used in this study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

HOW TO BUILD A PERFECT MARSH

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EXTENDED ABSTRACT

Projects utilizing the delivery method of Design-Bid-Build inherently have the potential to produce unforeseen outcomes as the means and methods used in construction may differ from the assumptions made during design. This is especially true for marsh creation projects. Fortunately, new tools and approaches are emerging which can help dredgers and engineers collaborate during construction to bridge the gap. By incorporating flexibility into certain elements of the design and tethering them to emerging technologies in monitoring and instrumentation (M&I), it is possible to increase reliability in construction of healthy marshes.

The historical approach for controlling the construction of marsh creation projects has been the quantity of material dredged or placed and a constructed marsh fill elevation. Traditionally, the target constructed marsh fill elevation has been established through geotechnical analyses during the project design phase. Software such as the Primary Consolidation, Secondary Compression, and Desiccation of Dredged Fill (PSDDF) program are used to predict long-term post-construction consolidation and desiccation of the hydraulically placed fill. Soil parameters used in these models are normally estimated through extensive field sampling and laboratory testing, including column settling and low-stress one-dimensional consolidation tests. Although these testing and analytical methods have often proven useful in characterizing the long-term state of the created marsh in terms of void ratio or density years after construction, the initial parameters input into the models are hard to predict. Input parameters such as the material characteristics of the slurry (e.g. the percentage of sand, silt, and clay present) can be measured and accounted for in the design, but another parameter is much harder to predict: the concentration of the slurry. The slurry concentration (i.e. slurry density, slurry specific gravity) can vary for any number of reasons including the size of dredge mobilized, the number of boosters used, the horsepower of the individual pumps, and pipeline alignment. The geotechnical engineer and design engineer must essentially guess which combination of equipment will be used and infer which slurry concentration will be produced in order to determine the target constructed marsh fill elevation and quantity of marsh fill.

When the operational parameters of the hydraulic dredge differ during construction from the design, the effectiveness of using the constructed marsh fill elevation as a control will reduce, along with the health of the constructed project. To account for the differing parameters assumed during design versus what is realized during construction, some designs incorporate a tolerance which allows the construction contractor to aim for a target and still miss by some allowable measure. This method, although satisfies the contractual

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element short term, can lead to a long-term marsh that is either too low or too high. The former meaning the created marsh will too quickly become inundated and erode and the latter meaning additional acreage of marsh could have been created using excess material. Either of these outcomes could be construed as a misappropriation of federal, state, and private funds.

Realization of this issue has led to changes in the design approach. Some designs incorporate a ranged approach where a project is designed to allow for a "leaner" and "heavier" concentration. Others have designs that do not dictate a target constructed marsh fill elevation, but a quantity that must be dredged and spread evenly across a marsh creation cell. However, the target constructed elevation cannot be determined until the dredge slurry is conveyed and the concentration of slurry is measured in place. In the latter case, further difficulty arises in spreading the slurry evenly.

M&I applies the use of tools such as collecting slurry samples during construction and in-situ instrumentation to allow dredgers and engineers to use real-time data to determine the concentration over the marsh creation area. The Coastal Protection and Restoration Authority of Louisiana (CPRA) has been on the forefront of using M&I for marsh creation projects. CPRA encourages the use of M&I to assist with evaluating the performance of hydraulically placed fill material in marsh creation areas (MCAs) through slurry sampling during construction and the use of instrumentation. A template for Instrumented Settlement Platess is illustrated in the CPRA's Marsh Creation Design Guidelines, Version 1.0 (CPRA 2017).

A fundamental concept that makes this method possible is the principle of effective stress. To assist with the discussion, below is an equation and terms:

$$\sigma' = \sigma - u = TPC - PZ$$

Where: σ is total stress, σ' is effective stress, u is pore pressure, TPC is the total pressure cell reading, and PZ is the vibrating wire piezometer reading.

Or,

Total pressure (water and soil particles, e.g. slurry) – water pressure (water in slurry) = amount of solids

This principle indicates that once the slurry has reached a given effective stress, or a given mass of soil solids in the slurry "column" in the marsh creation area, the long-term behavior and therefore the final settled constructed marsh elevation can be calculated.

Based on observed performance of previously constructed projects and results of geotechnical field M&I using in-situ instrumentation and collecting samples of slurry, the feasibility of measuring the vertical effective stress during fill placement stress is possible and has been extensively tested. This approach allows dredging contractors to control their means and methods, including slurry density and fill height, while enabling the owner to control the quantity of solids placed via direct real-time measurement of effective stress. In other words, the dredging contractor can pump the slurry lean to a higher elevation, heavy to a lower elevation, or any combination of these methods. The need for remobilizing a hydraulic dredge or other construction equipment to a project to pump additional material, fill in low spots, or grade higher areas will be unnecessary if the target effective stress is achieved and measured. This innovative approach is expected to improve project performance, while also reducing the overall cost of the project.

This M&I has been used in multiple CPRA projects in Louisiana. Further explanation of theory and data from these projects will be provided in the presentation.

Keywords: Dredging, beneficial use, settlement, instrumentation, slurry concentration, effective stress

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CITATION

Haynes, S.M., Tammineni, V., Mattson, G.A., II. "How to Build a Perfect Marsh," Proceedings of the Western Dredging Association Dredging Summit & Expo '22, Houston, TX, USA, July 25-28, 2022.

DATA AVAILABILITY

- Some data is property of CPRA and can be made available from the corresponding author by request.
- Some data is proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

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CREATING BIRD ISLANDS IN COASTAL LOUISIANA USING SEDIMENTS DREDGED FROM BAPTISTE COLLETTE BAYOU

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and J.F. Jung[4]

EXTENDED ABSTRACT

Dating to the late 1860s, Baptiste Collette Bayou was a small canal that extended between the Mississippi River and the historic Breton Island Sound. In a series of storm-related events and USACE dredging authorizations beginning in the early 1900s, a sub-delta that developed covering as much as 20 square miles by 1959, began to deteriorate due to considerable subsidence and ponding. The inception of the channel occurred in 1968 from a Congressional Authority to enlarge the waterway. Work began with emergency dredging events in 1972 and 1973 to provide relief to barge traffic on the Gulf Intracoastal Waterway while the Inner Harbor Navigation Canal lock was closed. The first bird island was born of this emergency maintenance.

Construction of islands to serve as coastal bird habitat began in 1978 when the New Orleans District (CEMVN) began to regularly maintain the Baptiste Collette navigation channel. The objective from the beginning was to create island features that could serve as nesting habitat for shorebirds. Beneficial use of sediment from maintenance of the Baptiste Collette Bayou channel now occurs on an annual basis with the placement of dredged sediment in shallow open water on either side of the channel. The unconfined placement is designed to create wetland habitat adjacent to the waterway's jettied entrance and islands seaward of the jetties that are suitable for colonial nesting seabirds. To attract these seabirds to established islands, the CEMVN intentionally covers plant overgrowth with sand dredged from the channel to keep the island relatively vegetation free and create large areas of bare ground necessary for the breeding colonies. Additionally, allowing the dredged sediments to flow outward unconfined from the wetland and island features creates broad intertidal flats that serve as foraging areas for a variety of coastal birds. Both the intentional smothering of plant overgrowth and creation of tidal flats represent current state-of-the-practice and are adaptions made over the Baptiste Collette's lengthy beneficial use history.

Periodic avian surveys made on Baptiste Collette's beneficial use sites have documented that the island and wetland features created with dredged sediment are utilized by seabirds for nesting and other purposes. The most recently constructed island (Gunn Island) was established in 2014 to accommodate shoaling further out in the bar channel and to avoid enlarging the existing islands while maintaining sufficient spacing between them. The initial construction of Gunn Island involved placement of ap-proximately 119,000 cubic

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yards (90,982 cubic meters) of sediment, although this placement did not result in the island breaking the water surface. Beneficial use activities on Gunn Island include placement of 836,000 cubic yards (639,170 cubic meters) of sediment in 2018 to achieve a +6.0 feet (1.8 m) Mean Low Gulf elevation, creating roughly 12 acres of birds nesting habitat. In 2019, 943,000 cubic yards (720,975 cubic meters) of dredged sediment was placed on Gunn Island, creating an additional 56 acres (23 ha) of bird nesting habitat.

In August 2020, the Louisiana Department of Wildlife and Fisheries observed over 50,000 seabirds occurring on Gunn Island. As part of the Baptiste Collette bird island chain, Gunn Island's seabird colony was composed of approximately 45% Royal Terns, 21% Black Skimmers, 14% Sandwich Terns, 8% Gull-billed Terns, 5% Caspian Terns, 5% Laughing Gulls, and the remaining 1% were comprised of 19 other species. In 2020, Gunn Island hosted the state of Louisiana's largest nesting tern colony with an estimated 10,000 breeding individuals. Since the initial construction of the Baptiste Collette navigation channel, over 1,000 acres of coastal habitat have been created by placement of sediment during routine maintenance dredging events. The bird nesting islands have been identified as a U.S. Important Bird Area because of the essential habitat they provide to significant numbers of breeding Caspian and gull-billed terns and black skimmers, as well as roosting habitat for pelicans. Five species of terns have been recorded as breeding on these islands.

In this study we will present by what means we are developing an improved understanding of shorebird and seabird response to placement activities in Baptiste Collette Bayou. From this information, we plan to gain insights into broader ecological benefits of these best practice sediment placement strategies so that they may be optimally applied here and elsewhere. We are conducting research to document seasonal ecosystem services at these sites and how this research will play a meaningful role in determining the efficacy and optimal use of such beneficial use applications in the future.

Keywords: Dredging, beneficial use, shorebirds, seabirds, ecosystem services.

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DATA AVAILABILITY

Data generated during the study are available from the corresponding author by request.

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DREDGING TO RESTORE THE CEDAR BAYOU AND VINSON SLOUGH INLET

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ABSTRACT

Cedar Bayou is a historical natural tidal inlet, located approximately 40 miles southwest of the Matagorda Ship Channel in Aransas County, Texas. Over its life, Cedar Bayou has separated San Jose Island and Matagorda Island and provided a hydraulic connection between Mesquite Bay and the Gulf of Mexico. When the inlet is open, it enhances the surrounding bay system by providing circulation to 22,000 acres of Vinson Slough marshes, serves as a migratory fish pass for marine life, and supports the economy of Aransas County. Cedar Bayou was artificially closed in 1979 to protect the bay system from an il spill in the Gulf. Since then, Cedar Bayou has been unstable, closing for long periods of time with short windows of connection between Cedar Bayou and the Gulf of Mexico. In 2020, Aransas County was approved for funding from FEMA and the Hurricane Harvey Fishery Disaster Grant for the reopening of the Cedar Bayou inlet and Vinson Slough. The objectives of the effort were to design a dredge template that would restore circulation to Vinson Slough and reestablish the migratory fish pass. The effects of channel reopening have been closely monitored through historical aerial photography and surveys. The data compiled through this extensive monitoring campaign was used to develop an adaptively managed dredge template that optimized dredge volumes, minimized habitat impacts, and maximized inlet longevity. In May 2021, an intricate combination of mechanical and hydraulic dredging removed approximately 300,000 cubic yards of material from Cedar Bayou and Vinson Slough, in very dynamic conditions.

Keywords: environmental monitoring, adaptive dredge template, numerical modeling, tidal inlet, estuarine wetlands.

INTRODUCTION

The Cedar Bayou inlet is an ephemeral tidal inlet located on the Texas Gulf Coast that divides San Jose Island from Matagorda Island. Historically, the inlet's hydraulic connection to the Gulf has frequently migrated and closed due to the dynamic conditions present. Frequent maintenance dredging efforts have been required to reopen it. It is vital that the connection be maintained because it enhances the surrounding bay system: providing circulation to 22,000 acres of Vinson Slough marshes, serving as a migratory fish pass for marine life, and supporting the economy of Aransas County. The relative location of the Cedar Bayou Inlet and surrounding Vinson Slough marshes can be seen in Figure 1.

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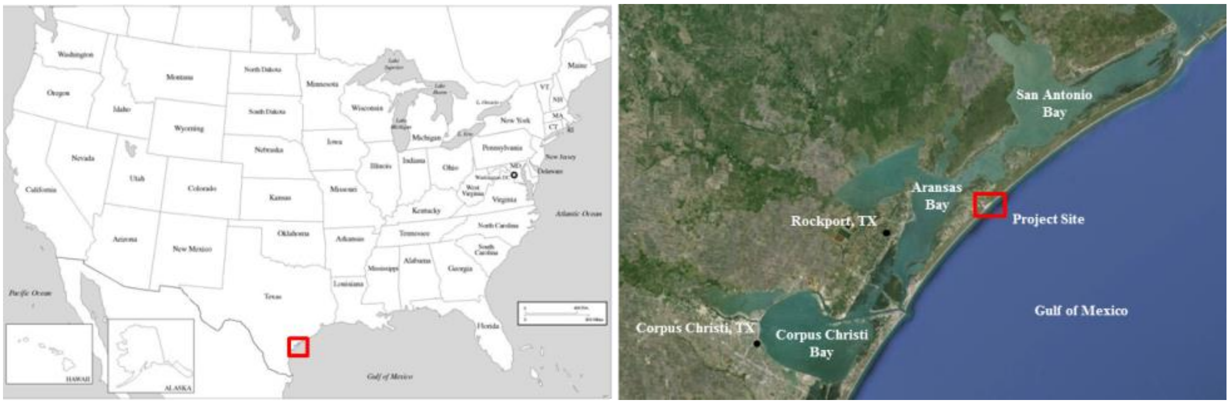


Figure 1. Relative location of the project site in the United States and a local map showing project site.

For this study, Mott MacDonald was retained by Aransas County to produce an optimized dredging design that would extend the time frame between maintenance dredging events. An adaptive management approach was developed to give Aransas County the ability to conduct a 10-year maintenance dredging program to maintain the Cedar Bayou and Vinson Slough inlet. The approach would authorize a channel dimension in which the layout of the template could be adjusted within a designated area based on the performance and frequency of the dredging events. This approach gives the County flexibility to adjust the alignment of the template, given the very dynamic nature of the project site. The final design dredge template alignment for the 2021 reopening would emulate the natural conditions of the inlet, reducing migration and consequentially inlet closure. The application of the adaptive management approach is discussed herein and compared to previous design efforts.

Dredging History

To better understand the history of the inlet and surrounding region, Mott MacDonald compiled historical data of significant morphological events affecting the inlet. Historical maps dating back to 1836 show evidence of Cedar Bayou, known then as Santos Pass, as a wide shallow pass connecting Mesquite Bayou to the Gulf of Mexico. The first recorded dredging event of the inlet occurred in 1939, after the inlet was closed by a hurricane. Later in 1979, the inlet was artificially closed to protect the interior bay system from an oil spill in the Gulf of Mexico. Over the years, a multitude of significant events have taken place. A detailed timeline of these events is shown in Figure 2.

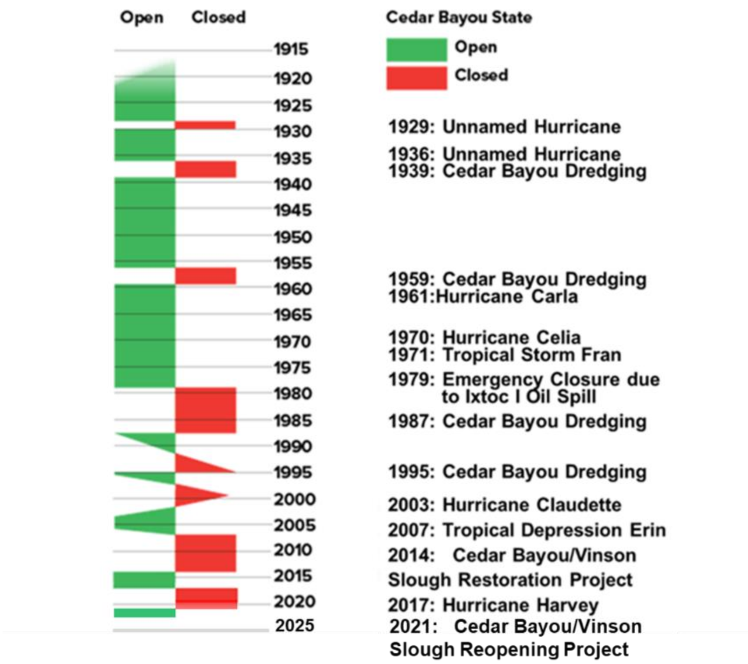


Figure 2. Summary of Cedar Bayou dredging events, storms, and estimated opened and closed states.

Previous Analysis

The analysis discussed in this section was performed to determine the optimal design cross section for the future dredging events. These analyses included evaluating the coastal processes, morphology of Cedar Bayou, channel stability, salinity impacts, and suitability of mitigation sites (MM, 2012).

The coastal processes were analyzed to understand the environmental conditions affecting the project site. Some key findings of the coastal process analysis are listed below:

- Predominate wind direction is from the southeast with occasional strong north winds.
- Predominate wave direction is from the southeast with an average height of four feet and five second period.
- Sediment transport moves in the southwest direction at a rate of approximately 270,000 cubic yards per year.
- A 100-foot-wide combined Cedar Bayou and Vinson Slough channel is stable during normal conditions.
- The channel tends to migrate from northeast to southwest, driven by the net longshore transport at an average rate of 265 feet per year.

Typically in this area, topography such as high dunes overwhelms the system, halting migration and leading to inlet closure. Using analytical and empirical methods, infilling rates of the channel were calculated to be between 138,000 to 144,000 cubic yards per year. The length of time that the channel would remain open without maintenance was determined to range from 7 to 17 years, with a weighted average of 9.4 years. This duration neglects the occurrence of an extreme event such as a hurricane impact or severe, extended period of drought. Extreme events, such as Hurricane Harvey discussed in the following section, are expected to alter the lifetime, and may greatly shorten or extend the lifetime depending on the event.

IMPACTS OF HURRICANE HARVEY

On August 26, 2017, Hurricane Harvey made landfall as a Category 4 storm just west of Cedar Bayou. This storm resulted in significant storm surge, wind, and waves directly impacting Cedar Bayou and Vinson Slough. This storm was a worst-case scenario for the system, as it approached from a direction most likely to result in high sedimentation of Cedar Bayou and Vinson Slough. Because of the head-on approach of Harvey, waves and surge likely forced material from the beach into Cedar Bayou and Vinson Slough, resulting in rapid sedimentation of the system. Figure 3 shows aerial imagery of Cedar Bayou before versus after Hurricane Harvey.

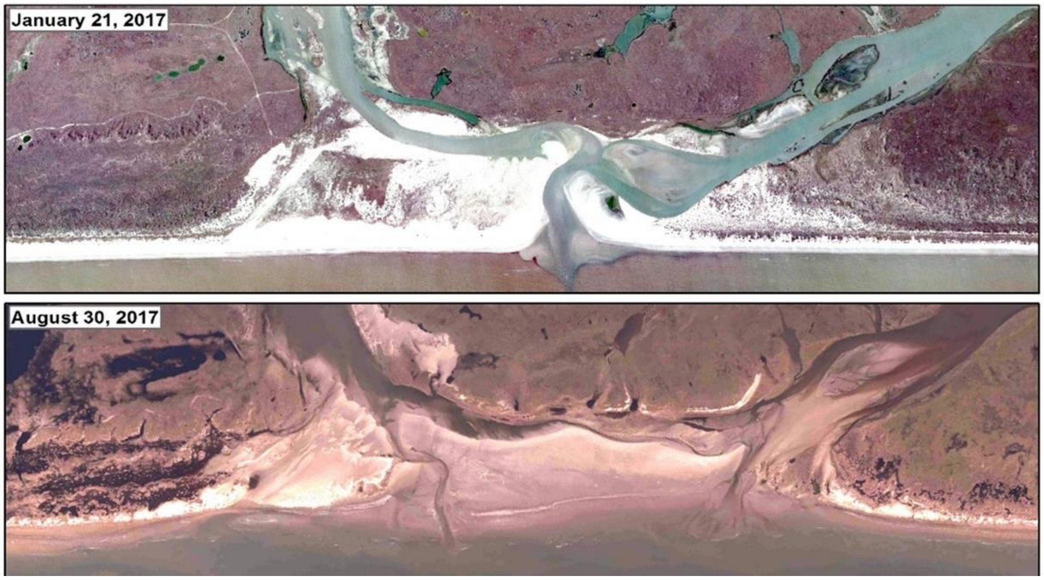


Figure 3. Aerial imagery before versus after Hurricane Harvey.

Hurricane Harvey resulted in dramatic changes to the habitat acreages all throughout the project area. Figure 4 shows a plot of the overall habitat timeline within the study area, and how habitats were affected by Hurricane Harvey and the subsequent closing of Cedar Bayou and Vinson Slough. When Cedar Bayou was initially opened in 2014 habitat acreage showed a steady increase, which was promising to the ecosystem but after Hurricane Harvey, the system was cut off from tidal circulation which decimated habitats that were thriving beforehand.

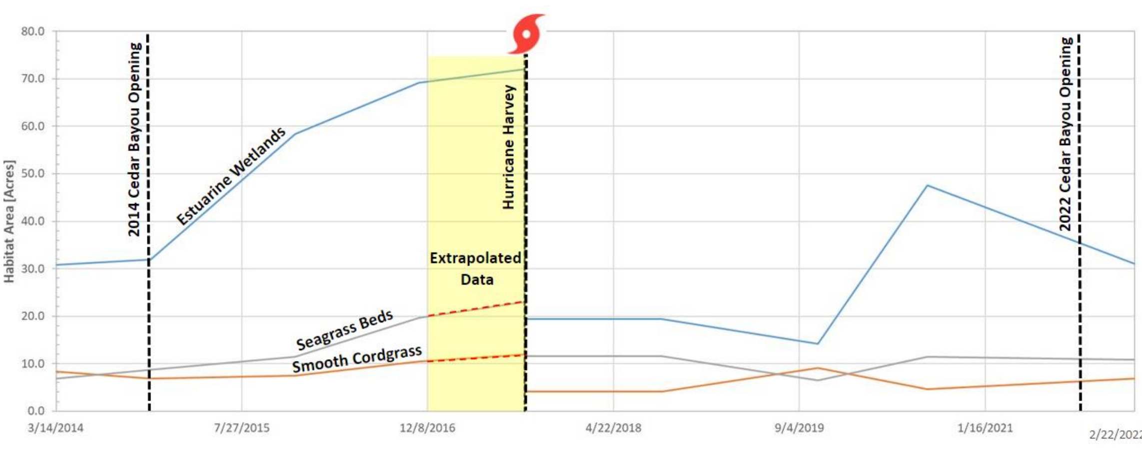


Figure 4. Cedar Bayou/Vinson Slough habitat timeline.

ADAPTIVE MANAGEMENT APPROACH AND DESIGN IMPROVEMENTS

Adaptive Management Approach

The results of the historical analysis have shown that Cedar Bayou continues to be a highly dynamic and variable system. Hurricane Harvey has further shown how unpredictable weather events can significantly impact the Cedar Bayou and Vinson Slough system, creating further uncertainty. To address the uncertainty and constant flux of Cedar Bayou, the dredge template was designed to be adaptable to the future state of the channel through an adaptive management approach. This approach involves implementing a customized dredging solution based on the channel conditions at the time of maintenance dredging. The dredge template position and orientation will vary during each dredging event, depending on the location of Cedar Bayou and Vinson Slough at the time of dredging. Because of this, a larger area that encompasses both Cedar Bayou and Vinson Slough was permitted to allow the dredge template layout to be optimized within the designated area for each subsequent maintenance dredging event. The permitted dredging areas is shown within the red polygon in Figure 5. The actual channel cross-section and mouth orientation were adjusted to minimize dredge volumes and avoid impacts to sensitive habitats for the 2021 maintenance dredging.

Figure 5. Adaptive management approach permitted dredge area.

The migration zone and surrounding areas of Cedar Bayou are constantly changing. To monitor the movement, new topographic and bathymetric survey data was collected from the project site (including placement areas near the mouth of Cedar Bayou and intertidal areas). In addition, aerial remote sensing was used to produce a high-resolution orthomosaic image and Digital Surface Model (DSM) of the survey area. A survey identifying sensitive natural resources in the project area was collected and used to establish the baseline conditions for realignment of the dredge channels, excavation areas, construction corridors, and staging areas. This includes characterization of the community, GPS delineation of the community boundaries, and photo documentation within the survey boundaries. These surveys were used for calculating habitat impacts in order to stay in compliance with a U.S. Army Corps of Engineers (USACE) permit. Historical thalwegs were analyzed to assess the natural flow patterns of Cedar Bayou and Vinson Slough. A thalweg is defined as the deepest part of a channel, typically where most of the flow is conveyed. Historical thalwegs were reviewed to gain insight into the location where the Cedar Bayou and Vinson Slough channels are most stable over time. The location of channel stability is important because the dredge template layout represents the general equilibrium of the Cedar Bayou and Vinson Slough channels. Remotely sensed aerial imagery dating back to 1969 was used to outline the approximate thalwegs throughout the project area, as shown in Figure 6. In the upper section of Vinson Slough, the thalwegs tend to stay in the western part of the channel corridor. The lower section of Vinson Slough tends to stay in the back, northern part of the migration zone until it joins with Cedar Bayou. In upper Cedar Bayou, the thalwegs tend to form on either side of the large shoal that remains in the bayou. In lower Cedar Bayou, the channel typically bends to form a 90° angle with the beach shoreline.

This analysis is used to guide the layout of the proposed dredge template, within the bounds of the USACE permit. Understanding the natural flow patterns of these channels allows us to design a natural, potentially more stable, connection of Cedar Bayou to the Gulf of Mexico.

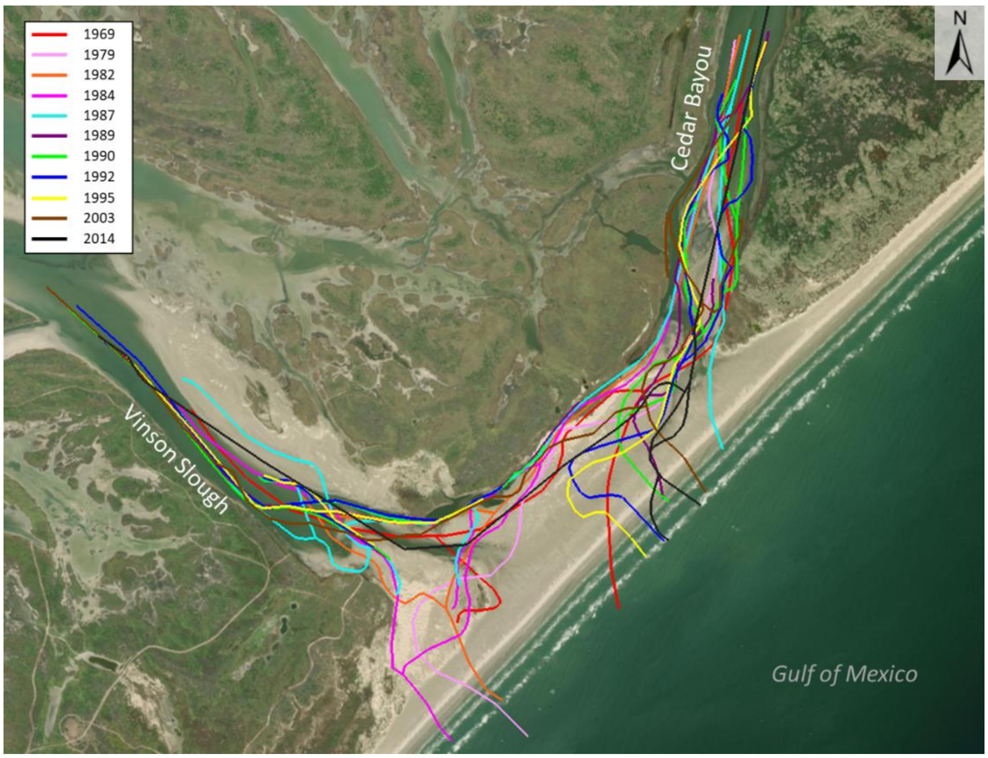


Figure 6. Historical thalwegs utilized in optimizing the 2021 dredge template layout.

2021 Dredging Design Approach

The hydrodynamic and environmental conditions at the project site were used to guide the design of the dredge template. Factors including sensitive habitat area, the historical migration of the Cedar Bayou and Vinson Slough inlet system, and present-day conditions of low channel elevation areas were carefully considered in the design process.

Historical attempts at dredging Cedar Bayou have been conducted with varying levels of success. The historical thalwegs, discussed in the previous section, represent stable channel conditions, and were utilized to predict the anticipated orientation of the channel once it is opened. During the design process, the dredge template was compared to the historical channel centerlines to best represent the natural flow patterns of the inlet system.

During the last reopening of Cedar Bayou in 2014, the channel quickly migrated as it attempted to reach equilibrium. Shortly after the opening, the previous connection of Vinson Slough to Cedar Bayou widened and the outlet turned to become perpendicular to the shoreline. Therefore, the proposed dredge template was designed to reduce the initial migration and allow the channel to reach equilibrium more quickly.

Present-day elevations below the Mean Sea Level (+0.5' NAVD88), recorded at the Port Aransas tide gauge, were mapped at the project site. The elevations below Mean Sea Level represent typical existing flow paths for the inlet systems. The proposed dredge template alignment was developed to maximize the amount of flow through Cedar Bayou and Vinson Slough by widening the lowest elevation areas and increasing the cross-sectional flow areas. Connecting and widening the low elevation areas will not only allow for more water to flow through the channel but will minimize the volume of sediment that will have to be dredged. This data was analyzed to utilize the deeper sections of the channel for the proposed dredge template and widen the present-day flow area.

A sensitive habitat assessment and mapping survey was conducted from August 13 to 18, 2020, by Belaire Environmental, Inc. (BEI) as part of the USACE permit authorization (SWG-2007-00813) and associated U.S. Fish and Wildlife Service Biological Opinion.

Prior to the preconstruction survey, BEI reviewed habitat characteristics that were field-determined during the initial February 2014 preconstruction survey and were utilized during the recent survey. BEI mapped 13 different habitat types within the 951-acre survey area at the project site. During the early stages of the dredge template design, the habitat survey was utilized to minimize impacts to sensitive habitats. The dredge template alignment was optimized to reduce impacts to newly established habitats that were surveyed on September 8, 2020, within the previously authorized dredge template. Sensitive habitats include estuarian wetland, smooth cordgrass, oyster reef, and seagrass. Figure 7 shows the dredge template design with the mapped areas of sensitive habitat.

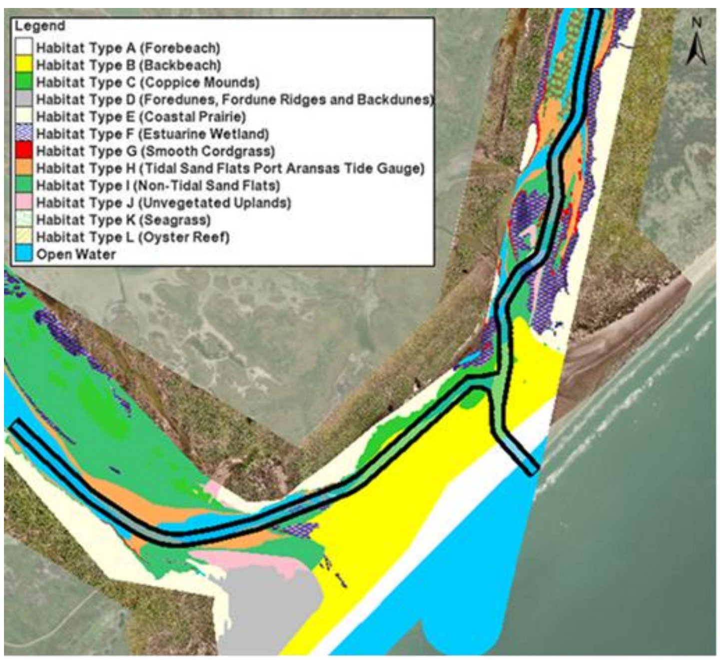


Figure 7. Design dredge template layout overlaid onto 2020 habitat survey.

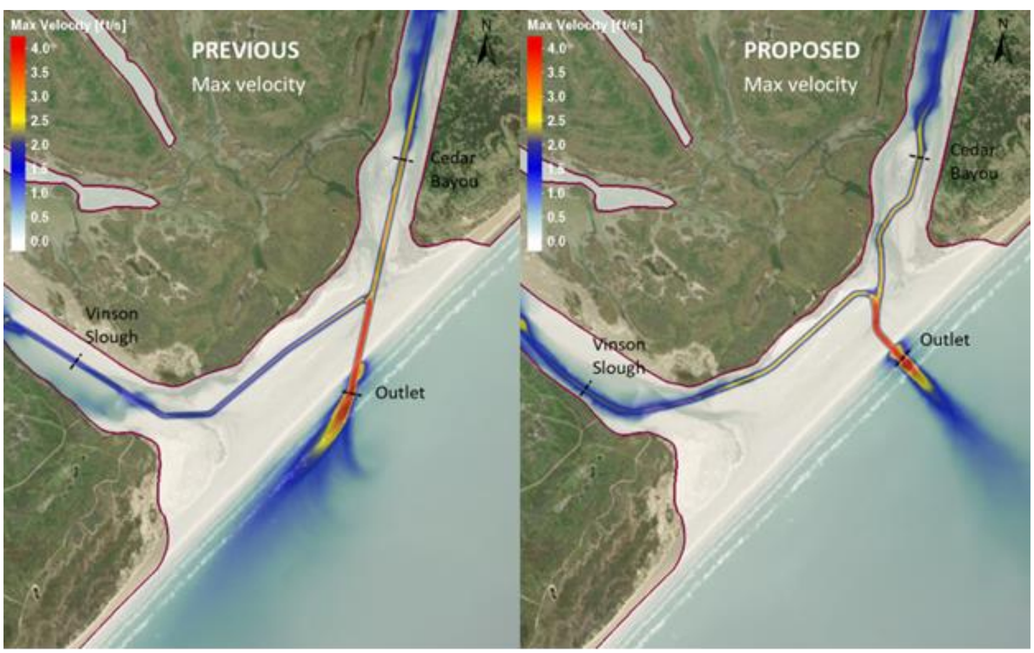
Numerical Modeling

Due to the complexity of Cedar Bayou and Vinson Slough tidal inlet, numerical modeling was utilized to simulate the hydraulics within the Cedar Bayou project site. Numerical modeling was conducted using the hydrodynamic model MORPHO (Kivva et al., 2007) to simulate tidally driven flows.

Numerical modeling of the Mesquite Bay inlet hydrodynamics enabled better understanding the interaction between the bay and the Gulf of Mexico achieved by dredging both the previous (MM, 2012) and new proposed channel layouts. The originally proposed channel (width of 100 feet and depth of 5.62 feet NAVD88) and four other channel cross-section areas having the same depth but varying widths (between 50 feet and 600 feet) were modeled to determine the relationship between channel area and the flow rates. The modeling grid covers a large portion of the Texas coast, with local grid refinement at the project site to fully capture the circulation across the Cedar Bayou project area.

Current velocities and flow rates throughout the Cedar Bayou complex were extracted from the model results to analyze the potential hydraulic improvements provided by the proposed design. The eased connection of Vinson Slough into Cedar Bayou allows for increased circulation through Vinson Slough, yielding higher velocities as observed in Figure 8. Further, similar current velocities, approximately three feet per second, are observed throughout the Cedar Bayou channel. The Cedar Bayou inlet is expected to be more stable due to the perpendicular velocity jet extending into the Gulf of Mexico. Channel flow rates were calculated in the upper portions of the Cedar Bayou and Vinson Slough dredge templates as well as the outlet to the Gulf of Mexico. A 3.5% and 21% increase in flow was observed over the two-month simulation at the Gulf outlet and Vinson Slough locations, respectively. An 8% decrease is observed at the upper Cedar Bayou location, which is likely a result of more flow being diverted into Vinson Slough due to the widened connection.

Additionally, the more natural, curved flow path included in the channel design may also contribute to the slight decrease in flows in upper Cedar Bayou. Results were based on typical tidal flows, to be conservative. During higher-flow cases the channel would likely scour quickly, increasing the potential flow in Cedar Bayou. As observed in the field and through data collection, the channel quickly adjusts to the higher flow environment, which are not captured in this modeling scenario.



(a) (b)

Figure 8. Maximum current velocity for the (a) 2014 and (b) proposed dredge template.

Regulatory Requirements

Mott MacDonald completed consultation with regulatory agencies regarding the permitting of an adaptive management dredging approach for Cedar Bayou and Vinson Slough. The USACE and other regulatory agencies have responded favorably to this approach and have approved the modification of SWG-2007-00813 for a 10-year maintenance dredging program for Cedar Bayou.

On March 4, 2020, Aransas County received an amendment to USACE Permit No. SWG-2007-00813. The permit was originally issued August 8, 2011, and authorized the reopening of the Cedar Bayou and Vinson Slough pass via hydraulic dredging and land-based excavation. Preconstruction activities began in August 2020, with the County's environmental contractor, Belair Environmental Inc., performing preconstruction sand compaction, piping plover, and habitat surveys of the project area in order to comply with requirements outlined within the USACE permit and the associated U.S. Fish and Wildlife Service's (USFWS) Biological Opinion.

During construction, the original permit restrictions apply, including but not limited to surveys of migratory bird nests prior to construction, biological monitors onsite throughout construction, installation of bird abatement measures, and daily nesting sea turtle surveys. Post-construction monitoring includes the following:

- Post-construction and 1-year habitat surveys of Cedar Bayou and Vinson Slough
- Topo/hydrographic surveys of the system collected immediately after construction
- Surveys of access routes immediately after construction is complete
- Compaction and escarpment monitoring immediately after construction until in compliance with regulatory requirements

Summary of Improvements

The proposed dredge template design for the Cedar Bayou and Vinson Slough reopening has been carefully designed from the conclusions of the data collection and modeling analyses. Numerous environmental and hydrodynamic factors guided the proposed dredge layout design. Therefore, it is important to summarize the design improvements included in the new template. Figure 9 shows the proposed dredge template and 2020 aerial imagery, with callouts related to the design improvement summary in this section.

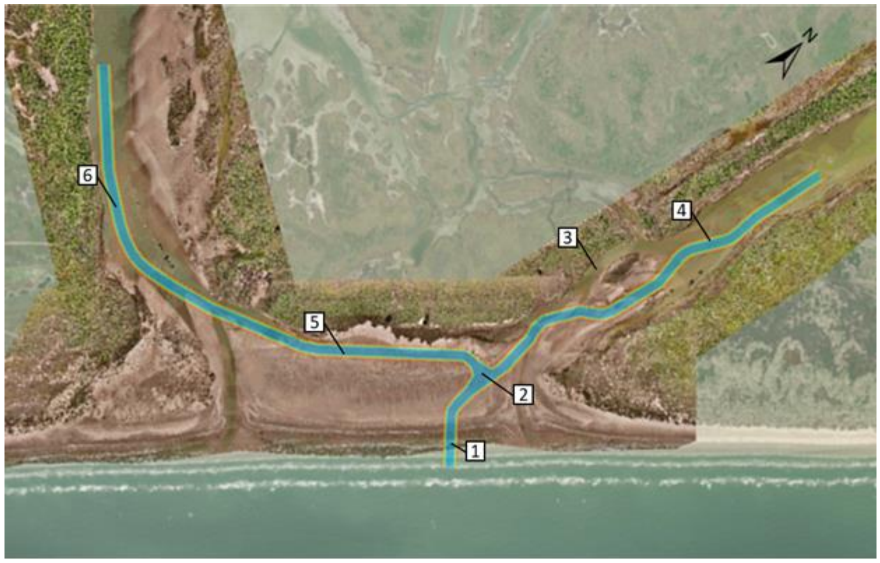


Figure 9. Design dredge template with callouts relating to the design improvement summary.

For the following list, please reference Figure 9. A summary of design improvements from the previous dredge template includes the following:

1. The connection of Cedar Bayou to the Gulf of Mexico is perpendicular to the beach shoreline. This design aligns with the natural flow path to the Gulf of Mexico, as observed in the historical thalweg analysis. Additionally, this design was based on the observed behavior of the channel after the initial previous opening where the channel quickly migrated to reach a perpendicular orientation.
2. A widened and eased connection at the confluence of Vinson Slough and Cedar Bayou allows for increased flow to the upper regions of Vinson Slough. This should improve overall circulation of the project site and yield a more stable connection between the two channels. Additionally, this design was based on the observed behavior of the channel after the initial previous opening where the connection between Vinson Slough and Cedar Bayou quickly widened. Further, it was observed from the model results that the widened connection allowed for better circulation through Vinson Slough.
3. The alignment of the Cedar Bayou dredge channel is designed to connect to an old remnant channel on the west side of Cedar Bayou. Although the numerical modeling efforts did not show flow in this region due to higher elevations in the remnant channel (-1 to 0 feet NAVD88), flow is expected on both sides of the existing sand shoal during higher-water events. Designing the alignment in this way optimizes the flow potential through Cedar Bayou while minimizing the dredge volume. The estimated dredge volume for the proposed template is approximately 430,000 cubic yards as opposed to the previous template that was 550,000 cubic yards.
4. The alignment of the Cedar Bayou dredge channel is designed to have more natural flow pattern compared to the previous design template. The purpose of incorporating the natural flow patterns into proposed dredge template was to reduce the initial migration and allow the channel to reach equilibrium more quickly after opening. The historical thalwegs show the natural flow path that represents the most stable alignment of Cedar Bayou. Additionally, sensitive habitats have populated this region. Therefore, impacts to these habitats must be minimized.
5. The lower portion of the Vinson Slough alignment is designed to extend through the northern part of the migration zone. The edges of the template connect to lower elevations in this region.
6. In upper Vinson Slough, the dredge template alignment extends through the western part of the corridor. This design aligns with the historical flow paths. Additionally, the elevations tend to be

lower on the western side of upper Vinson Slough, yielding less dredge material and larger flow areas.

CONSTRUCTION

Preconstruction activities began March 2021 with a preconstruction bottom elevation and habitat survey of the access route from Mesquite Bay to Cedar Bayou, the preconstruction dredge area survey, and a hazard survey of the proposed dredge template.

The USACE permit authorization required monitoring of endangered species and abiding by strict environmental regulations throughout construction. A biological monitor began on-site environmental monitoring activities in March 2021. They installed and maintained bird abatement measures and began the required daily migratory bird and turtle patrols. Due to the sensitive nature of the surrounding marshland, silt curtains were maintained around the dredge throughout the duration of Cedar Bayou dredging when in close proximity to sensitive habitat. A diffuser was maintained on the end of the pipe discharge for the duration of dredging activities.

Construction commenced on May 15, 2021, when the contractor arrived on-site with the first of two hydraulic cutter suction dredges. The crew installed stakes to mark the dredge cut centerline, design toe, top of slope, and the project limit boundary and access/staging areas. The contractor began dredging Cedar Bayou within the designed dredge template, working toward the Gulf of Mexico with two 0.3-meter (12-inch) cutter head dredges and transporting material to the designated beach placement area via approximately 4,800 meters of pipeline, as shown in Figure 10.

Figure 10. Cutter suction dredged deepening the Cedar Bayou Dredge Template.

Starting construction during the 2021 hurricane season led to unusual challenges during dredging, especially since the project site is approximately one hour by crew boat from the marina utilized by the contractor in Rockport, TX. On September 12, 2021, Hurricane Nicholas passed just offshore of Cedar Bayou. The storm surge caused the plug of material left between the dredge template and the open ocean to breach, which resulted in Cedar Bayou prematurely connecting to the Gulf of Mexico. The channel appeared to be stable after the initial opening, much different than previous openings of Cedar Bayou (2014) which resulted in a migration of the cut of about 200 feet in a matter of hours. With the mouth of the dredge template open, conditions in Cedar Bayou were very dynamic, and hydrographic surveys were collected almost daily to quantify material removed from the template.

The contractor was able to boost production through mechanical excavation, digging ahead of the hydraulic dredges within Cedar Bayou and transporting the material to the beach placement area via off-road trucks as shown in Figure 11.

Figure 11. Mechanical dredging efforts at Cedar Bayou.

Once a majority of the Cedar Bayou template was excavated and dredged to grade, the contractor focused the hydraulic dredging efforts within Vinson Slough. Simultaneously, the contractor moved the excavators to the southern end of the Cedar Bayou template to finish digging the template to designed elevations. Due to the complex nature of the project template, sequencing such as this was common throughout the construction.

As the environmental permitting window closed and whooping crane migratory season approached, the contractor demobilized from the project on December 1, 2021, before completing the proposed dredge design. The contractor completed dredging of approximately 65% of the template material, ending near the southwest side of the Vinson Slough migration zone. The contractor will remobilize to the site on May 1, 2022, to finish the remaining portion of the template through upper Vinson Slough.

Once the remaining portion of the Vinson Slough template is dredged, a complete hydraulic connection will be established throughout Vinson Slough and Cedar Bayou, improving the exchange from the Gulf of Mexico to Mesquite Bay. Figure 12 shows an aerial of the post-construction conditions at Cedar Bayou and Vinson Slough as of November 2021. Although the full template volume was not completed, the adaptive management approach to maintenance dredging Cedar Bayou allowed the project to function despite the full volume not being dredged. This would not have been possible in 2014, as this approach allowed the optimization of the template layout to target existing flow pathways and the flexibility to maintain the channel as long as regulatory requirements are met, an innovative approach to a project site that is remote and extremely dynamic.

Figure 12. Post-2021 construction aerial of Cedar Bayou and Vinson Slough.

CONCLUSIONS

A comprehensive coastal analysis was performed on the Cedar Bayou inlet, located along the Texas Gulf Coast, to gain an understanding of the complex project site dynamics. In 2017, the ephemeral inlet was closed after Hurricane Harvey passed near the project site, resulting in severe sediment buildup at the tidal inlet. Plans to reopen the inlet were initiated by Aransas County to improve the ecological and environmental factors of the system.

Previous modeling efforts and analyses were used to design a template alignment for dredging operations. The design template was optimized based on hydrodynamic and morphological conditions of the site while minimizing the amount of material needed for dredging. When the optimized design template was incorporated into the circulation model, it showed improvements in flow exchange compared to the 2014 design. Extensive permitting and planning requirements were completed to ensure compliant construction operations and to allow for continued maintenance.

Due to unforeseen setbacks, only 65% of the dredged template was completed before demobilizing for the whooping crane migratory season. During the summer of 2022, the remaining volume will be excavated from the dredge template, and the stability of the Cedar Bayou inlet will be improved further.

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DATA AVAILABILITY

Some data and models used during this study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

CITATION

Salazar, D., Everett, T., Dunn, M., Maristany, L.M., Horine, A. "Dredging to Restore the Cedar Bayou and Vinson Slough Inlet," *Proceedings of the Western Dredging Association Dredging Summit & Expo '22, Houston, TX, USA*, July 25-28, 2022.

NEXT GENERATION MARINE AGGREGATE DREDGER AS PLATFORM FOR INNOVATIVON AND BASIS FOR FLEET RENEWAL

O. Marcus[11], D. Dijxhoorn[1], F. de Hoogh[2] and F. Bosman[2]

ABSTRACT

A strong demand for building materials combined with an aging fleet of marine aggregate dredgers create an urgency to invest in new equipment. The move of resources further offshore and the environment taking an increasingly prominent role in the operation drive the need for innovation.

This paper is focused on the niche market of marine aggregate dredging in the UK and Western Europe. Although a vital part of the supply chain, the marine division of large construction material suppliers comprises a relatively small part of the business. Operating a rapidly aging fleet the ever-increasing demands on production, efficiency, safety as well as reduction of the environmental footprint call for the development of next generation aggregate dredgers.

Being large single asset investments with an operational lifetime of up to 30 years, the challenge to deliver a 21st century vessel with integrated equipment is a natural consequence. To meet this challenge a joint effort from operator, equipment specialists and shipbuilder is needed. The combination of years of operational experience and the latest insights in vessel design and equipment technology are the basis of a dredger designed specific to its operation. Efficiency and production capacity increase whilst maintainability and operator safety improve.

The result of an extensive design and development project results in a new type of aggregate dredger outfitted with the latest in aggregate dredging equipment. Most notably a revised trailing suction pipe system and dredge pump drive, new type of screening concept and production meter without a radioactive source.
The first of series vessel is named “Cemex Go Innovation” will start operations in 2020. Both operator and builder are committed to continue development and this vessel is an ideal platform to validate designs and foster further innovation.

Key words: offshore dredging, aggregates, innovation, collaboration

INTRODUCTION

The market for construction materials in Western Europe depends on the supply of base materials, either from land or marine resources. Marine aggregates have been a part of the supply mix for many years with future outlook to increase in both relative share as well as absolute volume. Marine aggregates are dredged from offshore licenses by a fleet of dedicated marine aggregate dredgers. Consisting of some 70 vessels with an average age of 30+ years, fleet renewal is needed to ensure a steady supply of material. A complete public list is not available, and figures are based on market research by Damen Shipyards into the marine aggregate fleet.

The aging equipment faces increasing cost of maintenance and challenges to meet required vessel uptime. In addition, the current demands on aggregate dredgers with regards to: technical ability,

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production capacity, efficiency and environmental standards no longer match technology and designs from the 1980's and 1990's.
To secure this vital part of the supply chain there is a demand for modern aggregate dredgers of increased capacity that are fitted with equipment that offers improved reliability and efficiency as well as reduced operational and maintenance cost.

Representing large single asset investments for the respective owners, aggregate dredgers are also required to meet corporate values on topics such as: sustainability, safety, and environmental impact.
To meet this challenge and given the long cyclic nature of vessel construction for the specific niche market an approach is needed that goes beyond mainstream common shipbuilding practice. Ship building and technology expertise are combined with extensive operational experience to form the basis of a joint development for the next generation aggregate dredgers.

WHY MARINE AGGREGATE DREDGING

As a resource that is recovered from the earth, aggregates are the most mined material in the mining industry. Aggregates are normally defined as being hard, granular materials which are suitable for use either on their own or with the addition of cement, lime or a bituminous binder in today's construction industry. Aggregates are typically classified according to grain size starting from coarse sand, illustration in Figure 1.

Figure 1. Example classification of aggregates

As commonly used construction minerals, aggregates are a relatively low-cost product and therefore used in very large quantities. Important applications include concrete, mortar, road stone, asphalt, railway ballast, drainage courses and bulk fill. They are essential to construct and maintain the buildings and infrastructure found in modern society. Demand for aggregates therefore is mainly driven by activity in the construction industry and the economy in general.

The primary source of aggregates are natural deposits that require minimal processing (classification) before use. In addition, secondary sources (by-products from industrial processes) and recycled aggregates are used.
Despite a substantial increase in the use of recycled aggregates, it is likely that the major proportion of future aggregate demand will be supplied from primary sources because there are limitations on the availability of material to be recycled into aggregates and technical limitations in their use. [Newell and Woodcock 2013]

Onshore aggregate resources are becoming increasingly constrained with environmental and social restrictions. [UNEP Global Environment Alert Service 2014, United Nations Environment Programme 2019] Where marine aggregates currently account for around 20% of the sand and gravel demand for England and Wales, forecasting models predict an upward trend. [British Geological Survey 2019]

Contrary to onshore deposits, marine aggregates are not located near urban areas or protected nature reserves and hence recovery does not face the same restrictions. As land-based sites often have a relatively short lifespan new areas need to be explored and developed continuously.
The combination of increasing pressure on land-based operations and a favorable economic outlook push the shift to offshore extraction, and through that the need for 21st century marine aggregate dredging solutions

Aggregate dredging is mainly focused on the larger grain sizes as these are most valuable as base material for the client downstream operation. The large particle size as well as the location of these natural deposits make for a very specific operation. This has implications for the dredger which needs to be able to work in open sea with as little weather delay as possible, contrary to "regular" hopper dredgers which are in general optimized for working close to shore in sheltered conditions.

The operation requires the aggregates to meet a client specific material specification (mainly grain size distribution and max water content) and needs to be dry on discharge. To classify the material and only load the desired fractions the dredger needs to be equipped with a screening installation. The cargo hold is fitted with a dewatering system to enable drainage of the cargo before it is offloaded by the on-board grab discharger and conveyor system. In regular dredging practice cargo remains fluid and is either discharged through bottom doors or pumped ashore, omitting the complex deck equipment installed on an aggregate dredger.

OPERATIONAL CHARACTERSTICS OF MARINE AGGREGATE DREDGING

Natural sand and gravel deposits can be found offshore at different geographical locations and conditions. However most aggregate dredging is done in coastal waters less than 25 km offshore and in water depths ranging from 15 m to 55 m. As resources are being depleted new areas have to be developed and result in a trend to move further offshore and to deeper waters. For the project and this paper, the focus was on the inner continental shelf off the UK coast. An indication of the area is given in Figure 2.

Given the location of aggregate deposits dredging is done in open sea and to ensure a steady flow of material to shore the operation is 24/7 year-round with minimal stoppage. This requirement places a strong demand on the capability of crew and vessel to being able to work in areas such as the English Channel or the North Sea in any type of weather. Apart from the weather conditions one has to consider other users of a relatively busy area. For example: gas pipelines or cable routes, offshore wind farms, fishery or shipping lanes. [Pascual and Jones 2018]

Marine aggregates being a natural resource the areas and conditions under which extraction is allowed are regulated by governmental bodies. For the UK this is the Crown Estate who issue dredging licenses for designated areas and control and monitor the extraction of material.

Modern sand and gravel dredgers have payload capacities ranging from 1 200 to 8 500 tons and deliver their cargo to different wharves located along the coast or further inland. Many locations are in areas that experience strong tidal differences which results in typical working cycles for a vessel taking 12, to as long as 36 hours per roundtrip.

The common means of extraction is by trailing suction dredging. A draghead connected to a suction pipe is pulled across the seabed at slow speed and a mixture of aggregates and water is pumped to the vessel. The passage of the draghead across the seabed leaves a groove about 2.5 m wide and 0.25 m deep and allows relatively thin deposits to be worked. To maximize effective payload deliveries to the wharfs, initial classification is done through a screening installation on board the dredger which discards unwanted fractions overboard. Further classification and processing of the material takes place after dry discharge at the wharf. As the wharves are typically located near the area of use, a major advantage is that high quality sand and gravel can be landed directly into areas of high demand. [British Geological Survey 2019]

INNOVATIVE SOLUTIONS AND DEVELOPMENT DRIVES

To meet 21st century demands for aggregate dredgers both the vessel and equipment have to be designed from an operator perspective. Lessons learned from many years of operating and maintaining aggregate dredgers had to be incorporated and provisions for potential future upgrades foreseen.

The goal is to set a new benchmark in the industry and hence the list of requirements is long. From an overall perspective the new aggregate dredger has to fit the business values of the supply chain of which it is a critical part. Safety, reliability, sustainability, and a reduced environmental footprint were to be

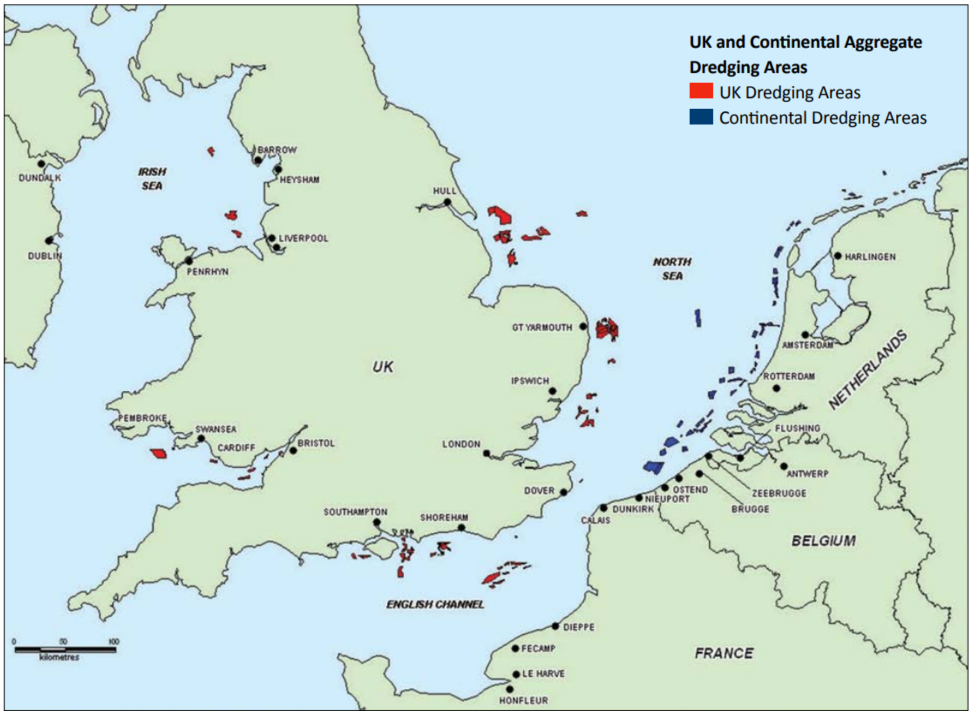

Figure 2. Marine aggregate dredging areas

at the heart of the design. From a business point of view there was an emphasis on operational cost (OPEX) vs initial investment (CAPEX).

The following main topics, focussing on the dredging equipment are described in this paper:

- Dredge pipe system solution without seawater through the vessel
- New design screening system
- Density meter without radioactive source

Dredge pipe system – eliminate the risk of flooding

Traditionally the dredge pump of a hopper dredger is installed in a dedicated pump room inside the vessel. As a result, the dredge piping that transports the dredged material from the draghead to the hopper will always pass through the inside of the vessel.

This layout has been used successfully in hopper dredgers for decades, however it does have some drawbacks. Dredge piping is subject to wear and requires regular monitoring of thickness and timely replacement of parts to prevent leakage.

Especially in aggregate dredging the dredged material can be highly abrasive which increases wear rates and through that the potential of material failure. With pump capacities in excess of 10.000 m3/h the effect of a leaking dredge pipe is a serious safety hazard with significant impact on the seaworthiness of the vessel. In addition to the inherent safety risks, the routing of heavy pipe sections through a vessel is not optimal in terms of maintenance and repair. Parts tend to be difficult to reach which makes replacement and handling a time-consuming task with potential for personnel injury.

To eliminate the risk of flooding and to improve maintainability of the system a solution is developed where all dredge piping is installed outside the vessel, as indicated in Figure 3. Mostly based on existing

Figure 3. Render of MAD3500 with dredge piping installed above deck

components and technology, the trailing suction pipe system cost and technical risks are limited. Where maintenance of the dredge piping system was previously a serious undertaking, it can now be performed by the crew with use of the on-board service crane, significantly lowering maintenance cost and increasing uptime.

Design

In search of a solution a balance has to be found between technical feasibility and risk, maintainability, operator interface and cost. With regard to technical feasibility the trailing suction pipe system is mostly based on known principles and technology. The trailing suction tube connects to the vessel through a conventional slide flange which runs in vertical guide tracks, thus providing a low pulling point and moment arm.

Due to a required dredging depth of -55m and vacuum limitations of a centrifugal pump it was no longer possible to install the dredge pump in an onboard pump room. The dredge pump is installed in the suction tube and to reduce space and weight it is integrated with its load bearing construction. As part of the push for improved efficiency the dredge pump drive is designed to be an electric motor of the permanent magnet type. Where conventional oil filled electric motors have an efficiency range between 70-80%, the permanent magnet, air filled electric motor achieved an efficiency of 97% during factory testing. With an absorbed power of approx. 1200 kW this will result in significant lower power demand whilst dredging and corresponding reduced fuel consumption. (Figure 4)

Although successfully used in applications such as: offshore wind, ship propulsion and smaller dredgers it is a first to install this type of motor as part of a trailing suction pipe. In addition to better efficiency the PM type motor has the added benefit of being more compact and lighter in weight which in turn has a positive effect on sizing of the gantries and hoisting gear. As a result, it is possible to design and build an installation that enables significant reduction in OPEX without increasing CAPEX of the newbuild vessel.

To transport mixture from the trailing suction pipe to the fixed dredge piping on deck a flexible solution was needed to compensate horizontal and vertical offsets between the pipe sections. To be flexible to accommodate working and store positions as well as being durable in operation proved a challenging

Figure 4. Dredge pump unit with integrated PM drive motor

combination. Several design iterations were made and after review of several possible concepts with operator, equipment specialist and ship design an acceptable solution was found. The final setup consists of a hinged section of dredge pipe behind the accommodation and a flexible mixture hose fitted with wear resistant liners, as indicated in the sketches of Figure 5.

