SYNTHESIS OF RESEARCH RESULTS

DREDGED MATERIAL RESEARCH PROGRAM

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TECHNICAL REPORT DS-78-2

PROCESSES AFFECTING THE FATE OF DREDGED MATERIAL

August 1978

Final Report

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Determination of the fate of dredged material placed on the bottom of an ocean, lake, estuary, or river is an environmental concern that requires consideration and adequate prediction in the planning of a dredging project, since various natural processes can alter the initial configuration of the deposit and subject the surrounding bottom to some level of environmental impact. In the selection process for a disposal site, consideration must be given to the

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eventual disposition of dredged material in order that adequate determination of the site capacity can be made.

The four primary environments that may contain subaqueous dredged material deposits are oceans, estuaries, rivers, and lakes, with various energy-related zones within each environmental system. Each zone has a unique set of physical factors and sedimentological properties that will determine the potential fate of a dredged material deposit.

Prediction of the fate of dredged material at a disposal site requires a knowledge of the following parameters: (1) currents, (2) waves, (3) tide, (4) suspended sediment concentrations, (5) seasonal energy fluctuations, (6) storms, (7) dredging/disposal operations, (8) shipping traffic, (9) fisheries activities, (10) bathymetry, (11) sedimentology, and (12) biological activity.

Methodologies for monitoring the actual physical changes that occur at a disposal site have been adequately documented at representative environments of deposition. As more knowledge is gathered, a better understanding of the interaction of the physical processes and the fate of subaqueous deposits of dredged material will be established.

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PREFACE

The preparation of this report was authorized by the U. S. Army Corps of Engineers, Waterways Experiment Station, Dredged Material Research Program (DMRP), and is based on the following work units:

> Work Unit 1B04, Contract Report D-74-8, Assessment of Factors Controlling the Long-Term Fate of Dredged Material Deposited in Unconfined Subaqueous Disposal Areas. Principal investigators were D. R. Basco, A. H. Bouma, and W. A. Dunlap of Texas A&M University, College Station, Texas.
>
> Work Unit 1B08, Technical Report D-77-22, Field Study of the Effects of Storms on the Stability and Fate of Dredged Material in Subaqueous Disposal Areas. Principal investigators were H. J. Bokuniewicz, J. Gebert, R. B. Gordon, P. Kaminsky, C. C. Pilbeam, M. Reed, and C. Tuttle of Yale University, New Haven, Connecticut.

This report, also being published as Engineer Manual 1110-2-5001, is one of two synthesis reports developed from DMRP Task 1B, Movements of Dredged Material, and should be used in conjunction with the other synthesis report, entitled Predicting and Monitoring Dredged Material Movement, for a full understanding of the techniques for predicting the spatial and temporal distribution of dredged material discharged into various hydrologic regimes.

Preparation of this synthesis report was under the general supervision of Dr. Robert M. Engler, Manager of the DMRP Environmental Impacts and Criteria Development Project, and Dr. John Harrison, Chief, Environmental Laboratory. Commander and Director of the Waterways Experiment Station was COL John L. Cannon, CE. Mr. F. R. Brown was Technical Director.

PROCESSES AFFECTING THE FATE OF DREDGED MATERIAL

INTRODUCTION

Dredged material deposited in a subaqueous environment may experience various natural physical and biological processes as well as disruptive man-made influences that alter the configuration of the deposit and cause a change in the surrounding bottom. It is this change and subsequent potential environmental impact that causes one to be concerned about the physical fate of dredged material. Prior to the initiation of the Dredged Material Research Program (DMRP), there were no effective means to ascertain the ultimate fate of dredged material and its potential impact on the surrounding area as a consequence of aquatic discharge.

The DMRP recognized a need to develop techniques for determining and predicting the spatial and temporal distributions of dredged material released into various hydrodynamic regimes. To fulfill this need two major topics were addressed: (1) the factors and processes which affect the fate of dredged material in subaqueous disposal areas and (2) the prediction of the dispersion, deposition, and transport of dredged material. This report discusses the first topic.

The results, information, and guidance in this report were derived in part from two DMRP reports entitled "Assessment of Factors Controlling the Long-Term Fate of Dredged Material Deposited in Unconfined Subaqueous Disposal Areas" (Work Unit 1B04) and "Field Study of the Effects of Storms on the Stability and Fate of Dredged Material in Subaqueous Disposal Areas" (Work Unit 1B08), and from site reports for DMRP field studies, and other recently completed research reports are discussed in the following section. This report, as the name implies, is a tool for use by those with the problem of evaluating processes that affect the final disposition or fate of dredged material released into a subaqueous disposal site.

