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LITERATURE REVIEW AND TECHNICAL EVALUATION OF SEDIMENT RESUSPENSION DURING DREDGING

by

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Maintenance of navigable waterways is essential for continuous traffic flow. The sediments in the waterways, however, have, in many instances, become contaminated over the years, resulting in a concern that dredging and disposal of the dredged material may adversely affect water quality and aquatic life. Conventional dredges such as hopper suction dredges, cutterhead dredges, dustpan dredges, and bucket or clamshell dredges share the burden of dredging. Most dredges in the United States are old and are not designed to handle highly contaminated sediments.

The present study is a literature review and technical evaluation of conventional and unconventional dredges, their dredging techniques, factors influencing the sediment resuspension characteristics associated with such dredges, the nature of improvements that have been made in such dredges to reduce their environmental impact, and further research needed in this field.

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This literature review indicated that all conventional dredges generate turbidity in the vicinity of the dredge to a varying degree depending on the type of dredge, the nature of sediment, and the dredging and disposal method adopted. The turbidity is usually of a short duration, and normal conditions are quickly restored. There was more turbidity in the case of open-water disposal than at the dredge itself. The turbidity was also found to be higher for fine material such as silt and clay than from coarse-grained material. The sediment resuspended by dredging may release into the water column some contaminants that affect the environment. Measures such as silt curtains are only partially successful in that these do not eliminate the impact on the benthic community along the bottom. Further research is recommended to study measures to reduce turbidity generation at the dredge.

Unconventional dredging systems such as Pneuma pumps, Oozer dredges, and Mudcat dredges appear to be successful in reducing sediment resuspension but are unable to handle large quantities of material. Therefore, detailed studies are recommended to evaluate sediment resuspension by these dredges.

SUMMARY

The literature review and technical evaluation of sediment resuspension during dredging reported herein were part of the US Army Engineer Waterways Experiment Station's study to evaluate existing dredging equipment and dredging techniques and to describe improved techniques for dredging highly contaminated sediments in order to minimize the environmental impact associated with such activities.

In the first phase of the study, data on dredging equipment and techniques were collected from various agencies such as US Army Corps of Engineers District Offices, the US Environmental Protection Agency, and authorities in the field of dredging in the United States, Japan, and Europe. These data were compiled and evaluated to establish a general database on the performance of conventional dredges and to identify factors that influence the generation of turbidity during the dredging process. Possible measures to reduce sediment resuspension and undesirable environmental impacts by conventional dredges were examined, and their relative merits and demerits were assessed.

In view of the development and large-scale use of unconventional dredges in Europe and Japan for highly contaminated sediments, these dredges were also studied, and possible use in the United States was examined keeping in view the limitations of such equipment.

PREFACE

The literature review and technical evaluation of sediment resuspension during dredging reported herein were part of the work being conducted by the US Army Engineer Waterways Experiment Station (WES) to evaluate existing equipment and dredging techniques and to develop improved techniques for dredging highly contaminated sediments. This study is one of several conducted under Work Unit 32433, "Contaminant Release Control During Dredging," of the Improvement of Operations and Maintenance Techniques (IOMT) Program, sponsored by Headquarters, US Army Corps of Engineers (HQUSACE). Overall management of the IOMT Program is assigned to the WES Hydraulics Laboratory (HL), and this work unit was further assigned to the WES Environmental Laboratory (EL). This study was performed under Contract No. DACW39-82-M-3249 to the Center for Dredging Studies, Texas A&M University, College Station, TX.

This report was written by Dr. John B. Herbich, Director, Center for Dredging Studies, and Head, Ocean Engineering Program, and Mr. Shashikant B. Brahme, Ocean Engineering Program, Texas A&M University. Data and reports were obtained from most of the District Offices of the US Army Corps of Engineers and the US Environmental Protection Agency. A part of the information was also obtained from agencies and individuals in The Netherlands and Japan.

This study was monitored by Dr. Raymond L. Montgomery, Chief, Environmental Engineering Division (EED), EL, WES, under the general supervision of Dr. John Harrison, Chief, EL. The IOMT Program Managers were Messrs. E. Clark McNair, Jr., and Robert F. Athow, Jr., HL. Technical Monitors for HQUSACE were Messrs. James L. Gottesman and Charles Hummer. Extensive review and revisions were provided by Dr. Robert N. Havis and Mr. Donald F. Hayes, both of the Water Resources Engineering Group, EED. Ms. Cheryl M. Lloyd provided assistance in preparing the report for publication. Technical reviews were provided by Dr. Havis and Dr. Michael R. Palermo, EED. The report was edited by Ms. Lee T. Byrne of the Information Technology Laboratory, WES.

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CONVERSION FACTORS NON-SI to SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic yards	0.7645549	cubic meters
degree (angle)	0.01745329	radians
feet	0.3048	meters
gallons (US liquid)	3.785412	cubic decimeters
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	25.4	millimeters
knots (international)	0.5144444	meters per second
miles (US statute)	1.609347	kilometers
square miles	2.589998	square kilometers
tons (2,000 pounds, mass)	907.1847	kilograms

LITERATURE REVIEW AND TECHNICAL EVALUATION OF SEDIMENT RESUSPENSION DURING DREDGING

PART I: INTRODUCTION

Background

1. The job of developing and maintaining the Nation's waterways is entrusted to the US Army Corps of Engineers (USACE). A large portion of the necessary work is conducted by private industry under contract with the Corps, which maintains a small fleet of dredges including hopper dredges, side casters, hydraulic cutterheads, and dustpans. The cost of dredging is increasing every year. A National Dredging Study conducted in 1975 indicated that a total of over 450 dredges belonged to the dredging industry (Murden and Goodier 1976) and ranged from hydraulic units, with and without cutterheads, to wireline-operated bucket dredges and dipper and dragline dredges. This 1975 National Dredging Study also revealed that the US dredging fleet was aged, suffered from obsolescence, lacked deep-dredging capabilities, and needed accurate production instrumentation. The study spurred substantial improvements and additions, both private and government-owned, to the US dredging fleet.

2. The contamination of sediments in many US waterways and harbors over the years has resulted in much concern that dredging and disposal of dredged material may adversely affect water quality and aquatic life. A number of localized studies have been conducted in the past to investigate the environmental impact of specific disposal practices and to explore alternative disposal methods. Since these studies did not provide sufficient definitive information on the environmental impact of disposal practices, it was concluded that a broad-based program of research was needed to develop the widest possible choice of technically satisfactory, environmentally compatible, and economically feasible disposal practices (Huston and Huston 1976). As a result, the USACE was authorized by the River and Harbor Act of 1970 to implement a nationwide program to provide more definitive information on the environmental impact of dredging and dredged material disposal operations. With the established importance of dredging and the need for environmentally

compatible dredging and disposal operations, much public emphasis has been placed upon the effects of dredging and disposal practices on water quality. At the same time, concern was expressed about turbidity created by dredging and disposal operations.

3. The past dredging practices in the United States have evolved to achieve the greatest possible economic returns through maximizing production with only secondary considerations given to environmental impacts. The conventional dredges, therefore, are not specifically designed or intended for use in dredging highly contaminated sediments. However, modifications to equipment and dredging techniques could potentially result in their use in dredging highly contaminated sediments with minimal adverse impact on the environment. The US Army Engineer Waterways Experiment Station (WES) is conducting studies to evaluate existing equipment and dredging techniques and to develop improved techniques for dredging highly contaminated sediments (Montgomery and Raymond 1982). Barnard (1978), published under the Dredged Material Research Program (DMRP), summarized several studies that investigated the amount of turbidity generated during dredging for various types of equipment and operating conditions. However, a more detailed review of existing research results is necessary to identify dredging equipment and techniques for use in minimizing turbidity and contaminant dispersion at the point of sediment excavation. Considerable information is available from various literature sources regarding the problem of dredged material resuspension during dredging. There is a need to evaluate all the available information and provide guidance in selecting the best dredges for various projects involving contaminated sediments. Such literature evaluation will also contribute to the assessment of needs for new improved equipment and techniques for dredging contaminated sediments. Turbidity will be the indicator parameter of sediment resuspension around the dredge.

Objectives

4. The study reported herein was undertaken in two phases. Task I basically consists of a literature review to determine what has been done to evaluate the environmental impact associated with different types of dredging equipment and techniques. This phase of the study includes collection and analysis of data available from various Corps Offices and other sources both

domestic and foreign. This establishes a general data base on the performance of conventional dredges. Based on knowledge, experience, and existing research results, the important factors influencing the generation of turbidity during dredging are identified. These factors include, but are not limited to, the type and characteristics of the dredge, the sediment types, and the environmental and operational conditions. The important turbidity-producing factors are identified for each conventional dredge, which includes hopper, cutterhead, plain suction, dustpan, and bucket. Unconventional dredging systems presently in use to pump slurries with high solids content or to minimize sediment resuspension are also considered. Past work on the use of hooded shields on cutterheads, silt curtains, and other equipment used to reduce turbidity around the dredge head is reviewed and evaluated. In compilation of the existing data, the resuspension of solids during the dredging process and the resulting turbidity are considered.

5. In Task II, the existing equipment and dredging techniques are evaluated, and a detailed report presents an evaluation of the solids resuspension potential for each type of dredge. The main objective in compiling and evaluating these data is to provide information to aid in the future development of rating factors that will be used in determining potential resuspension of contaminants for each of several dredging types and dredging conditions.

Inquiries and Data Collection

6. Most of the data perused for the literature review in the present study was obtained from the main library of Texas A&M University (TAMU) and the small library of the Ocean Engineering Program and Center for Dredging Studies, TAMU. The literature used consists of publications from the DMRP and the Environmental Laboratory of WES, the US Environmental Protection Agency (USEPA), the proceedings of the U.S./Japan Experts Meetings, the World Dredging Conferences, and journals related to dredging such as World Dredging and Marine Construction, Ports and Dredging, Hydro Delft, Land and Water International, and Dock and Harbour Authority. Efforts were made to contact knowledgeable persons in the field of dredging, both domestic and foreign. A list of persons contacted is given in Appendix A. A list of data and reports received from various organizations is presented in Appendix B. Appendix C contains abstracts of selected references and personal communications.

PART II: TURBIDITY AND ITS EFFECT ON THE ENVIRONMENT

7. Human activities such as dredging and filling operations and agricultural, industrial, and municipal effluents are contributing to the increase in turbidity and suspended material. Turbidity creates aesthetic problems associated with the reduction in water quality. In addition, some aquatic organisms are sensitive to increases in turbidity and resuspension material (Stern and Stickle 1978). Turbidity is not a simple parameter, but represents a complex composite of several variables that individually and collectively interfere with the transmission of light through a liquid medium. Confusion is created in view of the use of different interchangeable terms such as transparency, visibility, clarity, opacity, color, and suspended solids. In older literature, the word "siltation" has been used in place of turbidity quite often. Stern and Stickle (1978) have reviewed the various definitions on turbidity, and these are briefly explained in the following paragraphs.

Definitions

8. Several authors, including Austin (1973, 1974), Carranza (1973), and McCluney (1975), have thoroughly and critically reviewed the various definitions of turbidity appearing in the literature. The variety of substantially different turbidity definitions is due first to the differing needs of investigators in various disciplines and whether true extinction (unscattered light) or diffuse extinction (scattered and unscattered light) is involved, and, secondly, whether several optical properties rather than a simple optical property are operating.

9. A number of quantitative definitions based on optical and gravimetric principles are also available in the literature. The transmission of light through water is always associated with attenuation caused by two processes, absorption and scattering. According to McCluney (1975), some definitions do not apply to the reduction in transparency caused by both processes. Absorption is the conversion of radiant energy into other forms of energy, including heat and photosynthetic energy. Jerlov (1970) indicates that scattering is produced as a result of discrete particles and may be considered the deviation of the incident beam from rectilinear propagation.

10. In natural waters the dissolved light-quenching components absorb light, and the suspended particulates are responsible for absorption as well as scattering, with angular variation of particulate scattering proportional to the nature and size of the particles. In general, absorption predominates in clear lakes and oceanic waters, while scattering is the predominant optical property in rivers and estuaries.

11. The term "turbidity" has numerous definitions and units of measure and, for convenience, is used for all water clarity measurements. One of the most widely accepted qualitative definitions of turbidity is that proposed by the American Public Health Association (APHA) (1976). Turbidity is defined as "an expression of the optical property of a sample that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample." This definition is qualified with the additional statement that "attempts to correlate turbidity with the weight concentration of suspended matter are impractical because the size, shape and refractive index of the particulate materials are important optically but bear little direct relationship to the concentration and specific gravity of suspended matter." This has been demonstrated by numerous investigators (Stern and Stickle 1978). The recognition of this led Carranza (1973) to include within his definition the statement that turbidity must be defined and measured in a specific manner for each discrete particle system. Although the APHA definition encompasses a large number of other qualitative definitions found in the literature, several authors argue that it is inadequate because it is not clear what methods of measurement have been applied to turbidity and suspended material in aquatic environments. Because the concept of turbidity involves optical properties that cannot be correlated with the weight-volume concentration of suspended material (which directly affects the aquatic fauna), several investigators have suggested that the term be used only as a nontechnical descriptor of appearance.

12. In this report the term "turbidity" will be used when an optical measurement of water quality was made, and the term "total suspended sediments" (TSS) will be used when a gravimetric measurement of water quality was made. Also, the term "sediment resuspension" will be used to describe the mixing of sediment into the water column due to dredging activities except in cases where a specific term has gained acceptance in the literature such as Nakai's (1978) "turbidity generation unit" (TGU).

Turbidity Units

13. The units of turbidity measurement are as varied as the definitions of turbidity. In the early 20th century, the Jackson Candle Turbidimeter was used to measure turbidity. This turbidimeter consisted of a special candle and a glass tube that had been graduated in Jackson Turbidity Units (JTU). The measurement was made by pouring a turbid sample into the tube while observing the candle flame through the sample. The turbidity in JTU's corresponded to the depth of the sample in the tube at the point of image extinction. The candle turbidimeter is no longer widely used, but the scale remains and is the basis for all turbidity measurements in JTU's. In 1926 formazin was developed as an alternate standardizing material. The formazin turbidity standard has a Jackson turbidity value of 4,000 units. The new turbidity unit, the Formazin Turbidity Unit (FTU), has been widely adopted. A new unit, the Nephelometric Turbidity Unit (NTU), has been recently introduced into usage by APHA (1976). Nephelometric units are based on a formazin standard and tie the unit of turbidity measure (the NTU) to the instrumental principle (nephelometry) from which the unit is derived. Nephelometry measures the amount of light reaching a sensor at 90 deg,* rather than at 180 deg, to the incident beam as in most turbidimeters (Stern and Stickle 1978).

Turbidity Measurements

14. Stern and Stickle (1978) state that most of the currently used methods of measurement of turbidity and suspended material are either gravimetric or optical measurements based on either standard suspension of known turbidities or on the absolute measurement of some optical property. There is common agreement that the optical instruments in use provide an infrared rather than a direct measurement of suspended solids and that it is almost impossible to transfer the relationships between sediment concentrations and optical characteristics from one type of turbidimeter, standard suspension, or unit of measure to another. Gravimetric techniques probably represent a more accurate measurement of the effects of suspended solids on the aquatic fauna

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 8.

while optical measurements may be preferable for photosynthetic or aesthetic purposes (Stern and Stickle 1978). Another turbidity measurement method which is currently under investigation and has shown much promise is the multi-frequency acoustic profiler (Datasonics, Inc. 1983).

Effects of Dredged Material Resuspension on the Environment

15. Pequegnat et al. (1978) discussed in detail the various impacts of dredged material disposal on the ocean. These impacts are of short- and long-term nature and can be grouped into the following three broad categories: (a) physical impacts, (b) chemical impacts, and (c) biological impacts. Increase in turbidity is one of the most important of the physical impacts. The cloudiness associated with turbidity causes considerable unfavorable public response to some dredging projects. The increase in turbidity accentuates light to some extent. Pequegnat et al. (1978) found that turbidity is one of the important factors controlling horizontal and vertical distributions of bacteria and fungi in the ocean. A significant increase in turbidity is often accompanied by an increase in bacteria counts, while a decrease in turbidity generally causes decreasing numbers of bacteria. Other important physical impacts of turbidity are the aesthetically displeasing nature of turbidity, decreasing availability of food, migration of mobile organisms out of the environment, topographic modifications, and moderate modifications of bottom currents.

16. Pequegnat et al. (1978) examined the chemical impacts of dredged material on the disposal environment and stated that they are difficult to predict and even more difficult to control. The dredging and disposal practices are likely to affect adversely the water quality parameters such as oxygen, nutrients, trace metals, and pesticides that are known to affect marine life. In order to evaluate these effects, the USEPA (1973a, 1973b) recommends the elutriate test, which is designed to simulate open-water disposal of dredged material.

17. Keeley and Engler (1974) discussed the rationale behind the elutriate test development as follows:

> ...regulatory agencies faced with the legislative requirement of establishing dredged material criteria must strive to establish meaningful criteria based on the best possible knowledge, and avoid the tendency to set forth criteria that preceded the current technical state of the

art. Furthermore, regulatory criteria should be based on laboratory procedures that can be performed satisfactorily in routine testing laboratories as opposed to complicated procedures that can only be conducted in sophisticated research-level laboratories.

Figure 1 depicts the standard elutriate test. This test involves mixing sediment to be dredged with water from the dredging or disposal site, separating the two, and analyzing the water, especially for nutrients and known contaminants. The elutriate test has added greatly to the understanding of contaminant releases into the water column. Among the important chemical impacts are the changes in oxygen concentration; the uptake and release of nutrients; and the uptake and release of toxins such as trace metals, halogenated hydrocarbons, petroleum hydrocarbons, and unknown toxins as detected by bioassay. It is generally recognized that some oxygen loss will occur when any sediment is exposed to oxygenated water, but the magnitude of the loss will depend on the particular sediment and the chemical and physical factors in the disposal environment (Pequegnat et al. 1978). One measure of the potential loss is the chemical oxygen demand (COD) of the material. The Federal Water Quality

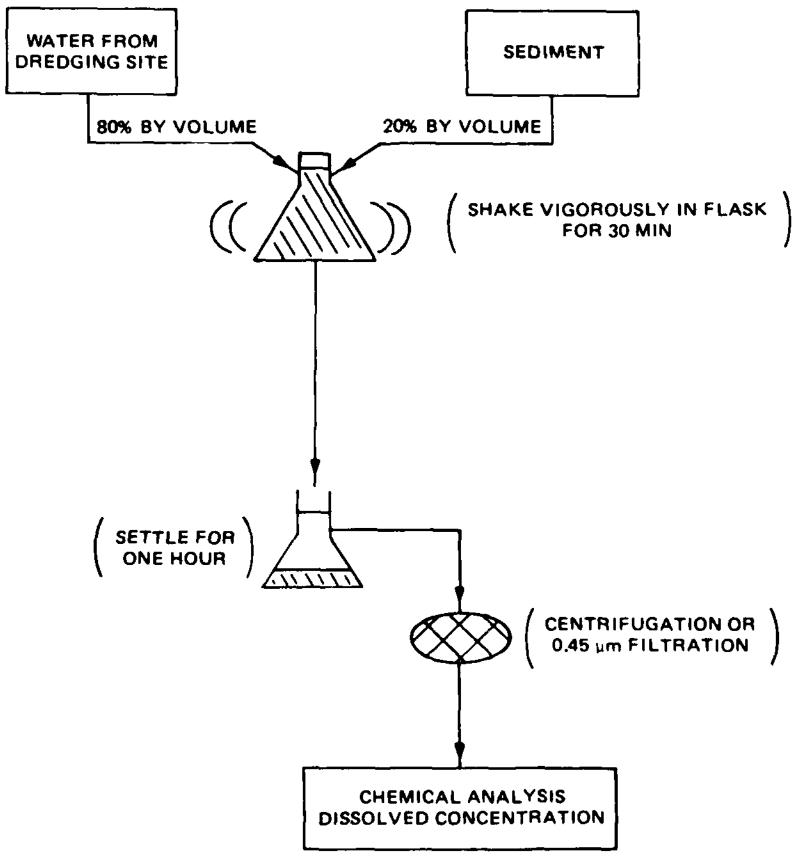


Figure 1. Standard elutriate test

Administration (FWQA) criteria for the suitability of the sediment for dredging and disposal gave a maximum value of 5 percent (i.e. 5 percent of the sediment, by dry weight, requires oxygen to stabilize). The uptake and release of nutrients can have potentially significant effects on both pelagic and benthic organisms. The extent of biological effects, however, is largely dependent on the rate of dilution of added nutrients and the rate of renewal of water. Studies conducted earlier by Ketchum (1972) have revealed that man's activities are drastically increasing the input of many metals to the ocean (Pequegnat et al. 1978). Some metals such as mercury, cadmium, arsenic, chromium, copper, and lead can act as powerful toxins, not only to marine organisms but also to man if he consumes seafood contaminated with these. The magnitude of impact from these sources would depend on the mobility of these materials and their availability to the biota. Lee (1976) found that the effects of chemical contaminants on the water column are primarily short term and are manifested either as toxicity to water column organisms or stimulation of noxious aquatic plants. He further stated that the real concern over chemical contaminants is from the potential long-term chronic toxicity effect and the transfer of contaminants from sediments to fish and other organisms.

10. Stern and Stickle (1978) concluded that turbidity and suspended material can play both a beneficial and a detrimental role in aquatic environments. Suspended material sorbs and removes contaminants from the water column and stimulates photosynthesis through the introduction of inorganic nutrients. There is also a possibility that the nutrients might stimulate excessive biological growth and that turbidity might reduce photosynthetic activities because of its interference with light penetration. Pequegnat et al. (1978) made a detailed study of the biological impacts of contaminated dredged material. Their analysis indicated in some detail the types of biological effects likely to occur within the areas most heavily impacted by disposal materials. Among the important biological impacts listed are destruction of spawning areas, smothering and suffocation of organisms, and sorption of toxic materials. Both Pequegnat et al. (1978) and Stern and Stickle (1978) have concluded from their studies that, although some temporary and local damage may occur to the benthic species, the temporary increases in turbidity and suspended material will not cause significant or long-lasting effects to the benthic species of the marine ecosystems.

PART III: WATER QUALITY AND USEPA REGULATIONS

19. Dredging and filling in navigable US waters have been regulated for 80 years under provisions of Section 10 of the River and Harbor Act of 1899. Since 1968, major Federal legislation has expanded the criteria for decision on Section 10 permit applications to include numerous public interest factors in addition to navigation. With the enactment of the Federal Water Pollution Control Amendments of 1972, Section 13 of the 1899 Act was amended and expanded to create a water pollution control program regulating discharges of all classes of pollutants into the Nation's waters. The new statute established the Section 404 program to regulate discharges of dredged or fill material with responsibilities for administration divided between the Department of the Army and the Administrator of the Environmental Protection Agency. The geographic scope of the Section 404 program is substantially broader than that available in the 1899 Act (Crowder 1980).

20. The National Environmental Policy Act of 1969, the National Historic Preservation Act of 1966, and the Coastal Zone Management Act of 1972 are the major environmental laws which, in combination with the River and Harbor Act of 1899, have substantially improved the degree to which environmental values are protected through the Department of the Army's Section 10 permit program. These statutes, together with a number of other environmental and other laws, have led to the Department of the Army's expansion of the public interest review of permit applications to embrace currently a total of 16 specifically named factors (Crowder 1980). These 16 factors are conservation, economics, aesthetics, general environmental concerns, historic values, fish and wildlife values, flood-damage prevention, land use, navigation, recreation, water supply, water quality, energy needs, safety, food production, and the needs and welfare of the people in general. The Federal Water Pollution Control Act of 1972 (FWPA) is a comprehensive water pollution control act and embodies a national goal "to restore and maintain the chemical, physical and biological integrity of the Nation's waters."

21. In the United States, there is much concern regarding toxic sediments in both marine and fresh waters. Sediments carrying toxic chemicals can enter the waters from several sources. Sediments already in place may also acquire toxic substances through waste discharges or accidental spills. Apart from sediments coming from soil erosion, the principal sediments are materials

discharged through pipes and materials dumped from ships and barges (Bartsch 1976). Some of these sediments become dredged material at a later time. The United States, like many other countries, has experienced a number of episodes involving toxic substances in bottom sediments, notably polychlorinated biphenyl (PCB), mercury, kepone, etc. Because these toxic substances entered into the food chain, it was found desirable to establish tolerance limits in food. Therefore, various agencies such as the USEPA and the US Food and Drug Administration established tolerance limits for various toxic substances in water.

PART IV: SEDIMENT RESUSPENSION

Classification and Properties of Dredged Material

22. The total quantity of sediment resuspended during a dredging process depends on the type of dredges used as well as the type of soil being dredged. A large volume of data is available on the soil characteristics at different dredging sites in the United States. Bartos (1977) conducted detailed studies on the classification and engineering properties of dredged material from various US dredging sites. The frequently dredged USACE navigation projects from where the sediment samples were taken are shown in Figure 2.

23. A number of standard soil properties tests were used to determine the physical and engineering properties of dredged material samples. Soil tests included (a) classification properties tests such as grain size, plasticity analyses, and organic content determinations and (b) engineering properties tests such as compaction, consolidation, and shear strength. In the

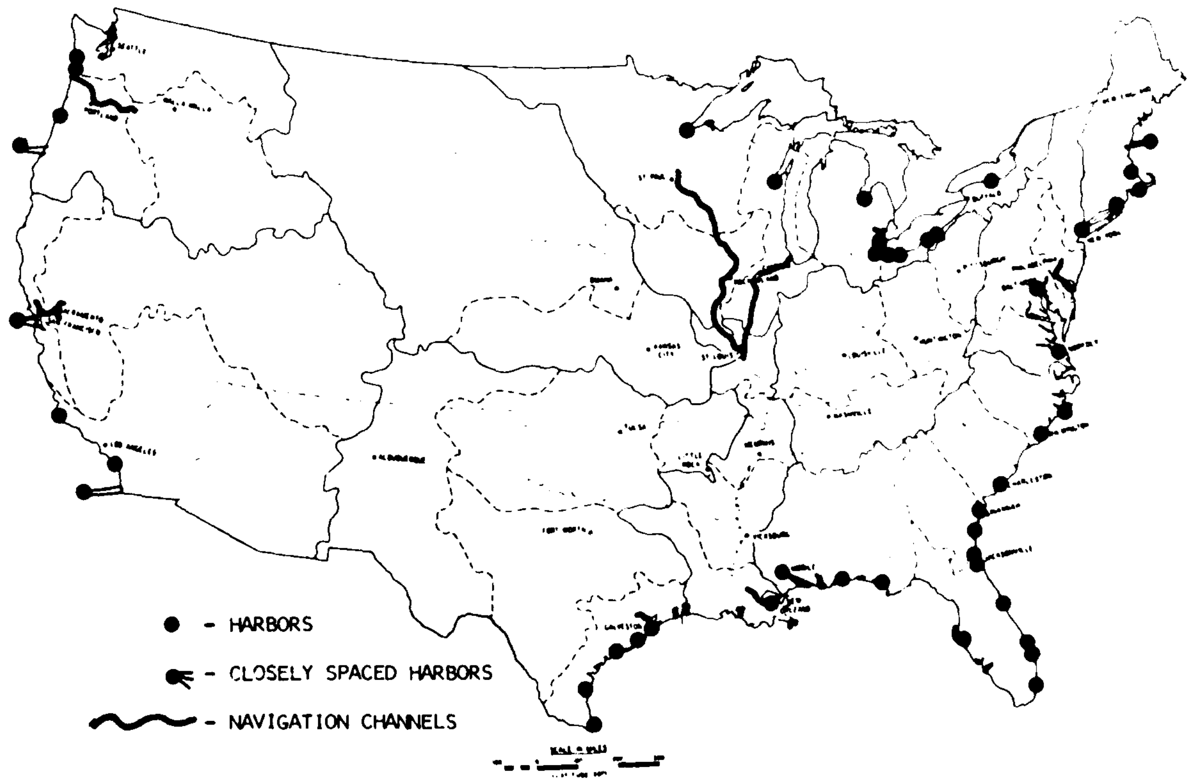


Figure 2. Location of study projects (from Bartos 1977)

study, the various dredging sites were grouped into five regions: region A, Gulf States; region B, South Atlantic; region C, North Atlantic; region D, Great Lakes; and region E, Pacific Coast. Figures 3 and 4 show the regional distribution of dredged material types according to the Unified Soil Classification System (USCS). Figure 5 gives grain-size distribution curves for typical samples from regions A to E. Table 1 shows the ranges of classification test data determined for the dredged material. The information presented in this report is indicative of the types of dredged material found in each of the study regions.

24. The samples of dredged material taken from within the Gulf States study region fell into seven of the USCS classification groups. Figure 3 shows that less than 33 percent of the samples were classified as sandy material and the remaining two-thirds (67 percent) consisted mostly of CH, which means inorganic fines of high plasticity. In the South Atlantic study region, the dredged material samples ranged from poorly graded gravels (GP) to plastic and organic clays (CH and OH). In the North Atlantic study region the samples consisted of 27-percent organic clay and 26-percent poorly graded sand, and the remaining samples were evenly distributed among 10 different classifications of the USCS system. In the Great Lakes study region, the predominant types of dredged samples were poorly graded sand (SP) and clay of high plasticity (CH). The majority of the fine-grained material was highly plastic (CH). There were no samples of organic dredged material. In the Pacific Coast study region, the material ranged from well-graded sand (SW) to organic fines (OH). The predominant type of dredged material was poorly graded sand (SP). Figure 4 shows the division of samples into four categories and is intended to show the fractions of the samples there were coarse, plastic, nonplastic, or organic.

