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Shell Island East Barrier Island Restoration
(photo courtesy of Great Lakes Dredge & Dock Company, LLC)

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IN THIS ISSUE

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DEDICATION

This edition of the *Journal of Dredging* is dedicated to Dr. Robert E. Randall and his immeasurable contributions to the modern dredging industry. Both papers are authored by Dr. Randall's graduate students with his expert guidance and assistance reflecting the breadth of his impact through the many students that he mentored over his illustrious career. WEDA awarded Dr. Randall its Lifetime Achievement Award in 2016 in recognition of his many contributions; the citation, republished on the following page, details a few of his many professional achievements.

While Dr. Randall's professional achievements are exceptional, his ethical and moral character and devotion to the profession are even more impressive. He invested countless hours on behalf of Texas A&M, WEDA, and the profession behind the scenes ensuring things were done professional and respectfully. He did not seek notoriety or desire recognition. I never saw him treat anyone with anything but the utmost respect. His humble nature defies his stature.

I benefited immensely from my many interactions with Dr. Randall over the years and look forward to many more. I learned a lot from him; I hope that I can put those lessons successfully into practice.

On behalf of the Western Dredging Association and the Editorial Board, I am proud to dedicate this edition of for the Journal of Dredging to Dr. Robert E. Randall, PE.

Dr. D. Hayes
Editor

THE WESTERN DREDGING ASSOCIATION TAKES GREAT PLEASURE IN PRESENTING ITS 2016 ANNUAL LIFETIME ACHIEVEMENT AWARD TO ROBERT E. RANDALL, Ph.D., P.E.

In recognition of over 50 years of outstanding service to the dredging and marine industry, and in particular, to the Western Dredging Association, WEDA is celebrating Dr. Robert Randall's longstanding accomplishments by conferring on him WEDA's 2016 Lifetime Achievement Award. His unselfish ability to share insights in dredging and marine engineering has been of tremendous value to not only members of WEDA, but also to dredgers worldwide. Currently serving as the W.H. Bauer Professor of Dredging Engineering at Texas A&M University, Dr. Randall continues to mentor and guide students in Ocean and Dredging Engineering.

Dr. Randall started his illustrious career with the United States Navy, from 1965 to 1967, on board submarines, USS Grenadier and USS Grouper. Following that, he obtained his Masters and Doctoral degrees in Ocean Engineering from the University of Rhode Island in 1972. Dr. Randall subsequently joined the Ocean Engineering faculty at Texas A&M University, College Station, in 1975, and has devoted his career to educating ocean and dredging engineers.

A long-standing WEDA member, Dr. Randall has made available to the dredging industry, information of far reaching consequences in the areas of navigation, dredging, beneficial uses of dredged material, capping, and marine construction. In his role as Director, Center for Dredging Studies at Texas A&M University, he has led the Annual Dredging Engineering Short Courses since 1993, and initiated the highly successful Cutter Suction Dredge Simulator Training in 1999.

Dr. Randall, an internationally recognized authority in dredging and marine engineering, has served on WEDA's Board of Directors since 1994, actively contributing to the betterment of the organization, and ever willing and ready to serve for WEDA, as requested. Dr. Randall has been editing WEDA's annual conference proceedings since 1994, and the high quality of the proceedings is a direct testament to his leadership and attention to detail.

He has also been serving as Associate Editor, WEDA's Journal of Dredging Engineering, since its initiation in 1999, and has actively contributed to the Journal.

The entire worldwide dredging industry is thankful to Dr. Randall for his many positive contributions to the field, over the years. Because of his outstanding support to the dredging industry and to the Western Dredging Association, it is with great pleasure that I present him with, WEDA's 2016 LIFETIME ACHIEVEMENT AWARD.

Given under my hand this 16th day of June 2016

Ram K Mohan

Ram Mohan, Ph.D., P.E.
President/Chairman, Western Dredging Association

PRODUCTION AND COST ESTIMATING FOR TRAILING SUCTION HOPPER DREDGE

Bohdon M. Wowtschuk[1] and Robert E. Randall[2]

ABSTRACT

Major dredging projects in the United States are typically contracted by the government using a competitive bidding process. A method for accurately estimating the total cost associated with performing the dredging work is essential for both government solicitation and the bidding contractors. This paper presents a method to determine production rate for trailing suction hopper dredges when minimal information is known about both the site to be dredged and the hopper dredge being used. The calculated production rate is then combined with financial inputs to obtain a first estimate a total dredging cost and project duration.

The production and cost estimation is incorporated into a publically available program designed on Microsoft Excel. The program utilizes slurry transport fundamentals, dimensionless pump curve analysis, and overflow loss assumptions to create a highly customizable program across a wide range of hopper dredge project types. In addition, the program allows a user to reduce or expand the scope of cost estimating depending on project requirements.

Results of the program were found to satisfactorily estimate total project costs and dredging operation costs for eight major dredging projects between 2013 and 2015. Through the utilization of default hopper specifications and project specific site characteristics the program generated a mean absolute percent difference of 21% for the total project costs and 20% for the dredging operation costs alone.

Keywords: Dredging, production, estimating spreadsheet, hydraulic dredging, cost comparison

INTRODUCTION

The trailing suction hopper dredge is a category of hydraulic dredges used primarily for coastal and open ocean navigation channels. Hopper dredges accounted for nearly 30% of the total dredging expenditure in the United States from 2013-2014, with over 400 million USD spent in 2014 alone (NDC, 2015). The majority of these projects were funded by the federal government's US Army Corps of Engineers (USACE), which either performs the work using Corps of Engineers owned vessels or contracts the work to private dredging companies.

Dredging contracts are awarded through a standard government procurement process, and typically through the competitive bidding process. In this manner, multiple companies bid on the

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cost of completing a dredging project and the contractor with the lowest reasonable bid is selected to complete the work. Most dredging is on a per-unit basis, so that the contractor estimates a cost per the volume of material specified in project plans. The actual final cost of the project is the per-unit cost bid times the actual amount excavated (Huston, 1970). It is crucial for the contractor to have an accurate cost estimation process to not only submit a competitive bid, but to also ensure a desired profit margin is maintained. The USACE also utilizes a cost estimating system in order to secure necessary government funding and verify the plausibility of the bids. Both private contractors and the government agencies use proprietary estimating systems which are not readily available to the public.

Objectives

The objective of this research is to develop, test, and validate a new user friendly software to forecast the cost of hopper dredge projects. The software is based in Microsoft Excel spreadsheet format and readily available to individuals outside the government-contractor community. In order to predict the cost of a dredging project, a production rate is first determined. Estimating the production is difficult due to the uncertainty of dependent variables, but once calculated, the total cost is determined using general pricing assumptions. Building upon a previously developed cost estimating software from the Center for Dredging Studies (CDS, 2014), this research increases the programs breadth of application, scope of inputs, and simplifies the user interface as outlined in Wowtschuk (2016). The operator needs only to input known or estimated equipment and site characteristics to have the software yield a total preliminary cost estimation.

TRAILING SUCTION HOPPER DREDGE

Trailing suction hopper dredges are self-propelled vessels with the capability to excavate, transport, and discharge seabed material. As a category of hydraulic dredges, which also includes cutter-suction dredges, hopper dredges utilize a centrifugal pump, blades in draghead, and water jets to cut and erode the sediment that is entrained in the water as a slurry for removal and transport. How about the blades and jets? The pump is not doing everything! A typical hopper dredge is illustrated in Figure 1. During dredging, the suction pipes, or drag arms, are lowered by winches and gantries so that the drag head reaches the dredging depth, the seafloor. As the vessel moves ahead, typically one to three knots, the drag head is pulled along the sea floor as the sediment/water mixture flows into the suction pipe. The combined effect of the dragging drag head and flowing water entrain and erode the sediment for removal. This mixture of sediment and water is called slurry, and upon reaching the desired sediment concentration, is drawn up the suction pipe, through the centrifugal pumps located onboard the vessel, and into the hopper bins. Either the concentration is determined by the erosion process under the draghead, or determined by the blades and/or the waterjets.

The hopper is typically outfitted with a distribution system that minimizes turbulence and ensures solids quickly settle out of the slurry mixture to the sediment level in the hopper. Overflow weirs are also installed in the hopper bins so that as the sediment falls to the hopper sediment level, the cleaner water overflows from the dredge and more slurry is pumped into the hopper. Overflow enables the hopper dredge to continue loading past the time it takes to initially fill with slurry mixture up to maximum overflow level, maximizing the load of sediment in the hopper bin. The rate of settlement depends on the type of material being dredged so that medium to coarse sands settle faster than smaller diameter particles like fine sand, silt and clay, which may not settle at all. Overflow is not typically used while dredging fine particles or when site restrictions prohibit the overflow of sediment back into the water (Bray et al., 1997).

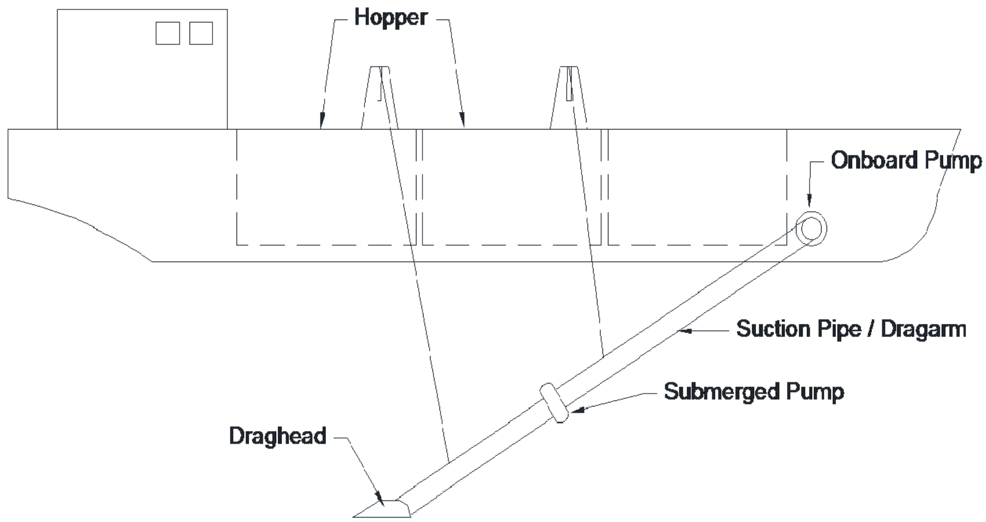

Figure 1: Typical Trailing Suction Hopper Dredge Components

When the hopper reaches the economical load capacity, the pumps are secured, drag arms are stowed back aboard, and the vessel sails to the designated placement site. The dredged material is typically removed from the hopper through a bottom door discharge, pump-out discharge or rainbowing. The placement method depends on the type of dredging project being conducted and capability of the dredge. Bottom discharge is used for maintenance dredging of a channel or harbor, while pump discharge is a method of sediment placement used for beneficial use projects such as beach nourishment. After the contents of the hopper are emptied, the dredge sails back to the dredging area and the cycle of load, sail to discharge area, discharge, and sail to dredging area, called the production cycle, begins again.

Trailing suction hopper dredges are ideally suited for the removal of non-cohesive materials like sands or loose silts, and are most commonly employed for maintenance dredging, or maintaining navigable depths in previously dredged channels or harbors. Hopper dredges may also be used for expanding existing channels or for dredging untouched sea beds, but lose effectiveness on hard packed soils and boulders. Hopper dredges are also used as sand haulers to build islands such as the Palm Islands in the Middle East and other land reclamation projects.

The main advantage of the trailing suction dredge arises from its mobility. While other hydraulic dredges, such as a cutter-suction dredge, are required to be partially anchored to the work site, hopper dredges are fully mobile and self-propelled. Mobility is an advantage while operating in active shipping channels or harbors. While a pipeline dredge requires a large working footprint that could inhibit navigation, hopper dredges have minimal impact on the traversing commercial vessels. The hopper dredge can also work continuously through shipping traffic, while a stationary dredge may have work delayed. Its mobility also makes the hopper dredge ideal for use in projects that require the excavated sediment be transported a long distance to the placement site, thus making the use of a pipeline impractical. Finally, the costs of transferring to a new dredging site, known as mobilization, tends to be lower than for other dredge types.

REVIEW OF LITERATURE

There has been extensive academic work on the creation of a reliable and replicable cost estimation procedure for hydraulic dredging work. A review of prior work in this field reinforces the importance of an accurate production rate based on hydraulic transport fundamentals and valid adjustment factors. Bray et al (1997) formulated a total production time, or maximum potential output for hopper dredges by analyzing the overall production cycle. For hopper dredges this is comprised of: loading time, turning time, sailing time to and from the site, and time taken to discharge dredged material.

Randall (2004) discusses how to arrive at an optimal flow rate by comparing the installed centrifugal pump characteristics and the system head curve. The system head curve is a summation of the dredging system's head losses, from drag head inlet to discharge into the hopper, and static head as a function of flow rate. Wilson et al. (2006) present a method for calculating energy losses of a slurry moving though a piping system and provided solutions for the hydraulic variables used to find the frictional head loss and modifications to account for inclined pipe flow, such as a lowered drag arm. The point at which the pump curve intersects the system head curve is called the operating point. Palermo and Randall (1990) studied the impact of overflow time on the loading of hopper dredges and determined that when dredging sediments that settle-out of suspension quickly, such as medium and coarse sands and gravel, having a period of overflow can significantly increase the solids load of the hopper. Conversely, when dredging silts and clay solids there is usually no benefit to overflow since the concentration of solids in the hopper does not increase substantially. The problem is fine sands with considerable overflow losses

Randall (2000) discussed the methodology for estimating dredging costs and the cost components to be considered when making an estimation. The methodology combined the production rate estimation with calculations for various cost components to form a reasonable total cost estimate applicable to hydraulic dredges. In addition, the difficulty for the government to estimate mobilization and demobilization costs was explained as a consequence of not knowing the dredge's proximity to the project site.

Miertschin and Randall (1998) describe the creation of a cost estimating program for cutter suction dredges, and influenced later dredging estimation programs developed by the Center for Dredging Studies (CDS). Non-dimensional pump curves were used to estimate pump characteristics for a wide range of dredge sizes. The use of non-dimensional pump characteristics makes production estimation more flexible as the total pump head, power, and efficiency can be reasonably estimated across different pump speeds and sizes without the need for specific characteristics curves.

Belesimo (2000) formulated a cost estimation spreadsheet for both cutter suction and hopper dredges using hydraulic transport fundamentals and unit cost assumption. The slurry flow rate was determined from dredging equipment configurations and the characteristics of dredged material. The cost estimate program yielded highly competitive results with an average 17.3% difference from the winning bid, while the government estimate averaged a 16.2% from winning bid for the same data. The most recent cost estimating system publically available from the CDS was published by Hollinberger (2010) and focused the scope of research on trailing suction hopper dredges. Hollinberger's cost estimating program improved the results from Belesimo, lowering the average difference from winning bid to 15.9%.