The setup with flexible mixture hose allows the use of a trunnion gantry at the slide flange and intermediate, - and draghead gantries to support the dredge pipe. Movement of the suction pipe is provided through dedicated winches that are normally installed outside on the vessel main deck. Apart from intensive maintenance required from being installed in such an exposed area, the steel hoisting wires run above the working deck creating a safety hazard. To mitigate these negatives the design accommodates space for the suction pipe winches below deck, moving the equipment from the main deck into a sheltered area, as shown in Figure 6.

From operational experience and maintenance records from the operator it became clear that maintenance to the dredge system is a major factor in vessel downtime and operational cost. Secondly the design of the equipment and layout of the vessel make for working decks full of large and heavy equipment. To keep the vessel in proper working condition it has to regularly travel to dry dock where facilities and equipment are available to make repairs.

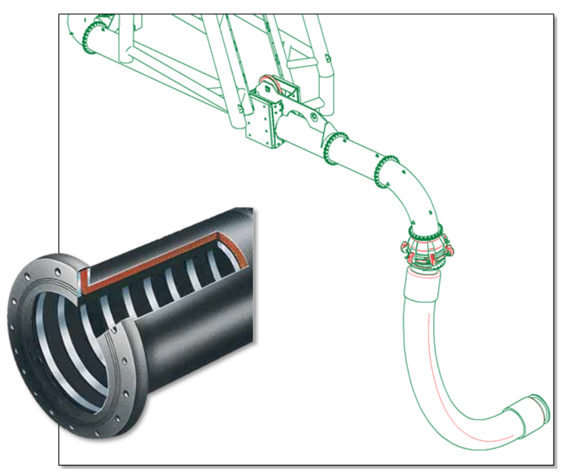

Figure 5. Details on flexible hose connection

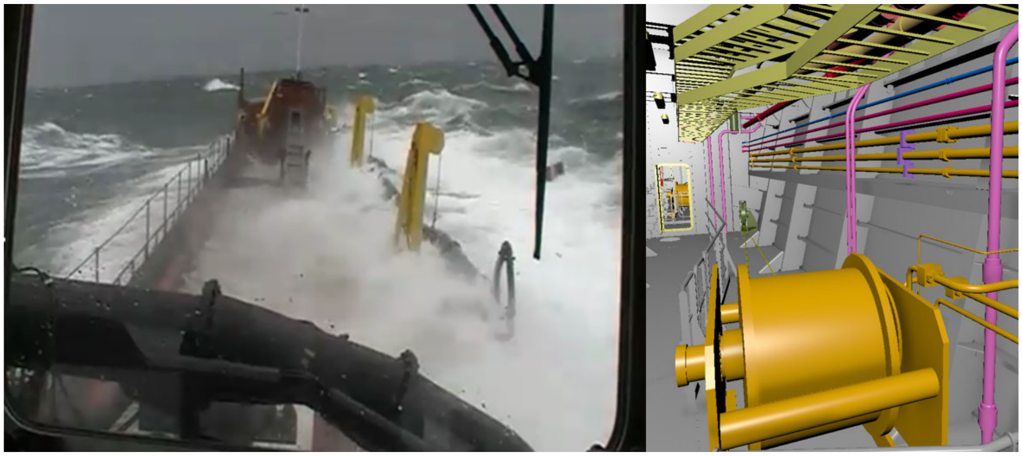

Figure 6. Example of working condition at sea and 3D model of current winches below working deck

To reduce downtime and dependency on a dry dock a philosophy of "replace instead of repair" was adopted. Instead of making repairs on the vessel the design had to accommodate easy exchange of parts and include onboard provisions to be independent from onshore facilities. Parts that are exchanged will then be sent to a workshop for refurbishment before returning to the spare parts pool.

For the vessel this meant that sufficient crane capacity and reach had to be installed for lifting all wear parts of the dredge system. Due to the weight of the parts in combination with layout of the deck a flexible solution was needed. By mounting a large service crane on top of the dry unloader machine it was possible to install sufficient capacity and cover the deck area by travelling along the hopper coaming.

By changing the approach in maintenance, the operator predicts a significant decrease in annual maintenance and repair costs. The target is to achieve a yearly reduction of 50% in total cost for maintenance and repair. In addition, the modular design of equipment and dedicated spare parts strategy will limit the overall downtime. Given the high demand for aggregates and 24/7 character of the operation this creates a potential for additional revenues. Additional effort was made in design of the equipment and although parts of the installation and the larger crane increased initial cost, this higher CAPEX was deemed acceptable versus the potential savings on OPEX over the lifetime of the vessel.

New design screening system

Marine aggregates comprise sand or gravel found in various grain sizes. To be able to deliver the desired composition of cargo to a specific wharf, aggregate dredgers are fitted with screening installations. Cargo is loaded into the hopper whilst unwanted dredged material is discharged over the side, as shown in Figure 7.

Aggregate dredgers are able to autonomously dredge, load, dewater and dry discharge their cargoes. This provides lot of flexibility to the operation, however, creates very specific challenges to the dredger itself. The different systems are installed on deck where they have to compete for limited available space whilst also taking into account an even longitudinal and transverse weight distribution.

Several types of screening installations are in use on different vessels. In the UK fleet the system of choice has been the installation of 2 rotatable loading towers next to the hopper. Material is pumped through the center of the tower, over a screen and then loaded into the hopper via loading chutes.

Figure 7. Existing aggregate dredger screening and cargo loading

Although the standard solution for many years a setup with loading towers has several limitations. Being a vital part of the operation and business potential of the asset, substantial effort had to be spent in designing a next generation system.

At the beginning of the project the following main targets were agreed on between operator and designer:

1. Increase screening capacity to improve cargo quality;
2. Improve component lifetime;
3. Reduce maintenance time, design the installation for " replace instead of repair";
4. Reduce number of spare parts;
5. Eliminate all discharge over the side of the vessel;
6. Fit a relatively narrow deck area due to vessel beam restriction at 16.4m;
7. Design to be compatible with different type of screen decks;

Design

The fleet of aggregate dredgers is relatively small, and the last series of vessels was designed and built in the 1990's. Being so cyclical in nature a lot of knowledge has disappeared over time and currently no manufacturers exist that produce off-the shelf screening systems for aggregate dredgers.

Although little design data existed, fortunately a lot of operational information in the form of loading logs, pictures and videos were available. Together with records from ship and equipment repair, a baseline situation could be established. It was decided, between the operator, ship repair yard and ship design, to combine all available information & knowledge and agree on a pragmatic approach to design a new generation screening installation. The first of series system will be installed on the MAD and used for further verification of the concept and as a testbed for possible further innovation.
The first design spiral evolved around the principle of 2 loading towers of improved design, as shown in Figure 8. The dredge pipe was routed outside the tower to simplify the construction and improve maintainability. In addition, the screen deck increased in surface by some 40%. Finally, the loading chute was arranged and designed in a way to enable all reject material to be discharged below the vessel instead of over the side.

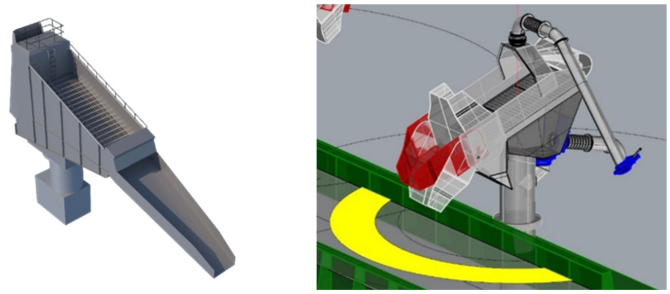

Figure 8. First iteration of screening installation

During review of the concept in iteration 1 it was found that this would be a viable concept and acceptable in terms of functional performance. However, maintainability being a large part of operational efficiency and cost justified an extra design spiral.

The focus on maintenance resulted in a quite radical change of concept as the system changed from rotatable towers to a fixed installation, as shown in Figure 9. Also, the screen deck surface increased to approx. 200% compared to existing loading towers, due to elimination of the space restriction which the two separate towers have. Limited screening area is the main operational limitation of the current screening towers, resulting in less-than-optimal screening efficiency and extended loading time to reach the required cargo quality.

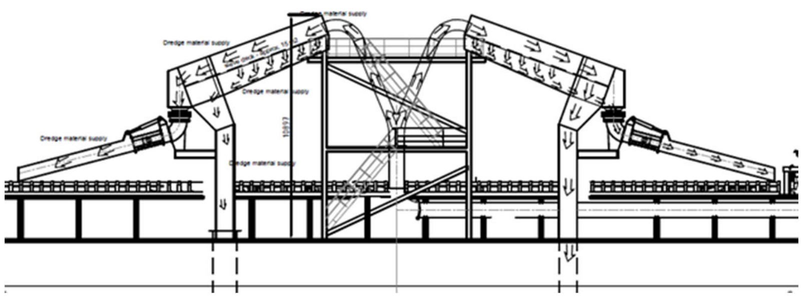

Figure 9. Second iteration of screening installation

Changing to a fixed installation also gave the opportunity to incorporate a philosophy of modular design. The components were designed as blocks that can easily be installed or removed independent from each other. To reduce the number of spare parts the forward and aft sections are mirror images.

Final step before construction was production engineering. The complete screening installation was modelled in 3D CAD software and optimized for strength vs weight. Given the dynamic environment of being installed on a seagoing vessel attention had to be paid to reaction forces and material fatigue over time.

The demand for cargo quality and limitations of conventional screening towers makes this part of the installation critical for the operation and one of the focal points for a new design. The increased screening capacity and fixed installation modular design result in a significantly larger and heavier installation compared to the conventional solution. Efforts were made to reduce the impact on weight and cost as much as possible but final cost of the installation remained in the range of 60-80% higher than a screening tower. The positive effect on OPEX of better cargo quality and improved maintainability still offset the increased CAPEX in the business case of the owner and were therefore incorporated in the newbuild vessel.

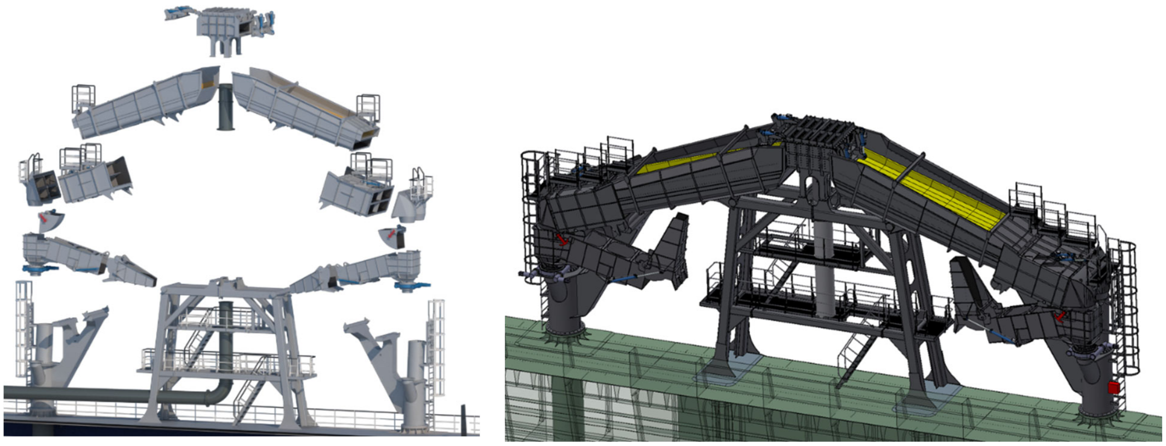

Figure 10. Final iteration of screening installation.

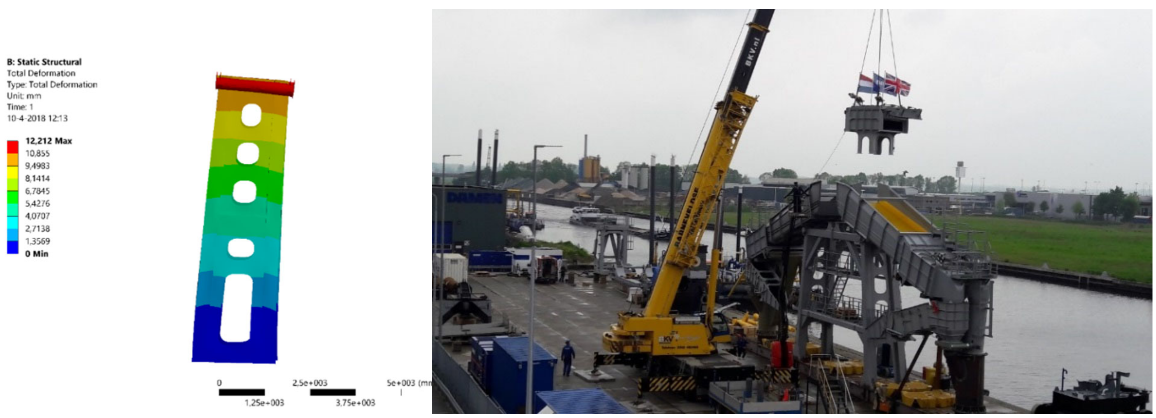

Figure 11. FEM result of central support and pre-assembly at construction yard DDE Nijkerk.

Introduction new and combined non-radioactive density and flow meter

The monitoring of production in dredging, as well as in aggregate dredging, is of significance in the performance of the annual production and supply of material at the wharfs. For several decades, radioactive density meters have been the principle method of measuring density, however utilizing a radioactive source can potentially implicate operational, safety and cost issues [McCormack, Primrose et al. 2016]. In anticipation of the above issues, regulatory issues and social opinion, alternative non-radioactive measuring principles have to be developed and adopted on board. This alternative principle suits the 21st century demands and needs for the aggregate dredger.

Equipment and instrumentation manufacturers Krohne and Industrial Tomography Systems (ITS) successfully combined their products and knowledge to develop and test the integration of the electromagnetic flow and Electrical Resistance Tomography (ERT) density instruments. ERT is a measurement method that utilizes the electrical properties of flowing material for understanding, measuring and controlling processes [Wang 2015].

After testing the separate sensors together in one system on full-scale in different conditions together with Damen Shipyards, the products were combined in one integrated sensor. A full-scale trail was performed to validate the laboratory tests done previously. The launching product (first of series) was tested on board of a Trailing Suction Hopper Dredger vessel specialized for aggregates from CEMEX Marine UK, the Sand Falcon. After the successful trails the integrated sensor will installed in the dredging system of the currently under construction MAD 3500. Figure 12 shows the installation as it was executed on board the vessel. The integrated sensor is placed in a horizontal dredge pipe section in line with the on board conventional radioactive density meter.

Figure 12. Installation of Integrated Sensor o/b TSHD Sand Falcon

The trial on Sand Falcon was conducted in March-April 2019 and 10 loading cycles of dredging data was collected. The trails took place in a gravel deposit area were an average D_{50} range of 0,3 to 50mm passed the sensor. As shown in Figure 13, the data of the two different sensor set ups showed equivalence. The average difference between gamma and tomography data sets was 2.08%, with an average correlation coefficient of 0.95. With the above data it was confirmed that the integrated sensor meets the industrial acceptance standards, qualitatively and quantitatively. [Wei, Qiu et al. 2019]

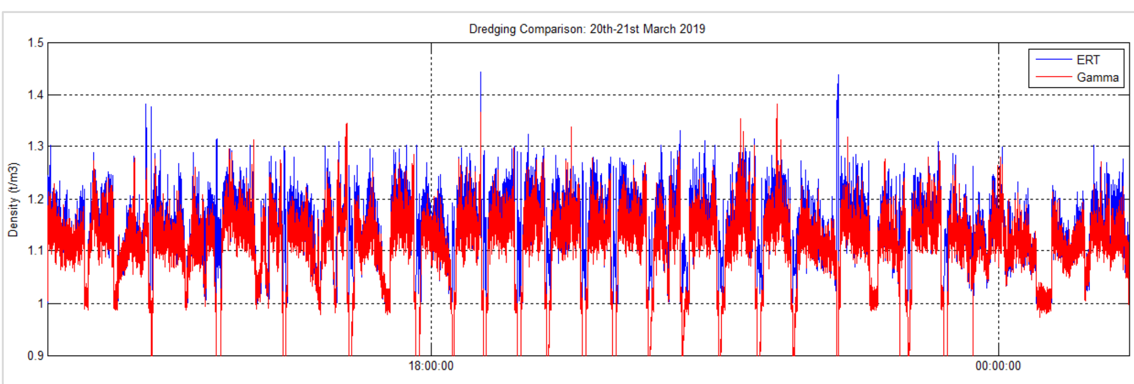

Figure 13. Comparison between individual gamma sensor vs. integrated sensor system

During the trails three additional benefits of the new integrated sensor in combination with the horizontal orientation were noticed on board. At first the benefit is the quick response time at the dredge master control station in contrast to the existing system onboard during the test.

Secondly a blockage at the entry of the trailing pipe system could be detected instantly, due to the horizontal orientation and the visualization of the tomogram in the user interface. With the blockage the flow will reduce, and gravel will settle at the bottom of the pipe, this will become visible in the profile view within the interface. The dredge master can lift the draghead, lower the pump power to remove the rocks and continue the dredge process.

At last large cobbles (too many heavy rocks in the pipe) can potentially be identified via the captured tomogram in the display, as shown in Figure 14. This is not possible with the conventional radio-active system. During the dredging operation the captured tomogram in the user interface allows the operator to determine solids distribution. Figure 15 shows an example of three density tomogram distributions. Having this real time solid distribution information, enables the dredge operator to maintain at an optimum dredging process with potential for faster and more cost-efficient operation.

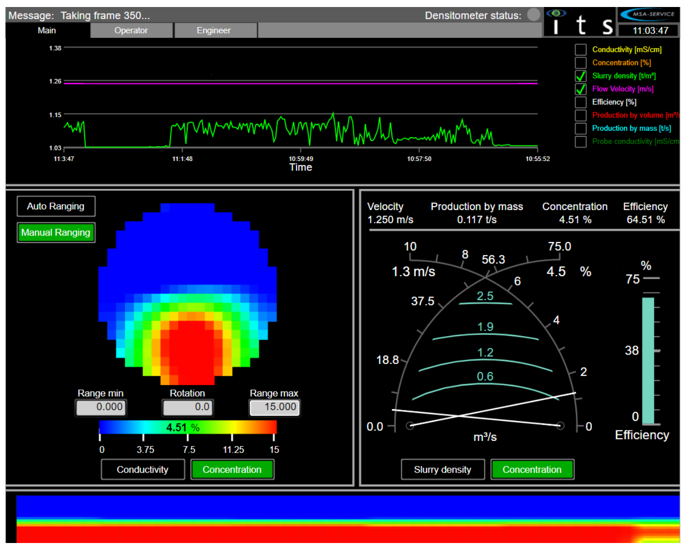

Figure 14. User interface of integrated sensor, with on the left the solid distribution profile

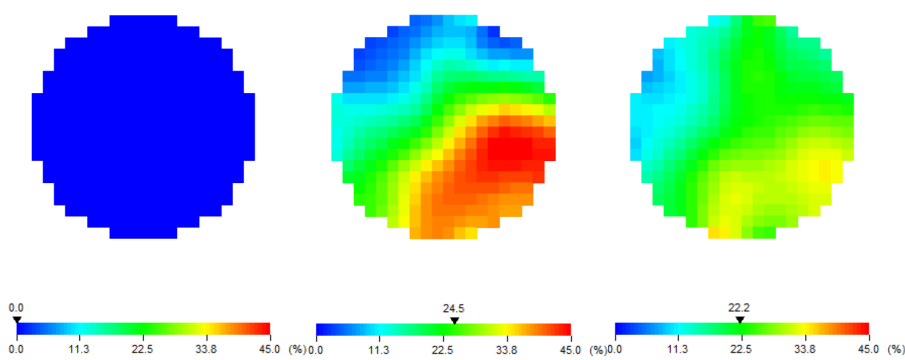

Figure 15. The measured ERT tomograms with different flow regimes and solids concentrations, where the red pixels represent solids concentrations within the pipe. Left tomogram shows a homogeneous water flow, Middle tomogram shows a moving bed flow and right tomogram shows a heterogeneous flow

CONCLUSION

This paper has addressed the necessity of the development project due to increasing constraints (environmental and social) on the use of land-based resources of aggregates, which results in an increased demand for marine aggregates. Based on the current inefficiency and the increasing importance of environmental and social factors also in the marine environments, the fleet of aggregate vessels is quickly becoming outdated. It highlights some background, the design process of the project and the outcomes of the next generation marine aggregate dredger, with a focus on the dredging technology.

To meet the demand for aggregates and ensure a reliable and sustainable base of the supply chain, specialized equipment needs to be developed or re-developed to be future proof. With a focus on safety, reliability, sustainability and a reduced environment footprint. From as business point of view always keep a strong focus on the OPEX vs CAPEX to be durable for the complete lifecycle of the vessel.

Develop new concepts for the dredge system, re-develop the concept of the screening installation and testing and integrating the latest industry standards, like the combined non-radioactive density and flow sensor. This all will contribute to the goal to set a new benchmark in the industry of marine aggregates.

The joint design and construction of a first of series provides a strong platform to develop new solutions for dredging and to validate preliminary predictions in real operational conditions. Also resulting in insights and development of equipment, which potentially could change the course of the marine aggregate industry.

ACKNOWLEDGEMENTS

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MONITORING DREDGING FOR SAFETY & IMPACTS ON ECOSYSTEM

A. North[1]

ABSTRACT

Safety on dredging vessels during operations comprises an overall approach towards ensuring the safety and health of personnel, the safety of vessels, impacts on the ecosystem and ensuring the quality of environment is in conformance with regulatory standards. In the past, project developments emphasized on design functionality and investment costs, resulting in engineering solutions that were focused more on hydrology and less on ecology. As more knowledge has been gathered through environmental impact assessments carried out, the need for an efficient method of dredging has never been greater for the pursuit of long-lasting and sustainable developments.

The core point of dredge monitoring in real time is to increase overall productivity and safety of personnel and equipment. Even when the equipment is working at optimal performance, challenges remain with on-site issues such as slope failure, production losses, over-dredging or re-dredging, undetected occurrence of slipped back material; factors which contribute to high operating costs and unnecessary personnel time. Over-dredging can still cause unnecessary disturbances in organic layers of the seabed, releasing toxic gases which can be exposed to the personnel.

Sonar technology (using sound waves) have been used in turbid waters with zero visibility, to provide water depth data and high-quality images of lakebed/riverbed. When integrated with accurate positioning systems, a digital terrain model (DTM) can be created, and a 3D visualization of the operating surface is displayed in near real time. Sonar technology has been used successfully for many years in the offshore oil and gas industries. The 3D visualization enables rapid identification of over-dredging or landslides occurring as a result of steep slope angles.

Mitigating impacts of turbidity in the dredging process requires managing the amount of suspended solids released at the dredging sites or entering sensitive areas. Sonar technology can also be used to detect sediment in real time by sending improved characterization Frequency Modulation (FM) pulses through the water column with a much longer range than is possible with optical type sensors. As in many operations, the acquisition, analysis and verification of data is a crucial function in the dredging operation. Data obtained needs to be manageable, easily understood and as near to real-time as possible in order to be cost effective. Innovative software can provide the dredging operator with not just a visualization and sediment detection of the dredging process, but also turbidity measurements, real estate boundaries, slope angles, tolerance ranges, morphology of the riverbed/lakebed, target and actual slopes, remaining material thicknesses at the current dredging position, dredging boundaries, enhancement of different dredging areas by colour coding, estimation of dredged quantities for output assessment., determination of the productive dredging times, layout plan of the dredging paths and ability to export the data into CAD or GIS programs.

Keywords: safety, near real-time monitoring of dredging, sonar technology.

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INTRODUCTION

Dredging operations can be both extensive and costly. Whether it is dredging for navigation to provide adequate access to ports and harbours, or dredging for construction for reclamation and mining, or dredging to remove contaminated materials or beach replenishment, the process has to be well planned for not only efficient dredging but also for safety of personnel involved. The assessment of the hazards and the risk of each activity of a project is an important procedure for preparation of a dredging bid.

In this paper, the focus is on finding solutions to minimize risk during the dredging operations by providing visibility to the operator as to the progress of the dredging. This can include preventing dredging beyond the legal limit, minimizing damage and dredging losses and early detection of slope failure. Even when slope stability analyses have been performed, the type of equipment and dredging method can have an unpredictable negative impact on the stability of the slope itself. This is more of a concern in near-shore borrow areas such as lakes, rivers and inland waterways where it is often limited by minimum allowable slope angles. Suction dredging, in some cases can initiate slope instability by erosive sand-water mixtures flows running down the slope. This slope failure initiation or breaching, retrogrades upslope with a velocity dependent on the permeability of the sand.[1]

DREDGING OPERATIONS

Dredging is required to maintain or create channels for shipping and boating, adequate channel depth being necessary to guarantee important trade links, and to allow safe access for fishing and other commercial and recreational boating. However, removal and disposal of sediments inevitably can have some impact on the environment. Aside from complying with best practice guidelines and obtaining dredging approvals/permits for a project, the main problem in carrying out the dredging operation itself is that the dredging operator has to rely on his/her skills and expertise to be able to dredge accurately and efficiently. Without having any type of sensors to provide an underwater image, the dredging operator is in effect dredging 'blind'. Only after the dredging process has been completed, and a bathymetric survey of the area is done, can the dredging operation be assessed. Without the ability to monitor the dredging process, there remains a high risk of over dredging with increased operating costs and increased dredging losses. Should there be a need for re-dredging, it would result in additional considerable costs for operation and personnel. Furthermore, without a monitoring system, it is not possible to detect slipped back material during dredging resulting in increased production losses.

Fig 1 shows the split view of 2D/3D map, cross section of the dredging operation with pre-set limits of dredging or dredging boundary and progress of the dredging operation itself in real time. This view is on the monitor screen in front of the dredging operator to enable him to monitor the process. With the limits of dredging clearly seen (as the red line), the riverbed/lakebed shown as the blue line, and position of the loosening tool shown on the screen, the risk of over dredging can be minimized. In order to produce the bathymetric map below, a Digital Terrain Model (DTM) is initially created from a hydrographic survey of the area. Parameters such as position and heading of the dredger, loosening tool, depth of water, are required for input in the monitoring software. Echosounders and sonars are used to obtain bottom detection.

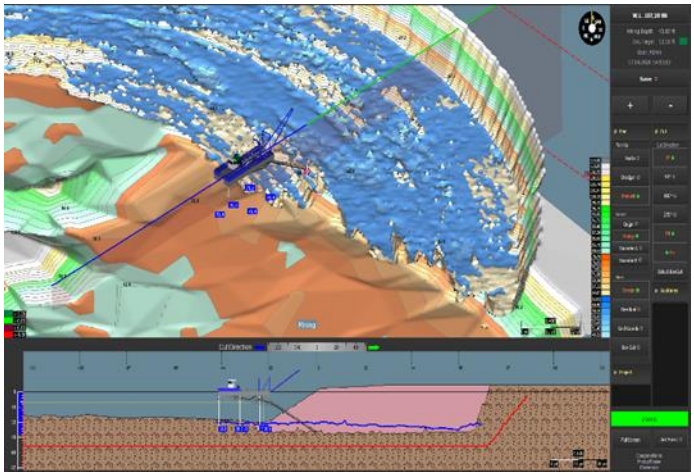

Figure 1. Split view & Cross section of dredge monitoring system.

In another view (Fig.2), the recorded dredged material depicted in orange, can be shown and detect any slipped back material happening in the process. Early detection is important for efficiency and safety as the dredger is still in the location to be able to dredge selectively as necessary. Slope failure risk can be minimized as well as operating costs for dredging losses.

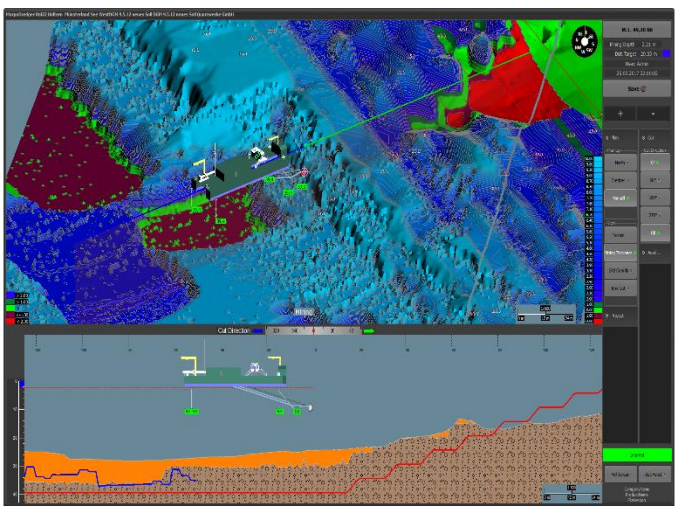

Figure 2. View of slipped material.

Use of the 360-deg scanning sonar creates a 3D map of the surrounding area by taking scans in both horizontal and vertical planes (Fig 3). The rugged design of the dual axis scanning sonars (Fig 4) is ideal for challenging environments. With no exposed moving parts, the transducer and rotator are contained within an adiprene, oil filled dome which is protected from possible damage from impacts of moving objects in the water column.

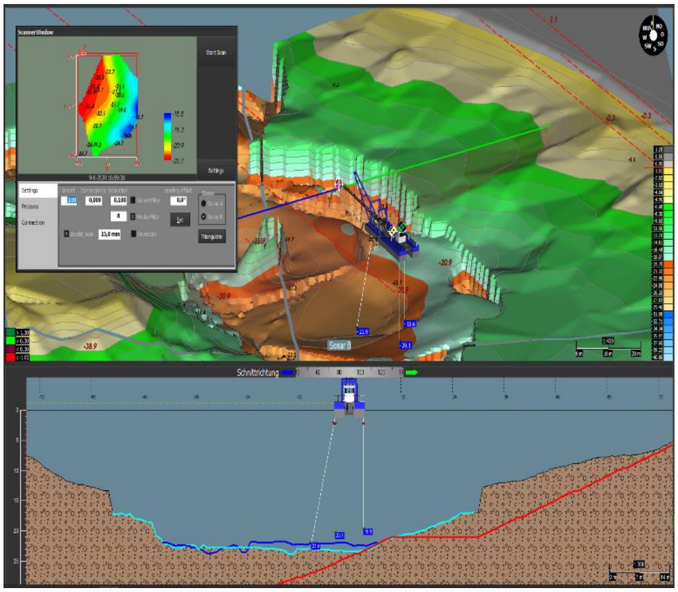

Figure 3. Using a 360 deg scanning sonar.

The dual axis scanning sonar has an operational range of 0.2 to 300 m with a horizontal coverage of three hundred and sixty degrees and a range resolution of 10 mm at the longest setting.

Due to its rugged design, it can withstand up to 30 m hydrostatic depth and challenging environmental conditions such as fast-flowing rivers or heavily loaded waters. The transducer has a 2.8-degree conical beam at 360-degree uninterrupted horizontal coverage with a vertical coverage of +5 degree to -90 degree. The scan can be done in steps of 0.225 degree minimum to the maximum of 7.2 degree. It has a diameter of 0.21 m, height of 0.39 m, and weighs 20 kg in air, 11.5 kg in water.

Figure 4. Dual Axis Scanning (DAS) sonar.

As well as monitoring dredging for safety and efficiency, it is equally important to monitor for the release of sediments into the water column that may have negative impacts on the ecosystem during the dredging process. Although there are various mechanisms for monitoring the water quality impacts, this paper is focused on using acoustics to do this.

Measurement units for turbidity are FTU (Formazin turbidity units) and NTU (Nephelometric turbidity units) that are converted to suspended solids concentration (SSC). Measurement in FTU and NTU are roughly equivalent. Formazin are microspheres of a polymer that is suspended in a measured volume of distilled water and used as a standard for calibrating the turbidity meter. Nephelometric refers to the principle of the turbidity meters (measuring scattered light) where 1 NTU is equivalent to 1 milligram of silica finely divided in 1 litre of distilled water. NTU was the original unit of turbidity and is gradually replaced by FTU. Current standard is FNU (Formazin Nephelometric Units) compliant with ISO 7072. FNU is best used when data is measured using an 860 nm light with a 90-degree detection angle while NTU is best used to represent turbidity readings captured using a white light at a 90-degree detection angle.

Using acoustic sensors, which send short pulses (10 microsecs) at a high frequency will produce scattering from different particle sizes which can subsequently be modelled. The acoustic sensors have the advantage of being non-intrusive, with a high temporal and spatial coverage. Over the past decades, several studies [2] have indicated that the use of acoustic back scatter intensity from acoustic sensors can be used to estimate SSC (Fig. 5). For the results to be reliable, the acoustic sensor must be calibrated to the water conditions during deployment. The major advantage of using acoustic sensors over optical sensors or water samples, is that acoustic sensors can measure SSC at a much longer range and not only at the specific location.

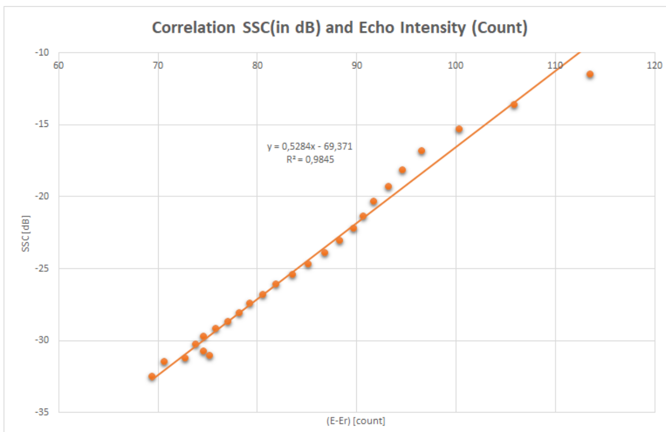

Figure 5. SSC vs Acoustic backscattering.

Fig. 6 shows the set-up of experiment for injecting different particles into the water column and using an acoustic transducer to transmit pulses or signals called CHIRP (Compressed High Intensity Radar Pulse). CHIRP allows for long range performance without compromising resolution and improved characterization.

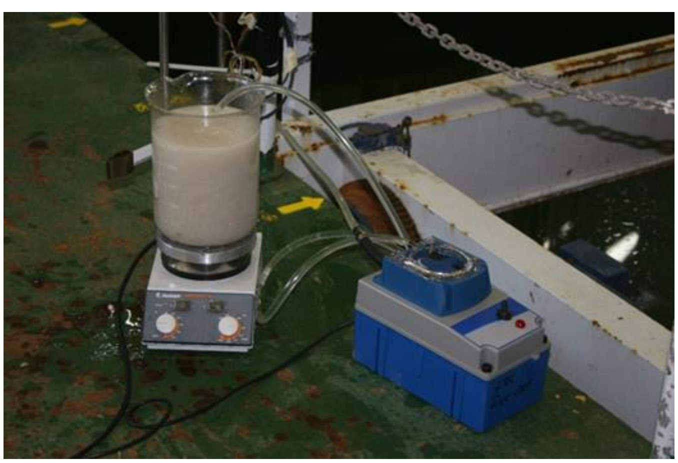

Figure 6. Injection of clay and grouting cement.

Since SSC values are highly variable, it is important that the acoustic back scattering is calibrated to the conditions at the time of collection. Calibration is also required to collect quantitative data. Typically, the acoustic sensor has tools for replaying and visualization of the raw data with biomass in predefined layers automatically calculated.

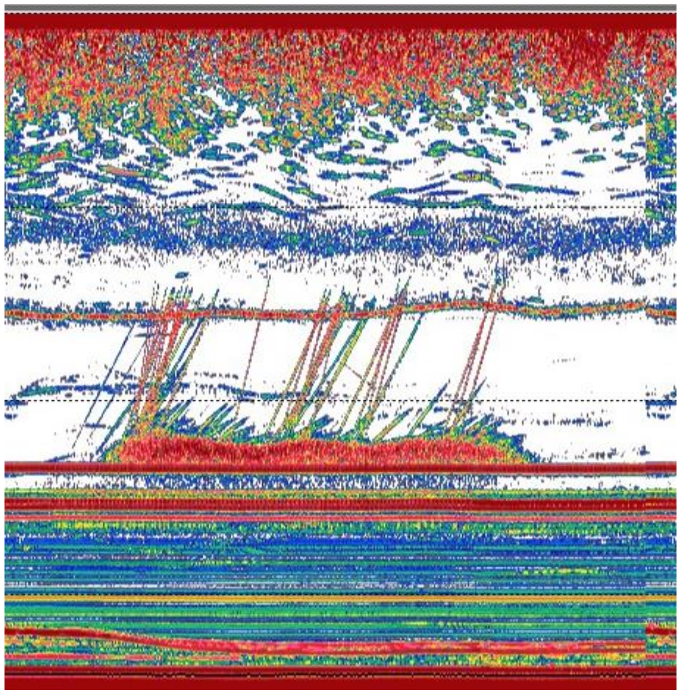

Figure 7. Injection of clay (very fine particles).

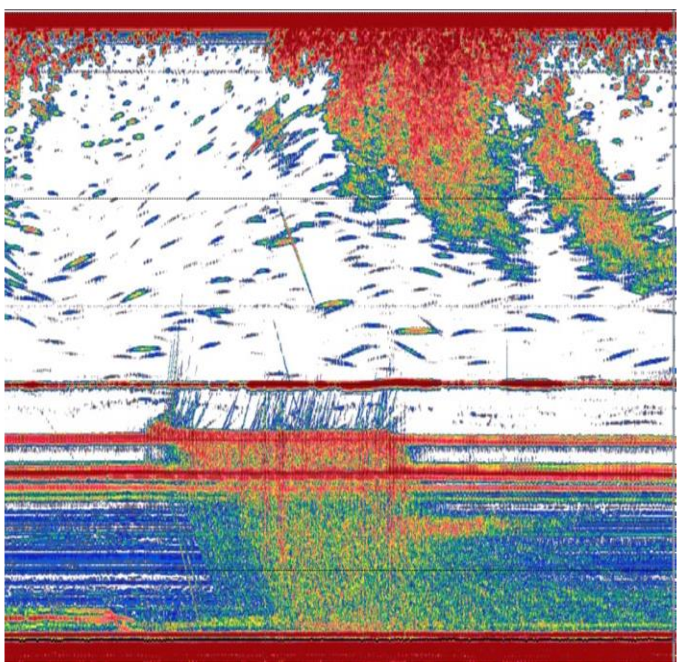

Figure 8. Injection of grouting cement.

CONCLUSIONS

Having real time monitoring for dredging can improve on the safety aspects of the operation, minimize risk of damage caused by human errors, reduce operating costs due to over-dredging or re-dredging, minimize slope failure risk, and subsequently contribute to better quality control of the process.

Monitoring the dredging process should also include a process of being able to monitor the transportation and deposition of suspended sediments using acoustic sensors as one of the methods for sediment detection.

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CITATION

North, A. “Monitoring Dredging for Safety & Impacts on Ecosystem,” *Proceedings of the Western Dredging Association Dredging Summit & Expo ‘22, Houston, TX, USA*, July 25-28, 2022.

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ESSENTIAL RESOURCE MANAGEMENT IN DREDGING HYDROGRAPHIC SURVEYING USING USV AND SV

P. Pocwiardowski[1]

EXTENDED ABSTRACT

The last couple of years exacerbated the shortage of resources to conduct hydrographic surveys for dredging industry. At the same time the companies started to invest in USVs (Unmanned Surface Vehicles) or small SV (surface vehicles) to improve the mobilization time and reduce the overall "footprint" of the operation. In this paper, we present a paradigm change in managing the essential hydrographic surveyor resources by utilizing the technology to divide the dredging hydrographic survey into two parts, design and execution of the survey. The survey "design" is done by a hydrographer or survey manager operating from the remote location setting up the essential parts of the survey. Then the survey execution is done by a skipper or USV operator at the actual job site. These two are connected via a dedicated software which seamlessly combines these two functions into one consolidated efficient solution.

The essential feature of the presented solution is that it allows a concurrent operation of the remotely located hydrographer and the local operator conducting the survey. The architecture of the system has been designed to facilitate the remote access and perform advanced tasks by the hydrographer while the operator uses the hand-held device to conduct the survey.

The hydrographer accesses the system on the USV remotely via web browser and sets up the mission. He prepares the design template satisfying the required clearance, ensures that the proper reference system, geodesy and other required items are chosen correctly. He prepares the local station offset file, the survey lines over for the vessel to run and loads it in the system, so the operator can easily see where to drive the boat. With that he prepared the background image overlayed on the map which loads to all connected displays. While the hydrographer sets up the system, the operator uses hand-held device and can observe the effect of that work.

When the survey is prepared, the operator starts the survey and collects the data. Concurrently, the hydrographer can independently access the data with his own displays, checks the coverage, plots and checks the profiles without disturbing the operator (Fig. 1). Hydrographer can verify the quality of the data by examining the standard deviation of the collected data and even seamlessly transfer the data to GIS software via build in WMS and WFS interface for further tasks such as report generation, volume computation and other processing tasks. When the survey is over the collected raw data can be reprocessed for the final delivery.

The hydrographer can access several other surveys in a similar manner. Remotely accessing each of the concurrent surveys via web interface allows him to improve the efficiency and lower the cost to the customer. His work has been optimized and the impact of his skills maximized while at the same time the boat operators conduct the quality survey and perform multiple other tasks.

[1]NORBIT, Product Director, Sonar Systems

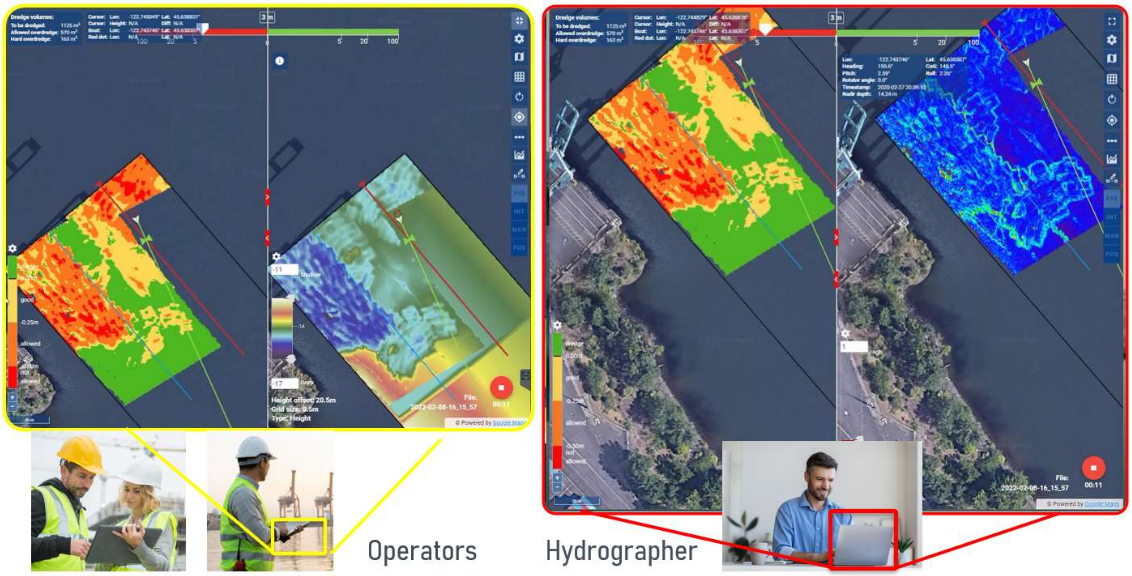

Figure 1. Concurrent remote and local access to the survey

In this paper we introduce new paradigm in hydrographic surveying for dredging industry. This new approach allows fully utilize the surveyor's experience to prepare and manage the survey allowing to use the needed skills more efficiently to run concurrent remote surveys. At the same time, the solution allows the skipper or the operator to manage the execution part of the survey with simple hand-held device. Dredging companies can lower operation costs by using hydrographers for the critical part of the survey and then utilizing skippers and operators to drive the vessels. At the same time, this technology allows the surveyors to manage more jobs from a remote location as well as optimize the cost of their service.

Keywords: Bathymetric survey, hydrography, multibeam.

CITATION

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USING SUBSURFACE UTILITY ENGINEERING PROTOCOL ON COASTAL LOUISIANA RESTORATION PROJECTS TO IMPROVE DREDGING SAFETY

R.J. Joffrion[1]

ABSTRACT

The Louisiana Coastal Protection and Restoration Authority, CPRA, has successfully designed and implemented marsh creation and restoration projects within the Louisiana Coastal Zone for decades to restore degrading coastal habitat. Typically, these project areas are located remotely within Louisiana's Working coast, which also includes existing oil and gas infrastructure. The use of a standard protocol for the identification and the delineation of existing pipeline infrastructure could aid in providing the dredging contractor with quality information, reduce risk, and improve project safety.

INTRODUCTION

The design engineer is typically responsible for collecting and depicting existing pipeline infrastructure information during the design phase of a project. However, this task is often complicated by the lack of existing pipeline operator data, lack of correspondence from a pipeline operator, limitations in surveying methodologies, and inconsistent protocol. The American Society of Engineers (ASCE) CI/ASCE 38-02, Standard Guidance for the Collection and Depiction of Existing Subsurface Utility Data, document has been used by the design engineer on coastal restoration projects to provide consistent protocol, identify and delineate existing oil and gas infrastructure, mitigate project risks, and aid in project safety. This effort is accomplished through the use of bathymetric, topographic, and magnetometer surveys, and coordination with the Professional Land Surveyor (P.L.S.).

DATA GAP ANALYSES

An existing infrastructure desk-top data gap analysis is the first objective undertaken in the data collection phase of a marsh restoration project. A data gap analyses typically includes collecting cultural resource data, and historical magnetometer/topographic/bathymetric survey data in or near the proposed borrow area, dredge pipeline corridor, equipment access corridor, and marsh creation area. This task can be accomplished through the use of online GIS databases such as the Strategic Online Natural Resource Information System (SONRIS), Louisiana Sand, Sediment Resources Database (LASSARD), and the Pipeline and Hazardous Materials Safety Administration websites. As-built survey data from nearby completed marsh creation projects can also be a worthy source for obtaining pipeline operator contact information and existing pipeline operator infrastructure information.

SUBSURFACE UTILITY ENGINEERING DATA COLLECTION

All survey work should be conducted as per the Owner's current survey standards of practice. The design engineer may also elect to utilize the current American Society of Civil Engineers, CI/ASCE 38-02, Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data, as supplemental guidance to aid in the identification of existing subsurface pipeline operators and utilities.

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The design engineer should identify all existing well heads, pipelines, and flow lines in and near the proposed marsh fill areas, borrow areas, dredge pipeline corridor, and equipment access corridors. As per CI/ASCE 38-02, the utility quality level is defined as a professional opinion of the quality and reliability of utility information. Obtaining a high utility quality level is very challenging in the marine and coastal environments. Each of the four existing utility data quality levels, A, B, C, and D, are established by different methods of data collection and interpretation by the P.L.S. For example, utility quality level B pipeline information is typically obtained through the application of appropriate surface geophysical methods to determine the existence and approximate horizontal position of subsurface utilities. Utility quality level D pipeline information is derived from existing records or oral recollections. The CI/ASCE 38-02 utility quality level should be determined by the design engineer and P.L.S. based on the proposed construction equipment, work effort, work limits, and related risk. For example, for project areas not requiring marine based equipment crossings and minimum disturbance, a minimum utility quality level D could suffice. Whereas, in areas of proposed excavation and hydraulic dredging, a utility quality level B accompanied with top-of-pipe probing's may be a minimum requirement.

SUBSURFACE UTILITY ENGINEERING DATA DELINEATION

Once the magnetometer survey data collection effort has been completed, the P.L.S. and the design engineer should review the data and collaborate to identify high risk anomalies located within the proposed marsh fill areas, borrow areas, dredge pipeline corridor, and equipment access corridors. The P.L.S. will typically develop anomaly data tables including horizontal coordinates, vertical coordinates, amplitude, duration, signature type, depth of cover, ground elevation, and top of pipe elevations. The interpretation of this magnetometer data should be evaluated by both the P.L.S. and the design engineer. This effort may result in the need for more data collection and is an iterative process. The review of this data can be accomplished quickly through the use of a GIS software such as Google Earth Pro or ArcGIS.

The collaborative interpretation of any high risk anomalies, and the horizontal and vertical locations of any existing pipeline infrastructure information should be clearly delineated on the construction plan sheets. At a minimum, the construction tolerance zones near excavation/dredging work should be shown on the plan views and section views. If known, specific pipeline operator tolerance zones should also be included in the construction documents. The Contractor should have a clear understanding of the proposed Work, pipeline operators, pipeline tolerance zones, and the level of effort conducted to help identify existing anomalies and pipeline infrastructure for the proposed restoration project site.

PROJECT RISKS

Project features requiring excavation, dredging, spudding, equipment access, and spoil placement, are typically the higher risk features encountered on Louisiana coastal restoration projects. A risk matrix may be warranted by the design engineer to aid in the evaluation of potential project construction impacts for the Owner. A project pre-solicitation meeting or workshop could also be utilized by the design engineer to discuss the existing infrastructure risks for the proposed project, prior to the commencement of any construction activities.

PIPELINE SAFETY GUIDELINES

The design engineer should develop construction protocol, which guides the Contractor to safely conduct Work operations in such a manner as to utilize current federal and local state pipeline safety, damage prevention, incident prevention, and emergency response practices, and not interfere with pipeline operations. These requirements are typically included in the Contractor's Work Plan.

The Engineer, Owner, and Contractor should be familiar with the most current publications of "Recommended Best Practices Guide for Safe Dredging near Underwater Gas & Hazardous Liquid Pipelines", developed by the Council for Dredging and Marine Construction Safety, www.cdmcs.org, and "Working Safely Near Underwater Pipelines", developed by the Coastal and Marine Operators Pipeline

Industry Initiative (CAMO) and the Lake Pontchartrain Basin Foundation (LPBF), http://www.camogroup.org/wp-content/uploads/2020/04/Working-Safely-Near-Underwater-Pipelines.pdf

CONCLUSIONS

The implementation of marsh creation projects is one of the primary restoration project types specified in the CPRA Master Plan and often requires the construction of restoration projects amongst existing oil and gas operators within Louisiana's working coast. Utilizing the American Society of Engineer's CI/ASCE 38-02 guidance document and current pipeline safety guidelines, enables the design engineer to utilize sound and consistent subsurface utility engineering principles for delineating subsurface infrastructure, in an effort to reduce risks to the Owner, Contractor, and Engineer of Record, and safely construct projects.

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DATA AVAILABILITY

No data, models, or code were generated or used during the study.

HOUSTON SHIP CHANNEL, PROJECT 11: UNDERWATER PIPELINE AND UTILITY COORDINATION

M. McCollum[1], G. Martinez[2], and G. McMahan[3]

ABSTRACT

The purpose of the Houston Ship Channel (HSC) Expansion Channel Improvement Project (ECIP), (also known as Project 11) is to widen the existing channel in Galveston Bay, Texas, from 530 to 700 feet (161.54 to 213.36 meters), deepen and widen the upper segments of the HSC from -41.5 to -46.5 feet (12.64 to 14.17 meters) and from 300 to 530 feet (91.44 to 161.54 meters) respectively, and to create beneficial use (BU) and placement area (PA) sites that can utilize the dredged material. Project 11 will also widen Bayport Ship Channel up to 455 feet (138.68 meters) and Barbours Cut Channel up to 445 feet (135.64 meters). To accomplish this, the project team needed to identify any existing underwater pipelines and utilities within the channel and to have them cleared or relocated to allow for safe construction. Accurately locating and identifying underwater pipelines are a crucial part of dredging and marine construction works. These underwater utilities form a vast-web-like network throughout the Gulf of Mexico and, specifically, off the coasts of Texas and Louisiana.

To confirm the existence of pipelines within the Project 11 limits, research and analysis were conducted of public geographic information system (GIS) databases maintained by the Texas Railroad Commission (TRRC) and the Texas General Land Office (GLO), records and permit documentation provided by Port Houston and U.S. Army Corps of Engineers (USACE), and as-built documents provided by cooperating pipeline owners. A common running theme was the lack of dependable and up-to-date information regarding most of the pipelines, particularly pipelines that were abandoned. Ownership of oil and gas pipelines often exchanged hands between many different owners, sometimes more than twice a year, and documentation (as-builts, permits, field investigation reports, etc.) were frequently lost or misplaced during the transfer of assets between companies. Additionally, pipelines that were permitted by USACE might never get constructed or might get relocated from the original permit location, but the original permit information continues to persist on TRRC and GLO GIS databases until the current owner formally notifies the TRRC and GLO otherwise. Consequently, information gathered on the pipelines, as in this case, quickly led to confusion and uncertainty as to which pipelines exist and where are they located. For Project 11, the data were cross referenced and field investigations (magnetometer surveys, sub bottom profiling surveys, probings, etc.) were conducted to establish the presence/absence of pipelines for the areas in question. As part of the advanced planning for Project 11, the pipeline research began over 18 months ahead of construction and was key to identifying pipelines and beginning communication with owners for the removal, relocation, or abandonment of pipelines, ultimately helping mitigate potential construction delays and providing for a safe channel expansion design.

Keywords: Dredging, underwater pipeline safety, marine construction, pipeline surveying, pipeline detection.

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INTRODUCTION

The HSC is the nation's top port in total waterborne tonnage and is expected to continue growing as exports and vessel sizes increase. Currently, vessels greater than 1,100 feet (335.28 meters) in size are prohibited from passing each other within the HSC without prior approval of the Houston Pilots. Expanding the HSC is critical if these post-Panamax vessels are to continue to call on Port Houston (hereinafter referred to as the Port). Expanding the channel can mean one of two things, to go deeper or to go wider. In the case of Project 11, both are scheduled to occur. To ensure that the plans to expand the channel are executed without fault, the project team had to first evaluate the impacts of pipelines that cross or are located near the HSC. This involved gathering information such as the following: the pipeline owners, pipeline status (abandoned or in-service), pipeline sizes, products, and, most importantly, their location. Since these pipelines are underwater and were most likely installed prior to the digital age of data storage, collecting, verifying, and analyzing this information were a significant undertaking but critical to moving the project forward. This paper discusses the methods used by the Project 11 team to collect both historical data and current field data, inclusive of magnetometer surveys, sub-bottom profiler surveys and field probings, and how the data were analyzed and applied to inform the final HSC expansion design.

PROJECT 11 CONSIDERATIONS

Aside from considerations related to removal of pipelines that would interfere with the channel expansion, considerations were given as to how the expansion design could best facilitate future operations and maintenance (O&M) of the newly expanded HSC. According to the USACE Galveston District guidelines for pipeline installment underneath deep draft channels (Figure 1), provided in the Regional General Permit SWG-1998-02143, a minimum of 20 feet (6.10 meters) of vertical clearance is required from the channel bottom to the pipeline and 50 feet (15.24 meters) of horizontal clearance required from the channel side slopes to the pipeline. The offsets required by the USACE allow for safe maintenance of the channel in future O&M dredging projects. Although dredging efficiencies and precision have improved dramatically over the last decade, a certain amount of over digging beyond the template may be required to fully clear the template of shoaled materials. The USACE clearance template also allows for safe operation of dredge spuds and anchors between the channel bottom and pipelines crossing underneath the channel.

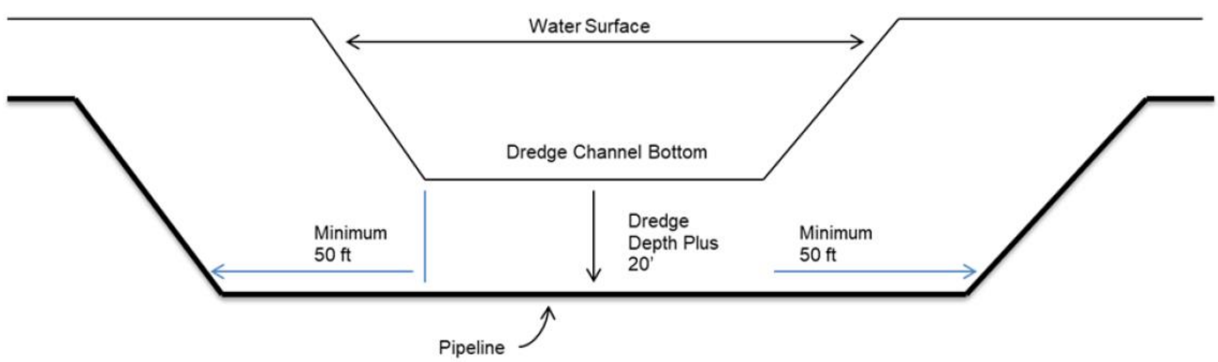

Figure 1. Deep Draft Channel Typical Utility Line Placement Requirement.

When analyzing and evaluating the locations of pipelines within the Project 11 footprint, the project team had to consider the impact that the pipelines would have on future maintenance events. Pipelines that cross underneath the HSC, are located beyond the USACE clearance template, and are owned by actively operating companies were cleared from design impacts with a signed Clearance Letter from the pipeline company to the owner. The Clearance Letter is a signed document by the utility owner acknowledging that it has received the dimensions and footprint of the Project 11 template and USACE clearance template and has determined for itself that its utility is beyond the vertical limits of both and will not be impacted by construction. Pipelines that do not cross the HSC but are within 500 feet (152.40 meters) horizontally of the project footprint were cleared from design impacts with a Letter of No Objection (LONO). The LONO states the same thing as a Clearance Letter except it is understood that the pipeline does not cross the HSC, and the owner is signing off that it has no objection to the Project 11 work. Pipelines found to exist within the Project 11 template are required either to be removed or relocated beyond the USACE clearance template.

HISTORICAL DATA COLLECTION AND SOURCES

During the initial phase of the pipeline research, the project team received from the Port a table of known in-service pipelines that were tracked by the Port since the pipeline owners operated facilities on Port owned land. The first steps were to contact the owners, provide them with a general overview of the planned construction, explain how that might impact their pipelines, and request any available data of the pipelines in their possession. These included as-built records of the pipelines from when they were constructed, and even updated records of pipeline maintenance performed by the owners themselves. From the data gathered, the pipelines were plotted horizontally in plan view and superimposed over the Project 11 work limits to determine whether the pipelines fell within the project footprint. If found to lie within the project footprint, the pipelines were plotted vertically in profile view and superimposed on the corresponding Project 11 template to determine whether the pipelines were cleared or had to be relocated. OneCall tickets were submitted through Texas811.org to verify that all in-service lines within the project footprint had been accounted for.

Public GIS databases maintained by the TRRC and GLO were also used to identify utilities not captured in the Port's records and OneCall tickets. The GIS viewer provided a plan view of the user's defined area with the pipelines delineated for those pipelines for which the state departments have a record of, either currently existing or that historically existed within that area. Additionally, the databases provided information on the latest utility owner, the permit number, and contact information. Based on the information collected, the project team requested copies of all permit documentation of the pipelines from the GLO and USACE. The permits contained drawings submitted by the pipeline owners of the proposed placement of their pipelines. These permitted drawings were often the basis for the plots generated in the GIS viewer rather than post-construction as-builts of the pipelines. Although the permits required that as-built documentation be provided once the pipelines were constructed, very few were found in the permit files. Pipelines missing as-built plots were marked for additional investigation before they could be cleared.

Another source of historical data came from the contract drawings and records of the previous HSC expansion project (referred to as Project 10). Dated from the late 1990s, the drawings contained information on the pipeline positions that conflicted with Project 10, which widened the HSC to its present dimensions. Several pipelines were contracted out for removal, but no records of this could be retrieved at the time of this research.

FIELD INVESTIGATIONS

Field investigations were performed over the entire new work dredging footprint to help verify abandoned pipelines listed on the public GIS databases and to identify any utilities potentially missing from the public records. Field investigations for this project included magnetometer surveys, sub-bottom profiler surveys, and field probings.

Magnetometer Surveys

Marine magnetometer surveys were the main source for identifying pipelines. The magnetometer was used to detect ferrous metals that lie on top or below the seafloor by measuring changes in strength of the magnetic field in areas designated for investigation. These changes were registered as anomalies during post-processing of the survey results. Magnetometer readings are impacted by factors such as depth of water, depth of seafloor above the object, size of the object, distance from the object to the magnetometer, etc. Consequently, magnetometer results can be highly subjective to individual interpretation. The best results were obtained from magnetometer surveys performed in the flats outside the existing HSC where water depths were typically 10 feet (3.05 meters) or less and only a minimum of 3 feet (0.91 meters) of bay bottom cover was required by the permit. Figure 2 represents the track lines that the survey boat followed while towing the magnetometer. The time-stamped circles are where the reported anomalies occurred. Figure 3 provides an interpretation of a pipeline deduced by connecting the detected anomalies across multiple survey lines. As shown, the magnetometer results can approximate the horizontal location of the anomalies but not their vertical location.

Figure 2. Anomalies Detected During Magnetometer Survey.

