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AIMS & SCOPE OF THE JOURNAL

The *Journal of Dredging* is published by the Western Dredging Association (WEDA) to provide dissemination of technical and project information on dredging engineering topics. The peer-reviewed papers in this practice-oriented journal will present engineering solutions to dredging and placement problems, which are not normally available from traditional journals. Topics of interest include, but are not limited to, dredging techniques, hydrographic surveys, dredge automation, dredge safety, instrumentation, design aspects of dredging projects, dredged material placement, environmental and beneficial uses, contaminated sediments, litigation, economic aspects and case studies.

UNDERWATER ROCK BLASTING FOR DREDGING

Carlos A. Reyes R.[1]

ABSTRACT

The dredging industry nowadays is facing fast growing challenges. Most ports and waterways are involved in deepening projects to maintain safe channels and harbors to dock bigger ships offering facilities near good's distribution centers at large cities. These projects require dredging of hard materials that is not always feasible without previous fragmentation by blasting. Rock hardness and the rock geotechnical characteristics at any dredging site have a major influence on the performance of a dredge. The rock characteristics must be identified prior to commencement of work to determine whether a dredge can handle the rock removal and how the dredge's output would be affected. There is no standard, universal system of descriptors that will directly indicate, or infer, the dredge ability of a rocky sub-bottom. Virtually all geotechnical engineering soil/rock classification systems were developed for land-based earthwork construction and are not, therefore, directly applicable to the needs of the dredging industry.

Underwater blasting covers a very wide range of projects under extremely varied conditions. It includes the removal of rock for deepening harbors and channels, building canals and levees, laying pipelines, cutting piles and other specialized jobs which must be accomplished underwater. In underwater blasting the final result must be obtained with the first shot, since the secondary drilling and blasting are extremely expensive and difficult. A bad shot causes tremendous problems. This paper presents an approach to designing and performing underwater blasting successfully to fragment a rock mass to be dredged. Correlation of material hardness and unconfined compressive strength with the energy implied within a given amount of explosive, and with the geometric parameter of the drilling pattern seems to be a useful means to ensure results on one time shots.

INTRODUCTION

Dredging projects on hard rock bottoms demand fragmentations that can be handled and removed at affordable low costs and competitiveness. Based on this demand, rock fragmentation by underwater blasting should be designed knowing the rock characteristics and the surrounding environment, and then performed with the understanding on how the energy is released and worked. In this paper, we will demonstrate an approach to correlate rock hardness (United Soil Classification System), with the explosive energy to establish a competent amount of explosive with drilling patterns to get appropriate or acceptable fragment distribution and enable the rock removal by dredging.

The "in situ" shear strength of cohesive (clayey) sediments is defined on the basis of the unconfined compressive strength of an undisturbed sample. Field strength test methods such as the Vane Shear Test are sometimes used to estimate the unconfined compressive strength. Note the difference between the Unified Soil Classification System (USCS) and the

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European-based Permanent International Association of Navigation Congresses (PIANC) definitions, which are shown in Table 1.

Table 1. Consistency of Cohesive Soils

Consistency Term	Unconfined Compressive Strength		
	USCS (HQUSACE 1960)		PIANC (1984)
	Tons/sq ft.	KPa	Kpa
Very soft	0 - 0.25	0 - 25	0 - 40
Soft	0.25 - 0.50	25 - 50	40 - 80
Medium (firm)	0.50 - 1.00	50 - 100	80 - 150
Stiff	1.00 - 2.00	100 - 200	150 - 300
Very stiff	2.00 - 4.00	200 - 400	
Hard	> 4.00	> 400	> 300

The strength of intact rock, shale, and cemented soils is generally defined by the unconfined compressive strength of a core sample and a breakdown of these strengths is given in Table 2. Once the intact rock has been broken into fragments, the dredgeability is similar to that of boulders, shales, and smaller grain sizes, except that the grains are much more angular. In general terms, drilling and blasting is performed in rock with hardness above 40 MPa; otherwise the dredging is not economical.

Table 2. Strength of Intact Rock

Relative Strength	Unconfined Compressive Strength	
	MPa	Tons/sq ft.
Very weak	< 1.25	< 12.5
Weak	1.25 - 5.0	12.5 - 50
Moderately weak	5.0 - 12.5	50 - 125
Moderately strong	12.5 - 50.0	125 - 500
Strong	50 - 100	500 - 1,000
Very strong	100 - 200	1,000 - 2,000
Extremely Strong	> 200	> 2,000

WATER BORNE SHOCKWAVES

The mechanism of an under-water blast presents some interesting phenomena associated with a media that is denser than air. The underwater explosion phenomenon is well documented in literature (Cole, 1948, Roth, 1983, Joachim et al, 1998). Detonation of an explosive charge results in a rapidly expanding gas filled cavity. When the reaction front meets the explosive-water boundary, a shock wave is set up in water. The energy contained in the shock wave dissipates rapidly as the wave front expands and propagates (initially at very high velocity but decaying to less than 2 km/s within 10 charge radii) into the surrounding water. Behind the shock front, the residual high temperature and high pressure explosion gases continue to expand, but at a much lower rate. The maximum pressure reaches a value of about 100,000 atm in the boundary layer of the explosive charge. At some distance from the charge, the value of 1000 atm is reached (Zoltan, 1976). At greater distances, the value decreases below 100 atm. The pressure within the resulting explosion gas bubble eventually falls below the ambient hydrostatic pressure at which point the process is reversed and the bubble is compressed till it reaches a minimum diameter, when the process is reversed again. Due to buoyancy, this oscillating bubble keeps on rising at the same time until it reaches the surface, where it finally collapses. Each re-expansion of the bubble is similar to an explosion of decreasing strength, and these results in a series of bubble pulses. The result is a pulsating bubble of gas slowly rising to the surface, with each expansion of the bubble creating a shock wave. Approximately 90% of the bubble's energy is dissipated after the first expansion and contraction. This phenomenon explains how an underwater explosion appears to be followed by other explosions. The time interval between the initial main shock and the first bubble pulse or the maximum bubble size yield an excellent measure of the energy in the explosion gases.[2] The duration of the pulse is very short and is measured in hundreds of milliseconds at a maximum. The time interval of the energy being returned to the bubble (the period of pulsations) varies with the intensity of the initial explosion.

In practice, for underwater blasting operations, the Cole formulas are usually applied in order to determine the parameters of the shock waves. The characteristics of the initial shock wave generated by the detonation of an explosive charge are a function of the shock energy or brisance of the explosive. The period of the oscillation of the gas bubble is a function of the gas or bubble energy of the explosive. The total underwater expansion work or the total energy of the charge (E_T) is expressed as:

$$E_T=E_b+E_s \tag{1}$$

Where E_b is the energy of the gas bubble related to the pulse period T_b and E_s is the shock energy.

Where E_s is defined as follows (Cole, 1948):

$$E_s=((4\pi r^2)/\delta C_w)\int_0^t P_t^2 dt \tag{2}$$

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[2] Mohanty, 2000

where δ is water density at charge depth, C_w is the speed of sound in water at charge depth; P_t is the peak pressure in the primary shock wave.

E_b is defined as follows:

$$E_b=(1/8C^3L_1^3)((1+4CT_b(P_h/P_{hh})^{5/6})-1)^3 \qquad (3)$$

Where $L_1=\delta/P_h$ and P_{hh} is the normalization pressure and P_h the hydrostatic pressure at charge depth and C is a constant related to the boundary effects.

The rapid expansion of the gas bubble formed by an explosion under water results in a shock wave being sent out through the water in all directions. The shock wave is similar in general form to that in air, although if differs in detail. Just as in air, there is a sharp rise in overpressure at the shock front. However, in water, the peak overpressure does not fall off as rapidly with distance as it does in air. Hence, the peak values in water are much higher than those at the same distance from an equal explosion in air. The velocity of sound in water is nearly 1500 m/s (1 mile per second), which is almost five times as great as in air. Consequently, the duration of the shock wave developed is shorter than in air (Cameron and Alastair). There is a shock loss factor that represents the primary shock energy that is dissipated as heat in the water during the travel of the shock pulse from the charge.