Resuspension Potential of Sediments--Laboratory Studies

25. In view of the potentially deleterious environmental effects caused by sediment resuspension by dredging and open-water disposal operations, detailed laboratory studies were conducted by Wechsler and Cogley (1977). Two purposes of these studies were (a) to develop a means of predicting the nature, duration, and extent of turbidity that a given sediment is likely to produce when resuspended by dredging operations and (b) to evaluate the

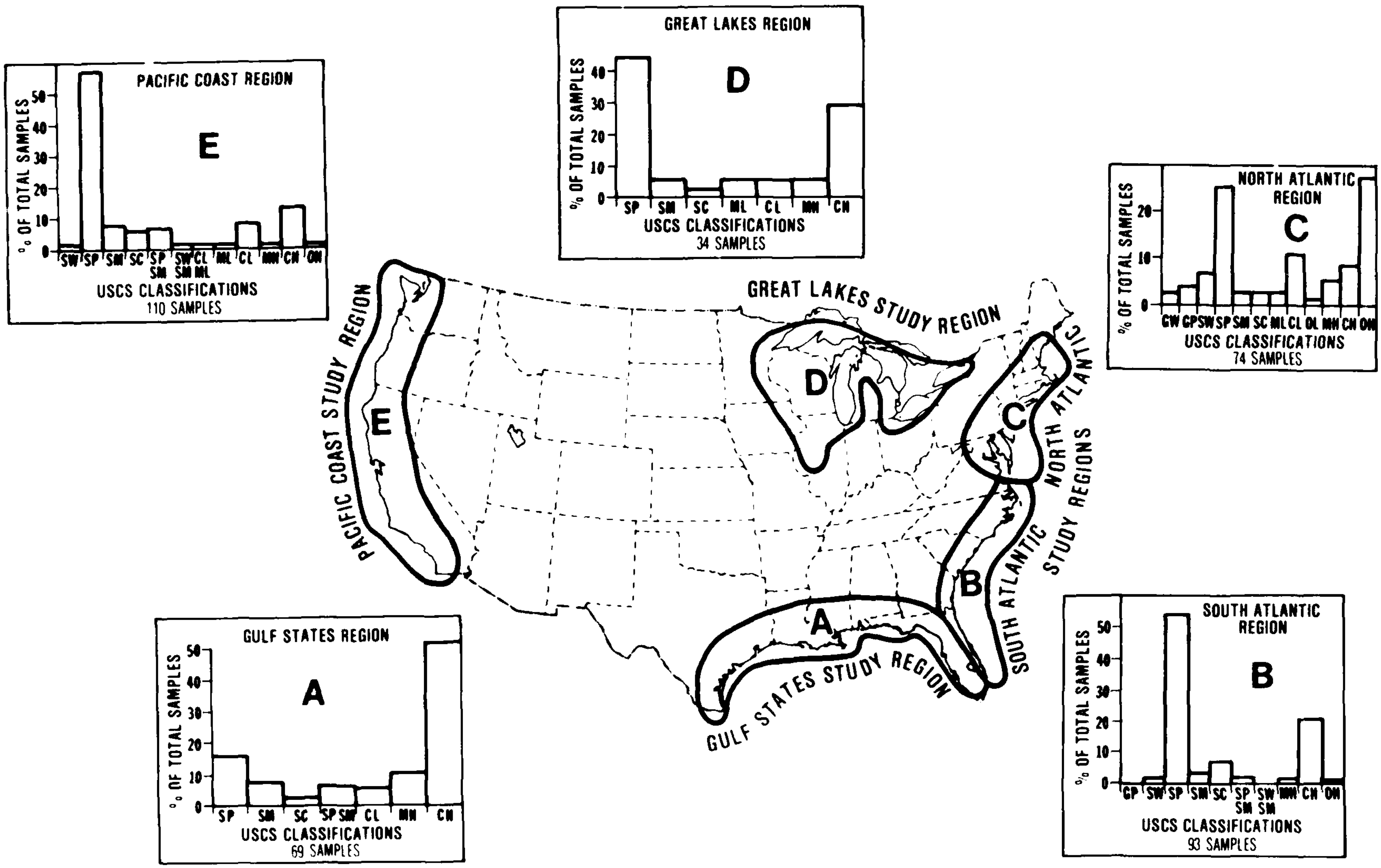
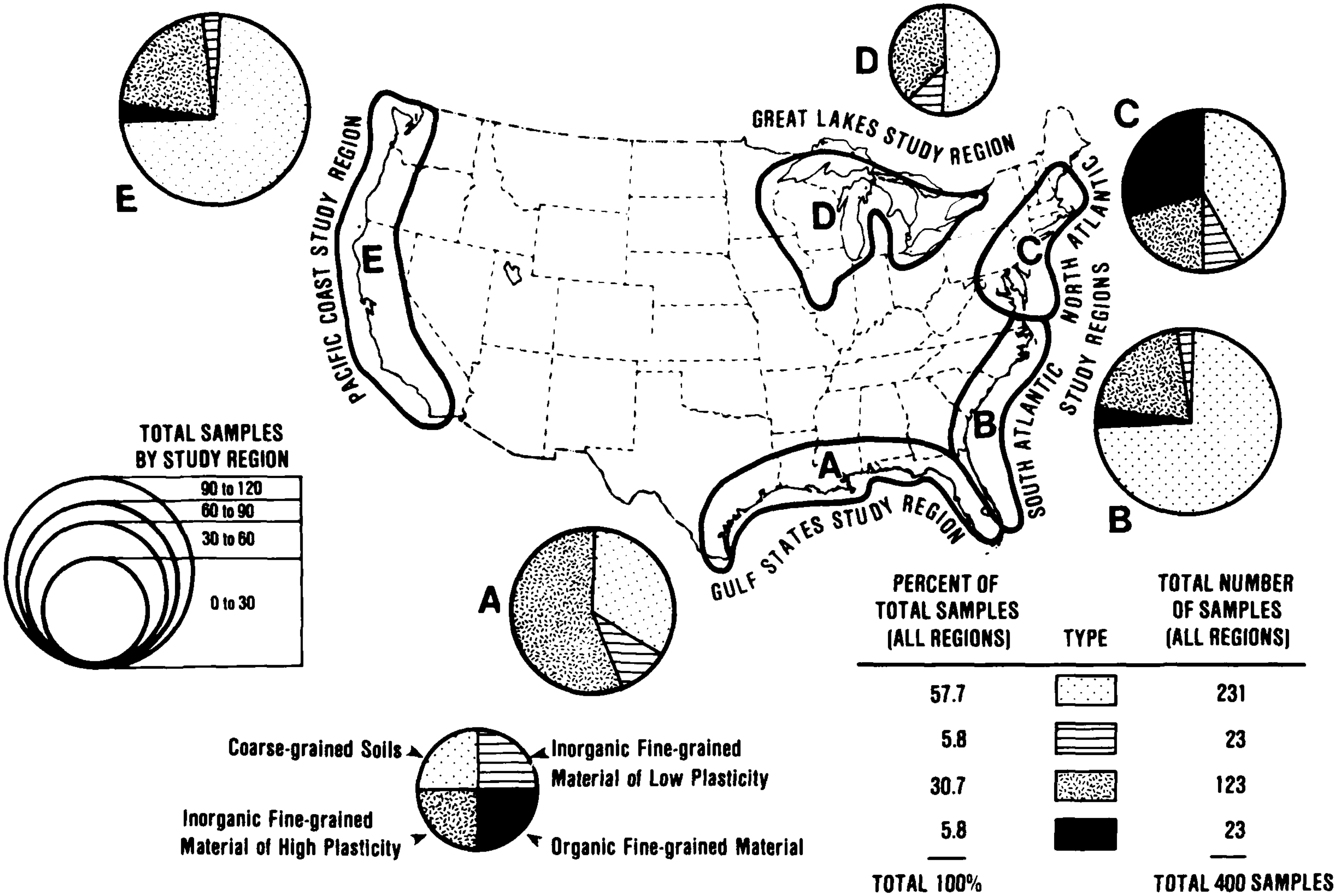


Figure 3. Regional distribution of dredged material types according to USCS classification (from Bartos 1977)



NOTE: Samples assigned to groups on basis of first letter of USCS classification

Figure 4. Types of dredged material samples by region (from Bartos 1977)

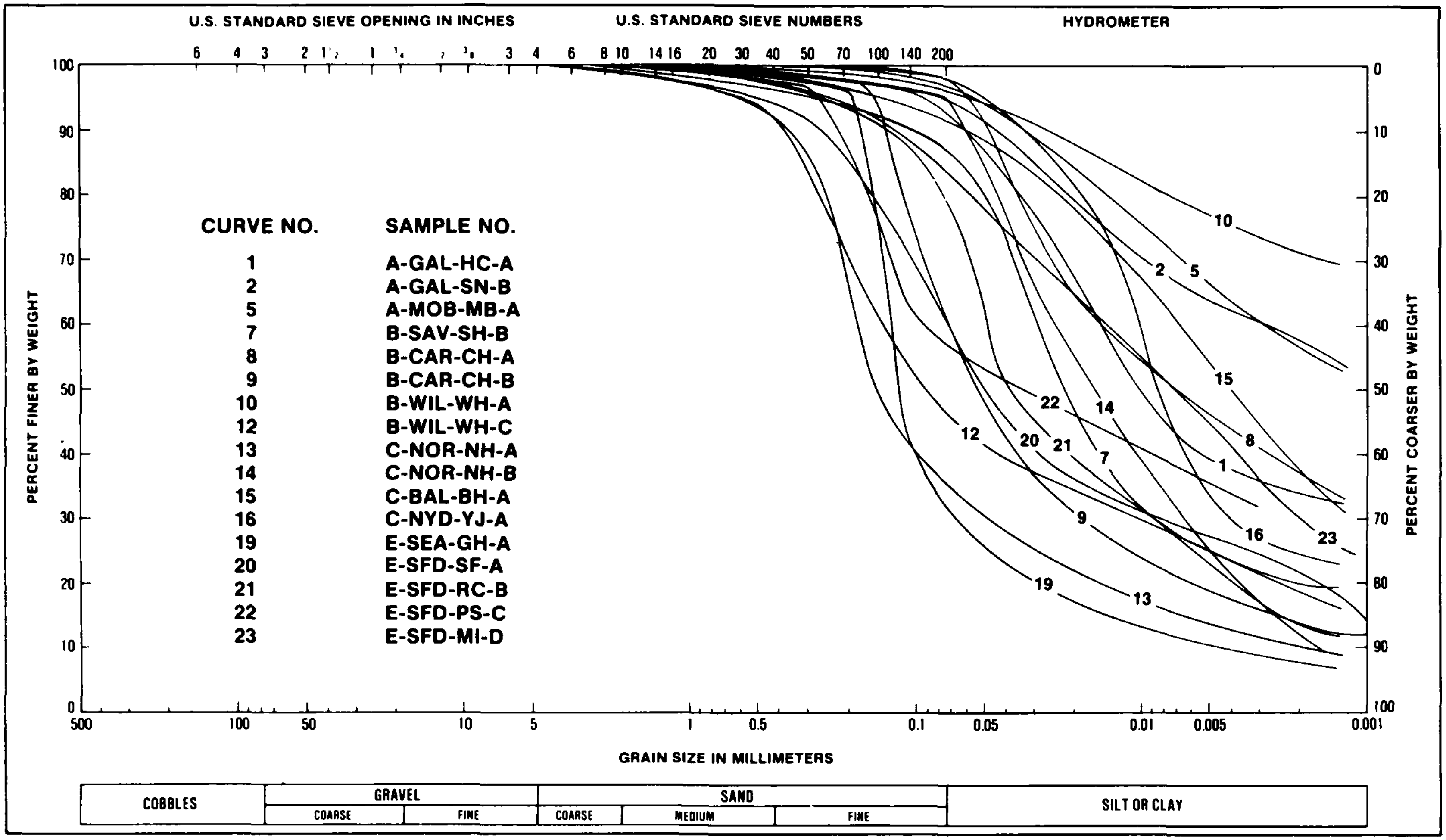


Figure 5. Grain-size distribution curves of dredged material samples subjected to engineering properties testing (from Bartos 1977)

Table 1

Ranges of Classification Test Data Determined for Dredged Material*

(from Bartos 1977)

Region	Total No. Samples	Type of Material**	Grain Size† D_{10}, mm	D_{60}, mm	D_{90}, mm	Percent Passing No. 200 Sieve	Atterberg Limits LL	PL	PI	Organic Content, %
A	89		81 <0.001-0.24	89 <0.001-0.42	89 0.0065-0.80	89 1-99 63	66 32-202 104	65 17-71 35	65 9-144 69	60 0.17-10.64 3.95
B	93		90 <0.001-0.47	89 <0.001-7.50	90 0.0057-12.00	93 1-100 26	34 21-273 100	33 15-90 35	33 1-183 68	9 0.13-9.61 5.76
C	74		46 <0.001-5.00	74 0.0019-78.00	20 0.008->78.00	74 0.5-99 50	38 29-152 89	38 17-82 41	38 9-98 48	10 0.32-9.74 4.53
D	34		34 <0.001-0.46	34 0.007-1.10	34 0.031-7.00	34 0.5-99 46	18 21-161 72	18 19-69 34	18 2-92 38	34 0.09-13.45 3.67
E	110		109 <0.001-0.45	110 0.0053-2.70	110 0.027-10.30	110 0.0-99 27	33 28-99 55	33 17-43 25	33 5-57 30	10 0.28-6.53 2.77
Nation	400		360 <0.001-5.00	396 <0.001-78.00	397 0.0057->78.00	400 0-100 40	189 21-273 88	187 15-90 35	187 1-183 55	123 0.09-13.45 3.95

Note: For the purpose of this table, silts plot below the A-line and clays plot above the A-line on a plasticity chart.

*Conclusions drawn on basis of data shown apply only to samples tested for this study. Data entries for each region are shown in the following *format:* xx *Number of samples*
xx-xx Range of values
xx Average value, if meaningful

**Legend for material types is as follows:

Sand and gravel (>50% retained on #200 sieve).

Silt (low plasticity fines).

Clay (high plasticity fines).

Organic material (soil with organic matter present)

† D_{10} = Grain size at 10% passing.
D_{60} = Grain size at 60% passing.
D_{90} = Grain size at 90% passing.

effects and relative importance of sediment and water compositional factors that influence particle settling rates. A review of pertinent literature was performed by Wechsler and Cogley (1977) to determine which sediment and water characteristics were likely to affect turbidity. Factors that were expected to be important based on earlier studies included sediment composition (particle-size distribution, clay mineralogy, and organic content), water composition (salinity, hardness, and pH), and physical effects (such as temperature and turbulence). Laboratory jar tests were used in these studies to investigate the effects of sediment and water components on turbidity, which for these data is presented in terms of a light-attenuation factor. Simple systems of pure clays and clay mixtures suspended in waters of various salinity, hardness, and pH were characterized first, followed by mixtures of clay with silt. The effect of initial sediment concentration was also studied. Turbidity data were statistically analyzed to determine which factors were significant in controlling turbidity.

26. A wide variation in turbidity responses was observed for the range of sediments and waters examined (Wechsler and Cogley 1977). Turbidity was found to be quite persistent in soft fresh waters, but the presence of hardness levels typical of natural fresh waters (200 mg/ℓ) led to slightly more rapid turbidity reduction. Low levels of salinity (1 to 5 ppt) were sufficient to induce flocculation and consequent rapid turbidity reduction according to the studies conducted by Wechsler and Cogley (Figure 6). The most important sediment compositional factor was the organic content. Clay and natural organics, when present together in an aqueous dispersion, can form complexes or aggregates that have colloidal properties different from one or both of the component parts. These complexes form when attractive forces (i.e. ion-dipole forces, van der Waals forces, or hydrogen bonding) can be overcome by the electrostatic repulsive forces resulting from clay surface charges and the accompanying electrical double layers. It is instructive to compare the formation of clay-clay aggregates (coagulation) with the formation of clay-organic aggregates. Clays with the highest surface charge densities (montmorillonite) would be expected to interact most strongly with many organics. Increasing ambient salinity levels tend to destabilize the repulsive forces between clay particles hence enhancing the flocculation of clay particles (Figures 7-9) (Wechsler and Cogley 1977). Clay mineralogy was not found to be a significant factor in experiments with natural sediments. Among other

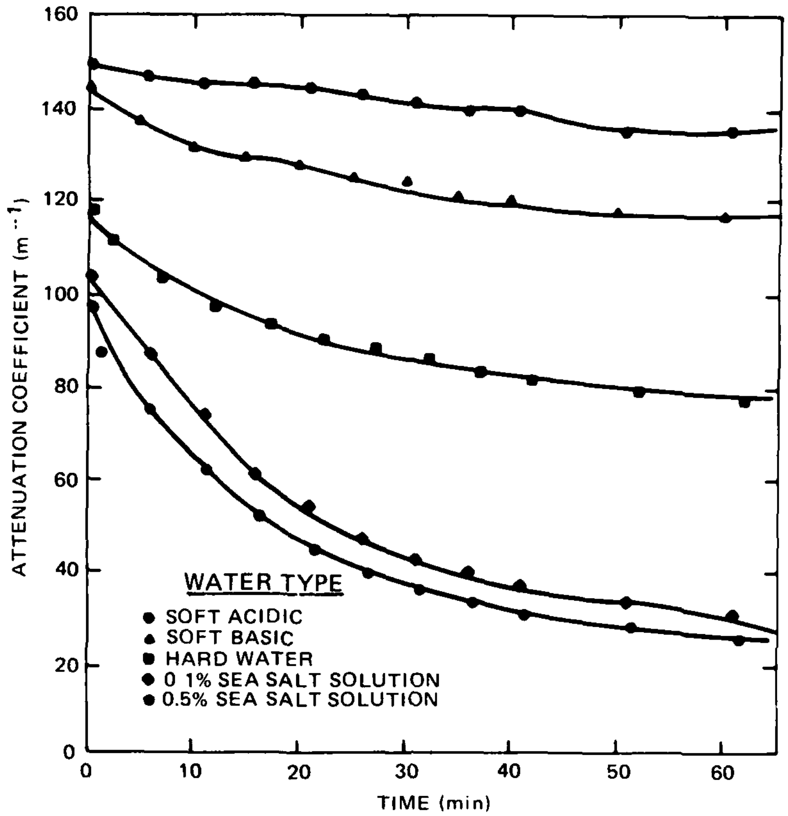


Figure 6. Turbidity of kaolinite suspensions in five test waters (from Wechsler and Cogley 1977)

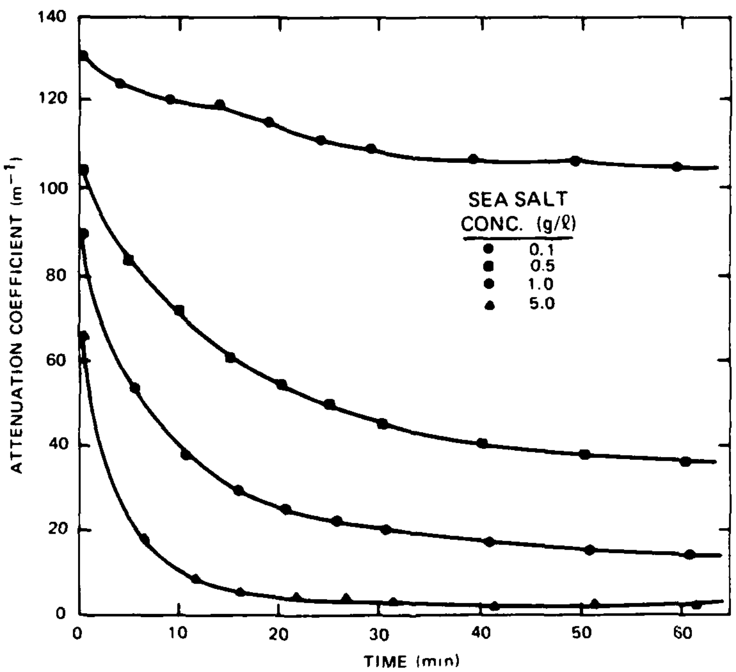


Figure 7. Turbidity of kaolinite suspensions at various sea salt concentrations (from Wechsler and Cogley 1977)

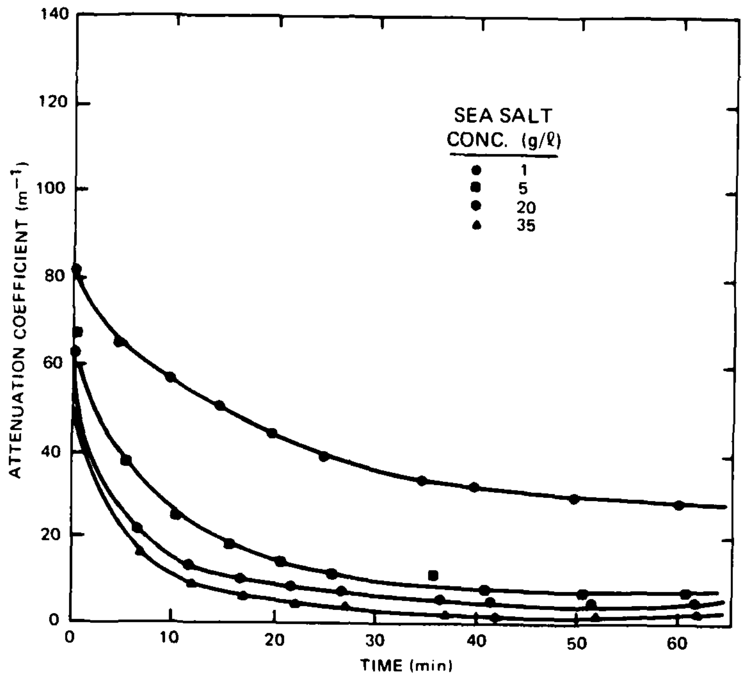


Figure 8. Turbidity of illite suspensions at various sea salt concentrations (from Wechsler and Cogley 1977)

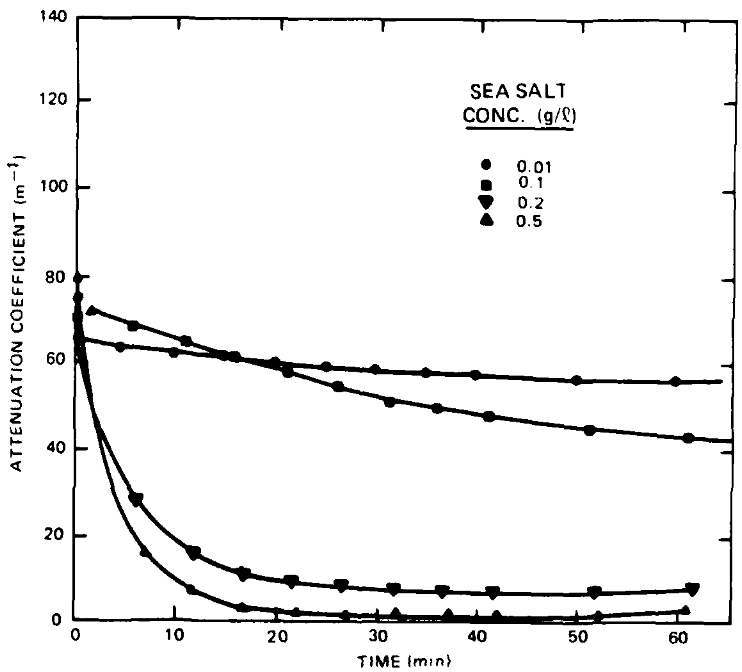


Figure 9. Turbidity of montmorillonite suspensions at various sea salt concentrations (from Wechsler and Cogley 1977)

factors, increased initial concentration of sediment has resulted in significantly more rapid settling. Figure 10 indicates turbidity of eight natural sediment suspensions in 0.1-percent sea salt solution.

27. No significant segregation of sediment components was observed during settling, with the exception of coarser silt particles that settled independently. These results indicate that particle agglomeration in dredged material suspensions is strongly affected by the natural organics present.

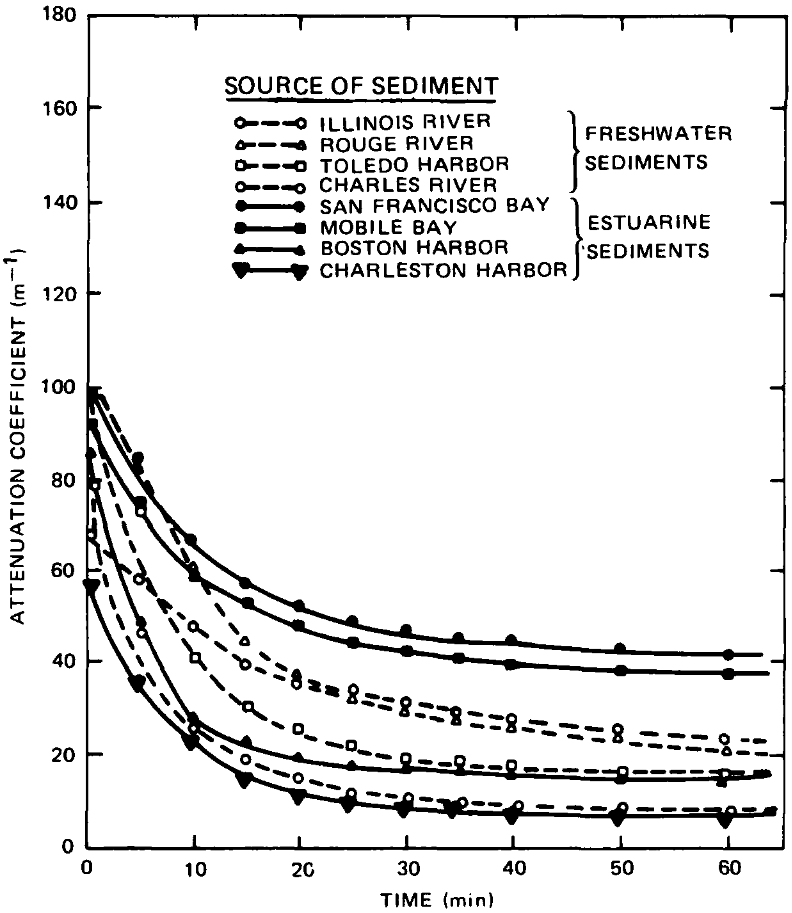


Figure 10. Turbidity of eight natural sediment suspensions in 0.1-percent sea salt solution (from Wechsler and Cogley 1977)

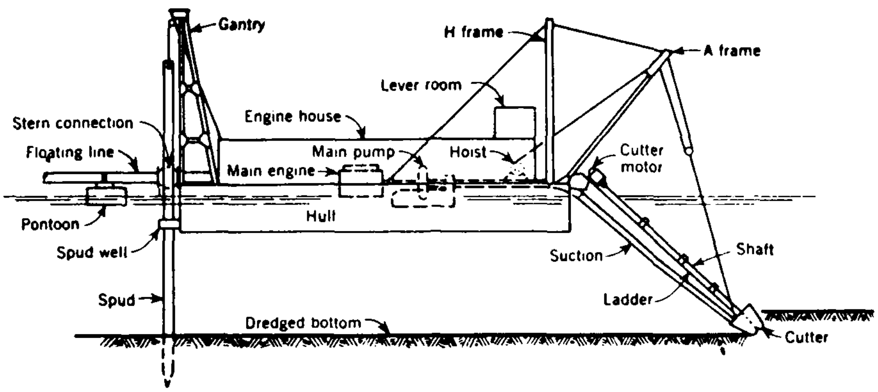
PART V: PREDICTION OF SEDIMENT RESUSPENSION CAUSED BY DIFFERENT DREDGES

28. The nature, degree, and extent of dredged material dispersion around a dredging operation are controlled by many factors (Barnard 1978). These factors include the characteristics of the dredged material such as its size distribution, solids concentration, and composition; the nature of the dredging operation such as the dredge type and size, discharge-cutter configuration, discharge rate, and operational procedures being used; and the characteristics of the hydrologic regime in the vicinity of the operation, including salinity and hydrodynamic forces (waves, currents, etc.). The relative importance of these factors varies from site to site.

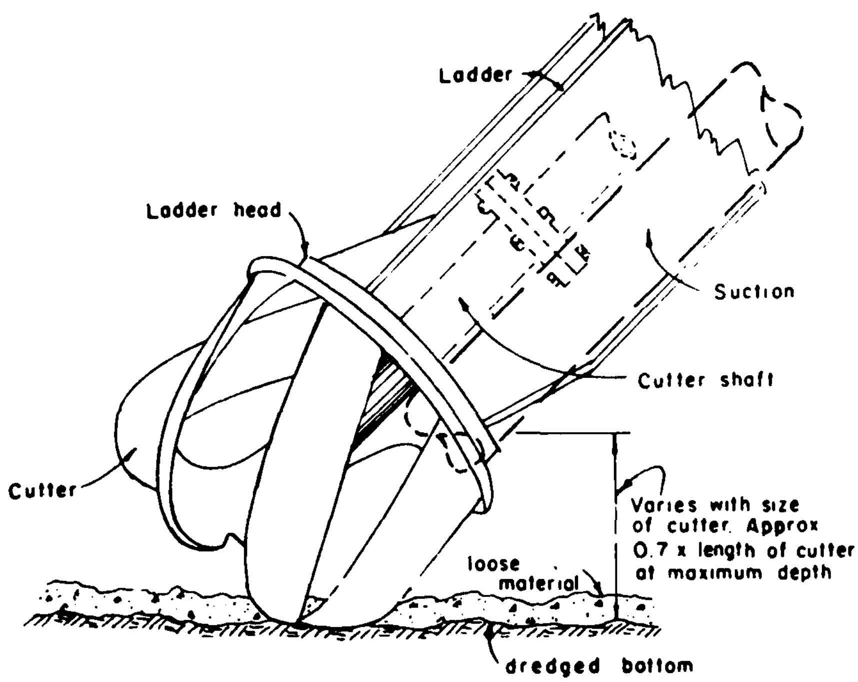
29. With a given set of environmental conditions, different types of degrees generate different levels of turbidity. Though the type of dredging equipment has a major effect on the amount and concentration of sediment that is resuspended, the techniques for operating this equipment also assume importance. Studies carried out by Huston and Huston (1976) indicate that operator training and performance are important contributing factors controlling sediment resuspension. Barnard (1978) indicates that it is difficult to evaluate the various parameters of a dredge's operation that reflect the skills of the operator. Huston and Huston (1976) observed that there was a lack of formal training, research, and development for dredging. As a result, it has been found in most of the literature concerning this topic that turbidity levels were measured with little regard to the operation of the dredges or their production rates. With this in mind, Barnard (1978) examined the turbidity levels generated by different types of conventional dredges.

Cutterhead Dredges

30. The cutterhead dredge (Figure 11a) is the most commonly used dredge in the United States and is very versatile. In this type of dredge, a rotating cutter (shown in Figure 11b) at the end of a ladder excavates the bottom sediment and guides it into the suction. The excavated material is picked up and pumped by a centrifugal pump to a designated disposal area through a pipeline as a slurry with typical solids content of 10 to 20 percent by weight (Barnard 1978). The size of the pipeline varies from 6 to 44 in. For conventional cutterhead dredges, the diameter of the cutter is approximately



a. Cutterhead dredge



b. Cutter

Figure 11. Typical cutterhead dredge and cutter (from Huston and Huston 1976)

three to four times the diameter of the suction pipe. A typical method of operating a cutterhead dredge is shown in Figure 12. A modern, more efficient method of advancing a cutterhead dredge is shown in Figure 13.

31. Most of the sediment resuspended by a cutterhead dredging operation (exclusive of disposal) is usually found in the vicinity of the cutter (Barnard 1978). The levels of sediment are directly related to the type and quantity of material cut but not picked up by the suction. The amount of material supplied to the suction is controlled primarily by the rate of cutter rotation, the vertical thickness of the dredge cut, and the horizontal velocity of the cutter moving across the cut. In addition to the dredging equipment used and its mode of operation, sediment resuspension can also be caused by sloughing of material from the sides of vertical cuts and inefficient operational techniques.

32. Field data are available for sediment in suspension in the vicinity of cutterhead dredges at various places. The limited data collected under low-current conditions show that elevated levels of suspended material appear to be localized to the immediate vicinity of the cutter as the dredge swings back and forth across the dredging site (Barnard 1978). Within 3 m of the cutter, suspended solids concentrations are highly variable, but may be as high as tens of grams per liter; these concentrations decrease exponentially from the cutter to the water surface. Near-bottom suspended solids concentration was found to be on the order of a few hundred milligrams per liter at distances of a few hundred meters from the cutter. Yagi et al. (1975) concluded from these observations that "in the case of a steady dredging of a thin sedimented mud layer, the effect of dredging on turbidity was almost found to be imperceptible at locations several tens of meters distance from the cutter."