METHODOLOGY FOR ESTIMATING PRODUCTION

The production rate of a dredge is defined by Bray et al. (1997) as the amount of in-situ material moved per unit of time. Once the production rate is determined, the time it takes to complete a project is estimated. The more time a project takes, the more resources and labor will be required to complete it and the more costly it is. Therefore, an accurate estimate of the production rate is required before there is an effective cost estimate. The production rate for the trailing suction hopper dredge is determined using a combination of hydraulic slurry transport theory, non-dimensional pump characteristics, overflow losses, and other recommended cycle limiting factors.

Hydraulic Transport

The efficient transportation of solid material suspended in liquid, or hydraulic transport, depends on accurate calculation of the power required to pump slurry mixture, and the rate at which sediment can be removed. In the context of a trailing suction hopper dredge, these calculations are utilized for slurry pumped through the drag arm, into the hopper bin, and out to a shore reclamation project. The hydraulic transport components are broken down into three components: critical velocity, energy lost to the system, and power supplied by the pump.

A sand-water mixture must maintain a certain velocity through a pipe to prevent particles suspended in that fluid from falling out of suspension and becoming stationary on the bottom. If the slurry does not maintain this critical velocity (V_c), then the sediment will settle out, restrict flow, and likely clog the pipe. The velocity maintained by the system should not fall below the critical velocity (V_c). Matousek (1997) developed the following equation based on the nomograph presented in Wilson et al. (2006) to determine the V_c in horizontal slurry pipe flow

$$V_c = \frac{8.8\left[\frac{\mu_s(SG_{so} - SG_f)}{0.66}\right]^{0.55} D^{0.7} d_{50}^{1.75}}{d_{50}^2 + 0.11D^{0.7}} \quad (1)$$

where μ_s is the dimensionless coefficient of mechanical friction between particles taken as 0.44, SG_{so} is the specific gravity of the solids, SG_f is the specific gravity of the fluid, D is the inside pipe diameter in meters, and d_{50} is the median particle diameter in millimeters. The critical velocity (V_c) is then used to calculate the critical flow rate (Q_c), which is the minimum flowrate at which the dredge should operate.

The energy lost as a slurry is transported through a piping system is referred to as head loss, and is used to determine the power required to deliver a certain flowrate. The system head losses are the summation of head losses from frictional effects of the pipe, termed major losses, and minor losses (H_m). The H_m losses, given in units of meters (feet), are head losses as fluid travels through various piping components, characterized by the loss coefficient K, and calculated by the following equation recommended by Munson et al. (2009):

$$H_m = \sum K \frac{V^2}{2g} \tag{2}$$

where V is the mean velocity of the slurry, and g is the acceleration due to gravity. The major losses, or frictional head loss (H_f) result from the frictional interaction between the slurry and inner pipe walls during flow. The H_f is determined by procedures described in Wilson et al (2006). These procedures are applied to heterogeneous slurry flow in both horizontal and inclined pipes. For horizontal flow:

$$i_{m(horizontal)} = \frac{fV^2}{2gD} + 0.22(SG_{so} - 1)V_{50}^{M} C_v V^{-M} \tag{3}$$

where

$$V_{50} = w\sqrt{\frac{8}{f}} \cosh\left[\frac{60d_{50}}{D}\right] \tag{4}$$

$$w = 0.9v_t + 2.7\left[\frac{(\rho_s - \rho_f)g\mu}{\rho_f^2}\right]^{\frac{1}{3}} \tag{5}$$

so that i_m is the head loss due to friction in meters (feet) of head per meter (foot) of pipe, f is the Darcy Weisbach friction factor for water, V_{50} is cross sectional averaged velocity of the fluid at which 50% of the solids are in suspension, M is a particle size parameter equal to 1.7 for uniform sands, for graded sands the value is smaller, C_v is the delivered concentration of solids by volume, v_t is the particle terminal velocity in meter per second, ρ_s and ρ_f are the density of solid and fluid respectively, and μ is the dynamic viscosity.

The friction factor chart developed by Moody (1944), is normally used to determine the friction factor (f), but Herbich (2000) and Randall (2000) recommend the following formula (Swamee and Jain, 1976) as a substitute:

$$f = \frac{0.25}{\left[\log\left(\frac{\epsilon}{3.7D} + \frac{5.74}{R^{0.9}}\right)\right]^2} \tag{6}$$

where ϵ is the pipe surface roughness in m and R is the Reynolds number. The v_t is achieved by a settling sediment particle at which there is zero acceleration, so that the submerged weight of the particle is in equilibrium with the drag force.

$$v_t = 134.14(d_{50} - 0.039)^{0.972} \tag{7}$$

This yields v_t in mm/s that must be converted to m/s for use in Equation 5. For purposes of this production estimate, d_{50} values below 0.039 mm were assumed to result in a v_t of zero. The spatial concentration of solids by volume, C_v, which is the ratio of solids to the total amount of water and sediment mixture is expressed as:

$$C_v = \frac{SG_s - SG_f}{SG_{so} - SG_f} \tag{8}$$

where SG_s is the specific gravity of the slurry, SG_f is the specific gravity of the carrier fluid, normally taken to be 1.03 for sea water, and SG_{so} is typically 2.65 for sand and silt particles. The delivered concentration is slightly less that the spatial concentration due to the sediment particles sometimes move slower than the average velocity of the carrier fluid in the pipe. For heterogeneous flows, the spatial and delivered concentration are the same which was assumed in this paper. Mention the difference between spatial and delivered concentration.

Wilson et al. (2006) also provided procedures to calculate the frictional head loss due to heterogeneous slurry flowing through an inclined pipe. This approach was used to approximate the major losses experienced by the slurry flowing through a lowered drag arm. While major losses tend to make up the predominant component of the total system losses when dealing with many thousands of meters of piping found in pipeline dredging, it is a small component on a hopper dredge pipe system, which does not typically extend beyond a few hundred meters.

Pump Power

Trailing suction hopper dredges utilize large centrifugal pumps to transport the dredged material. These pumps induce pressure energy, or dynamic head, into the piping system by changing the pressure of the slurry as it passes through the pump. The slurry enters the pump through the impeller eye, and is then thrust outwards toward the pump casing by a high speed rotating impeller. Upon exiting the impeller and entering the casing, the centrifugal pump adds pressure to the mixture as a result of centrifugal force causing the pressure to increase. The modified Bernoulli equation, or energy equation, can be used to represent the flow from suction pipe inlet to pump discharge into the hopper bin as shown in Equation (9) below:

$$H_p + \frac{p_s}{\gamma} + \frac{V_s^2}{2g} + Z_s = \frac{p_d}{\gamma} + \frac{V_d^2}{2g} + Z_d + H_f + H_m \tag{9}$$

where p is the pressure, γ is the specific weight of the slurry (mixture), V is the velocity, and Z is elevation. The suction side at the drag head inlet, and the discharge side into the hopper bin are denoted by subscripts (s and d) respectively. The equation also includes the addition of pump power, H_p, system frictional losses, H_f, and system minor losses, $H_{m.}$

The high complexity of flow through centrifugal pumps makes it necessary to determine performance experimentally through pump testing. Manufacturers present the test findings and detail the performance of a specific pump on characteristic curves which graph variation of pump head (H), brake horsepower (BHP), and pump efficiency (η) as a function of volumetric flow rate (Q) for water. These curves are in dimensional format and are only valid for a pump with the same impeller diameter and operating at a certain speed. To maintain an advantage when bidding on projects, most companies do not make the characteristics curves for their pumps available to the public. The estimating program enables the user to input actual pump head data, however, to ensure compatibility with a wide range of dredging projects, it also utilized dimensionless characteristic curves to find values of H, BHP, and Q for similar pumps operating at any speed.

The selection of which dimensionless characteristics curve to use depends on the suction pipe diameter, and the BHP of the pump then dictates the assumed pump speed, ω. The BHP was determined from the total installed power on the hopper dredge, multiplied by the ratio of pump power to total installed power. With the set of dimensionless curves selected it is possible to obtain a new pump head values by keeping impeller diameter, D_i, constant for each pump model and changing the ω. The pump efficiency is defined as

$$\eta = \frac{water\ horsepower}{brake\ horsepower} = \frac{\rho g Q H}{BHP} \tag{10}$$

It is assumed that a pump operates at or near its best efficiency point, so that η is nearly constant. Therefore the dimensionless parameters are equal to a constant value and the dimensionless head can be adjusted to match changes in pump power. At the same Q, ω, and D_i, a dimensionless Equation (10) can be expressed as

$$H_{dim_2} = \frac{BHP_{dim_2} H_{dim_1}}{BHP_{dim_1}} \tag{11}$$

where H_{dim_2} is the new dimensionless head produced by the pump with an adjustable dimensionless pump power BHP_{dim_2}, and $H_{dim_1}$and $BHP_{dim_1}$are the dimensionless head and power from the original dimensionless curve that change along the flowrate envelope of the pump. Then, a new dimensional BHP curve as a function of Q is created for any input pump power. The total system head curve in Figure 2 was created by plotting the calculated head losses as a function of the flowrate. The system head curve is then superimposed on the pump head curve created by plotting the dimensional solution to Equation (11) as a function of the same flowrate range. The point at which the system head curve intersects the pump head curve is the optimal flowrate for the system. This optimal flowrate is used as the flowrate Q of the dredge for estimating production and must be greater than Q_c.

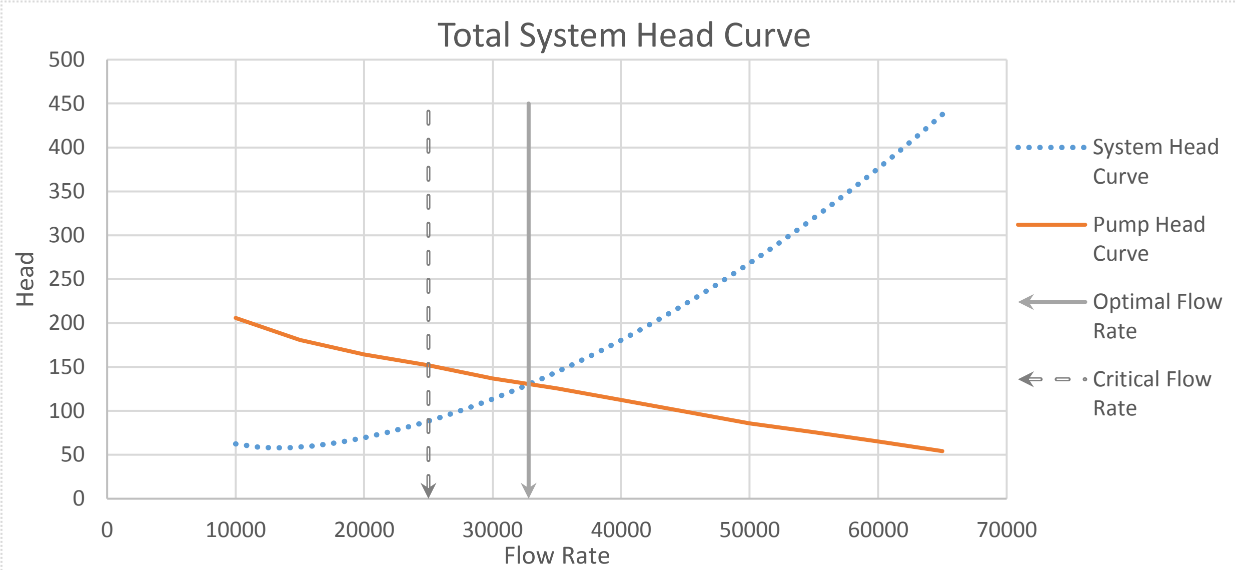

Figure 2: Example of System Head Curve Superimposed on Pump Head Curve

The Total Production Rate

The total production rate for a trailing suction dredge is a metric for determining the amount of dredged in-situ material excavated during the dredging cycle. Using an equation developed by Bray et al. (1997), the estimated the total production rate used by the program was:

$$P_{max} = \frac{\mathrm{C_H} C_v + P t_o (1 - r_l)}{B(t_{load} + t_{turn} + t_{sail} + t_d)} \qquad (12)$$

where P_{max} is the maximum total production rate in m^3/hr (yd^3/hr), C_H is the capacity of the hopper in m^3 (yd^3), P is the production rate at which dredged material is excavated from the sea floor, t_o is the overflow time, r_l is the overflow loss ratio, B is a bulking factor, and t_{load}, t_{turn}, t_{sail}, and t_d denote the time to complete different components of the dredging cycle. According to Turner (1996), the P can be approximated as:

$$\mathrm{P} = 0.297 Q C_v \qquad (13)$$

where C_v is found from Equation (8), and the SG_{so} is the in-situ value, typically 1.8 - 2.1 (Randall, 2004). The overflow ratio and overflow time are based on the sediment properties and are difficult to determine ahead of time. The overflow loss ratio (r_l) values used for this program are based on findings from Boogert (1973), and represents a mean loss ratio for various sand grain sizes. Larger heavier sediments have a lower value than smaller lighter sediments. Additionally, the program used a default overflow time of 0.75 hr based on typical loading times observed in both Bray et al. (1997), and Palermo and Randall (1990). It was assumed that sediment overflow was permitted for a project unless explicitly stated otherwise in the solicitation documentation.

Turning time, $t_{turn,}$ is the total time taken turning the dredge in the channel during the loading phase. The sailing time, t_{sail}, is the time it takes the hopper to travel to the placement area and back to the dredging site. The time to discharge the dredged material, t_d, depends on the method of disposal, and the time to load the hopper, t_{load}, depends on the C_H, the Q into the hopper, and the t_o.

The maximum total production rate (P_{max}) must be adjusted to account for the less than ideal efficiency of operating in a real world environment. Bray et al. (1997) recommended three reduction factors: the delay factor (n_d) accounts for time lost due to bad weather and maritime traffic, operational factor (n_o) accounts for the inefficiency of the dredging crew, and mechanical breakdown factor (n_b) accounts for the breakdown of equipment that leads to work stoppages. The corrected total production, or average total production rate is expressed as P_{avg}.

COST ESTIMATION

The P_{avg} is used in conjunction with price assumptions to estimate the cost of a dredging project. The cost is comprised of numerous factors but can be divided into two major components: operating costs and non-operating costs. Procedures set forth by Bray et al. (1997) and Randall (2004), will be used to combine the cost data with the estimated project completion time to calculate the project cost estimation.

Operating Costs

Operating costs are the summation of costs associated with dredging operations during the timespan of project execution. The estimated duration of the project was determined from the average production rate and the volume of sediment to be dredged. The duration was then used to find costs of various factors which were used to find a total operating cost. Randall (2004) recommend that the operating costs be comprised of the following factors: dredge crew, land support crew, fuel, lubricants, routine maintenance and repairs, major repairs and overhauls, insurance, depreciation, overhead and profit. Bray et al. (1997) provided assumptions and parameters that were applied to each of the cost factors for estimations purposes.