BURDEN VALUES FOR UNDERWATER BLASTING

The detonation of explosives in water naturally causes underwater shock waves. The most powerful shock waves occur when the explosive is suspended free or lying uncovered on the "sea" bed. Explosives enclosed in boreholes give rise to considerably smaller shock waves than charges which are not enclosed. The maximum pressure of the shock wave from an enclosed charge is only 10 to 14% of the maximum pressure of a shock wave from an explosive hanging free in the water (Tamrock Handbook for Surface Drilling and Blasting). Due to this, we could work out the above expressions and relate the Burden with a function of power factor, the explosive charge and rock's unconfined compressive strength to establish an approach method to evaluate underwater drilling patterns, as follow:

$$B^{1.28}=[5.2x10^2\ \delta\ (\sqrt[3]{W})^{1.28}]/0.7\sigma \qquad (4)$$

Where B is the burden of the drilling pattern in meters (m); W is the amount of explosive within a borehole in kilograms (kg); σ is the Unconfined Compressive Strength (USCS) in (kg/cm^2) of the rock and δ is the powder factor for the blast in kg/m^3.

The same formula related with the minimum borehole diameter could be expressed as:

$$d^{1.28}=6.61\delta(\sqrt[3]{W})^{1.28}]/\sigma \qquad (5)$$

And the maximum borehole diameter, would be:

$$d^{1.28}=12.06\delta(\sqrt[3]{W})^{1.28}]/\sigma \tag{6}$$

The above formulas (4), (5) and (6) are valid for rocks with USCS not less that 30 MPa. As previously mentioned, actually there are cutting suction dredges capable of excavating rock formations with hardness up to 40 MPa.

Since the cost of blasting is very closely related with the number of holes per pattern area it is essential for underwater blasting to reach the proposed goals with the minimum number of drill holes. Loading factors are therefore bigger when compared to normal bench blasting, since extra energy is required to displace the weight of water above the cut. Uniform rock fragmentation can also be obtained since the explosive column is usually loaded up to the collar of the hole. Thus, stemming is not necessary, because water above the cut acts as stemming, obviously this depends on the water depth at the site. At sites where close ground vibrations have to be established, the explosive column should be loaded up to 15 hole diameter lengths. Due to the extra energy required for breaking the rock underwater, geometric burden often equals spacing. Sub drilling underwater must exceed 60% of the burden length, and this will allow breaking the row at the intended new bottom level.

Table 3 shows recommended range (maximum and minimum values) for the borehole diameter, explosive charge in each hole and burden values for the blasting pattern in underwater blasting. They show a good approach to establish initial parameters that can be adjusted according to local conditions. One of the main advantages of this approach is that it is based on rock parameters and the amount of explosive.

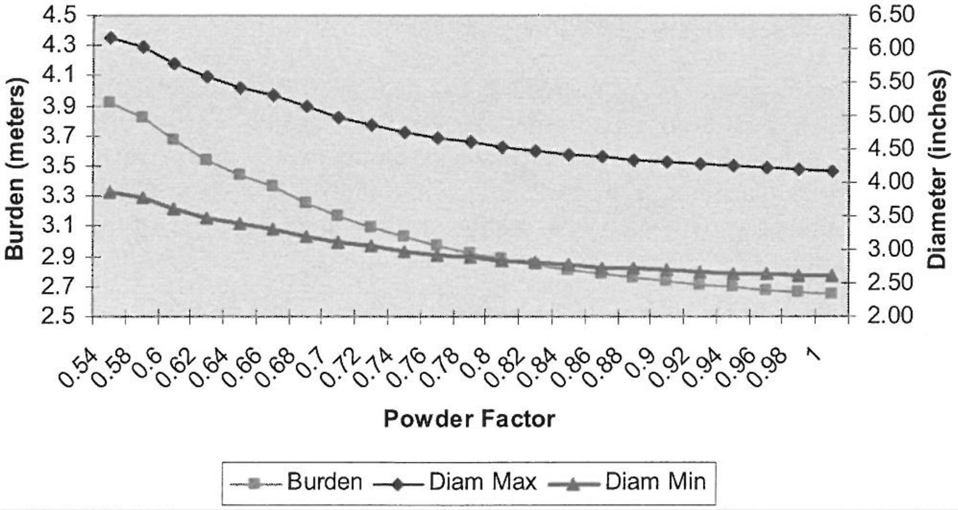
The formula was developed to work on rock with unconfined compressive strength values above 30 Mpa (UCS). Still it does give good references for "softer" rocks with lower UCS values in order to determine initial parameters since underwater drilling and blasting is performed using hole diameters between 2 inches (51 mm) and 4 inches (102 mm). The choice of hole diameter greatly depends on the drilling method, type of rock, type of explosive, depth of cut.

Once the drilling parameters, the loading factors are set, we could calculate the expected rock fragmentation and its distribution as per a Kuz-Ram fragmentation analysis. This is the only way to demonstrate the effectiveness of the data obtained from the approach and the dredgeability of the resulting fragments. As an example of a blast performed on rock with UCS of 80 MPa using a pattern of 2.92m x 2.92m, calculated by the formula (4), drilled with 117 mm (4 $^5/_8$ inches) hole diameter; hole depth of 5.18 m at 15 m water depth.

Table 3. Underwater Burden

Power Factor (kg/m3)	UCS (kg/cm^2)	Explosive Charge [kg (Pound)]	Burden (m)	Diameter Min. (in)	Max. (in)
0.54	305.7	32 (70)	3.93	3.86	6.18
0.58	356.65	36 (79)	3.83	3.77	6.02
0.6	407.6	40 (88)	3.67	3.61	5.77
0.62	458.55	44 (96)	3.54	3.49	5.58
0.64	509.5	48 (105)	3.44	3.39	5.42
0.66	560.45	52 (114)	3.36	3.31	5.29
0.68	611.4	54 (118)	3.26	3.20	5.13
0.7	662.35	56 (123)	3.17	3.12	4.98
0.72	713.3	58 (127)	3.09	3.04	4.87
0.74	764.25	60 (132)	3.03	2.98	4.76
0.76	815.2	62 (136)	2.97	2.92	4.68
0.78	866.15	64 (140)	2.92	2.88	4.60
0.8	917.1	66 (145)	2.88	2.83	4.53
0.82	968.05	68 (149)	2.84	2.80	4.47
0.84	1019	70 (154)	2.81	2.76	4.42
0.86	1069.95	72 (158)	2.78	2.74	4.38
0.88	1120.9	74 (162)	2.75	2.71	4.34

Figure 1. Underwater Burden Graph



Graph shows range of selection of borehole diameters for each Burden dimension. The practioner, could set adjustments after initial blast.