33. A properly designed cutter will efficiently cut and guide the bottom material toward the suction, but the cutting action and the turbulence associated with the rotation of the cutter will resuspend a portion of the bottom material being dredged. Excessive cutter rotation rates tend to propel the excavated material away from the suction pipe inlet. Huston and Huston (1976) conducted measurements of turbidity created by a cutterhead dredge in the Corpus Christi Ship Channel. The top 1.5 to 2 m of material was sandy clay. The underlying layer of about 6-m depth consisted of medium clay. The various samples collected in this channel and described by Bartos (1977)

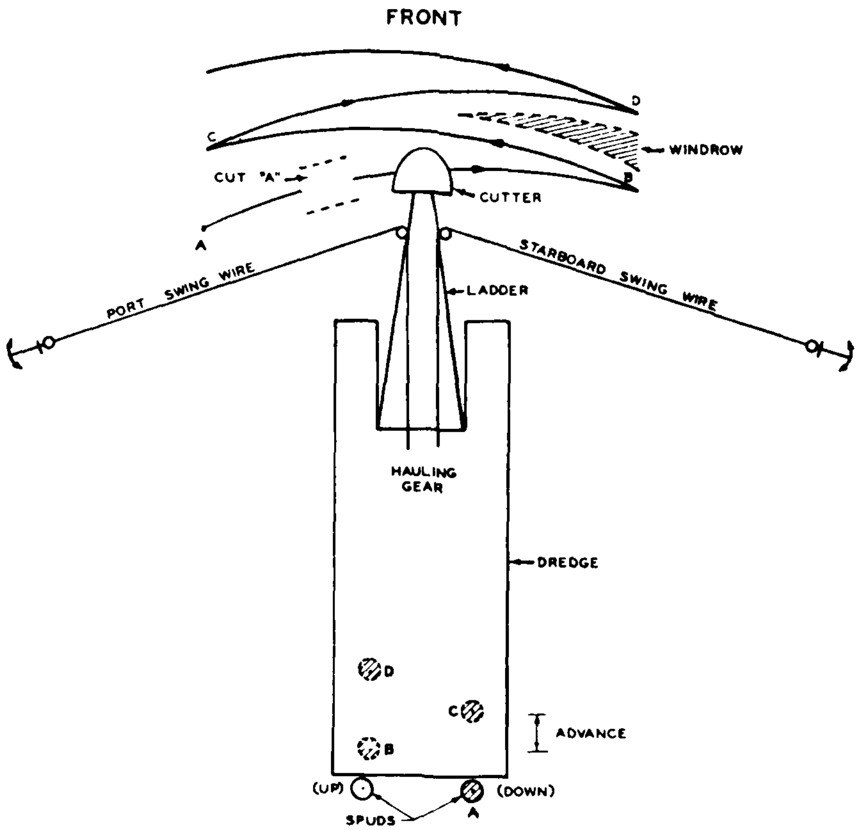


Figure 12. Typical (stabbing) method for operating a cutterhead dredge (from Barnard 1978)

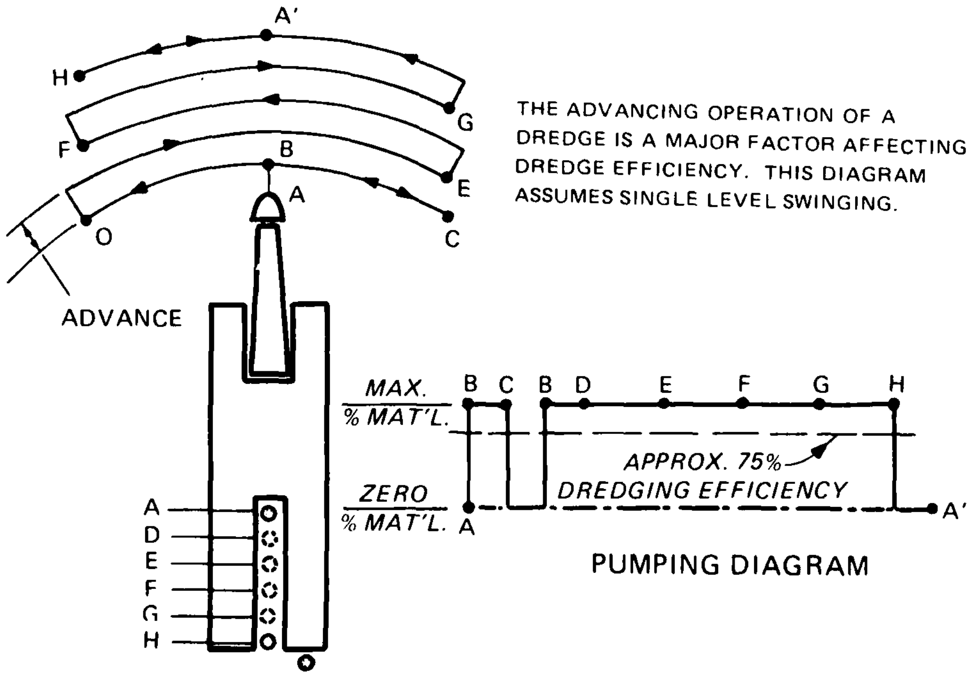


Figure 13. Production diagram, spud carriage (redrawn from Turner 1984)

showed that the sediment consisted of inorganic clays of high plasticity (CH) with the percent passing the No. 200 sieve varying from 76 to 98. Table 2 indicates the turbidity readings at three different cutter speeds. Table 3 compares the three turbidity unit measurements for background water 73 m from the dredge. It can be seen from Table 2 that the near-bottom suspended solids level within 2 m of the cutter of a 27-in. cutterhead dredge widening a portion of the Corpus Christi Ship Channel ranged from background concentrations to 580 mg/ℓ relative to the "background" levels of 39 to 209 mg/ℓ measured 73 m to the side of the dredge (Huston and Huston 1976). Similar data around a 24-in. cutterhead dredge excavated fine-grained maintenance material (96 to 98 percent passing No. 200 sieve--highly plastic inorganic clay (Bartos 1977)) from Mobile Bay Ship Channel showed near-bottom TSS levels of up to 125 mg/ℓ as opposed to background levels of 25 to 30 mg/ℓ, which occurred approximately 300 m in front of the cutterhead (Barnard 1978). The increase in the TSS was found only within 1.5 m of the bottom. Field data are also available from Yokkaichi Harbor, Japan (Barnard 1978). Levels of suspended solids under low-current conditions near the cutter of a 24-in. cutterhead dredge excavating fine-grained material in this harbor ranged from 2 mg/ℓ to 31 g/ℓ at a distance of 1 m above the cutter relative to the background levels of 1 to 18 mg/ℓ. Average TSS levels appeared to decrease exponentially from the cutter to the water surface. At a distance of 60 m in front of the cutter, TSS levels in the near-surface water ranged from 1 to 17 mg/ℓ, whereas near-bottom levels ranged from 5 to 205 mg/ℓ (Yagi et al. 1975).

34. The various studies conducted earlier have shown that operational conditions exert considerable influence on sediment resuspension in the vicinity of a cutterhead dredge. As indicated earlier, the levels of turbidity found near the cutter depend primarily on the type and amount of material that is excavated but not drawn into the dredge's suction. This "residual" material may remain in suspension or may settle into the existing cut, where it again becomes susceptible to resuspension by ambient currents and turbulence generated during subsequent cuts. Analysis of the data collected at Yokkaichi Harbor, Japan, indicates that, as the amount of this residual material increases, the turbidity levels around the cutter apparently increase exponentially. According to calculations made by Yagi as explained by Barnard (1978), the amount of residual material increases as the swing rate increases. Barnard examined the data further and found that in most cases the amount of

Table 2

Turbidity and Suspended Solids Concentrations at Different Cutter Speeds (Huston and Huston 1976)

Depth of Sample, m	10 rpm % T	10 rpm mg/ℓ	10 rpm NTU	20 rpm % T	20 rpm mg/ℓ	20 rpm NTU	30 rpm % T	30 rpm mg/ℓ	30 rpm NTU
Cut No. 1, 6.1 m									
0.9	55	26	8	70	22	6	72	154	4
2.7	65	89	10	65	12	6	68	91	4
5.4	42	161	43	5	187	44	24	580	45
Cut No. 2, 9.1 m									
0.9	47	114	3	56	--	7	66	106	4
3.0	41	64	9	45	46	7	65	80	5
6.1	44	102	15	38	--	8	50	11	15
9.1	17	55	14	5	37	37	4	208	26
Cut No. 3, 12.2 m									
0.9	54	144	3	55	75	5	66	125	4
3.0	48	150	10	58	--	6	66	72	8
6.1	52	25	7	60	165	10	63	56	9
9.1	30	--	5	47	94	8	26	138	22
12.2	7	52	12	24	176	30	2	266	57

Table 3

Comparison of Three Turbidity Unit Measurements for Background Water Near Dredge (Huston and Huston 1976)

Depth of sample m	NTU	% T	mg/ℓ
0.9	6	72	94
3.0	8	71	77
6.1	8	69	168
9.1	4	65	39
12.2	9	50	50
13.7	14	44	209

Note: Samples taken in channel approximately 73 m starboard of dredge.

residual material generally increases as the thickness of the cut increases. Consequently, as the thickness of the cut and swing rate increases, the turbidity levels generated by the operation increase exponentially (Barnard 1978). A similar relationship exists between sediment resuspension and rate of cutter rotation (Huston and Huston 1976).

35. The amount of material remaining in suspension from the previous cuts also controls the level of turbidity in the vicinity of the cutter. Yagi et al. (1975) found that, during the first four swings of dredging operation monitored, the levels of turbidity around the cutter increased with each successive cut. This was found to continue until a quasi-steady-state condition was reached. Barnard (1978) further analyzed the data in detail and found a relationship between the levels of turbidity around a cutterhead and the dredge's production rate. The relationship is for fine-grained material and is shown in Figure 14. There is some scatter in the data, but a general trend could be easily seen. The data within the shaded portion in the figure indicate that it is possible to increase the rate of a dredge's production up to a maximum rate without generating excessive levels of turbidity. Kuo, Walch, and Lukens (1985) developed a model to describe the turbidity plume induced by dredging a ship channel using a cutterhead hydraulic dredge. The model predicts the suspended sediment concentration within the plume and the resulting sediment deposition alongside the dredged channel.

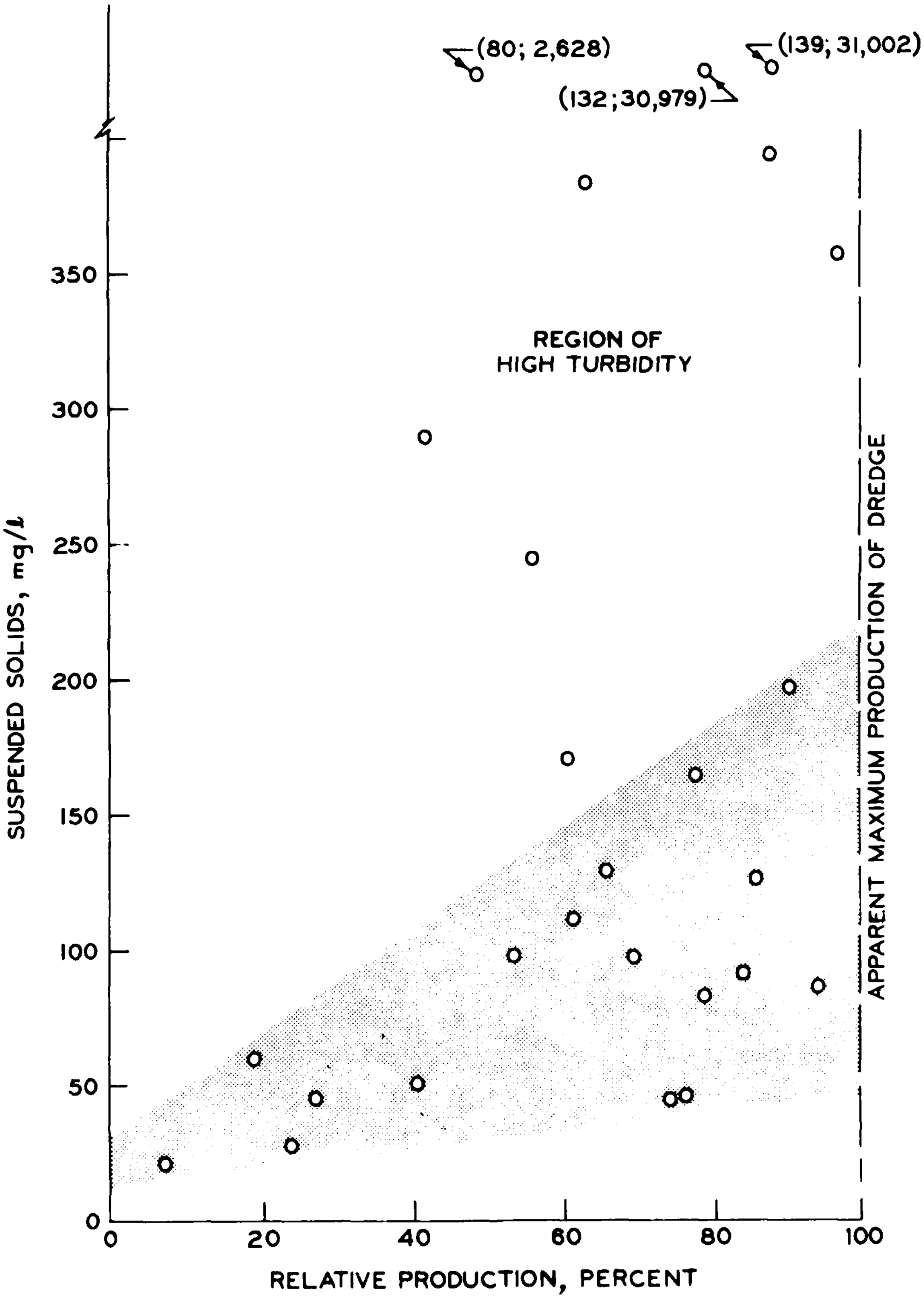


Figure 14. Relationship between the concentration of suspended solids 1 m from the cutter and the relative production of a 24-in. cutterhead dredge (from Barnard 1978)

36. Huston and Huston (1976) collected large amounts of information on cutterhead-dredge-induced turbidity and also carried out field studies at Corpus Christi Ship Channel. Based on the analysis of the turbidity data, they concluded that the turbidity data show several trends as follows:

- *a.* The transmission and scattering of data in most cases show an increase in turbidity above background levels only in the immediate vicinity of the cutter. The increased levels of turbidity around the cutter are probably due to suspension of fine-grained material created by the turbulence generated by the cutter.
- *b.* Apparently little of the turbidity created by the cutter goes into the upper water column, especially from depths of 9 to 12 m. This is also supported by the fact that no substantial visible surface turbidity is ever observed.
- *c.* Although the turbidity data collected in the immediate vicinity of the cutter are quite variable, probably due to cutter-generated turbulence, there also may be a general, but inconsistent, increase in turbidity with increasing revolutions per minute (rpm). This inconsistency may be due to cutter-generated turbulence, variability in material being dredged, or suction velocity.

37. Grimwood (1983) collected sediment resuspension data during cutterhead maintenance dredging off the Louisiana coast in an effort to assay potential environmental damage during both dredging and disposal operations. It was generally concluded that the material dredged during these investigations did not present a hazardous waste disposal problem, as dilution was rapid and increased concentrations of pollutants were confined to the disposal area or mixing zone.

Trailing Suction Hopper Dredge

38. The self-propelled trailing suction hopper dredge is a highly developed machine used throughout the world and is suitable for all but hard materials. Such a dredge will probably be used in areas characterized by heavy ship traffic or rough water. The hopper dredge consists of a ship-type hull with hoppers to hold the material dredged from the bottom. The material is brought to the surface through a suction pipe and draghead. Hopper dredges have been built with capacities as high as 9,000 cu m. The hoppers are usually unloaded through the bottom doors. In some modern dredges, pumping-out facilities are also available. Most modern hopper dredges have two or more

dragarms, mounted on the side of the dredge. Hopper dredges can work in swells up to 5 m.

39. Resuspension of the fine-grained maintenance dredged material during hopper-dredge operations is caused by the dragheads as they are pulled through the sediment, turbulence generated by the vessel and its propeller wash, overflow of turbid water during hopper-filling operations, and dispersion of dredged material during open-water disposal. Overflow water is the most obvious source of near-surface turbidity. Distributions of suspended solids in these overflow plumes are dependent on many factors such as nature of the sediment being dredged; design and operation of the dredge; and nature, concentration, and volume of overflowed material.

40. Field measurements of suspended solids concentrations in the vicinity of the hopper dredge CHESTER HARDING during a maintenance dredging operation at San Francisco Bay are available (Barnard 1978). These measurements indicated that a near-bottom turbidity plume of suspended dredged material extended up to 700 m downcurrent from the dredge. In the immediate vicinity of the dredge, a well-defined upper plume was generated by the overflow process, and a near-bottom plume was generated by draghead resuspension; 300 to 400 m behind the dredge, the two plumes merged into a single plume. With the increase in the distance from the dredge, the suspended solids concentrations in the plume generally decreased, and the plume became increasingly limited to the near-bottom waters. According to the studies conducted by Bartos (1977), the type of seabed material in the San Francisco Bay is inorganic clay of high plasticity with 58 percent passing the No. 200 sieve. Suspended solids concentrations in the upper and midwater column were rarely found to exceed several hundred milligrams/liter in relation to the background concentration of 31 to 35 mg/ℓ.

41. Near-surface measurements for suspended solids concentrations were also made in the overflow plumes generated by hopper dredge MARKHAM in Saginaw Bay Ship Channel, Lake Huron, and by hopper dredge GOETHALS in the Thimble Shoal Channel, Chesapeake Bay (Barnard 1978). These measurements are summarized in Figure 15. It may be seen that the suspended solids concentrations were as high as 200 g/ℓ in the overflow plume of the dredge MARKHAM. The solids concentrations dropped to 800 mg/ℓ at a distance of 1,200 m from the dredge overflow ports. A similar trend is seen for the dredge GOETHALS in Chesapeake Bay. The corresponding values for suspended solids concentrations

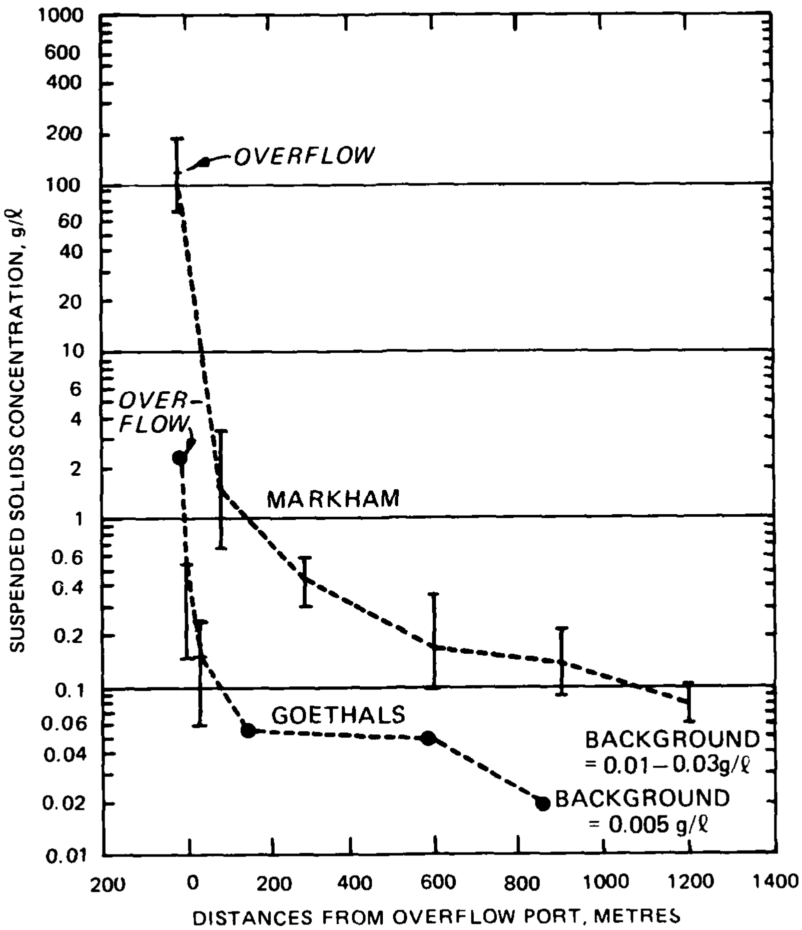


Figure 15. Relationship between concentration of suspended solids in the near-surface overflow plume and the distance (in meters) downstream of the overflow ports (from Barnard 1978)

were 2 g/ℓ and 200 mg/ℓ respectively. These measurements indicate that the suspended solids levels generated by a hopper dredge are primarily caused by overflow in the near-surface water and draghead resuspension in the near-bottom water. Suspended solids concentrations may be as high as several tens of grams per liter near the discharge port and as high as a few grams per liter near the draghead. It was found that plume concentrations exceeded the background levels even at distances in excess of 1,200 m.

Plain Suction Dredge

42. The plain suction dredge is the simplest of the hydraulic suction dredges. It employs a long suction pipe to dig and lift the material to the surface. This dredge, however, works best in free-flowing sand where gravity can feed the suction pipe. Digging may be supplemented by water jets at the suction pipe mouth. These dredges are designed to work in moderate swells and even in storm conditions. The dredge is quite useful for beach nourishment programs. Operating in a free-flowing sand, a plain suction dredge usually causes little solids suspension. The use of water jets, however, can create significant turbidity at the bottom. In general, the sediment resuspended by a plain suction dredge should be less than that caused by a cutterhead dredge because there is no rotating cutter.

Dustpan Dredge

43. The dustpan dredge is a hydraulic, plain suction, self-propelled dredge. It consists essentially of a dredge pump that draws in a mixture of water and dredged material through the suction head, which resembles a large vacuum cleaner or dustpan. This suction head is about as wide as the hull of the dredge and is fitted with high-velocity water jets for agitating and mixing the material. The dustpan is suitable mostly for high-volume granular material (Herbich 1975). Dustpan dredges have been developed and almost exclusively used in the United States. The USACE and private industry have extensively used such dredges for maintaining navigation on the Mississippi River.

44. The suspended solids concentration in the vicinity of a dustpan dredge depends on the type of soil being dredged. In the case of free-flowing sand, the turbidity developed for the dustpan dredge can be very small. Significant turbidity is expected at the bottom because of the water jets. Amalgamated Dredge Design* carried out dredging tests using a modified dustpan on the James River, Norfolk, VA, for the USACE. The preliminary analysis indicated that turbidity was as high for the dustpan dredge as for the

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* Amalgamated Dredge Design, 1982, "Results of Dredging Tests Carried Out on the James River," unpublished report, Norfolk, VA.

cutterhead. The low output and high turbidity of the dustpan dredge were attributed to the very poor hydraulic radius of the dustpan head, especially when pumping plastic clay. A comparison of the turbidity generated by cutterhead and dustpan dredges in the James River showed that there was no clear advantage to using a dustpan dredge over a cutterhead dredge.

Mudcat Dredge

45. The Mudcat dredge is designed to remove fine-grained sediments, weeds, sand, municipal sludge, and industrial wastes. The dredge is one of the several unconventional dredging systems developed in the United States and overseas to pump dredged material slurry with a high solids content or to minimize sediment resuspension (Barnard 1978). It is a relatively small, portable hydraulic dredge designed for projects where a discharge rate of 50 to 120 cu yd/hr is sufficient. It can remove sediments at a rate up to 1,500 gal/min with 10- to 30-percent concentrations. Instead of the conventional cutter, the Mudcat has a horizontal cutterhead equipped with cutter knives and a spiral auger that cuts the material and moves it laterally towards the center of the auger where it is picked up by the suction. This can remove sediments in an 8-ft width up to a depth of 15 ft. The dredge operates on anchor cables. The dredge leaves the bottom flat and free of the windrows that are characteristics of the typical cutterhead dredging operation (Barnard 1978).

46. The Mudcat is a minidredge and has operated successfully to remove silt at a rate of over 80 cu yd/hr from a lagoon channel at Ventura Keys, CA, in a test demonstration. The solids averaged 20 percent by dry weight. The dredge can operate in a depth as shallow as 27 in.

47. A unique retractable mud shield shrouds the cutterhead entrapping suspended material and minimizing sediment resuspension (Barnard 1978). During one operation, near-bottom suspended solids concentrations 1.5 m from the auger were usually slightly greater than 1 g/ℓ relative to the background concentration of 500 mg/ℓ (Nawrocky 1974). Surface and middepth concentrations measuring 1.5 and 3 m in front of the auger were typically less than 200 mg/ℓ above the background values of 4 to 65 mg/ℓ. In general, the turbidity plume was confined to within 6 m of the dredge (Nawrocky 1974). The Mudcat, in general, is quite suitable for shallow areas where less than a 130-cu-yd/hr

discharge is sufficient. Sediment resuspension by the dredge is moderate and confined to within a small area around the dredge.

Clamshell Dredge

48. The grab, bucket, or clamshell dredge consists of a bucket or clamshell operated from a crane or derrick mounted on a barge or on land (Barnard 1978). It is used extensively for removing relatively small volumes of material, particularly around docks and piers or within restricted areas. The sediment is removed at nearly its in situ density; however, the production rates are quite low compared with that for a cutterhead dredge, especially in consolidated material. The dredging depth is practically unlimited, but with increases in depth, the production rate drops. The clamshell dredge usually leaves an irregular, cratered bottom (Barnard 1978).

49. Sediment resuspension by a typical clamshell operation is high and can be traced to four major sources:

- a. Sediment resuspension occurring when the bucket impacts on and is pulled off the bottom.
- b. The surface material in an open bucket is rapidly eroded as the bucket is pulled up through the water column.
- c. Further loss of sediment is experienced when the bucket breaks the water surface.
- d. Turbid water leaks through the openings between the jaws.

50. Field measurements on turbidity by such dredges are available. These measurements, however, indicate a great variation in the amount of material resuspended by clamshell dredges because of variations in bucket sizes, operating conditions, sediment types, and hydrodynamic conditions at the dredge site. The following are a few field measurements on turbidity caused by clamshell dredges:

- a. Dredging clay with a 16.5-cu m bucket in San Francisco Bay, California, indicated suspended solids levels in the water column 50 m downstream of the operation to be generally less than 200 mg/ℓ (average 30 to 90 mg/ℓ) as opposed to the background level of 40 mg/ℓ. With the increase in the distance from the dredging site, the suspended solids concentration levels were found to decrease as the result of dilution and settling of the suspended material (US Army Engineer District (USAED), San Francisco 1976).
- b. In lower Thames River, Connecticut, a clamshell dredge with a 12.8-cu m bucket and barge-loading operations produced

suspended sediment concentrations as high as 168 mg/ℓ at the bottom and 68 mg/ℓ at the surface at a distance of 100 m downstream of the dredging operation. These maximum concentrations decreased very rapidly to background concentrations within a distance of 500 m (Bohlen and Tramontaro 1977).

c. Another 16.5-cu m clamshell operation at Brewerton Cutoff Angle, Patapsco River, Maryland, showed suspended sediment levels of the order of 30 mg/ℓ at near-bottom depths about 22 m downstream from the operation. The background sediment concentration level at this place was 10 mg/ℓ or less. The turbidity at the surface could be seen up to 460 m downstream (Cronin et al. 1976).

d. A few field measurements were also taken in Japan in Hori River in Nagoya and in Oyabe River Toyama Prefecture in the vicinity of a small 1-cu m clamshell operating in fine-grained material. The maximum suspended sediment concentration in the water column 7 m downstream of the dredging operation varied from 150 to 300 mg/ℓ compared with background levels of 30 mg/ℓ. The turbidity levels decreased by about 50 percent at a distance of 23 m. In general, the turbidity levels in the upper water column were usually somewhat less than those at middepth or near bottom (Yagi et al. 1977).

e. Field test in Fushiki Port, Japan, at the mouth of the Oyabe River were conducted to develop a relationship between a 4-cu m clamshell dredge and sediment resuspension. Twenty continuous recording optical-type turbidity meters were placed at different depths downstream from the dredge point. It was shown that turbidity is higher at the middle and lower depths than at the surface and turbidity is significantly lower 20 to 30 m away from the dredge than at the point of dredging. Also, a diffusion model of turbidity caused by clamshell dredging is proposed (Koiwa et al. 1977).

f. Sediment suspension studies were conducted before, during, and after clamshell dredging operations in the Patuxent River of southern Maryland. Samples were taken at four sites located upstream and downstream of the dredge site. Suspended sediment samples were analyzed using the automatic pipette-aliquot procedure. The increased concentrations of suspended sediments were found to settle to the bottom within a mile of the dredge site, and suspended sediments returned to before-dredging conditions within 19 days after dredging operations (Onuschak 1982).

51. These limited field measurements on turbidity caused by clamshell dredges showed that the turbidity plume downstream of a typical clamshell operation may extend approximately 300 m at the surface and 500 m near the bottom. It was also observed that the maximum suspended sediment concentration in the immediate vicinity of the dredging operation was less than 500 mg/ℓ and decreased rapidly with distance from the operation because of

settling and dilution of the material. The major source of turbidity in the lower water column was the resuspended sediment at the impact point of the clamshell.

Cleanup Dredge

52. Toa Harbor Works, Japan, has developed a unique cleanup dredge for highly contaminated sediment (Sato 1976a, 1976b). The cleanup head consists of a shielded auger that collects sediment as the dredge swings back and forth and guides it towards the suction of a submerged centrifugal pump (Figure 16). To minimize sediment resuspension, the auger is shielded, and a moveable wing covers the sediment as it is being collected by the auger. Sonar devices indicate the elevation of the bottom. An underwater television camera also indicates the amount of material being resuspended during a particular operation. Suspended sediment concentrations around the cleanup system range from 1.7 to 3.3 mg/ℓ at the surface to 1.1 to 7.0 mg/ℓ above the suction equipment relative to the background near-surface levels of less than 4.0 mg/ℓ.

Oozer Dredge

53. In recent years, in an effort to clean up the water environment, the Japanese have developed a new dredge called the Oozer dredge, which is capable of removing ooze deposited at the bottom of the rivers, lakes,

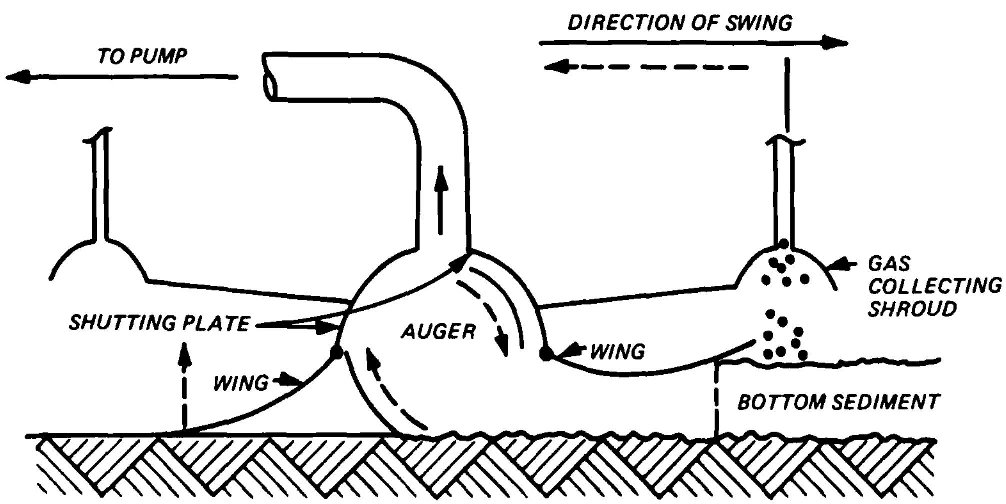


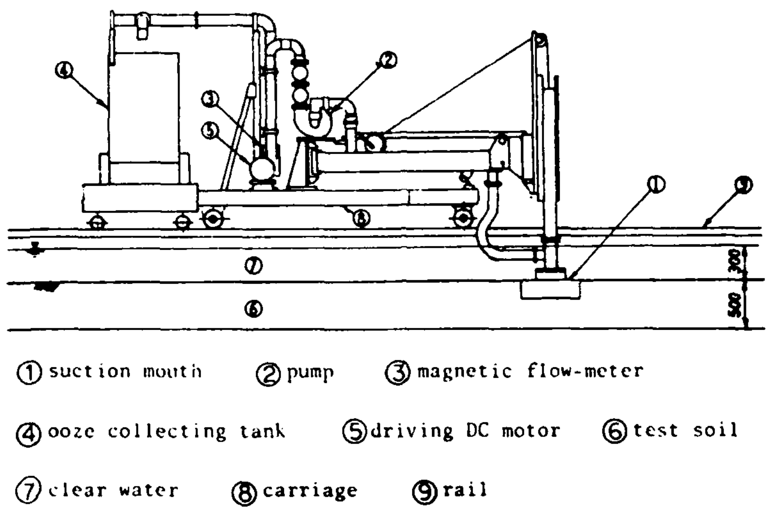
Figure 16. The cleanup dredge head (from Barnard 1978)

harbors, bays, etc. (Noguchi, Kato, and Niiyama 1980). The Japanese initially conducted studies on the model of a test suction mouth of an Oozer dredge in the laboratory (Figure 17); after successful completion of laboratory studies, the Oozer dredge KORYU, equipped with the suction mouth developed in the laboratory, was built. Trial tests indicated high solids concentration. Oozer dredging equipment called the "Drex," consisting of a suction mouth and a device moving the mouth back and forth, was later developed (Figure 17) which gave solids concentration up to 60 percent by weight (Noguchi, Kato, and Niiyama 1980). No detailed test results on turbidity are available in the reports. The Oozer dredge is reported to cause very little turbidity during dredging, even when the material being dredged is clay and soft mud.

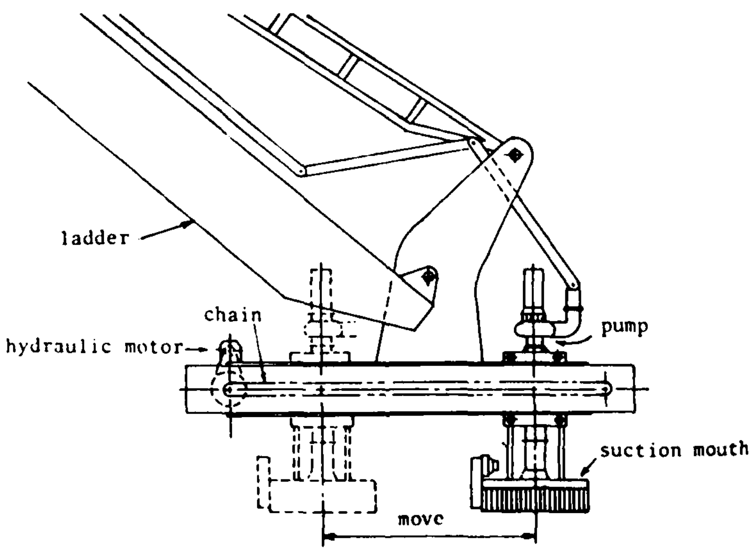
Pneuma Pump

54. The Pneuma pump is a compressed-air-driven, displacement-type pump with several major components (Richardson et al. 1982). The pump body (Figure 18), the largest of these components in dimensions and weight, incorporates three large cylindrical pressure vessels, each having a material intake on the bottom and an air port and discharge outlet on top. Each intake and discharge outlet is fitted with a check valve, allowing flow in one direction only. Pipes leading from the three discharge outlets join in a single discharge directly above the pressure vessels. Different types of attachments may be fitted on the intakes for removal of varying types of bottom material (Richardson et al. 1982). The Pneuma system was the first dredging system to use compressed air instead of centrifugal motion to pump slurry through a pipeline. It has been used extensively in Europe and Japan. According to the literature published by the manufacturer, this system can pump slurry with a relatively high solids content with little generation of turbidity.

