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PREDICTION AND CONTROL OF DREDGED MATERIAL DISPERSION AROUND DR--ETC(U)
AUG 78 W D BARNARD
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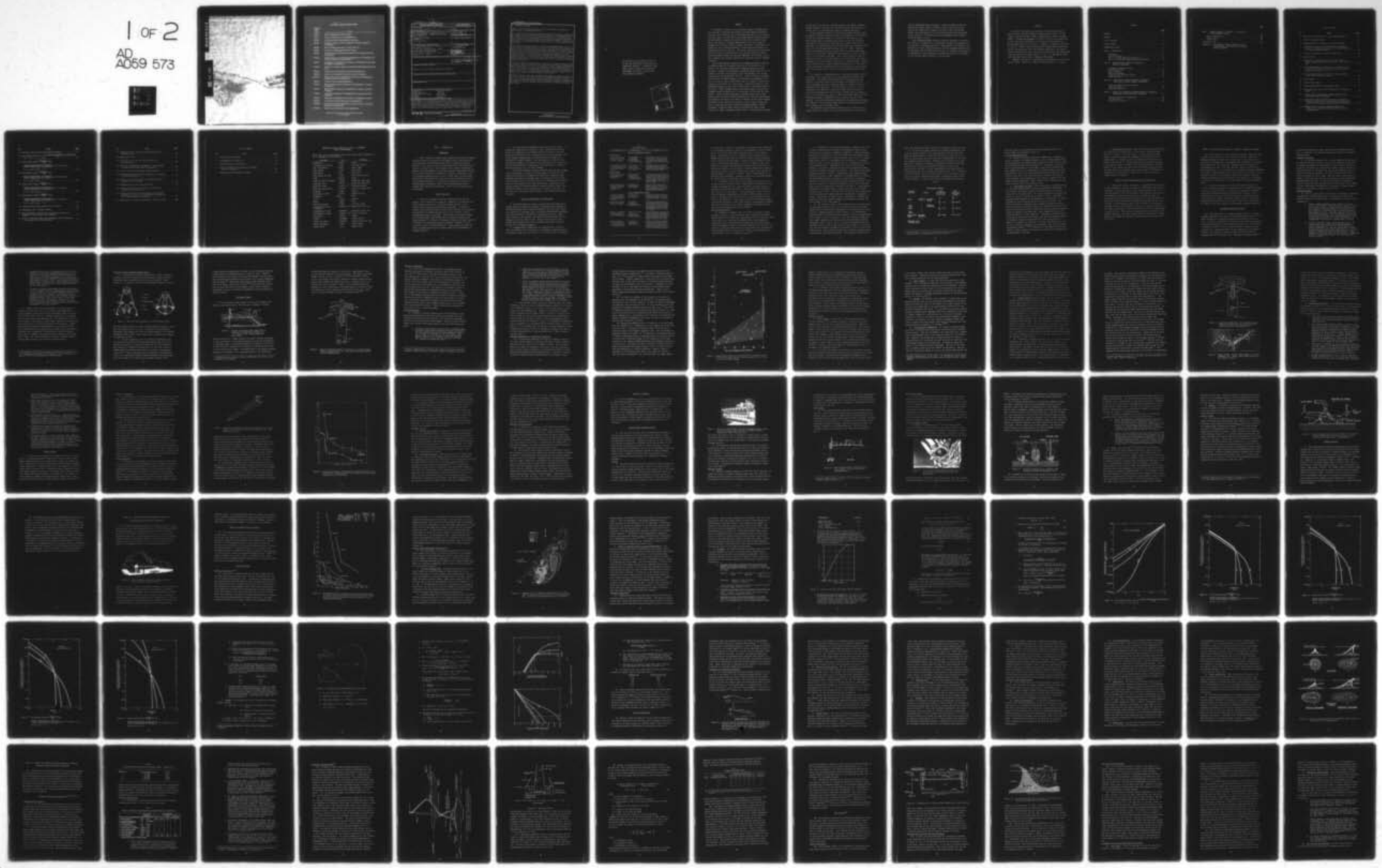

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In response to the concern over the potential impact of dredged material dispersion, Task 6C of the Dredged Material Research Program was established to develop the capability for predicting the nature, degree, and extent of dredged material dispersion in the vicinity of dredging and open-water pipeline disposal operations. In addition, methods for controlling this dispersion were evaluated. This report synthesizes the results of eight contract research studies and

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20. ABSTRACT (Continued).

summarizes the available literature concerned with turbidity generation by different types of dredging operations.