Table 4. Rock Characteristic Indexes

Blastability Index	6.345
Average Size of Material	14 cm
Uniformity Exponent	1.34
Characteristic Size	0.18 m

Table 5a. Expected Size Fragments from Blast

Fragmentation Target Parameters	
Oversize	0.5 m
Optimum	0.3 m
Undersize	0.1 m

Table 5b. Predicted Fragmentation

Predicted Fragmentation Distribution	
Percent Oversize	2.1% m
Percent In Range	61.8% m
Percent Undersize	36.1% m

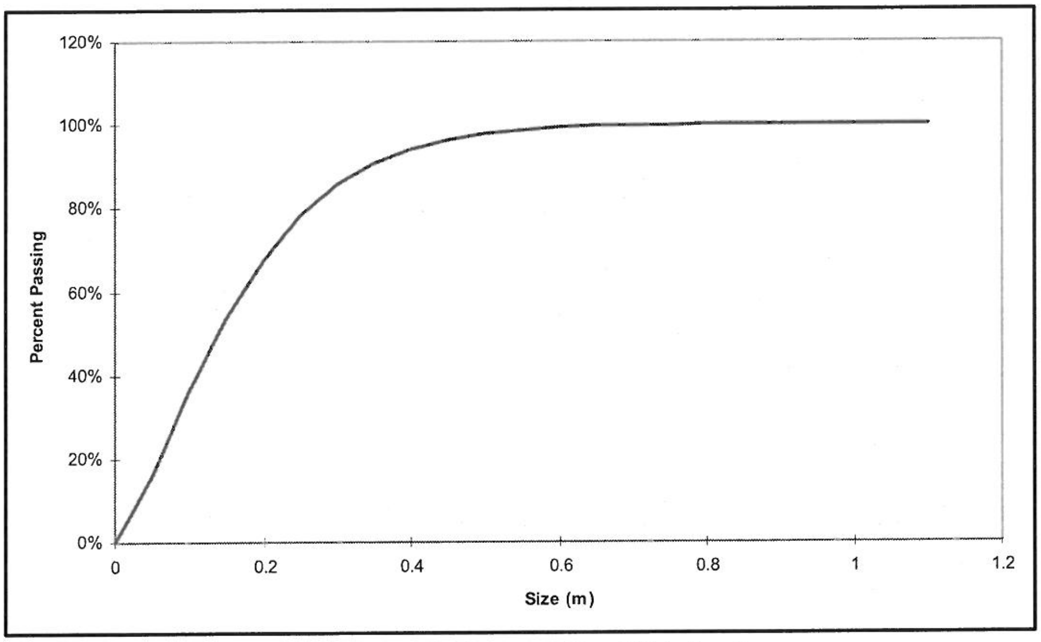


Figure 2. Percent Size Distribution

Table 6 – Particle Size Distribution

Percent Passing	Size (m)
0.0%	0
16.3%	0.05
36.1%	0.10
53.7%	0.15
67.7%	0.20
78.2%	0.25
85.7%	0.30
90.8%	0.35
94.2%	0.40
96.4%	0.45
97.9%	0.50
98.7%	0.55
99.3%	0.60
99.6%	0.65
99.8%	0.70
99.9%	0.75
99.9%	0.80
100.0%	0.85
100.0%	0.90
100.0%	0.95
100.0%	1.00
100.0%	1.05
100.0%	1.10

The size distribution of fragments after being blasted shows that 97.9% of them are smaller than the optimum target's oversize of 0.5 m. Effective cost removal of these fragments depends on the type of dredging equipment to be used.

The rock with 80 MPa of hardness is considered a strong rock that is not easily dredged directly from the bank by a suction cutter head. If a previous site investigation was performed and the rock material and mass properties are known, then suction dredging could be more feasible after blasting if the degree of weathering allows the operation. Also, once the rock is fragmented by blasting, then the rock could be mechanically dredged.

BLASTHOLE INITIATION SEQUENCE

The blast timing sequence in underwater blasting is quite similar with those used in land bench blasting. The timing employed on blast patterns are highly influenced by local conditions, and could be a topic of a separate analysis. Keep in mind that appropriate time for displacement of front rows should be allowed since movements in water are slower. New trends in blasting practices have tried to integrate dynamic characteristics of rock mass in order to improve results from interactions of waves between boreholes. Nevertheless in practical terms it is recommended to minimize firing times between holes in a row and maximize times between rows. These firing times must be determined according to local conditions, vibration constraints, and targeted fragmentation matched with dredging capabilities.

CONCLUSIONS

The dredging industry is facing an increasing use of underwater blasting for deepening projects at ports, channels and other maritime industry facilities where more hard materials and less sediment are found. Rock characteristics at a dredging site have a major influence on a dredge performance. The rock characteristics must be determined prior to the commencement of work to determine whether a dredge can handle the rock or if it is necessary for the rock to be drilled and blasted to fragment it first. Feasibility and cost competition for final removal prices are dependent on fragmentation and the variety dredging equipment. With the offered approach, it is possible to set initial drilling and blasting geometrical patterns and charge parameters related with rock mass characteristics to complete the submarine blasting with expected fragmentation, scheming ground vibration limited by appropriate loading factors, water shock waves and have power over rock throw. Variables guide the blasting strategies that match or sustain appropriate competitive dredging plans.

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OPTIMIZATION OF OPEN-WATER DISPOSAL SITE FOR DREDGED MATERIAL BY USING NLP

H. Valian[1], T.P. Williams[2], and M.A. Jafari[3]

ABSTRACT

Dredged material disposal in areas with environmental constraints requires that decisions about the placement of dredged material should be made with little margin of error. In this paper, a nonlinear programming model has been developed to assist in the management of open-water dredged material disposal sites; this model was developed by MATLAB. The model has been developed based on conditions at the open-water disposal site near the mouth of the Columbia River. The optimization model considers available capacity of cells within the disposal area to produce dumping plans without adversely affecting the environment and minimizing impact to the natural seafloor. This means that the dredged material would be placed through the entire site, both in space and time, using a regimented procedure to produce a uniform continuous layer on the seabed.

INTRODUCTION

Safe and efficient water borne transportation is essential for facilitating the productive flow of goods internally and for sustaining or improving the competitive posture of the United States in world trade (Ratick et al., 1992). Dredging, involving the removal of accumulated bottom sediments, is necessary to maintain channel depths for safe and efficient vessel operations. The general process of dredging sediment material begins with the sediment material being excavated from the channel (Ford, 1984). The final step in the dredging process is placement in either open-water sites, confined disposal sites, or for beneficial uses (USACE, 2005).

The U.S. Army Corps of Engineers (USACE) has long been involved in developing, improving and maintaining the nation's navigable waterways. Natural hydrologic and hydraulic processes such as variation in water stage due to river flow and tidal processes and reduction in the depth and width of channels due to shoaling, continually change conditions in the channel requiring that they be maintained by periodic and episodic dredging (Thorp, 1996). The U.S. Army Corps of Engineers (USACE) attempts to balance cost of disposal dredged material with environmental and engineering considerations under "base plan". Where the beneficial use project is not part of the base plan, but still contributes to a project's navigation or ecosystem restoration purpose, the base plan serves as a reference point for measuring the incremental costs of that beneficial use.

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For costs exceeding the base plan, one or more non-federal entity must enter into a cooperative agreement with USACE to participate in the project (Section 204, WRDA 1992). Most states, local governments and port authorities - the likely local sponsors - have not been able to come up with funds to cover these additional costs (Lameka, 2005).

Open-water disposal was selected at the Mouth of the Columbia River (MCR) Project after an extensive public involvement process; however, placing dredged material in an open-water disposal site still has extensive operational and management requirements (Moritz, 1994). Open-water disposal means that dredged material is placed at designated sites in oceans, estuaries, rivers and lakes such that it is not isolated from the adjacent waters during placement (USACE, 1992) and often have multiple and often competing placement requirements. Open-water disposal sites adjacent to maintenance dredging areas typically provide the least cost disposal option, but many of the designated open-water sites have either filled to capacity or have been discontinued due to environmental concerns, therefore; it is essential that their management be done with the most current placement techniques and available tools.

In this paper, a nonlinear optimization model has been developed to be used as a decision support tool for planning of disposal of dredged material in open-water sites. The model solves the problem of placing dredged material in a disposal site without adversely affecting the environment and minimizing impact to the natural seafloor. This means that the dredged material would be placed through the entire site, both in space and time, using a regimented procedure to produce a uniform continuous layer on the seabed (USACE 2006). The results of this model are a set of dumping plans that specify where the material is dumped within the disposal site. After the optimal dumping plans are found, the Multiple Dump Fate (MDFATE), a simulation program, can be used to predict the change in bathymetry at the disposal site resulting from a series of dredged material disposal events ("dumps"). The simulation operation is not part of this research. A whole picture of this paper is shown in Figure 1.