55. The operation principle of the pump body is illustrated in Figure 19. The system is based on the principle of employing static water head and compressed air. During the dredging process, the pump is submerged, and sediment and water are forced into one of the empty cylinders through an inlet valve. After the cylinder is filled, compressed air is supplied to the cylinder forcing the water out through an outlet valve. When the cylinder is almost empty, air is released to the atmosphere thus producing atmospheric pressure in the cylinder. This creates a pressure difference between the



a. Outline of dredge test apparatus



b. Schematic sketch of Oozer dredging apparatus "Drex"

Figure 17. Oozer dredge (from Noguchi, Kato, and Niiyama 1980)

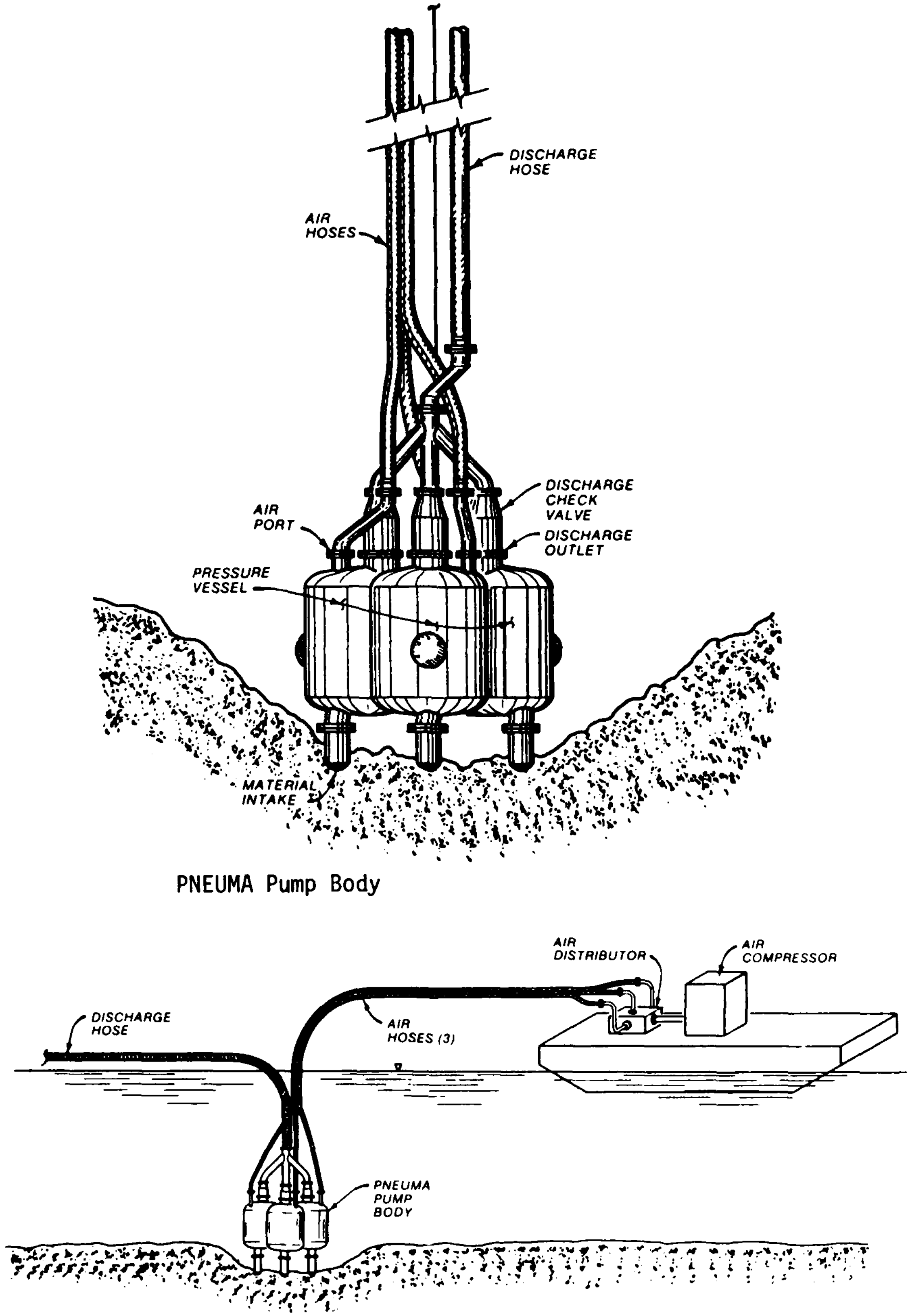


Figure 18. Major components of basic Pneuma system (from Richardson et al. 1982)

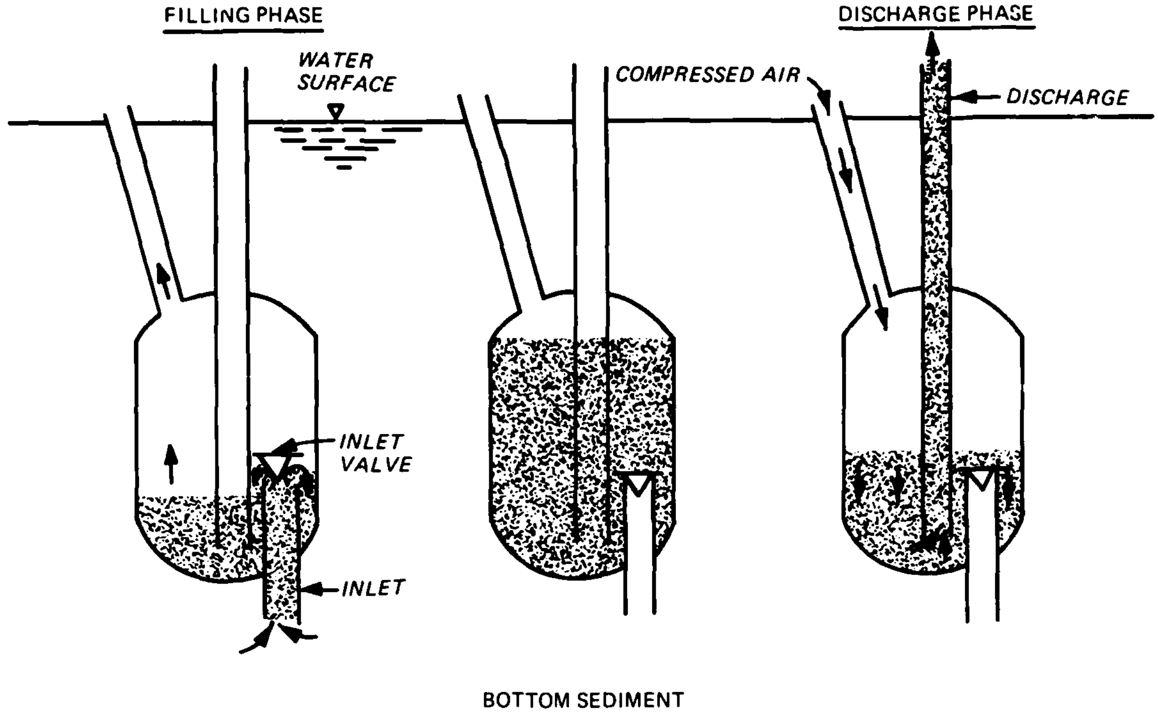


Figure 19. The pneumatic pump system (from Barnard 1978)

inside and the outside of the cylinder creating suction, thereby forcing the sediment into the cylinder. When the cylinder has been filled with sediment, compressed air is again pumped into the cylinder, expelling the sediment out of the cylinder (Figure 19). The capacity of a large plant (type 1500/200) is 2,600 cu yd/hr. The system has been used in water depths of 50 m; however, 100- to 200-m depths are theoretically possible.

56. Pneuma plants employed in Osaka Harbor, Japan, dredge polluted materials (mostly mud at a concentration by volume of between 82 and 95 percent). The manufacturer claims a 60- to 80-percent concentration by volume. However, data from SHIN KAI (a Pneuma dredge) indicate apparent specific gravity of 1.13 to 1.19 and solid content from 54.3 to 75.0 percent of 30- to 53-percent concentration by volume. The Pneuma plant was also employed to remove PCB's from Duwamish Waterway, Seattle Harbor, Washington. The USAED, Seattle (1976), stated that this method had three distinct advantages:

- a. Overdredging could be prevented by controlling cut depth and rate of travel.
- b. This method allowed the operator to follow the contours of the bottom.
- c. In fluid or low-viscosity materials, high concentrations of material could be obtained.

Some of the disadvantages of the Pneuma pump are (Richardson et al. 1982):

- a. The Pneuma pump was not able to dredge sand at in situ density.
- b. Discharge densities of any significance could not be sustained longer than 15 min in either silty clay or sand.
- c. The Pneuma pump has a very low power efficiency compared with a conventional centrifugal dredge.

57. Field observations at Osaka Harbor indicated there was no agitation of the muddy bottom and no change in water transparency at a distance of more than 20 to 30 cm from the bottom. According to unpublished data obtained by Barnard (1978), the amount of resuspension generated by the Pneuma system was found to be minimal. During one maintenance dredging operation at the Port of Chofu, Shimonoseki, Japan, suspended solids levels of 4, 10, 26, and 48 mg/ℓ were measured at depths of 7, 4, 2, and 1 m above bottom, respectively, approximately 5 m in front of a 30/60 Pneuma pump mounted on a ladder. Suspended solids levels 30 m from the system appeared to remain within the general background range of 1 to 3 mg/ℓ (Barnard 1978). During a second maintenance dredging operation at Kita Kyushu City, Kokuru, Japan, average turbidity levels measured 5 m from the ladder-mounted Pneuma pump were approximately the same as background values measured 50 to 100 m away. Only one suspended solids measurement taken 1 m above the bottom, 5 m from the system, indicated an elevated value of approximately 13 mg/ℓ relative to the background concentration of 6 mg/ℓ (Barnard 1978). Tests were carried out by WES (Richardson et al. 1982) on the model 600/100 Pneuma pump. These studies concluded that the results of turbidity monitoring, although not definitive, seemed to support the manufacturer's claim that the Pneuma pump generates a low level of turbidity in loosely consolidated, fine-grained sediments. It was also found that the Pneuma pump was able to dredge at almost in situ density in a loosely compacted, silty clay typical of many estuarine sediments. The Pneuma pump, however, was not able to dredge sand at in situ density. Turbidity and suspended solids analyses downstream of the Pneuma pump are presented in Table 4 (Richardson et al. 1982).

58. A Pneuma pump designed by an Italian firm (S.I.R.S.I.) in December 1971 was tested versus a 4-cu m closed-bucket type in Osaka Port, Japan, in order to compare the resulting sediment resuspension and determine pump performance. According to the results, the Pneuma pump dredge creates a turbidity layer in the lower part of the water column at a point 50 m away, but

Table 4

Turbidity and Suspended Solids Analysis, Run 21 Downstream of Pump (Richardson et al. 1982)

Sample*	Turbidity NTU	Suspended Solids mg/ℓ	Comments
21-10-0	5.0	11.50	25 ft downstream of pump
21-10-5	7.0	11.85	
21-10-10	7.0	4.15	
21-10-15	6.0	4.05	
21-20-0	7.0	4.55	25 ft downstream of pump
21-20-5	34.5	7.50	
21-20-10	12.0	5.85	
21-20-15	17.5	6.90	
21-30-0	8.0	4.47	25 ft downstream of pump
21-30-5	17.0	6.35	
21-30-10	20.5	5.95	
21-30-15	20.5	5.35	
21-40-0	8.0	5.12	100 ft downstream of pump
21-40-5	10.5	5.15	
21-40-10	17.0	7.45	
21-40-15	21.0	6.35	
21-50-0	13.0	8.80	100 ft downstream of pump in visible turbidity plume
21-50-5	68.0	13.40	
21-50-10	72.0	19.80	
21-50-15	40.0	21.50	
21-60-0	8.0	3.80	100 ft downstream of pump
21-60-5	5.0	4.40	
21-60-10	5.0	4.55	
21-60-15	60.0	26.40	
21-70-0	10.5	15.00	100 ft downstream of pump
21-70-5	57.0	38.40	
21-70-10	4.0	5.60	
21-70-15	14.0	7.40	
21-80-0	6.0	5.20	100 ft downstream of pump in visible turbidity plume
21-80-5	8.0	5.70	
21-80-10	10.0	6.40	
21-80-15	14.0	6.75	
21-90-0	5.0	5.30	100 ft downstream of pump
21-90-5	6.0	5.15	
21-90-10	8.0	5.45	
21-90-15	16.0	6.70	

* Sample xx-yy-zz where xx = run no., yy = minutes after start, zz = water depth of sample.

practically no turbidity was observed in the water at the upper and middle layers. In the case of the grab dredger, the grab often operates in a state where the bucket does not completely close after biting the rubbish scattered in the muddy bottom. Therefore, the turbidity at the measurement point (50 m away) occurs throughout all layers, surface to bottom, and tends to increase as dredging continues.*

Oozer Pump

59. The Oozer pump, developed by Toyo Construction Company, Japan, operates in a manner similar to that of the Pneuma pump system; however, there are two cylinders, instead of three, and a vacuum is applied during the cylinder-filling stage when the hydrostatic pressure is not sufficient to rapidly fill the cylinders (Barnard 1978). The pump is usually mounted at the end of a ladder and equipped with special suction heads and cutter units depending on the type of material being dredged. The conditions around the dredging system such as the thickness of the sediment being dredged, the bottom elevation after dredging, as well as the amount of resuspension are monitored by high-frequency acoustic sensors and an underwater television camera. A large Oozer pump has a dredging capacity ranging from 400 to 650 cu yd/hr. During one dredging operation, suspended solids levels within 3 m of the dredging head were all within background concentrations of less than 6 mg/ℓ (Barnard 1978).

60. Test dredging was carried out with the Oozer pump in Osaka Bay, where the bottom sediments are severely contaminated by organic material. The quantity of sediment resuspension around the suction mouth and its diffusion range were measured during the dredging work. Almost all suspended sediment measurements were found to be within the range of 5 to 10 mg/ℓ, and the values are within the mean background value of 9 to 10 mg/ℓ in the bay. Figures 20 and 21 present the results of measurements taken on two separate days (Koba and Shiba 1981).

* Shiro Kasajima, 1986, "On the Dredging Operation for Removal of Bottom Sediments in Osaki Port by the Pneuma Pump Dredge SHINKAI," Construction Division, Port and Harbor Bureau, City of Osaka, Japan.

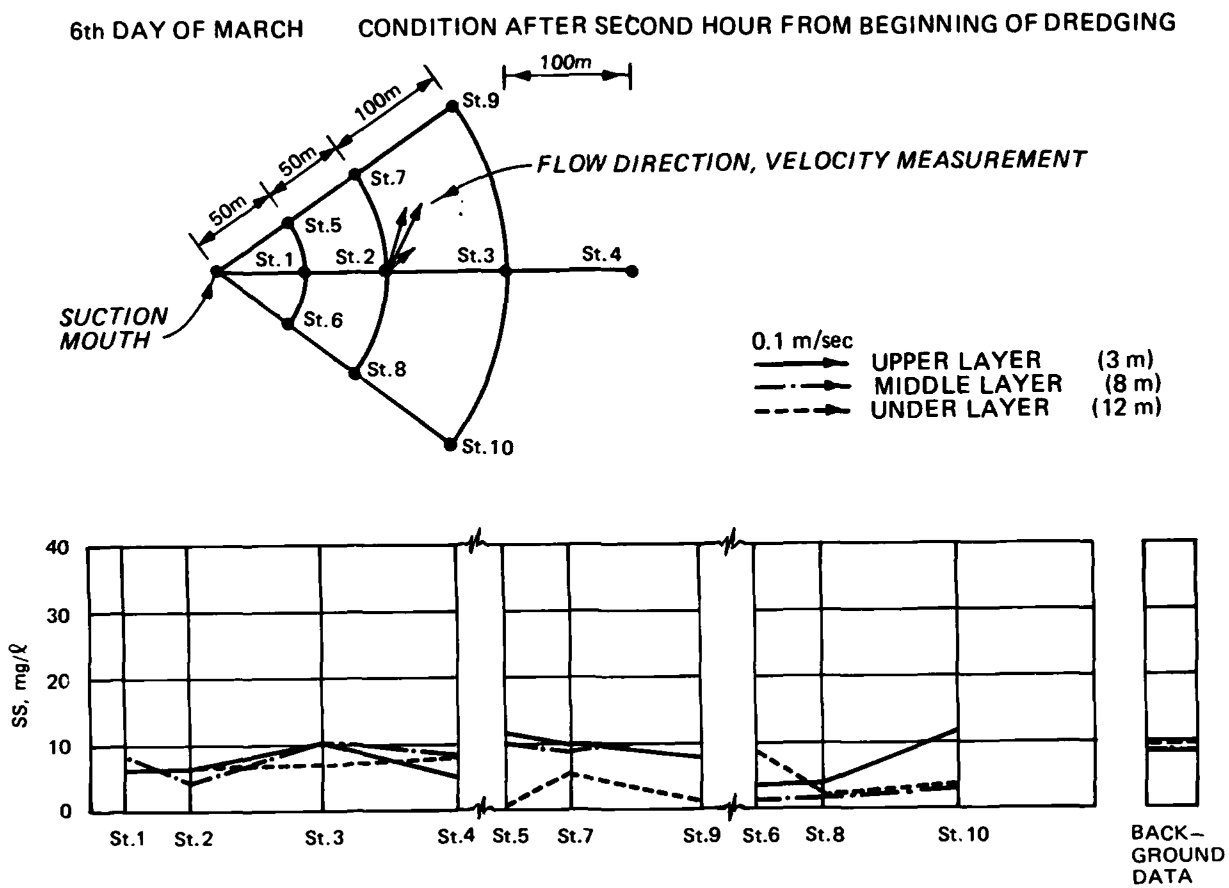


Figure 20. Muddiness in A Zone (thickness of dredged soil = 0.5 m) (from Kasajima, op. cit.)

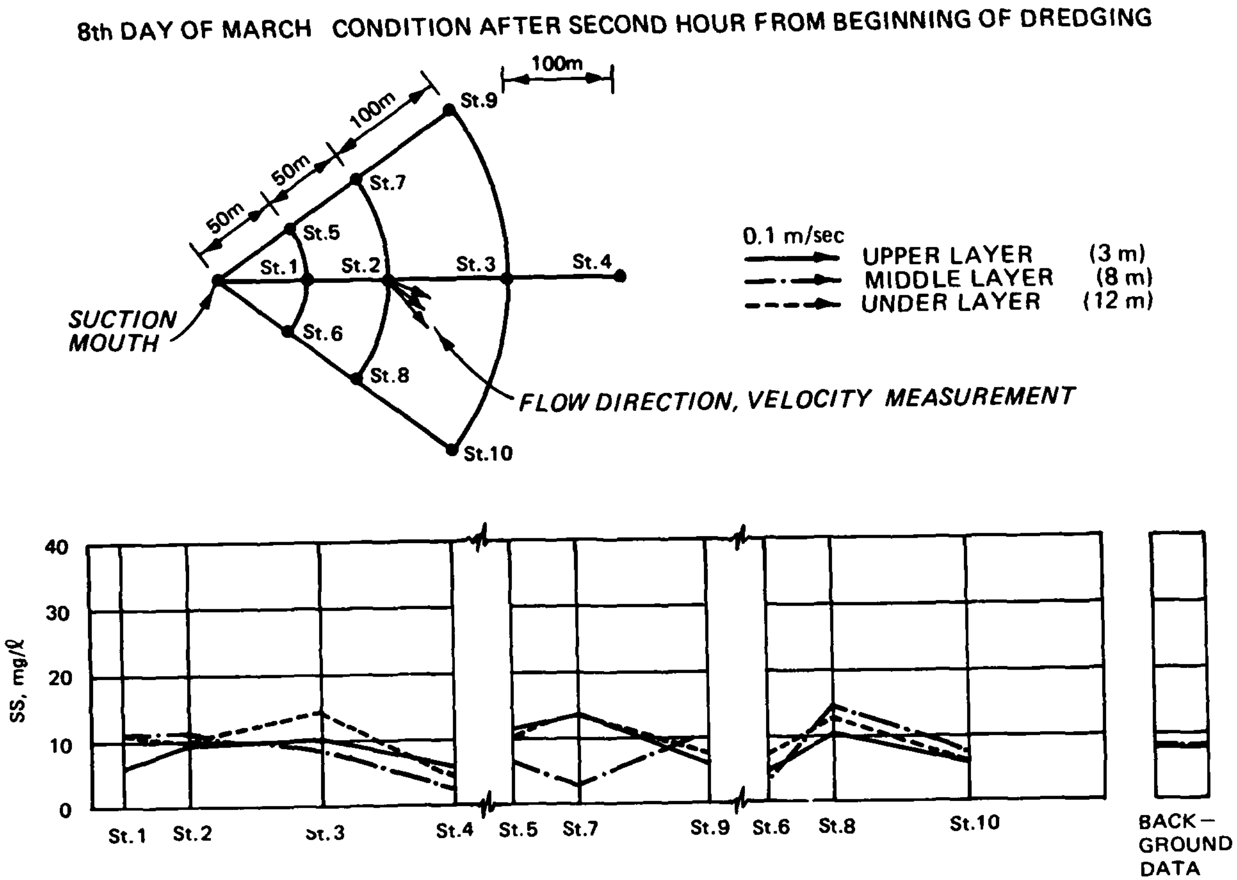


Figure 21. Muddiness in B Zone (thickness of dredged soil = 1.0 m) (from Kasajima, op. cit.)

61. Additional experimental dredging was conducted by a dredge equipped with a Pneuma pump.* A grab dredge equipped with a closed-bucket type was also employed in the experiments. Very little turbidity was observed in the upper and middle water column in case of Pneuma pump dredging. In case of the grab dredge, the turbidity was observed throughout the water column and increased as the dredging continued. Table 5 and Figure 22 present the summary of measurements obtained.

Waterless Dredge

62. The Waterless Dredging Company developed a dredging system where the cutter and centrifugal pump are enclosed within a half-cylindrical shroud. By forcing the cutterhead into the material, the cutting blades remove the sediment near the front of the cutterhead with little entrainment of water. According to the manufacturer, this waterless system is capable of pumping slurry with a solids content of 30 to 50 percent by weight with little generation of turbidity (Barnard 1978). Dredge pipeline sizes range from 15 to 30 cm. Since the waterless dredge development is relatively new (1978), experience with this type of dredge is quite limited.

Delta Dredge

63. The Delta Dredge and Pump Corporation developed a small portable dredge (Figure 23) that removes sediment at high solids concentration using a submerged 12-in. pump coupled with two counter-rotating, low-speed reversible cutters (Barnard 1978). According to the manufacturer, the dredge is capable of making a relatively shallow 2.3-m-wide cut without disturbing the surrounding sediment. The turbidity levels in the vicinity of the cutterhead are apparently quite low. The Delta Dredge and Pump Corporation development is relatively new (1977), and experience with this type of dredge is also quite limited.

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* Kasajima, op. cit.

Table 5

Result of Survey on Transparency and Turbidity of Aji River*

Point of Measurement, No.	Time of Measurement, hr	Depth of Water, m	Transparency	Turbidity, NTU** Upper Layer	Middle Layer	Lower Layer	Sequence of Measurement
			Pneuma Pump Dredger				
1	13:53	11.0	0.5	13.0	11.0	8.0	3
2		10.5	0.6	13.0	11.0	4.0	2
3	13:53	10.0	0.6	13.0	10.0	4.0	1
4		11.3	0.5	12.0	10.0	6.0	4
5		10.0	0.6	12.0	11.0	5.0	5
6		10.7	0.5	14.0	10.0	10.0	8
7		10.7	0.5	14.0	9.0	9.0	7
8		11.5	0.6	14.0	9.0	7.0	6
9		9.0	0.5	12.0	10.0	6.0	9
10	14:03	9.0	0.6	13.0	11.0	6.0	10
			Grab Dredger of Closed-Bucket Type				
11		5.0	0.4	20.	38.0	40.0	3
12		5.4	0.6	13.0	12.0	9.0	2
13	14:06	5.0	0.6	13.0	12.0	12.0	1
14		5.0	0.5	16.0	35.0	80.0	8
15	14:16	9.0	0.6	15.0	14.0	7.0	9
16		5.8	0.5	15.0	14.0	30.0	5
17		6.0	0.6	14.0	18.0	25.0	6
18		6.2	0.6	14.0	13.0	25.0	7
19		4.0	0.4	23.0	--	13	4

* Weather: Fine, temperature: 16° C during dredging operation at rising tide, 27 March 1979.

** Upper layer: 0.5 m below surface; middle layer: 2 m below surface; lower layer: 2 m above water bottom (from Kasajima, op. cit.).

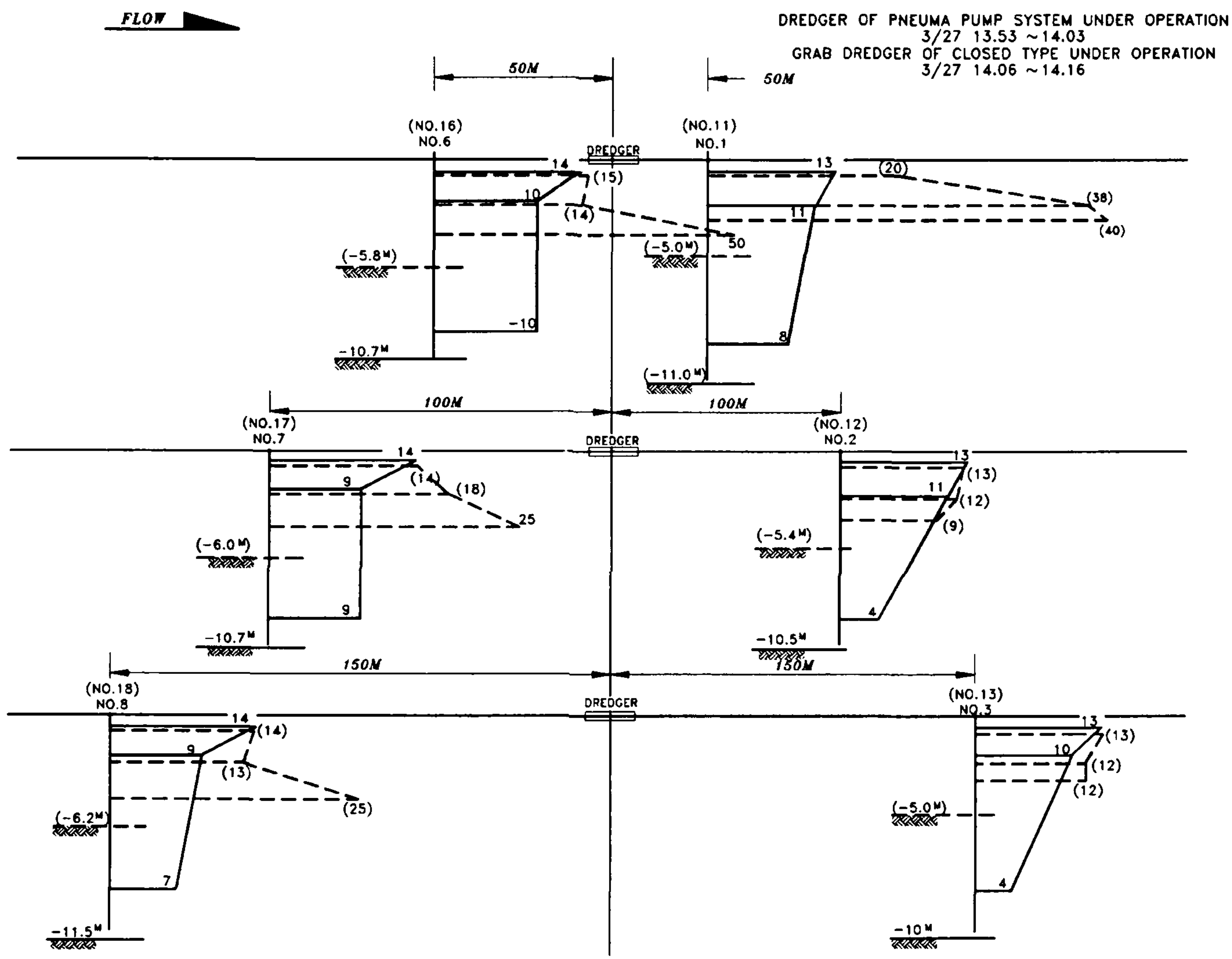

Figure 22. Comparison of turbidity measurements at two water depths (from Kasajima, op. cit.)

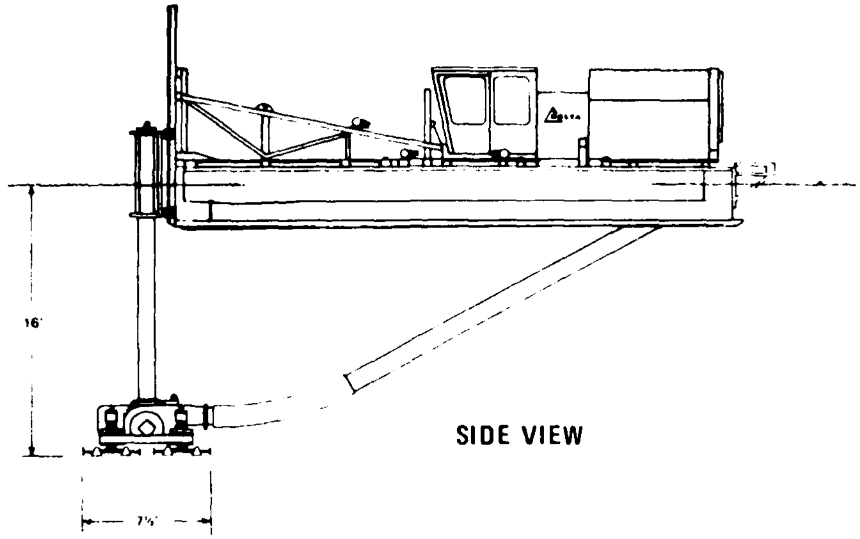

Figure 23. Delta dredge (from Barnard 1978)

Bucket Wheel Dredge

64. A large number of dredging plants with new types of dredging wheels for removal of soil have been invented in the past. These, however, could not survive alongside the bucket dredge or the cutter suction dredge. The bucket dredge offers a highly controllable and efficient digging process, whereas the cutter suction dredge provides an efficient hydraulic transport. The nucleus of the problem lies in the transition from excavation to transport, i.e. blockage of the wheel when dredging in adhesive soils. A thorough study of the dredging process indicates that the breakdown in the sequence of operations--cutting, guiding, and suctioning--lies in the guiding phase. Dutch and US engineers have recently designed a dredging wheel that replaces the cutter and eliminates this drawback (Ports and Dredging 1979). In the dredge wheel the buckets are bottomless. By placing the buckets close together and overlapping, a tunnel is created--the inner limitation of which is the suction mouth itself. Immediately after excavation, therefore, the soil is within the sphere of entrance to the suction force. The process sequence is excavation followed by suction. Because of the new design, the pieces of soil entering the tunnel are too small to become lodged. The trial tests indicate that such a dredging wheel may be expected to produce a

substantially higher output of solids than that of a conventional cutter suction dredge.

65. In the US design of the bucket wheel, the material that is dug is directed into the interior of the wheel, where it is immediately conveyed up the suction line. Modulation of the solids rate can be achieved by varying only the bucket wheel speed. The concentration of the cutting force on a much smaller cutting edge provides the bucket wheel with the capability of efficiently digging much harder material in either swing direction. The bucket wheel has an amazing capacity to deal with submerged stumps (Turner 1977).

66. No data on sediment resuspension by the dredge wheel or bucket wheel are available. However, because of the manner in which these wheels work, the turbidity generated by them is expected to be somewhat less than the bucket and cutter suction dredges.