Hopper dredges require a sufficient crew to conduct both dredging operations and the operations of a seagoing vessel. The number of crew members may vary widely from ship to ship depending on the size of the dredge, and automation of equipment. Hollinberger (2010) and Bray et al (1997) recommend hopper crew composition, and the USACE provided actual dredge crew organization. The hourly wage rate was based on information obtained from the U.S. Bureau of Labor Statistics (2015), the Federal Wage System (FWS) Special Salary Rate Schedules (DCPAS, 2015), and RS Means Heavy Construction Cost Data (RS Means, 2015).

Fuel costs make up a significant portion of the hopper dredge operating costs. The total installed power of a dredge and hours operating at 100% power were used to determine average diesel fuel consumption based on procedures outlined by Bray et al. (1997). Diesel fuel costs were for No. 2 diesel, averaged over an eighteen month period, and obtained from the U.S. Energy Information Administration (2015). Lubricant costs were assumed to be 10% of daily fuel cost.

The capital cost of a dredge is used to estimate the maintenance, insurance, and depreciation costs. Information from Bray et al. (1997) and RS Means (2015) annual cost indices were used in Figure 3 to estimate the capital cost of a hopper dredge based on year of construction and hopper capacity. Bray et al. (1997) provided an approximate capital cost in Dutch Guilders (f) for various hopper metric ton capacities for the year 1996. Guilders were converted to U.S. Dollars, based on the average conversion rate for the year 1996, obtained from the Federal Reserve Foreign Exchange Rate (Federal Reserve Statistical Release, 1999). Historical cost indexes were used to adjust the values to the years shown in Figure 3. The estimated average capital cost of all major hopper dredges in the United States, based on year built, was found to be approximately $18M.

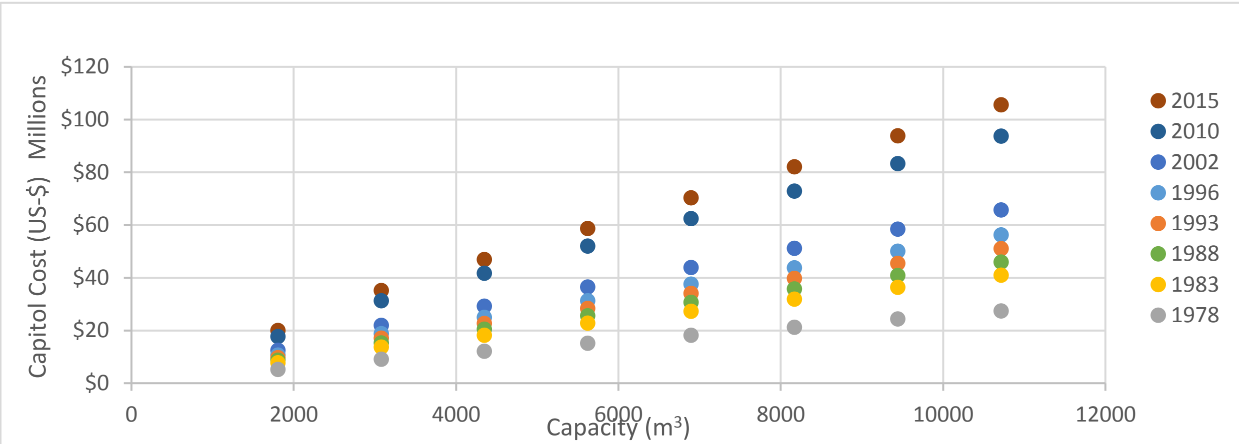

Figure 3: Trailing Suction Hopper Dredge Capital Cost

The repair and maintenance of a dredge can be divided into two categories: routine maintenance and overhauling. The daily cost for these repairs was obtained by multiplying the capital cost of the dredge by factors outlined in Bray et al. (1997). Depreciation and insurance depend on the owner's fiscal policy. Daily depreciation rate is the annual depreciation divided by the number of working days per year, and insurance was based on an annual premium of 2.5 percent of insured plant value. Overhead costs also vary from contractor to contractor but was assumed at nine percent of the total operating cost as recommended by Bray et al. (1997). Bonding is a guarantee of performance of work and Belesimo (2000) recommended it at 1.0% of the operating cost.

Since wages and fuel costs are location dependent, they were adjusted to reflect regional differences. The USACE collects data on regional differences and publishes a quarterly report containing state adjustment factors for civil works construction (USACE, 2015). RS Means (2015) contains a yearly cost index table which was used to adjust project costs for past years.

Mobilization, Demobilization and Additional Costs

Mobilization and demobilization cost is the price associated with the transportation of dredging equipment to and from the job site. As Randall (2000) outlined, these costs are difficult to predict for any given project. For trailing suction hopper dredges, the cost is primarily a function of the distance to and from the job site, the cost of flying in additional crew and equipment, and revenue lost due to downtime. A program recommended mobilization/demobilization cost of $1M was based on the median value of the cost estimates from the eight dredging projects investigated. A graphical representation of the government estimate and winning bid costs are shown in Figure 4.

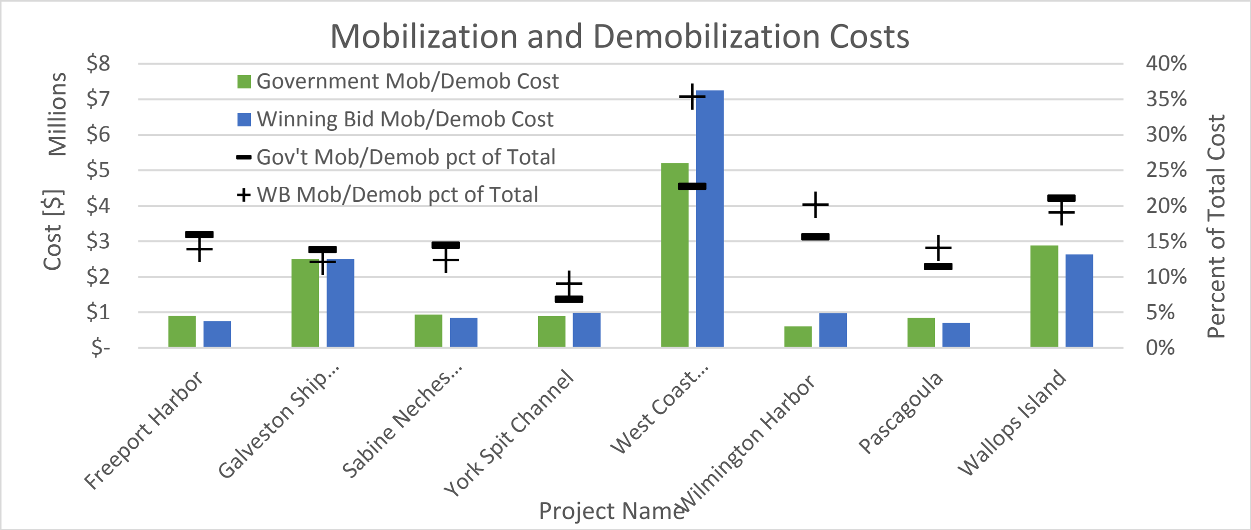

Figure 4: Mobilization and Demobilization Costs

Additional costs common to dredging projects vary greatly from project to project and may include site surveys, environmental protection devices, trawlers, or other miscellaneous items. The program recommended the median government cost estimate for the items found in USACE dredging project bids as shown in Figure 5.

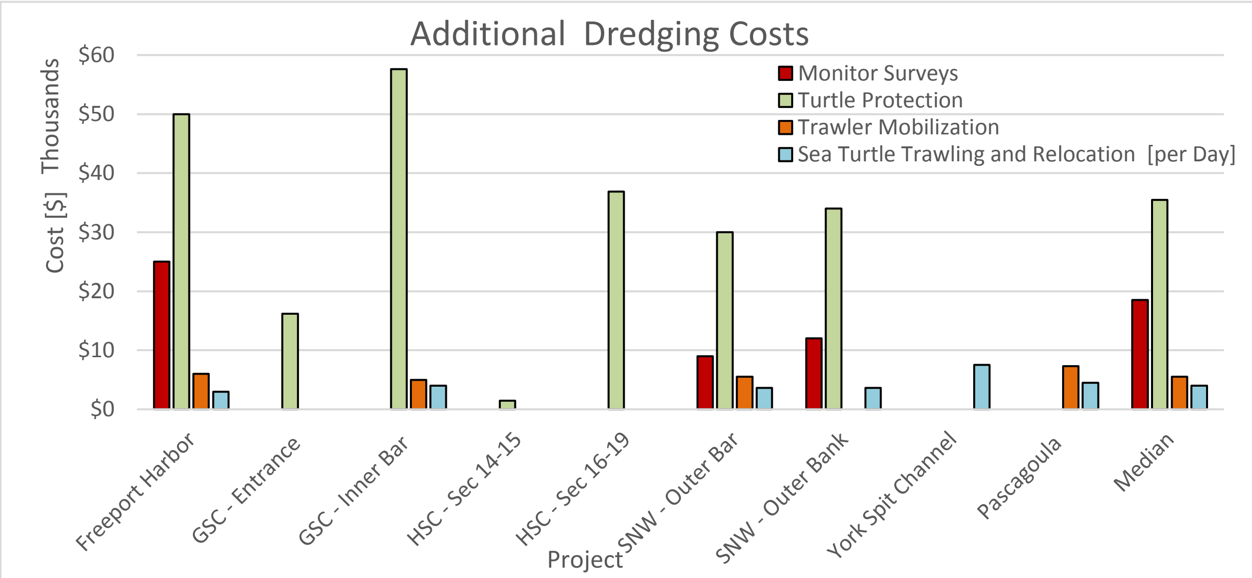

Figure 5: Additional Dredging Costs

RESULTS

The validity of this production method and accuracy of the cost estimating program was tested with data from actual USACE dredging projects. Dredging site specifications and bidding cost breakdowns used for the comparison were found from the USACE Navigation Data Center website (NDC, 2015), the federal government's database of contracting opportunities, FedBizOpps.gov (Federal Business Opportunities, 2015), and from NOAA navigational charts (OCS, 2015). Information not readily available online, such as project solicitations and site plans, were obtained from the USACE using Freedom of Information Act (FOIA) requests. The project site information used for the program estimate comparison are shown in Table 1.

Table 1: Project Information

Project Name	Location	Volume, m^3 (yd^3) [x1,000]	Distance to Disposal Site, km (NM)	Depth, m (ft)
Freeport Harbor (2013)	Gulf Coast	1,1643 (2,149)	6.48 (3.5)	14.3 (47)
Galveston Ship Channel (2015)	Gulf Coast	1,840 (2,407)	16.67 (9.0)	13.7 (45)
Sabine Neches Waterway (2014)	Gulf Coast	3,899 (5,100)	2.78 (1.5)	12.8 (42)
York Spit Channel (2015)	Central Atlantic	1,336 (1,747)	20.37 (11)	15.5 (51)
West Coast Maintenance (2015)	West Coast	4,511 (5,900)	5.56 (3.0)	14.9 (49)
Wilmington Harbor (2014)	Lower Atlantic	631 (825)	14.82 (8.0)	13.4 (44)
Pascagoula Entrance Channel (2014)	Gulf coast	789 (1,033)	5.56 (3.0)	14.0 (46)
Wallops Island Beach Restoration (2014)	Central Atlantic	497 (650)	22.22 (12)	10.7 (35)

Cost Comparison

The project costs estimated by the program were compared to actual project cost estimates made by the government and the winning contracting company bid. The government estimate (GE) is prepared by the USACE to evaluate acquisition feasibility of proposed project, and to determine the reasonability of a contractor's bid. The winning bid (WB) is the lowest price submitted by a contractor that has complete the project requirements. The bidding cost breakdown, known as the bid abstract, breaks down project costs into separate line items for mobilization, dredging, and various additional costs. The bids also breakdown the dredging project into multiple channel sections and optional additional work.

The accuracy of this program's cost estimate was evaluated using two different methods. The first method compared total projects costs estimated by the program to the total actual estimates from the bid. However, since mobilization costs and additional costs are typically project and contractor-specific and difficult to estimate, a second method compared only the dredging operation costs, and omitted line items pertaining to mobilization costs and additional costs. Both comparison methods utilized program cost estimates with predetermined variables referred to as the Wowtschuk Program Estimate (WPE). These default values assumes each cost estimate had the same: dredge information, suction pump, pipe information, crew information, and sediment composition. The WPE only required project variable input for: geographical location, volume to be dredged, distance to disposal site, and dredging depth. A complete list of the WPE defaults are shown in Table 2.

Table 2: Wowtschuk Program Estimate (WPE) Inputs

Dredge Information		**Project Site Information**	
Hopper Capacity, m (yd^3)	4052 (5300)	Length of Dredge Area, km (NM)	1.85 (1.0)
Total Horsepower, kW (HP)	7308 (9800)	Particle Diameter (d_{50}), mm	0.13
Sailing Speed, m/s (kts)	4.12 (8)	SG of Slurry	1.3
Capital Value, $M	18	SG of In-Situ Solids	1.9
Equipment Lifespan, yrs	30		
Suction Pipe Information		**Defaults Parameters**	
Suction/Discharge. Diameter, m (in)	0.737 (29)	Pump Power / Total Power	0.3
Dragarm Length, m (ft)	30.48 (100)	Overflow Time, hrs	0.75
Crew Information		100% Power per day, hrs	15
Cost per day, $	16,536	Reduction Factor	0.61
		Overflow Loss	0.5

These values were made based on average dredge characteristics, past academic findings, and program iteration. The SG_{so} of the in-situ sediment material was assumed to be 1.9 for all projects, within limits of typical dredged material (Randall 2004). A fine sand sediment, with a d_{50} of 0.13 mm was assumed for all projects, which results in an overflow loss ratio (r_l) of 0.5.

The comparison results for total project costs calculated by the WPE to the actual estimates are shown Table 3. The WPE total cost estimate (WPEt) used the production rate to calculate the dredging operation cost, a mobilization cost of $1M, and additional costs ranging in value from $200K -$300K. The actual estimate includes dredging operational costs, all the mobilization costs, additional environmental costs, and optional dredging line items from the contract bid abstracts.

The mean absolute percent error, or the average of the absolute percent error for all eight projects, was approximately 20% between the WPEt and both the winning bid and government estimate. Using +/- 50% as an acceptable tolerance, the WPEt was relatively accurate with percent error of under 50% from the winning bid. This level of accuracy indicates that the WPE makes realistic assumptions and can be used to provide a reasonable predictor of the total project costs.