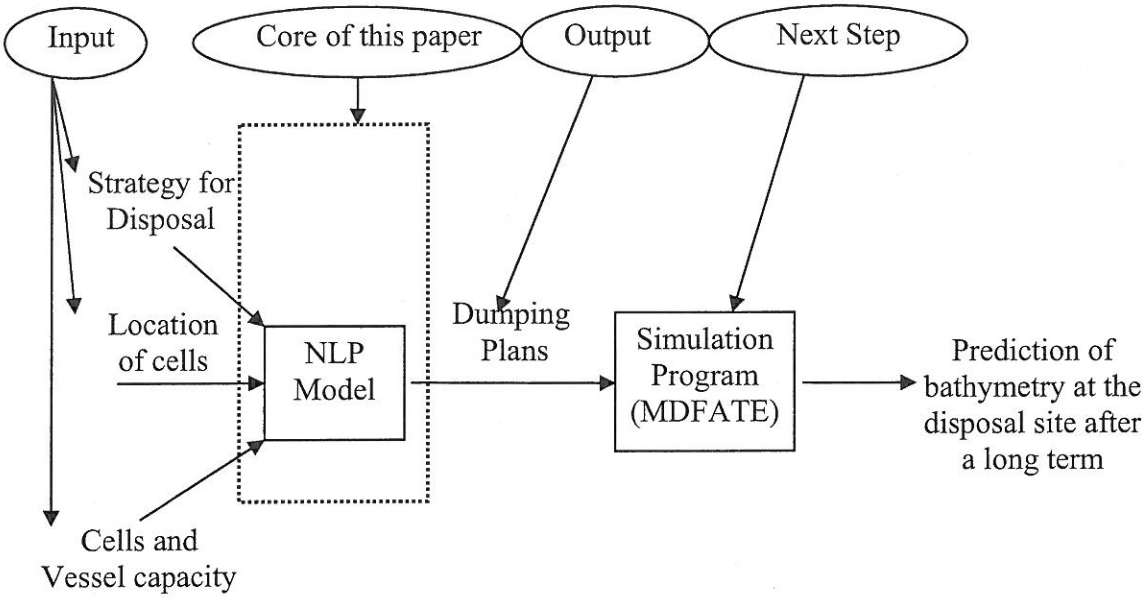

Figure 1. Paper Overview

BACKGROUND

The U. S. Army Corps of Engineers is responsible for the operation and maintenance (O&M) of the federal deep-draft navigation channel at the Mouth of the Columbia River (MCR). Each year, the Corps of Engineers-Portland District dredges 3-5 million cubic yards (MCY) of sand at the Mouth of the Columbia River (MCR) to maintain the inlet's 6-mile long deep draft navigation channel (USACE, 2006). Maintenance of the MCR project includes disposal of dredged material. The ocean dredged material disposal sites that were designated in the late 1970's had reached capacity and some had started adverse impacts to wave conditions during certain wave events. The selection of ocean disposal sites for the Mouth of the Columbia River project and in the future the lower river areas of the Columbia River project became a priority in the 1990's. This process culminated in two ocean dredged material disposal sites being designated by the U.S. Environmental Protection Agency on April 1, 2005; one of which is the Shallow Water Site.

The appropriate disposal of material dredged from navigation projects is a nationwide issue (Thorp, 1996). The Management objective for disposal site is to efficiently utilize the site's capacity for the disposal of MCR dredged material, without adversely affecting the environment. One of the purposes of the current disposal management at the Shallow Water Site is to limit the impact of disposal on the bottom both through time and space in order to minimize initial impact on mobile epibenthic organisms and allow them to relocate before being again impacted by a second disposal event. The potential effect of dredged material accumulation upon waves (mound-induced wave shoaling) is also an important consideration when planning disposal activities (Moritz et al. 1999).

Some early work by US Army Engineer District, San Francisco has been developed a model for dredged-material disposal Management (SPN-D2M2). Their model solves the problem of allocating material to different disposal sites to minimize the cost of operating the system (Ford, 1994). However, we want to allocate material in only one disposal site.

Ratick et al. (1992) develops a reliability based dynamic dredging decision model that employs a simulation-optimization approach combining a simulation model of stochastic channel conditions with a dynamic location model to schedule the optimal deployment and activity levels for dredges. Our paper contributes to find a set of dumping plans that specify where the material is dumped within the disposal site.

MODEL

A nonlinear programming model is a mathematical program that attempts to identify an extreme point of a function which satisfies a set of constraints. This paper develops a nonlinear programming model for solving the problem of allocating material in a disposal site to minimize the environmental affects to mobile epibenthic organisms.

The results of this model are a set of dumping plans that specify where the material is dumped within the disposal site. The potential benefit of this model is to maximize the amount of material that can be dumped at a particular disposal site while meeting the constraints of the site. The improved utilization of a site can result in additional material entering the nearshore littoral cell a highly desirable beneficial use and also reduced dredging costs because cheaper near shore sites can be fully utilized rather than transporting the material to more expensive sites farther offshore (Williams et al. 2005) where the material would be unavailable to the littoral cell.

The optimal solution can be found by evaluating all possible dumping plans. The advantage of this presented nonlinear model is to find the optimal solution. The nonlinear programming optimization model was programmed and run in MATLAB.

Objective Function

The optimization model considers the available capacity of cells within the disposal area to produce a plan that minimizes mounding and maximizes cell usage within the site. The object of the model is to fully utilize capacity of cells and prevent any placement on the avoiding zone. The objective function is defined as:

$$Min\sum_{i}\sum_{k} Cost_{X_{ik}} A_{ik} \qquad (1)$$

Where X_{ik} is the cell number of placement in plan ith at dump kth, and A_{ik} is volumetric amount of placement in plan ith at dump kth. The coefficients of the objective function (Cost) are specified based on the location and the revised capacity assessment after each dumping plan. The cost associated to each cell is used as a penalty to minimize mounding and maximize usage within the site.

Parameters

The model has 5 parameters as follows:

1. $Cell_i$: partition ith of the disposal site

   The disposal site is partitioned into a system of cells, for example 500 x 500 ft.

2. $Capacity_i$: capacity of cell ith

   The capacity of cell is the volume of dredged material that can accumulate within the cell's boundaries without unacceptable adverse impacts to the environment. In this context, the capacity for a given cell is defined by height and area over which dredged material can accumulate, with respect to a baseline condition.

   Based on the cell capacity and location, there are 3 levels that will be used for managing disposal site:
   - Level 1 (Dredged material accumulation is less than the cell capacity): Continue to use area of this cell appropriately.
   - Level 2 (Dredged material accumulation is equal to cell capacity or the cell is located on the edges): Avoid placement, continue to use adjacent areas within site appropriately.
   - Level 3 (Capacity level exceeded): Avoid placement in this cell and in adjacent cells.

3. $Path_{ij}$: existence of an available path from the cell ith to cell jth

   Based on the location of the cells, there are 3 possible values for this parameter:

$Path_{ij} = 1$ if cell i^{th} and cell j^{th} are neighbors
$Path_{ij} = -1$ if cell i^{th} and cell j^{th} are neighbors and common area is only one point
$Path_{ij} = 0$ otherwise

4. $Cost_i$: cost of dump in cell i^{th} as a penalty

   The cost of each cell is specified depending on the location and remaining capacity of the cell. A different cost is allocated to each cell as a penalty to avoid environmental effects:

   $Cost_i=1$ if the capacity of cell i^{th} is in level 1
   $Cost_i=10$ if the capacity of cell i^{th} is in level 2
   $Cost_i= Cost_j=100$ if the capacity of cell i^{th} is in level 3 and $Path_{ij}=1$

5. CapV: capacity of the vessel

   The capacity of vessel is the volume of dredged material that can be carried in each vessel.