LITERATURE REVIEW

Basco et al.[1] determined that factors that affect the movement of dredged material are identical with those influencing natural sediments and include resuspension by wind-generated waves, transport by tidal currents, salinity-induced flocculation, flood flow rates in rivers, and local boundary conditions. The study concluded that there was a paucity of research investigating sediment transport of cohesive, fine-grained material under various energy regimes.

Bokuniewicz et al.[2] concentrated most of their efforts on disposal sites in Long Island Sound where the dominant source of energy for the suspension and transport of sediment is the tide. However, dredged material placed on the bottom of the Sound may be affected by currents and waves from other energy sources. Their investigations during winter storms and a hurricane determined that fluctuations in current velocities are important in resuspension of dredged material, but that direct, wind-driven flow over the bottom in water depths greater than 60 ft is weak, limiting the potential resuspension of the bottom sediment layer. Repeated bathymetric surveys over a disposal mound in central Long Island Sound revealed that after initial self-consolidation, no significant changes in configuration or erosion could be detected. Bokuniewicz et al. have shown that a naturally deposited mud bottom is the best site to ensure that fine-grained dredged material will not move. Guidelines are given for determining disposal site capacity and how to best emplace the material to ensure minimum disturbance and maximum stability.

Nittrouer and Sternberg[3] investigated the fate of dredged material deposited in a tidal channel of Puget Sound. They determined that the following factors control the stability of a fine-grained dredged material deposit: dilution caused by the dredging and disposal operation, water depth at the disposal site, and the energy regime of the near-bottom environment at the site. They concluded that to maximize the stability of a dredged material deposit requires dredging and disposal techniques that minimize in-place sediment disturbance and the use of low-energy shallow water environments for disposal sites.

Other studies examining the stability and fate of dredged material deposits have been conducted. Saila et al.[4] investigated the disposal of 8.5 million cu yd of sediments from Providence River, Rhode Island, that were dumped in 100 ft of water. A pipeline disposal operation and the subsequent stability of the dredged material was investigated by Biggs[5] in the upper Chesapeake Bay: after five months, approximately 88 percent of the material remained and the stability was attributed to the fact that the Upper Bay is an area of suspended sediment deposi-deposition.

Westley et al.[6] compared the stability of dredged material disposed in different energy environments and from two different dredging methods in Puget Sound. They concluded that barge dumping in a low-energy area results in a stable deposit of dredged material, while fine material released in a high-energy tidal passage will be eroded and the mound will be reworked. Comparison of pipeline disposal to barge disposal indicates that pipeline disposal caused a much broader distribution of deposition than barge disposal and it was not easy to document the fate of this dispersed material on a similar bottom sediment.

The U. S. Army Engineer District, San Francisco,[7] undertook a unique investigation of the fate of dredged material released in San Francisco Bay near Mare Island Strait. Using a special tracer material, sediment was released through a hopper dredge at a disposal site adjacent to the Carquinez Strait Channel. Based on analysis of sediments from an extensive grid of sampling stations, the fate of the material was documented with time. Contained within this report is a discussion of those natural and man-made processes that effect the fate of dredged material deposited in San Francisco Bay.

Johanson et al.[8] investigated the potential of placing dredged material in borrow pits or depressions to enhance the postdepositional stability of the dredged material deposit. They offer guidance on how to use a barge or hopper dredge to release dredged material into subaqueous borrow pits, including suggested effective volumes, navigation techniques, and maneuvering and maintaining position over the pit during disposal. Their study suggests that proper modifications to the disposal equipment and careful handling of the material may reduce the potential for erosion and resuspension of the dredged material deposit within the borrow pits.

Several other field investigations have included documentation of the stability and fate of dredged material in open-water disposal sites; most of these represent contract reports to respective U. S. Army Engineer Districts or U. S. Navy dredging projects. A more detailed listing of these field studies is included in the Bibliography along with references to pertinent laboratory studies that investigated the response of fine-grained sediment and/or dredged material to various environmental parameters.

DISCUSSION

To predict or determine the postdepositional fate of dredged material requires a knowledge of the environment of deposition and the associated energy regime and bottom sedimentology, as well as a thorough understanding of the dredging and disposal operation. Prediction of the initial (predepositional) fate of dredged material requires a prior understanding of the hydrodynamic system and a mechanism such as a mathematical model to describe the complex interactions of erosion, transport, and sedimentation. A detailed methodology and a knowledge of available instrumentation must be developed on a case-by-case basis in order to undertake a field investigation of the fate of dredged material. This section will discuss various methods for investigating the stability and fate of dredged material and will help establish a mechanism for determining which parameters and environmental factors should be considered for a specific site.