It was observed that using the default in-situ $SG_{so,}$ of 1.9 for the Sabine Neches Waterway estimate, resulted in an error of +60%, therefore an SG value of 1.5 was used to obtain the results in Table 3. The 1.5 value matched the actual SG_{so} indicated by the project's daily dredging reports (USACE, 2014). The program also underestimated costs for the Pascagoula Entrance Channel and Wallops Island Beach Restoration projects. The Pascagoula project involved new dredging work, and the Wallops Island project incorporated beneficial use of dredged material. This required additional dredging equipment, and was outside the program cost estimating scope.

Table 3: Total Project Cost Accuracy Comparison

	GE [$1K]	WB [$1K]	WPEt [$1K]	GE vs. WB	WPEt vs. WB	WPEt vs. GE
Freeport Harbor (2013)	5,637	5,399	5,990	4.41%	10.94%	6.26%
Galveston Ship Channel (2015)*	11,202	11,762	9,717	-4.76%	-17.38%	-13.26%
Sabine Neches Waterway (2014)	6,488	6,875	6,455	-5.63%	-6.11%	-0.51%
York Spit Channel (2015)	12,908	10,859	10,248	18.87%	-5.63%	-20.61%
West Coast Maintenance (2015)	21,733	22,391	17,645	-2.94%	-21.19%	-18.81%
Wilmington Harbor (2014)	3,814	4,836	3,774	-21.14%	-21.96%	-1.05%
Pascagoula (2014)	7,401	4,963	3,296	49.13%	-33.58%	-55.46%
Wallops Island (2014)	13,625	13,743	7,072	-0.85%	-48.54%	-48.10%
Total:	**82,808**	**80,827**	**64,197**	**2.45%**	**-20.57%**	**-22.47%**
Mean Absolute Percent Error				**13.46%**	**20.67%**	**20.51%**

*Does not include optional beneficial use bid

In addition to the total project cost, a second comparison was conducted for the estimate of only dredging operation costs. The WPE dredging operation costs (WPEd) were assumed to be the WPEt less the mobilization costs and additional costs. In addition, the dredging projects for the WPEd were divided into multiple channel sections. Therefore, project cost comparisons contained multiple subsidiary comparisons of varying size and scope. This removed unpredictable additional costs from the estimate, and increased the number and variation of comparisons. Table 4 shows how the projects were divided, and how the dredging costs calculated by the WPEd compared with the government estimate and the winning bid.

Table 4: Dredging Operation Cost Accuracy Comparison

Project Name	GE vs. WB	WPEd vs. WB	WPEd vs. GE
Freeport Harbor	2.6%	10.6%	7.8%
Galveston Ship Channel			
Entrance Channel Sec 1-4	-16.1%	-15.5%	0.7%
Entrance Channel Sec 5-6	-33.6%	-39.0%	-8.1%
Outer Bar Sec 7-9	-38.6%	-22.6%	26.0%
Inner Bar Sec 10-13	-9.5%	-13.3%	-4.2%
Houston Ship Channel Sec 14-15	67.2%	36.5%	-18.4%
Houston Ship Channel Sec 16-19	59.7%	34.3%	-15.9%
Sabine Neches Waterway			
Outer Bar	-4.8%	-7.2%	-2.6%
Outer Bank	-11.0%	-6.9%	4.6%
York Spit Channel	20.4%	-4.9%	-21.0%
West Coast Hopper Maintenance			
San Francisco Main Ship Channel	-8.7%	-18.2%	-10.5%
Grays Harbor	14.4%	-13.6%	-24.5%
Columbia River Entrance	15.1%	10.2%	-4.2%
Columbia River	16.0%	-0.8%	-14.5%
Wilmington Harbor (2014)			
Baldhead Shoal Reach Channel 4	-14.6%	-25.5%	-12.8%
Pascagoula Entrance Channel	54.3%	-46.4%	-65.2%
Wallops Island Beach Restoration	-4.7%	-41.3%	-38.4%
Summation of Dredging Costs:	6.10%	-14.34%	-19.27%
Mean Absolute Percent Error:	23.02%	20.40%	16.43%

As with the total project cost estimate, the Sabine Neches Waterway Outer Bar and Outer Bank projects utilized a $SG_{so,}$ of 1.5 instead of 1.9. This reduced the percent error from approximately +64% to the roughly -7%, as shown above. The Pascagoula Entrance Channel and Wallops Island Beach Restoration projects were again the least accurate estimations with percent error at -46.4% and -41.3% respectively. Since this cost discrepancy was virtually unchanged from the total project cost comparison in Table 3, the additional work costs must have been included in the dredging cost line item of the bid and therefore outside the scope of this program.

Under these varying site conditions, the WPEd remained within acceptable tolerance with a percent error under 50% for all seventeen project sites. A graphical representation of the WPEd comparison data is represented in Figure 6. The project volumes are indicated by shaded bars, and the estimated dredging costs are overlaid on the graph as various markers. It can be seen on Figure 6 that the dredging costs per cubic yard of dredged material calculated by the WPEd, with the exception of the Pascagoula Entrance and Wallops Island projects, typically fell between the winning bid and government estimate cost. This figure also indicates that the accuracy of the program was not affected by the volume of material to be dredged.

Comparing the results of the WPEt analysis in Table 3 to the WPEd analysis in Table 4 show the mean absolute percent error between government estimate and winning bid increased from 13.5% to 23.0%. Conversely, the mean absolute percent difference between the WPE and winning bid remained essentially identical, decreasing slightly from 20.7% to 20.4%. This increased level of accuracy compared to the government estimates indicates that the dredging cost estimation method utilized for this program is reasonable across various project site specifications. In addition, it demonstrates a potential benefit to separating projects into multiple channel sections for cost estimating purposes.

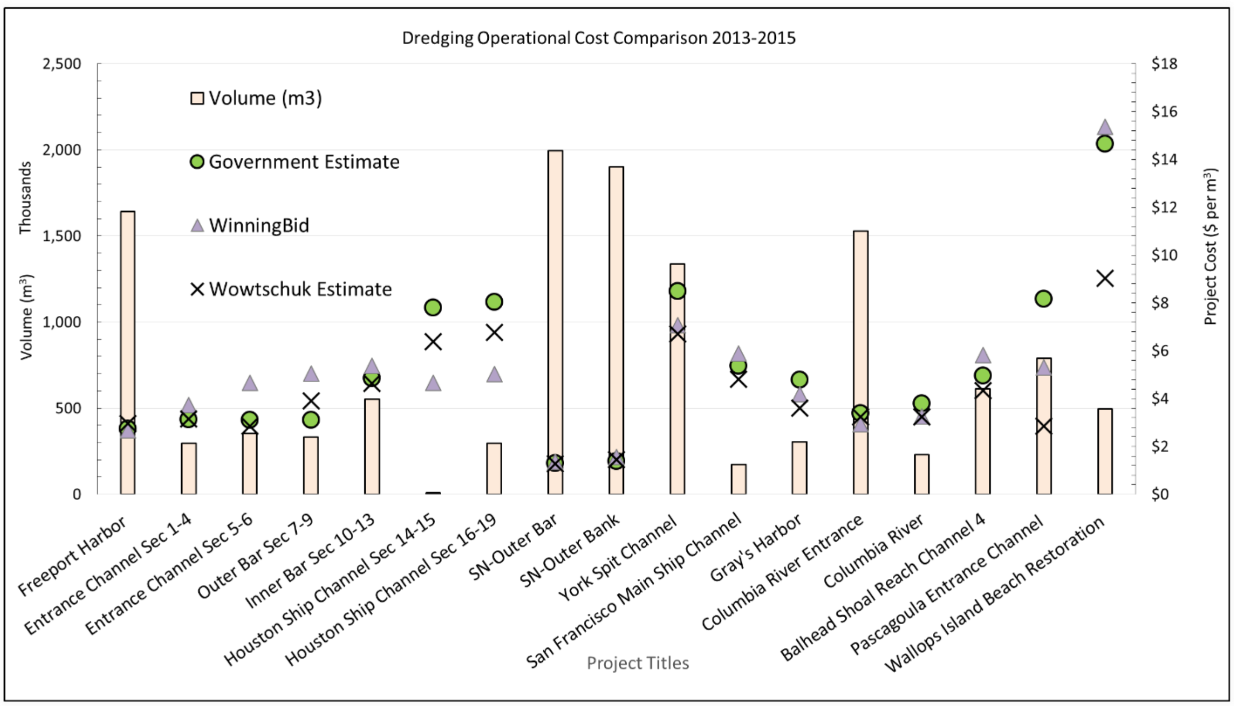

Figure 6: Dredging Operational Costs

Production Comparison

In addition to the cost comparison, the accuracy of the calculated production rates were compared with actual production rates from daily dredging reports. Daily dredging reports were provided by the USACE for the Freeport Harbor and Sabine Neches Waterway projects. These reports specified the hopper dredge used for the project, and production cycle information (USACE, 2013; USACE, 2014). These actual project values were then compared to the program estimated values from the WPE and from a Hopper Specific Program Estimate (HSPE), which used the specifications of the actual hopper dredge used on the project. Table 5 shows the WPE and HSPE hopper specifications, with the actual hopper dredges denoted as “A”, “B”, and “C.” The variables and default settings not relating to the hopper dredge specifications were kept constant between the WPE and HSPE production rate analysis. The comparison of the calculated production rates is shown in Table 6. As expected, the HSPE generated production rates closer to the actual production rates than the WPE. Production rate differences were minimal for Freeport Harbor, completed with hopper dredge “B”. While differences were most prominent in the Sabine Neches project, performed with two different hopper dredges “A” and “C”. These results are consistent with the hopper dredge characteristics from Table 5. The WPE hopper characteristic assumptions are the average specifications of major United States dredges, while dredge “C” is a comparably small dredge and “A” is a large one. This sizeable difference in dredge characteristics creates significant inaccuracy in the production calculations. On the other hand, dredge “B” has specifications similar to an average hopper dredge, resulting in similar WPE and HSPE production rates. The level of accuracy and consistency of results indicated that the program, and the use of Equation 12, is a reasonable estimator of the production rate.

Table 5: Hopper Dredge Specifications

	Wowtschuk Estimate	Hopper Specific Program Estimate		
Dredge Information		**“A”**	**“B”**	**“C”**
Hopper Capacity, m^3 (yd^3)	4052 (5300)	10322 (13500)	3822 (5000)	3058 (4000)
Total Horsepower, kW (HP)	7308 (9800)	8948 (12000)	7718 (10350)	4027 (5400)
Sailing Speed, m/s (kts)	4.12 (8)	4.12 (8)	4.12 (8)	4.12 (8)
Capital Value, $M	18	72	25	14
Equipment Lifespan, yrs	30	30	30	30
Suction Pipe Information				
Suct./Disch. Diameter, m (in)	0.737 (29)	0.965 (38)	0.762 (30)	0.66 (26)
Dragarm Length,m (ft)	30.48 (100)	36.58 (120)	30.48 (100)	30.48 (100)

Table 6: Production Rate Comparison

		Actual	Wowtschuk		Hopper Specific Estimate	
Freeport Harbor (B)				% Difference		%Difference
Production	m^3/hr (yd^3/hr)	832(1088)	732(957)	-12.00%	737(965)	-11.30%
	m^3/cycle (yd^3/cycle)	2,239(2,928)	1,821(2,381)	-18.70%	1,809(2,367)	-19.20%
	m^3/day (yd^3/day)	19,255(25,184)	17,562(22,970)	-8.80%	17,700(23,150)	-8.10%
Cycle time	hr	2.69	2.49	-7.50%	2.45	-9.00%
Cycles		9.6	9.6	11.60%	9.8	14.00%
Sabine Neches- Outer Bar (C)						
Production	m^3/hr (yd^3/hr)	837(1,096)	1,729(2,261)	106.60%	1,101(1,440)	31.60%
	m^3/cycle (yd^3/cycle)	2,008(2,630)	3,258(4,261)	62.60%	2,190(2,864)	9.00%
	m^3/day (yd^3/day)	18,478(24,206)	36,633(47,914)	124.60%	26,431(34,571)	43.00%
Cycle time	hr	2.4	2	-22.50%	1.99	-17.10%
Cycles		9.2	13	40.20%	12.1	31.50%
Sabine Neches- Outer Bank (A)						
Production	m^3/hr (yd^3/hr)	1,909(2,501)	1,526(1,996)	-20.00%	2,396(3,134)	25.60%
	m^3/cycle (yd^3/cycle)	5,493(7,196)	3,258(4,261)	-40.70%	6,062(7,929)	10.40%
	m^3/day (yd^3/day)	45,045(59,009)	36,633(47,914)	-18.90%	57,515(75,227)	27.70%
Cycle time	hr	2.88	2	-26.00%	2.53	-12.10%
Cycles		8.2	12	40.20%	9.5	15.90%

Sensitivity Analysis

Many independent variables and factors are utilized for estimating the production of a dredging project. A sensitivity analysis was conducted for sediment overflow time and overflow ratio impact on production rate. A bivariate sensitivity analysis, shown in Figure 7, was conducted to demonstrate the effect different overflow loss ratios and overflow times will have on the program's production rate. The plot shows that at a lower overflow loss ratio, the production rate increases with longer overflow times, however with a high overflow loss ratio, the production does not significantly increase with more overflow time. This concurs with findings by Bray et al (1997) and Palermo and Randall (1990), which show that there is no significant increased production gained from the overflow of slow settling sediments such as clay and silt.

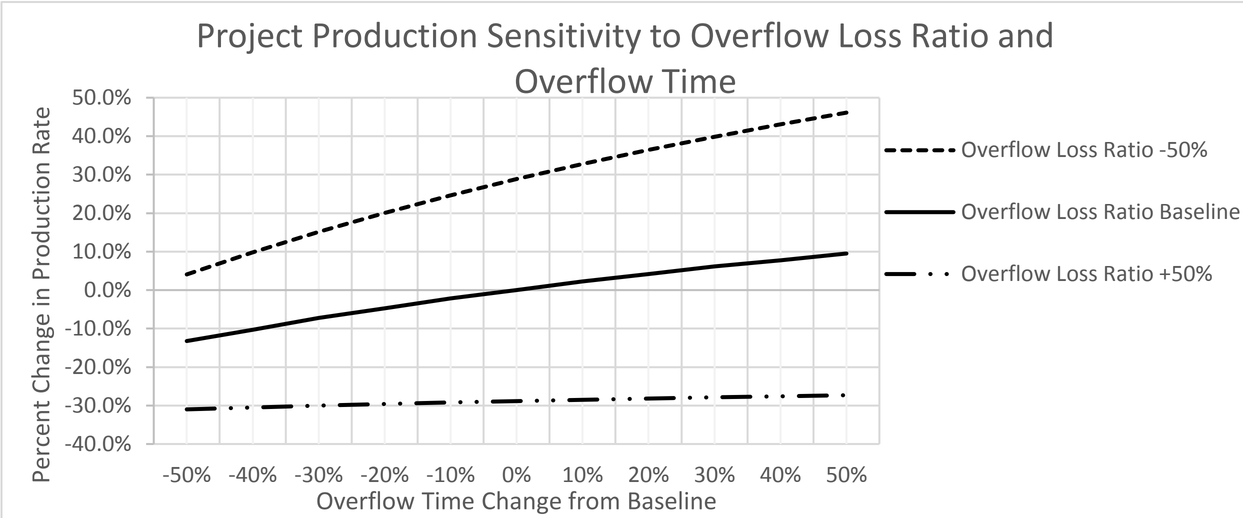

Figure 7: Production Rate Sensitivity to Overflow Loss and Overflow Time

CONCLUSION AND RECOMMENDATIONS

A publically available program for estimating trailing suction hopper dredging costs that builds upon the previous estimating programs created by Belesimo (2000) and Hollinberger (2010), was developed and validated in Microsoft Excel. The program used hopper dredge characteristics and project site specifications to find pump generated head and piping system head losses. The slurry flowrate is taken as the intersection of pump head curve and system losses curve as outlined by Randall (2004). The production rate was calculated using the slurry flowrate, slurry concentration, hopper capacity, overflow losses, and production cycle time based on the method proposed by Bray et al. (1997). The final dredging cost estimate was derived by combining the estimation of the dredging production rate with operating cost assumptions.