Sediments and Turbidity at Various Sites in the United States and Other Countries

67. Data on water quality and turbidity measurements taken during dredging in the United States have been received from the various USACE District Offices as well as USEPA. Data from all other available sources were also collected for the various dredging locations in the United States and other countries in the world. All these data are compiled in tabular form in Appendix D. Only sediment resuspended in the vicinity of the dredge and caused by the dredging operation is included in this table, and no information on the turbidity resulting from disposal is indicated. The type of dredge working at the site as well as the type of material being dredged is also given. Further details about the data sources are presented in the following paragraphs.

St. Paul District

68. Upper Mississippi River. In 1978, five dredging operations were monitored at various locations on the upper Mississippi River by the USAED, St. Paul (Anderson et al. 1981a). These operations included three hydraulic dredging operations and two mechanical (clamshell) dredging operations. Disposal of the dredged material in all these cases was on land. In these turbidity and suspended solids studies, only minor changes in the water quality

were found to have resulted from either the hydraulic or clamshell dredging operation.

69. The Wild's Bend dredge site was located at River Mile (RM) 730.5 of the uppei Mississippi River. The area was dredged approximately every 3 years from 1956 to 1977, with volume per job ranging from 14,000 to 63,000 cu yd. During the 1978 maintenance dredging season, two dredges--a 12-in. and a 20-in. hydraulic dredge--were employed for the job (Anderson et al. 1981a). The sediment consisted of about 90-percent sand, 5-percent gravel, and the remaining silt and clay. For assessment of turbidity levels, water samples were collected for background levels as well as during the dredging operation in the vicinity of the dredge. The data are presented at Site No. 1 in Appendix D.

70. The Read's Landing dredge cut in the upper Mississippi River was located at RM 673. The area was dredged approximately 2 out of every 3 years, with average volume ranging from 11,000 to 314,000 cu yd (Anderson et al. 1981a). In 1978, the site was dredged by a 20-in. hydraulic dredge. The disposal was made in a diked containment area. Water samples were collected at a control station and at six different locations in the vicinity of the dredge. For each station, samples were collected at two depths--one near the surface and one near the bottom. The sediment resuspension during dredging was found to be very low (Anderson et al. 1981a). These data are presented for Site No. 2 in Appendix D.

71. The methods of monitoring turbidity and suspended solids at Upper Lansing Light (Site No. 3, Appendix D), Franklin Avenue Bridge site (Site No. 4, Appendix D), and Head of Lake, Pepin (Site No. 5, Appendix D) were similar to those at the two stations described previously. These samples were also collected by the St. Paul District (Anderson et al. 1981a).

72. In 1979, the St. Paul District (Anderson et al. 1981b) conducted similar observations for turbidity and suspended sediment in the upper Mississippi River at five different stations: St. Paul Barge Terminal, Teepeota Point, West Newton Dredge Cut, Lake Street Bridge, and Island 58. The purpose of these observations was to investigate the water quality impacts of hydraulic and clamshell dredging operations at these five selected sites. The results of these studies indicated a slight increase in suspended sediment (1.2 percent) caused by clamshell dredging (Anderson et al. 1981b). The

effect disappeared within 200 ft downstream of the dredge. The suspended sediment concentration data are presented at Sites No. 6 through 10 in Appendix D.

73. Cumberland River. The dredging operation in the Cumberland River was located at RM 24.0, which is 6.6 miles downstream of Lake Barkley. The dredging work was accomplished by the use of a clamshell dredge (USAED, Nashville 1982). During the dredging operation, water samples were collected in July 1982 at a control station upstream of the dredge and at stations downstream of the dredging and disposal area. All the samples were collected with a Kemmerer-type water sampler at a 5-ft depth. The report stated that the increase in suspended solids concentration was only temporary (USAED, Nashville 1982).

USEPA

74. The USEPA, Region X, conducted a literature review on the environmental problems associated with dredging. Some case studies were discussed in brief in O'Neal and Sceva (1971). Among these were Calumet River Pilot Project; Portland Harbor; Depot Slough, Toledo, OR; and Santiam River. The Calumet River Pilot Project involved land disposal of material from the Calumet River (O'Neal and Sceva 1971). The material was excavated by a clamshell dredge and transported by scows to a temporary disposal site surrounded by a dike. This material was later transported to a permanent disposal site by a hopper dredge. It was found at this site that the clamshell dredge increased the turbidity from 20 to 39 JTU's. At Portland Harbor, the project involved removal of bed material and its disposal on land. No significant change in turbidity in the vicinity of the dredge was noticed (O'Neal and Sceva 1971). Depot Slough was a narrow channel that passed through the industrial town of Toledo before discharging into Yaquina River. This project involved maintenance dredging with a pipeline dredge in the lower end of the slough to a 10-ft depth. Bed material in the area consisted of 89-percent silt and clay. Water samples were taken prior to the start of dredging and during active dredging. The background turbidity was 6 JTU's, whereas that near dredge bottom during dredging was 11 JTU's. The Santiam River project involved maintenance dredging at the junction of Santiam and Willamette Rivers by the USACE (O'Neal and Sceva 1971). A cutterhead dredge was used to excavate the bed material and deposit it for bank protection along the south side of the river. General background turbidity was only 2 to 3 JTU's. During dredging the

turbidity increased to 5 to 10 JTU's. These data are listed as Site No. 12 through 16 in Appendix D.

Seattle District

75. Grays Harbor has had a long history of water quality problems (USAED, Seattle 1977). Studies carried out as early as 1940 indicated the presence of dead fish, dead aquatic animals, low dissolved oxygen, and high sulfide waste liquor. During 1975 USACE maintenance dredging in the outer harbor, water quality was studied in the vicinity of the pipeline dredge. Studies were also carried out in various disposal areas. A hopper dredge was used for the purpose of dredging. Water quality sampling was made in the vicinity of the hydraulic dredge. The data indicated that there was an increase in the turbidity above ambient by 22 to 55 JTU's (USAED, Seattle 1977). These data are listed as Site No. 17 in Appendix D.

Pittsburgh District

76. Data listed at Sites No. 18 to 20 were obtained from the environmental impact statement (EIS) prepared for commercial and gravel dredging operations in the Ohio River (USAED, Pittsburgh 1981). Six different companies dredge the Ohio River for commercially valuable sand and gravel. In view of the possible environmental problems resulting from such dredging, an EIS was made in 1981 to consider the renewal applications of these companies. The various types of dredges used were hydraulic, clamshell, and bucket. The data collected on turbidity showed some increases (Appendix D).

77. The remaining entries in Appendix D (Sites No. 21 through 28). are a tabulation of the field studies cited by Barnard (1978) in his earlier literature review. These data are included in Appendix D (Sites No. 1 through 28). Data for Sites 29 through 44 were obtained from various sources as listed in References in Appendix D.

PART VI: FIELD AND LABORATORY STUDIES

78. A considerable amount of work has been done in the past decade both in the field and in the laboratory on sediment resuspension by dredging and its impact on the environment. These studies could be grouped into different categories as shown below:

- a. Sediment resuspension by different dredges and dredging techniques.
- b. Resuspension potential of different sediments.
- c. Sediment resuspension from natural and man-made causes other than dredging.
- d. Fate of dredged material.
- e. Impact of suspended solids on the environment for:
  - (1) Low contaminated sediment.
  - (2) Highly contaminated sediment.

  The impact is further grouped into
  - (1) Physical impact.
  - (2) Chemical impact.
  - (3) Biological impact.
- f. Tests to properly assess the impact of dredging.
- g. Remedial measures to reduce the environmental impact of dredging.

79. Huston and Huston (1976) carried out field studies on sediment resuspension caused by cutterhead dredges in the Corpus Christi Channel in Texas. Their report discussed the various factors, including the operation techniques for the cutterhead dredges. According to Huston and Huston, the dredge-induced turbidity is found only in the immediate vicinity of the dredge plant. Unless the operator is very careless, the levels of turbidity generated by the dredging operation of hydraulic dredges are not very high. Measures to reduce sediment resuspension have also been recommended in the report. Some studies were also carried out in Japan by the Bureau of Ports and Harbors and the Port and Harbor Research Institute between 1973 and 1976 (Nakai 1978). In these studies, field investigations were carried out to develop a method for predicting the quantity of resuspended sediment by various dredges in different types of soil. A TGU was developed using the results of these calculations. A TGU, defined as the quantity of suspended solids generated per unit volume of dredged material can be effectively used to

predict the quantity of resuspended sediment. Table 6 shows the results of the investigations using a method that calculates the flux of suspended solids from water samples passing through a given line. The TGU's in Table 6 are normalized to the standard velocity of about 7 cm/sec. Dredge type, horsepower or bucket volume, and dredged material classification are factors affecting the magnitude of the TGU. It is evident from Table 6 that dredge type and sediment classification are the important factors controlling sediment resuspension. The following general characteristics of the TGU were concluded in these studies (Nakai 1978):

a. The TGU varies with different types of dredged material. The TGU for a dredge pump is approximately 40 kg/cu m for clay but only 0.2 kg/cu m for sand. For a grab dredge, the TGU is about 84 kg/cu m for clay and about 15 kg/cu m for silty loam. In general, the smaller the particle size, the larger the TGU.

b. There are enough data to compare the TGU's for clay among three types of dredges: the dredge pump, the grab dredge, and the trailing suction dredge. The TGU value of 25 kg/cu m is the smallest for the trailing suction dredge. The other values are 35 kg/cu m for pump dredge and 84 kg/cu m for grab dredge.

80. Sediment resuspension at several dumping projects in Japan was investigated (Nakai 1978) in addition to the studies on dredge-generated turbidity. The TGU's for dumping are calculated using the same method as for dredging. Some of the results are presented in Table 7. It can be seen that the TGU for sand is very low, whereas that for clay is very high.

81. In the Nakai (1978) field studies conducted in Japan, a relationship was also developed between sediment resuspension and the dredge-operating factors since the influence of these factors was considered very important. For a cutterhead dredge, the cutter's revolutions per minute, swing speed, and thickness of the dredged layer were found to influence sediment resuspension. For a grab dredge, the dredge layer thickness and the hoisting speed were found to be important.

82. Based on the field observations available at various sites in the United States and Japan, data on sediment resuspension by different dredges have been compiled and are present in Table 8.

Table 6

TGU's* for Different Dredges and Dredging Projects (Nakai 1978)

Type of Dredge	Installed Power or Bucket Volume	Dredged Material d**>74μ, %	d**>5μ, %	Classification†	TGU kg/cu m
Pump	4,000 hp	99.0	40.0	Silty clay	5.3
		98.5	36.0	Silty clay	22.5
		99.0	47.5	Clay	36.4
		31.8	11.4	Sandy loam	1.4
		69.2	35.4	Clay	45.2
		74.5	50.5	Sandy loam	12.1
	2,500 hp	94.4	34.5	Silty clay	9.9
		3.0	3.0	Sand	0.2
	2,000 hp	2.5	1.5	Sand	3.0
		8.0	2.0	Sand	0.1
Trailing suction	2,400 hp	92.0	20.7	Silty clay loam	7.1
	× 2	88.1	19.4	Silty loam	12.1
	1,800 hp	83.2	33.4	Silt	25.2
Grab	8 cu m	58.0	34.6	Silty clay	89.0
	4 cu m	54.8	41.2	Clay	84.2
		45.0	3.5	Silty loam	15.8
	3 cu m	62.0	5.5	Silty loam	11.9
		87.5	6.0	Silty loam	17.1
Bucket		10.2	1.5	Sand	17.6
		27.2	12.5	Sandy loam	55.8

* TGU = kg of suspended sediment per cu m material dredged.
** d = diameter of soil particles.
† Classification is according to the triangular soil classification system.

Table 7

TGU's* for Dumping Projects

(from Nakai 1978)

Type of Dredge	Barge Volume or Installed Power	Dumped Material d**>74μ, %	d>5μ, %	Classification†	TGU kg/cu m
Barge	500 cu m	36.5	13.0	Silty loam	14.9
		21.5	10.0	Silty loam	15.8
		20.5	15.0	Silty clay loam	10.6
	180 cu m	2.7	--	Sand	0.02
		57.7	27.5	Silty clay loam	8.3
	120 cu m	22.7	--	Sandy loam	3.8
		19.1	6.8	Sandy loam	143.5
Trailing suction	2,400 hp	68.6	19.4	Silty loam	22.7
	1,800 hp	82.2	33.4	Clay	123.4

* TGU = kg of suspended sediment per cu m material dredged.
** d = diameter of soil particles.
† Classification is according to the triangular soil classification system.

Table 8

Approximate Suspended Solids Levels Generated by Different Dredges

Type of Dredge	Suspended Solids Concentration	Remarks
Cutterhead		
10 rpm	161 mg/ℓ (sandy clay) 52 mg/ℓ (med. clay)	Observations in the Corpus Christi Channel (Huston and Huston 1976)
20 rpm	187 mg/ℓ (sandy clay) 177 mg/ℓ (med. clay)	
30 rpm	580 mg/ℓ 266 mg/ℓ	
18 rpm	1 to 4 g/ℓ within 3 m of cutter	Soft mud at Yokkaichi Harbor, Japan (Yagi et al. 1975)
18 rpm	2 to 31 g/ℓ within 1 m of cutter	
Plain suction dredge	Little turbidity for free-flowing sand. Significant turbidity at the bottom with water jets	
Dustpan dredge	Little turbidity for free-flowing sand. Significant turbidity at the bottom created by water jets	
Trailing suction dredge	Several hundred milligrams per liter above background (at surface and middepth). As high as several grams per liter	San Francisco Bay (Barnard 1978)
	2 g/ℓ at overflow 200 mg/ℓ at 200 m behind	Chesapeake Bay (Barnard 1978)
Mudcat dredge	1.5 m from auger, 1 g/ℓ near bottom (background level 500 mg/ℓ) 1.5 to 3.5 m in front of auger, 200 mg/ℓ surface and middepth (background level 40 to 65 mg/ℓ)	
Pneuma pump	48 mg/ℓ at 1 m above bottom 4 mg/ℓ at 7 m above bottom (5 m in front of pump)	Port of Chofu, Japan
	13 mg/ℓ at 1 m above bottom	Kita Kyushu City, Japan
Cleanup system	1.1 mg/ℓ to 7.0 mg/ℓ at 3 m above suction 1.7 mg/ℓ to 3.5 mg/ℓ at surface	Toa Harbor, Japan

(Continued)

Table 8 (Concluded)

Type of Dredge	Suspended Solids Concentration	Remarks
Oozer dredge	No data on turbidity available. Reported to cause very little turbidity even for soft clay and mud	
Stump dredge	No data on turbidity available	
Waterless dredge	Little generation of turbidity	
Delta dredge	Turbidity levels in the vicinity of the dredge are quite low	
Grab/bucket/clamshell dredges	Less than 200 mg/ℓ and average 30 to 90 mg/ℓ at 50 m downstream (background level 40 mg/ℓ)	San Francisco Bay (Barnard 1978)
	168 mg/ℓ near bottom 68 mg/ℓ at surface	100 m downstream at lower Thames River, Connecticut (Bohlen and Tramontaro 1977)
	150 to 300 mg/ℓ at 3.5-m depth	Japanese observations (Yagi et al. 1977)
Antiturbidity overflow system	6 mg/ℓ at surface 8.2 mg/ℓ at 1 m below surface	Side of the ship (Ofuji and Naoshi 1976) Japan
	6.5 mg/ℓ at surface 8.9 mg/ℓ at 1 m below surface	Aft of the ship
Antiturbidity watertight buckets	30 to 70 percent less turbidity than typical buckets	Japan (Barnard 1978)
	500 mg/ℓ at 10 m downstream from a 4-cu m watertight bucket	

PART VII: MEASURES TO REDUCE SEDIMENT RESUSPENSION

83. One of the major concerns about dredging operations involves the possible environmental impact associated with the resuspension and subsequent dispersion of fine-grained dredged material. This concern is particularly significant considering the fact that the vast majority of potentially toxic chemical contaminants present in bottom sediments is associated with the fine-grained fraction that is most susceptible to dispersion (Barnard 1978). Under certain environmentally or aesthetically sensitive circumstances, control of this dispersion may be advisable. Barnard (1978) analyzed the results of research conducted under the DMRP on sediment resuspension by different types of dredging operations and the measures to reduce it. The analysis is incorporated in a DMRP report by Barnard (1978). The various measures described in this report and other devices mentioned in the literature to reduce sediment resuspension in the dredging process are briefly described in the following paragraphs.

84. The nature, degree, and extent of dredged material dispersion around a dredging operation are controlled by many factors, as indicated previously in this report. The relative importance of these factors varies from site to site. The sediment resuspension and its dispersion would be different depending upon the type of dredge and the dredging operation, the nature of the bed material, and the environmental conditions. The skills of the operator are also very important. The various measures to improve the environmental condition for the conventional and unconventional dredges may not have been used widely in the United States, but since they appear to have some potential for reducing sediment resuspension, they are described briefly in the following sections.

Cutterhead Dredges

85. Huston and Huston (1976) discussed in detail the various measures to reduce sediment resuspension by the present dredges and dredging procedures. Design of the cutterhead assumes great importance in the dredge's production and sediment resuspension during the dredging process. The dredge's suction (Figure 11), which picks up the material that has been cut by the cutter, can be partially responsible for sediment resuspension around the cutter

if the energy provided to the suction by the dredge pump is not great enough to pick up all of the material disturbed by the cutter. Water-jet booster systems or ladder-mounted submerged pumps installed on cutterhead dredges have been found to enhance the dredge's pickup capability, increase the slurry density and potential production rate, and decrease sediment resuspension (Barnard 1978). According to Huston and Huston (1976), a proper cutter-suction combination can help in achieving the necessary increase in the output and reduction in sediment resuspension. They suggested that by reducing the distance between the suction mouth and the material to be dredged and by providing an approximate ideal bell-shaped mouth, the amount of energy lost at the suction mouth could be reduced and the cutter would more effectively feed material into the suction from top, sides, and bottom rather than just from bottom. All these factors would tend to enhance the pickup efficiency of the dredge and reduce the tendency to resuspend the material during the cutter operation. More research is, however, needed to examine the different aspects of the problem.

86. The operational parameters of the cutterhead such as the cutter rotation rate, swing rate, and thickness of the cut affect sediment resuspension at the cutter and must be controlled relative to the dredge's production. In many new dredges, production metering systems have been installed, and the production rate can be closely monitored. The method of swinging the dredging (stabbing) can also affect the dredge's production rate. By using a spud carriage system (shown in Figure 13), the production rate was found to increase substantially. After studying in detail the operational techniques of cutterhead dredges, Huston and Huston (1976) found that the leverman's techniques for operating a dredge assume great importance in increasing production and minimizing sediment resuspension. These techniques are given by Barnard (1978) and are reproduced below:

- a. Large sets and very thick cuts should be avoided since they tend to bury the cutter and may cause high levels of suspended solids if the suction cannot pick up all of the dislodged material.
- b. The leverman should swing the dredge so that the cutter will cover as much of the bottom as possible. This action minimizes the formation of windrows or ridges of partially disturbed material between the cuts: these windrows will tend to slough into the cuts and may be susceptible to resuspension by ambient currents and turbulence caused by the cutter. Windrow formation can be eliminated by swinging the dredge in close,

concentric arcs over the dredging area. This may involve either modifying the basic stepping methods used to advance the dredge or using a Wagger or spud carriage system.

c. Side slopes of channels are usually dredged by making a vertical "box cut"; the material on the upper half of the cut then sloughs to the specified slope, which should be cut by making a series of smaller boxes. This method, called "stepping" the slope, will not eliminate all sloughing, but will help reduce it.

d. On some dredging projects, it may be more economical to roughly cut and remove most of the material, leaving a relatively thin layer for final cleanup after the project has been roughed out. This remaining material may be subject to resuspension by ambient currents or propwash from passing ship traffic.

e. When "layer cutting" is used, the dredge will remove a single layer of material over a large portion of the channel; the dredge is then set back to dredge another layer. This continues down to the required depth of the project. Since loose material is often left on the bottom after each layer is dredged, this technique should be used only where resuspension of the remaining material will not create serious problems.

f. The propwash from the tenders (i.e. tugboats) used to move anchors, sections of pipeline, barges, and the dredge itself can resuspend a great deal of bottom material, especially in shallow water adjacent to the channel. Although propwash cannot be eliminated, oversize tenders should not be used in shallow-water areas.

g. In addition to propwash, significant resuspension of bottom material often occurs when the anchors used in support of the operation are dragged along the bottom while the dredge is being moved to a new location. Anchor dragging should be avoided.

h. During the course of a typical operation, the length of the pipeline may have to be adjusted by adding or removing sections. Before the pipeline is broken, it should be flushed thoroughly with water, not only to prevent clogging of the pipeline when pumping is resumed, but also to maintain low turbidity levels around the pipeline. Obvious leaks from poorly sealed ball joints between pipeline sections should also be repaired.

87. Experimental and theoretical studies carried out by Apgar and Basco (1973) for the flow field surrounding a suction inlet indicated the development of a separation zone about 8 to 10 diam above the bottom. They therefore suggested placement of an artificial shield as shown in Figure 24. This shield could artificially lower the zone of separation, increase velocities and turbulence near the bottom causing increased sediment entrainment, and help prevent turbid water from reaching the surface. The exact position

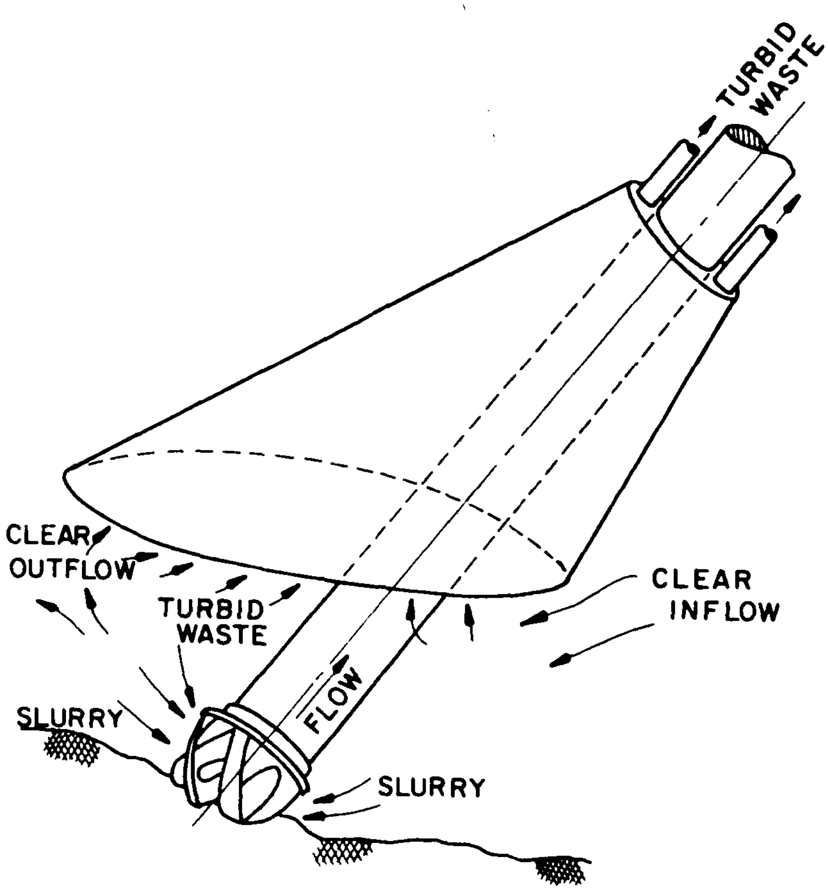

Figure 24. Hooded cutterhead suction (from Apgar and Basco 1973)

and shape of the shield would have to be developed in future studies. Such a device is expected to improve production and water quality (Apgar and Basco 1973).

Hopper Dredges

88. In the case of hopper dredges, the most obvious source of near-surface turbidity is the overflow water. Japan (Ofuji and Naoshi 1976) has developed a relatively simple submerged discharge system for hopper dredge overflow. The overflow collection system in the dredge was streamlined to minimize incorporation of air bubbles, and the overflow discharge ports were moved from the sides to the bottom of the dredge's hull. With this arrangement, the slurry descends rapidly to the bottom with a minimum amount of dispersion within the water column. The system can be incorporated in the

existing dredges through simple modifications of existing overflow systems. The Ishikawajima-Harima Heavy Industries Company, Ltd., Japan, has developed this system, shown in Figure 25. It has been successfully incorporated in three Japanese trailing-hopper dredges with capacities ranging from 2,600 to 5,200 cu yd. Tests carried out on the dredge KAIRYU MARU indicated considerable reduction in the turbidity at the surface and 1 m below the surface by the side of the ship and also behind the ship. The data are presented below in the following tabulation:

Average Concentration of Suspended Solids, ppm	Conventional Overflow System		Antiturbidity Overflow System	
	At Surface	1 m Below Surface	At Surface	1 m Below Surface
By the side of the ship	627	272	6.0	8.2
Aft of the ship	119	110	6.5	8.9

The advantage of the antiturbidity overflow system is that it can be relatively easily installed on existing hopper overflow dredges. The operation

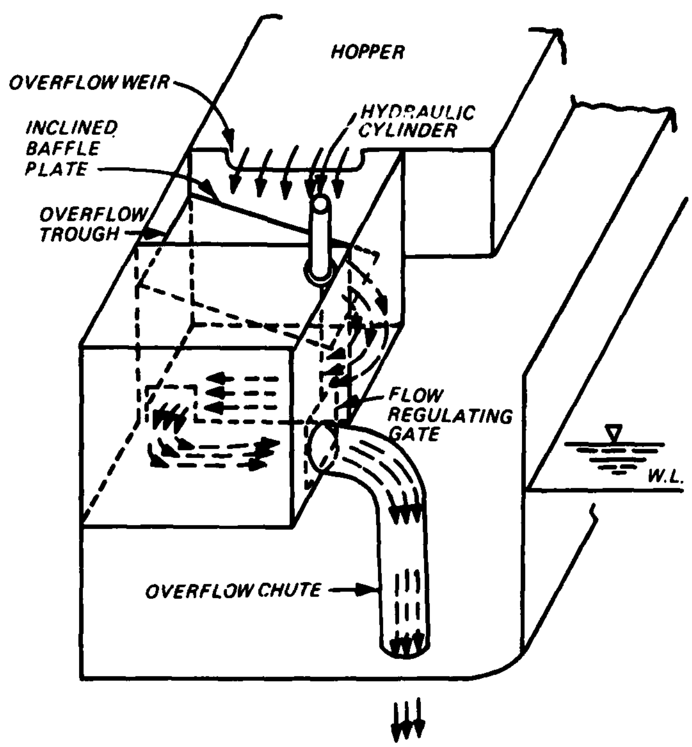

Figure 25. Antiturbidity overflow system
(redrawn from Ofuji and Naoshi 1976)

and maintenance of the system are also relatively easily performed. No data are, however, available on sediment concentration at the bottom of the water column by the side and behind the dredge.

89. There are various other techniques by which the turbidity in the overflow of the hopper is reduced. One of the techniques is to reduce the flow rate of the slurry being pumped into the hoppers during the latter phases of the hopper-filling operation (deBree 1977). By using this technique, the solids content of the overflow can be decreased substantially--from 200 to 100 mg/ℓ or less (Barnard 1978)--while the loading efficiency of the dredge is simultaneously increased. Among other techniques, increasing the rate of settling of sediments in the hopper by adding flocculant has been attempted by several researchers (Barnard 1978). These techniques, however, have been found to be not very effective, primarily because of the high solids content of the slurry. Tests were carried out in Saginaw Bay Ship Channel, Lake Huron, using polyelectrolytes to treat the overflow from the hopper dredge MARKHAM; this overflow has a typical solids content of 100 mg/ℓ or less. Average near-surface suspended solids concentrations in the plume at a distance of 1,350 m from the dredge's overflow ports averaged 58 and 36 mg/ℓ for the untreated and treated condition, respectively. Thus, it has been found that treatment of overflow has only a marginal increase in the settling rate of solids suspended in the overflow plume (Barnard 1978). Ofuki and Ishimatsu (1981) determined through model experiments that sea surface suspended sediment caused by overflowing water from a hopper dredge was principally caused by an air-lift phenomenon of air bubbles entrained in the muddy water. Hence, the AntiTurbidity Overflow System (ATOS) was developed to eliminate air bubbles from the overflowing water. The effect of ATOS was confirmed by actual dredging test. In fine sand or silt, ATOS reduced suspended sediment of the sea surface to as low as 10 ppm or lower in suspended solid concentration as compared with a level of over 400 ppm without ATOS.

90. In the case of trailing suction hopper dredges, turbidity resulting from overflow is generated at the surface, whereas turbidity caused by the draghead pulling through the soil is along the bottom. The turbidity generated at the draghead is low compared with that at the overflow. No techniques could be found in the literature to reduce turbidity generated at the dragheads. Further studies in this respect are needed.

Watertight Buckets

91. The Port and Harbor Institute, Japan, has developed a watertight bucket to minimize the turbidity generated by a typical clamshell operation (Barnard 1978). The watertight bucket has edges that seal when the bucket is closed (Figure 26). In addition, the top of the watertight bucket is covered so that the dredged material is totally enclosed within the bucket. According to the manufacturer, these buckets are best adapted for dredging fine-grained sediments and soft mud. A direct comparison of a 1-cu m typical bucket with a watertight clamshell bucket indicates that watertight buckets generate 30 to 70 percent less turbidity in the water column than the typical buckets.

Sediment Resuspension Control in Unconventional Dredging Systems

92. Unconventional dredging systems have been developed over the last few years in the United States and overseas to pump dredged material slurry with a high solids content or to minimize sediment resuspension. The eight unconventional dredging systems considered are Mudcat dredge, cleanup dredge, Oozer dredge, Pneuma pump, Oozer pump, waterless dredge, delta dredge, and bucketwheel dredge. Most of these systems are not intended for use on typical maintenance operations; however, they may provide alternative methods for unusual dredging projects such as chemical "hot spots" when the capabilities

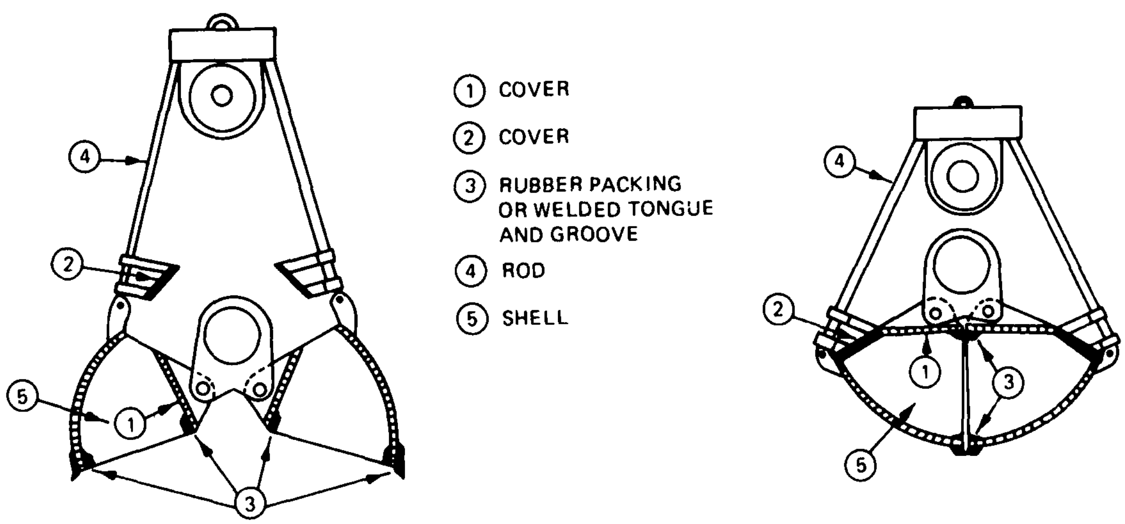

Figure 26. *Open and closed positions of the watertight bucket* (from Barnard 1978)

of a particular system provide some advantage over other unconventional dredging equipment (Barnard 1978). The various unconventional dredging systems have been described in detail in previous sections of this report, and the approximate suspended solids levels in each case are indicated in Table 8. It can be seen that the suspended solids levels in the case of the pneuma pump system, cleanup dredge, oozer dredge, and oozer pump are quite low. Very little data on sediment resuspension are available for the other systems.

Silt Curtains

93. Silt curtains are turbidity barriers that can physically control the dispersion of near-surface turbid water in the vicinity of the dredging operations in quiescent environments (JBF Scientific Corps. 1978). They are flexible, impervious barriers that hang vertically from surface flotation to a specified water depth (Figure 27). The flexible, nylon-reinforced polyvinyl chloride (PVC) fabric forming the barrier is maintained in a vertical position by flotation segments at the top and a ballast chain at the bottom. Anchor lines hold the curtain in a deployed configuration that is usually U-shaped or circular. Silt curtains are not recommended for operations in currents exceeding 50 cm/sec in areas frequently exposed to high winds and large breaking waves or around hopper or cutterhead dredges where frequent curtain movement would be necessary.