What are the Environments of Deposition?

There are four primary environments that may contain a subaqueous dredged material disposal site: the ocean, an estuary, a river, and a lake. Basco et al.[1] compiled and discussed a large number of reports concerning the investigation of factors that affect the fate of dredged material in various environments of deposition. Each environment contains a group of energy regimes attributed to its position within the system.

The ocean

Within the ocean environment four distinct zones should be considered: the deep ocean, the open shelf, the nearshore, and that zone adjacent to inlets, rivers, and estuaries (herein termed the inlet zone for simplification).

The deep ocean. This zone is that portion of the ocean with water generally deeper than 600 ft or the area beyond the continental shelf break. An excellent discussion of the physical factors and various bottom environments may be found in Pequegnat.[9] It is generally assumed that once material reaches the bottom of the deep ocean, the deposit will not move.

The open shelf. The outer limit of the open shelf is the well-defined continental shelf break; the shoreward limit, for the purposes of this discussion, will be the 100-ft depth contour. This zone experiences many physical processes and may contain a variety of sediment types. The primary energy is generated by tidal currents, waves, and semi-permanent shelf currents with substantial increases attributed to storms and frontal movements. Good references for most shelf processes can be found in Swift et al.[10] and Graf.[11] This zone of the ocean does not contain many disposal sites and few studies have been undertaken with respect to the fate of dredged material deposited on the open shelf.

The nearshore. This zone includes that portion of the ocean from the 100-ft depth contour to and including the breaker zone at the beach. The dominant energy forces are waves, longshore currents, and tidal currents. The bottom sediment is primarily sand. This is generally a high-energy zone with a substantial potential for dispersion and reworking of any deposit of dredged material. Most dredged material disposal sites in the ocean are found within this zone and various reports are available that address the fate of the deposits: Sternberg et al.,[12] Saila et al.,[4] Estes and Scrudato[13] and Moherek.[14]

The inlet zone. Adjacent to the mouths of estuaries, rivers, inlets, and bays directly flowing into the ocean is a complex zone where large volumes of sediment are constantly being reworked and where large volumes of material are dredged and disposed. This zone experiences energy extremes similar to the nearshore zone but additionally is subjected to strong tidal currents, multidirectional wave effects, and the effects attributed to control structures such as jetties and is significantly impacted during storms and major frontal systems. This high-energy erosional zone generally can accept large volumes of dredged material with little apparent net change to the bottom. This has been documented off Savannah, Georgia, by Oertel[15] and off Galveston, Texas, by Estes and Scrudato.[13] With the proper knowledge of where this material is going, planned disposal operations could help contribute to down-current nourishment of the beaches or facilitate effective side-casting operations.

The estuary

For this report an estuary is defined as a semi-enclosed coastal body of water that has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage.[16] This broad definition includes many different types of estuaries from the lower portion of the Mississippi River to the Chesapeake Bay. However, for the purposes of this discussion, an estuary will be more closely represented by the Chesapeake Bay system. Within this system there are four distinct zones where disposal sites may be located: the mouth or outlet, the central bay, the tributary entrance or mouth, and the upper bay. Lauff[17] has edited a useful reference book entitled Estuaries, which discusses all aspects of estuaries. Another useful reference for computational considerations is Ippen.[18]

The mouth or outlet. This zone of the estuary is differentiated from the inlet zone of the oceans in that the ocean inlet zone is that area seaward of the estuary mouth while the estuary outlet zone is that area from the mouth to some point inside the estuary. This area is generally dominated by ebb- or flood-tidal dominated sand shoals that may change with each tidal cycle, seasonally or only during storms. Besides the strong tidal flows, heavy wave action is usually experienced on the seaward side of the entrance zone. For good discussions of the flow and shoaling systems, refer to Ludwick[19] and Oertel and Howard.[20] Generally, this is a zone of much dredging but very little disposal.