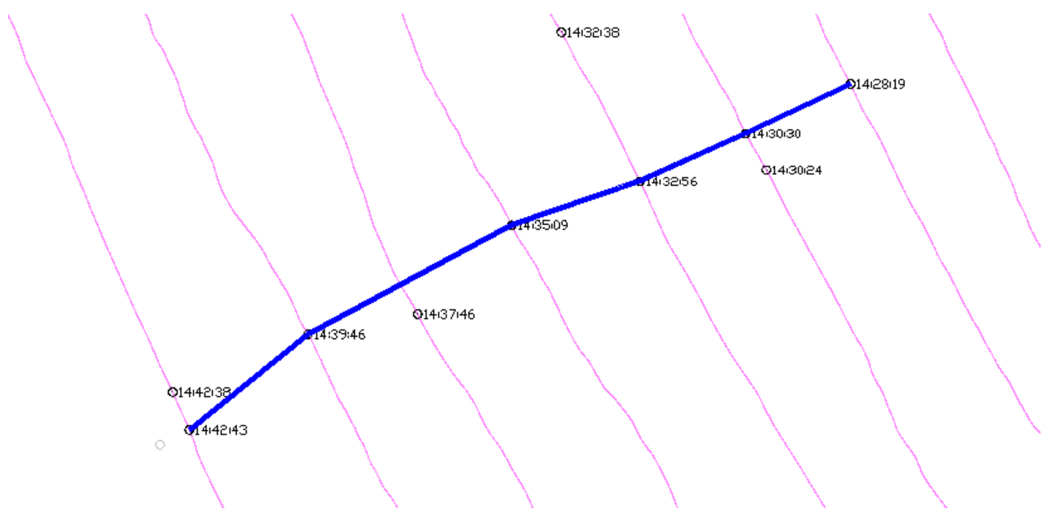

Figure 3. Pipeline Interpretation based on the Magnetometer Survey Results.

Sub-Bottom Profiler Surveys

The project team was able to horizontally locate pipelines (including unidentified or abandoned pipelines) in the project footprint using the magnetometer survey but needed to vertically locate these pipelines relative to the Project 11 channel template before the Project 11 widening design could be realized. For such a purpose, the project team used sub-bottom profilers for vertical location of the pipelines.

Sub-bottom profilers work by transmitting sound energy in the form of a short pulse towards the seabed. This sound energy is reflected from the seabed and the sub-surface sediment layers. The reflected energy intensity depends on the different densities of the sediments, the denser (harder) the sediments, the stronger the reflected signal. The reflected signal then travels back through the water to the receiver. The received signals are then amplified, processed, and displayed in the acquisition system (Ramsay 2017). In short, sub-bottom profilers send a signal to the sea floor that can penetrate soft or loosely consolidated bottom sediments. When the acoustic pulse reaches the seafloor, some of the energy will bounce off the seafloor, while the remaining energy will penetrate the seafloor and continue to propagate (Zheng 2021). As the sound energy passes through varied materials (sands, clays, mud) some of that energy is reflected to the profiler. Based on the intensity of the returning signal and the time it took to return to the profiler, an image of how thick the sediment or potential pipeline is given (Ramsay 2017). Considering a pipeline has a substantially different density than the bottom material around it, the pipelines are visible when viewed on a processed waterfall image as shown in Figure 4. It should be noted that interpretations and data processing are subject to the survey processor and end results/interpretations may vary between survey processors.

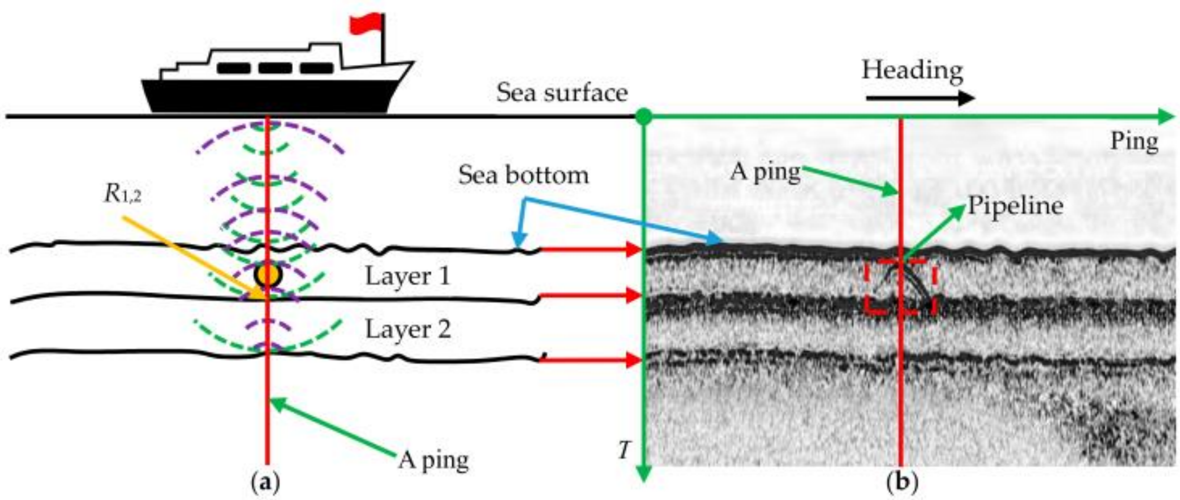

Figure 4. Sub-bottom Profiler Working Principle and Measured Waterfall Image (Zheng 2021).

The project team conducted sub-bottom profiler surveys over those areas identified in the magnetometer surveys that required additional investigation. Pipelines identified in the surveys that have active owners or have historic as-built documentation on them were not surveyed further since their locations had already been verified by other means. Figure 5 represents the results of a typical sub-bottom profiler survey. The red solid line indicates interpolated pipeline data using the green sub-bottom profiler contact points. The red dashed line indicates where no vertical data points were identified, likely due to the fact the pipeline is too deep beneath the seafloor for the profiler to register a pipeline exists. Figure 5 is an example of an abandoned pipeline within the Project 11 template that required removal by the Port to vertically clear the channel for construction.

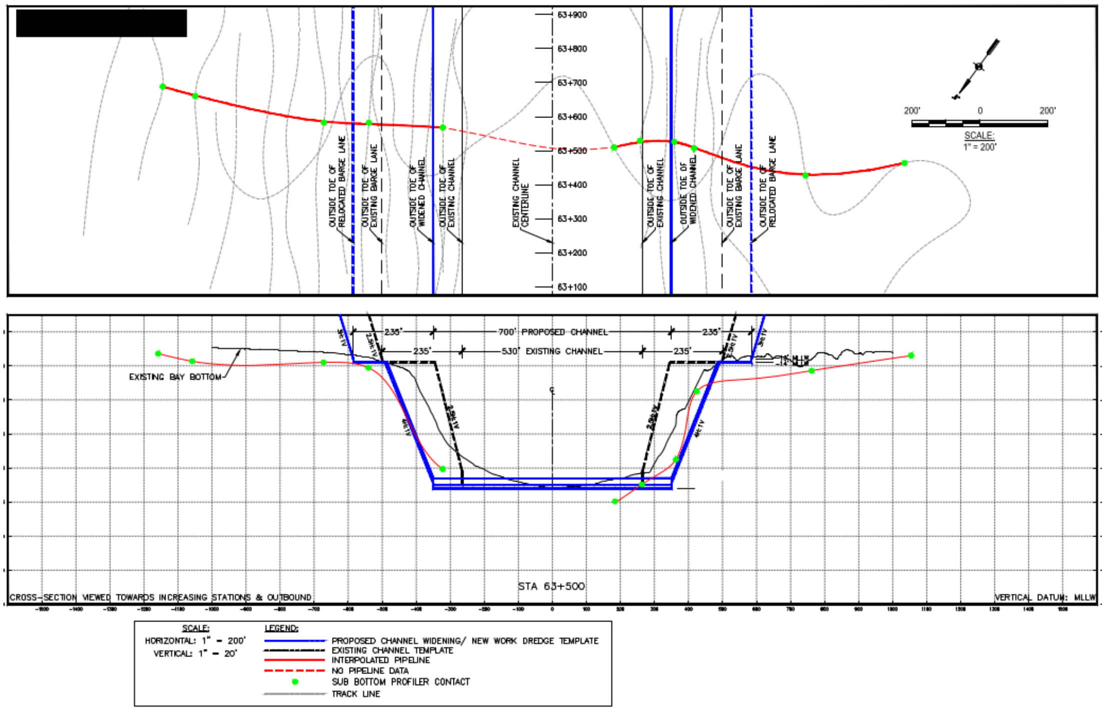

Figure 5. Sample Project 11 Sub-bottom Profiler Result.

Field Probings

The project team also conducted field probings from a vessel using a metal rod. The vessel was outfitted with a computer and GPS equipment in order to accurately determine horizontal positioning of the vessel relative to predetermined areas requiring investigation. This method was only used in areas where a pipeline was believed to exist, yet the magnetometer results were too erratic to identify the pipeline due to the large presence of ferrous shore protection (rock) nearby. A project field worker then probed within the area of interest until the probe came into contact with a potential pipeline. Field probing is seldom used because it is labor intensive and difficult to perform in greater than 10 feet (3.05 meter) of water due to the weight of the rod. In this case, the probing was also limited by the depth of the pipeline and the density of the bay bottom material, which could limit penetration to up to 1-foot (0.305 meter). It was difficult to tell whether areas of hard return indicated an encounter with a pipeline, bay bottom material, or some other dense material or debris. This method was the least successful and used only as a last resort.

DISCUSSION

Once the project team completed their research investigation into existing pipelines in the HSC, the results of the investigation were compiled into a report for use in respective Project 11 design packages. For instance, the results of the research were used by the dredging contractors to identify the pipeline owners and coordinate with them during the dredging phase of Project 11. All existing pipelines which were verified by the utility owners, whether in service or abandoned, were plotted on the Contract Drawings including a minimum 500-foot (152.40 meter) buffer zone surrounding the pipeline 250 feet (76.20 meter) to either side. No work was allowed within the buffer zones until the dredging contractor(s) coordinated with the individual utility owners on how the work would be performed and whether any working offsets were required by the utility owner to prohibit spudding or anchoring. Utility owners or their representatives were given the opportunity to be present onboard the dredge to observe the dredging conducted over the pipelines. Pipelines that were identified as abandoned and owned by bankrupt or nonexistent companies, were plotted on the Contract Drawings, and dredging contractor(s) were required to conduct their own investigation to confirm the presence of any pipelines prior to work. Through field investigations, four pipelines with nonexistent utility owners were identified within the HSC bay reach that conflicted with the Project 11 dredging template. A separate contract was developed by the Port for removal of pipelines beyond the Project 11 dredging template. Since the last known utility owners of the pipelines had filed for bankruptcy, the Port bored the cost of the removal. Conflicting pipelines with active utility owners in the upper bayou reach of the HSC were required to remove and relocate the pipelines prior to dredging work. The cost for relocating the pipelines were evenly split between the Port and the respective utility owners. Establishing pipeline removal and relocation limits not only took into consideration the Project 11 dredging templates but any additional channel expansion plans further out into the future. Table 1 summarizes the investigation results of the pipeline research and coordination.

Table 1. Pipeline Summary.

Segment Description	Description	Pipelines Identified	Pipelines Requiring Removal	Pipelines Requiring Relocation
1 - Bay Reach	Channel	16	6	0
1 - Bird Islands	BU/PA	11	0	0
1 - Oyster Reefs	BU	11	0	0
1 - Atkinson Island	PA	5	0	0
2 - Bayport Ship Channel	Channel	7	0	0
3 - Barbours Cut Channel	Channel	2	0	2
4 - Boggy Bayou to Sims Bayou	Channel	43	2	10
4 - Beltway 8	PA	5	0	2
4 - East 2 Clinton	PA	2	0	0

The goal of the pipeline and utility owner coordination performed by the Port was to allow for a Project 11 design which provided a safe and feasible construction template for the dredging contractor(s). The coordination has been an 18-month process which is still ongoing for the upper reaches of the bay. Significant time and resources were used to progress the pipeline and utility coordination to a point where the lower bay dredging contracts could be issued.

While the public GIS databases maintained by TRRC and the GLO and the permit application records maintained by the USACE are valuable resources, there is room for improvement if both the utility owners and public agencies were more proactively involved in providing updated and accurate information. Much of the data provided in the GIS databases are outdated or inaccurate; for example, pipelines are incorrectly shown or pipelines that exist in documentation but were never constructed. Many of the USACE permits include the original permit application drawings of the approximate location and depth of the pipelines, but no as-built drawings were made available, which is in violation of the condition stipulated in the permit that pipeline owners are to provide these drawings after construction. Additionally, it is too often the case that companies who file for bankruptcy have no legal obligation to remove their pipelines, thus leaving them as abandoned in place for other parties to deal with down the road, which is the case with pipelines that cross underneath navigational channels that are operated and maintained by USACE. Although the active pipeline companies assist the Port by providing as much information about the pipelines, many of the requested records have been lost over the lifetime of the pipelines as company assets are bought and sold many times over. Records of pipelines can date as far back as 25 or more years without any investigation or survey conducted by the owners to provide updated information on the pipelines.

CONCLUSIONS

The advanced planning for Project 11 undertaken by the Port to identify pipelines and begin coordination with utility owners has allowed for a safe channel design and also for the dredging packages to begin on schedule with fewer potential construction delays. The research led to a Port developed and procured pipeline removal package to remove several abandoned pipelines from the new channel template ahead of dredging. The communication with utility Owners has allowed for Owners to begin designing and preparing for removal, relocation and even abandonment of their assets ahead of the dredging contracts. Additionally, the Port’s coordination effort has provided easier avenues of communication between the current dredging contractors and active pipeline owners,

It is evident that there is more accurate and available information on pipelines that were built in the last decade than for older pipelines, such as often found in the HSC system, where information on a pipeline’s status and location is hard to come by since many of the original owners went bankrupt or dissolved. Oftentimes, the USACE and the Port had no records of the lines. With the advent of GIS, public agencies need to collaborate with pipeline companies to collect and store information on every pipeline into a GIS database, allowing information to be more quickly accessed and shared between engineering firms, channel stakeholders, and government agencies. The ultimate goal is to prevent a dredge or any piece of marine equipment from hitting an active line resulting in a potential severe accident and loss of life. The coordination undertaken by the Port has provided for a safe channel design and constructable channel, but the effort required could have been significantly reduced by a commitment between stakeholders, public agencies.

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DATA AVAILABILITY

Some or all data used during the study:

- Are available in a repository or online in accordance with data retention policies of Texas Railroad Commission and the Texas General Land Office.
- Are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

COMMITMENT BY PARTICIPANTS FOR BENEFICIAL USE

L. Wilson[1] and D. Cheney[2]

EXTENDED ABSTRACT

Dredged materials that are not contaminated are considered a resource and can be repurposed for economic, environmental, and beneficial uses. Habitat development is the primary focus of the Houston-based Beneficial Uses Group (BUG). This group, through proactive collaboration between federal and state agencies, has been instrumental in the success of the Houston-Galveston Navigation Channel (HGNC, Project 10) and Houston Ship Channel Expansion Improvement Project (HSC ECIP, Project 11).

As early as 1967, Congress reviewed the Project 10, with a General Reevaluation Report (GRR) and Environmental Impact Statement (EIS) (USACE 1995) nearly two decades later. However, during the 20-year time between the initial design review and planning documents, there were significant objections from the state and federal resource agencies, local stakeholders, and commercial and recreational boaters to open bay disposal, which resulted in the development of a U.S. Army Corps of Engineers (USACE) Interagency Coordination Team (ICT) in 1989. The following year, the BUG was formed as an ICT subcommittee to specifically focus on moving away from open bay disposal to a more sustainable dredged material management approach to utilize dredged materials as a resource rather than disposed spoil. The BUG includes a coalition of eight federal and state government agencies — USACE-Galveston District, Port Houston Authority (PHA), U.S. Fish and Wildlife Service (USFWS), National Marine Fisheries Service (NMFS), U.S. Natural Resource Conservation Service (NRCS), U.S. Environmental Protection Agency (EPA), Texas Parks and Wildlife Department (TPWD), and the Texas General Land Office (GLO). These agencies collaborated to identify environmentally and economically responsible ways to beneficially use dredged material.

Part of the Project 10 coordination, the BUG held numerous planning meetings between 1990-1998 with the Galveston Bay users and local interest groups for the development of the BUG Plan and continued to collaborate with these groups throughout construction of Project 10 and planning Project 11. Sponsored by the USACE and PHA, in the Fall of 1992, the BUG presented a conceptual plan (known as the “BUG Plan”) to build wildlife habitats with material dredged from the Project 10. The BUG Plan suggested the best way to use dredged material was to: construct approximately 4,250 acres of intertidal salt marsh, build a 6-acre bird nesting and habitat island, partially restore Redfish Island in Galveston Bay and Goat Island in Buffalo Bayou as re-established wildlife habitat, and construct an underwater berm to enhance fish habitat. The plan, the first of its type and size in the nation at that time, was adopted by the ICT and received unanimous support from all federal and state resource agencies.

In 1995 the BUG (with cooperation with NMFS, EPA, and Houston Light & Power) constructed a 220-acre “Demonstration Marsh” and 5-acre oyster reef with non-native oyster cultch to address design-and engineering-based questions:

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- Could a large-scale intertidal marsh be constructed of dredged material?
- Could large-scale dredging equipment place the material so that when the material dried, settled and consolidated it would be within intertidal range?
- Would marsh vegetation grow?
- Would the tidal creeks and ponds, essential to the success of the marsh, form?
- Most importantly, would the wildlife use it?

To progress the Project 10 effort, PHA took the initiative to expedite the process to address engineering- and science-based concerns of the BUG. PHA started by providing dredging, engineering, and environmental expertise to the BUG through their design consultant (Joint Venture), probing the Galveston Bay bottom to locate optimal placement site alternatives for the conceptual design and funded the NMFS to develop design criteria for constructing ecologically functional marshes.

The Demonstration Marsh, monitored by the BUG from 1995 to 2002, proved to be a success with the development of thick and lush vegetation, fishery spawning grounds, and bird island migratory nesting grounds. Dredging the HSC Extended Entrance Channel Project began the process of the BUG Plan in 1998. The initial construction of Project 10 was successfully completed in 2008 creating almost 3,000 acres of intertidal marsh and an 8-acre bird island.

Many lessons were learned throughout the Demonstration Marsh and Project 10 design and construction:

- Creating intertidal marsh is as much art and intuition as science and engineering.
- A committed hands-on interagency working partnership is essential for plan development, successful design and construction and continued monitoring, management, and maintenance of what is achieved.
- Public utilization issues arise early, as do public information needs.
- Quality control of reference marsh surveys is critical.
- Thorough geotechnical investigation and understanding of the proposed marsh site, as well as the dredged material is imperative.
- Plant establishment for seed production is more critical than plant spacing.
- Establishing a network of ponds and creeks is imperative to creating a functional habitat.
- Thorough circulation and flushing of the marsh are essential.
- A detailed monitoring program is needed to measure the functionality of the marsh over time and identify maintenance needs.

Since that time, the PHA has continued to support and fund the BUG. The long-term environmental benefits of a dredged material placement plan have become intrinsic to the Federal approval of navigation projects nationwide because of Project 10 success. The principles and success of the Beneficial Uses Plan and Project 10 were carried through in the formulation and acceptance of Project 11. More than half of the dredged material from Project 11 will be used to construct approximately 900 acres of intertidal marsh at three locations in Galveston Bay — six-acre Long Bird Island, 240-acre Three-Bird Island Marsh, and completing the Atkinson Island Marsh Complex (650 acres) – and two separate oyster reef mitigation sites (Dollar Reef and San Leon) totaling 303 acres. Construction of Project 11 commenced in April 2022 with BU portions expected to be complete in 2024, with final construction segments (subject to Federal appropriations) by 2025.

The commitment of the state and federal resource agencies for BU has provided for the successful completion of the Project 11 study and design. The improvements being constructed seek to ensure that the waterway continues to safely accommodate environmental stewardship in concert with growth of commerce as well as the national economy.

Keywords: Dredging, habitat development, dredged material disposal, wildlife habitat, marsh, Project 11, Houston Ship Channel, Beneficial Uses Group.

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DATA AVAILABILITY

- Some or all data, models, are available via a in a repository in accordance with data retention policies of Port Houston and may be requested from the corresponding author by request.

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Great appreciation to the U.S. Fish and Wildlife Service (USFWS), National Marine Fisheries Service (NMFS), U.S. Natural Resource Conservation Service, U.S. Environmental Protection Agency (EPA), Texas Parks and Wildlife Department (TPWD), and the Texas General Land Office (GLO) for over 30 years of dedication to a collaborative process and partnership. Without the commitment of these agencies to work together to achieve a common goal, Galveston Bay would not have flourished with the increase of fishery and bird habitat that it has today. The tireless work and commitment from the BUG helped set the bar for BU for the nation.

HOUSTON SHIP CHANNEL, PROJECT 11: DESIGN CONSIDERATIONS FOR THE CONSTRUCTION OF TWO BIRD ISLANDS

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ABSTRACT

As a result of the Houston Ship Channel Expansion Channel Improvement Project (HSC-ECIP), the HSC will be widened and deepened to accommodate the increasing demand for larger vessels that make use of the channel. The width of the HSC throughout the Galveston Bay reach (Project 11, Segment 1) will be increased to 700 feet (213.36 meter) from its current 530 feet (161.54 meter) design. The widening of the HSC along Project 11, Segments 1 and 2, will result in large quantities of dredged material that will require placement. Two new bird islands, Long Bird Island (LBI) and Three Bird Island Marsh (TBIM), will be constructed entirely with the beneficial reuse of the dredged material. The islands are to serve as habitats for wildlife, specifically as a seasonal resting spot for migratory bird species and as a site that provides a calming body of water for water birds. Each island is unique with respect to its size, layout, orientation, and design features, although the design of the islands is influenced by a number of factors, including the sites' geotechnical properties, underground utility avoidance restrictions, wind and wave force impacts, and shoreline and habitat protection. The focus of this paper are driven by two design considerations for LBI and TBIM, namely, the optimal design elevations for the islands and shore protection against the impacts of open water conditions. To address this, the paper reports on analyses conducted on wind, wave, and seawater levels at the two island sites and on the types of shore protection, including wave trips, needed to preserve the islands and their habitats against the elements in the long term.

Keywords: Dredging, beneficial use, dredged material repurposing, environmental restoration, marine construction.

INTRODUCTION

The Houston Ship Channel Expansion Channel Improvement Project (HSC-ECIP), referred to by the Houston Port as Project 11, is based on the U.S. Army Corps of Engineers (USACE) engineering standards along with input from stakeholders, including industry and local, state, and federal agencies. The aim of the HSC-ECIP is to widen and deepen the HSC, located in Galveston Bay and Trinity Bay in Texas, in order to upgrade the channel to accommodate more vessels and larger vessels in the future.

Project 11 consists of six separable segments. Two of the segments, the focus of the study that was conducted and reported in this paper, consist of the bay reaches of the HSC: Segment 1 – Bolivar Roads to Barbours Cut Channel, and Segment 2 – Bayport Ship Channel. The two segments are to be widened, but there are no plans for deepening them. For Segment 1, for instance, HSC at Galveston Bay reach will increase in width from the current 530 feet (161.54 meter) to 700 feet (213.36 meter).

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The widening of the HSC along Segments 1 and 2 is expected to produce more than 18 million cubic yards of dredged material that will require placement. Due to the different geotechnical properties of the soil, dredging will involve a combination of mechanical and hydraulic cutter-suction dredges for material removal and placement. Materials having geotechnical properties that are suitable for Beneficial Use (BU) sites will be used to construct two new bird islands adjacent to the HSC, Long Bird Island (LBI) and Three Bird Island Marsh (TBIM). Materials deemed unsuitable for building BU sites (lack geotechnical properties for use as foundations and lack shaping and grading qualities) will be transported to an existing offshore Ocean Dredged Material Disposal Site (ODMDS).

The islands are to serve as habitats for wildlife, specifically as a seasonal resting spot for migratory bird species and as a site that provides a calming body of water for water birds. Each island is unique with respect to its size, layout, orientation, and design features, although the design of the islands is influenced by a number of factors, including the sites' geotechnical properties, underground utility avoidance restrictions, wind and wave force impacts, and shoreline and habitat protection. The focus of this paper are driven by two design considerations for LBI and TBIM, namely, what are the optimal elevations for the islands and how to protect the islands against the constant barrage of waves, winds, and storm events. To address this, the paper reports on analyses conducted on wind, wave, and seawater levels at the island sites to help determine elevation levels for the islands and the types of shore protection needed to preserve the islands and their habitats against environmental impacts in the long term.

OVERALL DESIGN CONSIDERATIONS

The new bird islands, LBI and TBIM, will be located in open water and will be subject to the surrounding wind-wave environment. Hence, elevation levels and shoreline protection are key design elements that must be considered to preserve and protect the islands against winds, waves, storms, erosion, sediment loss, and settlement, which would reduce the effective lifespan of the islands and their wildlife habitats. The following is a brief general description of the islands designs considerations.

Long Bird Island

The LBI will be constructed in Galveston Bay, north of Bolivar and south of Red Fish Reef, using hydraulically placed dredge materials. The design of the island will be kept to under 10 acres to discourage predatory species from establishing. It would be subject to salt spray to prevent vegetation growth. The island would be capped with crushed limestone to mimic shell hash nesting habitat for the targeted species. A levee made up of a rip-rap armored dike would be installed parallel to the HSC. The island would include a calm water zone, situated between the island and an oyster reef wave trip that surrounds it, to provide a wading and feeding habitat for migratory birds.

Three Bird Island Marsh

The TBIM will be located in western Trinity Bay, south of Cedar Point and to the east of the existing Atkinson Island Marsh complex. The island includes a central marsh with three bird islands and perimeter levees that connect the islands together in a triangular configuration, with the bird islands located at the vertices of the triangle. The final orientation of the island was configured to avoid underground utilities, which are scattered throughout Trinity Bay. Outfall structures will be installed along the perimeter levees to control the outflow of water during dredging maintenance cycles. The central marsh will be created over time with dredge materials from the HSC. Once the interior has been pumped and consolidated to intertidal marsh grade, it will cease receiving dredge material. In the future, as part of a separate project, the interior areas may be seeded/planted with native marsh vegetation to expedite establishment.

Elevation and Shoreline Design Considerations

The design criteria for the islands must consider the size, location, and orientation of the islands; their surrounding natural environment (wind, waves, and fetch), the islands' various design features, including habitats creation. The criteria for determining elevations and shoreline protection include the following:

- The elevation should be sufficiently high to preserve the island and its habitats in the longer term against, wind-wave impacts, erosion, and settlement.
- The elevation of the island should be low enough to expose the island to salt spray to limit vegetation growth along the armored shorelines.
- To protect the shoreline against impact from passing vessel wakes, a barrier, such as a rip-rap armored dike would be installed parallel to the HSC.
- To reduce impacts to the shoreline from incoming waves, oyster reef wave trips would surround parts of the islands to break the incoming waves. The wave trip would also provide a calming body of water for water birds and create habitat for oysters.

WIND-WAVE AND WATER LEVEL DATA ANALYSIS

The design of LBI and TBIM, must take into consideration the sea state environment over time and under various return periods to determine how the physical features of the islands, such as the islands' elevation and shoreline, will be impacted. The main sea state factors are water level (including sea level rise), wave set up, and wave height. An additional factor that would lower the islands' elevation over time is settlement and consolidation of the islands' foundation and hydraulic fill materials.

To determine the estimated design wind speed for each of the new bird islands, an analysis of historical data was performed on records from Ellington Airfield, located approximately 20 miles (32.19 km) inland from the proposed bird islands. This data source was selected because it contained wind speed data dating back over 70 years, providing more extensive and comprehensive data records than the data provided by the nearby NOAA buoys located along the HSC. Wind speeds were determined for 1-, 2-, 5-, and 10-year intervals. To determine the return period, wind speed and annual max series (AMS) were calculated with values taken from years 1941 to 2019. The AMS was then used to create a generalized extreme value (GEV) distribution to estimate recurrence intervals by fitting the data to a known probability function. For this design, a Gumbel distribution was applied.

Due to the location and characteristics of the wind speed measurements recorded at Ellington Airfield, some processing of the wind data was required so that it could be used to calculate wave heights. The wind speed data utilized from the Ellington Air Force Base field gauge was reported on a 2-minute average speed. The wind speed gauge was positioned overland at a height of 9.8 meters (31.36 feet) above ground level. For the data to be utilized, equations in the Coastal Engineering Manual (CEM) (USACE 2002) had to be adjusted as follows:

- Adjust for duration, from an average of 2 minutes at gauge to 15 minutes.
- Adjust for elevation from 32.2 feet (9.8 meters) to 32.8 feet (10 meters).
- Adjust from overland to overwater.

This process was repeated for each 45-degree interval. Table 1 and Table 2 provides wind speed values for LB1 and TBIM, respectively.

Table 1. Resultant Wind Speed Values for LBI.

Direction (deg)	0-45	45-90	90-135	135-180	180-225	225-270	270-315	315-360
Return Period	**Wind Speed – mph (kph)**							
1 Year	10 (16.1)	6 (9.6)	5 (8.0)	12 (19.3)	10 (16.1)	7 (11.3)	6 (9.6)	11 (17.7)
2 Year	26 (41.8)	28 (45.1)	27 (43.5)	30 (48.3)	26 (41.8)	22 (35.4)	26 (41.8)	29 (46.7)
5 Year	30 (48.3)	33 (53.1)	37 (59.5)	38 (61.2)	33 (53.1)	28 (45.1)	35 (56.3)	36 (57.9)
10 Year	35 (56.3)	35 (56.3)	43 (69.2)	42 (67.6)	37 (59.5)	32 (51.5)	37 (59.5)	36 (57.9)

Table 2. Resultant Wind Speed Values for TBIM

Direction (deg)	0-45	45-90	90-135	135-180	180-225	225-270	270-315	315-360
Return Period	**Wind Speed – mph (kph)**							
1 Year	10 (16.1)	6 (9.6)	5 (8.0)	13 (20.9)	11 (17.7)	7 (11.2)	5 (8.0)	11 (17.7)
2 Year	26 (41.8)	23 (37.0)	27 (43.5)	28 (45.1)	26 (41.8)	22 (35.4)	29 (46.7)	31 (49.9)
5 Year	30 (48.3)	30 (48.3)	34 (54.7)	34 (54.7)	30 (48.3)	28 (45.1)	38 (61.2)	39 (62.8)
10 Year	35 (56.3)	35 (56.3)	36 (57.9)	35 (56.3)	34 (54.7)	32 (51.5)	44 (70.8)	45 (72.4)

The calculated wind speed values were then applied to determine the expected wave height at each proposed location of the new bird islands. Wind wave heights were calculated based on methods outlined in the CEM. For purpose of the design, the resultant wave values were either fetch, depth, or duration limited. As an example, in a scenario where the duration limited wave height of 3 feet (0.91 meter) (with durations taken from historical data) and a fetch limited wave height of 3.5 feet (1.07 meter) are compared at a finite point, only a 3-foot (0.91-meter) wave could occur at the point since the duration does not allow for sufficient sustained energy for a 3.5-foot (1.07 meter) wave to be fully developed.

A combination of the following factors was used to determine the wave heights for the bird island designs:

U_{10} (m/s) = wind speed at a 10-meter elevation

g (m/s^2) = gravity

u_* (m/sec) = friction velocity

X (m) = straight line fetch distance

C_D = drag coefficient

H_{mo} = significant wave height (feet)

T_p= wave period

t_x = duration required to be fetch-limited

t_s = sustained duration

X_t = duration-limited fetch

d = water depth

k = breaker coefficient (h/d)

ξ = surf similarity parameter

The depth limiting breaking wave height, which is the maximum wave height that is physically possible given the water depth at the site, was determined first. Previous surveys undertaken between 2019 and 2020 indicated that the water depth at the proposed placement sites was approximately 9 feet (2.74 meter) and 10 feet (3.05 meter) for LBI and TBIM, respectively. Therefore, using a breaker coefficient of 0.78 as recommend by the Federal Emergency Management Agency (2005), the max wave height was calculated to be approximately 7 feet (2.13 meter) for LBI and 8 feet (2.44 meter) for TBIM. This does not mean that the waves will reach these heights but that any waves greater than these heights will break before they reach the site.

The wave was then evaluated to determine whether it was limited by the fetch, which is the maximum distance a wave may travel from wind driven forces at a given time. Equation II-2-35 in the CEM (USACE 2015) was used to determine the required duration for the waves to be fetch limited. This number was then compared to the average sustained duration of the winds for a given speed. Site locations and their maximum possible fetch distances in Galveston and Trinity Bay are shown in Figure 1. The final wave heights and limiting factors are shown below in Table 3 for LBI and TBIM.

Table 3. Wave Return Period Results for LBI and TBIM.

Return Period	**LBI**		**TBIM**	
	H_{mo} (ft)	**Limiting Factor**	**H_{mo} (ft)**	**Limiting Factor**
1 Year	1.44 (0.43 m)	Fetch	1.67 (0.51 m)	Fetch
2 Year	2.94 (0.89 m)	Duration	2.82 (0.86 m)	Duration
5 Year	3.35 (1.02 m)	Duration	3.65 (1.11 m)	Fetch
10 Year	4.10 (1.25 m)	Duration	4.32 (1.32 m)	Fetch

Wave run-up is a component of the vertical height of waves impacting the placement area. To estimate the wave run-up at LBI and TBIM, the de Waal and Van Der Meer runup equations were used. The resultant values are shown in Table 4.

Table 4. Wave Run-up by Return Period.

Return Period	**LBI Run up (ft)**	**TBIM Run up (ft)**
1 Year	1.98 (0.60 m)	2.26 (0.69 m)
2 Year	3.73 (1.14 m)	3.60 (1.10 m)
5 Year	3.96 (1.21 m)	4.27 (1.30 m)
10 Year	5.05 (1.54 m)	5.21 (1.59 m)

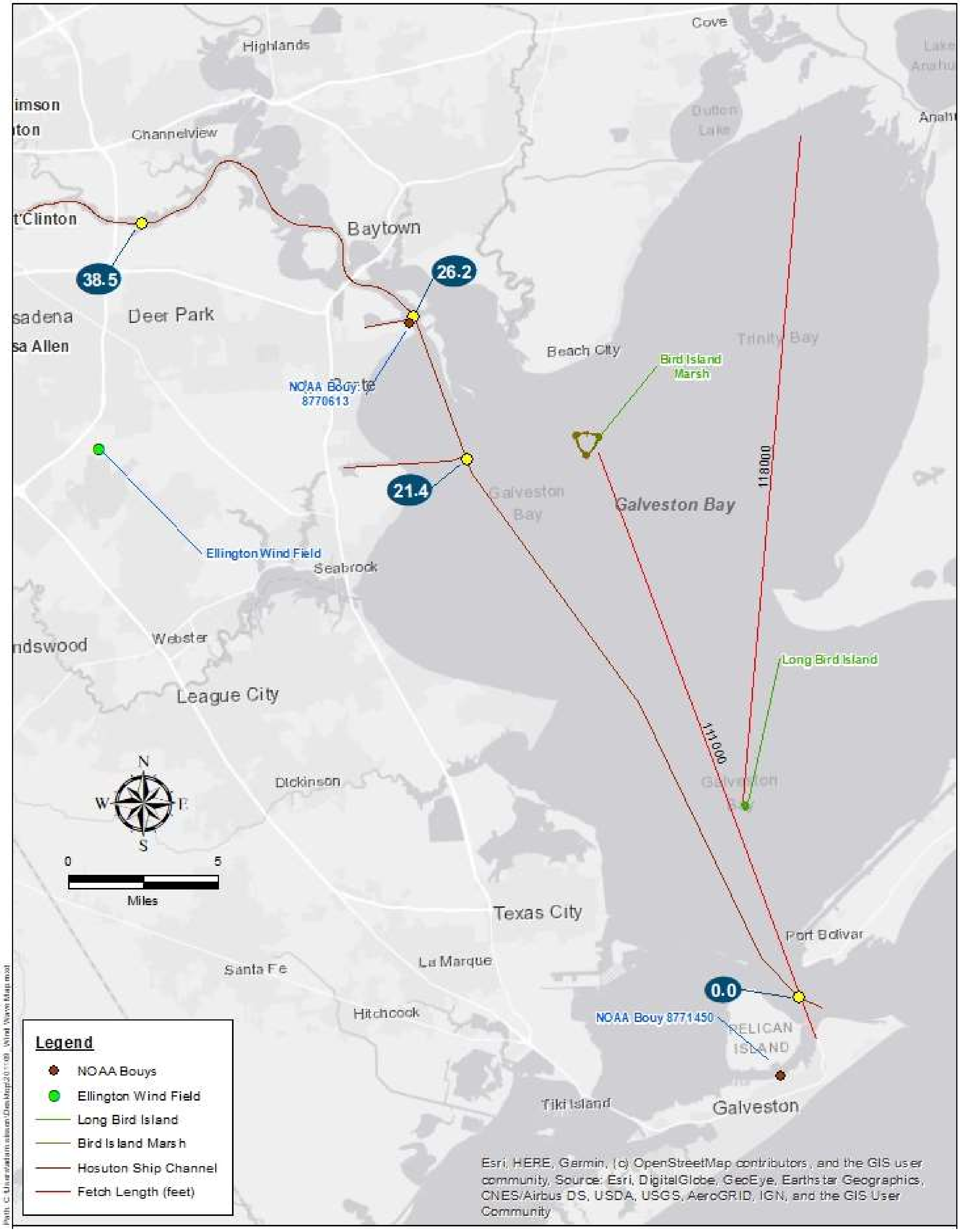

Figure 1. Bird Island Design Locations with Maximum Fetch Distances.

Additionally, wave setup was estimated in accordance with the FEMA (2005) guidelines. The guidelines recommended wave setup is approximately 0.232 of the significant wave heights as noted in Table 4. Table 5 summarizes the results of the wave setup utilized in the bird island design.

Table 5. Wave Set Up by Return Period.

Return Period	LBI Wave Setup (ft)	TBIM Wave Setup (ft)
1 Year	0.33 (0.10 m)	0.39 (0.12 m)
2 Year	0.68 (0.21 m)	0.65 (0.20 m)
5 Year	0.78 (0.24 m)	0.85 (0.26 m)
10 Year	0.95 (0.29 m)	1.00 (0.31 m)

To determine the recurrence interval water levels, historical storm surge data were used from NOAA tide gauges at NOAA station 8770613, located at Morgan's Point for TBIM, and NOAA station 8771450, located at Galveston Pier 21 for LBI. The same statistical process for wind speed determination was used for calculating water levels. Table 6 provides the results of this analysis.

Table 6. Resultant Water Levels.

Water Datum and Levels	TBIM Elevation (ft MLLW)	LBI Elevation (ft MLLW)
10 Year	6.03 (1.84 m)	6.33 (1.93 m)
5 Year	5.24 (1.60 m)	5.36 (1.63 m)
2 Year	4.03 (1.23 m)	3.91 (1.19 m)
HAT	1.97 (0.60 m)	2.41 (0.73 m)
MHHW	1.12 (0.34 m)	1.41 (0.43 m)
1 Year	1.04 (0.32 m)	0.31 (0.10 m)
MLW	0.06 (0.02 m)	0.30 (0.09 m)
LAT	-1.17 (-0.36 m)	-1.19 (-0.36 m)

Since both bird islands are included in a 50-year Dredge Material Management Plan, future water levels need to be considered during the design process. Therefore, an analysis of sea level rise was performed. Sea level rise (SLR) values were forecasted for 10, 20, and 50-year scenarios. These scenarios used methods in accordance with ER 1100-2-8162, *Incorporating Sea Level Change Civil Works Programs* (USACE 2019). This method factors in global (i.e., eustatic) sea level changes and changes in the land elevation (i.e., subsidence) when calculating local SLR changes. The tide gauge at Galveston Pier 21, NOAA Station 8771450 was utilized for this analysis as this process requires at least 40 years of recorded data to fully estimate historical patterns. To evaluate local subsidence monitoring data, recent data from the Harris-Galveston Subsidence monument GPS PA36 were reviewed, which indicated a rate of subsidence of 0.346 in/yr (8.8 mm/yr) for the last 5 years. This was coupled with the Pier 21 data to provide for a higher potential rate of SLR. Results are presented in Table 7. For design purposes, an average of the intermediate levels of the observed and monitored ranges was used.

Utilizing the wind-wave values and the accompanying parameters (H_{mo}, Run-up, Set-up, Water Levels, and SLR) as determined above, design elevations for the two bird islands were determined. The islands had to be designed to an elevation that would meet the expected design requirements mentioned in the Overall Considerations section. The recurrence interval design storm impacts were determined using the Joint Probability Method (JPM), which assumes that wind speed and water level occur as independent events. Therefore, the annual probability of a recurrence interval event can be calculated by the statistical probability of the water level and wind speeds occurring during a given storm event, as shown as Equations (1) and (2). SWE is the still water elevation, or storm surge water level..

Table 7. Calculated Sea Level Rise Values for Galveston and Trinity Bay, TX.

Method	10 Year RSLR (ft)	20 Year RSLR (ft)	50 Year RSLR (ft)
Pier 21 Observed Low (historic)	0.21 (0.06 m)	0.43 (0.13 m)	1.07 (0.33 m)
Pier 21 Observed Intermediate (mod NRC Curve I)	0.28 (0.09 m)	0.57 (0.17 m)	1.55 (0.47 m)
Pier 21 Observed High (mod NRC Curve III)	0.47 (0.14 m)	1.01 (0.31 m)	3.08 (0.94 m)
Subsidence Monitored Low (historic)	0.34 (0.10 m)	0.69 (0.21 m)	1.72 (0.52 m)
Subsidence Monitored Intermed (mod NRC Curve I)	0.40 (0.12 m)	0.83 (0.25 m)	2.20 (0.67 m)
Subsidence Monitored High (mod NRC Curve III)	0.60 (0.18 m)	1.27 (0.39 m)	3.72 (1.13 m)

Table 8 shows the estimated impact elevations for LBI and TBIM using the JPM. As these values do not take into account SLR and local settlement or consolidation over time, the impact elevations should generally increase as a function of time as the as-constructed elevation of the sites decrease and sea levels rise. For LBI and TBIM, the estimated 50-year settlement ranges between 2.0 feet (0.61 meter) and 2.5 feet (0.76 meter) (HVJ 2021).

$$P(SWE, Wind)) = p(SWE) * p(Wind) \quad (1)$$

$$p(Event) = 1 / (p(SWE, Wind)) \quad (2)$$

where p(SWE) = probability of Still Water Elevation, and p(Wind) = probability of Wind Speed

Table 8. Estimated Target Elevations of LBI and TBIM.

Return Period	LBI Target Design Elevation (ft MLLW)	TBIM Target Design Elevation (ft MLLW)
1 Year	3.0 (0.91 m)	3.7 (1.13 m)
2 Year	6.6 (2.01 m)	6.7 (2.04 m)
5 Year	8.1 (2.47 m)	7.9 (2.41 m)
10 Year	10.2 (3.11 m)	9.5 (2.90 m)

LBI and TBIM design profiles were ultimately developed based upon limiting factors of material availability and geotechnical stability of initial construction. To evaluate the wind-wave impacts to the sites, a time-based approach was derived analyzing the sites with respect to the design waves acting on the sites as their elevations decrease over time with respect to the water levels as resulting from SLR and settlement and consolidation of the bay bottom foundation and hydraulic fill itself. These analyses resulted in the timelines of anticipated site considerations shown in Tables 9 and 10.

Based on the analysis, the site elevations should generally protect the constructed features from wave attack under normal weather events and smaller storm events. Due to settlement and RSLR, the likelihood of overtopping increases with time and/or larger storm surge water levels.

Table 9. Time Analysis of LBI Site Impacts

Construction Year	Dike Elevation (ft)	RSLR (ft)	Recurrence Storm Event	Stormwater Elev. (ft)	Overtopping (ft)
0	9.0 (2.74 m)	0.00 (0 m)	1	2.6 (0.79 m)	NA
			2	6.2 (1.89 m)	NA
			5	7.7 (2.34 m)	NA
			10	9.8 (2.99 m)	0.8 (0.24 m)
1	8.2 (2.50 m)	0.03 (0.01 m)	1	2.7 (0.82 m)	NA
			2	6.3 (1.92 m)	NA
			5	7.7 (2.34 m)	NA
			10	9.8 (2.99 m)	1.6 (0.49 m)
2	8.0 (2.44 m)	0.07 (0.02 m)	1	2.7 (0.82 m)	NA
			2	6.3 (1.92 m)	NA
			5	7.7 (2.34 m)	NA
			10	9.8 (2.99 m)	1.8 (0.55 m)
5	7.4 (2.26 m)	0.17 (0.05 m)	1	2.8 (0.85 m)	NA
			2	6.4 (1.95 m)	NA
			5	7.8 (2.38 m)	0.4 (0.12 m)
			10	9.9 (3.02 m)	2.5 (0.76 m)
10	7.4 (2.26 m)	0.34 (0.10 m)	1	3.0 (0.91 m)	NA
			2	6.6 (2.01 m)	NA
			5	8.0 (2.44 m)	0.7 (0.21 m)
			10	10.1 (3.08 m)	2.8 (0.85 m)
20	7.3 (2.23 m)	0.71 (0.22 m)	1	3.3 (1.01 m)	NA
			2	6.9 (2.10 m)	NA
			5	8.4 (2.56 m)	1.1 (0.34 m)
			10	10.5 (3.20 m)	3.2 (0.98 m)
50	7.2 (2.19 m)	1.90 (0.58 m)	1	4.5 (1.37 m)	NA
			2	8.1 (2.47 m)	0.9 (0.27 m)
			5	9.6 (2.93 m)	2.4 (0.73 m)
			10	11.7 (3.57 m)	4.5 (1.37 m)

SHORE PROTECTION DESIGN

Due to the fact that these new bird islands will be created in open water and will be subject to constant wave energy impacts from natural wind and storm events, the bird islands will require shore protection. Failure to provide wind-wave and storm protection for the new islands would lead to the loss of sediment and reduce the effective lifespan of the islands. Thus, a rock shore protection revetment was designed in accordance with USACE EM 1110-2-1100 CEM Part VI (USACE 2002) and USACE EM 1110-2-1614, *Design of Coastal Revetments, Seawalls, and Bulkheads,* (USACE 1995). Median weight of stone (W50), layer thickness, and median stone diameter (D50) were determined utilizing the Hudson Armor Stone Equation for rubble-mound structures. A gradation of armor stone by weight at 0%, 15%, 50%, 85%, and 100% lighter was developed in accordance with the *Automated Coastal Engineering System (ACES),*

Table 10. Time Analysis of TBIM Site Impacts

Construction Year	Dike Elevation (ft)	RSLR (ft)	Recurrence Storm Event	Stormwater Elev. (ft)	Overtopping (ft)
0	10.7 (3.26 m)	0.00 (0 m)	1	3.7 (1.13 m)	NA
			2	6.7 (2.04 m)	NA
			5	7.9 (2.41 m)	NA
			10	9.5 (2.90 m)	NA
1	9.6 (2.93 m)	0.03 (0.01 m)	1	3.7 (1.13 m)	NA
			2	6.7 (2.04 m)	NA
			5	7.9 (2.41 m)	NA
			10	9.5 (2.90 m)	NA
2	9.3 (2.83 m)	0.07 (0.02 m)	1	3.8 (1.16 m)	NA
			2	6.7 (2.04 m)	NA
			5	8.0 (2.44 m)	NA
			10	9.6 (2.93 m)	0.2 (0.06 m)
5	8.5 (2.59 m)	0.17 (0.05 m)	1	3.9 (1.19 m)	NA
			2	6.8 (2.07 m)	NA
			5	8.1 (2.47 m)	NA
			10	9.7 (2.96 m)	1.1 (0.34 m)
10	8.5 (2.59 m)	0.34 (0.10 m)	1	4.0 (1.21 m)	NA
			2	7.0 (2.13 m)	NA
			5	8.2 (2.50 m)	NA
			10	9.8 (2.99 m)	1.4 (0.43 m)
20	8.3 (2.53 m)	0.71 (0.22 m)	1	4.4 (1.34 m)	NA
			2	7.4 (2.26 m)	NA
			5	8.6 (2.62 m)	0.3 (0.09 m)
			10	10.2 (3.11m)	1.9 (0.58 m)
50	8.2 (2.50 m)	1.90 (0.58 m)	1	5.6 (1.71 m)	NA
			2	8.6 (2.62 m)	0.4 (0.12 m)
			5	9.8 (2.99 m)	1.6 (0.49 m)
			10	11.4 (3.47 m)	3.2 (0.98 m)

Chapter 4-4 (USACE 1992). The rock was sized according to the results of the wind-wave analysis, with a 5-year wind wave taken from the 10-year JPM storm event, selected as the basis for the design of the rock armoring. The 5-year wind wave would produce an estimated 3.35-foot (1.02 meter) and 3.65-foot (1.11 meter) wave height at LBI and TBIM locations, respectively. To protect against erosion at the toes of the stone protection, a bench style of protection for the toes was designed per EM 1110-2-1614, Case III: Moderate-to-Severe Scour Potential. From the shore protection calculations, the minimum required shore protection specifications were derived as shown in Table 2 and Table .

Table 11. Bird Island Required Stone Characteristics.

	LBI	TBIM
W50 (lbs)	500 (226.8 Kg)	650 (226.8 Kg)
R (ft)	3.00 (0.91 m)	3.25 (0.99 m)
D50 (Inches)	18 (45.7 Cm)	19 (48.3 Cm)

Table 12. Minimum Required Stone Gradations for LBI and TBIM.

Gradation (% Lighter)	LBI (lbs)	TBIM (lbs)
100	2,000 (907.2 Kg)	2,600 (1179.3 Kg)
85	1,000 (453.6 Kg)	1,300 (589.7 Kg)
50	500 (226.8 Kg)	650 (294.8 Kg)
15	200 (90.7 Kg)	325 (147.4 Kg)
0	60 (27.2 Kg)	80 (36.3 Kg)

These calculated values were compared to historical shore protection projects in Galveston and Trinity Bay, which were deemed to be comparable to the shore protection of LBI and TBIM for similar design storm events. The selection of a larger storm event was considered; however, that would have required larger stones for a higher return period, which would be uneconomical and would increase the median stone size by almost 100%, yielding an unrealistic gradation that would have increased the required shore protection cross section.

Estimated tonnages of shore protection were calculated in accordance with the final design configuration of the islands based on cross sections drawn in Computer-Aided Design (CAD), the results of the final shape and length of the rock protection levees resulted in approximate required tonnages of over 34,000 tons (30,844.3 metric tons) and 127,000 tons (115,212.5 metric tons) of armor stone, including 6,000 tons (5,443.1 metric tons) and 18,000 tons (16,329.3 metric tons) of blanket stone, for LBI and TBIM, respectively.

Oyster Wave-Trip

Oyster reef wave trips will be designed to provide protection to some portions of the island while providing environmental benefit and oyster mitigation. This feature is the same general design for both LBI and TBIM, in which the dredged material is to be placed on the bay bottom to provide vertical relief and topped with a layer 100 feet (30.48 meter) wide and 30 inches (0.76 meter) thick of crushed limestone cultch approximately 3 inches (7.62 centimeter) in diameter to produce a final construction top elevation of -1.0-foot (-0.3-meter) MLLW before a state of equilibrium is reached between the feature and the environment. The elevation at the top of the wave trip is set to remain below the water level to ensure oyster recruitment. For LBI, the eastern side of the island will be protected by an oyster wave trip; at TBIM, each of the three bird islands located at the vertices will be protected by oyster reef wave trips. To determine the effectiveness of the wave trip, wave transmission coefficients were evaluated. Since the feature will always be submerged under normal design conditions, it will be evaluated following a method like a low crested breakwater, based on *Wave Transmission and Reflection at Low-crested Structures* (Van der Meer et al. 2005). During normal water levels and smaller storm events, the oyster wave-trip structure will reduce or induce breaking waves, providing protection by diminishing the wave energy impacting the islands. The structure will also reduce the effects of waves in slightly elevated water levels. However, the wave trip is intended to minimize impacts, but as water levels increase (i.e., storm surges), the effectiveness of the wave trips decreases, with increasingly higher waves than the reef. The overall design assumes that the features will reach a state of equilibrium with the normal wave climate and develop a living oyster reef. Once the reef has been established, the structure would be assumed to behave like a large homogenous mass, creating a resilient structure.

CONCLUSION

The HSC-ECIP, over the entire six segments involved in the study, will produce several million cubic yards of dredged material over the entire project footprint resulting from the channel widening and deepening efforts. For the two segments discussed in this paper (Segments 1 and 2) all useable dredge material will be used beneficially, creating two new bird islands, future marshes, and multiple new oyster pads and reefs. The beneficial re-use of dredge material was a key driver for the involved local, state, and federal stakeholders in the Galveston Houston region who helped move this project along during the feasibility study. Evaluation of the design considerations discussed in this paper guided the efforts to determine what was possible to build with the dredged materials resulting from the widening. Starting from historical wind data and progresses into wind-wave design characteristics to determine RSLR, run-up, set-up, and return period wave heights, the elevations of the islands were designed to and armored with rip-rap shore protection to a design that will meet the requested usable life of the islands.

It is estimated that it will take approximately eight to ten months to complete the construction of LBI with construction starting in summer of 2022. Construction of TBIM is estimated to take two years to complete and is forecasted to begin early 2023. With the completion of both new features, Galveston and Trinity Bays will gain two new environmental features that will provide habitat for shore birds and aquatic life in the greater Houston region and as a flyover rest stop for birds during migration seasons. These new bird islands are a result of numerous hours of coordination with local, state, and federal resource agencies resulting in the successful efforts of habitat creation for local and migratory birds.

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DATA AVAILABILITY

Some data used during the study are proprietary or confidential. This data may be provided upon request with restrictions on republication and use.

OYSTER MITIGATION OPPORTUNITIES FOR THE HOUSTON SHIP CHANNEL

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ABSTRACT

The Houston Ship Channel (HSC) Expansion Channel Improvement Project (ECIP), also known as Project 11, requires the widening of the existing channel from 530 (161.5 meters) to 700 feet (213.4 meters) and excavating bend easings and channel flares within Galveston Bay, Texas, and the creation of beneficial use (BU) sites with dredged material. The ship channel improvements directly impacted oyster reef along the HSC and Bayport Ship Channel (BSC) Flare through new work dredging . In accordance with U.S. Army Corps of Engineers (USACE) planning policy, credit for mitigation was determined by using USACE-certified habitat models to determine functional losses from impacts and functional gains (or "lift") from mitigation.

The mitigation method allows BU of dredged material to build relief above the surrounding bay bottom and cap it with a veneer of suitable cultch, which provides the hard substrate for natural recruitment and settlement of oysters during the spat set season. USACE and others have applied this BU technique to restore oyster reef habitat in the Chesapeake Bay estuary and in New York/New Jersey Harbor area.

The traditional mitigation technique in Galveston Bay involved the use of rock or other hard substrate to build the base of the reef to provide relief off the bay bottom, and to provide the spat settlement cultch layer at the surface. At significantly more cost, this design and construction technique uses a larger amount of hard material for non-recruitment volume than beneficially using dredged material. Using the dredged material to provide vertical relief, effectively raising the bottom of the bay at the oyster mitigation sites, provides a means to beneficially use dredged material generated from the HSC widening, helping to fulfill the BU objective for this project, while reducing project costs by using less rock material, and helping to increase the navigation project net benefit-cost ratio.

Mechanical dredging of channel materials to construct vertical relief and clutch layers at the mitigation sites is a component of an upcoming dredging contract. Mitigation construction of the oyster pads will be completed by a dredging contractor and monitored by Port Houston, and accepted by the USACE as mitigation for the oyster reef impacts caused by the HSC-ECIP.

Keywords: Beneficial Use, Dredging, Oysters, Mitigation, Houston Ship Channel, Project 11, Port Houston.

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INTRODUCTION

The Houston Ship Channel (HSC) Expansion Channel Improvement Project (ECIP) Final Integrated Feasibility Report and Environmental Impact Statement (FIFR-EIS) was completed in December 2019 (USACE 2019). To evaluate Federal interest in alternative plans for reducing transportation costs and addressing navigation safety issues, the HSC system was divided into six segments:

- Segment 1: HSC Bay Reach from Bolivar Roads to Morgans Point
- Segment 2: Bayport Ship Channel (BSC)
- Segment 3: Barbours Cut Channel (BCC)
- Segment 4: HSC Bayou Reach from Boggy Bayou to Sims Bayou
- Segment 5: HSC Bayou Reach from Sims Bayou to I-610 Bridge
- Segment 6: HSC Bayou Reach from I-610 Bridge to Main Turning Basin

Following the conclusion of the HSC ECIP Feasibility Study phase in 2020, the Preconstruction, Engineering, and Design Phase (PED) phase commenced to further refined and design the project elements. This effort resulted in nine separate design packages referred to Project 11 by Port Houston (PHA). This paper will focus on oyster mitigation for project elements of Project 11.

BACKGROUND

As summarized below, Segments 1 and 2 consist of channel modification to widen the HSC and Bayport Ship Channel (BSC), ease channel bends, expand existing turning basins, and constructing new ones. The widening through Galveston Bay, Segment 1, is also divided lengthwise into the three straight segments of the existing HSC alignment.

- Segment 1 – HSC Bay Reach
  - (1a) Lower Bay – Extends from approximate Station 138+369 near Buoy 18 to Station 78+844 at Redfish Light 1 referred to as Bolivar Roads to Redfish.
  - (1b) Mid Bay – Extends from Station 78+844 to Beacon 75/76 at Station 28+605, referred to as Redfish to BSC.
  - (1c) Upper Bay – Extends from Station 28+605 to Morgans Point at approximate Station 0+00, referred to as BSC to BCC.
- Segment 2 – Bayport Ship Channel

Through new work dredging necessary to widen channels and excavate bend easings and channel flares within Galveston Bay, Project 11 construction will permanently impact the oyster reef located within the footprint of the channel modifications.

Design Packages

The project elements within Segments 1 and 2 were originally designed under four separate [dredging] Packages 3, 4, 5, and 6. The work under Package 4 was later split and added to Packages 3 and 5. The revised dredging packages are now referred to as Packages 3/4a, 4b/5, and 6.

Additionally, Package 1 is associated with Segment 1, but pertains to a standalone mitigation project that was designed by PHA but procured and administrated by the U.S. Army Corps of Engineers (USACE). The mitigation provided under Package 1 accounts for the required mitigation from the National Economic Development (NED) portion of the Recommended Plan as defined in the HSC-ECIP FIFR-EIS (Segment 1a, four bend easings in Segment 1, Segment 2, and Segment 3). Additional mitigation features included in Package 4b/5 account for the incremental, additional mitigation associated with the Locally Preferred Plan (LPP) portion of the Recommended Plan defined in the HSC ECIP FIFR-EIS.

A project overview of the four packages is shown in Figure 1.