94. In many cases, the concentration of fine-grained suspended solids inside the silt curtain enclosure may be relatively high (i.e. in excess of 1 g/ℓ) or the suspended material may be composed of relatively large, rapidly settling flocs. The silt curtain provides an enclosure where some of the fine-grained suspended material may flocculate or settle and most of the turbid water and fluid mud flow under the curtain. In this manner a properly deployed and maintained silt curtain provides a mechanism for controlling the dispersion of turbid water by diverting its flow under the curtain, thereby minimizing the dispersion of the turbid water in the upper water column outside the silt curtain. Silt curtains are not designed to contain or control fluid mud flow. In fact, when the fluid layer accumulates to the depth of the skirt, the curtain must be moved out away from the discharge to prevent sediment buildup on the lower edge of the skirt, which will pull the curtain underwater and eventually bury it (JBF Scientific Corp. 1978).

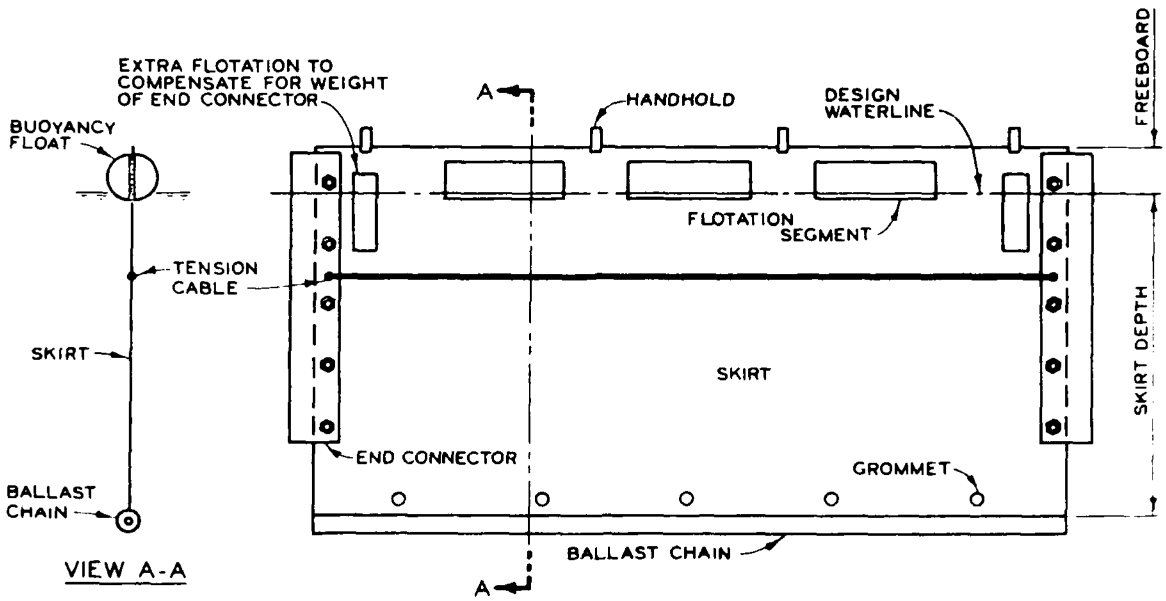

Figure 27. Construction of a typical center-tension silt curtain section (from Barnard 1978)

95. The effectiveness of a silt curtain, defined as the degree of turbidity reduction outside the curtain relative to the turbidity levels inside the curtain, depends on the nature of the operation; the characteristics of the material in suspension; the type, condition of, and method for deploying the silt curtain; the configuration of the enclosure; and the hydrodynamic regime present at the site. Under quiescent conditions, turbidity levels outside a properly deployed and maintained curtain may be reduced by 80 to 90 percent of the levels inside. The effectiveness of the silt curtains can be significantly reduced in high-energy regimes where currents are high. Increased turbulence around the silt curtain can resuspend the material and can increase the turbidity level outside the silt curtain. A current velocity of 50 cm/sec is considered the upper practical limit for deploying silt curtains (JBF Scientific Corp. 1978).

96. Johanson (1976) conducted analytical investigations and field tests at four different sites on silt curtains, and his conclusions on the study were as below:

a. Under low current (0.1 knot or less), a well-deployed, well-maintained top-tension curtain can be effective in reducing the turbidity in the upper water column beyond the curtain. There may be a turbid layer of material flowing under the curtain.

b. Under conditions of medium current (0.5 knot or less), a well-maintained center-tension curtain can be effective. However, turbulence generated by the curtain may cause the turbidity layer flowing under the curtain to quickly resurface beyond the curtain.

c. Silt curtains are not recommended for operations in currents exceeding 50 cm/sec, in areas frequently exposed to high winds, or around hopper or cutterhead dredges.

d. Curtain deployment geometries are critical to the performance of the curtain. The curtain length must be such that the skirt does not lie on the bottom during any part of the tidal cycle.

e. Curtain maintenance procedures, as presently practiced, are totally inadequate.

f. The maze configuration has been used on rivers but appears to be relatively ineffective because of direct flow through the gap between two separate curtains.

Hatano and Abe* investigated a new jointed-type antiturbidity curtain on Yokohama Harbor, Japan, in order to evaluate its effectiveness in containing suspended solids. Also, a mathematical model was developed to describe the curtain's influence on suspended solids. Field measurements were then successfully compared with computed results. The function of this new curtain can be regarded as increasing the particle size of the suspended sediment by approximately 10 times its original diameter. In such a way, the curtain plays an excellent role in promoting the settlement of suspended solids.

Pneumatic Barriers

97. In addition to silt curtains, Boyd et al. (1972) have indicated the possibility of using pneumatic bubble screens in a wide variety of circumstances involving the creation of a "barrier" to floating or suspended materials. In this case, two facts have become apparent: (a) current velocity must be minimal and (b) power requirements to supply adequate compressed air are high. The USACE and other investigators have tried to use this technique to confine turbidity, contain oil, etc., but the power requirement was found

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* R. Hatano and Y. Abe, 1986, "The Use of Antiturbidity Curtains at a Sand Compaction Piling Area in Yokohama Harbor," Japan Sediments Management Association, Tokyo, Japan.

to be very high and the technique was not found practical. Further studies on pneumatic barriers may be of value to the problem of confining turbidity.

Synthetic Flocculants

98. In connection with investigations on the treatment of material dredged in the Port of Hamburg, synthetic flocculants (polyelectrolytes) were used in bench scale experiments for cleaning and thickening the mud suspensions. The suspended solids as well as a large part of the heavy metals could be separated from the water (Hilligardt, Bauer, and Werther 1985).

99. Several flocculants of different electrolytic behavior were applied to determine the amount of flocculant needed for optimum sedimentation of the suspended solids. The results were tested in a lamella separator of a pilot size scale for different solid concentrations and suspension flow rates.

PART VIII: SUMMARY

100. The bottom sediments of many navigable waterways of the United States are contaminated with potentially toxic chemicals. These contaminants are generally associated with the fine-grained fraction that is most susceptible to dispersion. Various field and laboratory studies have shown that the toxic chemical contaminants could have adverse effects if they are released in the waters through dredging. The impact could be of long and short duration. There is, therefore, concern about dredging and disposal operations.

101. Many factors control the dispersion of dredged material. The relative importance of these factors varies from site to site. The type of dredge used, the method of dredging, the type of sediments being dredged, environmental conditions at the site, etc., decide the nature and degree of resuspension of sediment and its subsequent dispersion.

102. Among the conventional dredges used in the United States are cutterhead, trailing suction hopper, dustpan, plain suction, and clamshell dredges. The major portion of dredging is done by cutterhead dredges. The USACE has a number of hopper dredges which are also used for dredging. The remaining dredges are used on a much smaller scale compared with cutterhead and hopper dredges.

103. The sediments to be dredged in the navigable waterways of the Nation include clay, silt, sand, gravel, and organic matter of varying proportions. The contamination of these sediments by toxic chemicals widely varies from place to place. The extremely fine material such as clay and silt has a tendency to quickly go into suspension during the dredging process. Since the fall velocity of such fine particles is very small, these particles remain in suspension for a longer time compared with coarse-grained particles that settle fairly quickly. The degree of turbidity, therefore, largely depends on the size of the sediment particles.

104. Sediment resuspension varies from dredge to dredge and also largely depends on the dredging technique adopted. In the case of cutterhead dredges, turbidity is caused by the rotating action of the cutter and swinging action of the ladder. According to Huston and Huston (1976), the operation of the cutterhead dredge assumes great importance, and they have suggested operating techniques to reduce turbidity at the cutterhead. Very little research effort has been made so far to properly understand the flow mechanism at the

cutterhead intake that controls the pickup of suspended material. Further research is recommended to examine different aspects of the problem including measures to reduce the turbidity at the cutterhead, such as hooded intake suggested by Apgar and Basco (1973).

105. In the case of hopper dredges, sediment resuspension is caused by the dragheads pulling through the soil, the overflow of hoppers, and the dumping through the bottom of hoppers. The turbidity caused at the dragheads is fairly low compared with that at the overflow. Very little attention seems to have been paid to the reduction of turbidity at the dragheads. The turbidity plume caused by overflow is observed to extend up to a distance of over 100 m downstream. The turbidity, however, persists for a short period only. The Japanese have conducted some research to reduce turbidity at the overflow. The antiturbidity overflow system seems to be quite promising. Some field tests carried out in Japan on existing hopper dredges with antiturbidity systems are stated to be quite successful. Data on turbidity at the bottom are not available. The addition of chemical flocculants to increase the settling rate of sediment particles in the hopper is not recommended in view of the elaborate arrangements necessary to provide mixing and the marginal advantages it provides.

106. In the case of clamshell dredges, the watertight buckets appear to be quite useful as they reduce the turbidity by about 30 to 70 percent.

107. The plain suction dredge operates in a free-flowing sand and therefore causes less turbidity. The water jets at the bottom and the overflow at the surface can cause considerable turbidity. In general, sediment resuspension by a plain suction dredge should be much less than that by a cutterhead dredge in view of the absence of a rotating cutter in the plain suction dredge.

108. Among the conventional dredges, the dustpan dredge generates a considerable amount of turbidity because of high-velocity water jets, particularly in soft soil. To enhance the flow of granular material, water jets are provided along the top of the mouthpiece, and digging teeth are provided on the bottom. These features are undesirable for removal of contaminated silt (Hudson and Vann 1982) and would need to be removed. For removing the contaminated material from James River, Virginia, some modifications to the dustpan dredge were suggested. These modifications consisted of fitting the dustpan with a newly fabricated mouthpiece to present a hydraulically "clean"

opening to the material without trash bars and grates, and, to overcome the entry losses of the flat rectangular mouthpiece, a rollover plate shaped like a bulldozer blade was suggested. Wing plates were also suggested on the sides and a splitter plate at the center to curb the tendency of the material to spill over the sides.

109. The Japanese have developed many unconventional dredging systems to remove highly contaminated fine-grained material from the bottom. The oozer dredge is one such system. The pneumatic dredge, which was first developed in Italy, uses hydrostatic pressure and compressed air to remove contaminated sediments. By applying a vacuum to a pneumatic dredge, the Japanese were able to use the dredge is shallow water, thereby eliminating the constraint of needing a high hydrostatic head pressure. There are specific advantages of such a system, i.e. continuous and uniform flow, high solids content (60 to 80 percent), no disturbance of bed and hence quite suitable for removing polluted sediments, etc. The Japanese have also advanced other aspects of dredging technology through the development of a "cleanup" hydraulic dredge, watertight buckets, etc. Turbidity levels in the case of the Pneuma pump system, cleanup system, and Oozer dredge are quite low. The total capacity of such systems is, however, not quite adequate to handle large volumes of highly contaminated sediments.

110. Other types of unconventional dredges are the Mudcat, Delta dredge, bucket wheel, etc. Very little data on sediment resuspension by these dredges are available. The capacity of these dredges is also limited.

111. No adequate data are available to make a comparison of dredging efficiency and dredging output between conventional and special purpose dredges. Conventional dredges were designed to obtain high output, but little attention was paid to environmental impact. As a result, these dredges produce more turbidity compared with those special purpose dredges that were designed specifically to reduce sediment resuspension (Table 8). The output of the special purpose dredges is, however, low compared with that of the conventional dredges. For example, an oozer dredge can produce from 325 to 800 cu yd/hr when dredging silt with a 200-percent water content. The production is lower, however, for sandy materials. In the United States, where the quantities of contaminated bed material to be handled are high, it would be desirable to use conventional dredges with suitable modifications.

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APPENDIX C: ABSTRACTS OF SELECTED REFERENCES AND PERSONAL COMMUNICATIONS

Selected References

Calhoun, C. C., Jr., and Hart, T. L. 1982 (Sep). "Overview of Corps Environmental Research and Other Activities Related to Dredging and Dredged Material Disposal," Proceedings of the U.S./Dutch Memorandum of Understanding of Dredging Technology Meeting, New Orleans, LA.

A general overview is given of the research and other activities being conducted by the US Army Corps of Engineers on environmental aspects of dredging and dredged material disposal. Four Corps programs are described: Dredging Operations Technical Support (DOTS) Program; Long-Term Effects of Dredging Operations (LEDO) Program; Field Verification Program (FVP); and a work unit on dredging contaminated sediments. With the exception of DOTS, these studies were all initiated in 1982, and the results will be forthcoming over the next few years.

Chen, K. Y., et al. 1976 (Jul). "Water Quality Impact and Its Mitigation in the Disposal of Pollution Sediments," Proceedings of the Seventh World Dredging Conference, WODCON VII, San Francisco, CA.

The main concern in the disposal of polluted sediments is the resuspension and redissolution of contaminants. During dredging and disposal operations, fine particles that generally associate with high concentrations of contaminants can be resuspended into the water column. At the same time, trace contaminants and nutrients can also be released from sediments into the soluble phase because of changes of environmental conditions.

Most metal cations and nutrients can exist in several forms that differ in toxicity and bioavailability. Sorptive behavior and redox reactions of various chemical constituents (occurring within sediments during aquatic disposal and after redeposition) govern to a large extent the distribution of chemical constituents among various available and nonavailable forms.

In general, soluble contaminants are considered to be readily available for biological uptake, while those associated with detrital material can be consumed only by filter-feeding organisms and certain types of algae. Organic matter in the sediment affects to a great extent the behavior of trace contaminants related to their bioavailability. Trace contaminants may interact with organic compounds such as kerogen, humic and fulvic substances, proteins, hydrocarbons, etc., and form complexes with organic colloids that may not only alter the availability but also the toxicity of these substances.

In the current study, the migration of trace metals, chlorinated hydrocarbons, and nutrients was evaluated by simulating dredging and disposal operations. Column studies were conducted to evaluate the effect of flocculation by polymers for water quality improvement in the disposal of polluted sediments.

Crowder, J. P. 1980 (Sep). "The Section 404 Dredge and Fill Program," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the 5th U.S./Japan Experts Meeting.

Dredging and filling in the navigable-in-fact waters of the United States have been regulated for 80 years under provisions of Section 10 of the River and Harbor Act of 1899. Since 1968, major Federal environmental legislation has expanded the criteria for decision on Section 10 permit applications to include numerous public interest factors in addition to navigation. With enactment of the Federal Water Pollution Control Amendments of 1972, Section 13 of the 1899 Act was amended and expanded to create a water pollution control program regulating discharges of all classes of pollutants into the Nation's waters. The new statute established the Section 404 programs to regulate discharges of dredged or fill material, with responsibilities for administration of dredged or fill material, with responsibilities for administration divided between the Department of the Army and the Administrator of the Environmental Protection Agency. The geographic scope of the Section 404 program is substantially broader than that available in the 1899 Act, but the classes of activity regulated are to some degree similar.

Environmental criteria for the Section 404 programs are based on objectives that encourage minimization of impact principally through careful evaluation of material proposed for discharge and through rigorous evaluation of alternative disposal sites and methodologies.

Engler, R. M. 1978 (Sep). "The Regulation Guidelines and Criteria for the Discharge of Dredged Material: Prediction of Pollution Potential," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the Third U.S./Japan Experts Meeting.

Guidelines and criteria have been published for the ecological evaluations of the discharge of dredged and fill material into inland waters and the transportation of dredged material for dumping into ocean waters. These guidelines and criteria were published in the Federal Register, Vol 40, No. 173, Friday, 5 September 1975, and Vol 42, No. 7, Tuesday, 11 January

1977, respectively, for inland and ocean dumping. Implementation manuals have subsequently been published and are discussed herein. Relevant dredged material research is also presented. These manuals present evaluative procedures for pollution evaluation.

Engler, R. M. 1978 (Sep). "Impacts Associated with the Discharge of Dredged Material into Open Water," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the Third U.S./Japan Experts Meeting.

With few exceptions, impacts of aquatic disposal are mainly associated with the physical effects. These possible effects are persistent, often irreversible, and compounding. Geochemically, releases are limited to nutrients with negligible release of toxic metals and hydrocarbons. Biochemical interactions are infrequent with no clear trends, and elevated uptake of toxic metals and hydrocarbons are negligible to nonexistent.

Engler, R. M. 1982 (Sep). "London Dumping Convention: Policy and Technical Issues," Proceedings of the U.S./Dutch Memorandum of Understanding of Dredging Technology Meeting, New Orleans, LA.

Maintaining waterways and harbors for the purpose of navigation is essential to a nation's economy through trade links to the rest of the world. Navigation channel maintenance or new work for port expansion and development is routinely carried out by dredging. The dredging process, however, creates a by-product (dredged material) that is regulated by most developed nations as a waste material. This "waste material" accounts for a large percent by weight of the total amount of waste disposal in ocean waters. The ocean disposal of dredged material is regulated both domestically and by International Treaty through the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter. Domestic law and International Treaty for regulating dredged material disposal in ocean waters and ensuring a table trade economy are often at conflict. This conflict and an assumed conflict between domestic regulation and International Treaty can be resolved. A decade of research on the environmental consequences of dredged material disposal has shown that ocean disposal may, in most cases, offer the greatest level of environmental protection. Moreover, the ocean often has a greater assimilative ability for dredged material than land or estuarine alternatives.

Hayashi, T. 1978 (Sep). "Control of Toxic Effluents and Management of Toxic Bottom Sediments," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the Third U.S./Japan Experts Meeting.

In recent years, the decline in Japanese water quality has ceased, and there has been a trend toward slow recovery. Water pollution caused by cadmium and other toxic substances has stabilized, and pollution from organic substances has, since 1969, definitely slowed--even improved in certain areas. This is due to the rigorous control of effluents throughout the country in recent years. However, there are still areas where water pollution is severe, especially in rivers that run through cities with high populations and heavy industrial concentrations and in bays and inland seas where exchange rates with the sea are slow.

This paper explains the water pollution control measures designed to regulate the discharge of toxic substances and treat bottom sediments containing toxic substances.

Hoose, R. A. W. 1976 (Jul). "Environmental Assessment of an Ocean Dumpsite in the Strait of Georgia, British Columbia, Canada," Proceedings of the Seventh World Dredging Conference, WODCON VII, San Francisco, CA.

During the period 1975-76, Environment Canada undertook an investigative program to assess the effects of the ocean disposal of a variety of wastes upon the receiving environment at a designated ocean dumpsite located in 250 m of water, 4 miles west of the City of Vancouver, British Columbia. The wastes disposed were dominated by the native uncontaminated and polluted dredged spoils, but also included construction rubble, excavation material, and forest industry residue. Now under government control, the site continues to be used for the disposal of these materials from trailing suction hoppers, bottom unloading barges, and scows equipped with clamshells, bulldozers, or front-end loaders.

The program investigated many components of the receiving environment, including the water column, the water-sediment interface, and the sediments, as well as examining organisms inhabiting these zones. Water bottle casts, benthic grab and core sampling, beam trawls, and manned submersible visual and photographic procedures were among the assessment techniques employed.

General preliminary conclusions are that the site appears to be suitable for the ocean disposal of the wastes in question and that the deleterious impacts upon the resident biological communities are minimal. However, careful continued surveillance and monitoring of this area are required to ensure that dumping is carried out where designated, since a valuable trawl fishery exists in the waters between the dumpsite and the City of Vancouver. It is also necessary to ensure that levels of chemical contamination of the sediments and resident organisms remain at or below current levels.

Information gaps identified by this preliminary study were examined with a view toward extending the program to include analysis of concerns such as possible long-term (chronic) effects upon the receiving environment. Studies of this nature are presently being undertaken.

Huston, John. 1976 (Jul). "Techniques for Reducing Turbidity with Present Dredging Procedures and Operations," Proceedings of the Seventh World Dredging Conference, WODCON VII, San Francisco, CA.

Techniques for reducing dredge-induced turbidity fall principally in the categories of the cutter, ladder, suction, hull, pipeline, connections, barges, tugs, personnel, inspection, and plans and specifications. These techniques consist principally of good dredging procedures already known, but not always followed. When these techniques are constantly applied, not only will dredge-induced turbidity be reduced, but economical operation will prevail in most instances.

Johanson, E. E. 1976 (Jul). "The Effectiveness of Silt Curtains (Barriers) in Controlling Turbidity," Proceedings of the Seventh World Dredging Conference, WODCON VII, San Francisco, CA.

This paper presents the results of a study conducted for the US Army Engineer Waterway Experiment Station to determine the effectiveness of silt curtains in controlling turbidity around dredging and dredged material disposal operations. Silt curtain manufacturers were visited and test data collected to determine the physical characteristics and limitations of commercially available curtains. Dredging contractors were contacted to establish what field experience existed using curtains under a variety of environmental conditions. Laboratory studies were conducted to assess the importance of flocculation as a mechanism for accounting for the turbidity reduction experienced using impervious curtains. Extensive field measurements were made on typical silt curtain installations to establish the effectiveness of curtains under a wide variety of environmental conditions. The effects of current on the physical behavior of curtains were established as were the requirements for deployment and mooring systems. Manpower requirements for deploying and recovering curtains were established.

The paper presents the results of this study including a definition of the conditions under which curtains are effective, the optimum deployment techniques, and a summary of problems that have been encountered using curtains.

Koba, H. 1978 (Sep). "Recent Progress in Techniques for Managing Contaminated Bottom Sediments," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the Third U.S./Japan Experts Meeting.

This paper provides a brief introduction to recent progress on management techniques for contaminated bottom sediments. It includes comments on the technical guideline prepared by the Japan Dredging and Reclamation Engineering Association.

Mackenthun, K. M., et al. 1978 (Oct). "Approaches for Mitigating the Kepone Contamination in the Hopewell/James River Area of Virginia," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the Fourth U.S./Japan Experts Meeting, Tokyo, Japan.

The Kepone Mitigation Feasibility Project discussed at the Third U.S.-Japan Meeting on management of bottom sediments containing toxic substances has been completed. The four-volume project report was forwarded to the Governors of Virginia and Maryland, together with a recommendation of formation of a task force to consider and implement the report's recommendations.

This paper summarizes the nature of the contamination found in the Hopewell/James River area and describes the mitigation approaches evaluated and the mitigation actions recommended.

Extensive sampling efforts revealed that highly persistent Kepone contamination remains on the land in Hopewell, in sewage lines and streams, and in the James River. Accordingly, mitigation methods had to focus on the problems of land, water, and sediment contamination. Conventional (dredging), nonconventional, and degradation/biological approaches to mitigation were investigated.

The investigation of conventional mitigation/removal approaches included an analysis of worldwide dredging techniques, with an evaluation of the most promising dredging techniques for removal of contaminated sediments from specific sites, engineering studies to contain, stabilize, or remove contaminated sediments at points of inflow into the James River, and evaluation of the engineering requirements for removal of Kepone-contaminated sediments from the James River, assessment of dredged material disposal sites, fixation of the dredged material, and treatment of the elutriate.

A wide range of nonconventional mitigation approaches was evaluated for dredge spoil fixation, elutriate treatment, in situ stabilization, and isolation. Approaches ranged from silicate, organic- and sulfur-based fixation agents through use of retrievable and nonretrievable sorbents that would take up Kepone from the contaminated sediments and water.

Natural degradation and biological mitigation approaches were examined concurrently with engineering approaches. However, none of these approaches show high promise for Kepone mitigation at this time.

Mackenthun, K. M., et al. 1978 (Sep). "Mitigation Feasibility for the Kepone Contaminated James River, Virginia," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the Third U.S./Japan Experts Meeting.

As the result of carelessness in production and in waste disposal, the health of Kepone production workers at Hopewell, VA, has been jeopardized, and a 70-mile reach of the James River has been contaminated by this hazardous and persistent pesticide. In addition, Chesapeake Bay is threatened. The Environmental Protection Agency's (EPA's) Kepone Mitigation Feasibility Project was undertaken to address the threat posed by Kepone contamination and to recommend possible cleanup action. Responsibility for the project was assigned to the Criteria and Standards Division, Office of Water Planning and Standards, in the EPA, with support from an Energy Research and Development Agency laboratory (the Battelle Pacific Northwest Laboratories), the US Army Corps of Engineers, EPA's Gulf Breeze Environmental Research Laboratory, and the Virginia Institute of Marine Science. The project involves: (a) assessment of the biological and ecological impact of Kepone through literature search and laboratory and field studies; (b) assessment of the potential sources of continuing contamination by inflows into the James River; (c) sampling and evaluation of the contamination in the James River; (d) modeling the movement of contaminants; and (e) evaluation of potential conventional and nonconventional methods for mitigating the problems. Preliminary results indicate that continuing inflows of contamination into the James River exist and that there is no evidence of any degradation in the pesticide or indication that natural causes will substantially alleviate the problem in the foreseeable future. While some mitigation methods now look promising, their cost-effectiveness must be evaluated. A full report of EPA's Kepone Mitigation Feasibility Project and recommendations for alleviating the Kepone contamination problem was scheduled for March 1978.

Masch, F. D., and Espey, W. H., Jr. 1967 (Nov). "Shell Dredging: A Factor in Sedimentation in Galveston Bay," Report HYD06-6702, CRWR-7, Center for Research in Water Resources, University of Texas Tech, Lubbock, TX.

Detailed field studies were undertaken to determine the movement of sediments resuspended by dredging operations in a localized area of Galveston Bay, Texas. The extent and manner in which sediment movement occurred and the conditions under which dredged sediments could be expected to move onto natural reefs and possibly deposited are discussed. The effects of tidal currents, type of overburden sediments, topography, and number of dredges in operation have also been investigated.

Although this study provides information on currents and sedimentation that is applicable to other parts of the Galveston-Trinity Bay system, investigations were restricted to the area of most intense shell-dredging activity. This included an area of about 20 square miles between Redfish Island and Eagle Point. The study was carried out from an engineering standpoint, and investigations were restricted to the effects that the physical characteristics existing within the Galveston Bay system, and in particular the study area, had on the dynamic behavior of the sediments.

Controlled laboratory tests on sediment movement were also carried out. These tests provided data on the conditions under which a sediment density layer would form, the effects of water currents and bottom slopes, and the behavior of sediment density layers at abrupt changes in bottom topography such as reefs, dikes, trenches, and dredge cuts.

Based on field and laboratory observations, large-scale measures were devised to control sediment movement from dredging operations. Data are included on the effectiveness of a submerged dike and a trench as control measures. The effect of opening a pass and increasing the flushing action on sediment movement in a localized area is also noted.

Murakami, A. 1976 (Oct). "An Experiment in Removal of Organically Polluted Bottom Mud from the Seto Inland Sea," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the Second U.S./Japan Experts Meeting, Tokyo, Japan.

Since the 1950's, organic pollution of bottom mud in the Seto Inland Sea has been observed near the pump mill wastewater drain. By the 1970's, the polluted area had expanded. The Fisheries Agency examined this problem from August to October in 1974. According to the Agency, concentrated areas of polluted mud were observed in Osaka Bay, the eastern part of Hiuchi Nada, Hiroshima Bay, Beppu Bay, and some other areas. The upper 20 to 30 cm of the bottom was heavily polluted. The volume of organically polluted bottom mud (COD > 40 mg/g) is 10^6 cu m in the Seto Inland Sea, 85 percent of which exists in Hiroshima Bay.

The red tide in the Seto Inland Sea became harmful in the 1960's, and this is related to bottom pollution. Eutrophication in inshore waters contributes to the outbreak of the red tide, and the organically polluted bottom mud contributes to the eutrophication. Since 1976, the Fisheries Agency has been removing the polluted mud to reduce the eutrophication.

In this project, the organically polluted bottom mud is dredged using a variable volume volute pump to prevent the diffusion of mud. The dredged mud is transferred to the treatment pontoon by a suction pipe. Then the mud is treated through the processes of coagulation, sedimentation, and dehydration. Activated charcoal is used to filter the decanted water, which is then discharged to the sea. The settled sludge is hardened with cement and then dumped in a reserved land area.

There are still some problems to be solved in the experiment. Work needs to be done on the method of removing newly deposited materials from the surface of polluted bottom muds.

Murden, W. R., and Goodier, J. L. 1976 (Jul). "The National Dredging Study," Proceedings of the Seventh World Dredging Conference, WODCON VII, San Francisco, CA.

The controversy on whether dredging operations should be a governmental or industrial responsibility has to some extent been resolved. US dredging organizations have Congressional authority to enter the hopper dredging field, while the US Army Corps of Engineers has greatly curtailed its cutterhead pipeline dredging activities and gained an appropriation to modernize part of its hopper dredging fleet. The "National Dredging Study," completed in 1975, reveals, however, that the US dredging fleet is, for the most part, aged; suffers from obsolescence; lacks deep-dredging capabilities; and needs accurate production instrumentation, automated engineering, and devices to increase seakeeping ability. This paper defines the engineering and economic deficiencies and provides specific details on equipment requirements to develop a dredging fleet with increased capability to meet the needs of deepwater port, channel construction, and maintenance.

Nakai, O. 1978 (Sep). "Turbidity Generated by Dredging Projects," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the Third U.S./Japan Experts Meeting.

This paper discusses investigations into turbidity generated by dredging during port construction. The study was made by the Bureau of Ports and Harbors and the Port and Harbor Research Institute, Ministry of Transport, from 1973 to 1976.

Field investigations were conducted to develop a method for predicting the quantity of turbidity generated by various dredges in different kinds of soil. A turbidity generation unit (TGU) was calculated using the results of these field investigations. It is defined as the quantity of turbidity generated per unit volume of dredged material. The TGU can be effectively used to predict the quantity of turbidity.

Nishi, K. 1976 (Jul). "Dredging of High-Density Sludge Using Oozer Pump," Proceedings of the Seventh World Dredging Conference, WODCON VII, San Francisco, CA.

Japan is a small insular country with mountains covering more than 80 percent of its land space. Its population and industry are heavily concentrated in limited plain areas. It is this topographical condition that spurred large-scale reclamation of land from the sea to provide much-needed space for rapidly expanding industrial activities, when Japan entered the period of economic growth after World War II.

Most of the seabeds that are yet to be reclaimed are covered with layers of viscous matter which, at places, are topped with industrial waste containing hazardous materials. Sometimes, soft layers of sludge tens of metres deep lie atop solid bottom over very large areas.

Sludge on the seabed poses contamination problems, and its disposal is a challenging task. Realizing this, the Toyo Construction Co., Ltd., has directed its research efforts during the past several years toward the development of dredging equipment and related techniques, which are integrated into the Oozer pump dredger that is characterized by the same ease of operation as ordinary section pump dredgers and by the absence of secondary contamination problems.

Ofuji, I., and Naoshi, I. 1976 (Jul). "Antiturbidity Overflow System for Hopper Dredges," Proceedings of the Seventh World Dredging Conference, WODCON VII, San Francisco, CA.

The overflow system for hopper dredges accompanies problems--that of sea turbidity caused by overflowed water.

Recently, public consensus for environmental pollution has been rapidly widespread, and accordingly, legal restriction has become more severe. It is easily presumed that all dredging methods causing turbidity of seawater should be forbidden in the future.

The authors believe that the overflow system, however, is indispensable for obtaining the highest dredging efficiency and minimizing the dredging cost thereby. To prevent the turbidity of seawater, some of the methods may be available to a hopper dredge, such as installation of chemical processing equipment to remove the solid particles from the excess water; however, these methods would be more complicated and costly since they require huge apparatus and extra-wide space to treat the continuously large quantities of muddy water onboard.

In facing the difficult problem, the authors conducted model and actual dredging experiments in cooperation with Tokushu-Shunsetsu Co., Ltd., to clarify the mechanism of turbidity. Then they developed a simple and economical new overflow system that effectively prevents turbidity of the sea surface.