The central bay. Depending on the configuration and tidal amplitude of the eatuarine system, this zone is generally an area of potential sedimentation having a fine-grained bottom sediment. Central Long Island Sound is a good example of this type of depositional environment.[21] Here water depth and proximity to shipping channels will dictate the fate of dredged material deposits. This zone is usually dominated by tidal currents with a net nontidal component and wave action usually depends on the wind direction and fetch length.[2] Postma[22] described the processes of sediment transport and sedimentation in estuaries, while the U. S. Army Engineer District, San Francisco[7] described the specific processes and fate of dredged material within the San Francisco Bay estuarine system. According to Bokuniewicz et al.[2] areas of measured accumulation of fine sediment within this estuarine zone should be considered good potential disposal sites for dredged material if the water depth is sufficient. However, in order to ensure the effectiveness of this zone as a disposal site, careful planning must be undertaken to calculate the site capacity of each designated disposal area.

The tributary entrance or mouth. This zone may represent an area of shoaling, high tidal currents, and possibly significant wave activity. Dredging and disposal operations often occur within this zone and the sediment may vary from fine clay to sand. Material disposed in this environment will be subjected to periodic erosion from natural physical processes, fisheries activities, and shipping operations. The depth within this zone can vary from tidal flats to 100-ft-deep channels, and the zone represents a highly variable depositional/erosional environment. Any disposal operation within this zone must be carefully planned to ensure minimal impact to adjacent biologically active shoal areas where oystering or clamming may occur.

The upper bay. Within an estuary there will generally be found in the upper reaches of the system a relatively low energy tidal zone with fine silts and clays the predominant bottom sediment. This region usually supports a substantial fishery and in most major estuarine systems is highly populated and industrialized (e.g., Baltimore in the upper Chesapeake Bay). Consequently, there are conflicting opinions about whether such an area should be kept in a pristine condition.

This area usually experiences annual maintenance dredging, and disposal is often required on land or confined to ensure minimal impact on the fishery. However, many of these upper bay zones have well-defined depositional environments where open-water disposal could occur with little potential movement after deposition, such as the areas investigated by Biggs[5] and Westley et al.[6]

Rivers

Like estuaries, rivers have quite variable physical flow characteristics and configurations. The characteristics of a river are determined by the geological system through which it flows and range from unidirectional fresh-water tributaries to complete estuarine systems. The unidirectional flowing river has a relatively constant environment of deposition throughout its length, while the complex river system may have a full spectrum of depositional environments to consider: (1) unidirectional, (2) upper tidal, (3) salt-wedge zone, and (4) mouth.

Unidirectional. Rivers and those sections of rivers with this type of flow characteristic generally have sandy bottom sediments and are dredged by hydraulic suction dredges with pipeline disposal in areas adjacent to the channels. The fate of material in this zone is dependent on the current speeds and stage of the river. Material dredged and disposed at one section often will reenter the system and may be dredged again downstream.

Upper tidal. This zone experiences tidal fluctuations but is fresh water with seasonal low-flow periods when a salt-wedge may develop. Material dredged from this zone is usually disposed adjacent to the channel if it is too far to transport elsewhere. Studies have indicated that portions of this dredged material may return to the same channel reach[23] as fluid mud (fluff) during disposal or by tidal current reworking of the postdepositional mound. Ships' wakes and propellers may significantly affect the stability of these channel deposits.[24]

Salt-wedge zone. Where river water mixes with ocean water, there is a complex zone that is generally described as a salt wedge. At this section of a river or estuary, Krone[25] has described a mixing process that causes enhanced deposition and a turbidity maximum in the water column. This zone usually represents an area of constant shoaling and thus constantly requires dredging and disposal. If material is placed in this part of the river, it will experience tidal currents that may be sufficient to erode and rework the sediment.

River mouth. The mouth of the river can be a complex deltaic system such as the mouth of the Mississippi River or a relatively simple tidal opening into an estuary or ocean. The variability is as great as the number of rivers. This depositional environment will be site-specific and dependent on the energy regime and tidal range of each river. Many characteristics of estuary mouths and tributary entrances will be the same for this zone of a river.

Lakes

This environment of deposition primarily involves the Great Lakes region. The physical processes are very similar to those of an estuary or the open ocean, but the source of energy is not the same. Generally the bottom currents are affected by the wind direction, the thermal stratification of the water column, and proximity to rivers as described by Hough[26] and the U. S. Army Engineer District, Buffalo.[27] Unconfined subaqueous disposal of dredged material within the Great Lakes is in the open lake in depths ranging from 30 to 100 ft. Recent studies near Ashtabula, Ohio, by Danek et al.[28] have shown that dredged material deposits in 50 ft of water (or less) are susceptible to removal by winter storms.