Constraints

To be realistic, the model also must include equations to limit the decision variables as follows:

The values of the decision variables must be nonnegative:
$A_{ij}>=0$ (2)

$X_{ij}>=0$ (3)

Total amount of dredged material placed at each cell is limited by the cell's capacity:

$\sum_i \sum_k A_{ik} < capacity_j$ For all i, k which $X_{ik} = j$ (4)

The total volume placed by each plan can't exceed the capacity of the vessel:

$\sum_k A_{ik} \leq CapV$ For every i (5)

Every dump in each plan should be chosen uniformly. This means that no dump can be repeated until a dump has been made in every other cell:

X_{i1} is not member of the $\{X_{kj}, k=1\ldots i-1; j=1\ldots 5\}$ (6)
X_{i2} is not member of the $\{X_{kj}, k=1\ldots i-1; j=1\ldots 5\}$ (7)
X_{i3} is not member of the $\{X_{kj}, k=1\ldots i-1; j=1\ldots 5\}$ (8)
X_{i4} is not member of the $\{X_{kj}, k=1\ldots i-1; j=1\ldots 5\}$ (9)
X_{i5} is not member of the $\{X_{kj}, k=1\ldots i-1; j=1\ldots 5\}$ (10)

There is a path between each dump:

$PathX_{i1},X_{i2} \neq 0$ (11)
$PathX_{i2},X_{i3} \neq 0$ (12)
$PathX_{i3},X_{i4} \neq 0$ (13)
$PathX_{i4},X_{i5} \neq 0$ (14)

All dumps should be placed in one of the cells in the disposal site:

$X_{ik} \geq 1$ (15)
$X_{ik} \leq$ number of cells in the disposal site (16)

UTILIZATION OF MCR DUMP SITE SWS

Each year, the Corps of Engineers-Portland District dredges 3-5 million cubic yards (MCY) of sand at the mouth of the Columbia River (MCR) to maintain the inlet's 6-mile long deep draft navigation channel (USACE, 2006). Dredging is limited to summer when wave conditions are favorable for working on the bar (USACE, 2003a). This includes the dredging process itself, as well as developing sediment placement plans for dredging at each site. The dredged material is dumped into the disposal site according to a dumping plan that specifies where the material is dumped in the disposal site. Currently, there are three water disposal sites for material dredged from the mouth and the lower Columbia River: a Shallow Water Site (SWS), the North Jetty site (NJ) and a Deep Water Site (DWS). MCR open-water dredged material disposal sites available for use during 2006 are shown in Figure 2.

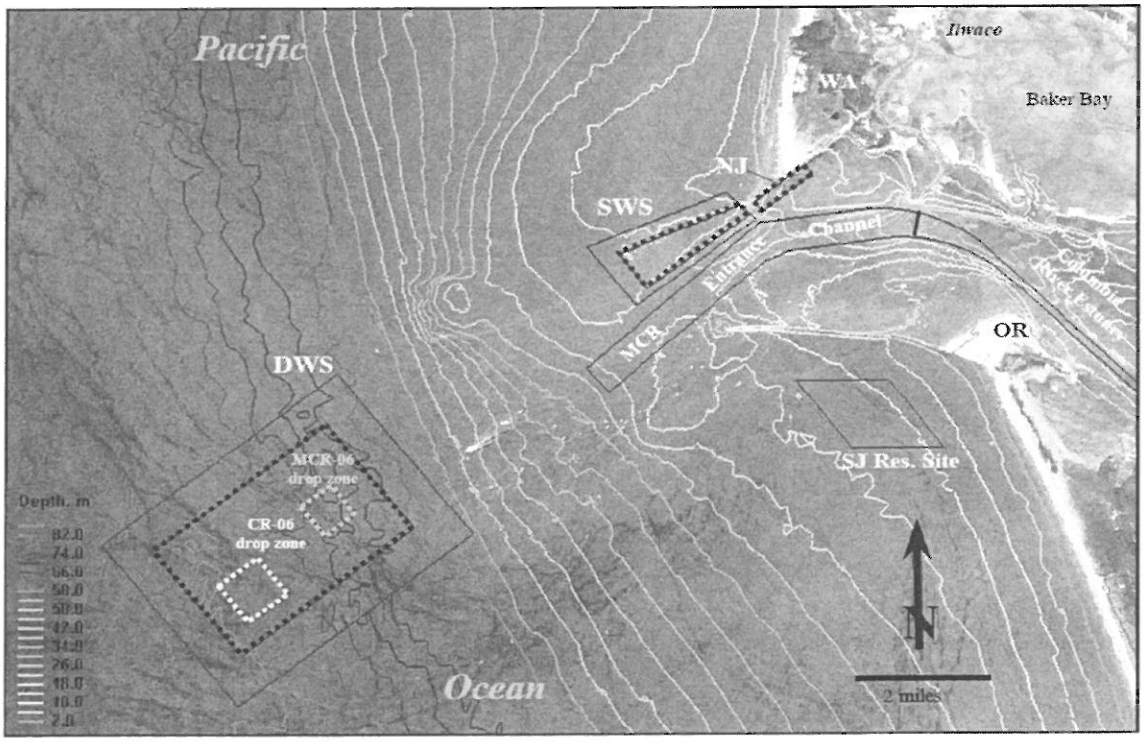

Figure 2. Available MCR Open-Water Dredged Material Disposal Sites (Courtesy of USACE Portland District)

The beneficial uses associated with placing dredged material placed at the SWS are preferred before dredged material is allocated to the DWS. Site SWS is located on the ebb tidal delta of the Columbia River, about ¼ mile seaward of the MCR north jetty.

The presented nonlinear programming (NLP) model is applied to site SWS. To achieve full utilization of the entire disposal site, the site was partitioned into a system of cells (about 500 x 500 ft). As it shows in Figure 3, each cell consists of a unique cell number for identification.