This new Anti-Turbidity Overflow System has been installed on three existing dredges in Japan. It was highly evaluated by the Japanese dredging field and received an award from the Secretary-General of Science and Technology Agency of Japan.

In this paper, the authors describe the process of the development, mechanisms of turbidity, new Anti-Turbidity Overflow System and results of actual dredging tests.

Peddicord, R. 1976 (Jul). "Biological Impacts of Suspensions of Dredged Material," Proceedings of the Seventh World Dredging Conference, WODCON VII, San Francisco, CA.

A series of laboratory experiments have been conducted to determine the impact of suspended sediment on marine and estuarine invertebrates and fish. The experimental facility provided controlled and stable levels of suspended solids, temperature salinity, and dissolved oxygen in large aquaria with an open, once-through flow of water.

Initial experiments screened a variety of species for sensitivity to suspensions of uncontaminated solids. Then the influence of temperature, dissolved oxygen, and the interaction of these variables on the lethality of suspended solids to the more sensitive species was determined. These experiments, which established a basic knowledge of responses to suspensions of uncontaminated particles, were followed by tests using suspensions of uncontaminated natural sediments. Current experiments with the same species are being conducted with contaminated natural sediment.

Results indicate many species are relatively insensitive to inert suspended solids. Sensitive species are more easily killed at warmer temperatures or reduction of dissolved oxygen. The combination of summer temperature and lowered dissolved oxygen is especially stressful. However, under most conditions suspended particles themselves are lethal only at concentrations higher than normally crested by dredging operations, with important possible exceptions. The effects of suspensions of uncontaminated natural sediments do not seem to differ significantly from those of inert clay minerals. Experiments with contaminated natural sediments indicate a much greater potential for adverse impact than would be associated with uncontaminated sediment.

Pequegnat, W. E. 1982 (Sep). "Special Care Measures for Dredging and Disposing of Polluted Material in the Marine Environment," Proceedings of the U.S./Dutch Memorandum of Understanding of Dredging Technology Meeting, New Orleans, LA.

The need for maintaining and improving ports and harbors the world over will continue to result in the generation of huge volumes of dredged material, some of which will be polluted. Unfortunately, at a time when this need may well increase, the use of some conventional means of disposal on land can be cut off by lack of suitable sites and rising public opinion pressures against upland disposal, especially around major industrial ports. One thesis of this paper is that the ocean can and should be utilized for disposing unpolluted dredged material and that it can be used for safe disposal of material containing Annex I substances, provided one employs an appropriate special care method of disposal. Thus, the principal thrust of this paper is that these measures reduce the possible environmental impacts of such material to levels no greater than those associated with Annex II substances. Several special care measures of disposal are then described, as well as the extent to which they are used in various countries.

Sameshima, T. 1976 (Oct). "Dredging of Contaminated Bed Sediment in Japan," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the Second U.S./Japan Experts Meeting, Tokyo, Japan.

Dredging of contaminated bed sediment has only recently started in Japan. In the Sumida River, Tokyo, the first dredging for the purpose of water pollution control was undertaken in 1958. In 1971 a dredging project initiated in Tagonoura Port was the first large-scale management of accumulated bed sediment in Japan. In 1972-73 the problem of fish contamination was recognized, and bed sediments were investigated all over the country. Concurrently, legal and administrative systems concerning pollution control were gradually formulated, and removal of contaminated bed sediments has been extensively undertaken.

This paper discusses the progress of dredging, present status of dredging, and legal and administrative issues concerning pollution control, especially the cost allocation system.

Sato, E. 1976 (Jul). "Application of Dredging Techniques for Environmental Problems - Dredging Methods for Bottom Sediments Without Polluting Water," Proceedings of the Seventh World Dredging Conference, WODCON VII, San Francisco, CA.

From the viewpoint of environmental protection, the fundamental matter regarding the dredging of the sediments accumulated on the sea bottom is investigated. Thereafter the structure, function, and performance of dredging equipments that have been developed based on this investigation are introduced.

Solomons, W., and Kerdijk, H. N. 1982. "Pollutants in Dredged Material, Their Origin and Impact on the Environment," Proceedings of the U.S./Dutch Memorandum of Understanding of Dredging Technology Meeting, New Orleans, LA.

In The Netherlands considerable dredging activities occur in both freshwater and estuarine areas. The metals present in the dredged material have been subject to a large number of processes during transport in the river systems in the lake or estuaries before they are deposited and subsequently removed by dredging. The disposal of dredged material on land influences the composition of the ground water. Disposal of dredged material in marine environment causes a mobilization of cadmium. Agricultural use of the landfill area is restricted as the result of cadmium accumulation in crops.

Sustar, J. F., and Wakeman, T. H. 1976 (Oct). "Dredging Conditions Influencing the Uptake of Heavy Metals by Organisms," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the Second U.S./Japan Experts Meeting, Tokyo, Japan.

Studies were conducted by the US Army Engineer District, San Francisco, from 1971 through 1976 to evaluate the impacts associated with dredging and sediment release at open-water disposal sites in San Francisco Bay. Although significant changes were observed in dissolved oxygen reductions, suspended solids increases, and trace elements, chlorinated hydrocarbon and nitrogen (nitrate and ammonia) releases, the changes were not found to be synonymous with biological impacts. Uptake and desorption of trace elements by organisms were observed. Containment levels in estuarine organisms appear to be controlled by a limited number of factors. Suggested factors are the long-term process of sediment resuspension-recirculation, seasonal fluctuations in salinity, and sources of contaminants both man-introduced and geologic formation.

Yagi, T., et al. 1976 (Jul). "Turbidity Caused by Dredging," Proceedings of the Seventh World Dredging Conference, WODCON VII, San Francisco, CA.

This paper discusses turbidity caused by two dredging methods: the pump dredger and the grab dredger using a closed-type grab bucket and a conventional one. These experiments were conducted in the field.

In the case of the pump dredger, the paper shows the relationships between turbidity and dredging conditions. Turbidity is measured around the cutter head and at several points farther than 20 m from the central point of dredging. As the factors affecting dredging capacity and turbidity, swing speed and dredging thickness are adopted. It is concluded that the turbidity has close relation with accumulative ratio of short-absorbed soil.

In the case of the grab dredger, the experiment concentrates on the comparison between the properties of turbidity caused by the closed-type grab bucket, which has covers attached to rods and shells, and those caused by the conventional bucket in reducing the turbidity.

The author adds the necessity for continuously recording turbidity and many of these kinds of tests.

Kleinbloesem, W. C. H., and van der Weijde, R. W. 1983 (Apr). "A Special Way of Dredging and Disposing of Heavily Polluted Silt in Rotterdam," World Dredging Congress 1983, Brighton, U.K.

In the Port of Rotterdam, the First Petroleum Harbor, dredged material heavily polluted by pesticides is present, caused by the locally discharged effluents from chemical industries located around this harbor. Maintenance dredging work could not be carried out for a number of years because of the lack of a suitable means of disposing of the dredged material. Several options for the disposal were considered (on a landsite, in the sea, behind a sheet piling dam, and in dredge pits). Consideration of the various options has led to the choice of a plan with dredge pits ("Putten Plan"). The principle of this plan is that pits are excavated in the first Petroleum Harbor and that the polluted dredged material is discharged into the pits. On account of legal regulations, the plan must be carried out in such a way that the dispersion of pollutants into the surface water and via the ground water is very low and acceptable. Special equipment for the dredging and the disposal of the dredged material is applied. Control measurements and calculations are made with regard to the dispersion of pollutants during the execution of the first phase of the plan.

Vellinga, Tiedo. 1984. "Development of Criteria for the Dredging and Disposal of Contaminated Dredged Material," U.S./The Netherlands Memorandum of Understanding, Charleston, NC.

In the Port of Rotterdam and the adjacent estuarine area, approximately 20-million cu m is dredged annually. The degree of contamination of the dredged material plays an important role in the choice of the method of work, and it is therefore necessary to establish criteria for the selection of the method of work.

The boundary conditions for the establishment of criteria are:

a. Acceptability with regard to the environment.

b. National law and international agreement.

c. Technical and economical feasibility.

d. Feasibility from the point of view of both management and enforcement.

A classification of dredged material is being developed for the Rotterdam area. The present classification is based upon the mixing factor between contaminated fluvial silt and very lightly contaminated marine silt.

Knowledge of the boundary conditions is at present insufficient for formulation of clearly defined criteria and thus the subject of a comprehensive research program. A part of this, relating to the investigation of the nature, extent, and dispersion of the contaminants brought into the environment as a result of dredging and disposal underwater, is explained. The turbidity that occurs as a result of dredging operations is generally known and, depending upon the dredger and the mode of work, can be plotted against the dredging costs.

With regard to minimizing turbidity during disposal, good results have been obtained by the use of a modified outflow opening. Research has indicated that it is technically possible to place dredged material in pits in the bottom of the North Sea. On the basis of these results supplemented by the results of further research, it should be possible to formulate more objective criteria and regulations governing the granting of permits. These should be related to the degree of contamination and local variables.

Nakazono, Y., Hamada, K., Saotome, Y., Miyazaki, S., Masuda, K., Ogata, Y., Okayama, Y., Kono, S. 1978 (Sep). "Turbidity and Operating Condition of Pump Dredger," Report No. 305 of the Port and Harbour Research Institute, Ministry of Transport, Nagase, Yokosuka, Japan.

The relationship between turbidity and operating conditions of a dredge was investigated in the field. This investigation was conducted in Matsuyama area of Kanda Port under the construction of anchorage, and the dredge was powered by a 2,250 PS diesel electric engine.

Among the operating conditions, dredging thickness and swing speed were varied, and their influence on turbidity was investigated. Suspended solids (SS) concentration was used as the representation of turbidity. Water samplings for SS were carried out at four points near the cutter and at four boats around the dredger. Water was sampled at every sampling point at the same time when the cutter reached the central point of its swing.

In order to estimate the dredging capacity, mud mixture ratio in a floating pipe, flow rate, and vacuum pressure of the dredging pump were measured.

The resuspended sediment near the cutter depended on effective suction ratio, defined by the ratio of the amount of soil sucked up by the pump to that excavated by the cutter and its swing. Turbidity was not detected at the boats located from 30 to 180 m from the cutter on the condition that tidal current was below 0.02 m/sec in many cases.

Shiratori, Y., Masuda, K., Kato, H., and Yamauchi, S. 1981 (Sep). "Model Experiment on Turbidity Caused by Pump Dredging," Note of the Port and Harbour Research Institute, No. 390, Ministry of Transport, Nagase, Yokosuka, Japan.

One of the important problems in dredging and reclamation is to control the water pollution that occurs around the dredging and reclamation area.

Cutter suction dredges are quite popular and have a good record with respect to the environmental effects of their operation.

In this study, the authors carried out a model experiment on turbidity caused by dredging in order to investigate the relationship between turbidity and operating conditions. Model bottom material consisted of flyash and bentonite, and real sea bottom deposits were used as test materials. Suspended solids (SS) concentration was used as an indicator of turbidity. The following results were obtained:

a. Vertical distribution of resuspended sediments around the cutter head is expressed by the exponential function. The SS concentration at the right side of cutter head is greater than that at the other side regardless of the swing direction. Turbidity is given approximately by the linear function of $|V_c - V_s|$, where V_c is peripheral velocity of the cutter and V_s is swing velocity. From observation of the cutting mechanism, turbidity is generated mainly in the swing to the right.

b. The ratio of unpumped to cutter's excavated soil, which relates the turbidity with dredging conditions, depends on the parameter $\phi = (V_c/V_s)$.

c. The amount of turbidity, W depends on both $|V_c - V_s|$ and ϕ. Relationship between W and β is given by the following equation.

$$W = \beta 10^{0.025\phi}$$

where $3 < \phi < 20$ and depends on tidal current and suction velocity of the dredge pump.

d. The formula of turbidity proposed by the authors was verified by the field data.

Shiratori, Y., Masuda, K., Kato, H., Yamauchi, S. 1982 (Jun). "Model Experiment on Turbidity Caused by Pump Dredging (Part 2)," Technical Note No. 420, the Port and Harbour Research Institute, Ministry of Transport, Nagase, Yokosuka, Japan.

Authors carried out model experiments on turbidity caused by dredging to evaluate the relationship between turbidity and operating conditions. The model bottom material consisted of flyash and bentonite. The scale ratio of the operation conditions was 1.

Turbidity is caused mainly by the contact of the cutter head with the bed. Swing to the dredging mechanism, suspended sediment (SS) concentration at the right side of the cutter head is greater than that at the other side regardless of the swing direction. Turbidity is mainly generated in the right swing operation. The amount of turbidity depends greatly on the peripheral velocity of the cutter and does not depend on the swing velocity.

The cutting depth, which is one of the operating conditions, also influences turbidity generation. When the cutting depth is less than a half of cutter diameter, the amount of turbidity is greater than those in other cases.

The influence of operating conditions on turbidity can be expressed by the following equation developed from the dimension analysis.

$$W_o = \frac{C}{X_a} \phi^{\beta} Fr \frac{\beta}{2+\gamma} \left(\frac{V}{V_p}\right) \gamma \frac{Is}{D} 2\gamma$$

where

ϕ = nondimensional number for the similarity of cutter's trace

V/V_p = nondimensional number for transfer of turbidity

V_p = peripheral velocity

I_s/D = nondimensional number of the contact length of the cutter with the bed

D = cutter diameter

In this experiment, β and γ equal to 2.12 and 2.06 respectively.

The turbidity formula proposed by the authors gives a reasonable value when compared with empirical field data.

Yagi, T., Saotome, Y., Nakazono, Y., Kono, S., Masuda, K., Hamada, K., Sato, Y., and Saito, M. 1977 (Dec). "The Investigation on Turbidity Due to the Drag Suction Dredger," Technical Note No. 279, the Port and Harbour Research Institute, Ministry of Transport, Nagase, Yokosuka, Japan.

The relationship between dredging performance and turbidity caused by the drag suction dredge KAIHO-MARU was investigated. The most important point of this study was to evaluate the effects of the antipollution apparatus, installed on the dredge for reducing turbidity at the sea surface.

The dredged materials were classified into sand and silty sand.

When the dredge is in operation, the turbidity is generated by the drag head and the solid-water mixtures discharged at the overflow gate.

The following results were obtained:

a. The diffusive area of turbidity changes with the nature of dredged materials. In case of sand, the turbidity does not occur around the drag head, but it increases with the continued dredging process.

b. The relationship between loading efficiency, or overflow losses, and turbidity is evaluated and is used to find the optimum operational point with high-loading efficiency and low turbidity.

c. The antipollution apparatus is not effective in case of sand, but the effect is remarkable in case of silty sand.

d. The diffusive coefficient is $1.1 \times 10^3 \sim 7.3 \times 10^3$ sq cm/sec .

In this paper, the numerical calculation with the assumption of Gaussian distribution in the original concentration distribution was compared qualitatively with the experimental results.

Lalancette, L. M. 1984. "The Effects of Dredging on Sediments, Plankton and Fish in the Vauvert Area of Lake St. Jean, Quebec (Effet du dragage sur les sediment, les plancton et les poissons, dans la region de Vauvert au Lac St. Jean, Quebec), Quebec University, Chicoutimi, Department des Sciences Fondamentales, Archive pour Hydrobiologie, Vol 99, No. 4, pp 463-477.

In 1977, the electrolysis and chemical company, Alcan, began dragging the shoreline of the Vauvert area of Lake St. Jean with a view to its restoration. Later in 1977 and in 1978, experiments were conducted to determine the impact of the dredging on sediments, plankton, and fish. It was discovered that after dredging, sediments lose their cohesion and fine particles are dispersed by the currents; it also appeared that the nature of the dispersed sediment in the form of particles facilitated their return to the lake by wind, rain, and waves. It was found that during dredging operations, plankton decreases because of turbidity but then grows back very quickly when dragging is ended. The effects of the dragging were therefore of short duration. Finally, the results of the dragging operations relating to fish were inconclusive; however, a turbidity such as that at Vauvert, created in a laboratory, irritates the gills of fish, and after some weeks the gills and the fish lose all their color. In the long run, the turbidity kills the fish.

Grimwood, C. 1983 (Feb). "Effects of Dredging on Adjacent Water," ASCE Journal of Environmental Engineering, American Society of Civil Engineering, Vol 109, No. 1, pp 47-65.

The results of the data collection program conducted by the US Army Engineer District, New Orleans, in response to implementation of Section 404 of the Federal Water Pollution Control Act Amendment of 1972 and Section 103 of the Ocean Dumping Act are summarized. The results of data collection during maintenance dredging are presented. Dispersion studies conducted during cutterhead pipeline dredging, an ocean-dumping operation, and agitation dredging are described, and the results are summarized. Specific conclusions reached as a result of each phase of the data collection program are presented, and it is generally concluded that the material dredged during these investigations did not present a hazardous waste disposal problem, as dilution was rapid and increased concentrations of pollutants were confined to the disposal area or mixing stone.

Cruickshank, M. J. 1985. "Anti-Turbidity Overflow System (ATOS) Used for Reducing the Dispersion of Fine Sediments from a Dredge Plane," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the 9th U.S./Japan Experts Meeting, Jacksonville, FL, pp 106-113.

In 1976 at the World Dredging Conference in San Francisco, CA, Ichiro Ofuji and Naoshi Ishimatsu submitted a paper entitled "Anti-Turbidity Overflow System for Hopper Dredger." By removal of air trapped in the overflow slurry from a hopper dredge and the placement of the overflow below the waterline, reductions in visible surface plume effects were achieved by a factor of 40 in silty sands. The effects were not so noticeable in coarse sands. The US Department of the Interior, Minerals Management Service (MMS), is responsible for managing the production of minerals from the Outer Continental Shelf.

In an effort to further quantify the effects of installations of an Anti-Turbidity Overflow System (ATOS) on a dredge used for mining offshore, the MMS and the United States/Japan Cooperative Program in Natural Resources are preparing a field test in Shimonoseki Port of Northern Kyushu. The purpose of the test is to characterize the magnitude and behavior of turbidity plumes associated with a dredging operation with and without ATOS. Plume characteristics, including magnitudes in three dimensions--trajectory, density, and density gradients and suspended sediments--will be measured as a function of time. The test is planned for the spring of 1984 from the dredging vessel HAIHO-MARU.

Koba, H. 1985 (Mar). "Dispersion of Sediment Resuspension Caused by Dredge Operation," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the 9th U.S./Japan Experts Meeting, Jacksonville, FL.

As a working model of dispersion of sediment resuspension caused by dredge operation, a model of turbidity levels as a function of distance from the dredge is useful. The level of turbidity near the sea bottom is estimated to be 5 ppm at a distance of 100 m and 3 ppm at 200 m from the dredge. Also, the level of turbidity near the water surface never exceeds that at the sea bottom. Therefore, it is not believed that dredging will cause turbidity over a larger area.

Spaulding, M. L., and Pavish, D. 1984. "A Three-Dimensional Numerical Model of Particulate Transport for Coastal Waters," Continental Shelf Research, Vol 3, No. 1, pp 55-67.

A Lagrangian marker particle in Eulerian finite difference cell solution to the three-dimensional incompressible mass transport equation was developed for predicting particular transport in coastal and estuarine waters. Special features of the solution procedure include a finite difference grid network that translates horizontally and vertically with the mean particle motion and expands with the dispersive growth of the marker particle cloud. The cartesian vertical coordinate of the three-dimensional mass transport equation has been transformed, using instantaneous water column depth to allow adaptation to flow situations with a temporally and spatially varying bottom topography and free surface. Results from this model for turbulent diffusion and advection of a uniform plug flow of sediment in an unbounded uniform flow field with various sediment settling velocities were in excellent agreement with the corresponding analytic solutions. Using current information from a two-dimensional vertically averaged hydrodynamic's model, the model was used to predict the long-term diffusion and advection of dilute neutrally and negatively buoyant suspended sediment clouds resulting from a hypothetical instantaneous release of dredged material waste at Brown's Ledge in Rhode Island Sound.

Irie, Y. 1984 (Jul). "Field Dredging Test of Soft Mud Layer by a Front-Open Type Drag Head," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the 8th U.S./Japan Experts Meeting, Tokyo, Japan.

This paper describes the result of a field-dredging test carried out as part of a study of a method of effective removal and disposal of bottom sediments in a vast closed-water area such as Tokyo Bay.

A new type of drag head was manufactured that can dredge soft mud in thin and wide layers at high density. A trailing hopper suction dredge (hopper capacity of 4,000 m) was equipped with this new drag head and field tested off Chiba in Tokyo Bay. Good results were obtained.

The Fifth District Port Construction Bureau manufactured a second drag head of the same type, installed it on the trailing hopper suction dredge SEIRYU MARU, and field tested it in Ise and Mikawa Bays.

Schroeder, P. R., and Shields, F. D., Jr. 1983 (Apr). "Chemical Clarification of Dredged Material," ASCE Journal of Environmental Engineering, American Society of Civil Engineers, Vol 109, No. 2, April 1983.

Laboratory and design procedures have been developed for chemical clarification of dredged material containment area effluents based on results of laboratory and field tests. The design is suitable for normal disposal operations including remote locations, high and variable flows and solids loadings, and temporary and intermittent operation. The treatment system requires minimal equipment and operation. Low-viscosity, highly cationic liquid polymer is applied at the drainage structure of the primary containment cell. Mixing for dispersing polymer and flocculation is provided by turbulence of flow through the discharge culvert. A small secondary cell is used for settling and storage of treated material. Design parameters are determined by jar test. Major cost components are polymer, labor, and construction. The cost for equipment, labor, and polymer should range from \$0.08/yd (\$0.10/m - 0.33/m)

(1981 dollars) of in situ sediment dredged and is dependent on the production rate, polymer dosage, and treatment system design.

Hulsemann, J. 1982. "Dynamics of Mud (Slick) and Suspended Matter in Estuaries. Applicability of By-Products of Surveys of German Coastal Agencies in View of Requirements for Future Needs," Deutsches Hydrographisches Institute, Hamburg, Germany, F. R., Deutsche Hydrographische Zeitschrift, Vol 35, No. 2.

In Germany, much like in other countries, designated governmental agencies are responsible for sustaining safety on waterways. This entails services to check and maintain certain conditions that are, time and again, altered by water movement and sedimentation. In estuaries scientific aspect of the problem are especially important because of close relation to economic consequences: stretches of waterways constantly require costly dredging.

Previous investigations reveal complex and complicated dynamic relations between mud (slick), mobile, and stationary suspension (fluid mud). Field data of German coastal agencies, as yet unpublished, are insufficient to unravel the problems. New techniques and dedicated, systematic observations are needed to elucidate the interplay of suspended matter, transport, and sedimentation. Its understanding may well serve as basis for more effective management and rehabilitation of the estuarine environment.

Kuo, A. Y., Welch, C. S., and Lukens, R. J. 1985 (May). "Dredge Induced Turbidity Plume Model," ASCE Journal of Waterway, Port, Coastal and Ocean Engineering, American Society of Civil Engineers, Vol 111, p. 3.

A model is developed to describe the turbidity plume induced by dredging a ship channel using a hydraulic dredge. The model predicts the suspended sediment concentration within the plume and the resulting sediment deposition alongside the dredged channel. The model applies to a dredging operation in a water body in which the current is primarily along the channel axis and the channel depth is large enough that no significant suspended sediment reaches water surface. Results of field measurements are presented and compared with the model. It is shown that the model describes the qualitative feature of prototype data and that the calibrated model parameters agree with independent observations by other investigators.

Galappatti, G., and Vreugdenhil, C. B. 1985. "Depth-Integrated Model for Suspended Sediment Transport," Delft University of Technology, Delft, Netherlands, Journal of Hydraulic Research, Vol 23, No 4.

A model for suspended sediment transport in unsteady and nonuniform flow is derived, in which the vertical dimension is eliminated by means of an asymptotic solution. The resulting depth-integrated model is tested for unidirectional flow cases. Also, an application is given to the siltation of a dredged channel.

The process of suspended sediment transport in rivers and estuaries is a three-dimensional (3-D) one. Some models already derived take the vertical direction explicitly into account (Smith et al. 1977, Kerssens 1980*) by considering a two-dimensional (2-D) vertical plane. Extension of these methods to 3-D situations, however, will be very costly, particularly if it is realized that long periods of time may have to be covered. Similar problems for dissolved substances have been solved by introducing the concept of dispersion through depth integration (e.g. Daubert 1974). This paper analyzes the possibility of using such concepts for suspended sediment.

The mass balance for suspended sediment in a flowing stream can be expressed in the form of a partial differential equation describing the processes of convection, turbulent diffusion, and precipitation in terms of the local sediment concentration. If the mass-balance equation is depth averaged, the process of vertical readjustment of concentration profiles, arguably the most important mechanism involved, is obscured and replaced by an empirical or semi-empirical entrainment function. The necessity to calibrate this very important effect will restrict the predictive power of such depth-averaged models. The verification of an entrainment function usually has to be done indirectly. Thus, there is a need to develop other approximate solutions for the mass-balance equation based on more explicit, easily verifiable assumptions.

In this paper, the adjustment of the concentration distribution is formulated in terms of similarity profiles, including the deviation from local equilibrium. The coefficients of the similarity profiles are shown to depend on the depth-averaged concentration c and its horizontal derivatives. Thus, for a vertically 2-D situation, the equations to be solved are reduced to one-dimensional and for 3-D situations the equations have to be solved in a (horizontally) 2-D region. Only the former case is discussed in this paper. The resulting model can be used together with the depth-averaged hydrodynamic

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* See References at the end of the main text.

equations in large regions. As usual, the similarity solution cannot be applied for small-scale (near-field) phenomena, but only at sufficiently large scales. Some considerations on these scales are also given in the paper.

Vann, R. G., and Willey, R. G., ed. 1982 (Feb). "O&M Dredging Experience as Related to Channel Deepening for Coal Ports," Proceedings, Seminar on Attaining Water Quality Goals Through Water Management Procedures, Dallas, TX, February 17-18, 1982, US Army Engineer District, Norfolk, Norfolk, VA.

The US Army Engineer District, Norfolk, has been involved in innovative channel design, dredging techniques, disposal operations, and environmental coordination that favorably impact on water quality. Innovative channel design for coal export shipping lanes will minimize dredging. The design will employ a computerized ship maneuvering simulator operated by the US Maritime Association and their Computer Aided Operations Research Facility. A dredging demonstration with nationwide application in the removal of contaminated sediments is underway on the James River. The demonstration will document the advantages of dredging in a riverine system with different dredge heads: a cutterhead and a dustpan head. Engineering studies indicate that a dustpan head will dredge at near in-place density and thereby reduce turbidity and disposal problems. The District, with the assistance of Federal and state environmental agencies, has made site-specific studies to determine the proprietary of seasonal dredging restrictions. In four cases the restrictions were found to be unnecessary. Predesignation studies of the new ocean disposal area (Norfolk Disposal Area) have also been conducted by the District. In addition, positive steps have been taken to effectively manage the Craney Island Disposal Area, with the ultimate view of significantly extending the site's useful life. Other beneficial usages of dredged material have been undertaken by the District, including marsh creation, beach nourishment, nesting habitat for waterfowl, and improved oyster-bed substrate. Beneficial usage is essential to successful environmental coordination prerequisite to the actual dredging. To that end, the District has instituted bimonthly environmental coordination meetings with the state and Federal environmental regulatory agencies. The meetings have proven to be the single most important factor in the successful accomplishment of the District's O&M dredging program.

Tavolaro, J. F. 1984. "A Sediment Budget Study of Clamshell Dredging and Ocean Disposal Activities in the New York Bight," Environmental Geology and Water Sciences, Vol 6, No. 3.

The purpose of this study was to quantify the dry mass of dredged material involved in each stage of typical clamshell dredging and ocean disposal activities in order to identify and quantify "losses" of dredged material. Turbidity plumes generated at dredging sites were also observed. Approximately 2 percent of the dredged material was lost at the dredging site. Of this quantity 61 percent was due to the dredging itself and 38 percent was due to intentional barge overflow. Approximately 3.7 percent of the dredged material was lost at the Mud Dump Site during disposal. Total loss of dredged material during these clamshell dredging and ocean disposal operations was calculated to be 5.6 percent. Observations revealed that turbidity plumes were local features that traveled along the bottom for several hundred feet. These plumes persisted only while dredging was occurring, and ambient conditions were established within a relatively short time after dredging ceased.

Onuschak, E., Jr. 1982. "Distribution of Suspended Sediment in the Patuxent River, Maryland, During Dredging Operations for Construction of a Pipeline," Bulletin of the Association of Engineering Geologists, Vol 19, No. 1.

A trench for emplacement of a natural gas pipeline was excavated by dredging across an estuarine portion of the Patuxent River in southern Maryland. The turbidity of the water was determined by analyzing water samples for total suspended solids before, during, and after dredging. The average turbidity during dredging increased a maximum of about two times over its preexisting baseline level. After completion of dredging, turbidity returned to baseline levels in less than 3 weeks. Estuarine currents in the Patuxent River were not capable of eroding dredged material stored in the river itself.

These observations indicate that temporary subaqueous storage of dredged material during construction in a tidal river can be an environmentally acceptable procedure, with far less potential impact upon the environment than alternatives, such as transportation of dredged material off the site for storage or disposal elsewhere.

Ofuki, I., and Ishimatsu, N. 1981 (Nov). "Marine Technology for Environmental Problems: Some Examples of Improved Systems on Work Vessels," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the 7th U.S./Japan Experts Meeting, New York.

(PART I) For dredging and processing of loose sediments containing toxic materials, a system (in sequence) of the following component processes: dredging-transportation of dredged slurry, unloading of cake solids, and disposal (reclamation) has proved most practical. Operational cost for 50-percent soil concentration in the dredged slurry is 10 percent lower than for 25-percent soil concentration and centrifugal dehydration gives 4 percent lower costs than press dehydration. Depreciation of initial investment, interest, and maintenance are three major items consuming 22 to 28 percent of total cost of all the equipment. The processing barge for dehydration and water processing is most costly, occupying some 60 percent of the total cost.

(PART II) The mechanism of sea surface turbidity caused by overflowing water from a hopper dredge was determined by model experiments to be due to air-lift phenomenon of air bubbles entrained in the muddy water, and the Anti-Turbidity Overflow System (ATOS) was developed to eliminate air bubbles from the overflowing water. The effect of ATOS was confirmed by actual dredging tests. In fine sand or silt, ATOS reduced turbidity of the sea surface to as low as 10 ppm or lower in suspended solid concentration, as compared with a level of over 400 ppm without ATOS.

Raymond, G. L. 1984 (Sep). "Techniques to Reduce the Sediment Resuspension Caused by Dredging," Miscellaneous Paper HL-84-3, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

As part of a larger effort under the Improvement of Operations and Maintenance Techniques Program to develop a method to predict the extent of sediment resuspension and contaminant release when dredging in contaminated sediments, the US Army Engineer Waterways Experiment Stations' Water Resources Engineering Group is conducting field studies to evaluate new and existing dredging methods. These studies consist of efforts to determine the level of sediment resuspended by a given dredge type in a given sediment. Whenever possible, the studies are conducted such that different dredges operate under the same conditions or even in the same locations. The studies also evaluate the effects of various operational parameters on the resuspension of sediments. This paper presents the results of the first 2 years of study and includes data from both field studies and extensive literature review.

Different dredge types produce different amounts of suspended sediment in different parts of the water column, while bucket dredges increase resuspensions throughout the water columns. The amount of resuspension caused by a given dredge type also depends on the operating techniques used with the dredge.

Sediment resuspension can be lessened by changing operating techniques, as in the case of the cutterhead, or by modifying the equipment, such as enclosing a clamshell bucket. Special purpose dredges can also be used to reduce sediment resuspension, but their lower production rates limit their application.

Schnoor, J. L., Giaquinta, A. R., Sato, C., Robison, C. P., McDonald, D. B. 1982. "Refinement and Verification of Predictive Models of Suspended Sediment Dispersion and Desorption of Toxics from Dredged Sediments," Iowa University, Institute of Hydraulic Research, Iowa City, IA.

A primary objective of this research was to refine and verify the accuracy of a mathematical model of suspended-sediment dispersion and a model of desorption and dispersion of toxic materials from dredged sediments. These models were developed during the GREAT II study, but additional sampling of suspended-sediment plumes associated with dredge disposal is needed to test the accuracy of the model at different stream velocities and for different sediment types. The refined mathematical formulas will provide users with a quantitative method for assessing water-quality impacts under the Federal Clean Water Act for dredging.