Methodology for Fate Determinations

When a depositional environment has been identified where dredged material will be deposited, a determination can be made about the fate of the material if appropriate data are available. If data are not available a field program will have to be established to measure the postdepositional changes. This section will show how to qualitatively predict the fate of dredged material released in a subaqueous environment, how to determine if sufficient information is available, and how to obtain the necessary data from the field to determine the eventual fate of the mound of dredged material.

Obtaining available data

To predict the eventual disposition of dredged material from a particular dredging project, one must understand the physical processes that may affect the disposal site. This would require searching the literature for previous investigations within or near the disposal area and reports of investigations from other similar areas. To determine if there is sufficient information, a list should be made of necessary considerations. Table 1 lists those parameters that can be obtained from the literature to predict the fate of dredged material at a specific site.

How Do You Use the Data?

With the information listed in Table 1, a good approximation can be made of the fate of disposed dredged material from a specific project. The data can be used to plan the placement of the material and could help in the design of a monitoring program.

To illustrate the process for determining the fate of a dredged material deposit, three examples are given. These represent hypothetical but realistic projects that have previously collected data that can be used for predicting the fate of the material.

EXAMPLE 1. A 6-wk dredging project will produce 200,000 cu yd of dredged material that will be removed by clamshell dredge and transported to a disposal site by 800-cu yd bottom-dumping barges. The disposal site is marked by a dump buoy 1500 ft from a ship channel in approximately 40 ft of water in an estuary whose long axis is oriented NE-SW. The material is fine-grained cohesive mud with a low in-place water content. The bottom has a shallow angle toward the channel but is generally featureless and has sediment properties similar to those of the material to be dredged.

Previous investigations have reported that the semi-diurnal tide (change in tide every 6 hr) generates bottom currents with maximum speeds of 20 cm/sec 3 ft off the bottom and moving parallel to the long axis of the estuary. Winter storms blowing from the NE are the only source of waves large enough to resuspend bottom sediments and there may be as many as four storms, each of three days duration, during a winter season.

Thus there is a basic understanding of the physical setting of the disposal area and the necessary sediment and disposal data to adequately

Table 1

Parameters for Determination of the Fate of Dredged Material

Parameter	Consideration	References
Currents	Near bottom (3 ft off bed) at disposal site; time varying, speed, and direction	Sternberg et al.[12] Bokuniewicz et al.[29,30]
Waves	Continuous measurements at ocean site to determine wave length, height and duration	Sternberg et al.[12]
Tides	Diurnal or semi-diurnal, amplitude, relationship with tides	Bokuniewicz et al.[30]
Suspended sediments	Relationship to tide, currents, waves, proximity of tributaries	Ludwick and Melchor[31] Bokuniewicz et al.[32] Sternberg et al.[12]
Seasonality of information	Summer vs winter conditions for above parameters	Sternberg et al.[12] Danek et al.[28] Bokuniewicz et al.[2]
Storms	Probability of major storms (hurricanes)	Bokuniewicz et al.[2] Beardsley and Butman[33]
Dredging/disposal operations	Hopper, pipeline, barge; stationary or moving	Westley et al.[6] Bokuniewicz et al.[32]
Shipping activities	Disposal site proximity to shipping lanes or channels, wakes, traffic level	Slotta et al.[24]
Fisheries activities	Bottom trawling, shrimping, crabbing, or lobstering.	

(Continued)

Table 1 (Concluded)

Parameter	Consideration	References
Bathymetry	Steep slopes, stable bottom topography, thickness of mound vs depth of site	Bokuniewicz et al.[30,32] Sternberg et al.[12]
Sediments	Grain-size distribution of disposal site sediments, dredged material	Bokuniewicz et al.32 Moherek[14]
Biological activity	Stabilize sediments, flocculation	Rhoads et al.[34]

predict the probable fate of the dredged material.

Specific data that can be used to determine the initial fate from the above example discussion are the sediment type (a cohesive fine-grained mud), the water depth (40 ft), and the 800-cu yd barges dumping at a buoy. These data indicate the material will be point-dumped and will effectively form a mound of cohesive mud with a high critical erosion velocity (the speed the current must attain to cause material to be resuspended from the bottom). The fact that there is a shallow slope suggests that a small amount of the material could move off the mound as a density flow back toward the channel. The environmental conditions suggest that if disposal occurred in late fall, winter storms could affect the fate of the mound to some degree. However, spring or summer disposal would probably allow enough time for the material to equilibrate with the hydrodynamic system and biological repopulation could help stabilize the deposit before winter. During the disposal operation some material may remain in the water column or at the surface; however, this involves the short-term fate of the dredged material, which is discussed in detail in the report on modeling the movement of dredged material.[35]

There was no indication from the example discussion about shipping or fisheries activities, which may affect the stability of the dredged material deposit. Consideration should also be given to the height of the mound: if the mound is too near the surface, it could be more susceptible to erosion and reworking of higher velocity near surface currents and wave activity.