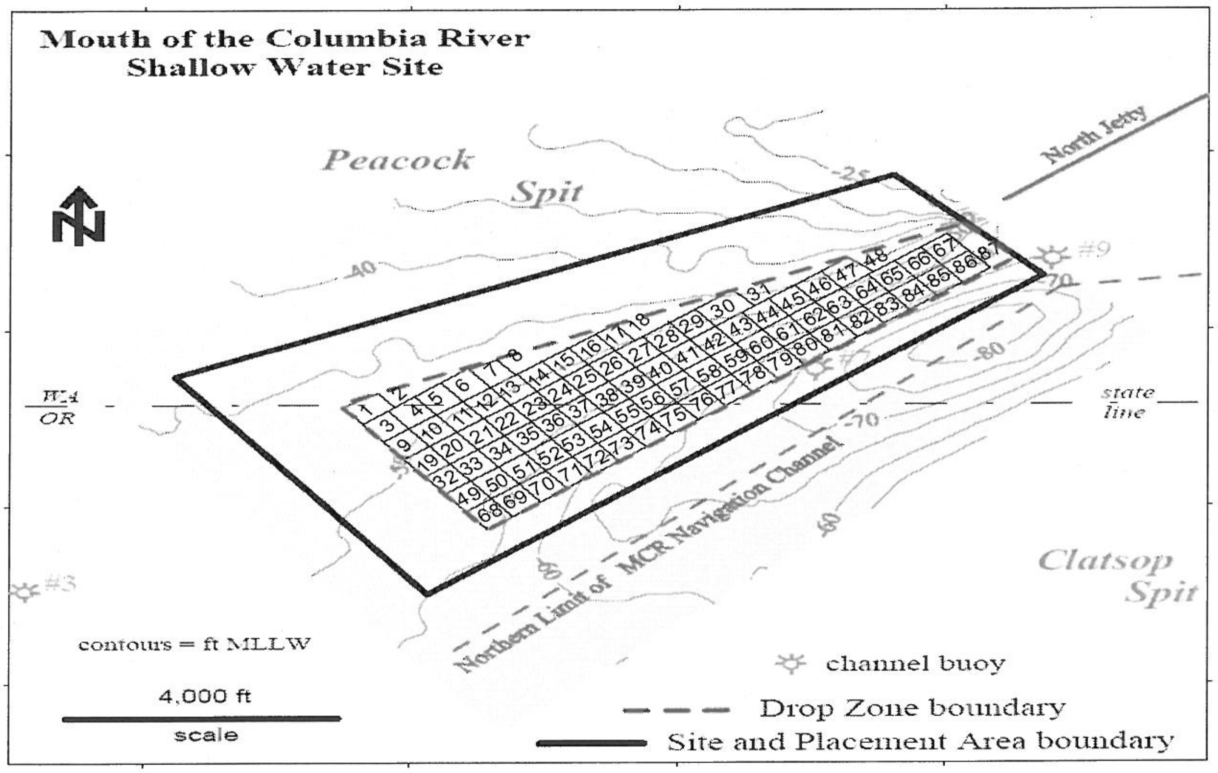

Figure 3. Partitioning of Site SWS and Cell Numbers

The remaining capacity of site SWS should be maximized in an environmentally acceptable manner. The capacity of each cell is defined by surveys. The frequency of the surveys is related to the volumetric rate of dredged material being placed into a site (USACE, 2006). A potential effect of a site exceeding capacity is mound-induced wave shoaling; therefore, if surveys and other indicators show there is a risk of reaching a constraint such as exceeding the site's capacity, an active disposal site may be temporarily discontinued (USACE, 2003a). Figure 4 shows the capacity of Site SWS based on the 29 April 2003 survey.

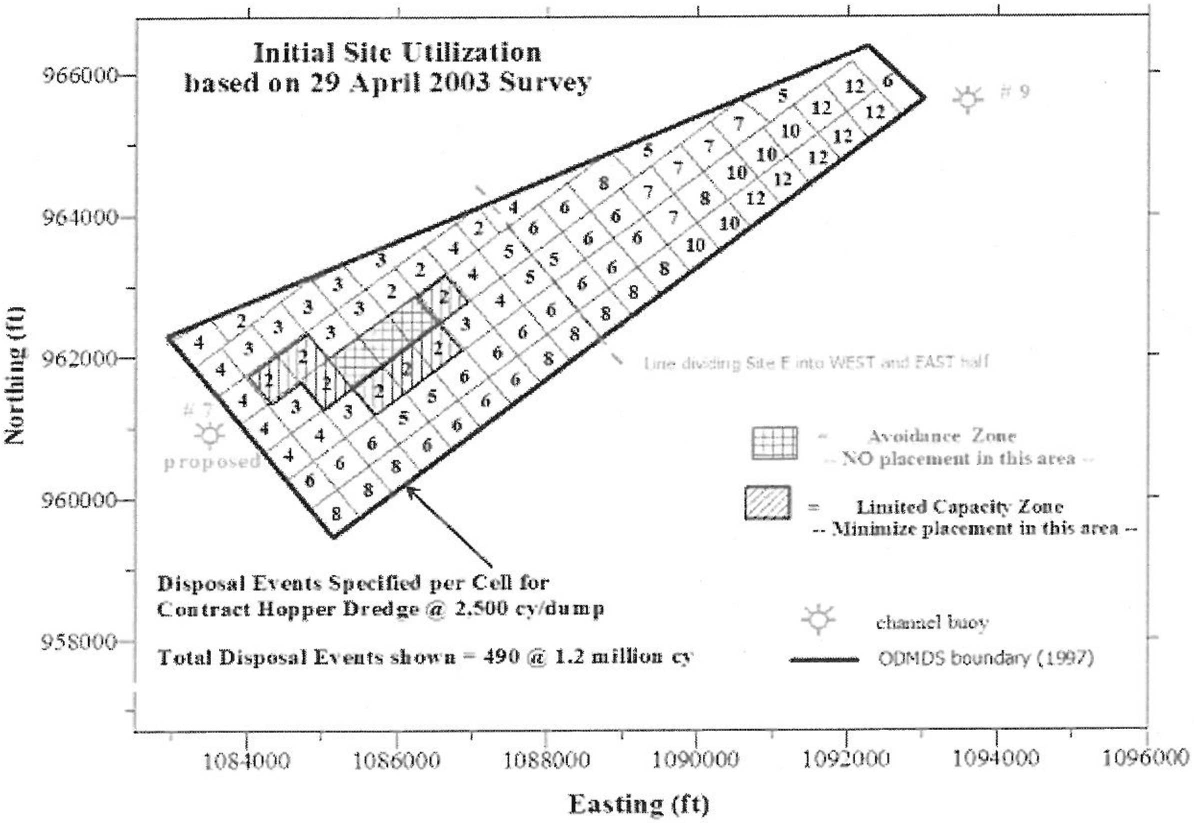

Figure 4. Capacity of Site SWS (Courtesy of USACE Portland District)

The site SWS has several constraints. First, the site SWS is near the shore, and is managed to prevent mounded dredged material from excessively amplifying waves due to shoaling and refraction. Second, normal dredging practice requires that one dump occurs in all of the dredging cells before a second dump can be made in the cell. Third, each plan shall be distributed across no less 2 cells and no more than 5 cells. Fourth, no part of the site can be filled more than its capacity. All of these concerns are reflected in the nonlinear programming model. The model is coded as program written in MATLAB. Output of program is cell numbers of dumping plans. For instance, by running the program for one day period, output shows 14 dumping plans within the disposal site (see Table 1).

Table 1. Dumping Plans

Dumping plan	Cell numbers	Dumping plan	Cell numbers
Plan 1	63, 46, 47	Plan 8	69, 50
Plan2	64, 83	Plan 9	58, 76, 75
Plan 3	51, 70, 71, 72, 73	Plan 10	30, 44
Plan 4	61, 80, 79, 78	Plan 11	45, 62, 81, 82
Plan 5	65, 48	Plan 12	66, 86, 87
Plan 6	28, 41, 40, 39	Plan 13	16, 8, 7, 6, 5
Plan 7	56, 38	Plan 14	34, 20, 9

Location of these dumping plans has been shown in Figure 5.