Soedergren, A. 1984. "The Effect of Sediment Dredging on the Distribution of Organochlorine Residues in a Lake Ecosystem," Laboratory of Ecological Chemistry, Sweden, ABMIO, Vol. 13.

Removal of sediment from lakes and rivers contaminated with persistent organochlorine residues may initiate recycling of the compounds in the ecosystem. A dredging operation in Lake Trummen, Sweden, removed a major part of the residues stored in the sediment. However, a redistribution and deeper penetration of the remaining residues in the sediment were observed after the dredging. The lack of significant bioaccumulation or magnification in the fish shows that sediment containing persistent residues may be dredged without contaminating the food web. Ten years after completion of the operation, polychlorinated biphenyl content in the surface sediment had increased, probably as a result of internal circulation of residues from areas not dredged or contributions from sources outside the lake ecosystem.

Kaneko, A., Watari, Y., and Aritomi, N. 1984 (Jul). "Specialized Dredges Designed for Bottom Sediment Dredging," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the 8th U.S./Japan Experts Meeting, Tokyo, Japan.

This paper describes the functions, characteristics, and turbidity prevention or controlling effect of specialized dredges designed for bottom sediment dredging and developed for exclusive use.

In bottom sediment dredging, the prevention or controlling of turbidity arising from the dredging operation is an important problem.

When compared with cutter suction dredging, the specialized dredges can significantly reduce the potential generation of turbidity.

Pavlou, S. P., Hom, W., and Hafferty, A. J. 1977 (Nov). "Release of Polychlorinated Biphenyls (PCB) in a Salt-Wedge Estuary as Induced by Dredging of Contaminated Sediments," Science of the Total Environment, Vol 8, No. 3.

An evaluation of the input of polychlorinated biphenyls (PCB) in the Duwamish River, Seattle, WA, resulting from the dredging of contaminated sediments is presented. The mean concentrations of PCB during the monitoring period were 12.8 to 24.5 ng/ℓ in water and 1.03 to 1.77 g/g dry weight in suspended particulate matter. These values were within the ranges normally observed in the river, suggesting that the dredging operations did not induce a significant PCB pulse of potential hazard to the estuary. The fractionation of PCB in suspended particulate matter was determined by computing component concentration ratios, K_d . These quantities indicate an enrichment factor of 10^5 from ambient water. Based on the ambient PCB load and normal discharge, the input of PCB into Puget Sound via the Duwamish River was estimated to be 56 kg/year.

Hilligardt, R., Bauer, W., and Werther, J. 1985 (Jun). "Thickening and Dewatering of Dilute Sludge Suspensions with the Aid of Synthetic Flocculants," J. Gas und Wasserfach, Wasser Abwasser, Vol 126, No. 6.

In connection with investigations on the treatment of material dredged in the Port of Hamburg synthetic flocculants (polyelectrolytes) were used in bench-scale experiments for cleaning and thickening of the mud suspensions. The suspended solids as well as a large part of the heavy metals could be separated from the water. Several flocculants of different electrolytic behavior were applied to determine the amount of flocculant needed for optimum sedimentation of the suspended solids.

The results were tested in a lamella separator of pilot scale size for different solid concentrations and suspended flow rates.

Datasonics, Inc. 1983 (Feb). "Dredge Spoil Plume Study, Acoustic Profile Summary," Cataumet, MA.

Multifrequency acoustic profiling has been under investigation since 1975 in an effort to determine feasibility of measuring concentrations of suspended matter in the water column. Much of the work has been carried out by the NOAA Atlantic, Oceanographic, and Meteorological Laboratory in Miami.

The work has included study of diffusion processes, significant particle size distribution on diffusion properties and on acoustic measurements, and development of a model to describe the relationship between concentrations of total suspended matter in the water column and acoustic profile observations.

Koba, H., and Shiba, T. 1981 (Nov). "Test Dredging of Bottom Sediment in Osaka Bay," Management of Bottom Sediments Containing Toxic Substances, Proceedings of the 7th U.S./Japan Experts Meeting, New York.

Field test dredging was carried out with cutterless dredges in Osaka Bay, where the severe organic contamination of bottom sediment took place. Limited studies on the Oozer pump dredge were conducted during the test. The results are as follows:

a. The sludges may be efficiently dredged adopting the method of having the suction mouth of the dredge swim up and down along the seabed.

b. If the operation is made setting the swing speed for dredging from 6 to 7 m/min or less, contamination in the vicinity of the suction mouth seldom occurs.

c. The efficiency of the dredge is 250 cu m/hr on the average, with a concentration of 30 to 40 percent.

d. The sludge dredged may efficiently be disposed of by pumping the dredged material to the barge and transporting it to the disposal site.

e. It is concluded that the main advantage of the Oozer pump dredge is the fact that excess water is not pumped during dredging and it is easier to dispose of slurry containing less water.

Sato, E. 1982 (Nov). "Bottom Sediments Dredger CLEAN-UP - Principle and Results," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the 8th U.S./Japan Experts Meeting, Tokyo, Japan.

Most of the secondary pollution caused by dredging occurs by the disturbance of corpuscular suspension contained in the bottom sediments or sludge. There are two main reasons: disturbance caused by movement of the suction equipment and disturbance caused by water currents during dredging.

Based on investigations a new dredge was developed, named CLEAN UP. This dredge is equipped with a movable wing in front of the equipment so as to lay on the bottom sediments, and it also has a movable shutting plate that intercepts the inflow of outer water, a mixing device contained in the equipment, and many sensors to check the dredging conditions. In addition to these devices, the equipment as a whole can control the contact pressure against the seabed and keep its position horizontal regardless of its depth.

Koba, H., and Shiba, T. 1982 (Nov). "Sediment Resuspension in the Vicinity of the Cutterhead," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the 8th U.S./Japan Experts Meeting, Tokyo, Japan.

Dredging work in Japan has been conducted, in most cases, by cutter suction dredges. This method has a greater dredging efficiency as well as a wider range of application to cope with the conditions relating to soil, water depth, discharging distance, etc. At the same time, it is known that when the bottom material is dredged by a cutter, the fine-grained dredged material is floated and suspended, thus causing sediment resuspension in the vicinity of the cutter head during the dredging operation.

In Japan, a good many marine products have been used for food since ancient times. In recent years, sea breams, young yellowtails, oysters, larvae, etc., have become quite active in the sea off the coast, thanks to the progress in the mariculture technology.

It is also feared that when the dredging is conducted in the sea adjacent to culture farms, sediment resuspension may cause detrimental effects on fish and larvae. Hence, it is often the case that the period of dredging work is restricted and that other dredging methods causing less sediment resuspension must be adopted instead.

To continue the low-cost by a cutter suction dredge in the future, it is necessary to study antisediment resuspension measures by evaluating sediment resuspension in the vicinity of a cutter head. In this connection, it was decided to study the mechanism causing sediment resuspension and to work out measures to prevent it by conducting a model study of the cutter.

Richardson, T. W. 1982 (Nov). "Performance Tests of Pneuma Dredge Pump," Management of Bottom Sediments Containing Toxic Substances: Proceedings of the 8th U.S./Japan Experts Meeting, Tokyo Japan.

Results of pumping performance and turbidity generation tests of air-operated Pneuma dredge pump, model 600/100 are summarized. Tests were conducted at four locations in sand and fine-grained sediments and in different water depths. The following are described: (a) test locations and characteristics, (b) data acquisition methods, (c) pumping performance results, (d) variations in performance with sediment type and water depth, (e) noteworthy characteristics of Pneuma pump operation, and (f) results of turbidity monitoring. Conclusions are given regarding pumping capabilities and recommendations made for potential improvements.

Montgomery, R. L., and Raymond, G. L. 1982 (Nov). "Overview of Corps Research Program on Dredging Contaminated Sediments," Management of Bottom Sediment Containing Toxic Substances: Proceedings of the 8th U.S./Japan Experts Meeting, Tokyo, Japan.

The problems of dredging contaminated sediment with existing conventional equipment and techniques are discussed. These problems exist because the dredging practices in the United States have evolved to achieve the greatest possible economic returns through maximizing production. As a result, conventional dredges are not specifically designed or intended for use in dredging highly contaminated sediments. However, many feel that dredges are the logical, and perhaps only, means of removing contaminated sediment that have been found in the Nation's harbors and waterways. It is also felt that some modifications to equipment and dredging techniques could result in their use in dredging highly contaminated sediment with minimal adverse impact on the environment.

This paper outlines active research at the US Army Engineer Waterways Experiment Station on equipment and techniques for dredging contaminated sediments. The question of dredging in contaminated sediments is being addressed in three ways: the assembly and evaluation of available domestic and foreign information concerning sediment resuspension and contaminant release, the development of appropriate laboratory tests to predict contaminant release from resuspended sediments, and the use of field studies to monitor performance and compare dredges operating under various conditions. Plans are discussed for evaluating existing dredging equipment to determine the best techniques for dredging sediments that are highly contaminated with toxic substances. Initial field studies have already been completed on evaluating sediment resuspension at the point of dredging for cutterhead, dustpan, and clamshell dredges. The results of these preliminary studies are discussed.

Hayes, D. F. 1986. "Development of a Near Field Source Strength Model to Predict Sediment Resuspension from Cutter Suction Dredges," M.S. thesis, Mississippi State University, Department of Civil Engineering, Starkville, MS.

Certain variable operating characteristics of cutter suction dredges such as the swing speed, cutter tip speed, thickness of cut, ladder angle, and suction velocity have been identified by previous researchers as contributors to the quantity and rate of sediment resuspension at the point of dredging. The mechanisms through which sediment is resuspended by a cutter suction dredge as a result of these operating characteristics were identified, and the contribution to the resuspension at the point of dredging of each operating characteristic was evaluated qualitatively. Dimensionless parameters containing the more important operational characteristics were developed based on the results of this evaluation, and an equation for equating the values of these dimensionless parameters to the average concentration of resuspended sediment at the point of dredging was developed. Average suspended solids data from within a few feet (<10 ft) of the cutter of an operating cutter suction dredge were gathered in October 1985 by the US Army Corps of Engineers in Calumet Harbor, Illinois. These data were used to determine the coefficients of regression for the equation to predict the average concentration of resuspension sediment at the point of dredging. A model for the movement of a cutter suction dredge was developed and used to extend this predictive equation to source strength models that can be used to predict the total quantity or rate of sediment resuspension from a cutter suction dredge or to develop input for far-field transport models that currently exist.

Koiwa, T., Miyazaki, S., Otomo, K., Shibuya, Y., Shiratori, Y., Kono, S., Nakazono, Y., Takahashi, H., Ilamada, K., Sato, Y., Matsumoto, S. 1977 (Mar). "Influence of Operating Conditions of Grab Dredger on Turbidity," Technical Note of the Port and Harbour Research Institute (Ministry of Transport), No. 257, pp 1-29.

This paper discusses the relationships between operating conditions and the turbidity caused by grab dredger having closed-type grab bucket whose capacity and empty weight were 4.0 cu m and 9.0 tons respectively. The power of the grab dredger was 640 PS and was supplied by two diesel engines. This field test was conducted in Fushiki Port, situated at the mouth of the Oyabe River.

The turbidity measuring points were located downstream. The turbidity was recorded continuously on recording papers. Twenty or thirteen turbidity meters, whose measurements were based upon the photo-scattering principle, were used. The measurement of turbidity was carried out at three water spaces, upper, middle, and lower spaces. The records displayed complicated variations.

It is confirmed that the turbidity is higher at the middle and lower spaces than the upper space and that the turbidity is very low several 10 meters away from dredging point. As an operational condition of the grab dredger, the hoisting speed of the grab bucket and dredging thickness were varied. Consequently, it is made clear that the turbidity is evaluated by the parameter of (grabbed weight per cycle) × (hoisting speed). It is also confirmed that the operational conditions that may reduce the turbidity to a minimum are possible.

A diffusion model of turbidity caused by the grab dredger is presented. The diffusion equation of turbidity composed of settling particles is solved on the basis of several simple assumptions.

Personal Communications

Koba, H., and Shiba, T. 1982. "Test Dredging of Bottom Sediments in Osaka Bay," Toyo Construction Company, Ltd., Japan.

Test dredging was carried out with cutterless dredges in Osaka Bay, where severe organic contamination of bottom sediments took place, and some studies on the Oozer pump dredge were attempted in this test work. As a result, the following were determined:

a. The sludges may be efficiently dredged adopting the method of having the suction mouth of the dredge swing up and down along the seabed.

b. If the operation is made setting the swing speed for dredging from 6 to 7 m/min or less, contamination in the vicinity of the suction mouth hardly occurs.

c. The efficiency of the dredge may be made approximately 250 cu m /ha on the average, with a concentration of 30 to 40 percent.

d. The sludge dredged may be disposed of efficiently by way of receiving it by the barge and transporting it to the disposal site.

e. The advantage of the Oozer pump dredge is that excess water is hardly sucked in while in dredging work and it is facilitated to deal with and dispose of the slurry.

Public Works Department. 1982 (Jul). "Silt Dispersion - Puttenplan (Dredge Pit Plan) - First Petroleum Harbor," Municipality of Rotterdam, The Netherlands.

To determine whether or not unacceptable damage to the environment would arise during the dredging and disposal of dredged material from the first Petroleum Harbor, the Public Works Department of Rotterdam conducted research into the possible effects of these activities.

In the first place this research involved the determination, by means of measurement, of the dispersion behavior of silt from the first Petroleum Harbor to the river during the execution of the first phase of the Puttenplan. The measurements obtained were then used to verify the theoretical assumptions relating to the transport of silt from both harbors. The theory that has been thus tested is employed to make a prognosis of the transport of silt during the execution of the second phase of the Puttenplan.

For the first phase of the execution of the Puttenplan, trailing suction hopper dredgers were used to remove silt from the mouth, central channel, and western arm of the first Petroleum Harbor. This silt was discharged into a specially excavated pit in the Botlek Harbor. The second phase of the Puttenplan will involve the removal of silt from the turning basin and the southern arm of the first Petroleum Harbor and the discharge of the dredged material into dredge pits in the same harbor.

Four groups of measurements have been carried out:

a. Control measurements in the first Petroleum Harbor and the Botlek Harbor before the execution of the Puttenplan commenced.

b. Measurements recorded during the entrance of a vessel with a deep draught.

c. Measurements in the mouth of the first Petroleum Harbor, during which the method used and the location of the dredging activity in the first Petroleum Harbor were varied.

d. Measurements of the dispersion of silt in the first Petroleum Harbor and the Botlek Harbor.

During almost all the measurements, the concentration on sediments and the speed and direction of currents were determined. The quality of the water-silt mixture in the mouth of the harbors was also measured during the control measurements of the transport of silt.

The research project produced the following conclusions:

a. As a result of the dredging in the first Petroleum Harbor, the amount of silt carried across the line of the harbor mouth into the river increased.

b. Dredging activities in the western arm of the first Petroleum Harbor resulted in increased sediment concentrations up to several hundred meters from the site of these activities. There was no increase in the transport of silt across the line of section of the mouth in the direction of the river.

c. No dispersal of silt outside the dredge pit occurred as a result of the discharge of spoil into the Botlek pit.

d. Dredging activities in the turning circle of the first Petroleum Harbor will not result in an increase in the amount of silt crossing the line of section of the mouth of the harbor in the direction of the river.

e. Dredging in the southern arm of the harbor will not result in an increase in the amount of silt crossing the line of section of the harbor mouth in the direction of the river.

f. Discharging into the pits in the first Petroleum Harbor even in the most unfavorable conditions which might be anticipated will not result in the dispersal of silt over the edges of the pits.

Vellinga, Tiedo. 1974. "Dredging and Disposal of Contaminated Dredged Material," Personal Communication. Public Works Department, Municipality of Rotterdam, The Netherlands.

Approximately 20 million cu m of material is dredged annually from the Port of Rotterdam and the adjacent estuarine area. For the most part, this is currently discharged into the sea; only a relatively small amount is disposed of on inland sites.

The dredged material contains substances that affect the environment. The amount and nature of these substances depend upon their place or origin in the port area. The degree to which these substances are present, i.e. the pollution grade, plays an increasingly important role in the choice of the disposal site and the method of dredging and disposal.

Hatano, R., and Abe, Y. 1986. "The Use of Antiturbidity Curtains at a Sand Compaction Piling Area in Yokohama Harbor," Japan Sediments Management Association, Tokyo, Japan.

Sea work such as dredging and sand compaction piling causes turbidity in the neighboring sea area. To prevent the diffusion of turbidity, in general antiturbidity curtains are used in the working area.

In such cases, it is important to know how the curtains act on suspended solids in seawater. Since the antiturbidity curtains were used at a sand compaction work area in Yokohama Harbor, the behavior of suspended solids around curtains was observed in 1984. This paper reports the measured data.

Kasajima, S. 1986. "On the Dredging Operation for Removal of Bottom Sediments in Osaka Port by the Pneuma Pump Dredger SHINKAI," Manager of the Construction Division, Port and Harbor Bureau, City of Osaka, Japan.

The Osaka Port, one of the representative ports in West Japan situated at the innermost part of Osaka Bay, has been suffering from the sediment of mud polluted with organic substances on the bottom of rivers such as Aji River, Shirnashi River, Kizu River, etc. Wastewater from factories and city sewage have caused deterioration of the environment by polluting the water and generating a foul smell.

As the countermeasure for it, the Authority of Osaka City had noticed the excellent performance of Pneuma pump system and undertaken the first mud dredging experiment in Japan with that system, which was introduced by an Italian firm S.I.R.S.I. in December 1971. Through this experimental dredging, the suitability of Pneuma pump system to the dredging of polluted mud was well proven.

As part of the pollution control project of the port and harbor, the Bureau completed the Pneuma pump dredger SHINKAI in July 1974 and then organized a dredging squadron together with the hopper barges that underwent necessary modifications. The squadron has engaged in dredging operations of polluted mud since November 1974 until today.

Toyo Construction Company, Ltd. 1986. "Survey on Turbidity Generated by Dredges," Japan.

In the dredge of sediments containing toxic substances, it is important to minimize, as little as possible, generation of the secondary pollution caused by the suspended solids (SS) diffusion during the dredging operations. A 50-year experience in the dredging field permitted study of this problem with reference to dredge design.

Strenuous efforts have been made for improvement of the suction mouth and monitoring devices since construction of the dredge TAIAN-MARU in 1974 in order to prevent pollution. The dredge has already dredged up contaminated sediment amounting to about 1,000,000 cu m.

Search for the secondary pollution has been conducted so far by way of measuring the disturbance from the suction mouth as the source and measuring the degree of turbidity at several measuring points.

However, data thus obtained were insufficient for analysis. In 1976, increased turbidity in weight was measured and shown as a base element figure in the degree of sediments containing mercury at Tokuyama Bay. In other words, the base element figure shows volume of turbidity generated in 1 cu m of dredged sediments.

From the figure, one can predict proper dredging time, amount of dredged sediments, and the degree of turbidity. This is done by means of simulation based on the water flow, particle compositions of sediments, or the diffusion factor of dredging area for a preliminary evaluation.

Yoshida, T. 1986. "Results of the Investigation of Turbidity Generated by Dredges at Yokkaichi Port," Japan Sediment Management Association, Tokyo, Japan.

This investigation was conducted at Yokkaichi Port using two specialized dredges to measure the quantity of turbidity generated by dredging works. Concentrations of suspended solids around the suction head were measured through filtration of the sampled water in the laboratory. This study indicates that the concentration of suspended solids around the suction head of specialized dredges is very low, approximately one-tenth that of conventional ones.

APPENDIX D: SUSPENDED SOLIDS AND TURBIDITY LEVELS AT VARIOUS SITES IN THE UNITED STATES AND OTHER COUNTRIES

Table D1

Suspended Solids and Turbidity Levels at Various Sites in the United States and Other Countries

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/ Turbidity	Reference*
1	Upper Mississippi Wild's Bend (mile 730.5)	Hydraulic cutter suction dredge	Coarse to medium size sand 90%	Cutter bottom Cutter top	9 NTU/s** 8 NTU's	Anderson et al. (1981a)
2	Upper Mississippi Read's Landing (mile 763)	Hydraulic cutter suction dredge	Not available	Control station upstream Surface Bottom	 13 mg/ℓ 11 mg/ℓ	Anderson et al. (1981a)
				100 ft downstream Surface Bottom	16 mg/ℓ 15 mg/ℓ	
3	Upper Mississippi Upper Lansing Light (mile 664)	Hydraulic cutter suction dredge	Medium sand 84% Coarse sand 8% Fine sand 4% Clay 2.5%	Control station Near cutter	30 mg/ℓ 32 to 64 mg/ℓ	Anderson et al. (1981a)

(Continued)

* See References at the end of the main text.
** Background data not available.

(Sheet 1 of 13)

Table D1 (Continued)

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/ Turbidity	Reference
4	Upper Mississippi Franklin Avenue Bridge Site (river mile 852)	Clamshell dredge	Coarse sand 65%	Control station		
				Surface	22 mg/ℓ	Anderson et al. (1981a)
			Medium sand 27%	Bottom	30 mg/ℓ	
			Clay 5.4%	Range	15 to 39 mg/ℓ	
				150 ft downstream of dredge		
				Surface	22 mg/ℓ	
				Bottom	28 mg/ℓ	
				During dredging		
				Surface	23.45 mg/ℓ	
				Bottom	26.47 mg/ℓ	
				After dredging		
				Surface	14.6 mg/ℓ	
				Bottom	19.6 mg/ℓ	
5	Upper Mississippi Head of lake Pepin (mile 784.6)	Clamshell dredge	Coarse to medium sand 82.3%	Control station		Anderson et al. (1981b)
				Surface	24 mg/ℓ	
				Bottom	52 mg/ℓ	
			Clay and silts 8.3% (more clay)			
				Downstream of		
				Surface	23 to 35 mg/ℓ	

(Continued)

(Sheet 2 of 13)

Table D1 (Continued)

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/ Turbidity	Reference
				Bottom	25 to 58 mg/ℓ	
6	Upper Mississippi St. Paul Barge Terminal (Cairo mile 837)	Hydraulic cutter suction dredge	Fine to medium sand 94 to 98%	Control Station	170.5 mg/ℓ	Anderson et al. (1981b)
				Near cutter	158 mg/ℓ	
			Fines 2 to 6%	(No turbidity after 1 hr)		
7	Upper Mississippi Teepeota Point (river mile 757.5)	Hydraulic cutter suction dredge	Silts and clays 1 to 2%	Control station	21.33 mg/ℓ	Anderson et al. (1981b)
			Medium to coarse sand	50 ft downstream of dredge	11.83 mg/ℓ	
				(Cutter had no effect on water quality)		
8	Upper Mississippi West Newton Dredge Cut (Cairo mile 746.6)	Hydraulic cutter suction dredge	Extremely coarse material	Upstream control	155 mg/ℓ	Anderson et al. (1981b)
			Silt and clay less than 1%	Downstream of dredge	163 mg/ℓ	
9	Upper Mississippi Lake Street Bridge (Cairo mile 850.3)	Clamshell dredge	Fine-grained sands	Control	12 mg/ℓ	Anderson et al. (1981b)
			Silts and clays 3.4%	100 ft downstream	22 mg/ℓ	

(Continued)

(Sheet 3 of 13)

Table D1 (Continued)

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/ Turbidity	Reference
10	Upper Mississippi Island 58 (Cairo mile 734.3)	Clamshell dredge	Medium to fine-grained sands Silts and clays <1%	Upstream control 100 ft downstream	21.3 mg/ℓ 20.6 mg/ℓ	Anderson et al. (1981b)
11	Cumberland River (mile 24) (1982)	Clamshell dredge	Not available	Background Near the dredge	15 to 38 mg/ℓ 15 to 51 mg/ℓ	US Army Engineer District, Nashville (1982)
12	Calumet River Pilot Project Great Lakes	Clamshell dredge	Not available	Background Downstream of dredge	20 JTU's 39 JTU's	O'Neal and Sceva (1971)
13	Portland Harbor	Hydraulic cutter suction dredge	75% silt and clay 25% sand	No significant change in the turbidity upstream and downstream of dredge		
14	Depot Slough, Toledo, OR	Hydraulic cutter suction dredge	89% silt and clay	Background Near dredge	6 JTU's 11 JTU's	O'Neal and Sceva (1971)
15	Santiam River	Hydraulic cutter suction dredge	Coarse sand and gravel	Background 200 ft downstream of dredge	2 to 3 JTU's 5 to 10 JTU's	O'Neal and Sceva (1971)

(Continued)

(Sheet 4 of 13)

Table D1 (Continued)

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/ Turbidity	Reference
16	Portland Harbor, Oregon	Clamshell dredge bucket	Not available	Background	8 mg/ℓ	O'Neal and Sceva (1971)
				Near dredge		
				Surface	23 mg/ℓ	
				Bed	15 mg/ℓ	
17	Grays Harbor, Washington	Hydraulic dredge	Sand 60% Silt 30% Clay 10%	Near bottom At the dredge	22 to 55 JTU's above ambient	US Army Engineer District, Seattle (1977)
18	Ohio River (mile 63.1) Stenbenville, OH	Bucket dredge	Sand	Background		US Army Engineer District, Pittsburgh (1981)
				Surface	9 mg/ℓ	
				Bottom	10 mg/ℓ	
				100 ft downstream		
				Surface	10 mg/ℓ	
				Bottom	115 mg/ℓ	
19	Ohio River (mile 139.0) Sisterville, WV	Hydraulic type	Sand	Background		US Army Engineer District, Pittsburgh (1981)
				Surface	10 mg/ℓ	
				Bottom	13 mg/ℓ	

(Continued)

(Sheet 5 of 13)

Table D1 (Continued)

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/Turbidity	Reference
20	Ohio River (mile 138.8)	Hydraulic type	Sand	Background 100 ft downstream of dredge	40 mg/ℓ 55 mg/ℓ	US Army Engineer District, Pittsburgh (1981)
21	Florida Keys, Florida	Bucket dredge	Coral sand	Background Near dredge	1 to 2.5 mg/ℓ 66 mg/ℓ	Griffin 1974)
22	Corpus Christi Channel, TX	Hydraulic cutter suction dredge (27-in. size)	Sandy clay at top Medium clay below	Within 2 m of cutter Background During dredging	 39 to 209 mg/ℓ up to 580 mg/ℓ	Huston and Huston (1976)
23	Mobile Bay Ship Channel, Alabama	24-in. hydraulic cutter suction dredge	Highly plastic inorganic clay	Near the cutter Background During dredging	 25 to 30 mg/ℓ 125 mg/ℓ	Barnard (1978)
24	Yokkaichi Harbor Japan	24-in. hydraulic cutter suction dredge	Fine-grained material	1 m above cutter Background During dredging	 1 to 18 mg/ℓ 2 to 30 mg/ℓ	Yagi et al. (1975)

(Continued)

(Sheet 6 of 13)

Table D1 (Continued)

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/Turbidity	Reference
25	San Francisco Bay, California	Trailing suction hopper dredge	Inorganic clay of high plasticity	Near bottom		Barnard (1978)
				Background	38 to 123 mg/ℓ	
				During dredging	few g/ℓ	
	San Francisco Bay, California	Clamshell dredge	Inorganic clay of high plasticity	50 m downstream		US Army Engineer District, San Francisco (1976)
				Background	40 mg/ℓ	
				During dredging	30 to 90 mg/ℓ	
26	Lower Thames River, Connecticut	Clamshell dredge	Not known	100 m downstream		Bohlen and Tramontaro (1977)
				Bottom	168 mg/ℓ*	
				Surface	68 mg/ℓ	
27	Patapsco River, Maryland	Clamshell dredge	Not known	22 m downstream		Cronin et al. (1976)
				Background	10 mg/ℓ	
				Bottom during dredging	30 mg/ℓ	

(Continued)

(Sheet 7 of 13)

Table D1 (Continued)

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/ Turbidity	Reference
28	Hori River, Nagoya, Japan	Clamshell dredge	Not known	7 m downstream Background At the bottom during dredging	 30 mg/ℓ 150 to 300 mg/ℓ	Yagi et al. (1977)
29	Osaka Port, Japan	Pneuma pump and grab dredgers	Silt, contaminated with organics	Series of stations 50 m downstream upper layer middle layer lower layer	23 mg/ℓ 38 mg/ℓ 80 mg/ℓ	
30	Osaka Port, Japan	Dozes pump	Silt, contaminated with organics	upper layer middle layer lower layer	5 to 10 mg/ℓ for all measurements and depths	Koba et al. (1981)
31	Tokyo-Bay, Japan	Front end type drag head (new)	Soft mud	Near drag head	5,000 mg/ℓ	

(Continued)

(Sheet 8 of 13)

Table D1 (Continued)

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/ Turbidity	Reference
32	Cape Fear River, Willington	Pneuma pump model	Fine-grained sediment	Downstream Dept:	Approx. max:	Richardson (1982)
				OM	12 mg/ℓ	
				1.5	13 mg/ℓ	
				3.0	5 mg/ℓ	
				4.6	7 mg/ℓ	
				30.4 mg downstream Depth: (m)		
				0	14 mg/ℓ	
				1.5	36 mg/ℓ	
				3.0	20 mg/ℓ	
				4.6	26 mg/ℓ	
33	Model test scale 1/25	Cutterhead	Sand	Vicinity of cutterhead	Range for cutter speed, swing speed and shape of cutters	Koba and Shiba (1982)
34	Imari Bay, Japan	Cutter	Clay	50 m. downstream	max (pgm)	Koba (1985)
				upper layer	6	
				middle layer	7	
				lower layer	61	

(Continued)

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Table D1 (Continued)

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/ Turbidity	Reference
					mean (pgm)	
				upper layer	2	
				middle layer	2	
				lower layer	6	
35	Osaka Bay (Hunnan Port) Japan	Cutterhead	Silty clay	50 m down current	max (pgm)	Koba (1985)
				upper	2	
				middle	5	
				lower	6	
					mean (pgm)	
				upper	0	
				middle	2	
				lower	3	
36	Osaka Bay (Osaka Port) Japan	Cutterhead	Clay	50 m down-current	max (pgm)	Koba (1985)
				upper	2	
				middle	9	
				lower	72	
				mean (pgm)		
				upper	0	
				middle	1	
				lower	6	

(Continued)

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Table D1 (Continued)

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/ Turbidity	Reference
37	Yokkaichi Port, Japan	Specialized suction head dredge (CHOSA1)	Sand 11% Silt 41% Clay 48% (Silty clay)	30 m down current		
				Center line of dredge swing 1.5 m above bottom	10 mg/ℓ	
				left edge of swing 1.5 m above bottom	8 mg/ℓ	
				right edge of swing 1.5 m above bottom	1 mg/ℓ	
38	Yokkaichi Port, Japan	Specialized suction head dredge (CHOSA2)	Sand 11% Silt 41% Clay 48% (Silty clay)	30 m down-current		
				Center line of dredge swing 1.5 m above bottom	3 mg/ℓ	
				left edge of swing 1.5 m above bottom	4 mg/ℓ	
				right edge of swing 1.5 m above bottom	1 mg/ℓ	

(Continued)

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Table D1 (Continued)

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/ Turbidity	Reference
39	Tokyo Bay, Japan	Specialized cutter suction dredge REFRESHER	Silty clay	Surrounding measurement grid	Average 4.5 mg/ℓ	Kaneko, Watari, and Aritomi (1984)
40	Tokyo Bay, Japan	Cutter suction dredge	Silty clay	Surrounding measurement grid	Average 200 mg/ℓ	Kaneko, Watari, and Aritomi (1984)
41	New York Harbor	Clamshell	Organic mud	Throughout water column	Average 73.4 ± mg/ℓ 126.3 mg/ℓ	Tavolaro (1984)
42	Jacksonville clamshell comparison	*Open clamshell*	*Not known*	Upper water column	Ave above 123.25 mg/ℓ	Montgomery and Raymond (1982)
				Lower water column	146.6 mg/ℓ	
	Jacksonville	Watertight	Not known	Upper water column	27 mg/ℓ	
		Clamshell	Not known	Lower water column	233 mg/ℓ	
43	James River demonstration project	Dustpan	Not known	Lower water column	71 mg/ℓ	Montgomery and Raymond (1982)

(Continued)

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Table D1 (Concluded)

Site No.	Project	Type of Dredge and Dredging Technique	Type of Material Being Dredged	Location of Measurement	Suspended Solids Concentration/ Turbidity	Reference
	James River	Cutterhead	Not known	Lower water column	40 mg/ℓ	
44	Patuxent River, Maryland	Clamshell	Organic Clayey Silt	Throughout watercolumn	Average 50-70 mg/ℓ	Onuschak (1982)

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