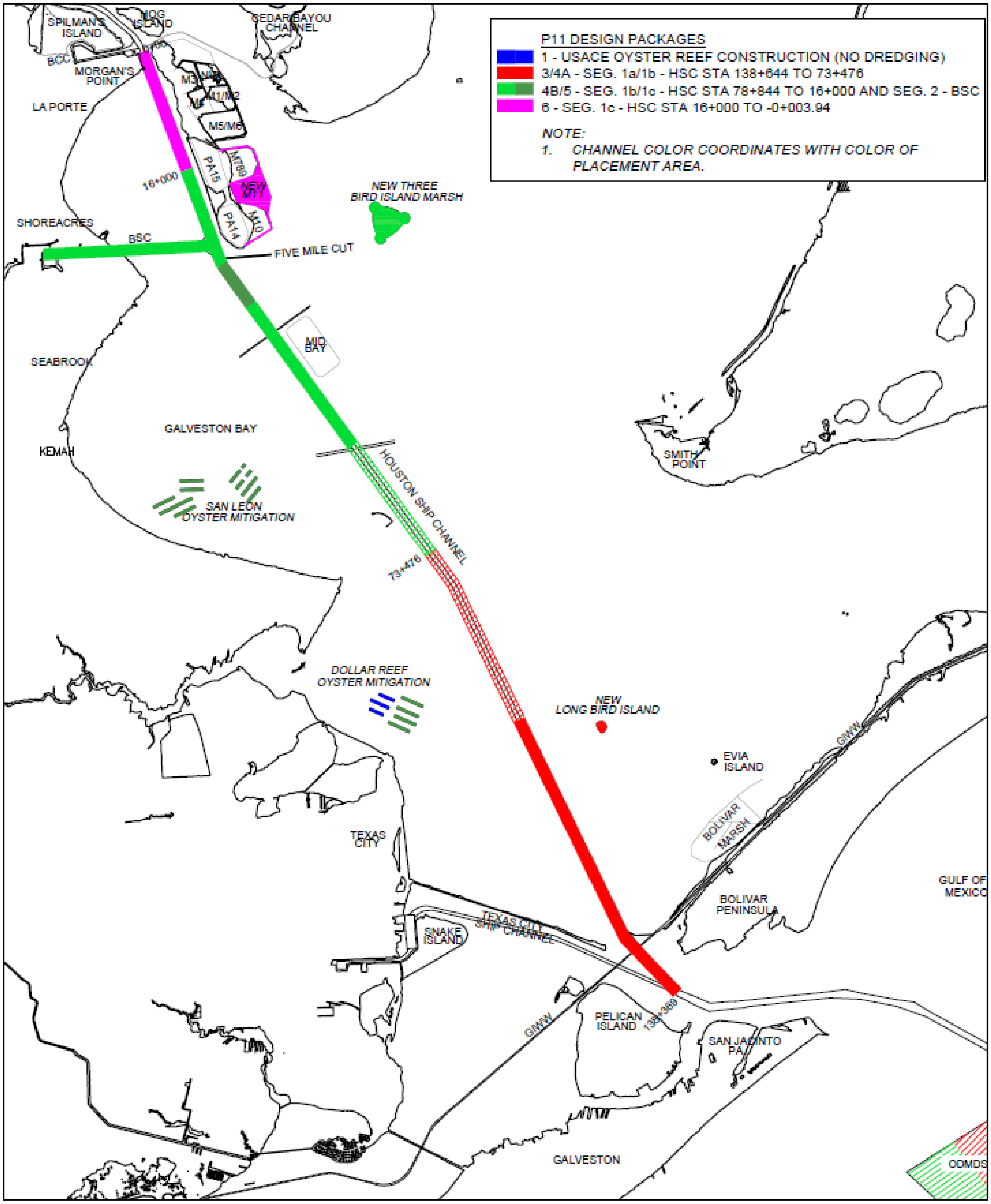

Figure 1. Project Overview of Project 11 Design Packages 1, 3/4a, 4b/5, and 6

IMPACTS

Due to the Project 11 dredging extent, most reef impacts occur along the margins of the HSC within Galveston Bay. The HSC channel widening through the Bay results in most of the impacts. The 700-foot (213-meter) channel width, determined via ship simulation was conducted with the participation of the Houston Pilots Association (HPA) during two simulation rounds. Sufficient width to realize the economic benefits necessary to justify the plan depends on having enough width for safe two-way traffic meeting of design vessels. The need to replace the existing shallow draft barge lanes directly adjacent to the main channel of the HSC and shift them outward of the revised channel also accounts for the remaining reef impact.

Oyster reef locations are not available above Morgans Point (northern limit of Segment 1). However, adequate salinity and unmaintained, shallow depth needed to support reef growth is limited in the NED areas above Morgans Point. Most of these areas are in portions of the existing HSC, turning basins, or adjacent to berths where waters are deepened and periodically maintained by dredging. Therefore, the potential for reef acreage is small compared to the potential impacts in the Galveston Bay.

The channel improvements under the Recommended Plan result in unavoidable, permanent adverse impacts to 352.5 acres (142.7 hectares) of oyster hard-bottom habitat. Mitigation for these impacts replace oyster habitat removed by the construction of Project 11 by restoring oyster habitat at the Dollar Reef Mitigation (DRM) and San Leon Mitigation (SLM) sites in Galveston Bay

Two different methods of construction were described in the FIFR-EIS:

1. The oysters required to be mitigated under the NED portion of the project would be solely constructed as part of Package 1 with limestone substrate with the desired relief of 18 inches (45.7 centimeters) above the bay bottom or allowing for 6 inches (15.2 centimeters) of settlement, approximately 24 inches (61.0 centimeters) of placement.

2. For the Recommended Plan portions of mitigation, the method includes beneficial use dredged new work material to build bottom relief berms capped with a thin veneer (e.g., 6 inches [15.2 centimeters] minimum) of suitable cultch (e.g., crushed limestone, river rock, or clean crushed concrete) and rely on natural recruitment to propagate growth during the spat set season. The type of cultch material has been successfully used in local mitigation projects, including the mitigation at Fisher's Reef for the BSC Improvements Project.

MITIGATION PLAN AND DESIGN

The primary objective of the mitigation project is to replace the significant net losses of oyster reef habitat impacted by modifications made to the HSC through the restoration of oyster habitat at one or more of the sites identified in Galveston Bay. Specifically, the mitigation plan provides the sufficient area of elevated relief and hard substrate surface for oyster attachment to compensate for the direct impacts associated with dredging the NED or the additional areas of the Recommended Plan. The restoration replaces the existing oyster habitat in Galveston Bay by providing the needed acres of hard surface area available for natural recruitment of oyster larvae.

Site Selection

In Texas, the main authority for managing oyster reefs falls under the Texas Parks and Wildlife Department (TPWD). TWPD's focus is on balancing the management of reefs as fisheries and as ecological resources. All natural oyster reefs are considered public resources, open to recreational and commercial harvesting from November through April, except for private leases, which have no closed season.

Restoration sites for Project 11 were selected from several locations impacted by Hurricane Ike-induced sedimentation in 2008 that were identified in the initial phase of planning under the HSC ECIP FIFR-EIS. Texas Parks and Wildlife Department (TPWD) has estimated that more than 50% of the reef in Galveston Bay were impacted by hurricane-induced sedimentation, and the oyster reef is a vital component of the commercial fishery of the State and Gulf Coast region.

The restoration replaces the oyster reef that contributes important ecological benefits to Galveston Bay, including provision of aquatic habitat structure for several fish and invertebrate species, improvement of water quality and clarity, as well as general re-establishment of essential fish and invertebrate habitat. Two of the restoration sites (San Leon and Dollar Reef) identified during planning were deemed more optimal due to the more favorable salinity. These sites were narrowed down further to general areas that would benefit the most by the construction of oyster reef mitigation pads with input from TPWD.

Mitigation Method

The mitigation method beneficially uses new work dredged material to construct the topographical relief above the surrounding bay bottom and with a veneer cap of suitable cultch, to provide the hard substrate required for natural recruitment of oysters during the spat set seasons. This approach provides a significant cost savings as rock is typically the most expensive component of these types of projects. And since oysters do not live below the surface layer, providing a solid medium of rock between the bay bottom and target relief is unnecessary.

This beneficial use (BU) technique to restore oyster reef has been successfully used by the USACE and others in the Chesapeake Bay estuary and in New York/New Jersey Harbor. Several variations of this method have been used or proposed including use of contained dredged maintenance material versus dredged new work material, and elevation of relief to provide an intertidal bar versus subtidal reef. However, all have beneficially used dredged material to build relief capped by a thinner cultch layer.

The traditional mitigation technique used locally in Galveston Bay involved using rock or other hard substrate to build the base of the reef to provide relief off of bay bottom, and to provide the spat settlement cultch layer at the surface. This uses a lot of hard material for non-recruitment volume at significantly more cost than beneficially using dredged material. Using the dredged material to raise the bottom of the bay provides a means to beneficially use dredged material generated which helps fulfill the BU objective for this project, and reduces costs by using less rock material, helping to increase the navigation project net benefit. The Dredged Material Management Plan (DMMP) developed for the HSC ECIP FIFR-EIS considered the existing geotechnical data for the dredge prism of the channel that will provide the new work material, and dredging cost factors, to plan how new work material could be used in a cost-effective and feasible manner to construct the mitigation pads. Chief considerations were the material type and ability to provide stable relief, which makes cohesive, stiff clays more desirable to use versus softer, unconsolidated sediments.

Agency Coordination

The conceptual orientation and layouts of the mitigation pads were presented to the Beneficial Uses Group (BUG) which is comprised of representatives from various state and federal resource agencies. Initial feedback included concerns that hydraulically pumping the dredged material may result in the unintended siltation of adjacent, existing oyster leases and reefs. Therefore, it was determined that oyster reef mitigation for NED Plan (Package 1) would be constructed with the traditional methods of using rock to create relief rather than beneficially using dredged material.

For the remaining portions of the mitigation, subsequent BUG meetings and coordination resulted in the determination to use a mechanical dredge (rather than hydraulic) to address the turbidity concerns. This decision was reached after a thorough literature review identified and considered a multiple tremie/diffuser hydraulic approach.

Design Considerations

The oyster mitigation pads are arranged based on several factors. These factors included:

- Avoiding existing pipelines transecting the pad sites.
- Avoiding areas of sloping bay bottom which complicate the construction and design of oyster pads with uniform height.
- Reorienting pads with respect to prevailing currents.
- Maintaining the recommended minimum distance of 800 feet (243 meters) between oyster pads where feasible.
- Avoiding other known areas of existing oyster reef or oyster leases.
- Increasing/decreasing mitigation acreage requirements that resulted from numerous dredging template change considerations.
- Providing a consistent elevation for the contractor to construct to in order to simplify the construction and acceptance criteria.

Coordination occurred regularly with the BUG regarding the oyster reef mitigation. In terms of orientation, the pads were situated in order to provide for the most advantageous level of oyster spat recruitment. This was done by providing approximate distances between the pads of 800 feet (243 meters) and orienting them to face predominant current directions. This promotes recruitment and discourage competition as well as provide necessary nourishment.

Design Elevations

Oyster reef construction must meet minimum requirements of relief above the bay bottom in order to achieve oyster recruitment and establish living reef. Therefore, another design and construction consideration are the methods used to achieve the required relief.

Discussions with the stakeholders revealed the necessary relief requirement of approximately 18 inches (45.7 centimeters). Typically, this would include some tolerance to allow for deviations typical of the construction method. In anticipation of some amount of settlement, industry standard typically includes the placement of 30 inches (76.2 centimeters) of solid cultch. Past projects have been performed where the target relief was specified as the requirement. Discussions with industry have shown that this is difficult to construct under water when there are moderate changes in depth. Therefore, the decision was made to provide for target grade elevations rather than minimum reliefs. Grade elevations have been designed for each of the pads based on the existing bay bottom elevations. Grades were selected to maintain a minimum relief of 18 inches (45.7 centimeters) after an allowance for estimated settlement and an allowance for the lower tolerance level of a +/- 0.5-foot (.15-meter) construction tolerance. In general, each pad will have an average relief of 24 inches (61.0 centimeters), with a minimum relief to be 18 inches (45.7 centimeters). Relief in this regard, is measured from the top of the cultch veneer down through the cultch and mechanical fill to the pre-existing bay bottom.

Clutch Veneer

A final point of consideration regarded placement of the cultch veneer to minimize losses due to settlement of material into and within the mechanical fill base pad. This is somewhat dependent on how the material is placed. The intention is to encourage a slower release of cultch material to be spread over a larger area, rather than a mass of cultch that would be more prone to sink into the fill. Construction methodology aside, a settlement of the cultch into the pad materials was considered. Based on the geotechnical properties, a maximum allowance of 6 inches (15.2 centimeters) of cultch loss into the fill was recommended. Adding this to the 6 inches (15.2 centimeters) of minimum cultch thickness required equates to a foot (0.3 meters) of cultch material, or roughly twice the originally proposed quantity. However, this is not expected to occur uniformly across all areas of the pads. The actual loss of cultch material into the fill could be zero in some areas, or up to 6 inches (15.2 centimeters) in others. Therefore, a buffer for losses was included to account for the potential of approximately half of the site area to require additional cultch placement to meet the required relief.

Dollar Reef Oyster Mitigation

DRM is located just northeast of Dollar Reef in Galveston Bay and is a composite of seven oyster mitigation pad sites. There are four 20-acre (8.1-hectare) pads (DRM pads B-1 through B-4), one 13-acre (5.3-hectare) pad (DRM pad A-1), one 17.4-acre (7.0-hectare) pad (DRM pad A-2), one 6.7-acre (2.7-hectare) pad (DRM Pad A-3) with a 1.0-acre (8.1-hectare) extension (Option 1 at DRM pad A-3), and 6.5-acre (2.7-hectare) extension (Option 2 at DRM pad A-3). The 20-acre (8.1-hectare) pads are each 2,904 feet by 300 feet (885.1 meters by 91.4 meters). The 13-acre (5.3-hectare) pad is 1,887.6 feet by 300 feet (575.3 meters by 91.4 meters). The 17.4-acre (7.0-hectare) pad is 2,531.3 feet by 300 feet (771.5 meters by 91.4 meters). The 6.7-acre (2.7-hectare) pad is 972.8 feet by 300 feet (296.5 meters by 91.4 meters). The 1.0-acre (0.4-hectare) extension is 145.2 feet by 300 feet (44.3 meters by 91.4 meters). The 6.5-acre (2.6-hectare) extension is 941.4 feet by 300 feet (286.9 meters by 91.4 meters). Refer to **Error! Reference source not found.** for the location of DRM.

DRM will be constructed in two parts. The first part will occur in a standalone contract using traditional design and construction techniques (under Package 1 procured and administered by USACE) for DRM pads A-1 through A-3, and the second part pads B-1 through B-4 will be built as part of dredging Package 4b/5.

For the pads at DRM to be built under Package 4b/5, materials from the HSC dredging will be mechanically dredged, transported, and placed over each of the areas to create foundation surfaces. Following this, a 6-inch (15.2-centimeter) veneer of cultch will be installed over the top of the filled pads. The combination of the mechanical fill and cultch veneer will provide an 18-inch (45.7-centimeter) relief above the bay bottom to meet the intended goals.

San Leon Oyster Reef Mitigation

The 179.8-acre (72.8-hectare) SLM is located just north of Eagle Point in Galveston Bay and is to be constructed during Package 4b/5 like those at DRM. Following the previously discussed reconfigurations and mitigation acreage requirements, SLM is now a composite of eleven proposed oyster mitigation pad sites of varying sizes. The proposed pads are listed below in **Error! Not a valid bookmark self-reference.**.

SLM pad sites will be constructed like the pads at DRM, using mechanically dredged and placed materials and covered by an approximate 6-inch (15.2-centimeter) veneer of cultch as shown in Figure 2.

The design of SLM and corresponding coordination occurred in conjunction with the DRM location. During the coordination, one of the 20-acre (8.1 hectare) pad sites from DRM was moved to SLM. Additionally, due to an area of steeper than anticipated slopes, the SLM pad configuration was adjusted to move into areas of relatively flatter bay bottom while maintaining offsets from pipelines and avoid potential obstructions found during site investigations. Refer to **Error! Reference source not found.** for the SLM location.

Table 1. SLM Pad Sizes and Dimensions

SLM Pad No.	Area (acres)	Area (Hectare)	Dimensions (feet by feet)	Dimensions (meter by meter)
S-1	20.0	8.1	2,904.0 x 300	885.1 x 91.4
S-2	31.0	12.5	4,506.0 x 300	1373.4 x 91.4
S-3	20.0	8.1	2,904.0 x 300	885.1 x 91.4
S-4	20.0	8.1	2,904.0 x 300	885.1 x 91.4
S-5	20.0	8.1	2,904.0 x 300	885.1 x 91.4
S-6	17.2	7.0	2,490.1 x 300	758.9 x 91.4
S-7	20.0	8.1	2,904.0 x 300	885.1 x 91.4
S-8	6.0	2.4	871.2 x 300	265.5 x 91.4
S-9	9.0	3.6	1,306.8 x 300	398.3 x 91.4
S-10	3.4	1.4	500.0 x 300	152.4 x 91.4
S-11	13.2	5.3	1,916.6 x 300	584.2 x 91.4

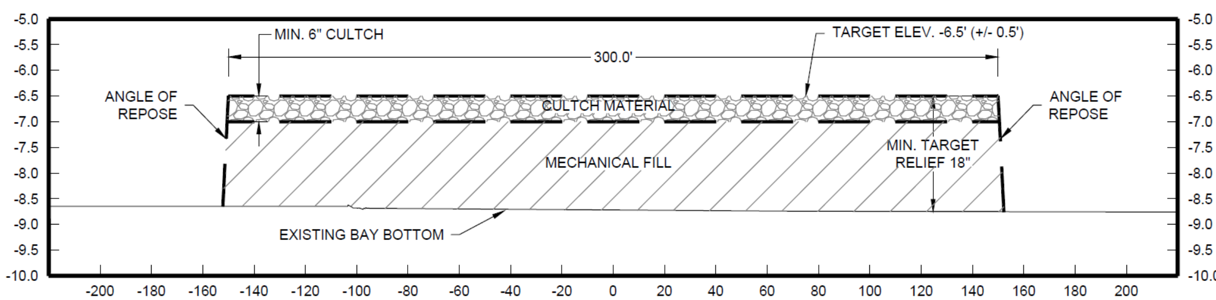

Figure 2. Mechanical Fill Oyster Pad Typical Section

CONCLUSION

Two mitigation areas at Dollar Reef and San Leon were selected as the most optimal sites. The sites selected were identified in conjunction with the resource agencies, including the TPWD, the primary managing agency of oyster reef in Galveston Bay. The DRM is a composite of seven oyster mitigation pad sites and will be constructed in two parts: one implementing traditional design and construction techniques, the second making use of dredged material from the HSC dredging. The SLM will implement the use of dredged material in the construction of its eleven oyster mitigation pad sites of varying sizes.

The mitigation method meets project goals by beneficially using project-dredged new work material capped with a veneer of cultch to construct the topographical relief above the surrounding bay bottom. This approach provides a cost savings to the project by reducing rock which is typically the most expensive component of these types of projects.

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DATA AVAILABILTY

Some data generated or used during the study is available from the corresponding author by request.
Some data generated or used during the study is proprietary or confidential. This data may be provided upon request with restrictions on republication and use.

M12 MARSH CREATION IN TIGHT QUARTERS

M. Cameron Perry, P.E.[1]

EXTENDED ABSTRACT

Port Houston and the U.S. Army Corps of Engineers (USACE) are working together on the Houston Ship Channel (HSC) Expansion Channel Improvement Project (ECIP), also known as Project 11. The HSC project is divided into several sections, with Segment 3 consisting of improvements to Barbours Cut Channel (BCC). The proposed project will widen the Barbours Cut Channel and increase the diameter of the turning basin at the intersection of BCC and the HSC to improve maneuverability into and out of the channel. Approximately 2.8 million cubic yards (y^3) or 2.14 million cubic meters (m^3) of new work dredged material will need to be accommodated, and the USACE's current Dredged Material Management Plan does not allow material from the Project 11 work to be placed within existing Dredged Material Placement Areas (DMPA). As a result, a new placement area is required for Segment 3 construction.

Port Houston and USACE have a longstanding relationship with the regional Beneficial Uses Group (BUG) that helps direct and implement beneficial uses of dredged material along the HSC and within the Galveston Bay system. These projects have included marsh areas, rookery islands, and oyster reefs. Several beneficial use areas have been constructed along Atkinson Island, which is located immediately east of Segment 3/BCC. These sites have been constructed by hydraulically pumping new work material to create containment berms. Marsh features were then created through placement of maintenance material within the new confined cells. This process was proposed for a new site designated M12, and the associated containment berms would be constructed from Segment 3 dredged material. The M12 site would be located at the northern end of Atkinson Island and adjacent to the existing Wildlife Management Area (WMA), that consists of marsh and upland bird nesting habitat.

The first phase of the M12 placement area design reviewed proposed berm alignments from the USACE Feasibility Study, as well as existing berm and Atkinson Island elevations. Previous berm projects had a minimum berm crest elevation of approximately 6.7 ft (2.0 m) NAVD. The proposed M12 berm would need to at least match that elevation after expected material settlement and sea level rise. In addition, the proposed design included using the Atkinson Island WMA as a portion of the containment system. A review of LiDAR elevation data from the National Oceanographic and Atmospheric Administration indicated that the island would not fully contain material. In addition, there were concerns that sedimentation would occur within existing marsh areas and would fill existing tidal channels and ponds. As a result, a shore parallel containment berm was developed to provide containment for material within M12 but would be offset from the WMA shoreline to allow tidal connectivity between the WMA and Galveston Bay. The construction of the berms may result in some sedimentation, but the project design includes monitoring of these areas, maintaining tidal connections, and creating an opening between an existing marsh cell and the WMA marsh to further enhance tidal exchange.

The USACE Feasibility Study (USACE 2019) for the project estimated that a single outer berm at the M12 site could be created to provide required containment for future creation from maintenance material placement. In addition, the berm would use all proposed new work dredged material from Segment 3.

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However, during the design phase and after collection of geotechnical borings, it was noted that foundation material characteristics along the berm alignment were much firmer than expected, which meant less foundation displacement was expected during the hydraulic placement of the berm. The reduction in displacement compared to the design in the Feasibility Study resulted in significantly less material needed to construct the berms. The Feasibility Study design used information from previous marsh cell projects at Atkinson Island, which was appropriate at the time considering detailed geotechnical investigations had not been performed. The volumes needed to create the outer berm and a newly designed inner berm were then updated using new displacement values along with material retention formulas provided by project geotechnical engineers were used. These formulas area based on previous project results, material types, and dredge pipeline length. Material characteristics from the proposed dredge site at BCC, along with varying pipeline lengths results in an estimated 1.04 million y^3 (0.8 million m^3) needed to construct the berms. This amount is considerably less than the total dredged amount of 2.8 million y^3 (2.14 million m^3).

This reduction in material to create the berm, along with an increase in dredge volume due to revisions in the dredge prism, resulted in a surplus of dredged material that required a solution for placement. Use of the M12 interior was then designated as the material placement site. However, the M12 site was intended to be marsh habitat that is typically created using maintenance material rather than new work material. Project designers worked with the project geotechnical consultants to estimate placement options of the new work material as upland and as marsh habitat. Analyses indicated that approximately 55 acres (22.3 hectares) of uplands would be created from clay ball material, approximately 111 acres (44.9 hectares) of marsh habitat would be created from clay ball material, and 87 acres (35.2 hectares) of marsh area would be develop created from the settlement fine grained material. The upland and marsh creation areas with the coarse-grained (clay ball) material will require significant movement of dredge pipe outfalls and likely mechanical reworking of the placed material. The amount of material and size of the areas will also be dependent upon the final amounts needed to construct the proposed containment berms.

The proposed M12 site will require detailed monitoring during construction and may result in changes to placement schemes after construction of the berms. Overall capacity at the site though is more than sufficient for the project. The creation of upland areas from the new work material will also present an opportunity to use that material for other areas within the Atkinson Island complex.

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DATA AVAILABILITY

All data, models, or code used during the study were provided by a third party. Direct requests for these materials may be made to the provider as indicated in the Acknowledgments.

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A TEXAS COAST-WIDE EFFORT TO RESTORE WETLANDS USING DREDGED MATERIAL

Daniel Opdyke[1], Todd Merendino[2], Angela Sunley[3], Jane Sarosdy[4], Ray Newby[5], Carter Coleman[6], Rick Coupe[7], Matthew Mahoney[8]

EXTENDED ABSTRACT

In 2017, the Deepwater Horizon (DWH) Natural Resource Damage Assessment (NRDA) Texas Trustee Implementation Group (TIG) adopted a Restoration Plan and Environmental Assessment that included a project to restore Texas coastal wetlands through the beneficial use (BU) of dredged material. This project contributes to fulfilling an identified goal of the *Deepwater Horizon Oil Spill: Final Programmatic Damage Assessment and Restoration Plan and Final Programmatic Environmental Impact Statement* (Final PDARP/PEIS) (DWHNRDAT 2016)—restoring and conserving injured habitat. This project has a clear nexus to the injuries described in the Final PDARP/PEIS because it would restore more than a thousand acres of wetlands, which is a habitat type that was injured as a result of the DWH incident. In addition, restoration of Texas coastal wetlands through BU of dredged material supports the goals of several conservation plans. These plans include but are not limited to the following:

- *Texas Coastal Management Program Final Environmental Impact Statement* (NOAA and State of Texas 1996)
- *Texas Coastal Resiliency Master Plan* (TGLO 2019)
- *Gulf of Mexico Regional Sediment Management Master Plan* (GOMAHCRT 2009)
- *Texas Conservation Action Plan 2012 – 2016: Gulf Coast Prairies and Marshes Handbook* (TPWD 2012)

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The team of Ducks Unlimited; Anchor QEA, LLC; Sarosdy Consulting, Inc.; and Texas Department of Transportation is working with the Texas TIG to implement the project.

The project goal is selection, design, and facilitation of the implementation of landscape-scale restoration of degrading Texas coastal wetlands through BU. Throughout the Texas coast, salt marshes are converting to open water even in sites near operations with BU-compatible dredged material that could be used to rebuild them. The project team worked with local stakeholders (e.g., landowners, state land managers, and nonprofit organizations) to identify 163 potential wetland restoration sites. The project team developed criteria for final site selection, which included the following important considerations:

- The site encompasses degraded saline marsh and is tidally influenced.
- The site has a willing landowner that will protect the site from development after restoration.
- The site is protected from erosive forces.
- The site is located near suitable dredged sediment.
- The site is sustainable over time.
- The site avoids significant impediments to permitting, such as existing oyster reefs or seagrass beds.

Using the initial list of 163 sites, the criteria above, and other criteria including ecological, logistical, and cost considerations, the Texas TIG selected eight sites. These include restoration footprints ranging from less than 50 acres to landscape-scale footprints of more than 1,000 acres at the following locations:

- Lower Neches Wildlife Management Area Old River Unit (Orange County, Texas)
- Texas Point National Wildlife Refuge (NWR) (Jefferson County, Texas)
- McFaddin NWR Willow Lake Terraces (Jefferson County, Texas)
- Anahuac NWR Roberts Mueller Tract (Chambers County, Texas)
- San Bernard NWR Sargent Oil Field (Matagorda County, Texas)
- Schicke Point (Calhoun County, Texas)
- Guadalupe River Old Delta (Refugio County, Texas)
- Goose Island State Park Cells (Aransas County, Texas)

For these sites, potential sediment sources include maintenance and new work dredging for the Gulf Intracoastal Waterway and other federally authorized navigation channels and private ship channels, as well as mining of existing dredged material placement areas.

For each of the eight selected sites, the project team performed field work and engineering design and prepared a 60% basis of design report, opinion of probable construction cost, and permit application package. To facilitate future implementation of these projects, the project team also authored Oil Pollution Act and National Environmental Policy Act compliance documents and monitoring and adaptive management plans. As nearly shovel-ready projects, these sites are attractive for grant programs, such as a future Texas TIG Restoration Plan; the Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States [RESTORE] Act; various Texas General Land Office grant programs; and the National Fish and Wildlife Foundation National Coastal Resiliency Fund.

This project is part of a larger effort to develop a Master Plan for BU material throughout the Texas coast for a variety of uses (e.g., beach nourishment, bird islands). The BU Master Plan for the Texas coast has been identified in the 2017 Texas Multiyear Implementation Plan (implementing a portion of the Texas Bucket 1 allocation under the RESTORE Act) and may be funded in the future.

Keywords: beneficial use, Deepwater Horizon, stakeholders, engineering.

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DATA AVAILABILITY

Supporting data are available from the corresponding author by request.

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WATER QUALITY IMPACTS AND BUCKET DREDGING OPERATIONS

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ABSTRACT

Dredges may release some sediment from dredge buckets and disturb some bottom sediment that is not captured by the dredging operation. Some of this sediment gets released into the water column. While some may resettle quickly to the bottom because it is in chunks or it is released at or near the bottom, some inevitably remains in the water column as suspended solids. These suspended solids increase turbidity and can release nutrients or toxic constituents if these are associated with the targeted sediment. In addition to these water quality concerns, redeposition of these solids can potentially impact fish larvae, coral, and other sensitive species if they settle in sufficient quantity. These concerns lead to a lot of interest in quantifying suspended sediment releases associated with dredging operations. This manuscript describes an intensive data collection effort conducted near a clamshell bucket dredging operation in Boston Harbor in 1999. Water samples for total suspended solids analysis and turbidity readings were collected at multiple depths in the immediate vicinity of the dredging operation over portions of three days. The dredge used a different bucket type each day (conventional clamshell bucket, enclosed clamshell bucket, and a Cable Arm navigational bucket). Hayes et al (2000) presented the suspended sediment data collected during this project along with some initial analyses. This paper focuses on the more robust turbidity data which have not previously been published or analyzed. Signal processing techniques and non-parametric statistics were used to reduce the noise in the turbidity data, allowing evaluation of turbidity variations during the dredging operation and estimates of near-field dredge mass emissions rates at four depths in a tidal harbor water column. Estimated mass emissions rates were statistically similar for three different dredge bucket types. Implications for water quality modeling and environmental impacts are discussed.

Keywords: Boston Harbor, sediment resuspension, environmental dredging, contaminated sediment, dredge monitoring.

INTRODUCTION

Some bottom sediment escapes capture by dredging operations and becomes suspended in the water column near the dredge. This suspended sediment moves away from the immediate vicinity of the dredge through advection and diffusion, resulting in a turbidity plume. The rate and direction at which the turbidity plume spreads depend on the mixing energy and currents associated with the local environment and those induced

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by the dredging operation. Suspended particulates settle as the plume moves. Redeposition of resuspended sediment can also be a concern. Sufficient depths of redeposited sediment may impact fish, seagrasses, larvae, coral, or other sensitive species. These concerns are heightened when targeted sediments contain elevated concentrations of nutrients or toxic constituents.

Hayes et al (2000) and Welp et al (2001) analyzed TSS data collected in the immediate vicinity of a bucket dredge working within the Boston Harbor Federal Navigation channel (Figure 1) in August 1999. Great Lakes Dredge and Dock (GLDD) Dredge 54 dredged sediment from a 40-ft deep section of the Boston Harbor Federal navigation channel located just outside the mouth of the Chelsea River over the 3-day study period of August 5, 6, and 7, 1999. As part of a comparison to evaluate the relative effectiveness of dredge bucket types for the project, the dredge used a 26-cubic yard (cy) Cable Arm[7] bucket on 8/5, a 39-cy enclosed bucket (constructed from a 26-cy conventional clamshell bucket) on 8/6, and a 26-cy conventional clamshell bucket on 8/7. Water samples were collected from the front of the dredge platform, typically within 10 m laterally of the dredge bucket's vertical path, during the daytime ebb tide and analyzed for total suspended solids concentration (TSS). Turbidity readings were also collected at 1 second intervals from the same depths using D&A Instruments OBS-3 turbidity sensors over the three days. These turbidity data have not been previously analyzed and are the subject of this study. Figure 1 shows the dredging locations and direction of dredge movement during the monitoring periods.

SITE CONDITIONS

The dredging project required deepening the Federal channel to a newly authorized depth of 40 ft MLLW. The contract allowed payment for sediment removal to 42 ft. MLLW, which the contractor took advantage

Figure 1. Dredge position and movement (based on GPS antenna) during data collection periods; red arrows show direction of dredge movement.

[7]Cable Arm manufactures environmental dredge buckets often considered the industry standard. A Cable Arm Navigation-type dredge bucket was used in this study. It is NOT likely representative of the performance of a Cable Arm environmental bucket.

of in most cases. USACE (1998) shows sediment elevations of about -10.7 m MLLW in the 8/5 dredging area and -10.4 m MLLW in the 8/6 dredging area. Two areas were dredged on 8/7. First, about 0.5 m was removed from a previously dredged area; the predredging sediment elevation was about -12.5 m MLLW in this area. The dredge then moved to a shallower area at about 10:30 am on 8/7 with a predredging sediment elevation of about -8.7 m MLLW. Previous dredging operations had removed native sediment in the dredging areas down to about -12.2 m MLLW. Sediments above that elevation were recently deposited dark, black silty clay underlain by Boston Blue Clay (BBC).

Six sediment samples were collected from the dredging areas as part of this study. Five samples were classified as dark gray sandy silt (ML); the other sample was classified as sandy clay (CH) (Table 1). Average sediment characteristics were water content of 143%, specific gravity of 2.69, 21% fine sand, 47% silt, and 27% clay. No significant variations were noted among the days, except that one sample from the 8/6 dredging area (Sample B) had 31% medium and coarse sand; the other five samples were almost purely fine sands, silt, and clay.

Table 1. Measured sediment characteristics dredge by date.

	8/5/99		8/6/99		8/7/99		Average
	A	B	A	B	A	B	
Water Content (%)	178.2	130.5	121.1	142.6	151.7	132.2	142.7
Specific Gravity, Gs	2.74	2.64	2.7	2.7	2.7	2.67	2.69
> 140 sieve (%) (medium and coarse)	0	0	0	31	2	1	5.7
Fine Sand (%)	19	23	23	9	29	21	20.7
Silt (%)	63	47	44	33	51	41	46.5
Clay (%)	18	30	33	27	18	37	27.2
Classification	Sandy Silt (ML), Dark Gray					Sandy Clay (CH)	

Tide data at NOAA tide Station 8443970 Boston Harbor, located about 3 km south of the study area, show the studies were conducted during ebb tide, with monitoring extending from the start of ebb through slack

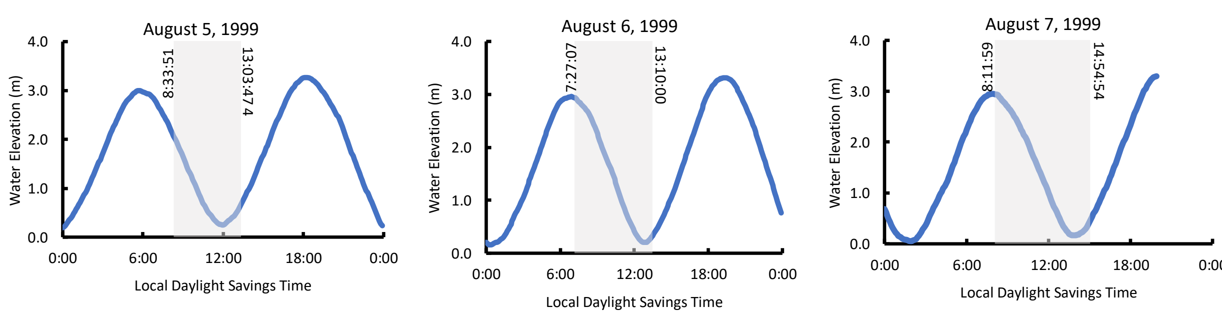


Figure 2. NOAA station 8443970 Tide variations during the study; shaded areas reflect sampling periods.[8]

[8]Tide data obtained on 10/14/2020 from https://tidesandcurrents.noaa.gov/waterlevels.html?id=8443970&units=standard&bdate=19990805&edate=19990807&timezone=GMT&datum=MLLW&interval=6&action=data.

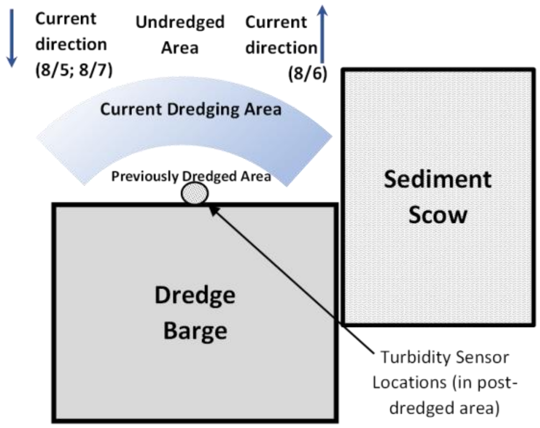


Figure 3. Layout of dredging operations during monitoring periods.

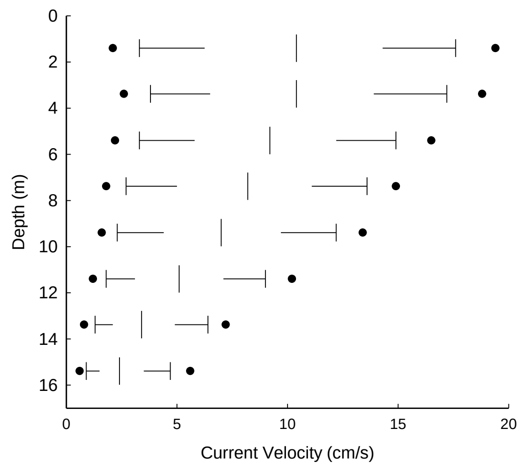


Figure 4. Ebb tide currents between June 21, 2011, and August 4, 2011, at Charleston Pier.

low tide all three days (Figure 2). Shaded regions reflect monitoring periods on each day. Figure 3 shows the general layout during the monitoring periods.

Current direction was generally from the bucket location toward the monitoring location (at the front of the dredge) on 8/5 and 8/7 (Figure 3). In contrast, flow was generally away from the monitoring location on 8/6.

NOAA reported current velocity at Charleston Pier (station BOS1118, located 4,200 feet (1.28km) south of the dredging area) from June 21 to August 4, 2011 (reference). Figure 4 shows the average ebb tide current profile from that study. Median currents during ebb tide were 10.4 cm/s at a depth of 1.4 m and 9.2 cm/s at 5.4 m. The average of currents at 7.4 m (8.2 cm/s) and 9.4 m (5.1 cm/s) was 6.6 cm/s while the average of currents at 11.4 m (3.4 cm/s) and 9.4 cm/s (5.1 cm/s) was 4.3 cm/s. The depth-average current over a 12.8 m depth is 7.7 cm/s. Battelle (2009) reported maximum ebb tide velocities of 35 cm/s in the main channel downstream of the dredging location during September 2009 under similar hydrologic conditions.

Water depths changed for each period because the dredge was in different locations (Figure 1) and because of continually changing tide levels. Table 2 summarizes the monitoring periods and associated site and dredging conditions.

DREDGE OPERATION AND DATA COLLECTION

Three different bucket types were used in this study. The Cable Arm navigation bucket and enclosed clamshell buckets had vents with rubber flaps to facilitate bucket descent. The conventional clamshell had an open top. Dredge operation was similar for all three buckets, although each had a different maximum dredge cut depth based on its design. Hayes et al (2000) reported cycle times of just over one minute (62 seconds) for the Cable Arm bucket and 56 and 51 seconds, respectively for the enclosed and conventional clamshell buckets.

Table 2. Summary of pre-and post-dredging water depths, dredge cut thicknesses, and sediment elevations.

Date	Dredge Bucket Used	Monitoring		Dredge Cut (m)	Before Dredging		Initial Tide* (m)	After Dredging Depth* (m)	Dredge Movement
		Start	End		Starting Depth* (m)	Sediment Elev. (m MLLW)			
8/5	Cable Arm (26 cy)	8:33:51	13:03:47	0.7	12.7	-10.7	2.0	13.4	Upstream
8/6	Enclosed (39 cy)	8:00:36	13:10:00	1.5	13.1	-10.4	2.7	14.6	Downstream
8/7	Convent. (26 cy)	8:27:34	10:29:59	0.5	15.3	-12.5	2.8	15.8	Upstream
		10:30:00	14:35:28	1.0	10.7	-8.7	2.0	11.7	

*These values varied with time due to tides; values shown reflect NOAA station 8443970 tide level at the beginning of the monitoring period.

Five (5) D&A Instrument Co. OBS-3 turbidity sensors calibrated for a range of 0 to 2000 FTU (Formazin Turbidity Units) corresponding to a 0 to 5-volt analog signal were used to collect turbidity data continuously during the monitoring periods. One-second interval turbidity readings were stored in a 13-bit Campbell Scientific CR10X datalogger that provided 8,192 levels of resolution, corresponding to an A/D uncertainty of +/- 0.244 FTU. The turbidity sensors, labeled A, B, C, D, and E, were deployed in a vertical array at the front center of the dredge barge. The sensors were located at depths of 0.3, 1.4, 5.6, 8.1, and 9.9 m, respectively, for most of the study. Sensors B, C, D and E were relocated to 0.6, 4.9, 7.3, and 9.7 m at 10:30 am on 8/7/99 when the dredge moved to a shallower dredging location. A time-stamp video camera synchronized with the datalogger clock recorded much of the dredging operation during the sampling periods.

The turbidity sensors were checked each morning using a 440 FTU Formazin suspension. Sensors B, C, D, and E remained within the manufacturer's standards during the entire study. Sensor A (0.3 m depth) failed its calibration check each morning and recalibration was unsuccessful. Thus, data from Sensor A are considered unusable and were discarded. Over 220,000 turbidity measurements were recorded during the three-day study period from the remaining four sensors. Turbidity sensor locations were always generally within 10 meters horizontally from the bucket's position.

There were times when the dredge was not actively dredging, such as when it was being moved forward to the next dredging location, moved to a new dredging area, or waiting for a full scow to be exchanged with an empty scow. Turbidity data were collected continuously (with a few exceptions when the sensors were removed from the water), regardless of dredge operation. Video records and field notes were used to segregate active dredging periods from non-dredging periods. The same video records were used to record bucket cycle information for as many periods as possible.

Table 3 lists the 46 dredging periods parsed from the video record and the number of bucket cycles in each period where it was compiled. The dredging period and position within the bucket cycle was integrated with the turbidity data to develop a comprehensive database.

ESTIMATING TSS CONCENTRATIONS

Turbidity is a common water quality monitoring parameter. It reflects some direct ecological concerns such as modifying fish behavior, but its primary advantage is the ability to collect much more data at a relatively low cost. Total suspended solids concentrations (TSS), however, are usually the primary concern. Thus, it is useful to translate the turbidity data to TSS for analysis. While turbidity and TSS are related, multiple factors conflate the relationship. However, a suitable correlation can be developed in many cases to facilitate estimates of TSS sufficiently accurate for many assessments.

In this project, water sample collection hoses were mounted adjacent to each sensor so that discrete water samples could be collected at the same location where turbidity readings were collected. Thirty-nine (39) discrete water samples (Table 4) were collected using a pumped system from the water column at a range of depths in Nalgene© bottles and later analyzed for total suspended solids (TSS) analysis using ASTM Method D5907 (ASTM 1996). Equipment limitations on Aug 5 restricted sample collection depths to 2.7 and 4.0 m.

Table 3. Summary of active dredging periods during study; the number in the dredging period indicates the August 1999 day of the period.

Dredging Period	Start Time	Duration (m:s)	Bucket Cycles		Dredging Period	Start Time	Duration (m:s)	Bucket Cycles
D-5-A	8:33:51	2:30			D-6-I	9:28:19	16:33	17
D-5-B	8:36:22	17:16	17		D-6-J	9:46:36	2:47	
D-5-C	8:56:01	6:51			D-6-K	9:49:24	15:35	18
D-5-D	9:02:53	13:11	11		D-6-L	10:05:00	9:59	
D-5-E	9:16:05	4:15			D-6-M	11:23:32	22:11	
D-5-F	9:37:24	4:55			D-6-N	11:46:49	19:01	
D-5-G	9:42:20	12:47	12		D-6-O	12:08:29	45:42	
D-5-H	9:56:51	3:07			D-6-P	12:55:18	14:42	
D-5-I	9:59:59	9:46	10		D-7-A	8:37:24	54:23	18
D-5-J	10:09:46	3:59			D-7-B	8:59:30	24:57	28
D-5-K	10:13:46	2:04	2		D-7-C	9:24:28	04:45	
D-5-L	10:18:48	2:43			D-7-D	9:29:14	3:46	5
D-5-M	10:21:32	7:08	7		D-7-E	9:33:01	4:11	
D-5-N	12:04:53	44:33			D-7-F	9:41:25	11:39	14
D-5-O	12:50:07	13:40			D-7-G	10:18:05	11:17	13
D-6-A	8:00:36	8:35			D-7-H	10:44:25	5:37	
D-6-B	8:09:12	9:49	8		D-7-I	10:56:26	11:33	
D-6-C	8:22:40	20:18	21		D-7-J	11:09:25	28:01	
D-6-D	8:43:57	3:06			D-7-K	12:31:43	28:16	
D-6-E	8:47:04	19:19	21		D-7-L	13:01:33	28:10	
D-6-F	9:07:13	11:59			D-7-M	13:33:55	20:31	
D-6-G	9:19:13	4:55	6		D-7-N	13:57:38	29:21	
D-6-H	9:25:31	2:47			D-7-O	14:27:55	07:33	

Turbidity values were averaged for 30 seconds on either side of the exact times of TSS samples shown in Table 4 to generate a turbidity-TSS relationship. A 30-second averaging period was found to be sufficient to avoid excessive influence of short-term signal variations. Slight adjustments to the start and end of a few periods were necessary to avoid periods with significant turbidity changes. Turbidity values outside of 1.5 times the inner quartile range (IQR) were excluded from the data set as outliers. Six consecutive samples starting with D-3-3-D and ending with D-3-5-A showed abnormally high TSS concentrations (Table 4). The dredge had just moved to a much shallower location prior to these samples and field notes indicate the sample hose was dropped into the mud layer, and this action is believed to have compromised the sampling device until the hose was cleaned prior to the 13:08:30 sample. Consequently, these six samples were not considered in the TSS-turbidity relationship development. The results, shown in Figure 5, provide a reasonably strong linear relationship with a correlation coefficient (r^2) of 0.9573. That relationship is:

$$\text{TSS (mg/L)} = 1.9417 * \text{Turbidity (FTU)} \quad (1)$$

The relationship in Equation 1 was used to convert recorded optical sensor turbidity data to TSS concentrations for use in all subsequent analyses.

DATA SMOOTHING AND OUTLIER REPLACEMENT

Evaluation of the raw optical TSS data showed a significant high-frequency component with fluctuation magnitudes dependent on sensor location in the water column. Since turbidity does not typically vary erratically, the individual high-frequency optical measurements variations mostly likely reflected optical anomalies. Several phenomena may have caused these anomolies including oscillating/rapidly moving particles, small spatial-scale, rapidly changing fluctuations in turbidity from eddies shed by the dredge bucket that would contain rapidly varying particulate concentrations due to incomplete mixing, and possibly other non-turbidity related items in the water column such as light flashes or occlusions from non-dredging detritus or debris, occasional reflections from aquatic organisms or electronic noise in sensor electronics.

The Kalman filter (Zarchan and Musoff, 2009) was chosen to remove high-frequency noise in the data because it employs estimates of data variance to progressively refine the data smoothing calculations. The

Table 4. Available total suspended solids (TSS) data.

ID	Date	Time	Depth (ft)	TSS (mg/L)	ID	Date	Time	Depth (ft)	TSS (mg/L)
D-1-1	8/5/99	9:50:50	2.7	35.10	D-3-1-C	8/7/99	9:09:30	8.1	68.10
D-1-2	8/5/99	10:10:20	4.0	14.13	D-3-1-D	8/7/99	9:13:30	10.5	199.90
D-1-3	8/5/99	10:27:20	2.7	65.55	D-3-2-A	8/7/99	9:20:30	1.4	63.80
D-1-4	8/5/99	10:33:10	4.0	30.10	D-3-2-B	8/7/99	9:23:30	5.6	73.30
D-1-5	8/5/99	12:12:30	2.7	253.85	D-3-2-C	8/7/99	9:34:30	8.1	7.60
D-1-6	8/5/99	12:22:30	4.0	204.60	D-3-2-D	8/7/99	9:36:30	10.5	9.60
D-2-1-A	8/6/99	8:32:30	1.4	29.20	D-3-3-A	8/7/99	9:40:30	1.4	74.30
D-2-1-B	8/6/99	8:35:30	5.6	21.50	D-3-3-B	8/7/99	9:47:30	5.6	58.20
D-2-1-C	8/6/99	8:41:30	8.1	17.40	D-3-3-C	8/7/99	9:52:30	8.1	10.50
D-2-1-D	8/6/99	8:48:30	10.5	74.60	D-3-3-D	8/7/99	11:27:30	10.5	895.70
D-2-2-A	8/6/99	9:12:30	1.4	56.80	D-3-4-A	8/7/99	11:30:30	1.4	201.80
D-2-2-B	8/6/99	9:24:30	5.6	11.90	D-3-4-B	8/7/99	11:32:30	5.6	296.20
D-2-2-C	8/6/99	9:28:30	8.1	25.30	D-3-4-C	8/7/99	11:34:30	8.1	397.40
D-2-2-D	8/6/99	9:33:30	10.5	62.50	D-3-4-D	8/7/99	11:36:30	10.5	676.40
D-2-3-A	8/6/99	11:33:30	1.4	81.10	D-3-5-A	8/7/99	13:06:30	1.4	588.80
D-2-3-B	8/6/99	11:36:30	5.6	8.90	D-3-5-B	8/7/99	13:08:30	5.6	53.30
D-2-3-C	8/6/99	11:38:30	8.1	20.10	D-3-5-C	8/7/99	13:12:30	8.1	114.30
D-2-3-D	8/6/99	11:43:30	10.5	197.80	D-3-5-D	8/7/99	13:21:30	9.3	106.40
D-3-1-A	8/7/99	9:02:30	1.4	15.00	D-3-6-D	8/7/99	13:24:30	9.3	137.30
D-3-1-B	8/7/99	9:07:30	5.6	45.90					

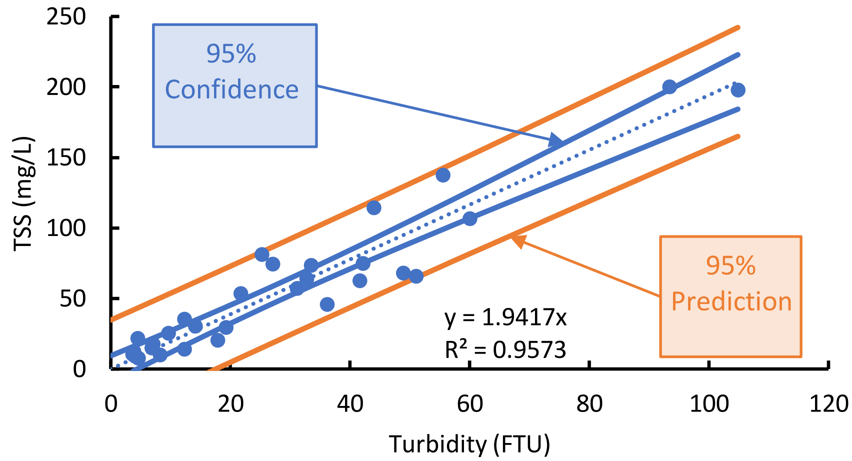


Figure 5. TSS -TSS relationship with 95% Confidence and Prediction Intervals.

Kalman filter has previously been used for removal of short-term fluctuations and elucidation of underlying trends in surface temperature time series in the Netherlands preparatory to evaluation of regression models (Visser and Molenaar, 1995). The Kalman filtering algorithm was written in MatLab® and tested using identical estimates of variance and variability of variance in all dredging and non-dredging data.

Outlier counts for raw and Kalman-filtered data were compared with the Hampel identifier algorithm as described by Pearson (1999, 2002) and ASTM (2016). The Kalman filter typically removed 80-90% of outliers in each data set. The Hampel identifier algorithm was written in the R language. The Hampel identifier algorithm evaluates the median and interquartile range in a moving data window consisting of three readings before and after each evaluated data point. If the data value at the center of the 7-point moving window is greater than or smaller than the 7-point median by a factor of 5.2 times the interquartile range, the data value is flagged as an outlier.

After initial trials, the Kalman-filter MatLab® code was employed first to remove high-frequency noise from the raw TSS data sets. The resulting Kalman-filtered TSS data sets were then processed with Hampel identifier R code, and the outliers flagged. Subsequently, a Microsoft Excel® macro replaced the flagged outliers with the median value of the 6 surrounding data points (Pearson 1999, 2002).

Statistical properties of Kalman-filtered data from 5th through 95th percentiles, showed little change in data distributions compared to raw data. Kalman-filtered residuals (computed as Raw - Kalman) showed a high frequency component with median values near zero. A final Kalman-filtered Hampel-outlier replaced data set was generated for each non-dredge and dredge period, and all files were consolidated into separate non-dredge and dredge master databases.

Analysis of the statistical results helped identify some inconsistencies. The most obvious was extremely high readings for Sensor B early during monitoring on 8/6 (enclosed bucket) both during dredging and non-dredging periods. A review of the field notes revealed an issue with Sensor B turning to face the barge during these periods, and data from periods D-6-A, ND-6-A, D-6-B, ND-6-B, D-6-C, and ND-6-C were determined to be invalid. They were not used in any subsequent analyses.

BACKGROUND TSS

Background TSS data from the study described by Welp et al. (2001) are not available, requiring another approach to estimate ambient turbidity conditions. In the absence of actual background data, turbidity measurements during non-dredging periods were analyzed for their potential to represent ambient background conditions in the vicinity of the dredging operation. Turbidity data from non-dredging periods were scrutinized to determine which most likely represented background conditions. Some non-dredging periods were excluded because they were too short or showed unexplained high turbidity values suggesting that other activities potentially generated turbidity. Two sets of background TSS values were determined for 8/7/99 because of the significant change in water depth.

Table 5 presents estimated background TSS concentrations by sensor during the study periods. The relatively low TSS values are consistent with ambient conditions during the study. Median TSS concentrations were subtracted from the converted TSS concentrations observed during the dredging periods to produce "net" TSS concentrations resulting from the dredge operation.

ANALYSIS OF NET DREDGING-INDUCED TSS

Standard parametric values (mean, standard deviation, skewness, kurtosis) were computed for each dredge and non-dredge period and each sensor. However, medians and 25th and 75th percentiles provide better descriptive statistics than mean and standard deviation since nearly all the datasets did not fit a normal distribution by the Shapiro-Wilk or D'Agostino tests ($p < .05$). Thus, the evaluations below are based primarily on medians and 25th and 75th percentiles.

Table 5. Summary of estimated background TSS concentrations (mg/L).

Sensor	Background TSS (mg/L)						
	Depth (m)	Obs	Min	25th Percentile	Median	75th Percentile	Max
8/5/99							
B	1.4	2406	5.8	7.2	7.5	8.1	12
C	5.6	2406	6.7	10.8	11.7	12.6	28.2
D	8.1	4812	17.2	29.7	32.4	39.2	534.5
E	9.9	4812	17.2	28.9	32.4	34.6	534.5
8/6/99							
B	1.4	2015	4.9	6.5	6.9	8.2	783.3
C	5.6	3000	4.1	7.0	8.0	9.0	24.8
D	8.1	1774	6.0	8.9	9.8	11.3	39.4
E	9.9	2443	13.8	41.3	50.9	71.3	324.7
8/7/99 – Phase I (Dredging Periods A-G)							
B	1.4	1791	5.6	7.2	7.4	8.6	50
C	5.6	2402	3.4	5.9	6.8	7.3	20.5
D	8.1	2402	4.5	6.4	7.0	8.4	60.1
E	9.9	1805	11.7	21.2	36.8	46	152.2
8/7/99 – Phase II (Dredging Periods H-O)							
B	0.6	701	0.0	21.2	5.8	46	102
C	4.9	1171	6.0	7.7	8.7	9.4	113.5
D	7.3	1047	6.7	11.9	12.6	17.4	118.9
E	9.8	1047	12.7	40.3	55.3	73.6	260.3

Combined Data

36,706 turbidity observations were collected during active dredging operations in this study and converted to net TSS concentrations, producing the most robust dataset of water quality impacts near a bucket dredging operation available. Analyses in a subsequent paper will evaluate differences in TSS concentrations among the three dredge buckets used in the study. However, it is useful to begin this evaluation by combining the data and analyzing as a single dataset. These results are shown in the box-and--whisker graph in Figure 6; statistical values are summarized in Table 6. It should be noted that these data represent different total water depths, thus different heights above the bottom. This is particularly important for Sensors D and E. Sensor depths from the surface are not provided since some of the data, about 20%, reflect slightly different values as described above.

The statistical results in Table 6 show some interesting aspects of the data. First, most of the datasets are positively skewed, that is more of the data are to the right of the median and mean values but the range of values greater than the mean and median is larger than those to the left. Only Sensor E data nears the cutoff for being normally distributed of 0.5. This is common for water quality data since negative values are

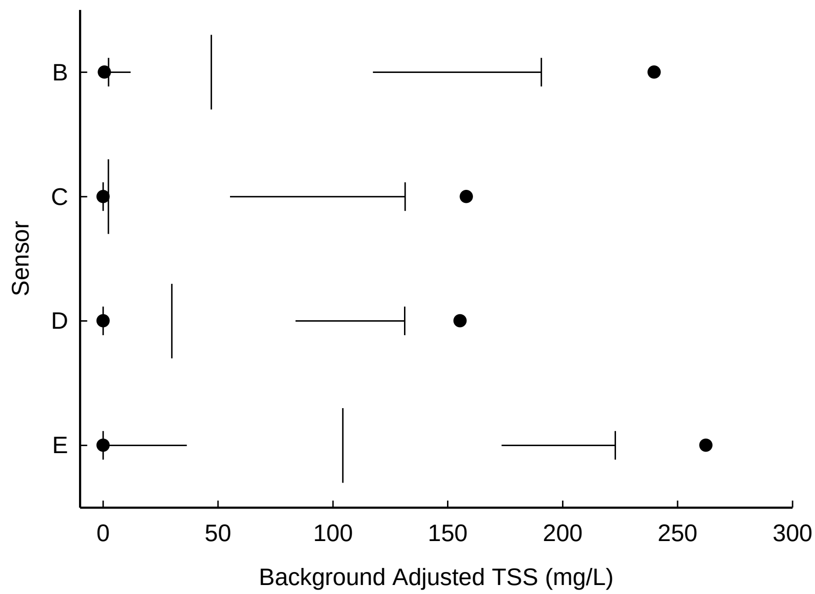


Figure 6. Box-and-whisker plot of all TSS data adjusted for background conditions during the 3-day study.

Table 6. Statistical summary TSS concentrations adjusted for background (mg/L).

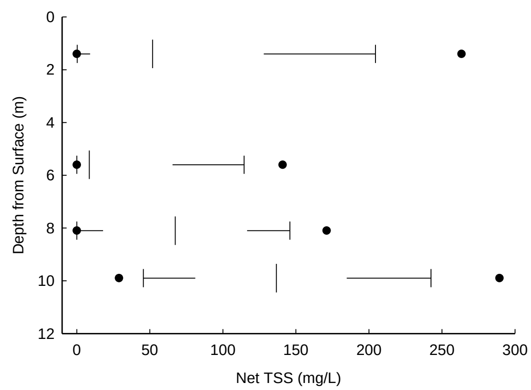
Sensor	Count	Max	Min	Median	Mean	Std Dev	25%	75%	Skewness	Kurtosis
B	36,706	2401	0.0	47.1	81.3	116.7	12.0	117.4	5.6	58.5
C	36,706	281	0.0	2.3	35.7	55.0	0.0	55.2	1.5	1.2
D	36,706	438	0.0	29.9	49.6	55.1	1.6	83.7	1.2	1.2
E	36,706	448	0.0	104.6	111.6	87.1	36.7	173.5	0.5	-0.3

infeasible. The data for Sensor B are Leptokurtic (peaked distribution) while the other data are Platykurtic (relatively flat distribution). A definite vertical pattern is also clear, with higher TSS concentrations near the surface (Sensor B) and near the bottom (Sensor E) with lower concentrations at midwater for Sensors C and D.

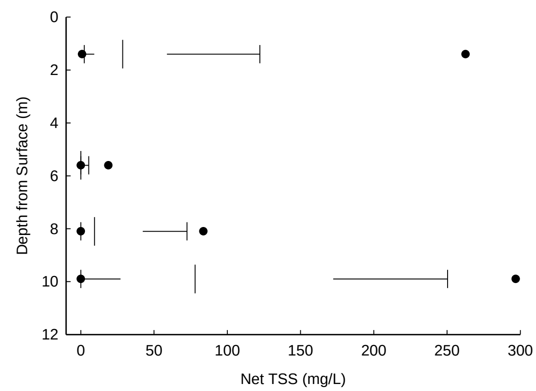
A comparison of the mean and median values in Table 6 shows that the mean TSS concentrations for Sensors B, C, and D are significantly influenced by some very high values while the majority of the TSS concentrations are measurably less. The mean and median values for Sensor E are more similar, suggesting fewer and less significant short-term TSS concentration increases. Sensor C shows that its 25th percentile value is 0, suggesting no measurable increase in TSS during a significant portion of the dredging observations. The possibility that this is associated with a particular bucket type will be investigated later.

Comparing Bucket Types

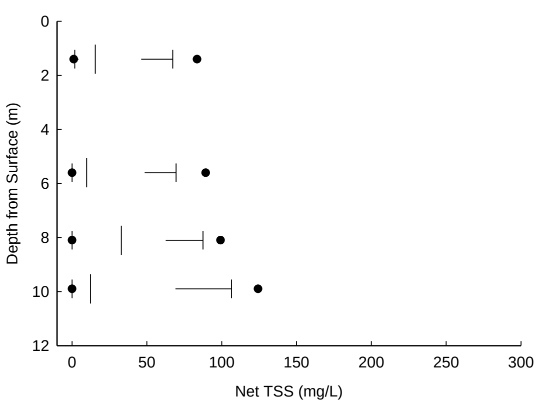
Comparing the three bucket types is complicated by the ever-changing site conditions (particularly water depth due to ebb tides and associated current velocity changes) and typical variations in dredging operations from day to day. However, comparing overall statistical characteristics of the TSS concentrations for each sensor during the four distinct monitoring periods provides useful insights into the magnitude and distribution of resuspended sediment for each bucket. Figure 7 illustrates these using box and whisker plots; note that all these plots use the same scales. Statistical values are shown in Table 7.