EXAMPLE 2. There are several small dredging projects, both Federal and private, which will each produce approximately 30,000 cu yd of dredged material. Some of the harbors to be dredged contain bottom sediments that are similar to the natural sediments of a nearby estuarine disposal site; one harbor contains only coarse sand shoals; and one harbor contains fine-grained muds with high water contents and contaminant concentrations that have caused environmental concern but that are within permissible limits for open-water disposal. All the dredging will be done by clamshell dredges and transported by bottom-dumping barges to the estuarine disposal site. The disposal site can be classified as a central bay site that has been used at least annually for the past 15 yr, and previous studies have indicated that certain parts of the site contain well-defined mounds of dredged material that have been observed for over 4 yr. However, there are areas where net erosion has occurred and that have a coarser-grained sediment distribution and less biological activity. The depth of the disposal site ranges from 45 to 110 ft with the coarse sediment generally found in the shallow depths.

The tide is the primary energy source generally developing near-bottom maximum currents of 15-25 cm/sec at midtide depending upon the depth (shallow areas have the higher velocities). Wave measurements indicate that currents from waves do not reach the bottom below 60 ft during periods of maximum wave heights and wave lengths. During midtide, maximum velocities increase near-bottom suspended sediment concentrations indicating a slight reworking of the fine fraction of the bottom sediments. However, analysis of current meter velocity records indicate no potential net transport of sediment with either the ebb or flood tide.

With the above information a series of decisions can be made about the disposal operations and a prediction can be made about the fate of the dredged material. The primary concern is the contaminated dredged material from the one harbor. If this harbor were excluded, then the options for the other harbors would be rather straightforward. The coarse sand dredged material could be placed in the shallow region of the site with little concern for its eventual fate. The dredged material from the other muddy harbors could be placed in the deeper part of the site at one buoyed location and would be expected to remain unaffected by physical processes and to experience little reworking of the material.

Considering the contaminated dredged material in the disposal process requires a chronology to be established. The dredging of each harbor should be scheduled to ensure the least impact from this sediment on the estuarine environment. It is apparent that this material should be placed in the deeper water to reduce the potential of reworking these sediments. However, there is little potential for resuspension if the contaminated material is disposed first and then the other sediments placed on them during disposal. If the contaminated material is released last (on top of the other sediments), it would be more spread out on the bottom and more likely to be reworked as the surface sediment.

The dilemma can be solved by using the material from all the harbors at one disposal site and accurately placing the material in a configuration that would effect the containment of the contaminated dredged material. This can be accomplished by initially placing the clean material into four separate mounds in at least 80 ft of water such that they form a closed square with a central area sufficient to act as a protected repository for the contaminated material. When this has been completed, the coarse sand can be released over this contaminated mound to cap the sediment and reduce midtide resuspension and reworking. Accurate navigation and surveillance and the use of taut-line buoys will ensure the accurate deposition of the dredged material. Bathymetric surveys should be undertaken during the disposal operation and immediately after to establish a basis for monitoring the changes which may occur in the mounds.

Because of the environmental concern with the contaminated sediments, a postdepositional monitoring program may be necessary. The previous physical investigations have documented the basic energy regime within the disposal site so that current meter measurements will not be a high-priority parameter to consider. Basically, the monitoring program should be able to address the resuspension and transport of sediments, the change in mound configuration, and the response to biological repopulation that is inevitable with any estuarine disposal site. Consequently, a detailed sediment sampling grid is necessary that can adequately document changes in sediment distribution or mechanical properties of the dredged material. Critical to any monitoring investigation is a statistically sound sampling design and the ability to quickly analyze the data prior to the next sampling period to ensure proper sampling. If the material is being transported in a certain direction, it may be necessary to expand the grid or bathymetry survey transects to include this change.

EXAMPLE 3. A portion of an intracoastal waterway that cuts through a broad shallow bay into a river must be dredged by a hydraulic suction cutterhead dredge with disposal through a pipeline approximately 1000 ft from the channel along one side. Approximately 90,000 cu yd of silty muds with high water contents will be removed. The grain-size distribution of the sediment is very similar to the natural bay sediments; however, the water content of the bay sediments is much less. The bay averages approximately 11 ft deep while the intracoastal waterway is maintained at a 15-ft depth. Tidal currents generally flow parallel to the channel with average velocities of the near bottom currents never exceeding 30 cm/sec except during periods of high river runoff and storms. Prevailing winds are mild and are generally from the landward direction causing little wave activity. However, storms generally approach normal to the channel (move across the channel) from right to left and may develop waves that cause substantial increases in the suspended sediment concentrations throughout the bay.