The program estimation of total project cost varied by a mean absolute percent error of 21% from the winning bid when the hopper dredge specifications were kept constant, and default values for mobilization and additional costs were utilized. This was slightly above the 13.5% price difference between the government estimate and winning bids over the same projects, but still within an acceptable tolerance. Subdividing the dredging operation cost estimates for these same projects and excluding consideration for the mobilization and additional costs resulted in a mean absolute percent difference of 20% between the program estimation and winning bid. This matched closely to the 23% absolute difference between the government estimate and winning bid.

The production rates calculated by the program with accurate hopper specifications, was shown to compare favorably to the actual production rates from three projects. The accuracy of the cost estimation and production rate estimation indicate this program cost estimate is a reasonable predictor of trailing suction hopper dredge maintenance dredging operations.

While the program estimations were reasonable, there are still limitations. The use of the default hopper dredge characteristics specified in the WPE were convenient for estimating costs when no hopper dredge information was known, but may not accurately estimate the production rates. It is recommended to not only include as much hopper dredge and project site information as available, but to confirm the cross-reference default values with actual project site characteristics. As indicated by the Pascagoula Entrance Channel and Wallops Island Beach Restoration, the program was not proven to be accurate for estimating costs of projects consisting of new dredging work or beneficial use dredging. This was due to the added costs associate with additional equipment and personnel required to complete the job. Finally, the default values for overflow time and overflow losses, were based on a reasonable assumption that may be applied to a broad range of projects and will not likely represent actual overflow figures for a project. As with all program values, it is recommended that users gather the necessary hopper and sediment characteristics and match program defaults accordingly.

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THE ESTIMATION OF PRODUCTION AND LOCATION OF PUMPS FOR A CUTTER SUCTION DREDGE USING A LONG DISTANCE PIPELINE

Chungkuk Jin[1] and Robert E. Randall[2]

ABSTRACT

Hydraulic dredging uses centrifugal pumps to transport dredged material and often requires a long distance pipeline and additional booster pumps. It is important to locate each pump at an optimum location along the pipeline and to estimate the dredge production. This paper describes a dredging-production-estimation program for a cutter suction dredge developed at the Center for Dredging Studies. The program objective is to determine the best location for each pump, including a main pump, a ladder pump, and booster pumps, and to estimate production. The ladder pump and the booster pumps are located with the consideration of pump cavitation and the power limitation of the pumps, respectively. The corresponding pump head curve, the system head curve, the available net positive suction head (NPSH) curve, the required NPSH curve, and the critical flow rate are used for determining the operating flow rate and production. The input for the program includes the water depth, the location of the main pump, pump rpm, pump horsepower, specific gravity of the slurry, and the length of a discharge pipeline. Correspondingly, the program estimates production as well as the locations of the main pump, the ladder pump and booster pumps for given operating conditions.

Key words: Dredging, cutter suction dredge, production estimation, ladder pump, booster pump

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INTRODUCTION

The development of the dredging industry, the increase in population, and larger draft vessels contribute to a rise in the demand of dredging for various purposes. Dredges build and maintain artificial islands, harbors, and channels (MacLeod and Butler 1979). Dredging increases the water depth of ship entrance channels in order to prevent a vessel from encountering the channel bottom. A dredge is also used for mining to obtain essential industrial materials such as gold, tin, rutile, etc. (Jewett et al. 1999, Hennart 1986).

The cutter suction dredge is one type of hydraulic dredge that is widely used in dredging navigable waterways (Randall et al. 2008). Because the cutter suction dredge can perform both excavation and transportation, its efficiency is higher than other types of dredges (Tang et al. 2009). The cutter suction dredge shown in Figure 1 uses a rotating cutter in front of the suction inlet to excavate bottom materials. The excavated material enters the pipe inlet on the suction side of a centrifugal pump and is transported to a barge or a placement site through a pipeline (Paulin et al. 2013). The maximum operating water depth for the cutter suction dredge without a ladder pump or submerged pump is approximately 30-35 m (Jukes et al. 2011; Pauline et al. 2014), but deeper operating depths are possible by adding a ladder pump.

Figure 1. Cutter suction dredge "California" showing spud carriage and pipeline (Courtesy of Great Lakes Dredge and Dock).

It is important to estimate production of the dredged material (Miedema 2008). For the cutter suction dredge, production is a function of the operating flow rate, the solids concentration by volume, and the dredging efficiency. In addition, the operating flow rate is highly related to the critical flow rate, the net positive suction head (NPSH), and pump characteristics. Turner (1996) estimates production for hydraulic dredges based on these parameters. In order to prevent pump cavitation and overcome the power limitation of any individual pump, the main pump, ladder pump, and booster pumps must be located properly.

A dredging-production-estimation program for the cutter suction dredge is described in this paper. This program estimates the production of dredged material and calculates whether a ladder pump is necessary to prevent pump cavitation, and it determines the locations of booster pumps to overcome the pump power limitation. This program also evaluates the operating rpm and horsepower of each pump.

For seven cases, the operating flow rate depends on the critical flow rate, the intersection flow rate of the pump head curve and the system head curve, and the intersection flow rate of the required net positive suction head ($NPSH_R$) curve and the available net positive suction head ($NPSH_A$) curve. In addition, production is determined from the calculation of the operating flow rate. The locations of booster pumps and the ladder pump are calculated using the energy equation or, as it is sometimes called, the modified Bernoulli equation.

PRODUCTION MODEL

Centrifugal dredge pumps transport dredged material through a long distance pipeline to the placement site. A ladder pump, used to prevent cavitation, is installed on the ladder that supports the suction pipe and booster pumps are located along the discharge pipeline to provide sufficient power to pump the dredged material to the placement site.

Production Estimation

Turner (1996) presents an equation for estimating the production of a hydraulic dredge. The solids production (P) of the hydraulic dredge is

$$P = AQC_{vave} = AQC_{v\max}E_D \tag{1}$$

where A is a conversion factor, Q is the average flow rate (m^3/hr), C_{vave} is the average slurry concentration by volume, C_{vmax} is the maximum slurry concentration by volume, and E_D is dredging efficiency based on the dredge advance mechanism. The conversion factor A for production expressed in SI units in m^3/hr is 0.222 and for English units of cy/hr it is 0.297. Dredging efficiency is different with respect to the spud type. The common dredging efficiency of two fixed spuds and spud carriage is 50% and 75%, respectively.

Slurry composition is the amount of dry solids divided by total amount of slurry with respect to volume or weight. In dredging, the concentration by volume (C_v) is

$$C_V = \frac{SG_m - SG_f}{SG_S - SG_f} \tag{2}$$

where SG_m, SG_f (1.0 for water and 1.025 for sea water), and SG_S are specific gravity of the slurry mixture, fluid, and solids, respectively. Sand, silt, and clays have a typical specific gravity of 2.65. In-situ specific gravity of sediment at the bottom of a water body normally ranges between 1.3 and 2.1 (Randall and Yeh, 2013).

In-situ specific gravity (SG_{insitu}) is determined from an undisturbed sediment sample, and it is normally calculated using the specific gravity of the solids (SG_s) and the concentration by volume in dredging calculations. Simply, in-situ specific gravity is

$$SG_{insitu} = SG_S \times \text{percent} + SG_f \times (1 - \text{percent}) \tag{3}$$

where percent means percentage of solid divided by the whole sample volume. The in-situ specific gravity is then used to calculate the in-situ production.

The flow rate of a dredge pump is an important factor for determining the production. The operating flow rate is determined by the intersection of the pump head curve and the system head curve. However, the operating flow rate must be greater than the critical flow rate that a fixed bed starts to move. In addition, flow rate must be less than the flow rate value at the intersection of the $NPSH_R$ curve and the $NPSH_A$ curve in order to prevent cavitation.

Critical Velocity

The critical velocity (V_c) is an important parameter to confirm the minimum flow rate that keeps sediment particles moving along the bottom of a pipeline. If the operating velocity in the pipeline is lower than the critical velocity, the sediment settles to the bottom of the pipe and may lead to pipeline clogging and plugging. Moreover, clogging will disrupt the dredging operation, reduce production, and the dredging process eventually shuts down. The critical velocity is highly related to the specific gravity of both the solid and the fluid, the median grain size, particle settling velocity and the inside diameter of the pipeline. There are two ways to determine the critical velocity in a horizontal pipeline: one developed by Wilson et al (1992) and another developed by Matousek (1997). Figure 2 illustrates the Wilson et al (1992) nomograph used to evaluate the critical velocity. In addition, Matousek (1997) developed an equation for the critical velocity based on the nomograph developed by Wilson et al (1992):

$$V_C = \frac{8.8\left[\dfrac{\mu_S(SG_S - SG_f)}{0.66}\right]^{0.55} D^{0.7} d_{50}^{1.75}}{d_{50}^2 + 0.11D^{0.7}} \tag{4}$$

where D is the inside diameter (m) of the pipeline, d_{50} is the median particle diameter (mm), and μ_s is the mechanical friction coefficient. The recommended value of the mechanical friction coefficient that best matches Figure 2 is 0.44.

The critical velocity increases for an inclined pipeline. Wilson and Tse (1984) developed an equation from experimental data to describe an additional term for an inclined pipeline as shown in Figure 3. The term Δ_D is a function of the angle of inclination. Using Δ_D, an additional effect from the inclination angle can be determined as follows:

$$V_C(\text{inclined}) = V_C(\text{horizontal}) + \Delta_D\left(\sqrt{2g(SG_S - 1)\,D}\right) \tag{5}$$

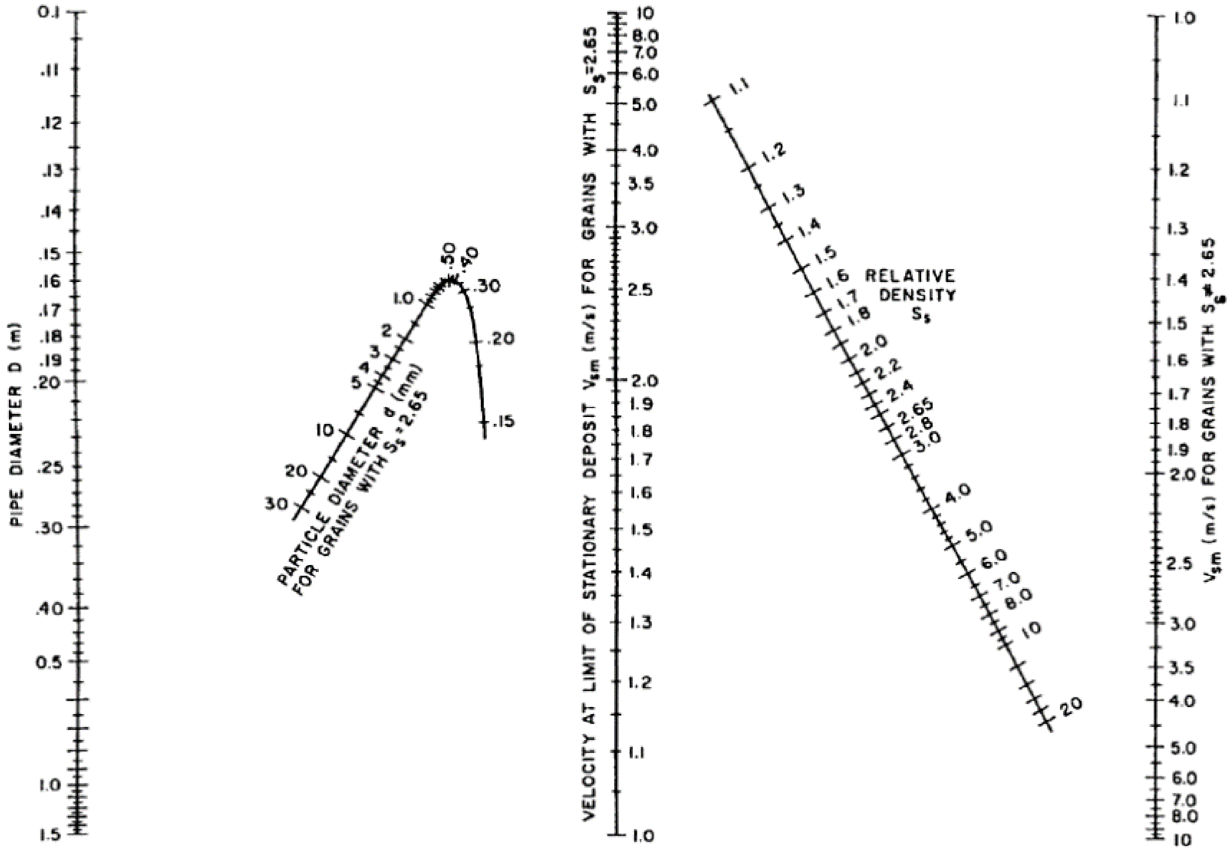

Figure 2. Nomograph for the evaluation of the critical velocity (Wilson et al, 1992).