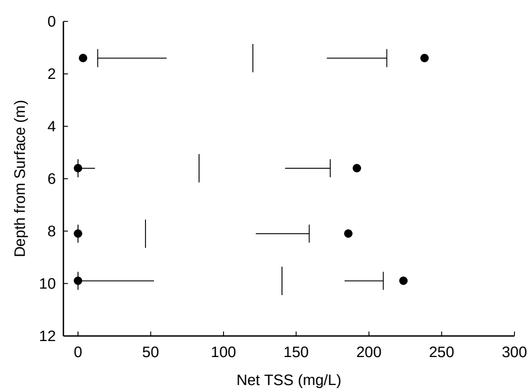
a) Cable Arm® Navigation Bucket



b) 39-cy enclosed bucket



c) 26-cy conventional clamshell bucket (Phase I)



d) 26-cy conventional clamshell bucket (Phase II)

Figure 7. Comparison of turbidity observations from all three days and bucket types by depth.

Table 7. Statistical comparison of net TSS concentrations (mg/L).

Depth (m)	Count	Minimum	25th Percentile	Median	75th Percentile	Maximum
Cable Arm Navigation Bucket 8/5/99						
1.4	8,940	0.0	9.1	51.9	128.0	1,494.3
5.6	8,940	0.0	0.0	8.6	65.6	187.7
8.1	8,940	0.0	18.0	67.4	116.6	438.3
9.9	8,940	0.0	81.1	136.6	184.9	447.5
Enclosed Bucket 8/6/99						
1.4	11,250	0.0	6.7	21.4	44.1	2,012.5
5.6	13,576	0.0	0.0	0.0	1.8	93.2
8.1	13,576	0.0	0.6	9.4	42.3	281.6
9.9	13,576	0.0	27.8	78.7	173.0	395.6
Conventional Bucket 8/7/99 – Phase I						
1.4	3,972	0.0	4.3	15.5	46.2	155.9
5.6	3,972	0.0	0.1	9.8	48.5	124.9
8.1	3,972	0.0	1.1	33.0	62.6	146.4
9.9	3,972	0.0	0.0	12.3	69.1	287.9
Conventional Bucket 8/7/99 – Phase II						
0.6	10,219	0.0	60.9	120.2	171.1	1,428.3
4.9	10,219	0.0	11.7	83.2	142.3	281.2
7.3	10,219	0.0	2.9	46.4	122.2	281.5
9.8	10,219	0.0	52.2	140.2	183.3	282.9

TSS concentrations were similar throughout the water column for the conventional clamshell (Figures 7c and 7d), with notably lower concentrations when the bucket was making thin cuts (Phase I). Median TSS concentrations were 16, 10, 33, and 12 mg/L during Phase I compared to 120, 83, 46, and 140 mg/L while making full cuts (Phase II). The difference in sediment cut thickness was a factor of 3 (0.5 m for Phase I and 1.5 m for Phase II); it is assumed that the bucket loading was proportional to these cut thicknesses. Depth-weighted averages are not computed because of the continually changing water depths. However, the simple averages are 18 mg/L vs. 97 mg/L. These values seem to show that the extent to which the bucket is loaded is important. More data are needed to determine if an optimal loading exists and, if so, what that might be. It is particularly interesting to note that the maximum median TSS concentrations occur at Sensor B and E (surface and bottom) for full cuts, but at Sensor D for the thin cuts.

Only full-cut data are available for the enclosed clamshell on 8/6 (Figure 7b). These show a very different vertical distribution of TSS; median TSS concentrations were 21, 0, 9, and 79 mg/L, with a simple average of 27 mg/L. The loading of the enclosed bucket was more than the conventional bucket, but probably less than proportional to the bucket volumes (39 cy vs 26 cy). The skew of the enclosed clamshell's plume towards the bottom also reduced downstream transport distances because the suspended particles likely settle to the bottom more quickly and closer to the dredging location. It must be kept in mind, however, that the dredge was facing down current while these data were collected (opposite of the other days). Thus, current was carrying the plume away from the sensors. Extensive mixing was observed and the currents in the area were relatively low as shown in Figure 4. However, the significantly lower concentrations suggest that the results were influenced (lower) by the current direction. Further analysis would be required to determine the extent of that influence.

The Cable Arm navigation bucket used on 8/5 (Figure 7a) produced results between the enclosed and conventional clamshell buckets. Median TSS concentrations were 52, 9, 67, and 137 mg/L with a simple average of 66 mg/L. Vertical TSS distribution for the Cable Arm navigation bucket was similar to the enclosed clamshell with reduced concentrations in the middle water column. Figure 8 illustrates TSS concentration variations with depth by bucket type and, for 8/7 cut depth in side-by-side plots with the same scales for more direct comparison.

A single dataset cannot be considered definitive and the change in dredging direction seems to have influenced the results. However, given the large sample sizes for each day, the collected data seem to show some reductions in the surface and mid-water column for the enclosed bucket. This is despite its flushing of significant volumes of turbid water each time the bucket broke the water surface as noted in the field notes and video record. Thus, reducing the volume within the enclosed bucket not filled with water should be even more effective. Even though it was not tested during this field experiment, there is reason to believe that the Cable Arm environmental bucket (and other buckets with similar design) may even be more effective because of their ability to fill the bucket cavity more completely.

Closer Look at Depth Variations

Numerous variations in site conditions, dredge operation, sediment characteristics, and other important influences occurred during the long data record. Most of these were too short or not documented sufficiently to analyze. However, continually changing water depths during the tidal ebb on each seemed to be an important influence that deserves further evaluation. The turbidity sensors were deployed in a manner that kept their vertical location relative to the water surface constant. The same sensor depths were used during all three days of the study except during Phase II on 8/7 when the shallower water depth required some adjustment. These depths have been used for all the analyses, charts, and tables presented above. Depth from the water surface is probably the most relevant reference for data from sensors B and C, since losses from the dredge bucket at the water surface are the most likely source of dredging turbidity they measured. Sensors D and E, however, were likely influenced mostly – if not exclusively – by bucket actions near the sediment surface. Thus, height above the bottom is probably a better reference than depth below the water surface for sensors D and E

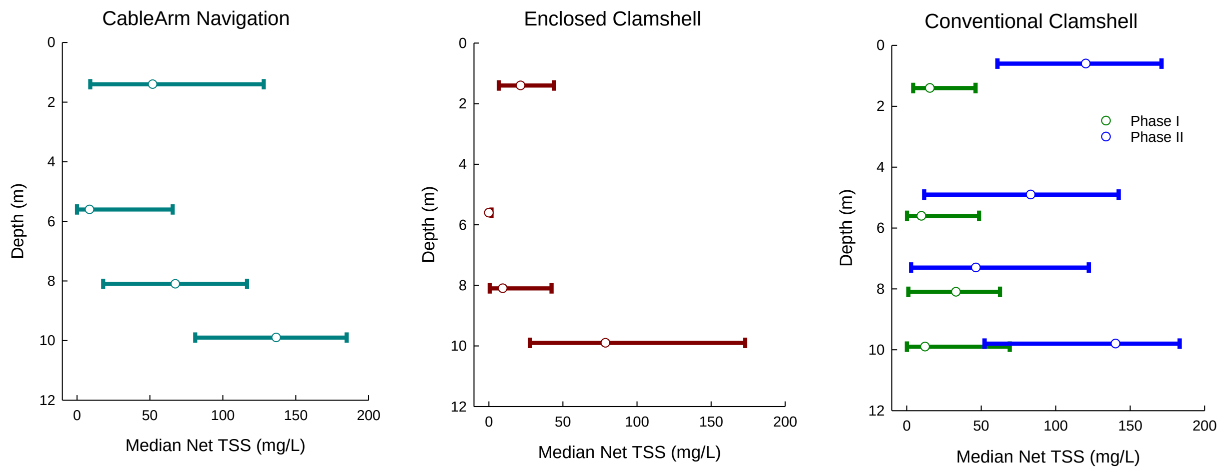


Figure 8. Comparison of TSS concentrations with depth for each monitoring period. Circles show median TSS concentrations while the bars represent the range between the 25th and 75th percentiles.

Figure 9 shows the distribution of TSS relative to elevation above the post-dredging sediment surface. Each horizontal line represents a single dredging period. Some increase in TSS concentrations with decreasing elevation above the bottom seems apparent for Sensor E and, to a lesser extent, Sensor D, for all monitoring periods except for Phase I of the conventional bucket on 8.7. In that case, however, deeper water resulted in no TSS data being collected within 5 m of the post-dredging bottom. The other monitoring periods show significant TSS concentration elevations for Sensor E as it dropped closer to the bottom during each day.

Comparing Figure 9 to Figure 7 seems to confirm that the primary source of turbidity recorded by Sensors B on all days and by Sensor C on 8/7 during Phase II (when it was closer to the water surface) was likely from bucket losses at or near the water surface. Losses of sediment were observed in video recordings when each bucket type emerged from the water surface and was being swung over to the scow.

In contrast, Figures 7 and 9 both seem to confirm that the primary source of turbidity and TSS to sensors D and E was from bucket losses at or near the sediment surface.

TSS Variations During the Bucket Cycle

This analysis was conducted to see if specific bucket and dredging actions could be tied to variations in turbidity readings. Seven distinct bucket positions were identified (Table 6) during each dredge cycle that may represent changes in the potential for suspended sediment loss to the water column. Video records allowed the dataset to be parsed by these locations for some dredging periods. Identifying positions 3, 4, and 5 required substantial judgement; thus, there could be some overlap among these three periods. Unfortunately, video recordings of the 8/7 conventional clamshell operation were not available during the time that regular cuts were being dredged (Phase II).

A preliminary analysis comparing recorded TSS to bucket position (Figure 10) did not show any sufficiently strong trends to clearly tie specific bucket actions to TSS concentrations. The distance between the bucket and sensor locations likely resulted in a lag such that the response would be delayed. It is also likely that dispersion during this lag blurred the signal to such an extent that it was indistinguishable from other parts

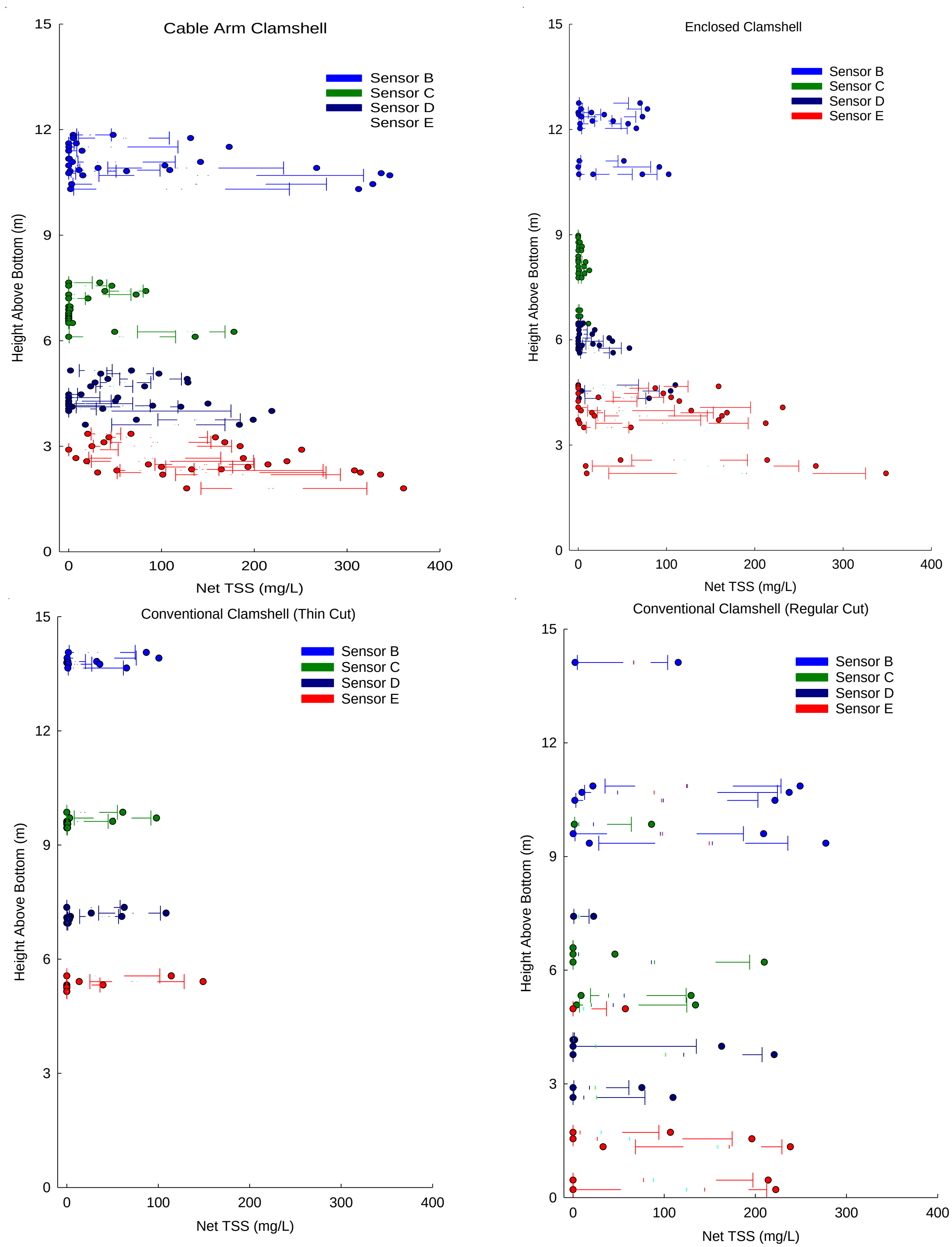


Figure 9. TSS concentration variations with depth by dredging period.

Table 6. Definitions of bucket positions within the dredging cycle.

Pos	Action	Pos	Action
1	Above water surface, ready to begin cycle	5	Breaks water surface; slew to barge
2	Descent through water column	6	Bucket over barge and being emptied
3	Bottom impact and closure	7	Slew to next dredging location
4	Ascent through water column		

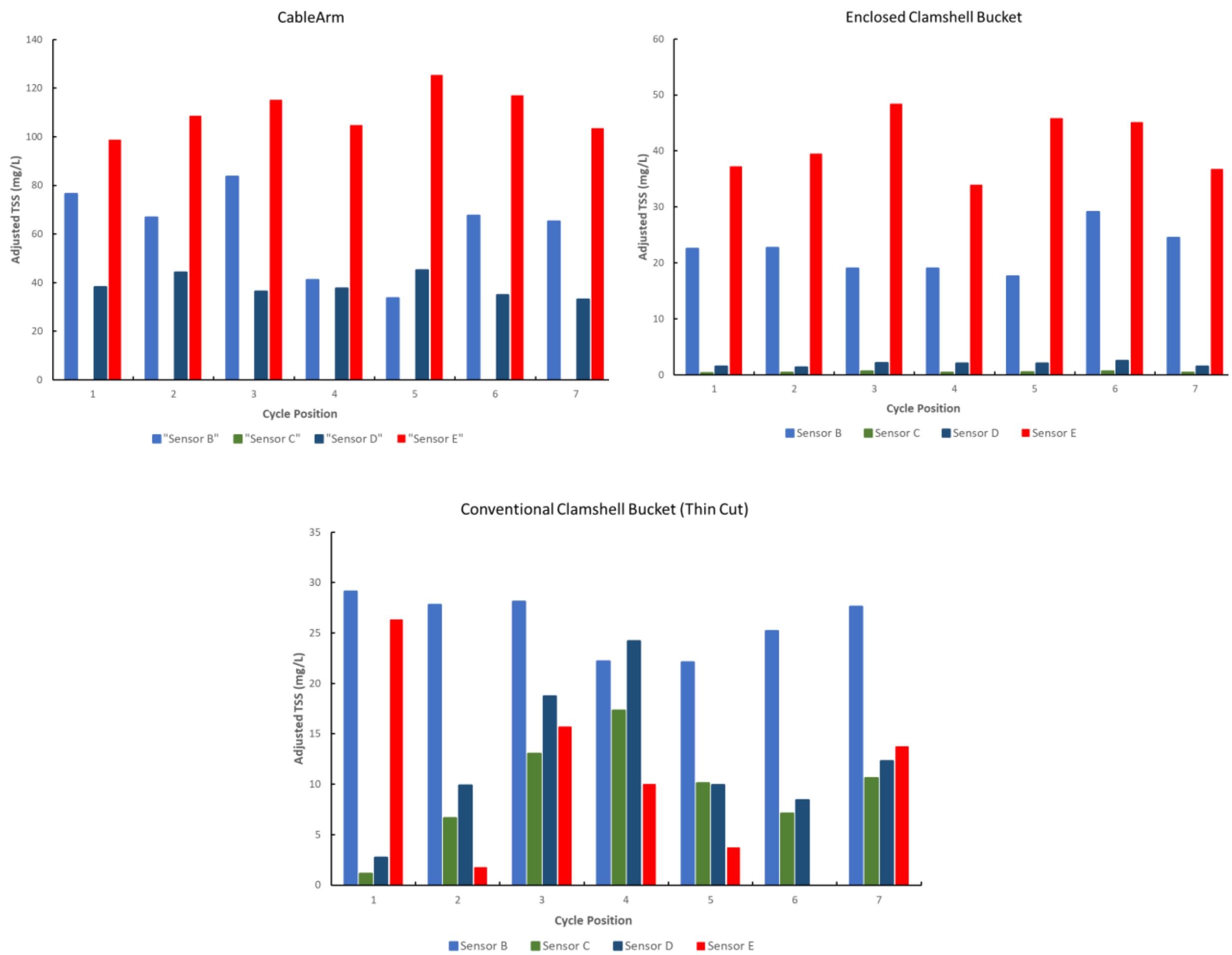


Figure 10. Median TSS concentrations by bucket position within the dredging cycle for 3 of the 4 monitoring periods.

of the dredge cycle. A more extensive analysis of these data may subsequently better identify these relationships.

CONCLUSIONS

An extensive turbidity data set collected from multiple depths near a clamshell bucket dredging operation in Boston Harbor shows a wide range of TSS in the water column in the immediate vicinity of the dredge.

The data show marked differences in TSS concentrations with sensor depth from the surface or sensor elevation above the bottom for the conventional and enclosed bucket. The results also indicate clear and substantial advantages for the enclosed bucket, primarily by reducing suspended sediment concentrations in the upper water column.

Unfortunately, data collection locations for the two buckets were completely opposite. Data collection for the conventional clamshell on 8/7 was directly downstream of the bucket action while turbidity data collected during the 8/6 enclosed clamshell operation came from directly upstream of the bucket action. More analysis is required to adjust for this effect and convert these data into reliable estimated sediment loss rates.

The Cable Arm navigation bucket is not commonly used and should not be used as a proxy for Cable Arm environmental buckets. Still, the 8/5 Cable Arm data also show some reduction TSS concentrations in the upper water column.

It is not surprising that the chaotic operation of the dredge generates extreme values. However, the data show extreme values to be short lived and TSS concentrations were mostly quite modest with the highest concentrations being between 100 and 200 mg/L. Most of the observations were much lower, usually less than 50 mg/L. It is important to keep in mind that these concentrations were observed within 10 m of the bucket operation and the sediment being dredged settles preferentially well in the environment.

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DATA AVAILABILITY

The turbidity data used in this manuscript are available from the corresponding author by request.

RECIPIENT SITE SELECTION AND ENVIRONMENTAL COORDINATION - KEY ELEMENTS IN SUCCESSFUL CORAL RELOCATION, SURVIVORSHIP, AND RESILIENCY DURING JETTY RECONSTRUCTIONS IN SOUTH FLORIDA

A. Laird[1]

EXTENDED ABSTRACT

In south Florida, the entrances into the Port of Palm Beach (Palm Beach County) and Port Everglades (Ft. Lauderdale, Florida) are accessed, respectively, through the Lake Worth and Port Everglades Inlets. Both inlets are bound by rock jetties to the north and south. Originally constructed in the 1920s and 1930s, the jetties have undergone several improvements and repairs over their lifespan. In 2017, as a result of Hurricane Irma, Lake Worth Inlet's north jetty and Port Everglades' south jetty were damaged by displacement and physical impacts to the rock forming these structures, potentially impacting navigation.

The Port of Palm Beach and Port Everglades are critical federal navigation projects and are important commercial processing hubs for billions of dollars in cargo. They are vital gateways for international trade, host dozens of cruise ships with thousands of passengers, and act as vital coastal defense stations. To halt further degradation of the damaged jetties, the US Army Corps of Engineers (USACE), as the federal sponsor, issued contracts in 2020 for the rehabilitation of the two jetties through the placement of new rock, and substantial manipulation of existing rock to restore them to their original design templates.

As part of the USACE contract specifications, the contractor hired to rehabilitate the jetties was also responsible for completing several of the federal, state, and county environmental permit special conditions. These included 1) conducting in-water surveys to document sensitive marine resources within the project areas, 2) relocating the coral colonies from within the project area, and 3) performing post-transplantation monitoring to record the success of the transplantation efforts.

Coral transplantation is a common requirement in south Florida and the Caribbean as part of various coastal construction and dredging projects with the burden often placed on the contractor hired to conduct the work. Although the success or failure of the coral relocation efforts is ultimately the responsibility of the permit holder and project sponsor, the contractor must frequently take on the liability of the work performed. Identifying suitable coral recipient locations to maximize coral survivorship continues to be one of the biggest challenges in coral relocation projects. Failed projects are often due to poor site selection – sedimentation (NOAA, 2015), excessive UV radiation and heat (personal knowledge), unsuitable water depths, incompatible substrate (personal knowledge), excessive currents, heavy predation (Chappell, 2021), and current or future exposure to disturbances (Jamaica Environmental Trust, 2015). As such, it is crucial that an experienced and knowledgeable team are charged with the work.

The prime contractor brought on an experienced, knowledgeable subcontractor with a real-world understanding of the challenges of coral relocation, in particular the ecological and physical requirements in selecting a coral recipient site. During the in-water benthic surveys, the subcontractor conducting the coral relocation documented over 250 coral colonies (>5 cm in diameter), including species listed as Threatened under the Endangered Species Act (Federal Register, 2014). Identifying suitable locations for receiving the coral colonies was conducted in phases following guidelines outlined in the US Coral Reef

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Task Force (USCRFT) Handbook on Coral Impacts (2016) and the Florida Fish and Wildlife Conservation Commission (FWC) recommendations on the selection of sites for acceptance of coral colonies. Using ArcGIS, several data layers including bathymetry, habitat types, artificial reefs, and LiDAR were overlain to initially determine water depth, habitat areas, distance from project area, and substrate type. In addition, staff from local government offices were consulted about future permitted, authorized, or reasonably foreseeable marine construction activities (e.g., dredging, beach nourishment, pipeline or cable installation) that may be planned within the general area and have the potential to cause direct or indirect impacts to coral habitats and outplanted corals. Grids were placed over the areas of interest and several potential sites were preliminarily identified for further exploration. A team of scientific divers conducted reconnaissance dives and collected qualitative data on the species present, condition of existing coral colonies, the potential presence of any disease, bleaching or excessive algal covers, and available substrate area for reattachment of coral colonies and future growth. Looking at multiple variables, natural hardbottom sites were proposed for the Port Everglades project, while some artificial reefs were selected for the Lake Worth jetties. The sites were prioritized and used to develop formal coral relocation and monitoring plans for agency submittal. Following approval by the state, federal, and county authorities, Special Activity Licenses were applied for and received by the FWC, Division of Marine Fisheries Management, pursuant to FWC rule 68B-8, Florida Administrative Code.

In both jetty locations, there is heavy commercial and recreational vessel traffic, and the areas are known for strong incoming and outgoing currents during tidal changes. Wave action can be unpredictable and highly dynamic causing challenges and safety concerns while detaching and transporting coral colonies. The timing of the relocation was important so that the construction was not delayed. Continual coordination with the client, the USACE, FWC, and the permitting agencies allowed for the team to remove all the coral colonies prior to mobilization of the contractor's equipment and crew. Of the over 250 coral colonies that were documented, roughly 200 of them were relocated, while the remaining corals were donated to Nova Southeastern University and the Florida Coral Rescue Team (FWC) as part of their coral conservation and research efforts in South Florida. Corals donated to these groups are being used to advance propagation and restoration goals via micro-fragmentation, aquaculture, and education. The required post-relocation monitoring of the transplanted coral colonies at the natural reef and the artificial reef showed 100% survivorship with no bleaching, disease, or predation.

The project's successful conclusion is attributed to effective coordination with the client and scientific-based site selection to ensure the coral colonies would thrive and with negligible impacts to the health of the coral colonies. The marine science team worked with the government regulators, resource managers, and various stakeholders to develop a solid plan to harvest the protected colonies and relocate them to suitable habitats with similar conditions. Timing, experience, successful site selection, and logistics were critical to ensure successful transplantation of the documented coral colonies and ensure the contractor could initiate construction on the jetties without delays.

Keywords: Environmental mitigation, environmental permitting, marine resources, jetty reconstruction, port development.

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DATA AVAILABILITY

No data, models, or code were generated or used during the study.

SATELLITE-BASED WATER QUALITY MONITORING: EXPLORING THE POTENTIAL FOR SPATIAL AND TEMPORAL MAPPING

T. Heege[1], K. Schenk[2], H. Bernert[3], P. Bauer[4] and E. Albada[5]

EXTENDED ABSTRACT

Water quality can be influenced by various natural and anthropogenic factors. Amongst the latter, dredging works and related sediment plumes create changes in water quality that can negatively impact surrounding benthic communities or coastal habitats. The tracking and monitoring of spatially heterogeneous sediment plumes under typically very dynamic sea conditions can be challenging for both industry and regulators to ensure compliance to environmental conditions, in particular with limited budgets for operational monitoring.

Traditional in-situ measurements of water quality can be costly, time consuming, and typically provide an incomplete perspective of a given area of interest. Although in-situ measurements can provide vertically resolved measurements, they lack the ability to represent larger areas in the horizontal domain and therefore cannot cover the full extent of spatial variabilities. Remote sensing-based techniques can fill these gaps between sample stations. Using special physics-based techniques, areas of hundreds and thousands of square kilometers can be covered in varying resolution, providing valuable insights of spatial dynamics of sediment plumes and marine dynamics.

In addition, water quality products from satellite data can be produced without requiring in-situ measurements by application of appropriate physics-based methods such as the Modular Inversion Processing (MIP) System developed by EOMAP (Heege et al., 2015, 2014, 2004, 2000; Kiselev et al., 2015; Richter et al., 2014). This approach is independent from the need of in-situ measurements due to its fully physics-based nature. This independence provides the possibility to not only obtain information in remote regions of the world, where in-situ measurements are sparse or nonexistent, but also to extract historical data at any location, which is impossible using traditional in-situ methods. Satellite data are available from the mid 1980's, which allows for the opportunity to gain consistent long-term insights into spatio-temporal variabilities and patterns over almost 40 years.

Satellite-derived information is usually a more cost-efficient method to measure water quality parameters. Often times, the raw satellite imagery is obtained under a free and open data policy (although there are also commercial providers of very-high resolution imagery), and the only costs come from the analysis itself. Traditional in-situ measurements, especially when they are sampled across larger areas, are by comparison more expensive as both field work and extensive laboratory analysis of the samples taken in the field are required.

Output from the increasing fleet of satellite sensors being launched into orbit is continuously integrated into the EOMAP processing chain. The more recent additions are the commercial, very-high resolution

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satellites Pléiades Neo from Airbus, PlanetLabs' SuperDove and SkySat, the open-data-policy, high resolution satellite Landsat 9, and the hyperspectral, currently mainly research-focused PRISMA satellite from the Italian Space Agency (European Space Agency 2022). Hyperspectral satellites in particular can revolutionize water quality remote sensing due to their very high number of spectral bands. While the 'traditional' multispectral satellite systems usually have spectral bands – depending on the specific system – in the range of single digits up to about 20 bands, these hyperspectral satellites have hundreds of different spectral bands. This high number of spectral bands allows for a better distinction of different in-water parameters, specifically optically active pigments such as suspended sediments or different kinds of phytoplankton. These systems can make the calculation of the different atmospheric and in-water properties much more reliable and also extend the product palette towards parameters that cannot be mapped by the current multispectral systems.

The most recent considerations within the processing chain applicable to the dredging industry is the relation between Turbidity and Total Suspended Solids. While this relation can be considered as linear under certain environmental conditions, a more complex relationship, for example seasonal variability, is often present. For applications near river mouths, sediment load and composition during peak discharge periods may be different from the sediment in the same waterbody during low-flow periods. To gain a better understanding of this potential variability, data from different sensors – satellites and in-situ devices – are currently being compared. This comparison requires a wide range and frequency of data at a location ideally in a water body with optically deep water, in order to avoid the influence of a visible seabed on processing the phase-resolving solution.

EOMAP's new atmospheric model will be tested and validated against AERONET stations. These stations from the AERONET (AErosol RObotic NETwork) project measure direct solar radiation, which is used to calculate aerosol optical depth (AERONET 2019). The comparison of the new atmospheric model with these measurements will improve the retrieval of Turbidity and Total Suspended Solids data from satellite imagery. The new and improved algorithm will allow for a more precise and accurate processing of water quality applications, including dredge monitoring and observation of off-shore construction projects such as renewable energy platforms. In addition to improvements within EOMAP's processing algorithms, and the increase in spectral resolution of new satellite systems, EOMAP benefits from increased spatial and temporal resolution offered by the growing number of new satellite sensors. These advances combine into an opportunity to monitor ongoing dredging works in spatial and temporal detail, and to trace potential plumes and delineating areas of elevated turbidity levels. For example, the upcoming PlanetLabs Pelican satellite mission will provide up to 30 captures per day in 30cm spatial resolution with quick access time to newly acquired data (Planet 2022). Multiple captures per day allow for intra-day observations to cover possible trends not yet visible in single daily images.

With these and future advances in the satellite remote sensing market, applications of satellite imagery for water quality monitoring will likely gain acceptance and popularity as a cost-effective alternative to in situ testing.

Keywords: Dredging, earth observation, off-shore construction, operational monitoring, suspended sediment, turbidity

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DATA AVAILABILITY

The MIP processing system mentioned in the abstract is proprietary to EOMAP. Data produced using this processing system may be provided upon request with restrictions on republication and use.

SEAGRASS MITIGATION THROUGH WIND WAVE REDUCTION

P. Todd[1], T. Stanton[2], M. Fonseca,[3] and E. Hodel [3]

EXTENDED ABSTRACT

The replacement of the Bonner Bridge over Oregon Inlet in Dare County by the North Carolina Department of Transportation (NCDOT) was estimated to permanently impact approximately 2.66 acres of seagrass in the Pamlico Sound. Mitigation included the removal of the existing bridge that unshaded 1.38 acres of suitable seagrass habitat. The NCDOT contracted CSA Ocean Services (CSA) to determine the best way possible to mitigate for the remaining 1.28 acres of anticipated seagrass impacts. CSA performed a reconnaissance survey in the vicinity of the project area which was unable to identify injured seagrass areas to restore as mitigation. Therefore, an experimental mitigation approach was recommended.

Based on past research by CSA staff on the relationship of seagrass landscapes to wave energy, CSA proposed construction of a wavebreak structure to reduce wave energy and thereby encourage natural coalescence of existing patchy seagrass habitat (specifically *Halodule wrightii*, *Ruppia maritima* and *Zostera marina*) to produce new, persistent seagrass acreage, which was the primary objective of the project (CSA 2015). The project was also designed to provide other ecosystem services including particularly essential fish habitat (EFH) creation. The project's goals were: 1) to provide seagrass mitigation for the Bonner Bridge replacement and 2) to contribute to a long-term effort to develop options for seagrass mitigation in coastal North Carolina.

The proposed implementation site for the experimental wavebreak structure was a physically stable shoal that supported patchy seagrass cover since at least 1998. CSA conducted a wave modeling study to set the location, orientation, and length of the structure needed to produce a wind wave attenuation pattern that would lead to seagrass bed coalescence. CSA then performed a feasibility study which evaluated eight potential types of structures in relation to installation logistics, secondary site impacts, maintenance, costs, wave attenuation, estimated resilience over 10 years, and potential for provision of EFH services. CSA selected the pile-based Reefmaker structure for implementation to achieve the project's goals.

The wavebreak structure was constructed from 101 individual Reefmaker "units" (each 4 ft high x 4 ft wide). Each unit was comprised of three tiers of concrete molded trays set with granite rock stacked on a solid base and all supported on a piling. The stack of Reefmaker units were installed flush on the seafloor with weight born on a supporting clamp and the piling. Reefmaker systems were designed to attenuate wave

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energy while still allowing for the exchange of water and the passage of organisms through, around, and under the structure's individual components. They were also designed for use in high energy wave environments and to survive the passage of large storms such as hurricanes. The benefits of this system included the ability to decrease the wave energy in a high energy environment, increase hard surface area for epibiota habitat, and a reduced benthic footprint compared to other structures. The Reefmaker systems have a smaller benthic footprint (16 ft^2 per unit) to reach the desired height and less installation impact versus a traditional rock wavebreak. A traditional rock wavebreak with even a steep, 2:1 side slope would have a 10,000 ft^2 benthic footprint.

The 500-ft long wavebreak structure was constructed in January 2017 in a chevron shape oriented due north. The structure length was determined by iteratively adjusting the wall length and running wave and seagrass forecasting models on each successive wall length until an increase in seagrass cover meeting the mitigation acreage of 1.28 acres was achieved. The wavebreak structure was installed in navigable but shallow water without the need of a dredged access channel, which would have resulted in additional seagrass impacts.

The NCDOT implemented a monitoring program to ensure structure stability and to study seagrass coalescence and ecosystem services around the structure. The stability monitoring was designed to study the potential for scour around the structure while the seagrass and ecosystem services assessments documented the health and coalescence of the seagrass, wave attenuation, sediment height changes around the structure and colonization of the structure by sessile biota.

Installation of the wavebreak resulted in the formation of narrow scour pit underneath the structure and development of a sand apron on the south side of the structure. Despite the formation of a scour pit, the piling clamps maintained the Reefmaker units suspended at their original elevation for over 90% of the units. The sand apron impeded seagrass colonization in the immediate vicinity for approximately 4 years. However, surveys and aerial photography in 2021 confirmed that seagrass had finally coalesced as forecast for this area immediately south of and adjacent to the wavebreak and that the mitigation acreage target for seagrass was exceeded.

Epibiotic cover (including algae, barnacles, cyanobacteria, hydroids, oysters) has steadily increased to nearly 100% of the regularly submersed portions. Oyster (*Crassostrea virginica*) colonization has also increased, particularly on the granite rock portions of the structure to an average of 10.6% cover (CSA 2022). From an EFH perspective, habitat linkages have been created, and the wavebreak structure has, and continues to provide, substantial EFH services. Seabirds and motile invertebrates have also been consistently observed on the wavebreak. Several fish species have been observed under and around the structure.

Additionally, this increase in seagrass may have promoted a cascade of increased seagrass cover to the southwest along the shoal, likely the result of a slight increase in shoaling (approximately 15-20 cm) that began concomitant with the installation of the wavebreak. While seagrass response was slow (approximately 4 years), this approach validated the concept of using wave attenuation to facilitate seagrass expansion on the seafloor. Any instance of wave energy reduction in seagrass habitats, whether of natural wind waves or importantly, boat wakes, stand to be mitigated by application of wavebreak structures. The project was included in the Corps of Engineer's *Engineering With Nature® (EWN®): An Atlas – Volume 2* (Bridges et al 2021).

Keywords: seagrass, mitigation, wave attenuation, living shorelines, essential fish habitat Pamlico Sound, Bonner Bridge

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DATA AVAILABILITY

All data, models, or code generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

INVESTIGATION INTO TURTLE MITIGATION STRATEGIES WITH TSHDS

K. Lank[1], T.C Roberts[2]

ABSTRACT

This paper discusses the efficacy, application, and concerns of standard and alternative sea turtle mitigation measures to prevent sea turtle entrainment and mortality by Trailing Suction Hopper Dredges (TSHDs). Environmental and contractual regulations often limit companies' ability to bid projects using standard turtle mitigation strategies, but application of alternative mitigation strategies could help expand their range. For example, physical cues are the most common strategy used to mitigate interaction between sea turtles dredge equipment (e.g. use of turtle exclusion devices [TEDs] on dragheads), but there is a potential to increase mitigation potential through elicitation of sea turtles' other senses. Research was focused around the commercial fishing industry and the different experiments that have been done to limit sea turtle bycatch in long nets. Strategies that exploited these stimuli most efficiently, i.e. eliciting a "flee" sensory response from the turtles, and the research supporting them were explored further. The physical and visual cues were the most effective deterrents and were the most flexible in their application. TEDs, turtle exclusion skirts (TESs), and turtle tickler chains (TTCs) were investigated as mitigation strategies predicated on physical cues. There is documentation supporting all of these techniques as successful in reducing sea turtle entrainment and mortality. Less documented in regards to dredging industry applications, but with extensive success in reducing bycatch, are the application of UV/LED lights/light sticks and deployment of predator silhouettes. Suggestions on how to apply these two techniques to TSHDs are discussed, with emphasis on how exploiting sea turtles' spectral range and biological "flee" response to predators are imperative to the success of the application.

Keywords: Dredging, hopper, sea turtle entrainment, bycatch, TEDs, predator silhouette.

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INTRODUCTION

The work schedules of TSHDs have historically been influenced by environmental and contractual obligations that act as safeguards to protect marine wildlife during vulnerable periods of their life cycle such as nesting/breeding and migration. During these "turtle windows," hopper dredge work is either fully prohibited or allowed to continue only with a series of mitigation measures in place to prevent interaction between the dredge work and wildlife. Common examples of these mitigation measures are the inclusion of TEDs on dragheads, relocation of sea turtles via trawlers, and 24-hr sea surface visual monitoring by Protected Species Observers (PSOs) onboard the dredges. Less common strategies, such as the installment of turtle excluder skirts (TESs) and turtle tickler chains (TTCs), are occasionally utilized but are not a standard requirement in most United States contracts. Despite these different mitigation strategies, sea turtle entrainment and mortality still occur, concerning because of the six sea turtles in US waters, four are endangered (NOAA Fisheries 2022). In an effort to further reduce turtle, research was conducted on experimentation performed in another industry experiencing turtle entrainment and mortality: the commercial fishing industries. The results of those experiments, and their potential application to TSHDs and their projects, are discussed in this paper. Potential methods are discussed in terms of how sea turtles biologically respond to three different types of cues: physical, visual, and auditory.

PHYSICAL CUES

Turtle Excluder Device (TED)

Turtle excluder devices (TEDs) function as a rigid plow attached to the forward side of a draghead, typically in a V-shape by a hinge. This hinge allows the plow freedom to move vertically over uneven ground. Attached to the plow is a metal chain "net" which connects from the top edge of the plow to the draghead, preventing the entrainment of sea turtles into the intake pipe (Figure 1). When dragged along the seafloor, the TED produces a sedimentation waves that, when felt by turtles, encourages them to move away from the dragheads, reducing the risk of taking the turtle. TEDs of various design are widely used in the dredging industry, but their usage is restricted by contract specifications and environmental conditions of different jobs. Included in Figure 1 shows a TED design by Great Lakes Dredge & Dock.

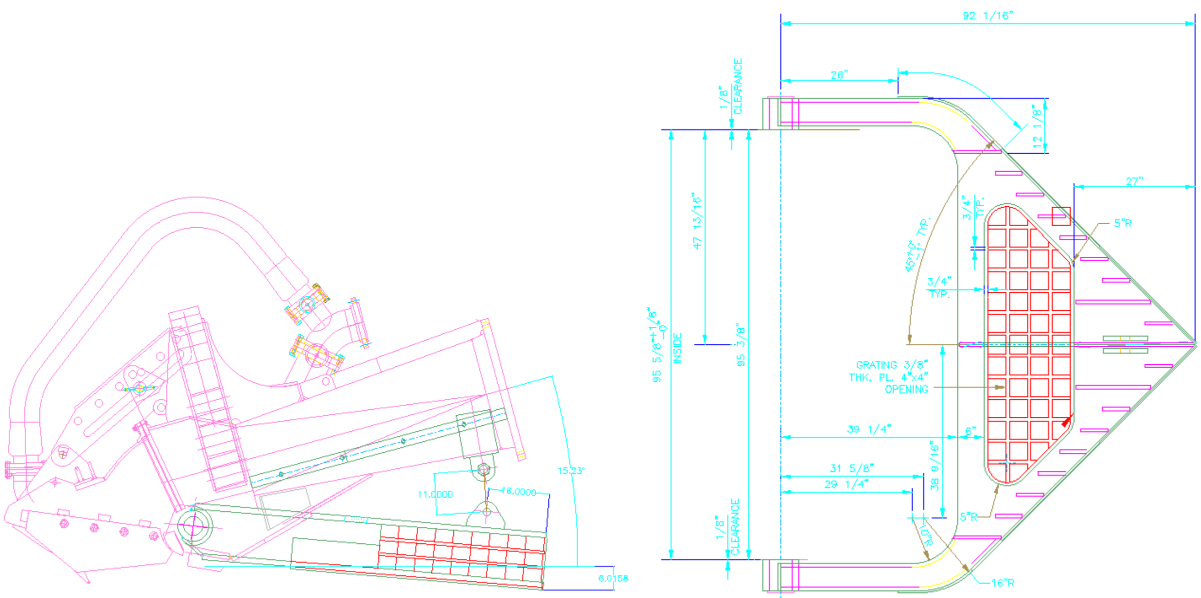

Figure 1. Profile and Plan View of GLDD TED Design.

Application Concerns

TEDs have an excellent success rate with reducing sea turtle entrainment, but are limited by the rigidity of their frame and weaknesses in uneven seafloor environments (Henriksen et al. 2015). Large rocks or obstacles have the potential to damage the TEDs, potentially damaging the TED itself or detaching the apparatus from the draghead. Detached pieces could be sucked into the draghead and cause further damage, or be unrecoverable and left on the seafloor creating issues for future dredging operations. Dredge production is also hindered by the addition of these devices.

Turtle Excluder Skirt (TES)

Similar to a TED, a TES is an attachment to hopper dragheads that follows a similar principal of creating sedimentation waves to remove sea turtles from the path of the draghead. Where the TED is a rigid structure, the TES is a flexible network of weighted chains held in a V-shape by a centrally placed cable connecting the leading edge of the "skirt" to the draghead at a 90^{o} angle (Henriksen et al. 2015). The chain that makes up the edge of the skirt is of a heavier weight of the chains which make up the mesh of the skirt, effectively weighing down the apparatus so it remains in contact with the ocean floor. Figure 2 is a TES design from the United States Army Corps of Engineers (USACE).

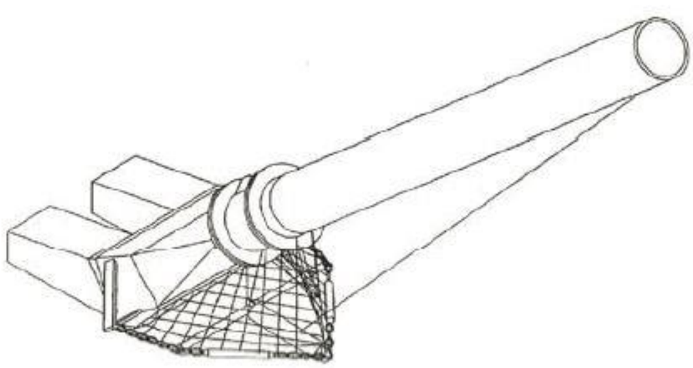

Figure 2. USACE "Combined Chain & Bar Deflector" Design (Henriksen et al. 2015).

Application Concerns

The TES system is less susceptible to damage from encountering obstacles or being dragged along an uneven seafloor, but the chains are a more fragile material than the forged metal plates of the TEDs (Henriksen et al. 2015). The exposed chains are susceptible to breakage or damage that could compromise the integrity of the device and negatively impact production schedules by requiring frequent delays. Additionally, pieces of broken chain have the potential to be left on the seafloor or taken up by the draghead, resulting in damage to equipment. This less-robust design limits the strength of the sedimentation waves that it generates and could achieve less penetration of the seafloor than TEDs. Both of these situations would reduce the system's efficiency to deter turtles. Special care must also be taken when calculating the mesh size of the skirt to avoid sea turtles being caught in the mesh and drowning (Dickerson et al. 2018).

Turtle Tickler Chains (TTC)

Turtle "tickler" chains (TTC) as a turtle mitigation method have primarily been used in international dredging operations and the commercial fishing industry; there has not been any regular implementation in the United States (Dickerson et al., 2018). The chains function by dragging along the seafloor ahead of the draghead, alerting sea turtles and other marine life to the hazard and encouraging them to leave the path of the draghead. Chains can be attached from a single end of the chain and installed along the dragarm (curtain) or from both ends and installed on the draghead (draping).

Curtain TTC

The TTC curtain assembly consists of a series of chains attached to a single piece of metal which is mounted perpendicular to the longitudinal axis of the dragarm, forward of the draghead (USACE 2019). TTCs installed as a curtain provide a wider spread and increased number of contact points between the chains and the seafloor, thus increasing potential contact with sea turtles via sedimentation wave contact. The distance of the curtain forward of the draghead and length of the chains of the curtain would be dredge-specific and influenced by the dredging site conditions. Once the dragarms are lowered, the weight of the chains holds them in contact with the seafloor. A GLDD-design TTC curtain assembly used in tandem with a TED employed on a project in Corpus Christi, TX, USA is included in Figure 4.

Figure 4. Curtain TTC application on TSHD Ellis Island.

Draped TTC

Draped chains are attached to the draghead itself, at a measured distance from the flange to the heel pad of the draghead, and dragged along the seafloor as the draghead moves. Figure 5 shows an installed draped chain assembly used on the Wheatstone Project LNG in Onslow, WA, Australia. The draped assembly does not share the same installment flexibility as the curtain assembly, being installed to the draghead rather than along the drag arm. However, the draped curtain assembly can also be outfit with "curtain" chains, as Figure 5 demonstrates, to increase the points of contact with the seafloor.

Figure 5. Draped TTC application (Wheatstone Project LNG 2013).

Application Concerns

Sea Turtle Entanglement

The foremost concern of the TTC system was the risk of entangling sea turtles and causing them to drown as the chains shifted in the water column. Field tests performed by the USACE in Hawaii with the dredge Essayons allayed this concern. Acoustic, high-definition, and GoPro cameras paired with and various light sources were installed along the draghead and dragarm to record the curtain's movement during dredging operations. The results of the recordings showed that the chains remained in contact with the seafloor for the duration of the field test, the chains predominantly hung perpendicular to the arm, and adequate spacing remained between the chains (Dickerson et al. 2018). A profile view of the field test set up has been included for reference in Figure 6. The efficiency of this system is greatly influenced by the composition of the seafloor, as the material type affects the behavior of the chains as they are dragged. It was noticed during the Essayons field test that the chains showed greater vertical and horizontal fluctuation on soft, silty bottoms compared to sandy bottoms (Dickerson et al. 2018).

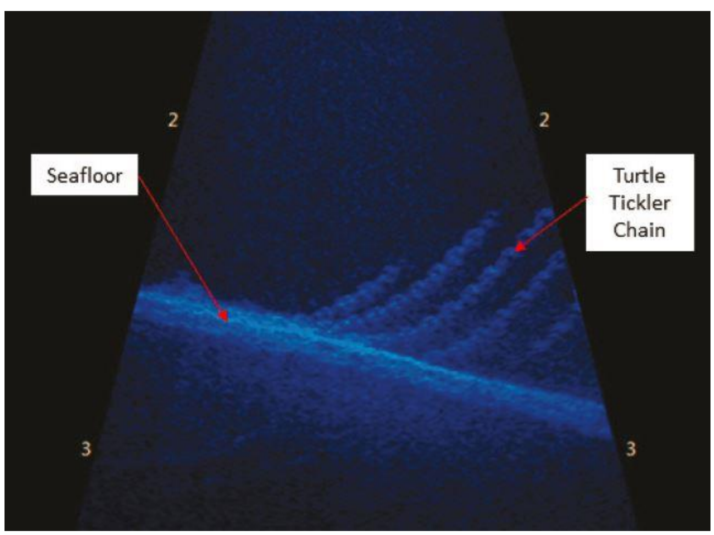

Figure 6. Acoustic camera image of TTC curtain in sandy material (Dickerson et al. 2018).

Contact of Device with Vessel, Equipment

Careful consideration for the installation of these curtains must be made to prevent damage to the dredge from interactions with the apparatus (e.g. mount, chains). The physical interaction between the system and the ship would have to be addressed on an individual dredge basis to ensure no damage would be done to either the ship or the apparatus itself. Some of the concerns of contact include: long-term effects of chains rubbing against the hull of the ship as the dragarms are brought back to deck or placed in the cradle, the necessary safeguarding of mechanical deck equipment (e.g. winches, shiv) to prevent chains from being caught, and the potential modification of the ship to allow the chains to be brought on deck without interference with or tangling in the railing.

VISUAL CUES

Light Sticks, LEDs, & Ultraviolet LED Lights

Exploitation of the acuity of sea turtles' vision has received much attention in turtle mitigation experimentation. Consequently, the efficacy of using illumination as a turtle mitigation strategy has been verified through experiments performed in North, Central, and South America and the Mediterranean (Wang et al. 2013, Ortiz et al. 2016, Virgili et al. 2017). Experimentation has largely concentrated on the prevention of sea turtle bycatch in longline and gillnet fishing operations, but these same principles can be applied to the dredging industry. The greatest successes in reducing bycatch were through attaching chemical light sticks, UV LED light sources, and LED light sources along the nets (Wang et al. 2009).

Sea turtles are able to see the UV spectrum, though through a limited spectral range that varies with turtle species and age (Southwood et al. 2008). Experiments discussed in this paper were predominantly performed on green, loggerhead, and leatherback turtles of varying age in both field and laboratory settings. Generally, fishing nets were affixed with light sources placed at a distance of 5m and 10m apart before netting was deployed at night. Illuminated nets were deployed alongside a control net and the nets' respective catches were compared. A summary of the reduction in sea turtle bycatch in Baja California from 2006 and 2007-2009 is included in Figure 7.

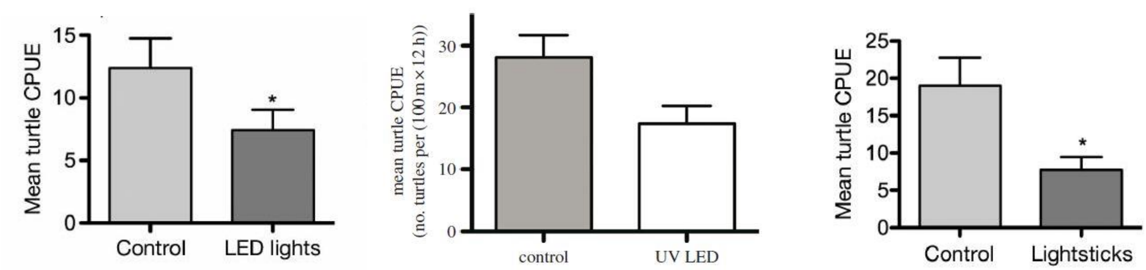

Figure 7. Mean turtle catch rates (CPUE) for light source experiments (Wang et al. 2009 & 2013).

In cases where the nets were illuminated, sea turtle by catch was reduced upwards of 60% for chemical light sticks, 40% using LED (Wang et al. 2009), and 39.7% ultraviolet (UV) LEDs (Wang et al. 2013). The capture-per-unit-effort (CPUE) was also calculated for each experimental and control net experiment. Wang et al. (2013) calculated the catch-per-unit-effort of the nets as:

$$CPUE = N_{TC} / (L / 100) * (t / 12) \quad (1)$$

Where CPUE = capture-per-unit-effort, N_{TC} = number of turtles captured, L = length of net (m), and t = soak time i.e. time spent in water of net (hr).

The resulting mean capture-per-unit-effort (CPUE) of each experimental net vs. the control pair are shown in Table 1.

Table 1. Comparison of CPUE for 2006 & 2007-2009 experiments (Wang et al. 2009 & 2013).

Deterrent Type	Experimental Net CPUE	Control Net CPUE
Chemical Light Sticks	7.8 +/- 1.7 (SE)	19.0 +/- 3.7 (SE)
LED Lights	7.4 +/- 1.6 (SE)	12.4 +/- 2.4 (SE)
UV Lights	16.1 +/- 2.5 (SE)	26.7 +/- 3.3 (SE)

The colors of the LEDs and chemical light sticks were chosen based on the spectral range of sea turtles, with green being the most effective deterrent (Southwood et al. 2008). Experimentation with blue, violet, yellow, and orange also elicited a positive response of recognition from turtles, but were not as successful as green light in field tests (Southwood et al. 2008). It was hypothesized that the light sticks produced greater reduction because the sticks emit a broader spectrum of light, which contain multiple peaks and less irradiance than is emitted by LED lights (Wang et al. 2009). However, the light sticks light strength decays over time which could in turn affect efficiency throughout their deployment. In Figure 8 is an example of how and what kind of lights were used in experiments performed in Peru from 2011-2013.

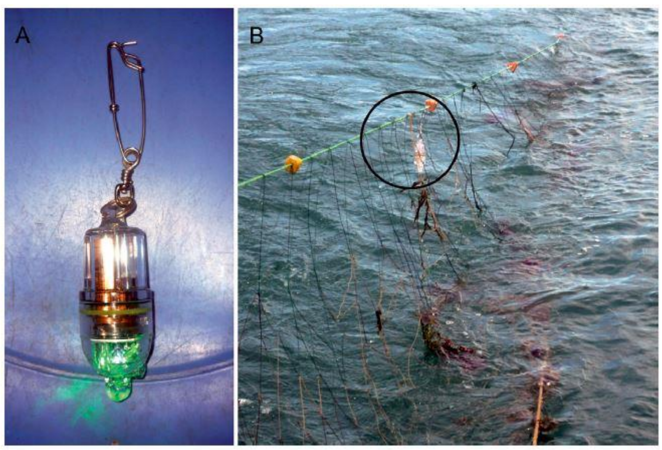

Figure 8. LED lights and attachment strategy (Ortiz et al. 2013).

It has been theorized that success is achieved using this mitigation technique because the light sources illuminate the hazard (e.g. the netting) which sea turtles can then avoid, and not the light sources alone that deter them. A similar approach may be applied to the dragheads, otherwise quiet and inconspicuous to sea turtles, by highlighting them with LED lights (Henrikson et al. 2015). Figure 9 is an example of how lighting can be incorporated onto the hull of a TSHD. The material composition of the dredged material and turbidity of the surrounding water influence what light source could be used as a dredging application. Because dredging operations decrease water transparency, it is suggested that UV LEDs be utilized due to their increased ability to penetrate through turbid conditions (Virgili et al. 2017). There remains the potential of illumination sources being incorporated into other mitigation techniques, such as TTCs or predator silhouettes, to increase their effectiveness. This possibility will be discussed later in the paper.

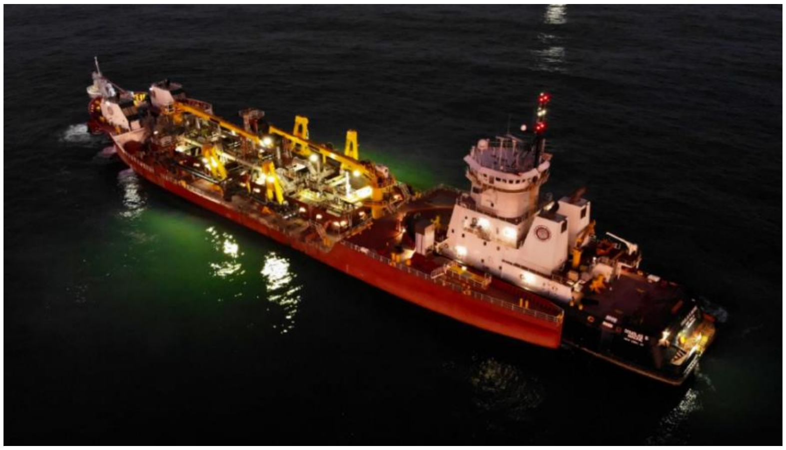

Figure 9. TSHD Ellis Island outfitted with green lights working in Corpus Christi, TX, USA.

<u>*Application Concerns*</u>

Attraction to Lights

Some researchers have voiced concern that juvenile turtles may be attracted to light sources, due to the pivotal role light plays in orienting newly emerged sea turtle hatchlings towards the ocean, rather than be deterred by it (Southwood et al. 2008). However, experts have noted that how sea turtles respond to light, "… comes down to 'how an animal responds to a sensory cue in context'" implying that each turtle may react differently in different circumstances (Gibbens 2018). Additionally, laboratory experiments performed with juvenile loggerhead turtle hatchlings have shown an observed aversion to light within the 500 to 600 nm spectral ranges (Southwood et al., 2008) that was further substantiated by research performed in 2006. In the latter experiment, the behavior of sea turtles towards broad spectrum white LEDs and LEDs with a limited spectral range of 560 to 600 nm was examined (see Figure 10, Swimmer et al. 2007). The results of this experiment corroborated earlier findings that sea turtles were less likely to approach lights of this specific spectral wave. This information could be applied when to only select LEDs which would illuminate equipment without simultaneously acting as a "homing beacon".

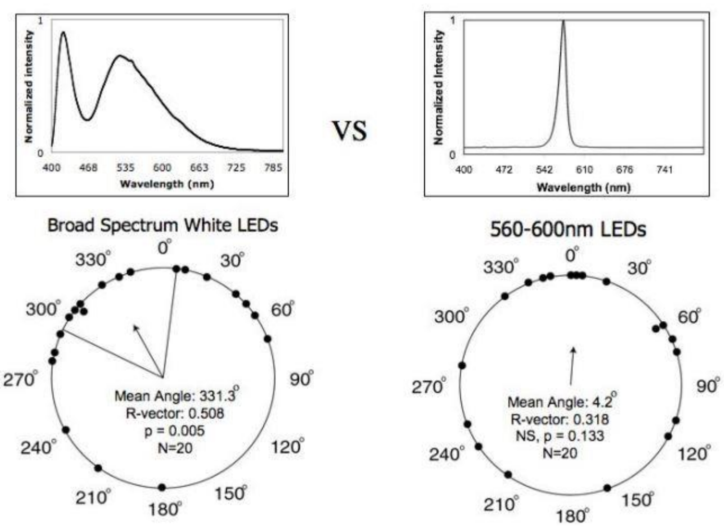

Figure 10. Range-specific LEDs vs. general broad-spectrum white LEDs (Swimmer et al. 2007).

Potential for Waste

Prior to applying any technologies to current dredging practices, the cost and capacity for waste of the application process must be heavily considered. Chemical light sticks yielded ideal sea turtle reduction results, but have the potential to generate a large amount of waste, as chemical light sticks last for a period of 24-hrs once they have been activated (Wang et al. 2009). Battery-powered UV LED lights have a longer lifespan than chemical light sticks, lasting as long as a month while staying continually lit (Wang et al. 2009), which would generate less waste and reduce the time lost to replacing individual units. Duke Conservation Technology has worked on creating a "sea turtle LED" that is a self-contained, chargeable LED which could reduce battery waste associated with numerous LEDs, and there is also the potential to incorporate solar-powered LEDs (Ortiz et al. 2016).

Shark/Predator Silhouettes

The visual acuity of sea turtles is vital to their behavior around predators. Research has been conducted to investigate how the image of a sea turtle's predator can affect their behavior for the benefit of the company e.g. encouraging them to avoid certain areas. The theory of using predator (shark) silhouettes or "scarecrows" has been experimented with in deterring various marine bycatch in fisheries and other interference from sea turtles (Wang et al. 2009, Reef Doctor 2017). Sharks are sea turtles' primary predator and seeing their image triggers an ingrained "flight" response, even those bred in captivity without having ever encountering a shark (Southwood et al. 2008). In 2006 and 2009, researchers deployed a series of bottom-set gill nets with silhouettes of sharks affixed to them in Baja California, Mexico. The silhouettes were made out of PVC plastic that was then painted black and weighted so that the silhouettes were negatively buoyant and placed at 10m intervals along a length of netting. Control nets that were not affixed with silhouettes were deployed twice throughout the day, in the morning and evening. No nets were deployed at night. The nets with shark silhouettes had a 53.9% reduction of turtle bycatch as compared to nets without the silhouettes, resulting in a mean CPUE of 5.6 +/- 1.1 in the experimental nets vs. the control net's CPUE of 12.1 +/- 3.1 (Figure 11, Wang et al. 2009).