Water-column turbidity generated by dredging operations is usually restricted to the vicinity of the operation and decreases rapidly with increasing distance from the operation due to settling and horizontal dispersion of the suspended material. Turbidity levels around dredging operations can be reduced by improving existing cutterhead dredging equipment and operational techniques, using watertight buckets, and eliminating hopper dredge overflow or using a submerged overflow system.

During open-water pipeline disposal of fine-grained dredged material slurry, 97 to 99 percent of the material descends rapidly to the bottom of the disposal area where it forms a low gradient fluid mud mound. Suspended solids concentrations within the fluid mud layer increase with depth from 10 g/ℓ at the water column/fluid mud interface to levels of 300 to 500 g/ℓ at the bottom of the layer. One to three percent of the discharged slurry will remain suspended in the water column in the form of a turbidity plume. Average plume concentrations of several hundred milligrams per litre decrease rapidly with distance downstream from the discharge point and laterally away from the plume center line due to settling and horizontal dispersion.

The relative degree of dredged material dispersion at open-water pipeline disposal operations can be best controlled by using different discharge configurations. Water-column turbidity can be all but eliminated by using a submerged diffuser system at the end of the pipeline. The dispersion of near-surface turbidity can often be controlled to a certain extent by placing a silt curtain downstream or around certain types of dredging/disposal operations located in quiescent environments where current velocities are less than 50 cm/sec.

Although the impacts associated with existing dredging and disposal operations are not as severe as previously alleged, by implementing the guidelines given in this report for selecting dredges, improving operational techniques, properly using silt curtains, and selecting appropriate pipeline discharge configurations, any dredging or disposal operation can be conditioned to minimize its environmental impact.

# SUMMARY

In response to concern over the potential impact of dredged material that may be suspended and dispersed during dredging and disposal operations and the aesthetically displeasing appearance of near-surface turbidity plumes, one task within the Dredged Material Research Program was established to develop the capability for predicting the nature, degree, and extent of suspended dredged material in the vicinity of dredging and open-water pipeline disposal operations. Furthermore, the program set out to evaluate methods for controlling the dispersion of dredged material when necessary. This report synthesizes the laboratory and field results of eight separate, but related, contract research studies performed within this task and summarizes the available literature concerned with turbidity generation by different types of dredging operations.

Water-column turbidity generated by dredging operations involving fine-grained material is usually restricted to the vicinity of the operation and decreases rapidly with increasing distance from the operation. Maximum concentrations of suspended solids within 500 m of a clamshell operation will probably be less than 500 mg/ℓ, with average concentrations of approximately 100 mg/ℓ. Elevated levels of suspended solids around cutterhead dredges are restricted to the immediate vicinity of the cutter, where concentrations may be as high as a few tens of grams per litre within 3 m of the cutter. Near-bottom levels of a few hundred milligrams per litre may be found within a few hundred metres of the cutter. Hopper dredges without overflow may generate near-bottom suspended solids concentrations of a few grams per litre near the draghead(s). During overflow operations, turbidity plumes with average concentrations of several hundred milligrams per litre may extend behind the dredge for distances up to 1200 m. Turbidity levels around dredging operations can be reduced when necessary, but not without appreciable cost, by improving existing cutterhead dredging equipment rational techniques, using watertight buckets and eliminating hopper dredge overflow, or using a submerged overflow system. Unconventional dredging

systems such as the Mud Cat, Waterless dredge, Delta dredge, pneumatic pumping systems, or the Clean Up system may provide some advantage on certain types of environmentally sensitive dredging operations.