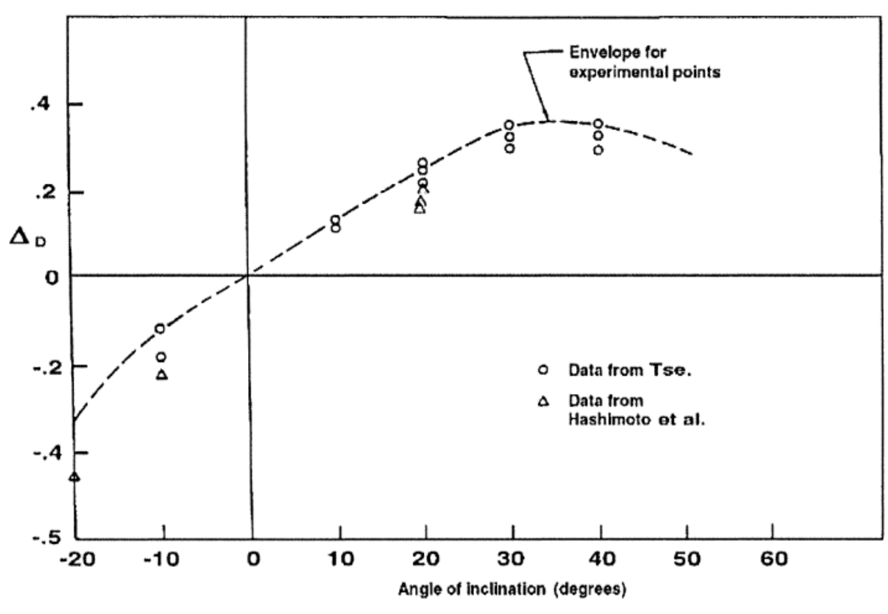

Figure 3. The effect of the inclined angle of the pipeline on the critical velocity (Wilson and Tse, 1984).

Calculation of Head Losses

In order to determine the friction head loss, which is the major component of losses in the system, the derivation of the hydraulic gradient (i_m) is required. It is the head loss due to friction per unit length of the pipeline. Wilson et al (1992) developed the hydraulic gradient (i_m), which is

$$i_m = \frac{fV^2}{2gD} + 0.22(SG_S - 1)V_{50}^{1.7} C_V V^{-1.7} \tag{6}$$

where f is the friction factor, V is the average velocity in the pipeline, and V_{50} is the fluid velocity at which 50% of solids are suspended. Moody (1944) developed a chart that is widely used in the determination of the friction factor, which is a function of Reynolds number and relative roughness of the pipeline. Later, Swamee and Jain (1976) developed a convenient equation for the evaluation of the friction factor. This equation is valid if the Reynolds number in the pipeline is between 5×10^{-3} and 10^8, and the relative roughness (e/D) is between 10^{-6} and 10^{-2}. The friction factor equation is

$$f = \frac{0.25}{\left[\log\left(\frac{e}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^2} \tag{7}$$

where e is the absolute roughness of the pipeline, D is the inside diameter, log is to the base 10 and Re is the Reynolds number. The velocity (V_{50}) that suspends 50% of solids in the fluid is

$$V_{50} = w\sqrt{\frac{8}{f}} \cosh\left(\frac{60d_{50}}{D}\right) \tag{8}$$

where w is the particle-associated velocity and defined as,

$$w = 0.9V_T + 2.7\left[\left(\frac{SG_S - SG_f}{SG_f}\right)g\nu\right]^{\frac{1}{3}} \tag{9}$$

where V_T is the particle terminal velocity, g is gravitational acceleration, and ν is the kinematic viscosity of the fluid.

There are some minor losses because of the entrance loss, pipe joints, bends, and swivels in the system. Since the length of a pipeline can reach thousands of meters leading to the high friction loss in dredging process, minor losses are normally far less than the friction loss (i.e. less than 10%). The minor loss (h_m) is

$$h_m = K\frac{V^2}{2g} \tag{10}$$

where K is the minor loss coefficient, V is the average velocity in the pipeline and g is gravitational acceleration (9.81 m/s^2 or 32.2 ft/s^2). Minor loss coefficients are found in basic fluid dynamics (Munson et al, 1998) or dredging short course notes by Randall (2016).

Evaluation of System Head and Available Net Positive Suction Head

The energy equation, also known as the modified Bernoulli equation, evaluates the system head, which is the head provided by one or more pumps in the system. Figure 4 illustrates the basic system for the cutter suction dredge. The modified Bernoulli equation for this system with respect to slurry is

$$\frac{p_1}{\gamma_m}+\frac{V_1^2}{2g}+z_1+h_P=\frac{p_3}{\gamma_m}+\frac{V_3^2}{2g}+z_3+h_L \tag{11}$$

where p is pressure, γ_m is specific weight of the slurry, V is the average velocity in the slurry pipeline, h_P is the head provided by the pumps, z is the elevation above the channel bottom, and h_L is the losses due to friction and minor losses. If the main pump is the only pump installed, h_P is the head provided by the main pump. If more pumps are added, then the total head provided by all pumps has to meet h_P.

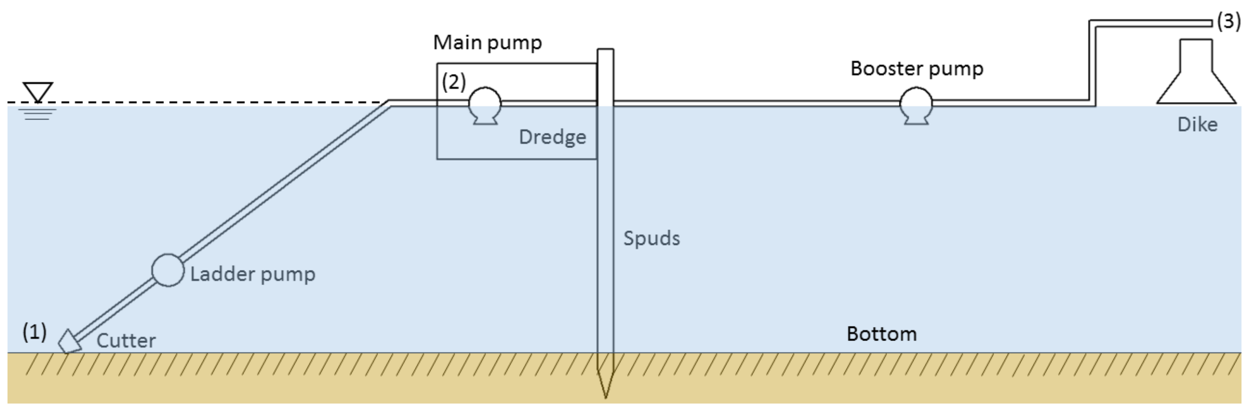

Figure 4. The basic configuration of hydraulic dredging system using the cutter suction. dredge.

The calculation of $NPSH_A$ determines whether the pump cavitates and is expressed as

$$NPSH_A=\frac{p_a}{\gamma_m}-\frac{p_v}{\gamma_m}+\frac{d}{SG_m}-z_2-h_L \tag{12}$$

where p_a is the atmospheric pressure, p_v is the water vapor pressure, d is the water depth, z_2 is the vertical distance between point (1) and (2), and h_L is the losses in the pipeline between point (1) and (2). The datum is the bottom of the ship channel. The elevation (z_2) and water depth (d) are the same only when the dredge pump is located at the water surface

The series operation of ladder, main, and booster pumps

In specific situations, additional pumps are required to transport the dredged material not only with the proper production but also without pump cavitation. In this case, several pumps operate in series. Higher head is developed with a series arrangement of pumps, while maintaining a desired flow rate. The intersection point of the pump head curve and the system head curve determine the operating head and flow rate. Figure 5 shows an example of the pump head curve and the system head curve. The system head curve is calculated using the energy equation, and the pump head curve is the pump's unique characteristics provided by the dredge pump manufacturer. If two or more pumps are in series, then it is required to add heads of each pump at each flow rate and then find the intersection point. The flow rate and head at the intersection point are the appropriate operating flow rate and head.

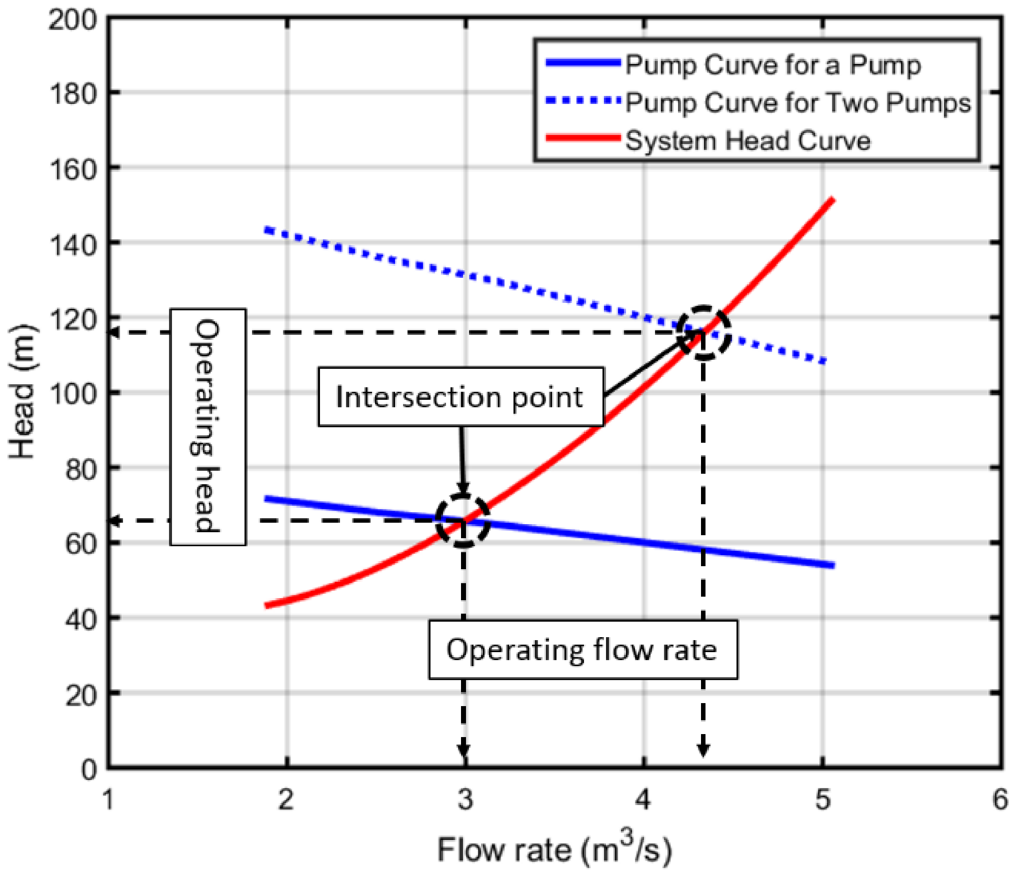

Figure 5. Pump head curve (blue) and system head curve (red) for the series operation of two pumps.

RESULTS AND DISCUSSIONS

The previous Figure 4 illustrates the basic configuration of the cutter suction dredge. Table 1 gives the major variables used for seven cases, and Table 2 gives constant parameters used in the simulation. Centrifugal pumps are used in the simulation and the pipeline has an inside diameter of 0.76 m. A fixed two-spud system or a spud carriage advances the cutter suction dredge along the centerline of the dredged channel.

Table 1. Description of dredging simulation cases.

Case number	Water depth (m)	Pump location (m) (z = 0 at water surface)		RPM (Horsepower)	Specific gravity of slurry	Discharge pipeline length (m)
		MP	LP			
1	10	0	NA	300 (4,500)	1.2	1,000
2	20	0	NA	300 (4,500)	1.2	1,000
3	20	0, -3, -6, -9	NA	300 (4,500)	1.2	1,000
4	20	0	-10	MP: 300 (4,500) LP: 150 (1,500)	1.2	1,000
5	20	-6	NA	300 (4,500)	1.15, 1.20, 1.25, 1.30	3,000
6	20	0	-10	300 (4,500)	1.2	15,000
7	10	0	NA	350 (6,000)	1.2	10,000

* Main pump: MP, Ladder pump: LP

Table 2. Basic parameters for the simulation.

Parameter	Value
Dike height	3 m
Suction pipeline inside diameter	0.86 m
Discharge pipeline inside diameter	0.76 m
Suction pipeline inclination from bottom	20 degrees
Discharge pipeline inclination from bottom	0 degree
Suction minor loss coefficient	1
Discharge total minor loss coefficient	5
Specific gravity of in-situ solids	2.0
Specific gravity of fluid	1.03

Example 1: Cutter Suction Dredge in Shallow Water

In example 1, the water depth is 10 m in order to simulate dredging in shallow water. The corresponding length of the suction pipeline is 29.2 m and has an inclination angle of 20 degrees. The horizontal discharge pipeline has a length of 1 km, and the main pump is located at the water surface with no ladder pump. The specific gravity of slurry is a constant 1.2. Figure 6 (a) and (b) show the intersection of the pump head curve and the system head curve and the intersection of the $NPSH_R$ curve and the $NPSH_A$ curve for example 1. The operating flow rate is the intersection of the pump head curve and the system head curve (Q_{PCSH}). However, if the flow rate at the intersection of the $NPSH_R$ curve and the $NPSH_A$ curve (Q_{NPSH}) is lower than Q_{PCSH}, the operating flow rate should be equal to or less than Q_{NPSH} to prevent pump cavitation. This means that the operating flow rate should be within the range where the $NPSH_A$ is higher than the $NPSH_R$, so that pump cavitation does not occur. As shown in Figure 6, Q_{PCSH} is 3.1 m^3/s, which is lower than Q_{NPSH} that is 3.3 m^3/s. Thus, Q_{PCSH} is the operating flow rate, and no pump cavitation occurs. In addition, the critical flow rates for both suction and discharge pipelines are lower than Q_{PCSH}. Thus, solids do not settle on the bottom of the pipeline.

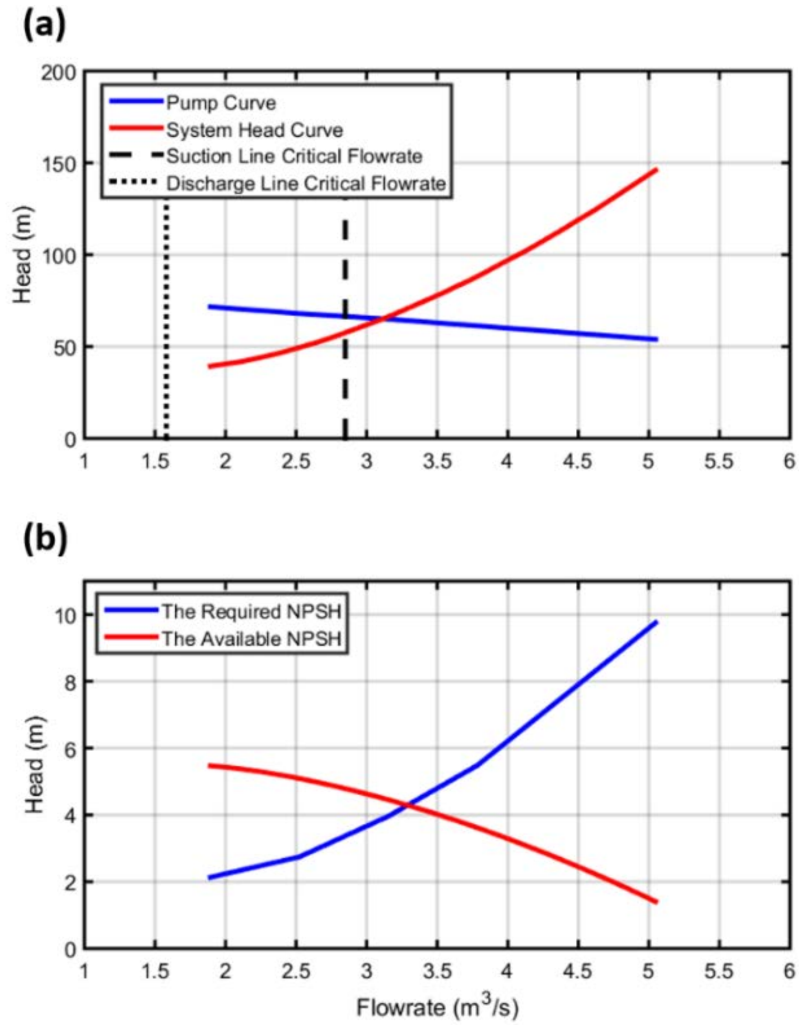

Figure 6. The intersection of the pump head curve and the system head curve (a) and the intersection of the $NPSH_R$ curve and the $NPSH_A$ curve (b) for example 1.