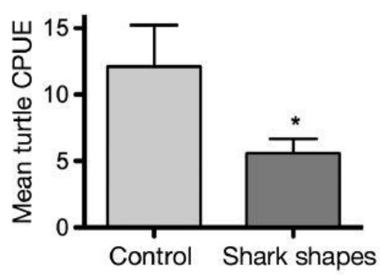

Figure 11. Effect of shark silhouettes on mean green turtle CPUE (Wang et al. 2009).

These researchers suggest that the use of silhouettes could be applied to other areas where unwanted sea turtle interactions occur, such as power plant seawater intakes and desalination facilities (Wang et al. 2009), or dredging operations. No published studies on the methods or efficacy of deploying predator predator silhouettes to reduce sea turtle bycatch in dredging operations are currently available, so the methods from fishery experiments were examined for potential application to dredging. Two methods were considered: attaching silhouettes directly to the dredging equipment and towing silhouettes using underwater unmanned vehicles (UUVs) or, more simply, underwater drones.

Deployment Methods

Like the fishing nets, shark silhouettes could be installed directly on the equipment so that, as the dredge moves, the silhouettes are pulled along. Successful application with this method would rely heavily on the materials used so as to avoid unaccounted for stress on the dragarm. Advantages of this application are that the silhouette would be deployed every load and requires minimal assistance to deploy. However, the sphere of influence of the silhouette would be limited to the dredge's trail path. The use of an underwater drone would be more advantageous from this perspective. Underwater drones have been used successfully to track marine life and collect of environmental data (Raoult et al. 2019) and advancements continue to make them more accessible for recreational uses (Mondal 2019). Some underwater drones include towing packages so that the silhouette could be moved around a dredge area at the discretion of the operator or software. This 360^{o} maneuverability could extend the influence of the silhouette throughout the dredge area and remove the additional cost and risk of modifying existing equipment.

Material & Design

The successful shark silhouettes investigated for this paper varied in material and design. Wang (2009) used plyboard and black paint in experiments in 2006, switching to rigid PVC plastic in 2007-2009 experiments. Part of Wang's suggestions for future projects was to incorporate materials that react with UV light so as to increase their being noticed by sea turtles. For example, shark-shaped banners of UV-absorbent plastic would be viewed as a solid shape when backlit by the sun or by UV LED lights without the use of paint. This installation would provide a flexible, lightweight alternative to stationary, bulky silhouettes that are susceptible to damage (Southwood et al. 2008) and simplify the silhouette design. Reef Doctor (2017) and Bostwick et al (2014) incorporated 3D designs: the first composed of steel wire/mesh and the second of plastic and painted with attributes of the black tip reef shark, great white shark, and shortfin mako shark. Photos of the models are included in Figure 12. Bostwick et al specifically suggests deploying a silhouette akin to the "Children's Day Koinobori kite[s], which they proposed could "fly" underwater. This design could be made with UV-absorbent plastic to increase the silhouette's impact as a deterrent.

Figure 12. 3D Predator silhouette examples (Reef Doctor 2017 & Bostwick et al. 2014).

<u>*Application Concerns*</u>

Deployment Methods

Depending on whether a rigid or banner-like representation of a shark silhouette is elected, the installation onto the dragarm could vary in difficulty. A free-flowing banner would be the easiest to incorporate, but the weaker structure is more susceptible to tearing off. A rigid metal silhouette could be affixed at a set angle along the dragarm, but considerations would also have to be taken for the varying angles dragarms are held at as they target different depths. To prevent the structure from damaging the equipment, the silhouette should be mounted so it does not contact the dragarm cradle, hull, or deck railing. Using an underwater drone to tow the silhouette reduces the risk of damaging the equipment, but introduces concerns about navigating safely around different parts of equipment. Concerns will likely differ dependent on the type of underwater drone that is utilized: a tethered drone may have limited accessibility around site, an untethered drone may have a low battery-life. Furthermore, the dredging environment (i.e. water transparency, time of day, etc.) the efficiency of these silhouettes could be impacted. Potentially the drone could be outfit with an UV LED light source, or series of, in order to provide additional illumination of the silhouette in fluctuating turbidity levels.

AUDITORY CUES

Acoustic Deterrent Devices (ADDs)

The use of sound to alert sea turtles to the presence of a threat, be that a fishing net, power plant, or dredging equipment, has been the focus of much research and pilot tests (Swimmer 2007, Wang 2007). Typical applications of sound include air horns and acoustic alarms, also called “pingers” (Barkan, 2010), which emit a sound at a frequency that disrupts seat turtles’ normal foraging behavior. These are then attached to netting or structures where sea turtle interaction is to be avoided. The frequencies can be adjusted to certain auditory ranges, isolating the impact of the ADD to a single type of marine animal, such as sea turtles or porpoises, deterring only that animal from interacting with an area (Pfleger, 2016). The use of sound as opposed to light is attractive to some because sound waves can move much easier underwater and are not hindered by dynamic environmental changes like water clarity.

<u>*Application Concerns*</u>

Ongoing experimentation with attaching auditory devices to netting is demonstrating great success in reducing sea turtle bycatch; in some cases entrainment was reduced by 65% (Pfleger, 2016). Despite these successes, there is great variability with using sound as a core turtle mitigation tool. Studies have shown that while sea turtle may be initially deterred, they are likely to grow used to the sound after a short amount of time (Southwood et al. 2008). Alarmingly, during some fishing net experiments, sea turtles became attracted to the sound, associating it with a food source. There are the additional concerns of targeting a frequency that all sea turtles would register as an alarm, as sensitivity to sound varies between sea turtle types and age, and the negative effects of impacting behaviors of uninvolved marine life.

FaunaGuard

A unique application of using acoustic alarms is the FaunaGuard, an ADD designed by Van Oord and SEAMARCO (Van der Meij et al. 2015). Unlike other ADDs, FaunaGuard is “designed and tested scientifically for specific marine fauna species or groups of species” (Van der Meij et al., 2015). Through this system of categorically emitting the frequency best-suited for individual species, the threat of negatively impacting additional species is lessened. It is designed predominantly to be deployed in an area prior to underwater operations, like dredging, commencing so when operations begin marine wildlife will have already evacuated the area. The apparatus could also be deployed for the duration of underwater operations, if desired.

Figure 13. FaunaGuard transducers and hydrophone (Van der Meij et al. 2015).

Application Concerns

FaunaGuard as a marine life deterrent has proven successful in the wild with fish and porpoises, but experiments with wild sea turtles have yet to achieve similar results (Van der Meij et al., 2015). Field tests have been performed using FaunaGuard and targeting Atlantic green sea turtles since 2016, though data shows that the signal emitted by the equipment is still too quiet to be an effective/reliable deterrent (Moore 2019). For this reason, FaunaGuard could be kept in mind as a future turtle mitigation tool, but it cannot be realistically applied in the short-term until further research is completed.

CONCLUSIONS & RECOMMENDATIONS

This report explored how conventional and alternative turtle mitigation strategies that could be incorporated into TSHD to help reduce sea turtle entrainment and mortality. The most effective strategies utilize the physical, visual, and auditory cues recognized by sea turtles to control their behavior, influencing them to leave and/or avoid an area where the strategies are implemented. Physical and visual cues were the most successful in causing these desired behaviors. Considering this, and the application potential of the different methods discussed, the following applications should be investigated further: TTC curtains, shark silhouettes, and UV LED light sources. Research, specifically pilot tests, is required, to concretely assess the impact that the use of these different mitigation strategies would be on projects. Cooperation from local/federal environmental groups as well as dredging experts is encouraged to limit any adverse effects on wildlife while maintaining a realistic implementation to dredging equipment/operations.

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A PIANC ENVICOM REPORT ON THE BENEFICIAL USE OF DREDGED MATERIAL

Burton Suedel[1], Victor Magar[2], and Luca Sittoni[3]

EXTENDED ABSTRACT

Background

Annually, billions of cubic meters of material are dredged globally to maintain safe navigation for commerce and recreation. Navigational maintenance is integral to the world economy, without which the safe waterborne transport of cargo, cruise ships, and pleasure craft would not be possible. With the need to manage dredged material, several constraints pose challenges to increasing sediment beneficial use due to concerns over impacts to surface waters, displacement of aquatic habitat, release of contaminants into the environment, or logistics. These constraints in the face of growing societal needs motivate the development of innovative and sustainable alternatives, including identifying sediment beneficial uses that foster multiple engineering, economic, social, and environmental benefits.

Beneficial use is naturally aligned with sustainability, life-cycle analyses, and circular-economy approaches and the United Nations Sustainable Development Goals (SDGs). The use of sediment as a resource represents opportunities towards enabling sustainable practices that can realize engineering, environmental, social, and economic benefits. Sediment beneficial uses include coastal resiliency management to counteract coastal erosion, manufacturing of locally produced building materials, establishment of wetlands and other habitats, and land reclamation. Infrastructure and community resilience, climate-change impacts, habitat management, and costs all can be leveraged to successfully identify and integrate sediment beneficial use into projects.

PIANC Working Group Report

PIANC Working Group (WG) on Beneficial Use (WG214) is developing a report that will provide technical information and guidance regarding the state of the practice for dredged sediment as a resource, drawing from existing approaches and best practices. The report's objective is to provide a decisive step towards internationally mainstreaming BU. Because current socio-economic challenges likely require local and regional understanding of governance-related issues, the report is focused on the information collected by extensive interaction with stakeholders and on regional considerations. In this manner, the report builds on relevant reports published by PIANC (1992, 2009), the Central Dredging Association (CEDA 2019a,b,c), the International Association of Dredging Contractors (IADC; Laboyrie et al. 2018), and the European Sediment Network (SedNet), among others. The report considers and evaluates the following: Concepts of sediment use and existing scientific knowledge related to different uses; sediment contamination and how contamination can constrain sediment reuse alternatives; use of cost-benefit and ecosystem services frameworks as tools to better understand how the value of different beneficial use options can be quantified; and compare different beneficial use and disposal alternatives.

This report provides details about how dredged sediment can used to deliver environmental and other societal benefits. It describes the key issues associated with such beneficial use projects and identifies valuable international practices. It informs and provides motivation for the increasing beneficial use of dredged material on a global scale. Increased beneficial use, in harmony with nature (i.e., Working with Nature, Building with Nature, and Engineering With Nature®; Bridges et al. 2018, 2021; EcoShape 2020;

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PIANC 2008; Van Eeklen and Bouw 2020), will foster greater circularity and improved environmental and social sustainability. Achieving these ambitions will necessitate substantial changes to established perspectives and sediment management practices. Greater strategic and collaborative planning will enable more projects to be identified and delivered in the future.

In an increasingly circular economy, conventional disposal methods including the use of confined disposal facilities and offshore disposal in oceans or lakes are finding limited stakeholder acceptance. These are increasingly no longer permittable due to local, regional, or international restrictions. At the same time, areas near ports and navigation channels need sediments to re-establish their natural equilibrium or as a substrate for waterborne infrastructure (e.g., dikes or land expansion). Ecosystems that are likewise sediment starved often lead to coastal erosion, subsidence, and loss of habitat. With climate change and increased anthropogenic pressures on coastal environments, coastal resilience, habitat adaptation, and carbon sequestration become increasingly important drivers for improved sediment management decisions.

This report provides technical information and guidance regarding the state of the practice for sediment BU by drawing from existing approaches and best practices worldwide, with specific focus on how to mainstream beneficial use. The WG identified three key barriers to mainstreaming beneficial use: cost; perception and governance; and contamination and environment. The report also provides information about how to overcome these barriers, through for example, focusing more on added value and less on cost, engaging multiple stakeholders and partners in projects, and consider contamination from a risk-based perspective. Aspects of the report to be presented include an overview of global sediment beneficial use practices, technologies, and limitations. Case studies will be presented that illustrate recent successes of applying innovative beneficial uses of dredged material as nature-based solutions (Figure 1).

Figure 1. The Horseshoe Bend project on the lower Atchafalaya River, Louisiana, USA is an example of sediment beneficial use as a nature-based solution (Foran et al. 2018; Photo USACE New Orleans District).

Keywords: Beneficial use, sediment, sustainability, nature-based solutions, Working with Nature

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DATA AVAILABILITY

No data, models, or code were generated or used during the study.

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BENEFICIAL USE OF DREDGED MATERIAL ALONG THE TEXAS LOWER COAST

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ABSTRACT

The Texas General Land Office (GLO) awarded a Coastal Management Program Project of Special Merit grant (funded through the Gulf of Mexico Energy Security Act) to Ducks Unlimited, Inc. (DU), to coordinate with stakeholders and identify restoration sites for the beneficial use (BU) of dredged material. The Port of Corpus Christi Authority, a project partner, has also contributed staff and financial resources to expand project scope. Collectively, the project team has developed 10% designs for 20 sites in GLO Planning Regions 3 and 4 of the Texas coast. After completion of the 10% designs, 11 of the designs were selected to continue to 30% designs and at least five of those designs will be chosen for 60% designs and permit applications. Through coordination with stakeholders, selection and completion of the 10% designs, and selection of the sites for 30% designs, the team has identified methods and techniques for restoration and creation of marsh habitat at four sites, restoration and creation of rookery habitat at four sites, protection and restoration of seagrasses at one site, and restoration of tidal flats at three sites. The chosen sites have favorable indications of success as future BU sites along the lower Texas coast.

Keywords: Beneficial use, dredged material placement, marsh creation, marsh restoration, rookery island, bird island, maintenance dredging, feeder berm, seagrass restoration, seagrass protection, tidal flat restoration

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INTRODUCTION

Navigation channels along the Texas coast are in frequent need of dredging. In the past, the majority of dredged material has been placed in existing permitted upland or open bay placement areas, neither of which provide significant ecological benefits. This method results in the loss of a valuable resource that could be used to restore wetlands, rookeries, tidal flats, beaches, and other ecologically and economically important habitats.

The implementation of BU of dredged material projects typically requires a multi-year, collaborative effort. Through funding from a Coastal Management Program Gulf of Mexico Energy Security Act grant as well as the Port of Corpus Christi Authority; Ducks Unlimited, Inc.; and the Port of Corpus Christi Authority, with the support of Anchor QEA, LLC; Sarosdy Consulting, Inc.; and the Texas Department of Transportation, worked with stakeholders in the lower Texas coast to identify and prioritize more than 70 potential BU restoration sites. These sites span a wide range of restoration types and indicate a strong demand for dredged material along the lower Texas coast. Of these sites, 20 were selected for 10% design, 11 are currently being designed at the 30% level, and at least 5 of those 30% designs are being carried forward to 60% designs, cost estimates, and permit application packages. This effort will result in several high priority projects that will be strong candidates for final design and construction under future funding streams and will ultimately take advantage of the valuable material dredged annually from Texas navigation channels.

Simultaneously developing preliminary designs of 20 sites provides a unique opportunity to prioritize and coordinate restoration activities. Among the 11 sites selected for 30% designs are marsh creation and restoration sites, beach nourishment, rookery island creation and restoration, seagrass protection and restoration, and tidal flat restoration sites. Evaluations of the proposed type of BU by the stakeholders with the existing conditions within the lower Texas coast have led to the identification and initial designs of several promising techniques for future BU. This paper presents an overview of those techniques for 10 of the sites selected for 30% design.

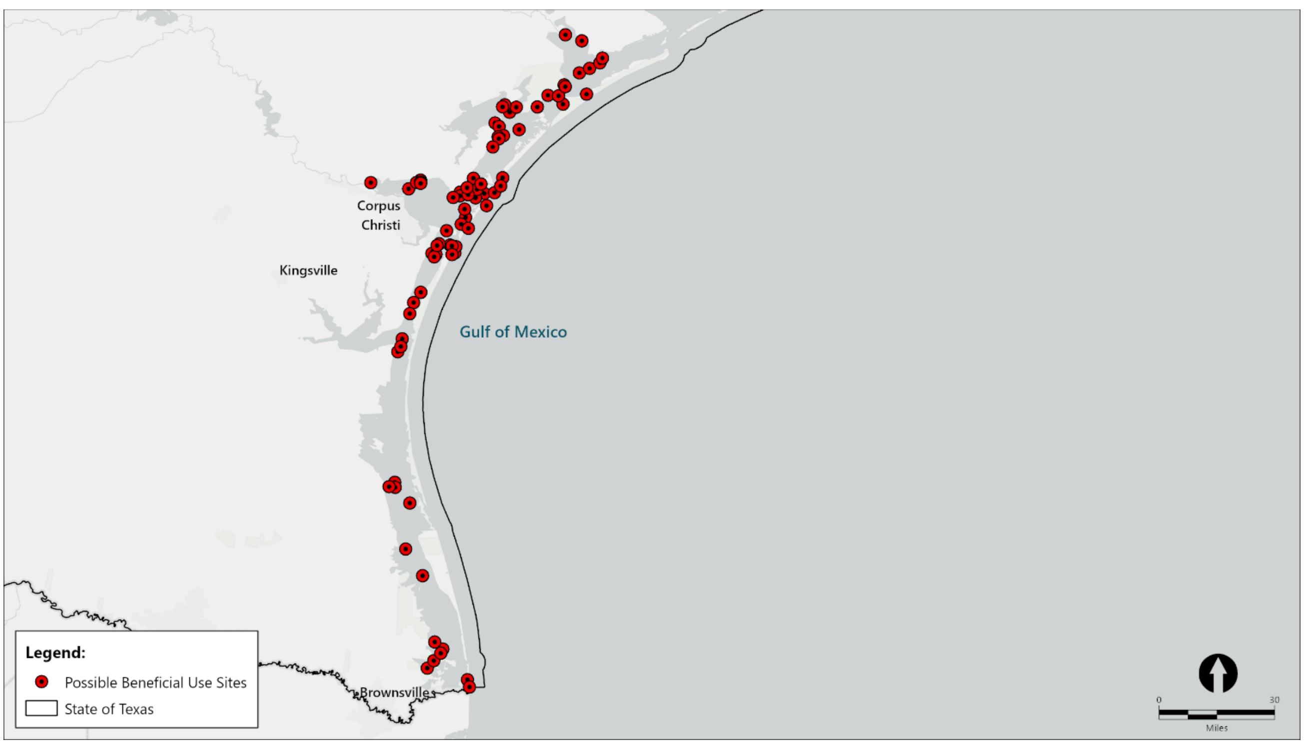

Figure 1. Potential BU Restoration Sites

LAGUNA MADRE BIRD ISLANDS

Background

Conservationists identified the Laguna Madre as an important location for creating and restoring bird habitat (CBBEP 2020a). Four rookery island locations within Laguna Madre were selected for 10% designs. Two of those sites, Rabbit Island South and dredged material placement area (DMPA) #214 Bird Island, were selected to continue to the 30% design level due to existing productive rookery habitat as well as less potential impacts on adjacent sensitive habitat during construction (TPWD 2021). These sites, as well as many other islands along the Gulf Intracoastal Waterway (GIWW) in the Laguna Madre, were formed from sidecasted new work dredged material during the original construction of the GIWW (circa 1945). While these islands are degrading, as are similar nearby islands, they have shown a fairly high degree of resilience over several decades in the absence of armored protection (see Figure 3, which illustrates a chain of islands north of DMPA #214). This material is considered to have superior structural characteristics than the maintenance dredged material removed from the GIWW in this region (Morton et al. 2001).

Figure 2. Rabbit Island South and DMPA #214 Bird Island

Figure 3. Chain of islands Laguna Madre from 1995 (left image) to 2021 (right image)

Design Concept

The design concept for Rabbit Island South and DMPA #214 Bird Island is to use the readily accessible, higher-quality relict new work material (i.e., material placed during the original construction of the GIWW) to build a naturally resilient rookery island. The construction would take place in two main phases:

1. A containment berm would be built around the site using existing relict new work material within the footprint of the site.
2. The site would be filled with hydraulically dredged material from a combination of maintenance material from the GIWW and relict new work material from submerged mounds adjacent to the site.

It is expected that once placed, the site would stabilize at a natural slope similar to other islands formed with relict new work material within the Laguna Madre. The target acreage for these sites identified by the stakeholders is 4 to 10 acres. This strategy takes advantage of a readily available source of favorable sediment found throughout the Laguna Madre and would benefit by the U.S. Army Corps of Engineers (USACE) paying for dredge mobilization costs during a maintenance dredge cycle. Conceivably, this relict new work material could be used at many sites throughout the region.

CORPUS CHRISTI SHIP CHANNEL PLACEMENT AREAS

Background

Two sites directly adjacent to the Corpus Christi Ship Channel (CCSC) were selected at the 10% design level and were subsequently carried over to 30% designs: PA9-S and Pelican Island (M3) (Figure 4). These sites are planned to provide both intertidal marsh and tidal flat habitats within Corpus Christi Bay. These sites have favorable characteristics for restoration due to readily accessible maintenance material dredged from the CCSC as well as potential new work material from the proposed CCSC Channel Deepening Project.

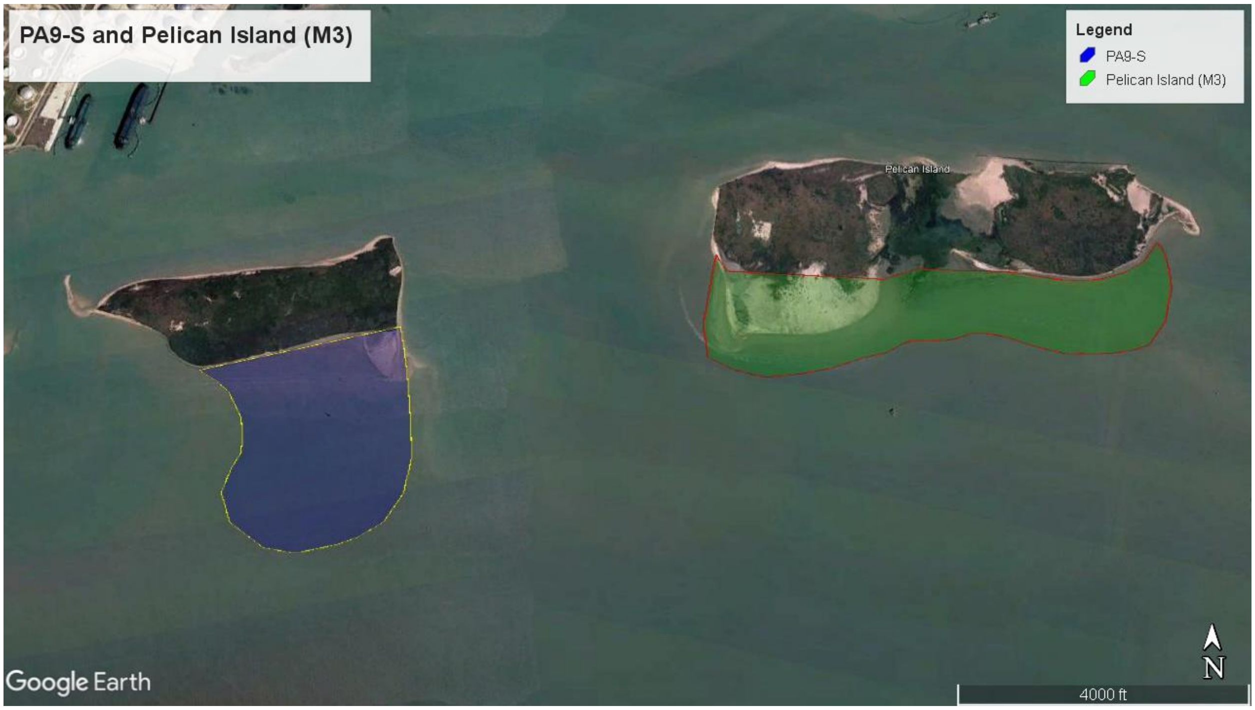

Figure 4. PA9-S and Pelican Island (M3)

Design Concept

The southern end of the PA9-S site was extended into water depth greater than 10 feet mean lower low water (MLLW) to maximize the quantity of material that could be received at the site. This ensures that not only is valuable habitat being created, but that there is significant capacity for material from the CCSC. Pelican Island (M3) was extended to the furthest depth that could be achieved without encroaching on submerged pipelines. These pipelines will be evaluated during subsequent design phases, and the footprint of Pelican Island (M3) may be extended. Due to the lack of protection from the predominant southeast winds and relatively deep water conditions surrounding the sites (greater than 6 feet North American Vertical Datum of 1988 [NAVD88]), similar armoring and containment is proposed for hydraulic placement of material from the CCSC for both sites. The construction for these sites would occur in three main phases:

1. An earthen dike would be hydraulically constructed of stiff clay dike fill surrounding the bay facing the perimeter of the site.
2. Once settlement and consolidation of the dike has completed, marsh buggies would be used to shape the dike above the MLLW level, and a rock breakwater would be placed below the MLLW level on the gradually sloped submerged portion of the dike (see Figure 5 for Typical Dike from PA9-S 10% design).
3. Hydraulically dredged fill material from the CCSC would be placed at marsh and tidal flat elevations within the dike over several dredging events.

Placing a breakwater on the bay side of the earthen dike allows for easier maintenance of the dike in the event of a storm event. The breakwater along the dike provides added protection for storm events. Any dike maintenance that is necessary post-storm events could occur by reshaping with a marsh buggy. If the armoring was placed as a revetment, potential failure from the back side of the dike could result in failure of the armoring. Constructing PA9-S will create approximately 150 acres of marsh and tidal flat habitat with a dredged material capacity of 3.6 million cubic yards (cy). Pelican Island (M3) will provide 1.2 million cy of capacity and create approximately 170 acres of marsh and tidal flat habitat.

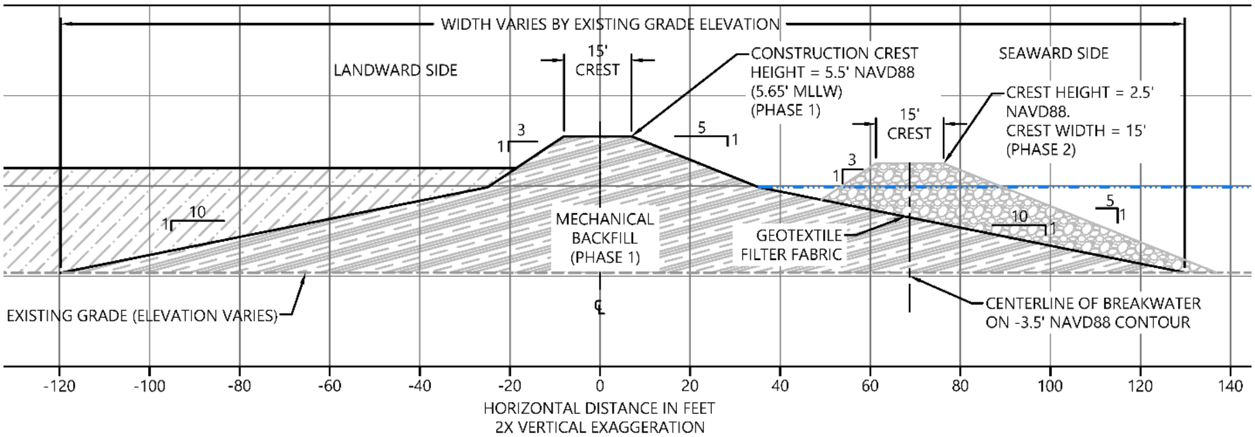

Figure 5. Typical dike PA9-S

FEEDER BERM NORTH OF FISH PASS

Background

The stretch of shoreline on Mustang Island from Fish Pass to Port Aransas is in an erosive environment resulting in coastline retreat (BEG 2019). Erosion of these beaches causes damage to both humans and wildlife because the beach provides economic value as well as habitat for breeding and foraging wildlife (Marbán et al. 2019). This is especially important for beaches on Mustang Island because the island serves as a habitat for threatened and endangered species including all five species of sea turtles (USFWS 2021; NPS 2022). Conversations with Deidre Williams of the Conrad Blucher Institute resulted in the identification of an area north of Fish Pass (a shoaled in, relict channel on Mustang Island) as an ideal location for a feeder berm (Williams 2021). Figure 6 shows an approximate location of the proposed feeder berm.

Figure 6. Feeder Berm North of Fish Pass

Design Concept

The conceptual berm is designed to be rectangular in shape oriented parallel to the shore. The proposed area of the site is 75 acres and would consist of approximately 500,000 cy of dredged material. The fill material could be sourced from the CCSC Entrance Channel or Ocean Dredged Material Disposal Sites. Designing the berm within the -10 to -15 feet NAVD88 contour is proposed to reduce the volume of sediment transported beyond the depth of closure and out of the active beach system (Williams 2022). One of the benefits of using a feeder berm for this site instead of direct beach placement is that a wider range of borrow sources can be used. Non-beach quality, but mostly sandy material can be placed within the berm with the expectation that sandy material will be transported to the beach while finer particles will be transported offshore (Gailani et al. 2019).

DAGGER ISLAND

Background

Dagger Island is located in Redfish Bay, Aransas Pass (Figure 7). The bay has several areas of seagrasses that are protected by strings of islands that have suffered shoreline erosion from storm events and wave energy from wind and ship traffic. The areas targeted for this project are open water areas to the southwest of Dagger Island that currently provide limited protection for the more than 700 acres of seagrasses within Redfish Bay.

Figure 7. Dagger Island

Design Concept

The proposed design is to fill breaches with a protective berm for the seagrasses to the north of the site and fill open water areas inside the berm up to healthy marsh or existing island elevations with dredged material from the CCSC. The berm would be armored with a rock revetment to mitigate erosion due to wind waves and vessel wakes from the CCSC. The selected area for the berm is situated between potential seagrasses (TPWD 2021), and seagrass surveys are planned to evaluate current sensitive habitat near the site footprint. The site footprint may be modified depending on an evaluation of potential seagrass impacts during construction of the berm.

LITTLE BIRD ISLAND NORTH

Background

Little Bird Island North is a rookery island creation site located within San Antonio Bay (Figure 8). The bay has been identified as an important location for rookery island creation and restoration (CBBEP 2020a; Hardegree 2014). There is an existing Little Bird Island in San Antonio Bay across the GIWW from the Little Bird Island North location; however, it is surrounded by oyster habitat (GLO 2021) and has limited natural protection from wind waves, making it less favorable for restoration than the Little Bird Island North Site.

Figure 8. Little Bird Island North

Design Concept

The concept for Little Bird Island North is to use maintenance dredged material from the adjacent GIWW and the nearby Channel to Victoria. As shown in Figure 8, there are oyster habitats on two sides of the site on shallow mounds of sediment, which are expected to act as a natural barrier and reduce wave heights from those directions. Due to this natural protection, proposed armoring is a rock breakwater with an open end on the southwest of the site. This open end would be temporarily contained with an earthen berm during construction to contain fines during fill material placement. The temporary berm would be removed after settling and consolidation of the fill material, and the contained fill would transition to a natural angle of repose, creating habitat for wading birds and allowing ingress and egress of aquatic organisms and wildlife to the site. Armoring on the northwest and east of the site may be reduced during subsequent designs.

NUECES DELTA

Background

The Nueces Delta is an area containing more than 10,000 acres of wetlands on the western end on Nueces Bay. Stakeholders have identified rapid degradation of this marsh (Dunton et al. 2019), which is supported via aerial imagery shown in Figure 9. Placing material in this degrading marsh has been an unsolved problem due to relatively shallow water depths and long sail distances from consistent supplies of dredged material. Stakeholders have suggested constructing a permanent pipeline from the Port of Corpus Christi Authority Viola Turning Basin directly to the delta beneath the Joe Fulton corridor (composed of county road, railroad tracks, and the Nueces River). The delta end of this pipe could be extended with traditional pipelines to discharge dredged material from the CCSC into targeted areas of the delta. This proposed restoration is a single use of the pipeline to create an area of marsh behind breakwaters planned for construction on the edge of a portion of the marsh.

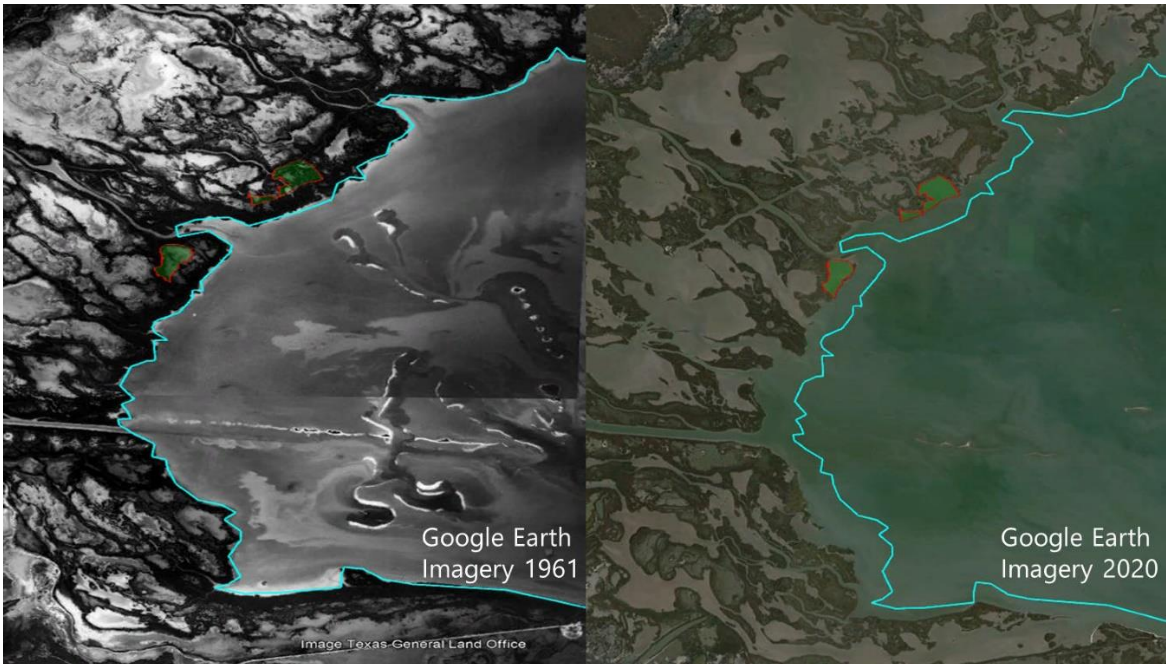

Figure 9. Nueces Delta Shoreline change 1961 to 2020

Design Concept

The concept of the marsh fill design is to use dredged material from the CCSC to create marsh habitat behind breakwaters that will be constructed along the edge of the Nueces Delta. This material would be contained behind the breakwaters, with temporary containment along sections of the perimeter to contain placed fines. With construction of the pipeline directly from the Viola Turning Basin to the delta, the approximate pipeline distance to the site would be 2 to 3 miles. Feasibility of the pipeline is currently under evaluation and will inform the current marsh restoration plans as well as future marsh restoration opportunities within the Nueces Delta.

PORTLAND NUECES BAY MARSH

Background

Nueces Bay is a shallow bay averaging less than 3 feet of depth and is dominated by mudflats and oyster reefs (CBBEP 2005). Coastal Bend Bays & Estuaries Program (CBBEP) stakeholders noted the success of the Nueces Bay Marsh Creation Project in nearby areas of Nueces Bay and indicated a desire for expanded marsh creation in the same area. In the southeast corner of the bay adjacent to the City of Portland, there is a narrow existing marsh that stakeholders identified as a favorable location for marsh expansion. This site is also in a favorable location for access to dredged material due to its proximity to the La Quinta Channel. Figure 10 shows the location of the site in yellow. The gray areas to the west and northwest of the site show potential existing oyster habitat (GLO 2021).

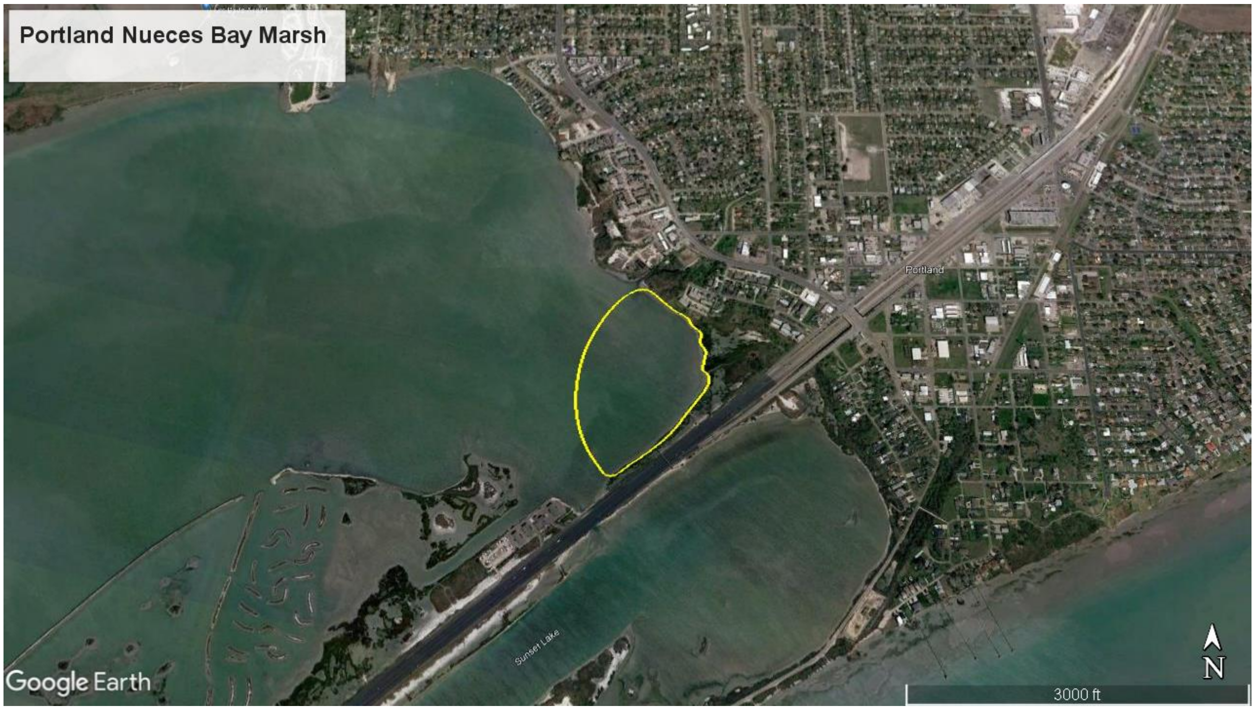

Figure 10. Portland Nueces Bay Marsh

Design Concept

The preliminary proposed design for this site is a uniform marsh extending from the existing marsh out into the bay with a natural angle of repose creating up to 40 acres of marsh habitat. Hydroseeding of the bayside edge of the marsh is proposed to increase resilience to erosion. CBBEP stakeholders indicated a potential need for armoring due to erosion seen on the previously unarmored protecting berms at the Nueces Bay Marsh Creation project to the west of the site. Due to shallow depths (2 to 3 feet NAVD88 at the edge of the site), the preliminary proposed armoring for the site is a rock berm to reduce the energy of incoming waves. The rock sill would not only reduce wave energy to the marsh but could also provide oyster habitat by recruiting oysters from adjacent identified oyster reefs. The proposed armoring will be further evaluated during subsequent phases of design based on wind wave modeling and geotechnical evaluation.

CAUSEWAY BIRD ISLAND

Background

Causeway Bird Island is located on state-owned submerged land adjacent to the Rincon Canal in Nueces Bay, Nueces County, Texas (Figure 12). The Nueces Bay rookery islands have been identified by conservationists as important locations for protecting and restoring bird habitat (CBBEP 2020b; Hackney et al. 2016). This area is favorable for BU because it has close proximity to source material from Rincon Canal and the CCSC and a rock breakwater, constructed in 2022, around the island (Figure 13). Placement of dredged material within the breakwaters was identified as an effective method to increase bird habitat in a region with degrading coastal bird habitat.

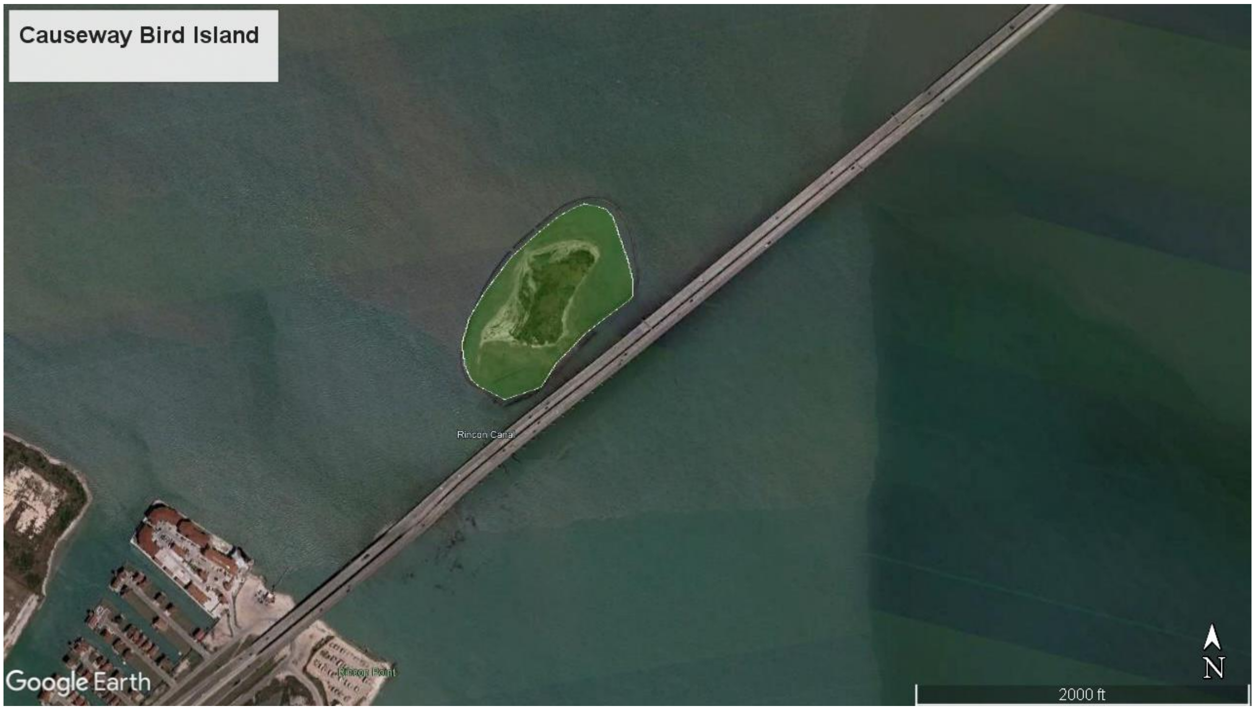

Figure 12. Causeway Bird Island

Figure 13. Submerged portion of Causeway Bird Island leading up to rock breakwater

Design Concept

Causeway Bird Island is an existing island with open water leading up to a surrounding breakwater. The proposed design is to fill the site with dredged material from the Rincon Canal and the CCSC to expand the current rookery island. To accommodate different species of birds, there will be channels cut into the fill at the locations of gaps in the breakwater. These cuts will follow a natural slope up to the existing elevation of the Bird Island. Channels with shallow angles of repose will generate habitat for wading birds while expanded upland areas at the existing elevation of the island will increase the acreage of habitat of already productive rookery habitat to approximately 16 acres. This will have beneficial effects on the regional ecosystem and will more than double the habitat for the herons, egrets, terns, skimmers, and pelicans that currently reside on the island (CBBEP 2020b)

CONCLUSIONS

Through the support of GLO and the Port of Corpus Christi Authority, and using input from numerous stakeholders, the project team was able to identify and prioritize more than 70 potential BU restoration sites. By evaluating these sites based on their need for dredged material and ability to become successful BU sites, the project team was able to select 20 sites for 10% designs. Of those 20 sites, 11 are currently being designed at the 30% level and at least 5 of the 30% designs will be taken to 60% designs and permitting. This paper focuses on those sites that were selected for 30% design.

Through this collaboration, several restoration types spanning marsh creation and restoration sites, beach nourishment, rookery island creation and restoration, seagrass protection and restoration, and tidal flat restoration sites were evaluated at the 10% level as well as are currently being evaluated at the 30% level for regions of the lower Texas coast. Several techniques and methods for restoration have been identified for each of the sites that have promising indications for success.

- The use of the abundant relict new work material with superior structural characteristics provides an opportunity to restore valuable rookery habitat throughout the Laguna Madre.
- The use of hydraulically placed stiff clay dike fill potentially from the proposed CCSC Channel Deepening Project to generate earthen dikes with rock breakwaters on their bayward toe, allowing for reduced costs to repair failed dikes during storm events than a traditional revetment.
- The use of feeder berms to nourish beaches along Mustang Island, and elsewhere, that have a strong need for nourishment, so that a potentially wider range of borrow sources could be used.
- The use of dredged material to plug holes in the shoreline along Redfish Bay, protecting more than 700 acres of seagrasses within the bay.
- The use of relatively shallow oyster reefs in San Antonio Bay to reduce costs for armoring rookery islands.
- The installation of a permanent pipeline to provide access to dredged material to areas of the Nueces Delta marsh that have experienced significant marsh degradation.
- The use of a rock berm in Nueces Bay to take advantage of the shallow depths and provide potential oyster habitat while protecting new marsh habitat.
- The use of existing breakwaters to expand existing rookery habitats.

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CITATION

Freddo, A., Merendino, T., McNeil, H., Garza, S., Newby, R., Smith, H. and Opdyke, D. (2022). "Beneficial Use of Dredged Material along the Texas Lower Coast." *Proceedings of the Western Dredging Association Dredging Summit & Expo '22, Houston, TX, USA*, July 25-28, 2022.

DATA AVAILABILITY

Some data are available from the corresponding author by request.

CLEAN SEDIMENTS AND CLEAR CHANNELS FOR HOWARDS BAY AND FRASER SHIPYARDS – COMBINED NAVIGATION AND REMEDIATION DREDGING

M. Erickson[1], M. Gravelding[2] E. Dievendorf[3], L. Tomlinson[4], S. Hill[5], P. Viana[6], and A. Kohler[7]

ABSTRACT

Background/Objectives. Howards Bay is a 300-acre embayment within the St. Louis River Area of Concern (SLRAOC). It is the home of Fraser Shipyards, Inc. (Fraser), providing critical dry dock and maintenance services to the Great Lakes fleet for over a century. Federal navigation channels in the bay required dredging. Sediments throughout Howards Bay required remediation to help delist the SLRAOC. A partnership including the Wisconsin Department of Natural Resources (WDNR), the City of Superior (City), the United States Environmental Protection Agency (USEPA), the United States Army Corps of Engineers (USACE), and Fraser (collectively the project partners), collaborated to enable a clean and prosperous future for Howards Bay. This partnership designed and completed an integrated project to accomplish navigational and remedial dredging, leveraging USEPA cleanup program funds, USACE navigational dredging funds, and contributions from WDNR, the City, and Fraser. This presentation showcases that collaboration and the cost-effective approach to accomplish the project partners' objectives.

Approach/Activities. The project development path followed a remedial investigation and feasibility study process. This work was co-funded by USEPA through the Great Lakes Legacy Act, in-kind technical services and funds provided by WDNR and Fraser, and planning support and in-kind services by the City. The selected remediation approach included dredging throughout most of Howards Bay, placement of a post-dredging cover based on confirmation sampling, and enhanced natural recovery by thin-layer placement in limited areas. In parallel, USACE planned maintenance dredging using their Strategic Navigation Dredging funds. A portion of the navigational material had low-level contamination and could be managed at USACE's Erie Pier facility, with the remainder requiring landfill disposal with other remedial dredge material. Combining the designs, using the same staging area and City-provided disposal location, and a single contractor and project team created cost savings.

Some highlights of the project approach included:

- Navigation dredging was completed first, to protect that material from remedial dredging redeposition and to expose deeper sediment requiring separate disposal
- Remedial dredge extents were based on mercury, lead, tributyl tin, and polycyclic aromatic hydrocarbons (PAHs) clean up levels
- Removal to native clay was accomplished in many areas
- Dredge residuals management by confirmation sampling and sand cover placement

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- Sand cover placement to enhance natural recovery in limited shallow areas
- Dredge limits included structural offsets and sloping to protect shorelines and infrastructure
- The shipyard remained active and required coordination with construction vessels
- A waiver of environmental windows was granted given the level of controls implemented
- Remedial dredged material was stabilized with Portland cement for landfill placement

Results/Lessons Learned. The project serves as a successful precedent for similar future partnerships, and may offer a cost-effective model where adjacent navigation and remediation dredging needs exist:

- The spirit of collaboration that emerged provided momentum, creativity, and combined goals
- This spirit of collaboration encouraged agreeable, timely solutions
- Cost savings were achieved in design, permitting, and planning phases by combining navigation and remedial dredging in one project
- Construction cost savings were achieved via a single contractor, construction management team, staging site, and monitoring program
- Rapid confirmation sampling data evaluation by the project partners was aided by graphical summaries and results mapping to support project completion within budget
- Monitoring and management controls to protect water quality were important for meeting regulatory expectations, and response actions successfully mitigated concerns

Keywords: Dredging, dredged material handling and disposal, resuspension control, active shipyard, contaminated sediment, Great Lakes Legacy Act (GLLA).

INTRODUCTION

Howards Bay is a priority area for remediation within the St. Louis River Area of Concern (SLRAOC). The bay is within the twin ports harbor of Duluth, Minnesota and Superior, Wisconsin. Shipyards, grain terminals, commercial fishing, and other industrial operations have occurred in the bay for well over 100 years. It is the home of Fraser Shipyards, Inc. (Fraser), which provides critical dry dock and maintenance services to the Great Lakes fleet. Federal navigation channels in the bay required dredging. Sediments throughout Howards Bay required remediation to help delist the SLRAOC. A partnership including the Wisconsin Department of Natural Resources (WDNR), the City of Superior (City), the United States Environmental Protection Agency (USEPA), the United States Army Corps of Engineers (USACE), and Fraser (collectively the project partners), collaborated to enable a clean and prosperous future for Howards Bay. USACE provided technical and engineering support to USEPA. Arcadis worked with USACE to design and complete an integrated project to accomplish strategic navigation dredging (SND) and remedial dredging, leveraging USEPA cleanup program funds, USACE navigational dredging funds, and contributions from WDNR, the City, and Fraser. This presentation showcases that collaboration and the cost-effective approach to accomplish the project partners' objectives.

Howards Bay is located on the east side of the St. Louis River within the City of Superior and is bisected by the Interstate 535 Bridge (Blatnik Bridge; see Figure 1). It includes three ship slips and two dry docks along the south shore and in total is about 300 acres (121 hectares). Shorelines include sheet pile, riprap, former wooden and concrete wharf structures (some of which are dilapidated), existing and former bridge approaches and abutments, and earthen banks. Water depths vary from very shallow along the north shore to approximately 33 feet (10 meters) below the low water datum within the federal channel that runs nearly the entire length of the bay. Commercial maritime needs in the bay are met by this channel which provides access to the ship slips and dock areas. It is approximately 100 to 275 feet wide (30 to 85 meters) with an authorized project depth of 27 feet (8.2 meters). The three slips are used for loading and unloading ships at grain elevators, long-term layup of ships, and servicing boats and ships at the shipyard facility. Historical ship painting and repair operations, urban stormwater discharges, and industrial activity resulted in sediment in the bay being contaminated by lead, mercury, tributyltin, polycyclic aromatic hydrocarbons (PAHs) and other contaminants. This contamination was the focus of remedial investigations and a feasibility study by the project partners.

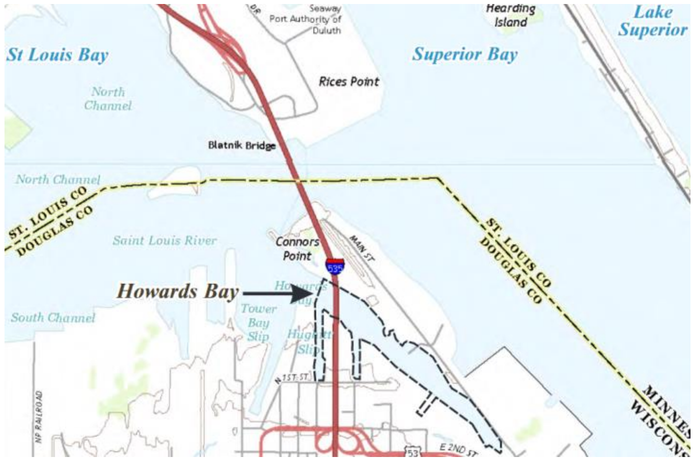

Figure 1. Site location.

Arcadis supported the project partners throughout the project development path, which followed a typical remedial investigation and feasibility study process and led to a selected remedy and subsequent design. The design was a joint effort by USACE for the SND portion and Arcadis for the remedial portion. The project was co-funded by USEPA through the Great Lakes Legacy Act, with in-kind technical services and funds provided by WDNR and Fraser and planning support by the City. The selected remediation approach included dredging 89,000 cubic yards (cy) (68,000 cubic meters [m^3]) over 18 acres (7.3 hectares) and placing a thin layer cap (6 inches or 15 cm of sand) to enhance natural recovery over 0.7 acre (0.3 hectare). The combined dredging and remediation areas extended throughout approximately 20 percent of Howards Bay.

INVESTIGATION AND REMEDY SELECTION

Sediment data were collected during several sampling events from 2007 through 2017 to characterize the nature and extent of contamination in sediments. More than 500 sediment data points from approximately 160 sample locations were collected with core depths extending up to 9.25 feet (2.82 meters) below the sediment surface.

PAHs, tributyltin, mercury, and lead were identified as contaminants of concern (COCs). Organic COC data were normalized to total organic carbon (TOC). Concentrations of COCs vary due to the history of various sources, dredging activity, construction projects and other activities within the bay, including ship movements and ice breaking. Tributary flows to the bay include a small creek and several urban combined sewer overflows, although these inputs are small and flushing rates are low. Sampling results were compared to the WDNR recommended sediment quality guidelines, including Threshold Effect Concentration (TEC) and Probable Effect Concentration (PEC) screening levels, which are levels at which the potential for toxicity to benthic organisms are predicted to be unlikely and probable, respectively. The Midpoint Effect Concentration (MEC) is the average of the TEC and PEC values. In comparison to the WDNR MEC values (Table 1), impacted sediments were present in the slips and east end of Howards Bay for lead; in the slips for mercury; in the slips and near the Blatnik Bridge for PAHs; and in the slips, in the federal channel near the slips, and near the mouth of the bay for tributyltin. In the shallower water, north of the federal channel, large areas exhibited low COC concentrations.

Table 1. Sediment screening levels.

COC	Unit	TEC	MEC	PEC
Total PAH17-TOC	mg/kg-TOC%	1.61	12.205	22.8
Tributyltin-TOC	mg/kg-TOC%	0.00052	0.00173	0.00294
Lead	mg/kg	36	83	130
Mercury	mg/kg	0.18	0.64	1.1

Notes: mg/kg = milligrams per kilogram; mg/kg-TOC% = milligrams of organic constituent per kilogram of dry-weight sediment normalized at 1% total organic carbon

The site was divided into polygons based on the sample locations, guided by bathymetry and physical features. Polygons with COCs exceeding the MEC defined the remediation footprint. Target dredge depths were defined by the core profile results in each location. Several alternatives and remedial technologies were considered and dredging and engineered natural recovery (ENR) in limited areas were selected. The decision was driven by COC concentrations, depths of exceedances, and water depth. Shallow areas to the north of Howards Bay were selected for ENR as effects of ship activity were limited in this area, which reduced the potential for resuspension and erosion.

The alternatives analysis considered a range of disposal options for remedial dredge material including placement onsite, in a USACE disposal facility, at a commercial landfill, and at a municipal landfill. A combination of municipal and commercial landfill disposal was selected.

DESIGN

Parallel to the environmental evaluations, USACE planned maintenance dredging using their SND funds and USACE's Erie Pier facility to receive dredged material. The volume requiring removal to restore navigational depths was 35,000 cy (26,800 m^3). The acceptance criteria for Erie Pier determined what materials required alternative disposal (MPCA 2022). Within the remediation area, an additional 75,000 cy (57,000 m^3) of sediments were identified below the SND dredge depth that exceeded the MEC.

To leverage the SND and GLLA funding together while pursuing the lowest overall cost, it was recognized that the SND and remediation dredging designs could be developed in parallel, utilize a single contractor, be managed by a single team, and thereby the implementation cost would be minimized. USACE self-performed the SND design and contracted the remedial design work to Arcadis. USACE was the technical and construction management agency for the design and construction, seamlessly providing this service for both the SND dredging and remedial activities on behalf of USEPA and the project partners.

The City of Superior provided a disposal site at the Wisconsin Point landfill for the remedial dredged material that met their criteria for placement beneath the cover or as cover material. The remainder of the remedial dredged material was disposed at a commercial landfill. The Wisconsin Point landfill was inactive and the design included opening the landfill, placing stabilized dredged material to raise the elevation and improve drainage slopes, regrading and closing the landfill with a soil cover, and constructing public use amenities such as a trail, benches, and an improved roadway. Roadway improvements were included to mitigate impacts of trucks delivering dredged material to the landfill.

The first step of the design process was generating a three-dimensional model of the site bathymetry, chemical data, and proposed removal area boundaries using the Mining Visualization System (MVS) software (see Figure 2). This allowed visualization of removal areas to confirm removal limit assumptions and support development of the dredge plan. The output from the model also allowed comparison of chemical data to disposal criteria to categorize the sediment to be dredged for placement within the Wisconsin Point landfill as cover or subsurface materials. Approximately 10,600 cy (8,100 m^3) of sediment with the highest COC concentrations was anticipated for offsite disposal at a commercial landfill.

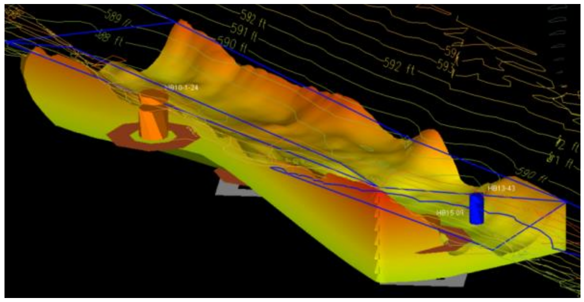

Figure 2. Example model output.

The model was refined to develop the dredge prism. Dredging offsets from structures were applied and side slopes were established based on a shoreline and structure stability evaluation, sloping between adjacent dredge areas, and constructability adjustments, such as smoothing contours and transitions. Minimum dredging offsets of 10 feet (3 meters) were applied for all structures. Maximum side slopes were 2:1 (horizontal:vertical [H:V]) for the majority of the dredge area and 3:1 (H:V) adjacent to the head of Hughitt Slip. Review of the model from a constructability perspective also led to an increase in ENR area (to 1.1 acres or 0.45 hectare).

Development of the dredge prism was tied to discussions about the confirmation sampling approach. The dredge areas were divided into subareas for sampling with an aim of 1 sample per 3,600 square feet (sf) (330 square meters [m^2]). The subareas were determined with constructability in mind as potential actions based on sampling results were re-dredging with residual cover, residual cover (no re-dredging), or no action. To facilitate in-field decision making, the project partners collaborated on a decision tree – a flowchart that outlined the decision-making process based on analytical data.

As part of the design process, WDNR reviewed typical environmental windows and controls in the SLRAOC and other sediment remediation sites. They issued a site-specific memorandum with detailed requirements for turbidity monitoring and resuspension controls during construction. These requirements were incorporated in the design. The level of planning and controls allowed for a waiver of the standard environmental window, which would have required an additional two months before on-water work could commence.

Arcadis performed a treatability study in parallel with the other design efforts. WDNR collected the required samples. Arcadis performed a series of tests to evaluate stabilization agents based on paint filter, shake, and pocket penetrometer testing, and testing a subset of samples for geotechnical and analytical properties. The design selected 4% calciment to stabilize material for commercial landfill disposal and 7.5% Portland cement for Wisconsin Point landfill disposal (strength requirements were higher for Wisconsin Point).

The addition of Portland cement led to a rise in pH, with values over 12. WDNR worked with an agricultural laboratory and found that an expensive nutrient amendment process would be necessary to use these materials for landfill cover soils. As such, WDNR worked with USACE to determine that prior navigational dredged material stockpiled at USACE's Erie Pier facility could be beneficially used as cover soils and this was included in the design.

In addition to the analytical requirements for surface versus subsurface material placement, other Wisconsin Point landfill design drivers were to minimize disturbance of the existing materials, maintain a maximum 10:1 (H:V) side slope and minimum 3:1 (H:V) top slope, and maintain positive drainage post-construction. The design also included requirements for diversion swales and monitoring well extensions.

Once the environmental design was complete, Arcadis and USACE collaborated to combine the environmental and SND designs into a cohesive package for bidding. Prospective contractors bid the comprehensive design with the aim of performing the SND and environmental work in parallel during one construction season or in sequence over two seasons.