Previous investigations in this area of the bay have found abundant populations of small burrowing organisms. Bathymetric surveys have indicated that there is a slight shoaling in the proximity of the old disposal sites adjacent to the channel.

The first decision to be made concerns the placement of the material to ensure that it does not return to the channel. From the data and information given, the only direct effect on transporting the dredged material back into the channel would be the storm waves moving across the bay generally right to left. If the pipeline disposal occurs on the left side, this problem would be avoided. This does not mean that the dredged material will not be affected by the storm waves, but it will help reduce the probability of the sediment refilling the channel.

Another operational consideration that could help to secure the fate of the dredged material is the number of positions along the channel where the discharge pipe may be placed. Would it be better to maintain the discharge at one point or move along the channel and allow discharge at various points? From the observations by Nichols et al.,[23] if the pipeline discharge forms a mound with a slope steeper than 1 on 200, the low-density dredged material will flow as fluid mud away from the discharge point. Considering the shallow depth of the disposal site and the large volume of dredged material, it would be advisable to move the discharge point several times during the disposal operation. The thickness of the low-density dredged material should be kept to a minimum to assure rapid consolidation and stabilization. It is recommended that the DMRP report entitled "Prediction and Control of Dredged Material Dispersion Around Dredging and Open-Water Pipeline Disposal Operations"[36] be read to better understand the processes and operational considerations of pipeline discharge projects.

Once the material is deposited in various low profile mounds along the left side of the intracoastal waterway channel, the processes that may affect the fate include the tidal currents, storm wave activity, vessel wakes, biological activity, and fisheries activities. The presence of a large biological population may be an effective mechanism for stabilizing the dredged material deposits. Burrowing organisms can rework the sediments and may cause some of the material to be resuspended, but the overall effect will be to stabilize and enhance the consolidation of the material. Microbial activity and smaller organisms living in or on the silty material can bond the particles with their mucous secretions, increasing grain size and shear strength. Filter-feeding organisms may remove the suspended sediments and deposit them as fecal pellets and rejected particles on the disposal mounds.

It is likely that the dredged material will be reworked to some extent over time as the physical processes within the bay system will try to degrade the deposits to some equilibrium depth. An effective way to monitor the changes in the mounds may be to use silt stakes placed in the bottom prior to the dredging operation in a grid or cross pattern with one transect parallel to the channel and one transect perpendicular to the channel extending far enough to have at least one or two stakes outside the initial influence of the disposal operation. It is important to secure the stakes in such a manner that they will not tend to move up or down in the sediment with time. Bathymetric surveys could be used to observe the changes in the mounds, but care has to be taken to ensure that good tidal control is maintained. In a shallow bay system, winds may cause unusual fluctuations in the water levels that are out of phase with the astronomical tides and could cause substantial errors in water depth corrections.

General Monitoring Methodology

The preceding examples serve to describe methods that can be used to adequately predict the fate of a particular dredged material deposit and to help anticipate the factors that may affect the stability of the sediment. The examples indicate the potential need for field monitoring even when adequate literature is available to document the physical factors present. A basic monitoring design can be developed that can be used with appropriate additions or modification at almost all dredged material disposal sites.

Once the material is deposited, an accurate bathymetric survey should be made with a navigation system (e.g., microwave system or theodolite triangulation) that will allow transects to be run that can be reproduced over time. A statistically sound sediment-sampling grid should be established and replicate samples collected immediately after disposal for analysis of water content, bulk density, shear strength, and grain-size distribution. If similar analyses were made of the material to be dredged or within the disposal vessel, comparisons could be made with the postdepositional properties to determine the depositional character during the disposal process. If, for example, the water contents are lower in the deposit than in the sediments in the disposal vessel, compaction of the material has occurred during initial deposition and may help stabilize the mound. Periodic sampling of these sediment properties will indicate if the erosion potential is changing with time.

At or near the disposal site, at least one continuous recording current meter should be implaced near the bottom. If the disposal site has a range of depths within the site like the Example 2 case, additional sampling at other depths should be undertaken. If restrictive shoals or abnormal topographic highs or lows are evident, sampling of the flow structure around or over these features will be necessary.