During open-water disposal of fine-grained dredged material slurry generated by pipeline dredge operations, an estimated 97 to 99 percent of the slurry descends rapidly to the bottom of the disposal area. Where bottom slopes are greater than 0.75 deg (1:76), the resulting fluid mud will in most cases flow downslope as long as that slope is maintained. On nonsloping bottoms, the fluid mud will accumulate in the form of a fluid mud mound with average slopes of 1:500. Suspended solids concentrations within the fluid mud layer increase with depth from 10 g/ℓ at the water column/fluid mud interface to levels of 300 to 500 g/ℓ at the bottom of the layer. One to three percent of the discharged slurry will not descend rapidly to the bottom, but will remain suspended in the water column in the form of a turbidity plume. Average plume concentrations of several hundred milligrams per litre decrease rapidly with distance downstream from the discharge point and laterally away from the plume center line due to settling and horizontal dispersion.

The dispersion of dredged material at open-water pipeline disposal operations can be controlled best by using different discharge configurations. The simple open-ended pipeline, discharging above and parallel to the water surface, will maximize the dispersion of the slurry throughout the water column and produce a relatively thin, but widespread, fluid mud layer. In water depths in excess of 2 m, the dispersion of the material in the water column can be decreased by vertically discharging the slurry through a 90-deg elbow at a depth of 0.5 to 1 m below the water surface. Most water-column turbidity can be eliminated by using a submerged diffuser system at the end of the pipeline. This latter discharge configuration also maximizes the mounding tendency of the fluid mud dredged material, thereby minimizing its areal coverage over the disposal area.

The dispersion of near-surface turbidity can be controlled, to a certain extent, by placing a silt curtain downstream or around certain types of dredging/disposal operations. Under quiescent current conditions (less than 5 cm/sec) turbidity levels in the water column outside the curtain may be reduced by as much as 80 to 90 percent; however, the effectiveness of silt curtains decreases with increasing current velocity. Silt curtains are not recommended where currents exceed 50 cm/sec (1 knot).

Since dredging/disposal projects should be evaluated on a case-by-case basis, it is imperative to concurrently consider all components of the operation, including excavation, transportation, and disposal of the material as a total integrated system. The best dredging system may not be compatible with the best disposal system. In addition, the impact of each component of the system must be objectively evaluated with respect to the cost and overall benefits of the operation.

# PREFACE

This report synthesizes the results of eight research studies within Task 6C, entitled "Turbidity Prediction and Control," of the Disposal Operations Project (DOP), Dredged Material Research Program (DMRP). Planning and management of Task 6C as well as the preparation of this report were performed by Dr. William D. Barnard under the general supervision of Mr. Charles C. Calhoun, Jr., manager of the DOP; Dr. Roger T. Saucier, Special Assistant for Dredged Material Research; and Dr. John Harrison, Chief, Environmental Laboratory. The Task 6C research synthesized in this report was performed by private engineering firms and universities under contract to the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi.

Commander and Director of WES during the preparation of this report was COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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## CONVERSION FACTORS, METRIC (SI) TO U. S. CUSTOMARY UNITS OF MEASUREMENT