CONSTRUCTION

Following USACE's bidding process the selected contractor was J.F. Brennan Company, Inc. (Brennan). USACE managed the construction process, including holding the contracts for Brennan and Arcadis as the engineer during construction. Submittal review, field decisions, and other key decisions were directed by USACE in coordination with the project partners. Weekly coordination meetings were held. USACE and Arcadis provided full-time onsite construction oversight and project partner team members regularly visited the site to observe the work.

Construction started in the fall of 2020 with the removal of the SND material. This work concluded in the spring of 2021 while preparation activities commenced for the environmental dredging work. The SND work was performed first to limit redeposition of resuspended environmental dredging materials on otherwise unimpacted areas and because, in many locations, SND material overlaid the environmental material. SND material was managed in a barge, as necessary, and transported to Erie Pier for offloading.

Environmental dredging proceeded from May through November 2021, with backfill and cover placement in October through December 2021 (see Figure 3). Dredging of the highest concentration areas generally occurred first. Resuspension controls included air monitoring, turbidity monitoring, and containment measures (turbidity curtain, oil boom, and air bubble curtain). Dredging in some areas produced visible sheens on the water. The work area was visually monitored for sheens, and these were addressed by deploying sorbent booms and pads.

Figure 3. Environmental dredging.

Dredging completion was determined using a decision framework applied to each area. Dredging was completed to native clay in some areas, in which case no further action was required. In most locations, confirmation samples were collected, analyzed, and assessed to determine if the cleanup goals were achieved for each dredge area. If the goals were not met on the first pass, the project partners determined whether to perform additional dredging (and, if so, the required dredge depth) and place a sand cover, or to place a sand cover in the area in question. project partner decision-making on field data and confirmation results was collaborative and nearly real-time, leading to efficient construction operations and attainment of remedial goals. Re-dredge depths were most commonly 6 inches (15 centimeters) and ranged from 6 to 36 inches (15 to 91 centimeters). Residual sand cover typically was 6 inches (15 centimeters) and ranged from 6 to 18 inches (15 to 46 centimeters). A total of 90,200 cy (69,000 m^3) of sediment was dredged, including 13,000 cy (9,900 m^3) of re-dredge material. A total of 16,100 cy (12,300 m^3) of residual sand cover was placed. Final dredge quantities were verified by survey and residual cover thickness was verified by survey and core collection/observation (1 per 3,600 sf or 330 m^2). Consensus decisions on the appropriate approach for each area facilitated completing the project on schedule and within available budgets. USACE’s project engineer and construction management team played an important role in this process, obtaining needed input from the project partners on a weekly basis.

Sand cover was placed to enhance natural recovery in shallow areas that were not dredged. This was conducted by placing a nominal 6 inches (15 centimeters) of sand over the existing bed surface with an excavator, although quantities varied up to 11 inches (28 centimeters) in places to account for loss and consolidation during placement. Final ENR cover thickness was verified by survey and core collection/observation (1 per 3,600 sf or 330 m^2). A total of 800 cy (600 m^3) of ENR sand cover was placed.

The shipyard remained active throughout construction activities (see Figure 4); however, Fraser made available a berth space for staging and dredged material management that was consequently unavailable to service ships during the project. Conducting the work during active use of the shipyard required close coordination between Brennan and Fraser, both on the water and in the upland staging and support areas. These efforts ensured a safe and successful completion of on-water work. Arcadis and Brennan combined for over 50,000 person-hours onsite with no lost-time injuries.

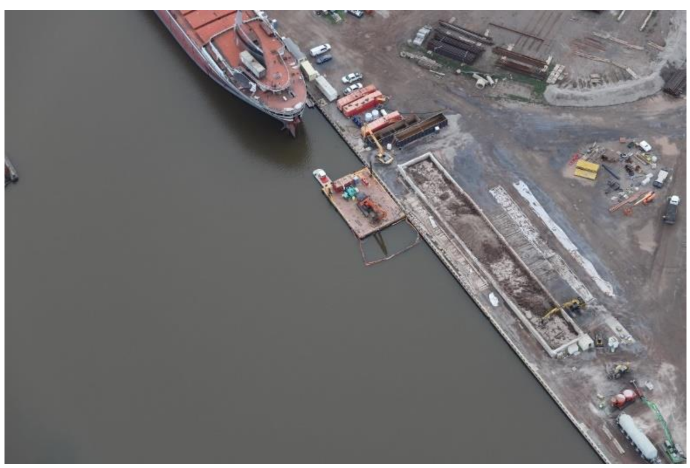

Figure 4. Active dredging near a large vessel. (WDNR Photo)

Dredged material generally was gravity dewatered and stabilized, as necessary, on a barge before offloading to the material staging area. Staged material was managed on the dewatering pad to promote additional water drainage before loading and transport via trucks to the final placement or disposal facility. Decant water from the barge and drainage water from the staging area were collected for pretreatment in a temporary onsite water treatment plant. Pretreated effluent was discharged to a nearby storm sewer for final treatment at the City’s water treatment facility. The staging area was situated immediately adjacent to the

Fraser bulkhead. Stabilized materials were loaded onto haul trucks that traversed across the shipyard property to surface streets for transport to disposal sites.

Wisconsin Point landfill operations generally proceeded in accordance with the design. A second temporary staging area was installed at the landfill entrance to allow material stockpiling prior to placement and grading. Materials requiring subsurface versus surface placement were staged separately to facilitate placement sequencing. Approximately 74,500 cy (57,000 m^3) of stabilized material was placed in Wisconsin Point landfill.

Figure 5. Material placement at Wisconsin Point landfill. (WDNR Photo)

The project partners were able to communicate well with each other to facilitate rapid decision making. WDNR and the City were required to make several key decisions with limited review time and maintain positive communications with the public. Their leadership proactively addressed potential community concerns.

CONCLUSIONS

The project can serve as a successful precedent for similar future partnerships and may offer a cost-effective model where adjacent navigation and remediation dredging needs exist and creativity can be applied in working within the available funding programs. In urban waterways around the country, navigation and remediation dredging needs are intertwined. The public interest in maintaining and restoring these waterways is more rapidly achievable through partnerships that can lower cost and speed timelines to construction. This project model of shared development, funding, and implementation demonstrates the value of creative partnerships to achieve the shared goals of federal and state agencies with industry. The spirit of collaboration that emerged provided momentum, creativity, and combined goals and encouraged agreeable solutions.

Cost savings were achieved in the design, permitting, and planning phases by combining the navigation and environmental dredge projects. Additional construction cost savings were achieved via a single contractor, construction management team, staging site, and monitoring program. Disposal costs savings were achieved in beneficial use of navigation dredged material, and the City of Superior accommodating the dredge material within the Wisconsin Point landfill, which produced a closure beneficial to public use. The team committed to completing the work within a defined schedule and budget and was able to meet this challenge. Funding needs were expeditiously addressed during implementation so that the value of a single contractor mobilization would not be lost. During construction, rapid confirmation sampling data evaluation by the project partners was aided by tabular summaries and results mapping to support project completion within budget. Monitoring and management controls to protect water quality were important for meeting regulatory expectations, and response actions successfully mitigated concerns. This project is an important step toward restoration and delisting of the SLRAOC.

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CITATION

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DATA AVAILABILITY

All data and models generated or used during the project are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

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EXPERIENCES WITH BENEFICIAL USE OF DREDGED MATERIAL IN SENSITIVE HABITATS IN COASTAL NEW JERSEY, USA

W. S. Douglas[1], M. J. Marano[2], M. Lunemann[3], S. Flanigan[4] and J. Heeren[5]

ABSTRACT

The Atlantic coastal region of New Jersey (NJ) is home to one of the US coastlines most vulnerable to the impacts of sea level rise. Recent events have spurred a shift in sediment management policy from one of upland confined disposal to beneficial use aimed at keeping as much of the sediment in the system as possible. Theoretically, this will allow sediment to naturally maintain the extensive marshland and beach system which protects the communities in coastal NJ from sea level rise, storm surge and wave damage. Not only does this system provide recreation opportunities for millions of people, but it is also home and feeding grounds for a diverse array of resident and migratory fish and wildlife. The NJ Department of Transportation's Office of Maritime Resources (NJDOT/OMR) is responsible for operations and maintenance of 200 nautical miles [nmi] (370 kilometers [km]) of shallow draft navigation channels in the Atlantic coastal region. This marine transportation system connects an extensive number of berths, terminals, and private docks that provide access for recreation, fisheries and emergency response vessels to the 105 nmi (195 km) federally maintained Intracoastal Waterway and the Atlantic Ocean. Proper maintenance of this system requires the dredging of approximately 300-500,000 cubic yards [CY] (230-380,000 cubic meters [m^3]) per year of mostly clean sand and silt, not including storm damage response. In the past decade the NJDOT/OMR has dredged 1.2 million CY (917,000 m^3) of sediment and beneficially used over half of that in resiliency projects ranging from shoreline stabilization and marsh enhancement to restoration of shallow water habitat. Another 2.0 million CY (1.5 million m^3) of sediment has been dredged by the US Army Corps of Engineers (USACE) in the same timeframe, with 60% being used in resiliency projects. This paper describes these projects, lessons learned and considerations for moving forward in a sustainable manner.

Keywords: habitat enhancement, shoreline stabilization, beach replenishment, navigation dredging, regional sediment management

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INTRODUCTION

Between the US Army Corps of Engineers (USACE), State agencies, local municipalities and private berth owners, millions of cubic yards [CY] (cubic meters [m^3]) of sediment are dredged in the United States every year. The material ranges in quality from clean sand to fine silts and clays contaminated by both legacy and ongoing pollution to prehistoric clays, glacial till and rock. Dredging is by itself challenging, but often is overshadowed by the difficult task of transporting, processing, and placing dredged material in a safe and

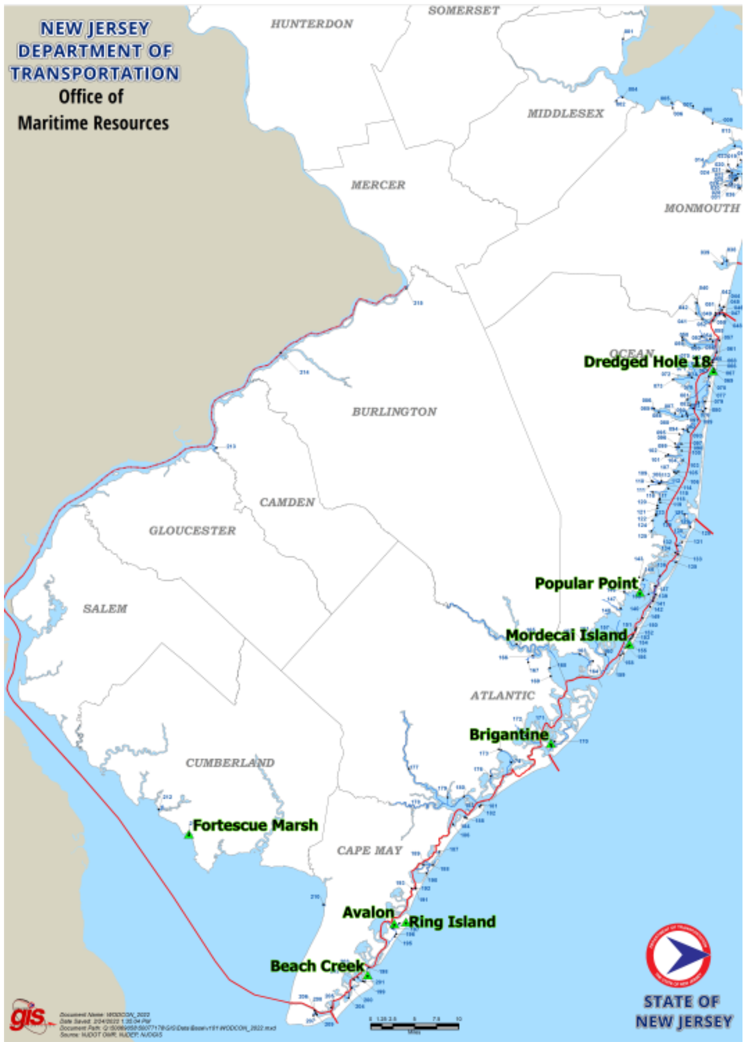

Figure 1. NJ MTS in Atlantic and Delaware River Regions and Locations of Beneficial Use Projects

affordable manner. In addition, the public, and particularly those concerned about the environment, have long taken a negative view of dredging and dredged material management.

The State of New Jersey’s marine transportation system is the largest in the country, with over 600 miles [mi.] (970 kilometers [km]) of engineered waterways ranging in depth from 5 to 50 feet [ft] (1.5 to 15 meters [m]) (Figure 1). The State is divided into three regions, each with its unique mix of channels, sediment, and management techniques dictated by economics, geography, and land use. The New York/New Jersey (NY/NJ) Harbor region is typified by deep draft (35 to 50 ft [12 to 15 m]) commercial channels and large volumes of sediment ranging from clean sand to contaminated estuarine silts and clays. Dredged material is managed primarily through ocean disposal (for clean material) and upland placement (for contaminated material). The Delaware River region also has deep draft commercial channels with large maintenance volumes, but the material is either clean or moderately contaminated and is managed in upland confined disposal facilities (CDFs). The third region, the Atlantic Coast region between Sandy Hook and Cape May, is a large network of shallow draft channels ranging in depth from 5 to 15 feet (1.5 to 4.5 m). Primary usage is recreational, but a large and productive commercial fishery and shellfishery fleet is also served. Dredged material has been historically managed via beach placement (for coarse-grained material) or confined upland disposal (for fine-grained material). In recent years, dredging in NJ's Atlantic coastal region has been hampered by a lack of capacity at existing dredged material management facilities and a lack of alternatives (Douglas et al., 2019).

Also in recent years, there has been increasing interest in marine transportation to manage highway congestion. At the same time, coastal communities have seen an increase in tourism and year-round residential development. Both trends put more pressure on transportation managers to improve the marine transportation system and keep it in a state of good repair. This is true for both the large commercial channel networks as well as the shallow draft recreational networks. This is occurring at the same time that climate change and sea level rise are increasing both regular and catastrophic storms and concomitant storm surge and flooding. These storms not only wreak havoc on developed coastlines, but also increase erosion of marshes and beaches, resulting in increased shoaling, which necessitates more and more frequent dredging to maintain safe navigation.

In coastal NJ, the ravages of Superstorm Sandy in 2012, and subsequent storms since, have spurred the State to look carefully at the resiliency of coastal communities. It is now widely accepted that healthy coastal marshes, dunes, beaches and other "green infrastructure" are an essential component of sustainable coastal living. What has become increasingly apparent is that sediment, rather than being at best a nuisance and at worst a pollutant, is a vital and important resource for maintaining and improving resiliency for both the natural and built environment. Beaches and dunes protect ocean front homes from storm surge and damaging waves, whereas coastal marshes, of which NJ has over 300,000 acres [ac] (121,500 hectares [ha]), dampen storm surge, attenuate waves, and reduce flooding of bayside homes and businesses (NJDEP, 2021).

The increased frequency and violence of coastal storms damage beaches and marsh shorelines. Increasing sea level causes frequent inundation and slow drainage of seawater from coastal marshes, resulting in destabilization of marsh platforms and eventual loss. Some 59,000 ac (24,000 ha) of marsh have been converted to open water since 1977, and another 74,000 ac (30,000 ha) are in danger of being lost if something is not done to reverse these trends (Ferencz et al., 2017). Since slowing climate change and sea level rise are global management issues, and will require many years if not decades to accomplish, there is an immediate need to put sediment back into dunes, beaches, and marshes and to come up with ways to keep it there, so those features can protect coastal communities and enhance coastal resilience. At the same time, valuable habitat for wildlife and fisheries will hugely benefit through the restoration of damaged coastal ecosystems. Undoubtedly, the marine transportation industry, particularly those agencies charged with operation and maintenance of the channel networks, is able to help with this crisis.

A DREDGED MATERIAL MANAGEMENT STRATEGY FOR NJ'S ATLANTIC COASTAL ZONE

The NJDOT/OMR is responsible for the operation and maintenance of 200 nautical miles [nmi] (370 km) of state navigation channels in the coastal region. These channels connect local channels and berths to the federally maintained NJ Intracoastal Waterway (NJIWW) and Atlantic coastal inlets. NJDOT/OMR is also responsible for the State's recovery efforts from Superstorm Sandy's damage to the channel network, a decade long effort set to be completed by 2024. Dredging in coastal NJ has historically been accomplished with small to medium sized hydraulic cutterhead pipeline dredges, with the sediment either used for beach replenishment or stored in CDFs located primarily on coastal marshes. While there is evidence and record of hundreds of CDFs throughout the region, many are either full, reverted to natural areas from disuse, or been leveled and developed for housing. What remains are a few dozen CDFs, leaving gaps in the system where there are few if any dredged material management options (Barone et al., 2012).

Since the late 1970s, increasing environmental regulation of dredging and dredged material management has created a system that is often at odds with transportation agencies and the dredging industry. Both the marine transportation industry and the environmental agencies both look at sediment as a problem, rather than a resource. This has led to a negative regulatory approach that places large burdens on the industry through reduced permitted work windows and limited management options, even for clean sediment, resulting in both increased costs and deferred maintenance. In some parts of coastal NJ, dredging has not been possible for decades due to a combination of inadequate funding and lack of affordable dredged material management options.

Since taking over routine operation and maintenance of the system in 2013, NJDOT/OMR has been actively pursuing innovative solutions for managing dredged material for those areas where traditional management options are not available. Marsh enhancement, shoreline stabilization, and confined and unconfined benthic restoration are a few of the techniques that have been demonstrated over the past 9 years. These projects would have been infinitely more difficult, if not impossible, without the cooperation of resource agencies such as the NJ Division of Fish and Wildlife (NJDFW), the NJ Department of Environmental Protection (NJDEP), the US Fish and Wildlife Service (USFWS), and the National Marine Fisheries Service (NMFS), as well as non-governmental entities such as The Nature Conservancy and The Barnegat Bay Partnership, among others. This forward-looking approach has made it possible to dredge and beneficially use over a half million cubic yards of sediment. Our understanding of how to place sediment efficiently and safely in sensitive ecosystems has vastly improved over the past decade. However, to date, the scale of these projects has been small, the costs relatively high, and the timelines too long for sustainable dredged material management.

What is needed now are more efficient techniques for larger scale projects, regulations that encourage beneficial uses and increase predictability, and a better accounting of benefits provided to coastal communities, fisheries and shellfisheries, and wildlife to support the increased costs. The following is a summary of the beneficial use projects conducted in NJ since Superstorm Sandy, their associated costs and timelines, challenges and considerations, and a plea for a coordinated approach moving forward.

BENEFICIAL USE CASE STUDIES

The following case studies summarize experiences with implementing different types of beneficial use projects in coastal NJ.

Ring Island

Beneficial Use Type: Upland Habitat Creation

The Ring Island Marsh, is an 600-ac (240-ha) saltmarsh island located in Avalon, Atlantic County, NJ. It was comprised of stunted and sparse vegetation, mixed with bare areas. The objectives of these two experimental projects were to: (1) increase the elevation of a low-lying marsh by spraying a thin-layer of sandy dredged material (96% fine sand), 3 and 6 inches [in.] (7.5 and 15 centimeters [cm]) thick onto two (2) 0.5 ac (0.2 ha) areas of the marsh platform, ultimately resulting in increased cover and vigor of native salt marsh vegetation, and (2) create elevated nesting habitat (ENH) for the State-endangered Black Skimmer (*Rynchops niger*) and other colonial nesting shorebird species of concern. The dredged material for these projects came from a nearby short reach of the NJIWW. In August 2014, approximately 1,000 CY (765 m^3) of fine-grained sand were sprayed on two (2) 0.5-ac (0.2-ha) sections of the existing marsh, and approximately 6,000 CY (4,600 m^3) of the sand were used to create an approximately one ac (0.4 ha) colonial shorebird ENH (Pecchioli et al., 2021).

Lessons Learned:

- Multiple applications may be required to achieve project goals if mitigation for coastal processes is not provided.
- Long term management efforts may be required to maintain as-built conditions. In this case, vegetation re-established in sand areas quickly post construction, reducing the desirability of site for the target species.

Mordecai Island

Beneficial Use Type: Island Restoration

Mordecai Island is an undeveloped 45-ac. (18-ha) marsh island in Barnegat Bay, on the western shore of Beach Haven, Ocean County, NJ. It shelters and protects the highly developed bay shore of Beach Haven from the brunt of wind and waves coming across Barnegat Bay, but over the years had been reduced and fragmented by the same wind and waves. The local citizenry, led by the Mordecai Land Trust, had long advocated for the repair and enhancement of the island for wildlife and coastal resiliency.

In 2015, the USACE, dredging sand shoals in the NJIWW, hydraulically placed 25,000 CY (19,100 m^3) of sand in shallow water between two of the larger marsh fragments, effectively joining them. To protect extensive beds of submerged aquatic vegetation (SAV) adjacent to the island, a system of hay bales and silt curtain was deployed to retain the solids (USACE, 2019). Besides effectively joining the two fragments, the project created valuable shorebird breeding habitat and restored the coastal protection provided to Beach Haven. Additional applications of material have been made since first constructed to replace consolidation losses and to raise the area high enough to avoid nest losses during storms.

Lessons Learned:

- Multiple applications may be required to achieve project goals due to consolidation and losses from coastal processes that caused the initial loss.

- Be prepared for unintended wildlife utilization which may result in the need for adaptive management.

Avalon

Beneficial Use Type: Marsh Enhancement

The Cape May Wetlands Wildlife Management Area (WMA) is a 1,000-ac (400-ha) saltmarsh comprised of eroding marsh edge, increasing pool size, and stunted and/or sparse vegetation on the marsh platform located in Avalon, Cape May, NJ. The objectives of the project were to (1) convert unstable, expanding pool/panne complexes into stable and vegetated marsh plain, and (2) create more resilient native salt marsh plant communities. It was decided that maintenance dredged material from the nearby NJIWW would be suitable for this purpose.

In order to hold sediment in the targeted pool areas, approximately 15,300 ft (4,660 m) of coconut fiber coir logs were manually installed. In some cases, the logs were stacked to provide sufficient containment for the hydraulically dredged slurry.

The project was conducted in two phases: In Phase 1, approximately 6,000 CY (4,600 m^3) of fine-grained dredged material (65% silt/clay, 34% fine sand) was hydraulically dredged using a 10-in. (25-cm) cutterhead pipeline dredge and sprayed across 7 ac. (5.4 ha). In Phase 2, a total of 49,300 CY (37,700 m^3) of fine-grained dredged material (72% silt/clay, 27% sand) was hydraulically dredged using a 14-in. (36-cm) cutterhead pipeline dredge from the same area and sprayed and/or pumped across 45 ac. (18 ha) (Pecchioli et al., 2021).

Lessons Learned:

- Establish project goals and adaptive management strategies before the start of construction.
- Remove containment materials as soon as possible. The containment was not always effective at retaining the dredged slurry at the targeted location; however, it did reduce normal tidal exchange resulting in alterations of sediment chemistry (pH, redox, sulfides) that caused temporary vegetative die off.
- Be patient, recovery takes time. The recovery of the saltmarsh vegetation required several years, even after the containment was removed and despite planting efforts.

Fortescue Marsh

Beneficial Use Type: Shoreline Stabilization, Marsh Enhancement

The Fortescue Marsh is located within the 1,300-ac (525-ha) Fortescue Wildlife Management Area (WMA) in Downe Township, Cumberland County, NJ. The marsh has a tidal range of 6 ft (1.8 m) with salinities ranging from 14-20 parts per thousand (ppt) and contains both high and low marsh habitats with vegetation typical of the region. The marsh had been evaluated and was impacted by considerable shoreline erosion as well as subsidence of the marsh platform caused by poor drainage brought on by sea level rise (Kreeger et al., 2015). Stakeholders agreed that adding sediment to the marsh had the potential to reverse the damage and restore the marsh (Pecchioli et al., 2021).

The remote fishing village of Fortescue, on the shore of the Fortescue Marsh, is surrounded by the Fortescue WMA. Local commercial and recreational fisherman are heavily reliant on the 3,800-ft, 9-ft deep state-maintained Fortescue navigation channel for access from Fortescue Creek to the Delaware Bay. Condition surveys indicated that over 80,000 CY (61,000 m^3) of sediment would need to be removed to return the channel to its full authorized depth.

Over the course of two dredging seasons, 37,140 CY (28,400 m^3) of sediment was dredged from the Fortescue channel and placed on the marsh and beaches using a 12-in (30-cm) cutterhead pipeline dredge. Approximately 8,500 CY (6,500 m^3) of fine-grained sediment was pumped directly into the marsh via a network of high density-polyethylene (HDPE) pipelines and valves. Sediment slurry was contained on the target areas using approximately 20,000 ft (6,100 m) of compost-filled polyethylene tubes. Another 21,000 CY (16,000 m^3) of course grained material was used to reconstruct an 1,100-ft (335-m) long by 100-ft (31-m) wide protective dune on the leading edge of the marsh. The sand was placed into a surge pit constructed on the marsh and the sand removed using an excavator and bulldozed into place. The remaining 7,000 CY (5,400 m^3) of coarse-grained material was utilized to replenish two nearby beaches; one a remote wildlife beach, the other a village bathing beach (Douglas et al., 2021a).

Lessons Learned:

- Consider the physical characteristics of the dredged material available and have placement locations defined for all material, with contingencies for over-runs.
- Carefully consider the need, type, and amount of containment. Installment of containment resulted in extensive, albeit temporary damage to the marsh platform.
- Avoid over-engineering. As with containment, there is a concern that construction of elaborate distribution systems will result in more damage to marsh platform. Using a marsh excavator to move the pipeline appears to be operationally acceptable, while minimizing damage.
- Consider pre- and post-construction hydrology. High tide events, combined with wind and precipitation, may help to distribute material across the marsh in a less intrusive manner than using mechanical equipment.
- Tidal redistribution and consolidation will result in a loss of elevation over time. Multiple applications of material may be needed to maintain target elevations, particularly in areas vulnerable to sea level rise.
- Marsh platform enhancements can be protected with shoreline stabilization. Recent inspections of the project indicate that the rate of shoreline loss in front of the dune has been significantly reduced.

Beach Creek

Beneficial Use type: Unconfined Benthic Restoration

Beach Creek is a state navigation channel that connects the western shore of North Wildwood with Hereford Inlet, providing access to the Atlantic Ocean for several marinas and a large number of residences. Unfortunately, the highly dynamic nature of the Hereford Inlet moves a considerable amount of sand through the area, and the mouth of Beach Creek shoals regularly making safe navigation impossible. Previous projects have pumped the sand to the front bathing beach, however, this requires running a pipeline through the Inlet itself, which is dangerous. In addition, the navigation channel is shallow draft (6 ft (1.8 m) mean low water [MLW]) and only 100 ft (31 m) wide, making it necessary to use small dredging equipment. The volume of sediment required to be dredged to restore navigation is typically less than 25,000 CY (19,000 m^3) making an economy of scale difficult to achieve. Consequently, a cheaper, easier and safer alternative was sought.

Following Winter Storm Jonas in 2016, an emergency permit was granted to hydraulically dredge the storm induced shoal and place the material into the ebb tide of the Absecon Inlet, with the desired effect of having the tide take the sand out to the ebb shoals (valuable wildlife habitat) or the recreational beach to the south. In late 2017, 11,350 CY (8680 m^3) of sand was hydraulically dredged from Beach creek using a 12-in. (30-cm) cutterhead pipeline dredge and placed into the ebb tide of the Inlet. The inlet bottom in the vicinity of the pipe discharge was surveyed prior to project start, and turbidity was monitored regularly during placement. At the end of the project, only a small amount of sand, directly below the pipe outfall, was able to be identified as having come from the project. The inlet is over 45 ft (14 m) deep in this area, so no navigation impacts were anticipated from this action. It is assumed that the majority of the material found its way to either one or more of the ebb shoals or to the bathing beach, but this could not be confirmed. No turbidity was detected above background conditions at any time during the process. Drone overflights conducted during the placement were also unable to detect a visible plume from the activity (Farrell, 2018).

Lessons Learned:

1. Placement of coarse-grained material into a dynamic inlet is effective at managing dredged material.
2. No negative impacts to navigation were observed
3. No negative impacts to water quality were observed.
4. The sediment was assumed to be transported to a more beneficial site by natural processes

Dredged Hole 18

Beneficial Use Type: Confined Benthic Restoration

Dredged Hole 18 is a 9-ac (3.6-ha) subaqueous borrow pit in northern Barnegat Bay, Ocean County that was originally mined in the early 1960s for beach replenishment projects. The hole was more than 20 ft (6 m) below MLW and had nearly vertical sides. (Average depth in this portion of the bay is less than 4 ft (1.2 m) below MLW.) The unnatural bottom configuration impeded normal tidal circulation resulting a stratified water column in the hole. Evaluations of water quality and benthic life performed by Stockton Coastal Resource Center in 2014 and 2015 indicated low dissolved oxygen and a no benthic life in bottom sediments (Howard et al., 2015). In contrast, the adjacent sand flats contained valuable habitat with annually occurring SAV including widgeon grass (*Ruppia maritima*). The site had been previously identified by the USACE as a good candidate for restoration using dredged material from nearby navigation projects (Murawski, 1969).

The NJDOT/OMR identified more than 240,000 CY (183,500 m^3) of dredged material in nearby State channels that could be used to fill the dredged hole and restore the benthic habitat. The material varied in quality and characteristics from clean sand to silty clay that was contaminated with metals, pesticides, and petroleum at levels slightly above residential soil remediation standards. The sediment was dredged mechanically, transported to the site, and placed into the hole. The more contaminated silty material was placed at the bottom, followed by coarser and cleaner material. A 3,100-ft (945-m) turbidity curtain was deployed around the entire site to prevent loss of fines. Approximately 83,500 CY (63,800 m^3) of coarse-grained material (> 75% sand) were reserved for the required 2-ft (0.6-m) thick cap. Placing this material at the top of the fill resulted in rapid consolidation and stabilization of the site. An additional 35,000 CY (27,000 m^3) of clean sand was added one year later following an evaluation of the thickness and grain size of the cap. Monitoring of SAV recruitment and benthic recolonization are ongoing as of the writing of this paper.

<u>*Lessons Learned:*</u>

1. Carefully evaluate the need and size of turbidity curtains. Turbidity from operations was rarely detectable, however wind-induced turbidity was common in the shallow embayment (Douglas et al., 2021b).
2. Expect consolidation of material over time. Additional applications of material may be necessary to maintain target elevations.

Good Luck Point

<u>*Beneficial Use Type: Marsh Enhancement, Shoreline Stabilization*</u>

The Good Luck Point Marsh is a 20-ac (8-ha) saltmarsh located within the Edwin B. Forsythe Wildlife Refuge in Berkeley Township, Ocean County, NJ. The marsh was previously identified as a candidate site for marsh enhancement by the US Fish and Wildlife Service as part of a larger effort to identify marshes at risk from erosion and sea level rise (AMEC/Foster Wheeler and EA Engineering, 2016). The marsh suffered from extensive mosquito ditching and hydrologic impediments caused by surrounding high ground and a roadway. All tidal exchange was forced through two undersized culverts. This resulted in long periods of inundation that were slowly degrading the marsh platform. It was decided that raising the platform by 0.7-1.1 ft, (0.2-0.3 m) as well as replacing the culverts, would dramatically improve tidal flushing (AMEC/Foster Wheeler and EA Engineering, 2016), improve vegetation coverage and health, and increase wildlife utilization. The amount of material needed to accomplish this was estimated to be 17,000 CY (13,000 m^3) of fine-grained material.

In addition, it was observed that the leading edge of the marsh exhibited moderate to severe erosion, and that the narrow 1,700-ft (520-m) beach that protected the marsh edge had slowly decreased over the years to a narrow ribbon a few meters wide. This isolated beach was not used for recreation but was utilized by shorebirds and other wildlife. To protect wildlife without hindering the project, it was not desirable to utilize traditional placement and grading techniques.

The NJDOT/OMR partnered with the USFWS by providing 10,200 CY (7,800 m^3) of maintenance dredged material from nearby navigation channels. The material was a mix of coarse and fine-grained material. Using a 10-in. (25-cm) hydraulic dredge, approximately 4,000 CY (3,000 m^3) of fine-grained material was pumped onto the marsh. Based on the experience at Fortescue, containment was deployed strategically. Polyethylene filter socks filled with compost were installed in mosquito ditches and along the eastern side of the site, with the goal of preventing sediment from clogging the main drainage ditches feeding the tidal culverts. To evenly distribute the material, the discharge point was moved around the site using a marsh excavator.

Approximately 6,000 CY (4,600 m^3) of coarse-grained material was hydraulically dredged and placed directly into the shallow open water along the beach placement area. The discharge end was mounted on a scow and the scow moved along the beach as areas were filled. Tidal currents and waves quickly integrated the sand into the existing beach.

<u>*Lessons Learned:*</u>

- Perform coastal modeling to better place sand for remote beach replenishment. A post-construction storm event moved the sand about considerably, but the majority of the sand settled within the project template, effectively enhancing and protecting 750 linear feet (230 linear meters) of marsh shoreline (Barone, 2021).

- Closely monitor sedimentation control structures. Sediment blocks were quickly overtopped during an above normal tide event and required intervention and enhancement during the project to prevent clogging of drainage pathways.
- Understand hydrology of the site. While a complete hydrologic model for the site was developed, damage caused by machinery access dramatically reduced drainage of a portion of the site, requiring repairs.
- Seek creative ways to achieve project goals. It was shown that dragging the discharge pipeline strategically across mounded areas was effective at leveling the placed material while avoiding having to traverse sensitive areas with heavy equipment.

Brigantine

Beneficial Use Type: Unconfined Benthic Enhancement

The Brigantine channel is a 6-mile (9.7-km) channel located in Absecon Bay on the western shore of Brigantine Beach, NJ. The channel provides access to the Absecon Inlet and the Atlantic Ocean for numerous private slips and a dozen marinas. Severe shoaling of hard packed sand at the southern end of the channel had resulted in partial channel closure. A condition survey conducted in November 2019 indicated that 27,000 CY (20,600 m^3) of sediment needed to be removed from a 2,000-ft (610-m) reach to reopen the channel. Unfortunately, there were no available options for managing the material. Previous dredging had utilized unconfined placement on nearby Boot Island marsh, but this area was now the home of a heron rookery, eliminating it from consideration. OMR initially proposed placing the material on a sand spit off Boot Island, but this was not approved as it might result in human visitation that would disrupt the heron rookery.

While the Brigantine uplands are highly developed, the surrounding marshes and intertidal subtidal shallows are extensive and heavily utilized by birds and other wildlife. After consultation with resource agencies (NJ DFW, NMFS and USFWS), it was decided that the material would be used to increase shallow water habitat, stabilize the shoreline, and restore shellfish habitat.

Two areas for benthic enhancement were identified on two marsh islands adjacent to the channel reach requiring dredging. Both islands exhibited extensive shoreline erosion and could benefit from raising the bottom elevation for both shellfish and wading birds.

Approximately 7,650 CY (5,850 m^3) of material was hydraulically dredged with a 12-in. (30-cm) cutterhead pipeline dredge into the open water adjacent to Sunflower Island and integrated into the shoreline using a marsh excavator. The sand stabilized 550 ft (170 m) of shoreline and reintegrated two remnant portions of marsh back into the island. Another 9,400 CY (7,200 m) of material was placed into the 21.4-ac (8.7-ha) subtidal depression at Boot Island to achieve a final elevation of 2 to 3 ft (0.6 to 0.9 m) below MLW. In total, approximately 23.6 ac (9.6 ha) of benthic habitat were created.

Lessons Learned:

- Partner with resource managers to explore creative ways to keep dredged material in the ecosystem. While the site had not been previously identified as requiring restoration or stabilization, engaging with resource managers early in the process identified locations that would benefit from receiving the dredged material, eliminating costly upland processing and placement.
- Open water placement of coarse-grained material using hydraulic equipment was effective and efficient. Sand did not migrate outside of target areas.

- Open water placement of coarse-grained material using hydraulic placement was environmentally safe. While turbidity could be detected around the dredge and at the placement sites, it was not detected in the surrounding waters (McKenna et al., 2021).

Popular Point

Beneficial Use Type: Marsh Enhancement/Restoration and Shoreline Stabilization

The need for both navigation improvement and improved coastal resiliency continues to drive the approval of these beneficial use projects in NJ. Navigation programs need to continue to build on lessons learned from previous projects to increase efficiencies and bring project costs down. The following case study summarizes a project that is currently being designed and permitted that takes this into consideration by increasing scale, reducing the use of machinery, and hopefully increasing efficiencies that will bring down the cost per cubic yard (cubic meter).

The Popular Point marsh is a 120-ac (49-ha) saltmarsh located south of the residential lagoon community of Beach Haven West on the western shore of Barnegat Bay, NJ. The site was targeted for development of additional residences in the 1960s, but the development was halted by protective land use regulations implemented in the 1970s. During the aborted development, some canals were cut into the marsh platform and a partial berm constructed around the site. In addition, the site is cut with shallow narrow mosquito ditches. Despite this, the marsh platform appears to be largely healthy, however, the berm has steadily eroded over the years and with damage caused by Superstorm Sandy, has largely disappeared. The unprotected marsh edge is now subject to the full brunt of wave and storm energy and is likely to deteriorate rapidly. The marsh provides critical protection to the 4,500-home lagoon community of Beach Haven West.

The Beach Haven West and other nearby communities suffer from moderate to severe shoaling in many of the collector and local channels serving the area. At this time, NJDOT/OMR and Stafford Township have identified over a million cubic yards (cubic meters) of dredging need. However, there are limited options for dredged material management. Historical CDFs located nearby are now protected habitat and not available for use. Partnering with the USFWS, who own and manage the Popular Point marsh, NJDOT/OMR is developing a project which will result in the ability to manage at least a third of the available material and restore the marsh as a critical nesting habitat for the endangered Saltmarsh Sparrow, as well as providing needed coastal protection for the community of Beach Haven West.

Based on extensive hydrologic modeling of the site, as much as 95,000 CY (72,600 m^3) of fine-grained material can be pumped onto the marsh and allowed to flow over the marsh and fill in mosquito ditches and the aborted lagoon canals. An additional 40,000 CY (30,500 m^3) of coarse-grained material could be used to construct a 2,000-ft (610-m) long 100-ft 31-m) wide nearshore berm and dune that will tie into the existing eroded shoreline and protect the marsh.

DISCUSSION

Project cost and available funding can often be a significant factor in the selection of dredged material management methods, including beneficial use projects. In our experience, the construction costs of traditional beach and CDF placement projects typically average around \$60 per CY (\$80 per m^3), whereas testing these innovative techniques has ranged from \$35 to \$285 per CY (\$45 to \$370 per m^3). While construction and oversight are the lion's share of project cost, the cost of engineering and permitting can be as high as 20% and monitoring can add another 30% to the cost of the project (see **Table 1**). While difficult to calculate, the indirect costs of reduced project size, multiple placement locations and schedule delays may be an even greater impact to the bottom line.

While costs for these projects are often, but not always, higher than traditional technologies, there is a need for increasing sustainable options for dredged material management as well as to provide a model for improving green infrastructure in the face of climate change. Few debate the economic impact of the increasing severity of storms, but it is harder to calculate the cost of damage caused by daily incremental increases in coastal processes of wind wave and tide brought on by sea level rise. Green infrastructure, like saltmarshes and sand dunes, have been identified as an important part of improving the resiliency of coastal communities. Dredged material has been shown to be effective at improving and protecting the health of marsh and beach ecosystems. While it is often difficult to identify funding for the protection of marsh and beach habitats, it is not difficult to identify funding to protect coastal communities and reduce economic risk. What is desperately needed is a way to tie navigation dredging needs to coastal resiliency and resource management goals so that all programs can realize the benefits and help justify the increased costs of dredging.

Regulatory Requirements

Regulatory requirements can add a level of uncertainty to dredging projects that either increases the cost considerably or prevents them from being built altogether. While policy makers are fully aware of the cost of environmental dredging restrictions designed to protect sensitive wildlife (so called “dredging windows”), they are only just beginning to hear about the costs and delays associated with data collection needed to support more innovative beneficial uses before, during, and particularly post construction (see **Table 2**). It is not sustainable for a transportation agency, for example, to carry long term monitoring.

Table 1. Cost Summary of Beneficial Use Projects

Project Name	**Beneficial Use Type**	**Placed Volume (CY)**	**Overall Project Cost (US $)**	**Construction (%)**	**Engineering and Design (%)**	**Monitoring (%)**	**Total Cost/CY placed**	**Acres Restored/ Created (Linear Feet of Shoreline Restored)**
Ring Island	Upland Habitat Creation	7,000	$706,970	63.8	5.9	30.3	$101.00	1 upland
Mordecai Island	Island Restoration	28,000	$981,100	84.7	12.7	2.5	$35.04	4 upland
Avalon	Marsh Enhancement	55,300	$2,796,270	72.4	10.8	16.8	$50.57	52 marsh
Fortescue	Marsh Enhancement/ Upland Habitat Creation/ Beach Replenishment	37,140	$5,200,744	79.1	9.4	11.5	$140.03	6.6 marsh, 1.6 beach (1100 shoreline)
Beach Creek	Unconfined Benthic Enhancement	11,350	$577,246	61.1	22.5	16.4	$50.86	unknown

Dredged Hole 18	Confined Benthic Restoration	244,106	$19,065,195	95.9	2.9	1.1	$78.10	9 subtidal habitat
Good Luck Point	Shoreline Stabilization/ Marsh Enhancement	10,200	$2,891,470	75.8	20.0	4.2	$283.48	5.2 marsh, (750 shoreline)
Brigantine	Unconfined Benthic Enhancement	24,843	$1,678,307	76.9	14.5	8.6	$67.56	23.6 intertidal/ subtidal shallows (500 shoreline)
Popular Point[1]	Marsh Restoration/ Marsh Enhancement/ Shoreline Stabilization	125,000	$13,961,981	94.1	3.3	2.5	$111.70	13.0 marsh, (2000 shoreline)

[1] estimates only, project not yet initiated. 1CY = 0.76m^3; 1ac = 0.4ha

commitments to an ever-increasing number of project sites. The question here is not that whether the data are relevant, necessary, and important to a coastal program that seeks to improve habitat and increase resiliency, but how it should be paid for. Certainly, dredging budgets, especially for shallow draft channels are limited, but natural resource budgets are even more strained.

Given historical practice and the fierce competition over land use in the shore region, it can often be viewed as a conflict of interest for proponents of dredging projects to suggest locations for habitat enhancement or resiliency projects. This can and should be the job for regional emergency managers and property/resource managers. While some effort has been made to align dredging and resiliency needs in coastal NJ, progress has been slow.

Table 2. Data Collection Needs by Project Phase for Beneficial Use Projects

Beneficial Use Type	Preconstruction	During Construction	Post Construction
Marsh Enhancement	Vegetation, infauna, avian, topographic survey, geotechnical/geochemical, hydrologic analysis	Placement elevations and extent	2-4 yr vegetation, infauna, avian, topographic survey, aerial photography
Unconfined Benthic Enhancement	Benthos, SAV, hydrographic survey, coastal engineering, geochemical/geotechnical	Turbidity, water quality	Hydrographic survey, repeat period site specific
Upland Habitat Creation	Vegetation, infauna, avian, topographic survey, tide, geotechnical/geochemical	Placement elevations and extent	Avian, topographic survey, vegetation encroachment, repeat period site specific
Confined Benthic Restoration	Benthos, SAV, hydrographic survey, geochemical, fisheries, water quality, coastal engineering	Turbidity, placement elevations	1-3 yr survey, SAV, cover quality, benthos/fisheries, hydrographic survey

Shoreline Stabilization	Benthos, SAV, topographic and hydrographic survey, geotechnical/geochemical, coastal engineering	Turbidity	2-4 yr vegetation, infauna, topographic survey
Island/Marsh Creation/Restoration	Benthos, SAV, fisheries, hydrographic survey, geotechnical/geochemical, coastal engineering	Turbidity, water quality	Topographic survey, data and period site specific
Beach Replenishment	Geotechnical/geochemical, topographic survey, coastal engineering evaluation	Wildlife utilization	Topographic Survey

Timelines

Another important consideration is the time required for a project. While habitat restoration projects typically have no set deadline for implementation, there is often a greater urgency to get resiliency projects, and certainly dredging projects, completed. Bringing the three project types together can result in considerable consternation among stakeholders as the project is developed, since schedules are often tied to sources of funding with strict requirements. Pressure to complete evaluations, site selection, design and permitting can be high, and some stakeholders feel that this compromises project and programmatic goals. What is needed is a touchstone document that outlines process and procedure, identifies sites or at least site characteristics, and has widespread acceptance as being reflective of regional goals.

Need for Regional Sediment Management Plan (RSMP)

The USACE have several models which have proven highly successful at tackling politically divisive and technically difficult challenges. The NY/NJ Harbor region managed to beneficially use millions of cubic yards (cubic meters) of contaminated fine-grained sediments and achieve a 50-ft (15-m) deepening of harbor channels using a combination of Dredged Material Management Planning and RSMP tools. The principles used for these programs in the Harbor could well be applied to the Atlantic Coast region. Although there are a larger number of potential stakeholder groups, there is no reason to suspect that a good faith effort to reach common ground cannot be similarly achieved in the Atlantic Coast region.

Several working groups already meet regularly to discuss topics related to coastal resiliency and habitat loss. What is needed is to bring them together with transportation agencies, so dredged material management needs can be identified and included. Projects already identified as being needed on the land management side can then be more easily paired with projects that are identified on the transportation side. A common project goal will often result in reduced regulatory and public perception hurdles to overcome. The NJDOT/OMR will be initiating an RSMP process in 2022.

No amount of planning will accomplish such a lofty goal without an implementation strategy. The USACE model of Regional Dredging Teams (RDTs) that regularly bring stakeholders together to discuss dredging projects has worked well in the Harbor and Delaware River regions of NJ and elsewhere. NJDOT/OMR will be looking to establish a RDT for the Atlantic shore region once the RSMP is developed and accepted by the region.

CONCLUSIONS

The following conclusions can be reached from this work:

1. Beneficial use projects can often cost more than traditional dredged material management methodologies; sometimes significantly more so, however, the benefits of these projects should be accrued across multiple programs.
2. The sustainability of beneficial use in habitat and resiliency projects requires a concerted policy development effort that links programs to ensure proper evaluation of costs and benefits.
3. The timelines for beneficial use projects are often much longer than traditional dredged material management methodologies. This is a function of site selection and evaluation as well as post construction monitoring. These efforts should be shared across the agencies that are accruing the benefit, not just the transportation agency.
4. Establishing project goals and success criteria up front allows for assessment of lessons learned which can be used to increase efficiencies and decrease cost of beneficial use projects.
5. Establishment of a RSMP and RDTs could help to improve sustainability of beneficial use programs.

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DATA AVAILABILITY

All data, models and code generated or used during the study are available from the corresponding author by request.

BENEFICIAL USE OF CONTAMINATED SEDIMENTS: A LITERATURE REVIEW WHITE PAPER

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EXTENDED ABSTRACT

Beneficially using the significant volume of sediment dredged from waterways worldwide as a resource can offer environmental and societal advantages over managing the sediment as a waste requiring disposal. Examples of these advantages include:

- Reduces the need for limited landfill space for disposal
- Reduces the overall environmental footprint (e.g., lowers energy use, fuel use for long transport routes and treatments, etc.)
- Supports the demand for fill for shoreline and coastal infrastructure (e.g., bank stabilization, shoreline erosion control, etc.) to address pressing needs
- Avoids local or widespread erosion, accumulation, and subsidence challenges; supports ecosystem restoration

In consideration of this observation, the objective of this presentation is to provide a summary of a literature review white paper on beneficial use of sediments in North America and Europe, undertaken for the Sediment Management Work Group (SMWG) to identify the current state of the practice for this important topic, with explicit focus on contaminated sediments.

Beneficial use of contaminated sediment has been an important topic since the 1990s. Accordingly, the literature review identified more than 170 references through existing information known to the authors, integrated with internet searches of professional and scientific literature and regulatory and related non-governmental organizations charged with aquatic resource management. The research process relied on the foundation provided by the recent work of the PIANC Working Group 214 (PIANC 2018), the SedNet Working Group (SedNet 2021), the Western Dredging Association (WEDA 2021), and the Central Dredging Association (CEDA 2019a, b).

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Assessment and management of sediment is performed for many purposes worldwide, including the heavy reliance of free-flowing United States commerce on well-maintained navigation infrastructure, which often requires the removal and relocation of sediment accumulated in navigational channels (EBP 2021). A generation ago, it was evident that decisions regarding how to address contaminated sediments could involve very costly options and that selecting from among the options could be highly controversial (NRC 2001).

Contaminated sediment management in the United States represents significant liability to the U.S. Department of Defense (DOD), private industry, ports, and governments. Current estimates of sediment contamination liability at DOD facilities alone approach $2 billion (SERDP and ESTCP 2021). Private US industries spend $100s of millions each year managing legacy contaminated sediments in the nation's waterways with remedies at certain multi-party sites projected to cost multiple billions of dollars. Significant legacy sediment projects are occurring with oversight by the U.S. Environmental Protection Agency (EPA 2021d), including those managed under the Great Lakes Legacy Act (EPA 2021b). Additionally, the USACE—tasked with maintaining federal navigation channels, ports, and harbors to facilitate efficient maritime transportation through its dredging program—spends $10s to $100s of millions annually to manage nearly 200 million cubic yards of sediment, which includes approximately 1% to 5% requiring special management due to contaminants (Moore 2022). Additionally, available landfill space is decreasing. These factors necessitate evaluating other options that are more socio-economically and environmentally sustainable over time.

Concerted advocacy since the 1990s has resulted in many countries recognizing that dredged sediment is a resource, resulting in an increasing allowance of, and in some cases demand for, sediment used for a myriad of helpful (i.e., non-waste) purposes (CEDA 2019a; USACE 2021b, PIANC 2022). Most regulatory entities across North America and Europe evaluate dredged material as if it were a waste material; however, some programs have evolved to consider the beneficial uses of dredged sediment, when it can be done in an environmentally appropriate manner (e.g., USACE 2021a; EPA 2021a).

The white paper includes more than 50 annotated key references from the 170 included in the white paper bibliography, which are organized into five categories for presentation and discussion: Regulatory Guidelines; Examples of Beneficial Use ("What Works"); Barriers to Use ("What Doesn't Work"); Remediation Decision-Making Frameworks and Strategies; Techniques and Technologies. This presentation identifies and discusses some of the key observations from the literature review white paper.

When sediment is collected from a site, whether for routine maintenance dredging of ports, harbors, navigation channels, marine infrastructure safety, contamination removal, or other purposes, it can either go to a landfill or be used as a resource for a beneficial function. Beneficial sediment uses includes cement stabilization, relocation to manage risks (i.e., as a part of a cap/cover, within a wharf/embankment, etc.), and shoreline and coastal infrastructure fill.

Some of the barriers to beneficial use identified in the literature include the often complex and unclear permitting and licensing requirements for beneficial use projects; conservative screening criteria, even if exposure pathways have been reduced; and the lack of public trust or acceptance of using products that include contaminated sediment as a raw material. As the literature reflects, those barriers have been successfully addressed through a growing interest in evaluating how to use sediment as a resource rather than as a waste. This is particularly true among researchers and organizations publishing in Europe (CEDA 2019a, PIANC 2009).

Regional sediment management/planning efforts have been helpful for facilitating programmatic approaches to beneficial use, and regional efforts promoting beneficial use of clean and contaminated sediments are commonly cited as essential to successful acceptance and permitting. Acceptance of beneficial uses of contaminated sediment depends on education and transparency. Education and early involvement of stakeholders where beneficial use can be incorporated is key to creating opportunities. Effective communication and ideation rely on 1) understanding and incorporating stakeholder perspectives and 2) demonstrating why beneficial use alternatives make sense from different stakeholders' perspectives (Cappuyns et al. 2015).

Many publications call for increased focus on research to develop and improve technologies that increase the versatility of beneficial use options and reduce the environmental risks of using contaminated sediment as a resource. Pre-treatment of contaminated sediment can expand beneficial use options by reducing the bioavailability/mobility of chemical contaminants, demonstrating environmental safety, and leading to greater acceptance. The literature review identified that the final disposition of the sediment, including any treatment or processing to reduce contaminant bioavailability, or placing it such that exposure pathways are reduced or eliminated, is important in determining the human health and/or ecological risks of beneficial use and therefore, its acceptance by stakeholders.

Several studies since 2017 have suggested new decision-making frameworks for sediment remediation emphasizing Green and Sustainable Remediation (GSR) and Life Cycle Assessments (LCAs). These more holistic approaches offer criteria and incentives for environmental and socio-economic benefits. Such multi-dimensional decision-making frameworks help promote solutions that are comprehensive and realistic. This literature review emphasized that viewing sediment management options through a sustainability lens creates opportunities for beneficial use and identified numerous precedents for incorporating beneficial use in resilient sediment management.

Finally, this literature review highlighted the importance of incorporating adaptive management strategies to achieve effective and sustainable sediment management. Well-designed monitoring programs are essential for assessing and documenting environmental conditions before and after the implementation of beneficial use remedies to evaluate risks and assess risk acceptability.

Keywords: Dredging, beneficial use, sediment management, contaminated sediment, sustainability, lifecycle assessment, stakeholder engagement, marine infrastructure, risk-based decisions.

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DATA AVAILABILITY

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WHY VIBRACORE SEDIMENT ACQUISITION MONITORING IS BEING CONSIDERED AT MORE SITES FOR REMEDIAL DESIGN—ONGOING REFINEMENTS TO V-SAM TECHNOLOGY

C.D. Lamb[1], T. Dreher[2], A. Cerruti[3] and A. Lutey[4]

ABSTRACT

The paper will present observations obtained over three projects and more than 140 sediment cores advanced using Vibracore Sediment Acquisition Monitoring (V-SAM). The measured recovery data shows how changes in in-situ conditions through the drive length affect sediment recovery through expansion, compaction, plugging and bottom loss. The application of this data in real-time resulted in the ability to acquire sediment more effectively through various intervals. Live observations of V-SAM data during coring led to the coring contractors modifying their methods (e.g., by changing the speed at which the core is advanced and intensity of vibration) which improved the quality of the sediment cores, acquisition of sediment intervals, and overall reliability of the data for dredging design.

Keywords: Sediment sampling, sample processing, depth of contamination, DOC, sample recovery.

INTRODUCTION

Until recently, vertical control accuracy in dredging equipment exceeded the accuracy of vertical depth data from sediment vibracoring. To design a successful remedy, characterizing the nature and extent of contaminated sediment is necessary, which requires collecting sediment samples at various depths below the mudline and analyzing them to establish the depths and concentrations of the chemicals of concern (COC). The results of the COC data are used to establish the maximum depth of contamination (DOC) which can then be tied to an elevation of contamination (EOC) at the site. The accuracy of the EOC has significant impacts on remedial design and implementation.

Recovered sediment often makes up only a fraction of the distance the tube was driven into the sediment, with recovery (length of sediment in core divided by distance the core was driven) often being in the range of 60 to 80 percent. The uncertainty inherent in conventional vibratory coring associated with in-situ depths below mudline (bml) is well documented and can result in miss-classifying the EOC by as much as two feet or more, often increasing with core tube length.

Recovery less than 100% can be due to multiple conditions that have traditionally been difficult to identify: compaction of the sediment in the core tube; development of a plug at the cutting edge; encountering debris

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during the drive; sediment falling out of the bottom of the tube during extraction; or some combination of all of these factors. V-SAM helps to demystify these unknowns and increases coring accuracy.

SEDIMENT CHARACTERIZATION FOR REMEDIAL DESIGN

Environmental dredging is the act of removing contaminated sediment from an aquatic environment and should be performed with sufficient accuracy to avoid excessive removal of clean sediment (Palermo et al 2008). Sampling for environmental dredging as a remediation approach requires obtaining data for both depth and extent of COCs. When sediment core data has been analyzed and assigned a depth interval, the depth of contamination (DOC) is determined by the interval at which the sediment chemistry is below the regulatory requirements for active remediation. The DOC then becomes the lower boundary of the cross section of material targeted for removal.

Depth references can become problematic over time in dynamic marine/riverine systems due to changing sediment surface elevations (shoaling/erosion). To address this, the DOC can be converted to elevation of contamination (EOC) for dredge plans by subtracting the DOC from the mudline elevation at the time of the core and core location.

EOC: The elevation that corresponds to the contact between sediment containing COCs exceeding regulatory criteria and underlying sediment below those criteria.

Defining the EOC using recent high-resolution bathymetry, real-time kinematic GPS positioning, and accurate water depth levels at the time of sampling will establish and preserve the EOC at that location regardless of future shoaling or scouring events, providing more certainty for accurate removal of contaminated sediment.

Accuracy in Environmental Dredging

Many factors influence the ability to accurately remove contaminated sediment. There are two categories of accuracy associated with environmental dredging, dredging accuracy and removal accuracy. Dredging accuracy relies on the physical characteristics and mechanics of the dredging equipment, approach, and even the personnel while performing the work. Removal accuracy relies on the multiple streams of data and physical conditions of the site and sediment that need to be combined to target an accurate EOC when designing a dredge prism. One of the most problematic factors is the sediment coring process, which has traditionally been “fraught with potential error with respect to defining the EOC based on the resulting boring data” (Palermo and Kern, 2013).

Vertical Control Accuracy in Dredging

Many different types of dredging equipment exist and can be used in environmental dredging as appropriate for the conditions and setting of the work to be performed. Dredges vary from hydraulic to mechanical, and from lattice boom cranes to fixed arm excavators. Each equipment type possesses unique levels of accuracy associated with the mechanics and removal mechanism. Advancements to dredging equipment such as buckets, pumps, and spudding systems, paired with the ongoing development of positioning control technology, has allowed for the increased accuracy of dredging equipment, oftentimes achieving accuracy within tenths of a foot (Palermo Kern 2013). However, a system is limited by its least accurate component, and the overall ability to set a precise EOC is limited by the accuracy of the elevation data obtained during coring used to create it.

Conventional Vibracoring Accuracy

A challenge inherent to conventional vibratory coring is that the sediment obtained within the core tube upon retrieval is often a fraction (60% to 80%) of the depth that the core was driven into the sediment (Fuglevand et al. 2021). Traditionally, this method is referred to as the *percent recovery* (%R) and represents the ratio of sediment *recovered* in the core tube to the length the tube was advanced below the sediment surface. This value is calculated in the following steps (Hvorsley, 1949):

$$L = H - S \tag{1}$$

where L = recovered length, H = length the core tube was advanced below the sediment surface, and S = the measured length from the top of the sediment surface to H, also called the headspace.

The %R is then calculated as follows (Hvorsley, 1949).

$$\%R = L/H * 100 \tag{2}$$

Conventional vibracoring does not provide a mechanism to establish why the recovery in a core is less than the overall length the core was driven, introducing uncertainty in the actual depth that sediment represents, and subsequently uncertainty in dredge plans that are based on conventional vibracoring results. The target dredge elevation may differ from the actual in situ EOC by many feet, which, when compounded across as site can lead to over- or under- dredging large quantities of sediment.

Vibratory Coring With V-SAM

Conventional Vibracore sampling equipment was instrumented to simultaneously measure the penetration of the core tube into the sediment and the acquisition of sediment within the core tube during driving. The initial application of this system was on the Marine Sampling Systems, LLC (MSS) vibracore setup consisting of an “A-frame” with a vibratory drive-head that travels on a drive guide system within the frame, and a relatively wide base that can be adjusted for the slope of the river bottom. In 2020, this system was configured with two specialized fathometers (Figure 1) for the purpose of monitoring sediment acquired over drive length during coring (Fuglevand et al 2021).