Example 2: Cutter Suction Dredge in Deep Water

When dredging in deep water, one of the most critical problems is cavitation. Pump cavitation normally happens when pressure in the suction inlet is low due to the low $NPSH_A$. In example 2, the water depth is 20 m and the length of the suction pipeline is 58.5 m. Other parameters are same as in example 1 in order to demonstrate the effect of the water depth on pump cavitation.

Figure 7 (a) shows the intersection of the pump head curve and the system head curve, and Figure 7 (b) shows the intersection of the $NPSH_R$ curve and the $NPSH_A$ curve for example 2. As shown in Figure 7 (a), Q_{PCSH} is 3.0 m^3/s, which slightly decreases with the increase in the water depth compared with example 1. Even though Q_{PCSH} is higher than the critical flow rate of the suction pipeline, the difference between them is within 4 %. In this case, the dredged material will not settle on the bottom of the suction pipeline. In addition, as shown in Figure 7 (b), the $NPSH_R$ is always higher than the $NPSH_A$ in a flow rate range between 1.9 m^3/s to 5.1 m^3/s, where pump cavitation always happens regardless of Q_{PCSH}.

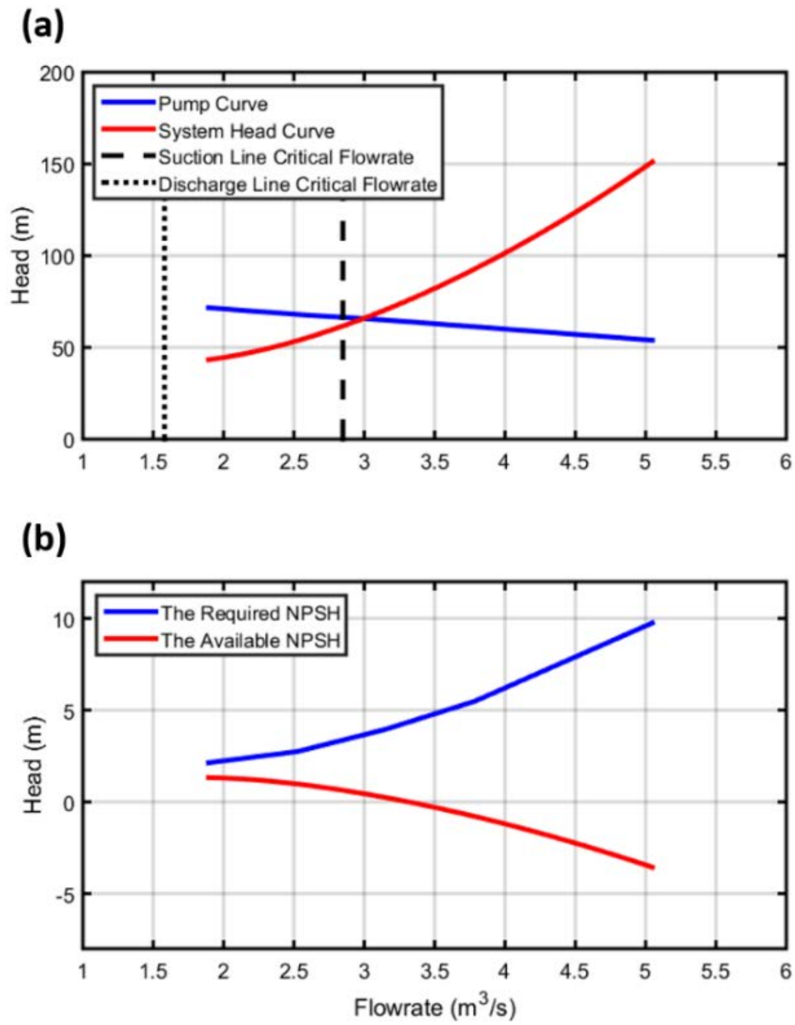

Figure 7. The intersection of the pump head curve and the system head curve (a) and the intersection of the $NPSH_R$ curve and the $NPSH_A$ curve (b) for example 2.

Examples 3 and 4: Prevention of Pump Cavitation

Pump cavitation leads to the damage of a pump shaft, erosion of the impeller blades, reduced head and efficiency, and a decrease in production. There are several suggested solutions to prevent pump cavitation. Two feasible methods are to lower the position of the main pump and to install a ladder pump. Figure 8 shows the effect of the main pump locations on the $NPSH_A$ at a water depth of 20 m. In example 3, submerged depths of the main pump are 0 m, 3 m, 6 m, 9 m while the other parameters are same as for example 2. The $NPSH_A$ increases as the elevation of the main pump decreases. The Q_{NPSH} is 3.1 m^3/s, 4.0 m^3/s, and 4.6 m^3/s at the submerged depth of 3 m, 6 m, and 9 m, respectively. When the submerged depth of the main pump is 3 m, Q_{NPSH} is higher than Q_{PCSH} that is 3.0 m^3/s. Thus, when the submerged depth of main pump is 3 m and Q_{PCSH} is the operating flow rate, there is no pump cavitation.

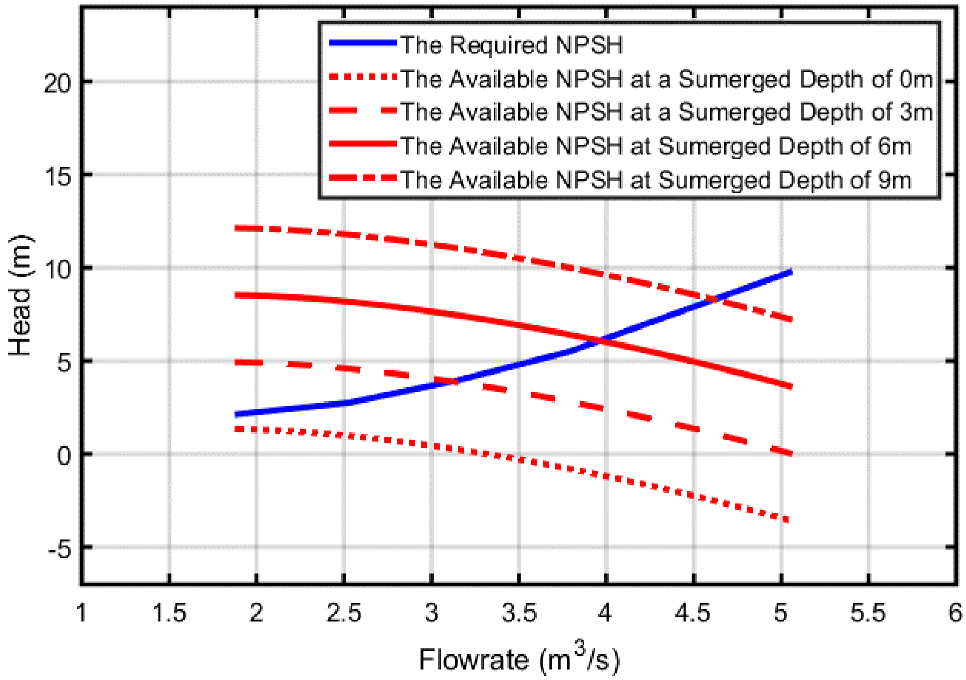

Figure 8. The NPSH$_A$ curves with respect to submerged depths of the main pump in example 3.

Figure 9 shows the effect of the ladder pump installation. In example 4, the ladder pump is at a submerged depth of 10 m, which is the intermediate position of the suction pipeline. Normally, the ladder pump has the same diameter as the main pump, but with lower pump rpm and horsepower. The purpose of the ladder pump installation is to deliver slurry to the main pump with positive pressure. The main pump is located at the water surface. Pump rpm and horsepower for the main pump are 300 RPM and 4,500 HP, respectively; while a 1,500 HP ladder pump is operated at 150 rpm. The ladder pump installation contributes to both an increase in the flow rate and a higher total head provided by the two pumps. As shown in Figure 9 (a), Q_{PCSH} is 3.0 m^3/s without the ladder pump. The flow rate increases to 3.3 m^3/s after the ladder pump is installed, which corresponds to 10 percent increase in the flow rate. Compared with the main pump that provides a head of 64.1 m, the ladder pump provides a smaller head of 10.9 m because of its lower pump rpm and horsepower. As shown in Figure 9 (b), Q_{NPSH} for the ladder pump is 4.7 m^3/s, which is higher than Q_{PCSH}. Thus, no cavitation occurs.

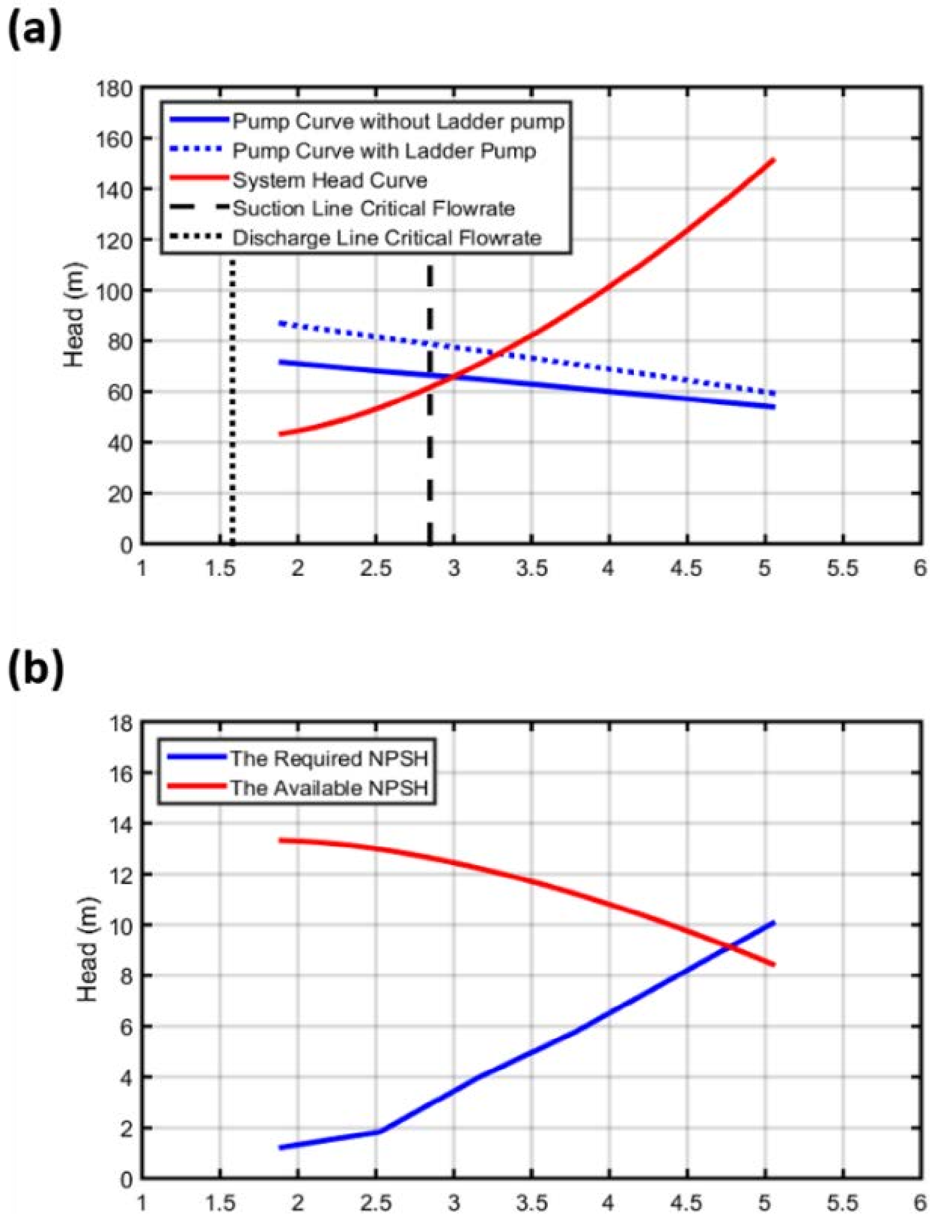

Figure 9. The intersection of the pump head curve and the system head curve before and after adding the ladder pump (a) and the intersection of the $NPSH_R$ curve and the $NPSH_A$ curve for the ladder pump (b) for example 4.

Example 5: Effects of Specific Gravity of Slurry and Production

The specific gravity of the slurry is a major factor for determining the operating flow rate and production. Figure 10 (a) and (b) show the effect of the specific gravity of the slurry on solid and in-situ production as a function of the length of the discharge pipeline. In example 5, thirty different lengths of the discharge pipeline ranging from 100 m to 3,000 m are used to analyze the effect of the discharge pipeline length on the production. Average values used for the specific gravity of slurry are 1.15, 1.2, 1.25, and 1.3.

As shown in Figure 10, there are three phases for production. The first phase is the range that Q_{NPSH} is lower than Q_{PCSH} as the length of the discharge pipeline is short. In this phase, Q_{NPSH} is the operating flow rate to prevent pump cavitation, and production is constant regardless of the variation of the discharge pipeline length. For a slurry specific gravity of 1.30, the solid and in-situ production is 1,702 m^3/hr and 2,844 m^3/hr respectively until Q_{NPSH} is lower than Q_{PCSH}. Higher production is obtained as specific gravity of slurry increases in the first phase. The second phase is the range where Q_{NPSH} is higher than Q_{PCSH}. In this phase, production decreases as the length of the discharge pipeline increases. As the specific gravity of slurry increases, production has a tendency to decrease sharply with an increase in the pipeline length. The third phase is a range where Q_{PCSH} is lower than the critical flow rate in the discharge pipeline. In this phase, the solids dropout on the bottom of pipeline; thus, there is no production. The maximum length of the discharge pipeline for the solid and in-situ production decreases with an increase in the specific gravity of slurry. The lengths of the discharge pipeline that reaches zero production are 2,600 m, 2,200 m, 1,900 m, and 1,600 m for a series of the specific gravity of slurry of 1.15, 1.2, 1.25, and 1.3, respectively.