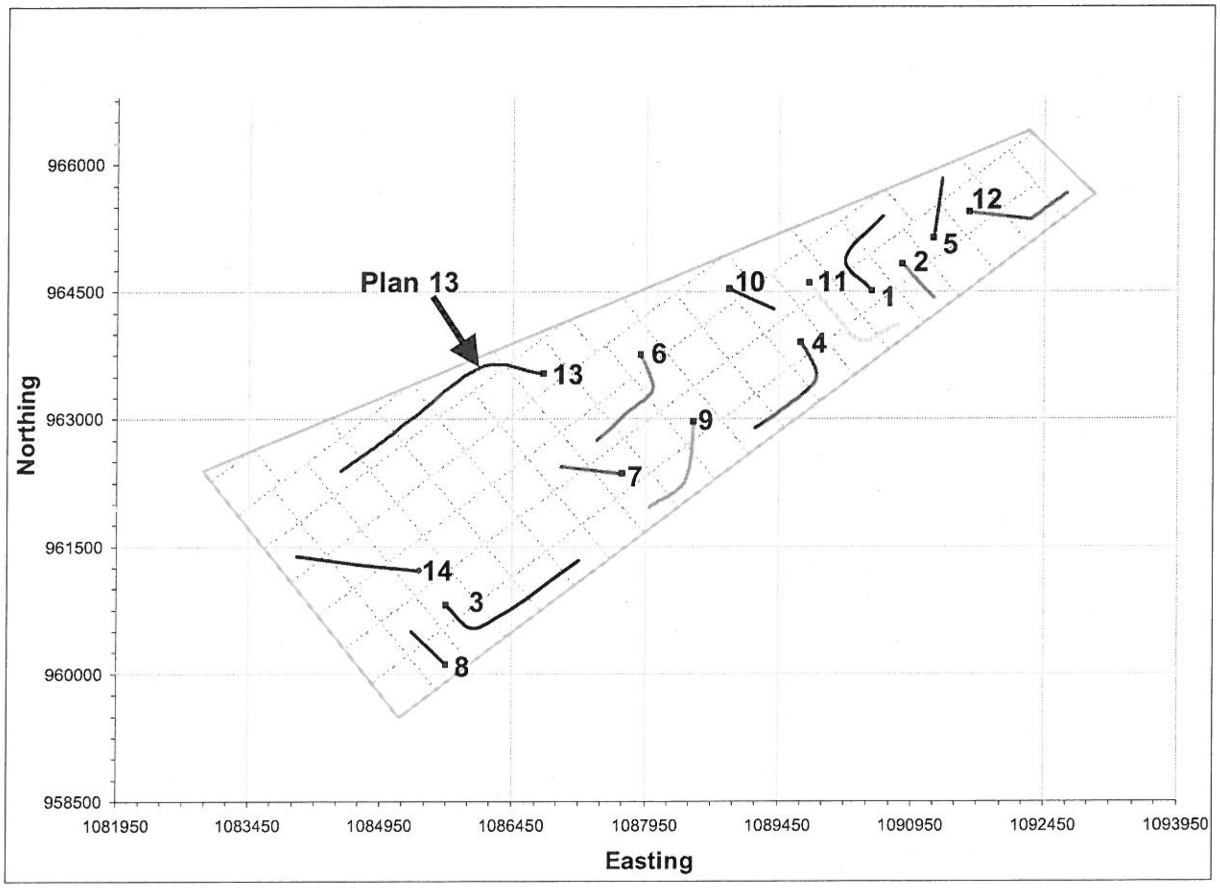

Figure 5. Location of Dumping Plans in Site SWS

If a period of 14 days is considered, 160 plans will be assumed. By running the program, the dredge will have 160 dumping plans within the disposal site. As an example, consider cell 76 with capacity 20 thousand cubic yard (8*2.5). Output of program will give us 160 dumping plans which cell number 76 has placements at plan 9, plan 35 and plan 141 with amounts of 1.5 thousand cubic yard, 1.25 thousand cubic yard, and 2.25 thousand cubic yard by sequence. Based on that, material shall be credited to cell number 76 and a new capacity will be calculated. That means the original capacity in cell number 76 before generating 160 dumping plans in the site is 20 thousand cubic yards. This compares to a capacity of 15 thousand cubic yards (20-(1.5+1.25+2.25)) after 160 plans. Figure 6 and Figure 7 show the Pre-placement and Completion capacity of site SWS.

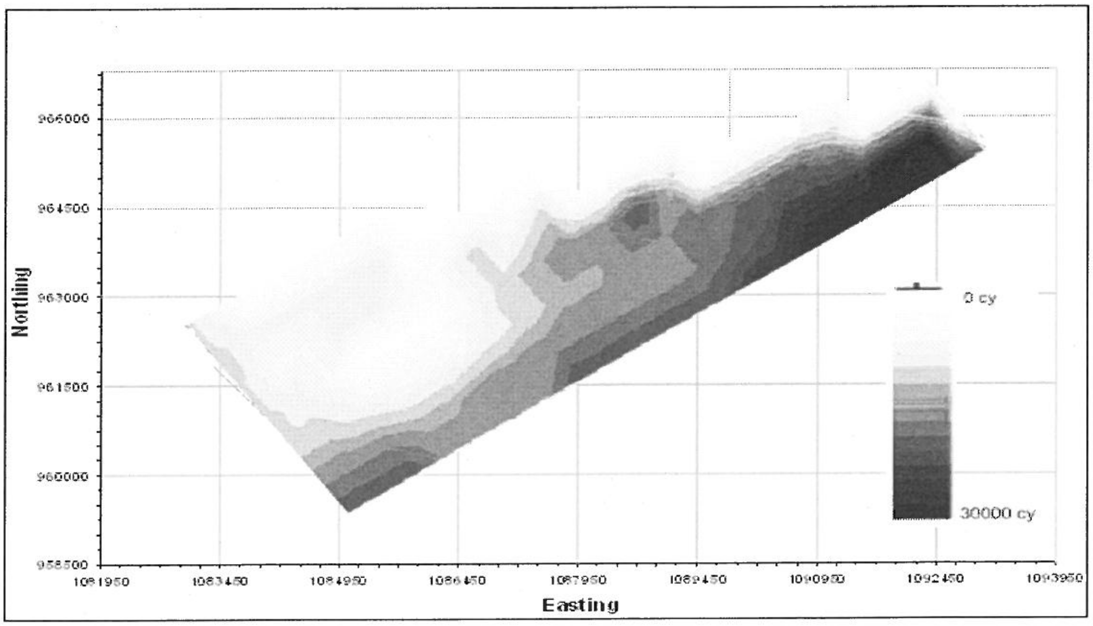

Figure 6. Pre-Placement Capacity of Site SWS

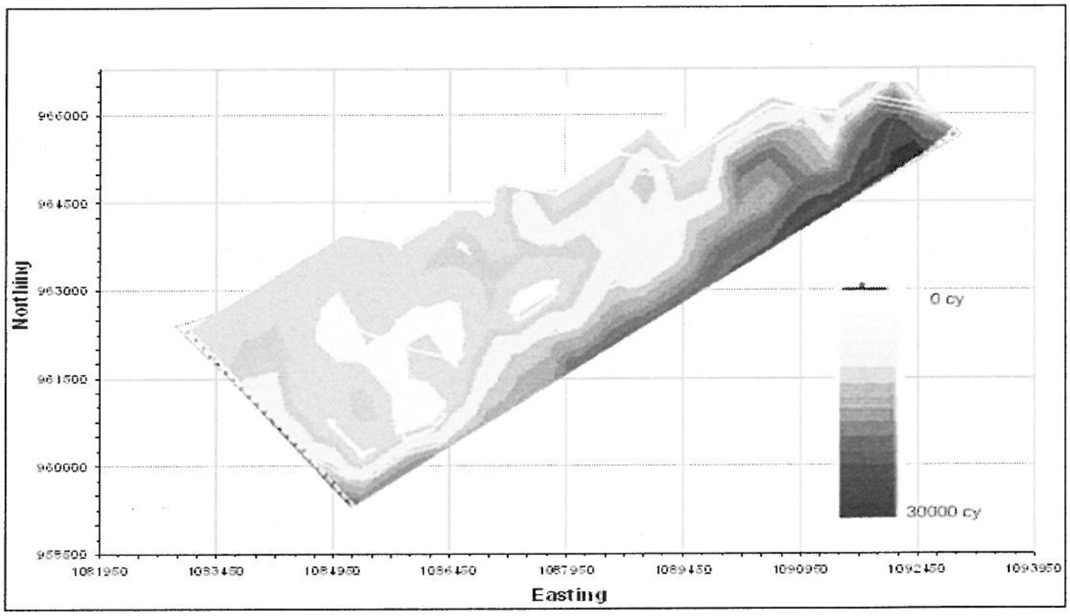

Figure 7. Completion Capacity of the Site SWS

In order to avoid drastically changing the wave patterns, mounded dredged material is not recommended and is actively prevented in any dumping plans. One of the issues for the model with respect to site SWS is ensuring that the dumping plans would result in uniform layer of material.