Underwater television inspection or bottom photography at regular intervals over the disposal site are useful for visually observing either biological or sedimentological changes. These observations become especially useful after storms or strong wave activity when changes may occur in the bottom sediments. Suspended sediment sampling upstream and downstream during a complete tidal cycle can yield correlative information about the resuspension and transport of the dredged material. Instrumentation for collection of these data are well documented in various DMRP field study reports and site reports and in other literature discussed earlier. As in any field program using instrumentation for collection of data, it is extremely important to calibrate the instruments before and after the periodic sampling. This will ensure valid data that can be used by other investigators, in environmental assessments, and, when necessary, in legal proceedings.

The number of sampling periods depends on the environment and the energy regime at a specific disposal site. If the meteorological records indicate that there are distinct periods or seasons with substantial changes in the weather patterns, such as reversals in the predominant wind direction, sampling periods should be frequent enough to address the potential changes that may occur to the sedimentological environment. Sampling frequencies should consider when expected periods of stratification occur in the water column, especially in the Great Lakes, because of the potential changes in currents that may occur concurrently.

Documentation and observation should be made of the shipping activities and the effects of deep-draft vessels passing over a disposal site. In some estuaries, ships' wakes generate abnormally large waves that move out of the channel onto the shoals. These waves can be a significant mechanism for eroding and resuspending dredged material deposited within this environment.

In areas such as the Gulf Coast, intense shrimping activities can effectively obliterate a dredged material disposal mound (as a result of the nets dragged along the bottom) and must be considered in the documentation of factors potentially detrimental to the stability of dredged material. Other fisheries activities can affect the bottom sediments as well, including lobstering, crabbing, oystering, and clamming operations.

Some disposal sites experience annual or continual disposal throughout the year, making it difficult to monitor the long-term fate of material from a specific disposal operation. If a certain project must be monitored within a site that constantly receives dredged material, it may be necessary to place the material to be monitored in a separate section of the site.

Almost every disposal site will be unique in some respect and will require modification of a general monitoring methodology; however, the parameters in Table 1 will be the same and can be used for all sites.

It would be appropriate to supply a set of equations or graphs that could be used to quantitatively describe the postdepositional fate of any dredged material deposit in any environment. However, the variability of physical processes, the broad distribution of sediment grain sizes and mechanical properties, the inherent fluctuations in the rate of volume discharge by various disposal methods, and the unpredictability of the weather preclude the generation of these equations or graphs. Most of the previous work on sediment transport relationships has been concerned with homogeneous sediments and primarily coarse-grained, noncohesive particles. Dredged material can contain a mixture of sand, silt, and clay; unusually high percentages of water; or cohesive clumps or clods. There are no formulae that can be applied to this type of sediment that will describe the erosion potential under various hydrodynamic regimes.

There are disposal sites where dredged material has remained in place in spite of strong currents and waves that could readily erode the individual particles, suggesting the need for a process-oriented sediment classification system for dredged material. Conversely, there are disposal mounds that have literally vanished with little indication of the eroding mechanism. This phenomenon may be attributed to a lack of proper environmental monitoring and instrumentation rather than a "Bermuda Triangle" syndrome. The physical processes that may affect the postdepositional stability of dredged material can be recognized, but the interactive response and rate of change are still to be understood.

SUMMARY

Dredged material placed on the bottom of an ocean, lake, estuary, or river may experience various natural processes that could alter the initial configuration of the deposit and subject the surrounding bottom to some level of environmental impact. Thus determination of the fate of dredged material is an environmental concern and requires consideration and adequate prediction in the planning of a dredging project. In the selection process for a disposal site, consideration must be given to the eventual disposition of dredged material in order that adequate determination of the site capacity can be made.

The four primary environments that may contain subaqueous dredged material deposits are oceans, estuaries, rivers, and lakes with various energy related zones within each environmental system. Each zone has a unique set of physical factors and sedimentological properties that will determine the potential fate of a dredged material deposit.

Prediction of the fate of dredged material at a disposal site requires a knowledge of the following parameters: (1) currents, (2) waves, (3) tide, (4) suspended sediment concentrations, (5) seasonal energy fluctuations, (6) storms, (7) dredging/disposal operation, (8) shipping traffic, (9) fisheries activities, (10) bathymetry, (11) sedimentology, and (12) biological activity.

Methodologies for monitoring the actual changes that do occur at a disposal site have been adequately documented at representative environments of deposition. As more knowledge is gathered, a better understanding of the interaction of the physical processes and the fate of subaqueous deposits of dredged material will be established.

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