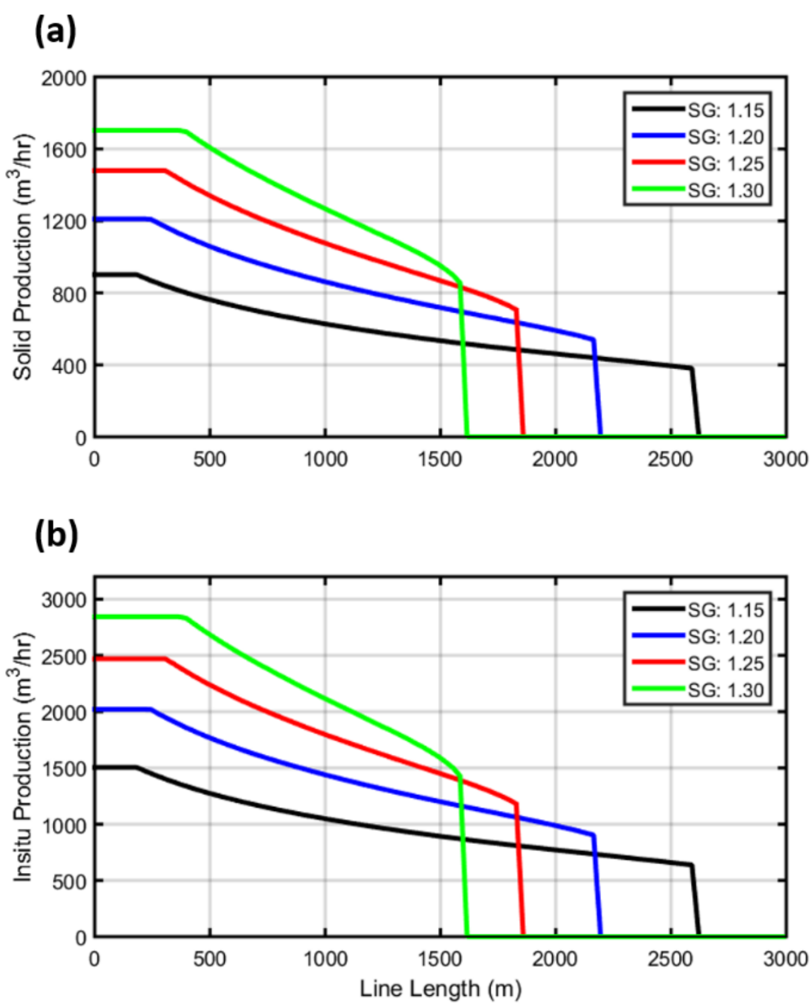

Figure 10. Solid production (a) and in-situ production (b) with different lengths of the discharge pipeline for example 5.

Example 6: Locations for Booster Pumps for a Long Distance Pipeline.

In example 6, the length of the discharge pipeline is 15 km, and it is unlikely for a single main pump to transport the dredged material that distance to a placement site. Booster pumps are installed for a long discharge pipeline due to the power limitation of a main pump. The size and specification of booster pumps are normally same as those of the main pump and provide the same head as the main pump. The water depth is 20 m, so the ladder pump is at a water depth of 10 m to prevent pump cavitation.

Figure 11 (a) shows the locations of the booster pumps operating at 300 rpm for a long distance pipeline with five booster pumps. The minimum number of required booster pumps is five to maintain Q_{PCSH}. The main pump provides the head of 69.8 m. The minimum head allowed for each booster pump is 15 m. Thus, the booster pumps are located at the distance where the head in pipeline reaches 15 m. After the dredged material arrives at the placement area and exits the discharge pipeline, the head reduces to zero (atmospheric pressure). The operating flow rate is 2.2 m^3/s and the production is 1044 m^3/hr.

As higher production is required, increases in rpm and/or the number of booster pumps are required. Figure 11 (b) shows the relationship between the number of booster pumps and production as well as the number of booster pumps and the head provided by each pump. Q_{PCSH} increases by installing more booster pumps, which leads to higher production. On the other hand, the head provided by each pump decreases with the number of booster pumps.

Example 7: The Locations of Booster Pumps for the Pipeline with Complex Geometry

There are some complex cases for the pipeline arrangement in real situations. Figure 12 shows the example of the complex arrangement of a pipeline. In this case, many factors can have negative influences on production of the dredged material. As mentioned in the section on the production model, the critical flow rate and hydraulic gradient, i_m, change with respect to an angle of inclination of the pipeline. In this case, the variation of i_m determines the proper location of the booster pumps.

Figure 13 shows the location of booster pumps. Because the variation of the inclination angle of the pipeline is small until the length of the pipeline reaches 9 km, there is no remarkable change in the slope of head loss. As the inclination angle of the pipeline increases to 10 degrees after 9 km, the head loss sharply decreases with the length of pipeline. The inclination angle of the pipeline determines the optimum location of booster pumps.

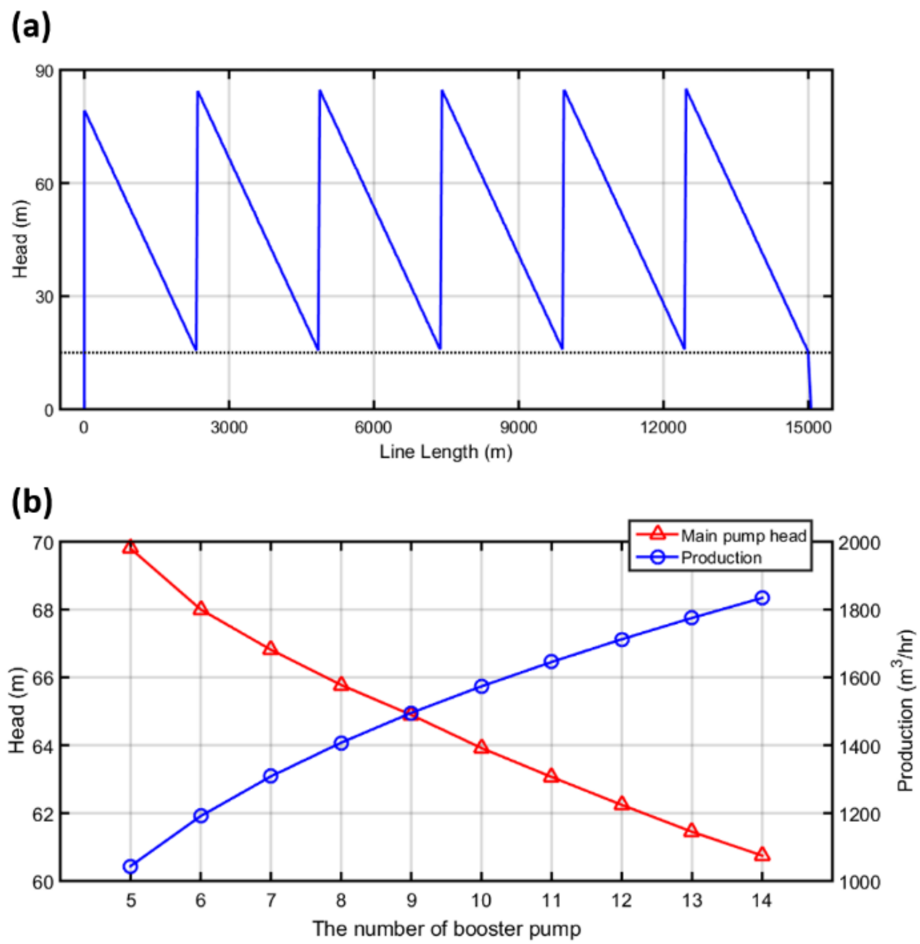

Figure 11. The locations of booster pumps for a long pipeline (a) and the flow rate and the distance between booster pumps with respect to pump rpm (b) for example 6.

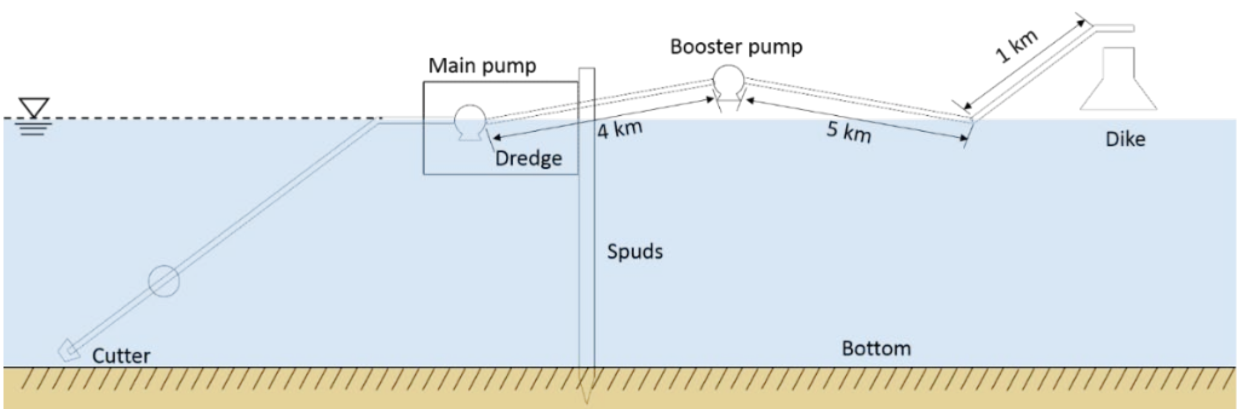

Figure 12. The schematic drawing for example 7.

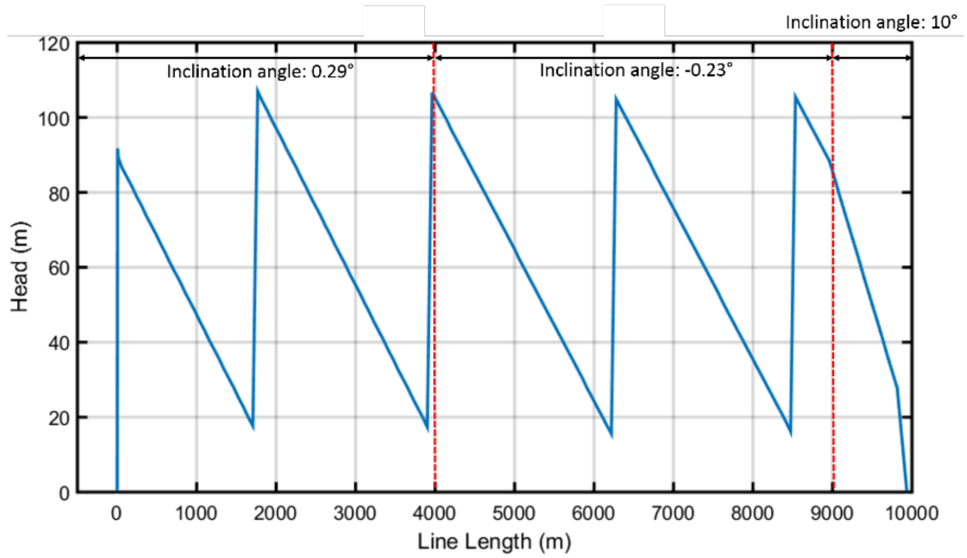

Figure 13. The locations of booster pumps for example 7.

CONCLUSION

A dredging-production-estimation program for a cutter suction dredge considers the critical flow rate, the pump head curve, the system head curve, the $NPSH_A$ curve, and the $NPSH_R$ curve to determine the operating flow rate. The operating flow rate also depends on the specific gravity of slurry. Production is a function of the operating flow rate, the concentration of solids by volume, and dredging efficiency (fixed spuds or spud carriage). Production decreases as the length of the discharge pipeline increases or as the specific gravity of slurry decreases. Dredging in deep water of 20 m causes main pump cavitation. Locating the main pump at a lower position or installing a ladder pump is a good solution. The long distance pipeline causes the power limitation of the main pump, which is resolved by installing booster pumps. The booster pumps are located along the pipeline in order to maintain the minimum head that prevents pump cavitation in the system. The locations of booster pumps depend on the losses in the system. The friction loss is a main parameter to determine the location of booster pumps, which varies with respect to the vertical angle of inclination of the pipeline.

NOMENCLATURE

Symbol	Definition
$\triangle_D$	Coefficient from Figure 3
γ_m	Specific weight of slurry (N/m^3)
μ_S	Mechanical friction coefficient
ν	Kinematic viscosity of the fluid (m^2/s)
A	Conversion factor (0.222 for m^3/hr)
C_{vave}	Average concentration by volume
C_{vmax}	Maximum concentration by volume
C_v	Concentration by volume
D	Inside diameter of pipeline (m)
d	Water depth (m)
d_{50}	Median particle diameter (mm)
E_D	Dredging efficiency
e	Absolute roughness of the pipeline (m)
f	Friction factor
g	Gravity acceleration (9.81 m/s^2)
h_L	The losses due to friction and minor losses (m)
h_m	Minor loss (m)
h_P	Head provided by pumps (m)
i_m	Hydraulic gradient (Head loss due to friction per unit length of the pipeline) (m/m)
K	Minor loss coefficient
NPSH	Net positive suction head (m)
$NPSH_A$	Available net positive suction head (m)
$NPSH_R$	Required net positive suction head (m)
P	Solid or in-situ solid production (m^3/hr)
p	Pressure (N/m^2)
p_a	Atmospheric pressure (N/m^2)
p_v	Vapor pressure (N/m^2)
percent	Percentage of solid divided by the whole sample volume
Q	Average flowrate (m^3/s)
Q_{PCSH}	Intersection of the pump head curve and the system head curve (flow rate) (m^3/s)
Q_{NPSH}	Intersection of the required NPSH and the available NPSH (flow rate) (m^3/s)
Re	Reynolds number
SG_f	Specific gravity of fluid
SG_{Insitu}	In-situ specific gravity
SG_m	Specific gravity of slurry
SG_S	Specific gravity of solid
V	Average velocity in the pipeline (m/s)
V_C	Critical velocity (m/s)
V_T	Particle terminal velocity (m/s)
V_{50}	Velocity at which 50% of solids are suspended by the fluid (m/s)
w	Particle-associate velocity (m/s)
z	Elevation (m)
z_2	Vertical distance between point (1) and (2) (m)

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AIMS & SCOPE OF THE JOURNAL

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$$y = a + b + cx^2 \tag{1}$$

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