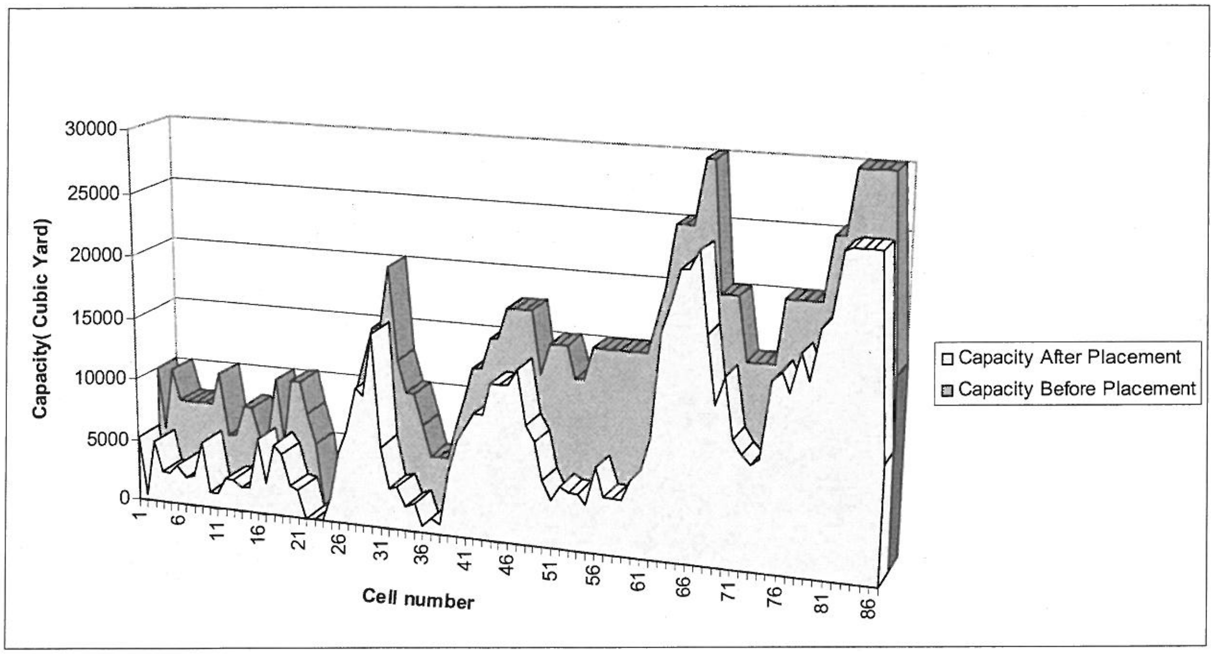

Figure 8. Capacity of Cells Before and After 160 Plans

The result of the optimization model (Figure 8) indicates that the program produces reasonable dumping plans, because as it shows in Figure 8, after placement the dredging material there is no new cell with capacity zero and also produces a uniform continuous layer on the seabed.

VALIDATION

The model was run varying the cell capacities and vessel capacities randomly to examine the sensitivity of the optimal solutions to these parameters. Random values of cell capacities for each cell were generated assuming normal distributions around the mean values with a standard deviation equal to 10 percent of the mean.

The model was run 10 times. The optimal level of the objective function was highly sensitive to the cell and vessel capacities. Proportion of uniformity is calculated in each run as follows:

Step 1.Subtract capacity after Running NLP from capacity before placement dredging material for each cell.

Step 2.Find number of cells which result of step 1 is equal to mode.

Step 3.Divide the result in step 2 by 87.

Figure 9 shows that we have from 30 to 58 percent proportion of uniformity in our placement. Actual placement plans have %31 proportion of uniformity .Therefore; the result of this model has better proportion of uniformity than the actual dredging plans.

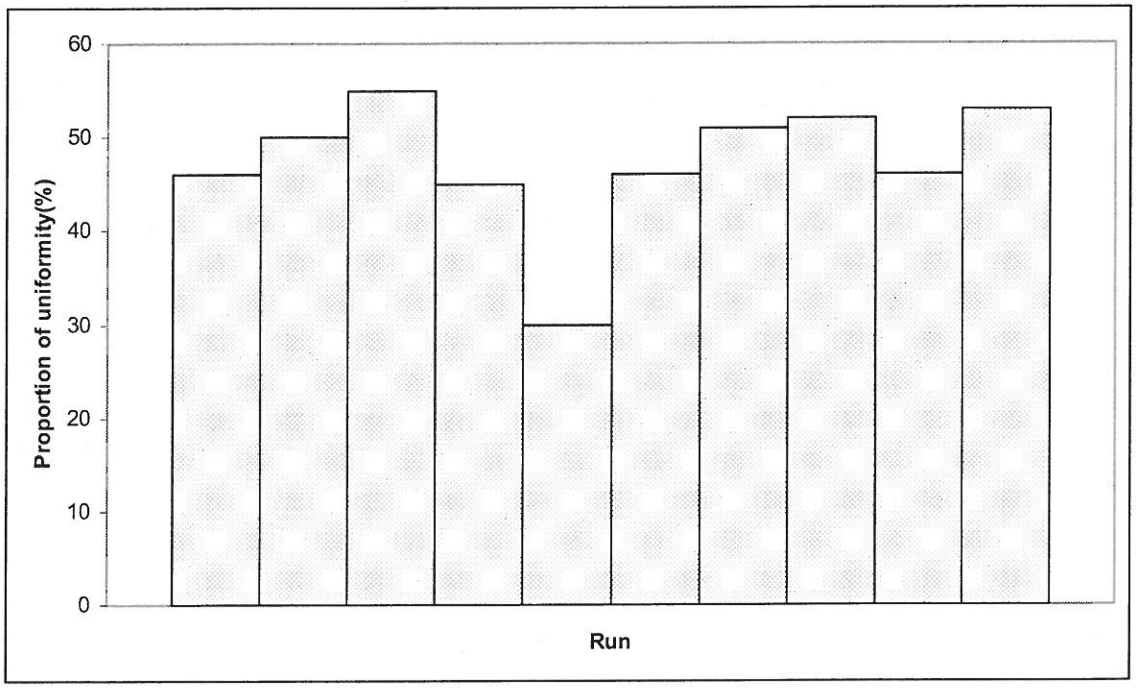

Figure 9. Proportion of Uniformity in 10 Runs

CONCLUSIONS

Dredged material disposal is one of the biggest challenges facing most ports in the United States today. While often more cost effective than upland disposal, the option of placing dredged material within the open-water introduces additional concerns to the overall management of dredged material disposal. The most of the open-water sites have either filled to capacity or have been discontinued due to environmental concerns. The goal of this modeling is to enhance the revisions made to dredging plans so they utilize an open-water disposal site in the optimal manner. It means that the potential benefit of this model is to maximize the amount of material that can be dumped at a particular disposal site.

The model produces optimized dumping plans based on the constraints at the ocean dumping site. This model was programmed and run in MATLAB. After the optimal solution is found, the Multiple Dump Fate model (MDFATE), a simulation program can update the condition of the disposal site. The used of the optimization model combined with MDFATE may allow for dumping plans to be updated more frequently, and for the production of dumping plans with longer time horizons.

This initial model has been developed specifically for the conditions at Site SWS. We plan on exploring how various constraints in the model could be turned on and off to allow it to be tailored to conditions at different sites. The model itself could be further examined for any potential improvements, such as modifying constraints for sites with different conditions.

NOMENCLATURE

X_{ik}	the cell number of placement in plan ith at dump kth	-
A_{ik}	volumetric amount of placement in plan ith at dump kth	1000cy
$Cell_i$	partition i of the disposal site	-
$Capacity_i$	capacity of cell ith	2500cy
$Path_{ij}$	existence of way from cell ith to cell jth	-
$Cost_i$	cost of dump in cell ith	-
CapV	capacity of the vessel	1000cy

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The contents of this article reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the U.S. Army Corps of Engineers.

The study was conducted under the following ERDC supervision: Dr. Robert M. Engler, DOER Program Manager; Mr. Thomas W. Richardson, Director, ERDC Coastal and Hydraulics Laboratory. At the time of preparation of this article, Dr. James R. Houston was Director of ERDC, and COL James R. Rowan, EN, was Commander and Executive Director.

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

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