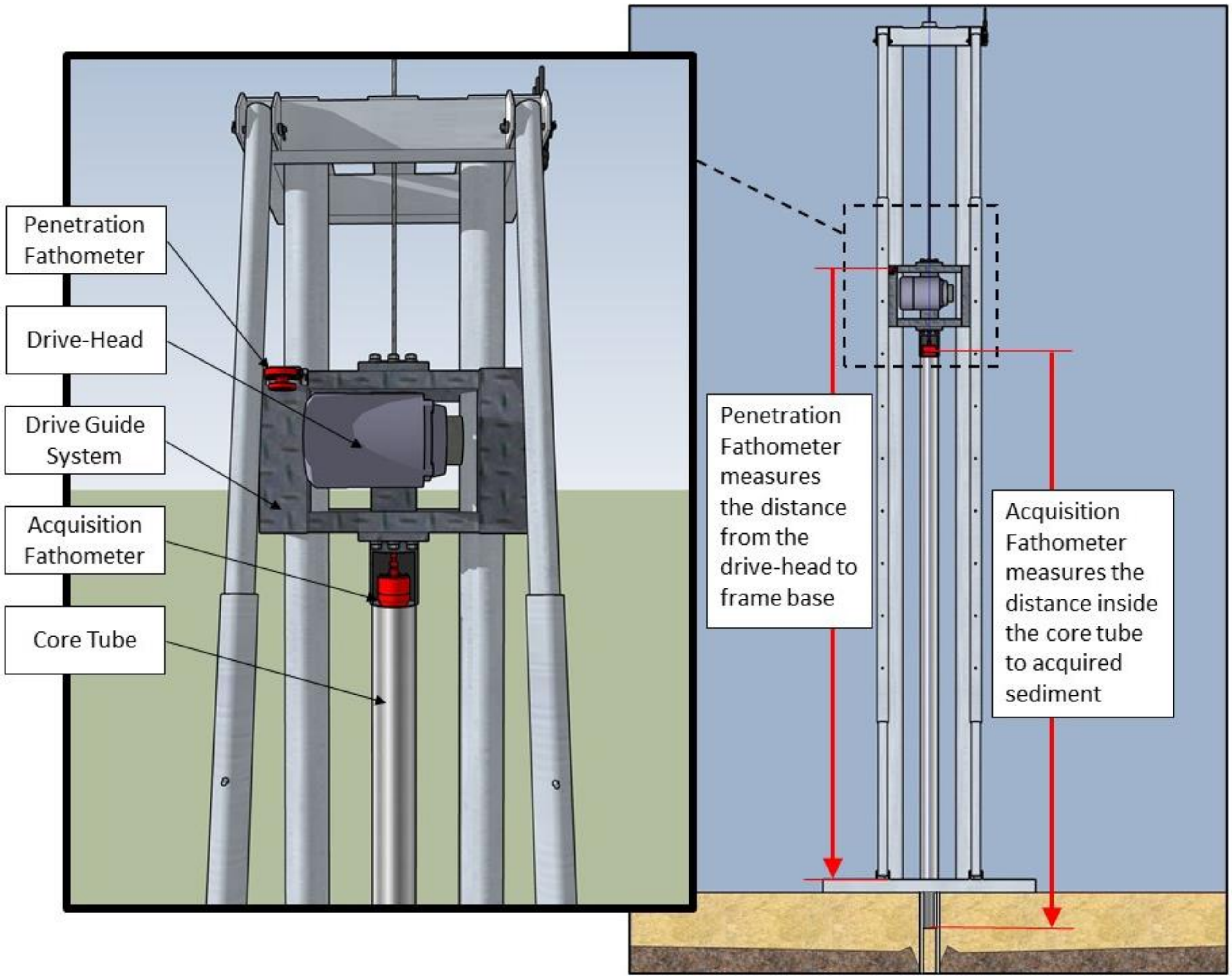

Figure 1. MSS Vibratory Coring System with V-SAM.

The Penetration Fathometer, mounted on the A-frame drive-head, measures the incremental penetration of the core tube below mudline (H) by recording the changing distance as the drive-head advances the core and moves closer to the sediment bed (Figure 2). The Acquisition Fathometer, located at the top of and inside the core tube, measures the incremental length of sediment acquired in the core tube (L) by recording the distance to the top of the sediment as the core is advanced into the sediment bed during driving.

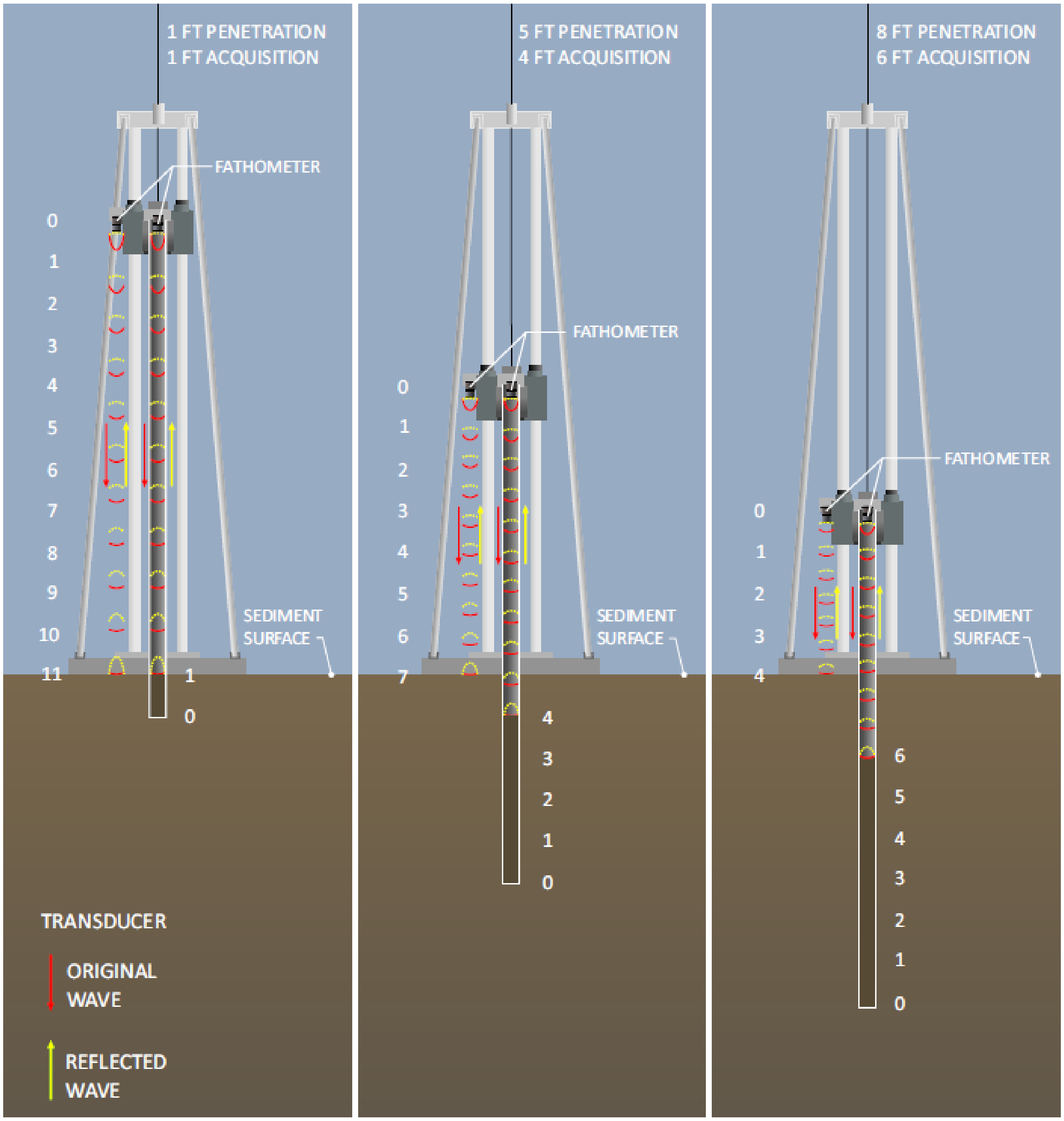

Figure 2. Fathometers for MSS Vibratory Coring System with V-SAM.

H and L values are read from the digital displays attached to the instrumentation (Figure 3) and recorded in approximately 3-foot drive increments during coring, where the core is advanced, and then the vibrating head is turned off briefly for the fathometer to report a clear reading.

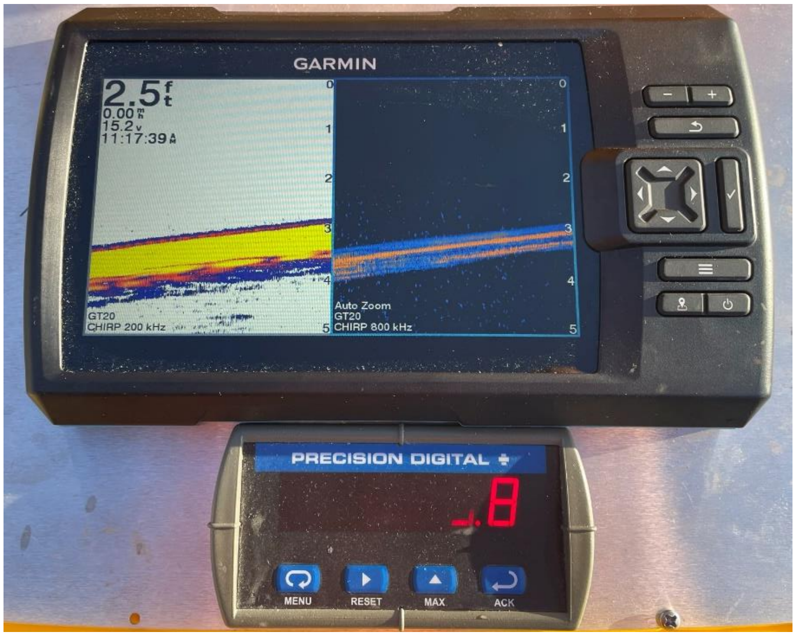

Figure 3. Example Digital Readout for V-SAM

Once the reading is collected, the measurements are plotted on a curve of acquisition vs. penetration, referred to as a V-SAM acquisition curve (Figure 4).

Fathometer Readings		TUBE (ft.)		Increment		Core Cut Plan (ft.)	
Depth	Acquire	Drive	Acquire	% Recover	Comment	In-Situ	Core
12.1	20	0.0	0.0			HS	3.2
15	18.9	2.9	1.1	38%		0.0	0.0
18	17	5.9	3.0	63%		1.0	0.4
21	14.1	8.9	5.9	97%		2.0	0.8
24.1	10.7	12.0	9.3	110%		3.0	1.2
27.2	7.5	15.1	12.5	103%		4.0	1.8
30	4.8	17.9	15.2	96%		5.0	2.4
31.1	3.4	19.0	16.6	127%		6.0	3.1

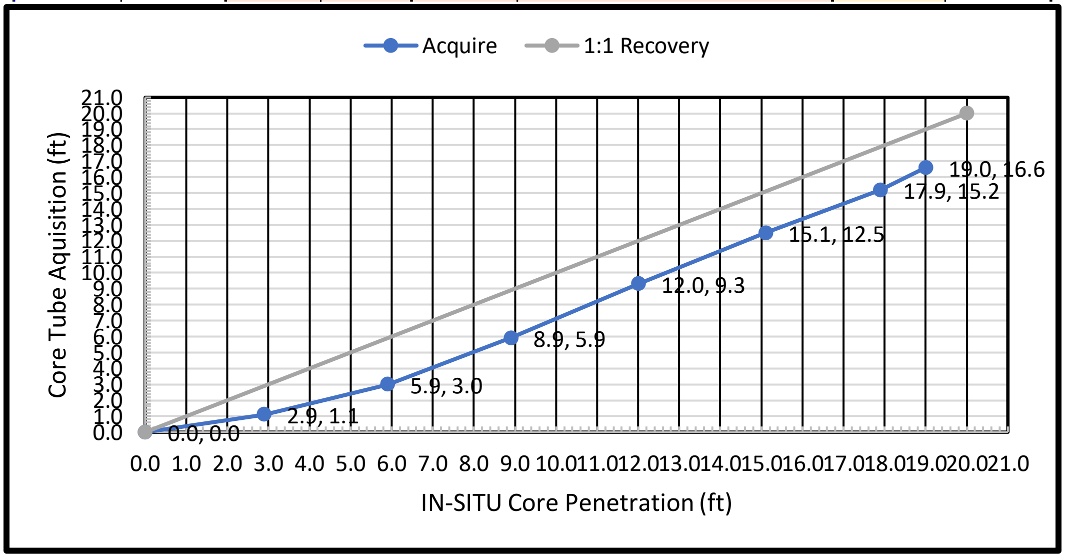

Figure 4. Core Data and Acquisition curve

Core log data and incremental acquisition percentages are collected in close coordination with the coring contractor and vibracore operator during the coring process, and decisions on core acceptance criteria are made in real time.

ONGOING REFINEMENTS AND FIELD ADJUSTMENTS

Subsequent implementations of V-SAM on different projects have led to refinements in both instrumentation and equipment, as well as application in practice for monitoring and even influencing sediment acquisition over desired intervals.

Updated Instrumentation

The MSS V-SAM system was updated in 2021 with newer generation fathometers for further coring work in 2021, and the acquisition fathometer (inside the core) was replaced with a lower, dual frequency 70 to 200 khz instrument. The digital readouts were also updated, and the newer instruments provided clearer readings and more easily interpreted measurements were observed.

Second System Development

In 2021 Gravity Marine configured their vibracore system—a frameless cable suspended multi-frequency drive head—with a combination of instruments to measure acquisition over drive during coring. This system was provided with two different types of sensors, a pressure sensor for logging penetration and a fathometer for monitoring acquisition (Heinz, 2021):

Depth Pressure Sensor. A high accuracy pressure transducer depth senser with a Precision digital readout. Logging the continuous depth readout in combination with the length of the core tube and current depth of water provide the ability to record the penetration of the core into the sediment.

Fathometer. A high frequency chirp (400-800 khz) fathometer at the drive head positioned inside the core barrel and connected to a Garman readout that provided a measure of the distance to the sediment surface within the core while vibracoring.

The frequency of the unit can be adjusted in the field to limit disturbance of the sediment substrates or for improved collection of representative layers.

Field Observations and Adjustments

While implementing V-SAM, additional real-time benefits of using the measurements while coring were identified. In addition to generating a core acquisition curve (Figure 3), the data was found to be very useful for optimizing the coring equipment during V-SAM operations.

Freefall—Poor Acquisition in Shallow Intervals

Poor acquisition during coring was observed to be due to missing sediment in the shallow intervals of a drive more commonly than losing material from the bottom of the core during retrieval (Dreher et al 2022). Typically, during coring—depending on the equipment configuration—the contractor will lower the core to the sediment surface until the core reaches material of a composition that resists the core and stops further advancement. This process allows for the coring equipment to settle and come to rest before the vibratory head is engaged and the core is advanced under power. The distance the core moves from the measured sediment surface to where the condition of the sediment is strong enough to stop the core is called the “freefall” and sediment can often be acquired through that process. The acquisition of sediment during freefall is often measured and recorded during V-SAM.

Freefall: The distance the core is advanced under gravity alone as the coring equipment settles at the sediment surface.

Adjustments to Coring Techniques

No Freefall. While coring in areas with soft sediment it was observed that the core tube would advance several feet during freefall without acquiring comparable sediment, sometimes passing intervals targeted specifically for the project as requiring sampling and analysis. Because of the unique picture V-SAM provides, the repeated non-acquisition in the soft surface sediment was noted. To address the missed intervals, the contractor and engineer performing the data collection collaborated to adjust the conventional freefall step and speed of advancement by holding the equipment and frame at the sediment surface, engaging the vibration to help coax sediment into the core tube, and advancing the core barrel slowly through sediment that would have otherwise been passed up. Through these adjustments, targeted shallow sediment intervals were able to be acquired at acceptable percentages, and valuable data that would have otherwise been missed or miss estimated was collected.

Adjusting Vibration. Alternately, it was observed that when the core encountered more resistant material at higher frequency vibrations, often acquisition greater than 100% would be observed. Recovery greater than 100% was most common with clean sands and gravels and when encountered, the coring equipment operator would often increase the vibration frequency in an attempt to get through the material (Dreher et al 2022). To address over acquisition, especially at deeper intervals or when approaching refusal, the contractor and engineer worked together to limit over energizing the core head when dense sands and gravels were encountered. Additionally, once advancement of the core was slowed or stopped, additional attempts to drive through the resting interval was limited and drive refusal was noted. Accepting refusal early enough to not over vibrate or “blow up” the core provided better data through the intervals where vibracoring was capable of acquiring sediment.

CONCLUSIONS

Conventional coring is a sampling methodology that provides uncertain information regarding the actual in-situ depth of sediment recovered in a core. V-SAM has been shown to be a better tool for identifying where the sediment acquisition and losses are occurring, which can improve environmental dredging removal accuracy by increasing the accuracy of the EOC, and V-SAM allows live monitoring of sediment acquisition to adapt coring in real-time and obtain cores that are more representative of in-situ sediment conditions.

Throughout the implementation of V-SAM, it became evident that the measurements being taken allowed for real-time adjustment during core advance to improve sediment acquisition and limit excess recovery:

- Eliminate freefall of the coring system in very soft sediment
- Advance the core slowly in soft sediment with managed vibration to improve collection of sediment into the core
- Limit application of high energy vibration in dense sands and gravels to help limit over-acquisition or %R>100

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USE OF VIBRACORE SEDIMENT ACQUISITION MONITORING (V-SAM) IN THE FIELD – DATA COLLECTION AND PROCESSING TO OPTIMIZE SEDIMENT DREDGING DESIGN

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ABSTRACT

This paper presents the methods used to implement vibracore sediment acquisition monitoring (V-SAM) during core collection and processing, and the corresponding benefits including more accurately correlating depth of sediment with laboratory analysis. V-SAM is a newly developed system that is used during collection of sediment cores to better understand where sediment gains and losses are occurring in real-time during the core drive. This data is then used to create a core cut sheet that is applied during processing and logging the sediment core. Through implementation over three projects and over one hundred cores, the application of V-SAM data during core processing is the step that most significantly deviates from conventional methods, and consequently confusion among processing teams. The purpose of this paper is to describe specifically how to implement V-SAM data during core processing and logging.

Keywords: depth of contamination, sediment sampling, sample processing, vibracore, V-SAM

INTRODUCTION

Vibratory coring is a commonly used method for sediment sampling to characterize the nature and extent of contaminated sediment for remedial dredging design. Core tubes are advanced into the sediment via a heavy vibratory head which is deployed from a nimble workboat. Once the drive is completed or refusal is met, the continuous sediment core is retrieved for processing. Discrete sediment samples collected during processing are submitted for chemical analysis and the results are used to characterize the types, concentrations, and corresponding depths of chemicals of concern (COCs) (Fuglevand, 2021). Recent application of V-SAM technology has refined the acquisition of sediment within the core sampler over a discrete interval and has provided a mechanism to understand where material loss or "shortening" within a sediment core originates from.

Conventional Vibracoring

Conventional methods for processing sediment cores collected using standard vibracore tooling has required assumptions based on total sediment recovered (L) over total drive length (H), which is used to determine a percentage of recovery (%R) utilizing two methods:

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- Static Method. Assumes the position of sediment in the core directly represents the in-situ depth. If %R<100% it can only be assumed to be due to loss on retrieval from the bottom of the core.
- Stretch Method. Assumes a uniform representation of sediment across the length of the core by applying the overall %R to each interval. For example, if the %R for the core was 80%, each foot in-situ would be represented by 0.8 feet in the core tube.

Neither of these approaches to collecting and processing sediment cores provides a mechanism to establish where the difference between L and H occurred within the core tube (Fuglevand, 2021).

Vibracore Sediment Acquisition Monitoring Technology

Recent application of V-SAM for more than 140 sediment cores from three projects has refined the methods to implement the data collected during sediment core collection. In general, conventional vibracoring equipment is retrofitted with two specialized instruments, either fathometers, transducers, or a combination of the two. One instrument is set to record the depth of penetration as the vibratory head is driven toward the sediment surface, while the second instrument records the headspace within the core tube as sediment enters the sampler. Incremental penetration of the core tube into the sediment and corresponding headspace within the core tube is presented as a digital read out on instrument panels aboard the vessel and those values are recorded on an acquisition log. The resulting data presents a record of sediment acquired within each drive interval, creating a higher resolution understanding of representative depths of material preserved in the sample core.

CORE COLLECTION AND PROCESSING

The following sections describe the methods used to collect and process sediment cores using the V-SAM system.

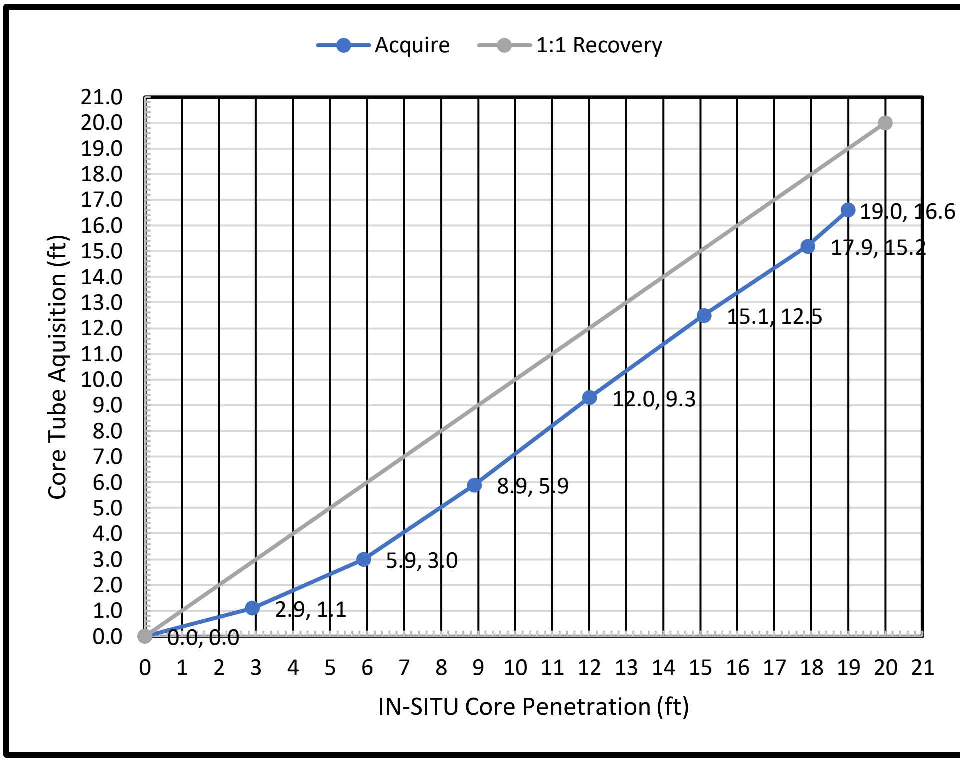
Core Collection

Projects that have used the V-SAM system to collect and process cores have used one of two styles of vibracore:

- Frame suspended and hydraulic controlled vibratory head equipped with an external fathometer and an internal acquisition fathometer (Lamb, 2022).
- Frameless, cable suspended multifrequency vibratory drive head. This drive head is equipped with a pressure sensor for logging penetration depth and a fathometer to record internal acquisition.

Both systems have the capability to deploy unlined aluminum or Lexan lined aluminum core tube in varying lengths to collect subsurface sediment samples. During coring, a record of each incremental drive is recorded and plotted on a curve of acquisition feet per core penetration feet building what is called the acquisition curve (Fuglevand, 2021).

The acquisition curve is then used to create the core cut plan by taking the in-situ core penetration for each foot and matching it with the corresponding core tube acquisition from the graph. An example acquisition curve and corresponding core cut plan is shown in Figure 1 below.



Core Cut Plan (ft.)	
In-Situ	Core
HS	3.2
0.0	0.0
1.0	0.4
2.0	0.8
3.0	1.2
4.0	1.8
5.0	2.4
6.0	3.1
7.0	4.1
8.0	5.0
9.0	6.0
10.0	7.1
11.0	8.2
12.0	9.3
13.0	10.3
14.0	11.4
15.0	12.4
16.0	13.4
17.0	14.3
18.0	15.3
19.0	16.6

Figure 1. Example Acquisition Curve and Corresponding Core Cut Plan.

The core cut plan is then used for core processing to mark the in-situ depths based on the acquisition data, as described below.

Core Processing

Processing a sediment core involves cutting open the core tube; logging the physical data regarding sediment type, debris found, odors encountered, etc.; and taking samples at various pre-determined intervals. Using conventional methods, the in-situ depths are determined using either the Static or Stretch methods defined above. These methods introduce a high level of uncertainty if the %R for the core is less than 100%. Alternatively, using the information documented from the V-SAM system during core collection, the in-situ depths are determined based on the produced acquisition curve, which can greatly reduce the uncertainty typical with conventional vibracoring.

Core Acceptance and Retrieval

Upon acceptance of a sediment core, which is based on project guidelines for minimum percent recovery, number of attempts, specific target depths, etc., the core is retrieved and brought on-board the vessel. Once the base of the core is just above the water surface, a cap is secured to prevent sediment loss during handling of the core. An observation regarding material type at the end of the core tube, if available, is relayed to the onboard professional and noted on the core acquisition log. A measurement is recorded for headspace from the top of the core barrel to the top of sediment in the core. There should always be a measurable headspace since it is best practice to limit the depth of penetration to less than the total length of the core (Fuglevand, 2021). The core is secured to a stand on the boat in a position approximately 30-45 degrees from level for initial processing. The core tube is sectioned into smaller, more manageable sections for transport and processing. The newly exposed sediment surface of each segment are covered with aluminum foil and capped to prevent material loss. Segments are clearly labeled with the location, segment name, and orientation. Each segment of the core is maintained in as close to an upright position as possible for storing and transport to the processing facility.

Core Logging and Sampling using V-SAM

Once a core or core segment is ready to be processed, the core segment holding the surface sediment is uncapped and headspace is remeasured to confirm those recorded upon initial retrieval upon the vessel. A mark on the outside of the core tube helps to provide a visual of the surface of sediment since there tends to be slight sloughing once the core is laid horizontally and cut. The cap is then resecured, and the segment is laid horizontally upon the cutting apparatus table. Lengthwise cuts are made 180 degrees from each other, and the intact sediment core is transferred to the processing table, which is generally lined with poly sheeting and a surface covering of a heavy-duty construction or butcher paper.

The next step in processing using V-SAM data is to designate locations along the length of sediment in the core tube that represent the targeted in-situ sample locations. For example, using the Core Cut Plan in Figure 1, a targeted in-situ sample depth of 4 to 5 feet below mudline would be located at 1.8 to 2.4 feet from the top of the sediment in the core tube. The designation of estimated in-situ depths that correspond to the actual core segment intervals is generally completed as follows.

- The core tube is placed horizontally on a processing table, underlain by a sheet of paper for marking the location of each planned sample location in the tube.
- An engineer-scale measuring tape is laid alongside the unopened core with the end of the tape set at the top of sediment in the core to indicate the collected length of sediment in the core tube.
- Using the Core Cut Plan of the acquisition log (see Figure 1 above), the processing team uses the engineering-scale to draw hash marks on the underlying paper at each measurement recorded in the "Core" column. Each mark is then designated with the corresponding estimated depth below mudline from the "In Situ" column of the Core Cut Plan. For example, at 1.8 feet along the engineer-scale tape a hash mark is made and designated as 4 feet in-situ, per the Figure 1 cut plan.
- Stainless steel utensils are then used to split the core into halves. Slice, from bottom to top, through the two lengthwise halves of the core within each sample interval to prevent vertical cross contamination. Then the split the core barrel is the opened to reveal the sediment in the core tube, and to log the core based on the in-situ markings. It is important to recognize that the core is not logged based on the engineering scale as it does not represent the estimated in-situ profile of the material in the core tube.
- The opened core tube is photographed to show the material in the tube and the relation between the "Core" and "In-Situ" values on the Core Cut Plan.
- Using those in-situ markings the sampling team then collects and designates sediment samples based on the in-situ depths noted at the hash marks on the paper. For example, using the Core Cut Plan in Figure 1, a sample collected from 1.8 to 2.4 feet from the top of the sediment in the core tube would be designated and logged as a sample from 4 to 5 feet below mudline and submitted for analysis.

Figure 2 is a photograph of another core, different from that represented in Figure 1. It shows an engineering tape measure placed along a sample core with the one-foot in-situ intervals marked on the underlying paper along with the associated depths in the core tube. For example, 5-6 ft in-situ is located at 3.6 to 4.5 ft. in the core. In the case where a discrete interval has poor recovery, the project may decide to combine two or more intervals to meet the required sample volume to run analytical testing.

Observations made by the processing team during sediment core logging supplement the quantitative V-SAM data. In several instances during coring, V-SAM data showed a sudden drop in sediment acquisition over a specific drive interval that correlated with a plug of hard material observed during logging. A solid plug of material could push softer sediment aside until reaching a denser material. The ability to correlate the V-SAM data with sediment conditions in the core provides a better understanding of the mechanisms that can result in %R<100.

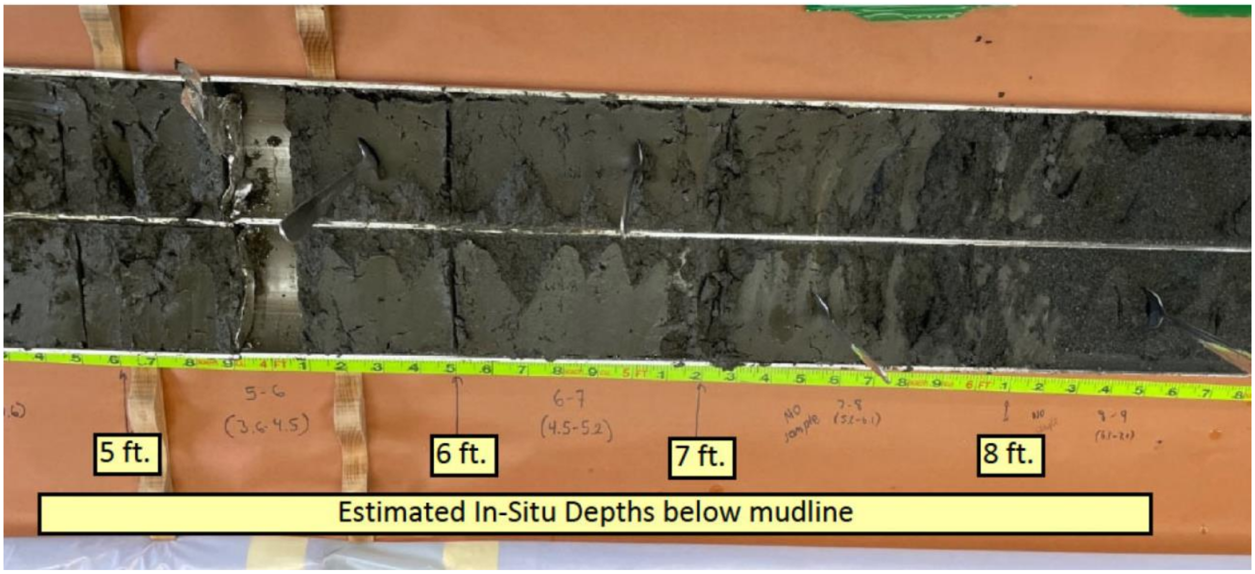


Figure 2. Example Sediment Core with V-SAM Data Applied for Sample Depth Interval.

CONCLUSIONS

By applying V-SAM data throughout the processing phase of core collection, in-situ sample depths are directly correlated to the lab sample intervals. Sample intervals assigned estimated-situ depths below mudline, based on V-SAM logging, more closely reflect in-situ conditions as opposed to the Static and Stretch Methods used for conventional coring.

Collection and processing methods for V-SAM data are evolving as the data set grows. Identifying trends and limitations within material types, object characteristics, and tooling through consistent application of foundational V-SAM processing techniques will further improve our understanding of the acquisition of sediment within the incremental depths. V-SAM data and their application during processing, provide an improved method to cost effectively identify the depth of contamination at each core location. An accurately and precisely identified depth of contamination is critical to effective and efficient sediment remediation design and ultimately remedial action success.

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CITATION

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BENEFITS OF V-SAM IN SEDIMENT REMEDIATION – TRENDS OBSERVED FROM DATA COLLECTION AND IMPLICATIONS TO FUTURE REMEDIAL COSTS

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ABSTRACT

Correctly characterizing the depth and extent of contamination of sediments in a waterway has a large impact on the total cost of a remediation project. If the depth of contamination (DOC) is incorrectly identified, either too much sediment may be removed which will increase the project length and cost of disposal, or too little sediment will be removed which could lead to costly re-dredging and possible remobilization of equipment.

This paper will present trends observed from 140 cores collected in a riverine environment using vibracore sediment acquisition monitoring (V-SAM) technology and the corresponding potential implications to a remedial dredging project in terms of cost and schedule. Information on how various sediment types affect recovery, and how that can impact perceived overall percent recovery will be presented.

Keywords: Sediment sampling, acquisition, sample processing, depth of contamination, DOC, sample recovery.

INTRODUCTION

Vibracoring is a sediment sampling method that is used to characterize the nature and extent of contaminated sediment for remediation dredging design. Sediment coring has been shown to be a significant source of error in defining the Depth of Contamination (DOC) for a remediation site (Palermo & Kern 2013), which can have a significant impact on remedial costs and project schedule.

In order to try and reduce the error from conventional vibracoring, the recently developed vibracore sediment acquisition monitoring or V-SAM (Fuglevand et al, 2021) system was implemented to collect over 140 cores in a riverine system. Data collected using the V-SAM system was analyzed and observed trends are discussed below.

CONVENTIONAL VIBRACORING VS V-SAM

Vibracoring is a method of continuous sediment sampling that uses a heavy vibrating drive head to advance a lined or unlined core tube into the substrate. The added energy from the vibrating drive head transfers through the core tube to the sediment and causes the layer of sediment particles at the interface with the core to mobilize, reducing friction and allowing for the tube to be advanced in a continuous fashion. When

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the core tube has either fully penetrated or has met refusal and will not advance further, the tube is extracted for transport and processing.

Core Recovery

Core recovery is the ratio of actual sediment recovered to the length of the core drive. The recovered length (L) is found by measuring the headspace (S) within the core tube after retrieval and subtracting this number from the drive length (H) (Hvorsley, 1949):

$$L = H - S \tag{1}$$

where L = recovered length, H = depth of penetration of the core tube into the sediment bed, and S = the distance that the recovered length of sediment is short of the penetrated length of the core tube.

The percent recovery (%R) is then defined as the ratio of recovered length to the depth of penetration (Hvorsley, 1949):

$$\%R = L/H * 100 \tag{2}$$

Incomplete recovery (%R < 100%) is a common occurrence though conventional vibracoring does not provide a mechanism for establishing the cause of the difference between the recovered sediment (L) and the drive depth (H) (Fuglevand et al, 2021). Common causes of incomplete recovery include the following:

- Non-sampling at the surface due to soft material (Palermo & Kern, 2013)
- Loss from the bottom of the core tube during retrieval
- Compaction of the sediment in the core tube
- Plugging of the core tube due to stiff/hard sediment or debris
- Rodding due to high friction between the core tube and the sediment

Uncertainty in Conventional Vibracoring

The inability to determine the cause of incomplete recovery during conventional vibracore sampling causes uncertainty, which is then carried over to the remedial design when using coring data to establish the DOC and the Elevation of Contamination (EOC). Even with percent recovery of 80%, which is generally considered satisfactory, the calculated DOC could be off by up to four feet (ft) in a 20-ft core drive.

There are two common approaches to handle this uncertainty when assigning in-situ depths below mudline (bml) (Fuglevand et al, 2021):

- Static Method – This method assumes that the difference between the acquired sediment and the drive depth is due to loss out of the bottom of the core upon retrieval and therefore assumes that the estimated in-situ depth bml of a sample is equal to the position of the sample within the core tube.
- Stretch Method – This approach takes the %R and uniformly distributes it over the length of the core. For example, if a core is driven 10 ft bml (H=10 ft) and there is 8 ft of sediment in the core tube upon retrieval (L=8 ft), then each 0.8 ft of sediment within the core tube would be representative of 1 ft in-situ.

Use of V-SAM with Vibracoring

To reduce the inherent uncertainty with conventional vibracoring techniques, V-SAM has been developed to measure the amount of sediment within the core tube in real time during the drive, so the L and H values at different increments during the drive are documented and the uncertainty relating to incomplete recovery is greatly reduced.

V-SAM is achieved by using specialized fathometers attached to both the drive head, which measures the incremental penetration of the core tube into the sediment, and inside of the core tube itself, which measures the distance between the top of the core tube and the top of the sediment within the tube. Using this information, the L and H values at different increments during the drive can be calculated. The vibracore drive must be temporarily halted in order to get the acquisition readings, so the process becomes semi-continuous rather than continuous. The increment of recording data is generally at the discretion of the marine contractor and the engineer, but typically an increment of 1-3 feet is used.

As opposed to using the Static or Stretch methods described above, the use of V-SAM while collecting sediment cores allows for the more accurate V-SAM method to assign in-situ depths below mudline, as described below:

- V-SAM Method – A %R will be calculated for each increment and be applied to the sediment within that increment.

Considerations for the V-SAM System

While the uncertainty in vibracoring is greatly reduced using the V-SAM system, there are a few things to consider:

- Drive Increment – While a smaller increment used for data collection will reduce the amount of uncertainty (every foot for example) as you will get a higher resolution on the data, the drawback with doing this is that every time the drive has to stop and start the force of static friction must be overcome and additional rodding may occur, reducing the overall acquisition over the entire drive. A collection increment of 2-3 ft is common.
- Shallow Water – The fathometers need to be submerged in order to get readings, so samples taken in shallow water will not have any data until the system is fully submerged.
- Soft Sediment – Soft, soupy sediment in the top of the core tube can interfere with the fathometers and give false readings.
- Losses upon Retrieval – The instrumentation can often show losses out the bottom of the core tube upon retrieval by reading the fathometer right after the core is pulled up. Alternatively, the difference between the final reading and the measured headspace (S) can show what was lost out the bottom.
- Instrument Precision – The final reading from inside the core tube on the instrument at full penetration or refusal should theoretically be equivalent to the headspace (S). After retrieval, the difference between the measured headspace and the final reading (ΔS) can be an indication of the precision of the instruments (after noting loss upon retrieval and any consolidation or expansion of material).
- Percent Recovery – With the knowledge about where sediment losses occurred from the V-SAM system, the overall percent recovery (%R) becomes less important with regards to uncertainty. With good acquisition data, the uncertainty is greatly reduced and %R then correlates more to whether or not there is enough sample volume per interval.
- Uncertainty – The data collected will better show where any significant sediment losses occur, however there is still some uncertainty between each increment. Smaller drive increments will reduce the level of uncertainty.

DATA COLLECTION

140 cores were collected in a riverine system across three different remedial sites. V-SAM was used for all of the core collection. Two different marine contractors were used for sampling and their V-SAM systems were slightly different, but both were able to measure the drive depth and the corresponding headspace within the core tube.

For each sediment core that was collected, an on-board engineer worked with the marine contractor to read the fathometer data and record the measurements throughout the drive. 4-inch aluminum core tubes, a portion of them unlined and a portion of them lined with lexan were used for all of the vibracore samples. The length of the core tubes varied based on location but ranged from 10-feet to 20-feet. All core tubes were equipped with core catchers to limit the amount of sediment lost from the bottom on retrieval. Data from all 140 cores were compiled along with the corresponding geotechnical logs from the processing of the cores so that relationships between sediment type and percent recovery could be correlated. A summary of the data analyzed is shown in Table 1 below.

Table 1. Summary of vibracore data using V-SAM.

Number of Cores	Average Increment of Data Collection	Average %R, Total	Average Δhs[1] (+/-)
140	2.2 ft	86%	0.2 ft

[1]Δhs is the difference between the final acquisition reading for headspace and the measured headspace after retrieval.

OBSERVED SEDIMENT TRENDS USING V-SAM

Losses from the Bottom during Retrieval

One of the conventional assumptions to handle incomplete recovery is to use the Static Method and assign any difference between drive depth and acquired sediment (S) to a loss out of the bottom of the core tube upon retrieval. Based on an analysis of the collected data, only 4 cores out of the 140 had a loss out of the bottom of greater than 6 inches of sediment. The maximum loss out of the bottom of a core tube was 1.7 feet. The average change from the final acquisition reading to the measured headspace (Δhs) was a positive 0.1 feet (a positive ΔS would correlate to a gain in volume upon retrieval, either from expansion of the material within the core tube or due to the precision of the instrument).

Missing Sediment from the Start of the Drive

As previously mentioned above, non-sampling (failure to collect sediment in the tube) at the surface due to soft sediment is a factor that has increased the uncertainty for conventional vibracoring (Palermo & Kern, 2013). In order to determine whether that was a factor for the collected cores, the first interval of collected data for each core was analyzed for average %R and then compared to the average %R for other intervals. Figure 1 below shows the range of %R for the first interval, middle intervals, and the end interval.

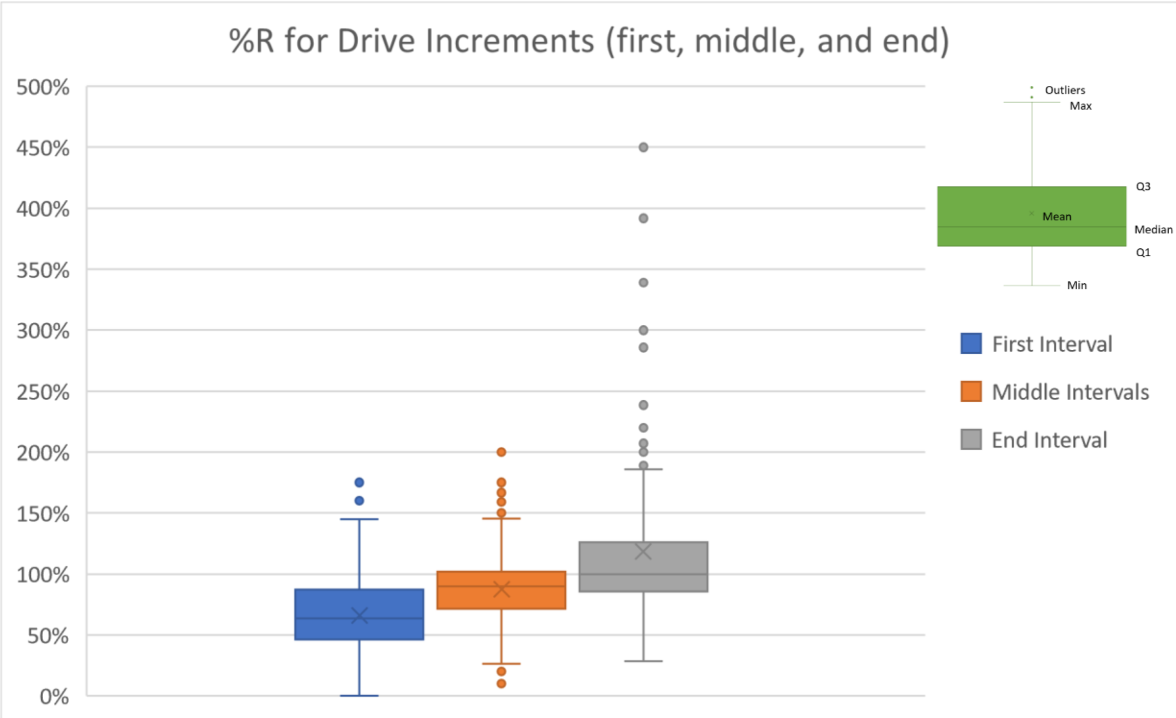

Figure 1. Percent recovery for first, middle, and end intervals of vibracore drive using V-SAM.

From Figure 1, it is apparent that missed material in the first increment of the drive is significant, much more so than material lost out the bottom of the core. 30% of the cores had a percent recovery in the first interval (with an average drive length of 2.2 feet) of 50% or less, which means that over 40 cores missed at least 1.1 feet in the first increment of the drive, with some cores missing more than 5 feet. The average and median percent recovery for the different drive intervals are shown in Table 2 below, as well as the percent of the core intervals with less than 50% recovery and greater than 100% recovery.

Table 2. Percent recovery for first, middle, and end intervals of vibracore drive using V-SAM.

Drive Increment	Average %R	Median %R	Percent of Intervals with less than 50% Recovery	Percent of Intervals with greater than 100% Recovery	Number of Samples
First	66%	63%	30%	9%	140
Middle	87%	90%	9%	25%	516
End	118%	100%	7%	47%	140

Increments with Greater than 100% Recovery

As shown in Figure 1 and Table 2 above, many drive increments had recorded percent acquisition of greater than 100%. This can be an indication of material expanding within the core tube and occupying more volume than it did in-situ as a result of the energy applied by the vibratory drive head (Fuglevand et al, 2021). The data shows that over 47% of the final increment in a drive had percent recoveries that were greater than 100%. At the end of a drive, especially if hitting refusal, the marine contractor will often increase the vibration and drive throttle in order to try and break through whatever material is inhibiting core penetration. This additional energy, in combination with sediment type, is likely the cause of the expansion of material seen in the final increment of the core drive.

Increments with greater than 100% recovery can also add additional inaccuracy when using the stretch method because it can bring the overall %R closer to 100%, which would mask any sections of poor recovery in other parts of the core.

Sediment Types and Percent Recovery

The geotechnical core logs from the processed cores were compared to the core acquisition logs to determine what type of material correlated to the percent recoveries in each increment. Many increments had more than one type of sediment, but the dominant type for each increment using the Unified Soil Classification System was used. A couple of notes regarding these comparisons:

- 58% of the intervals was classified as primarily silt (ML), so more data was available for use.
- Sediment that was missed during the drive would not be included, so the softer silts that were likely missed in the first drive interval would not be factored, and therefore the percent recovery for silt is likely biased high.
- Only 13 out of almost 800 intervals looked at was primarily gravel (GP or GW), so this data was included, but the sample size was very small relative to the other sediment types.

Figure 2 and Table 3 below shows the range of percent recovery for the different sediment types.

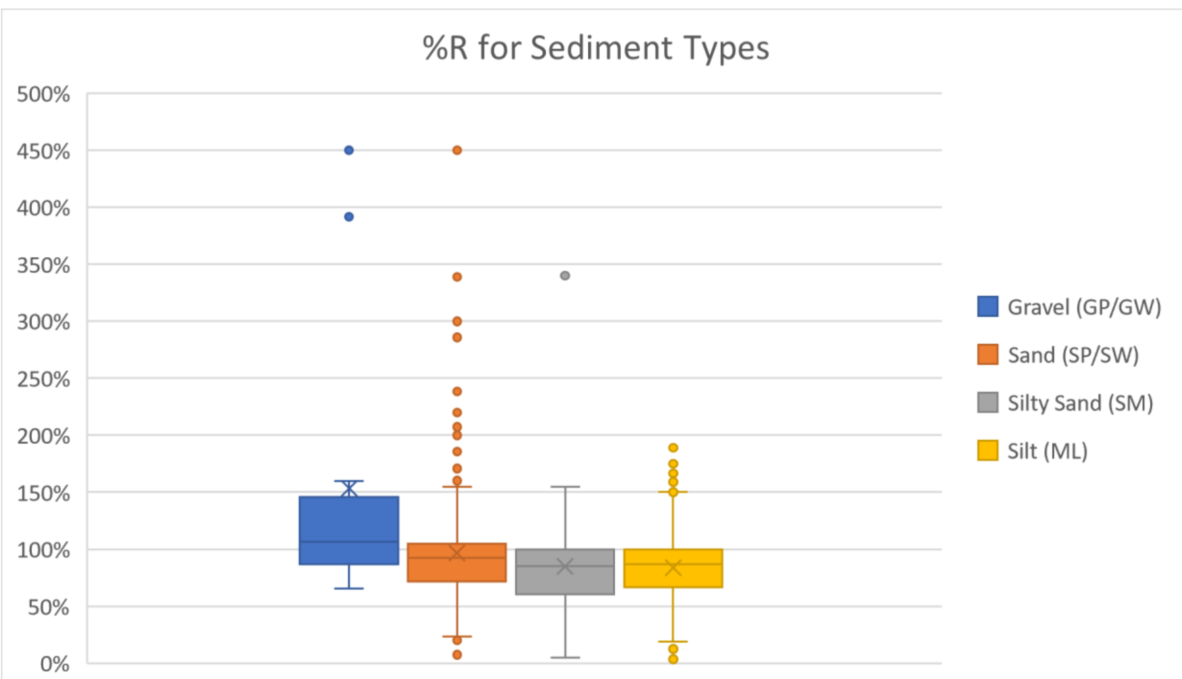

Figure 2. Percent recovery for different sediment types using V-SAM.

Table 3. Percent recovery for different sediment types using V-SAM.

Sediment Type	Average %R	Median %R	Number of Samples
Gravel	114%	106%	13
Sand	92%	92%	251
Silty Sand	82%	85%	68
Silt	84%	87%	458

From the data, the intervals that were primarily gravel had a higher percent recovery and were more likely to expand within the core tube to take up more volume than they were in-situ. Clean sands had an average percent recovery 8-10% higher than silty sands or silts and had more instances of greater expansion within the core tube.

Increments with excess recovery (%R>100%) are not well understood at this time, but seeing that recovery greater than 100% is most common with clean sands which are generally more resistant to core penetration, a possible mechanism for this process is the excess energy created by the operator increasing vibration and throttle on the drive to get through the denser material causes the material to approach the Critical Void Ratio and expansion can occur.

POTENTIAL IMPLICATIONS ON COST AND SCHEDULE

The uncertainty associated with estimating in-situ DOC bml can limit the efficacy of precision remediation dredging, which can affect the cost, schedule, and overall success of remedial actions (Fuglevand et al, 2021). Based on the trends observed from the collected data over three different remediation sites, the estimation of the DOC and in turn the EOC could be quite different depending on which method is used (Static Method, Stretch Method, or V-SAM Method).

Theoretical Differences in Calculated In-Situ Sample Depth versus Using V-SAM Technology

In order to estimate the difference in calculated in-situ sample depth bml using the collected data, an assumed in-situ sample depth of 5 feet bml using the V-SAM Method was selected for comparison purposes. The actual core data was then taken and used to calculate the equivalent sample depth for each core using the Static Method and the Stretch Method.

An example calculation on one of the cores is shown below. For this core, the drive and acquisition readings, as well as the Core Cut Plan (used for processing the core) is shown below, along with the corresponding acquisition curve.

Fathometer Readings		TUBE (ft.)		Increment		Core Cut Plan (ft.)	
Depth	Acquire	Drive	Acquire	% Recover	Comment	In-Situ	Core
12.1	20	0.0	0.0			HS	3.2
15	18.9	2.9	1.1	38%		0.0	0.0
18	17	5.9	3.0	63%		1.0	0.4
21	14.1	8.9	5.9	97%		2.0	0.8
24.1	10.7	12.0	9.3	110%		3.0	1.2
27.2	7.5	15.1	12.5	103%		4.0	1.8
30	4.8	17.9	15.2	96%		5.0	2.4
31.1	3.4	19.0	16.6	127%		6.0	3.1
						7.0	4.1
						8.0	5.0
						9.0	6.0
						10.0	7.1
						11.0	8.2
						12.0	9.3
						13.0	10.3
Process core? (y/n/b/x)*		y				14.0	11.4
	n	*Interpolated value*				15.0	12.4
	*	"Accepted"/"Rejected"/"Bulk Sample Only"/"No Core Recovered"				16.0	13.4
						17.0	14.3
						18.0	15.3
						19.0	16.6

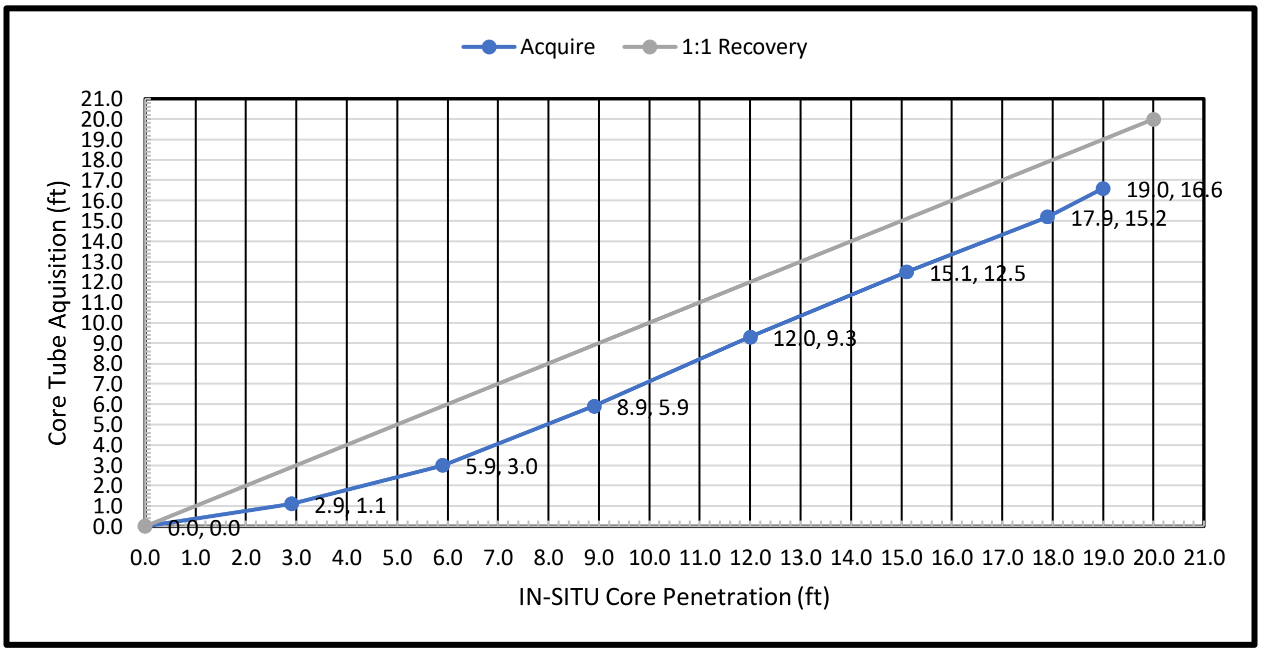

Figure 3. Example acquisition curve and core cut plan.

From the data, a sample collected using the V-SAM method at 5-feet bml would correspond to 2.4-feet from the top of the core, which would be the associated Static Method location. Since this core had an overall recovery of 87%, the associated sample location using the Stretch Method would be 2.8-feet from the top of the core. This same calculation was done for all 140 cores and the differences between the Static and Stretch methods versus the V-SAM method when looking at an in-situ sample depth of 5-feet bml is shown in Figure 4 below.

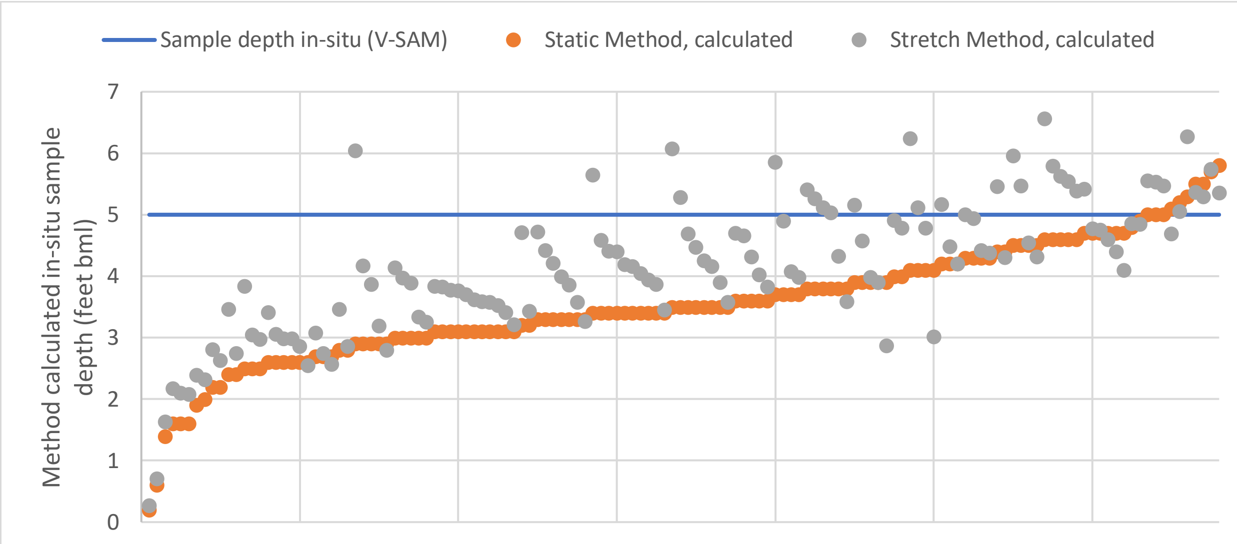

Figure 4. In-Situ sample depth below mudline (bml) calculated using static and stretch methods on 140 cores collected in riverine environment versus a sample depth of 5-feet bml for V-SAM method.

Figure 4 shows that both conventional methods have a large amount of variation from the V-SAM. Because a lot of the cores showed material missed at the start of the drive, there would be missed contaminated material if using these methods to inform the remedial design. This would likely result in costly re-dredging. Results from the calculated data are shown in Table 4 below.

Table 4. Calculated in-situ DOC vs V-SAM.

Method of Calculation	Percent of Cores Underestimating Sample Depth for V-SAM at 5-ft	Average Distance above V-SAM Method	Percent of Cores Overestimating Sample Depth for V-SAM at 5-ft	Average Distance Below V-SAM Method
Static Method	93%	1.6 feet	5%	0.4 feet
Stretch Method	76%	1.3 feet	23%	0.6 feet

Based on results shown in Table 4, the Static Method would have missed an average of 1.6 feet of contaminated material across 93% of the area and would have over-dredged an average of 0.4 feet across 5% of the area. The Stretch method would have missed an average of 1.3 feet of contaminated material across 76% of the area and would have over-dredged an average of 0.6 feet of material across 23% of the site.

Theoretical Cost and Schedule Implications from Calculated Methods

Based on the variations from the V-SAM Method using the Static and Stretch methods calculated above, and assuming that each core is representative of a 50-foot by 50-foot area (2,500 square feet), for a total area of approximately 8-acres, calculations have been done to assess the potential cost differences associated with using the Static and Stretch methods versus using the V-SAM technology.

Static Method

The Static Method underestimated the in-situ depth of contamination in 93% of the cores collected compared to the V-SAM results. At most the difference was 4.8 feet and on average it was 1.6 feet. If this method had been applied to the collected cores and used for the remedial design, potentially 93% of the site would have to be re-dredged due to missed contaminated material and would be on the order of 19,000 cubic yards (CY) and approximately 260 CY of presumed clean material would be dredged.

Stretch Method

The Stretch Method underestimated the in-situ depth of contamination in 76% of the cores collected compared to the V-SAM results. At most the difference was 4.7 feet and on average it was 1.3 feet. If this method had been applied to the collected cores and used for the remedial design, potentially 76% of the site would have to be re-dredged due to missed contaminated material and would be on the order of 13,000 cubic yards (CY) and approximately 1,800 CY of presumed clean material would be dredged.

CONCLUSIONS

V-SAM is a recently developed technology that can reduce the uncertainty when estimating DOC and EOC using vibracore samples versus conventional methods. 140 vibracore sediment samples were collected using V-SAM and trends were looked at. From these cores, it was observed that missing material during the start of a drive was a more common occurrence than losing material out of the bottom of the core upon retrieval. Given this, when comparing the in-situ DOC calculated using conventional methods, the majority of the locations would have underestimated the extent of contamination, which could result in costly re-dredging.

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EFFICIENT SHALLOW WATER REAL-TIME DREDGING MONITORING

P. Pocwiardowski[1], C. Sullivan[2] and M. Mutschler[3]

EXTENDED ABSTRACT

Shallow water dredging projects are often periodic and highly dynamic operations. The dredger must move quickly from one place to another and swiftly change operation from dredging to rock dumping. Contemporary advanced dredging projects are driven by tight specifications and multilayered structure where the dredging is followed by deposition of several layers of different size rocks, each of which has its own elevation and thickness requirements.

In such dynamic projects the hydrographic surveys conducted for dredge and rock dumping monitoring become a logistics issue and impacts the dredging time and efficiency. The dredger must often move out to let the survey vessel pass through. The survey data must be swiftly processed and passed back to the dredger operator to show the compliance with the design. This iterative process results in inefficient use of time and materials and often requires expensive reworks.

In such situations there is a need for a different approach for bathymetric data acquisition and processing. The process shall provide instantaneous feedback to the dredge operator with simple displays allowing them to take a corrective action on spot without waiting for the survey and data processing to complete. At the same time the solution must provide full transparency for the survey manager and hydrographers. The survey manager requires instant access to the data remotely, perform GIS operations, prepare progress reports, approve, and manage the data. That must be satisfied without any degradation of the bathymetry data quality and adhere to the required standards for hydrographic surveys.

The paper presents a real-time dredging monitoring turn-key solution facilitating the above outlined needs used during the Parallel Thimble Shoal Tunnel Project for Chesapeake Bay Bridge-Tunnel. The technology is being used by Chesapeake Tunnel JV during the construction of a second two-lane parallel tunnel under the Thimble Shoal navigation channel next to the existing tunnel.

Keywords: multibeam, hydrography, surveying

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