Metric (SI) units of measurement used in this report can be converted to U. S. customary units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| centimetres | 0.3937 | inches |
| centimetres per second | 0.3937 | inches per second |
| cubic centimetres | 0.610 | cubic inches |
| cubic metres | 1.308 | cubic yards |
| cubic metres | 35.31 | cubic feet |
| cubic metres per hour | 1.308 | cubic yards per hour |
| grams | 0.03527 | ounces |
| grams per cubic centimetre | 0.03613 | pounds per cubic inch |
| grams per litre | 3.61273 | pounds per cubic inch |
| grams per second | $2.205 \times 10^{-3}$ | pounds per second |
| grams per square metre | 0.02949 | ounces per square yard |
| kilograms | 2.2046 | pounds |
| kilograms per metre | 0.6720 | pounds per foot |
| kilometres | 3281.0 | feet |
| litres | 0.2642 | gallons |
| metres | 3.2808 | feet |
| metres per second | 3.2808 | feet per second |
| milligrams per cubic centimetre | $0.03613 \times 10^{-3}$ | pounds per cubic inch |
| milligrams per litre | 0.00361273 | pounds per cubic inch |
| milligrams per second | $0.03527 \times 10^{-3}$ | ounces per second |
| millimetres | 0.03937 | inches |
| newtons | 0.2248089 | pounds (force) |
| newtons per metre | 0.0057101 | pounds (force) per inch |
| square centimetres | 0.1550 | square inches |
| square metres | 1.196 | square yards |

# PART I: INTRODUCTION

## Background

1. One of the major concerns about dredging and open-water disposal 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 the potentially toxic chemical contaminants present in bottom sediments is associated with the fine-grained fraction that is most susceptible to dispersion.[1] However, evaluating the fate of resuspended dredged material is not a simple task, especially when dealing with fine-grained (silt and clay) slurries generated by maintenance dredging operations. In addition, regardless of the degree of dredged material dispersion, under certain environmentally and/or aesthetically sensitive circumstances, control of this dispersion may be advisable.

## Task 6C Research

2. Task 6C of the DMRP,[2] entitled "Turbidity Prediction and Control," was established to develop the capability for predicting the nature, degree, and extent of suspended dredged material in the vicinity of open-water pipeline disposal operations. In addition, several studies evaluated physical and chemical methods for controlling the dispersion of dredged material slurry in the vicinity of both dredging and disposal operations. The biological and chemical impacts were evaluated under related DMRP Tasks 1A (Aquatic Disposal Field Investigations),[3] 1C (Effects of Dredging and Disposal on Water Quality),[4] 1D (Effects of Dredging and Disposal on Aquatic Organisms),[5] and 1E (Pollution Status of Dredged Material).[6] Hopper dredge and barge disposal of dredged material were evaluated under Task 1B (Movements of Dredged Material).[7]

3. The eight studies comprising Task 6C are listed in Table 1. In addition to synthesizing the results of these research efforts, this report also summarizes the available literature related to turbidity generation by different types of dredging operations and describes some of the dredging equipment that has been developed to minimize the dispersion of dredged sediment. The nonavailability of much of this specialized equipment in the United States and the scope of this project did not permit testing or comparison of the capabilities or turbidity reduction potential of any of this equipment.

4. This study addressed the major problems associated with dredged material dispersion. Because of the high degree of variability associated with different environmental and operational parameters, many phenomena associated with dredged material dispersion can only be described qualitatively at this time, based on an integration and interpretation of both laboratory and field observations. Quantitative, empirical predictions are given whenever possible based on "worst" case situations; however, these estimates may be revised in the future as more data are collected and understanding of the controlling processes increases.

## Types of Dredged Material Suspensions

5. Field and laboratory studies concerned with the dispersion of dredged material indicate that sediment resuspended during dredging or open-water disposal either remains suspended in the upper water column at relatively low concentrations or forms high concentration suspensions that cover the bottom. The material suspended in the water column is often referred to as turbidity; the dense near-bottom suspensions are commonly called fluid mud or fluff. Because these terms are often misused and confusing, they will be defined and discussed in greater detail in the following paragraphs.

6. Dredged material suspensions are quantitatively classified and/or described by their concentration of suspended solids expressed in milligrams or grams per litre (mg/ℓ or g/ℓ), percent solids (by weight),

Table 1

Task 6C Research Studies

| Research Study | Contractor | Objective |
|---|---|---|
| | Prediction of Dredged Material Dispersion | |
| Turbidity Research | | |
| Laboratory Study Related to Predicting the Turbidity-Generation Potential of Sediments to be Dredged | Walden Research Division of ABCOR, Inc.<br>Wilmington, Mass.<br>(Mr. Barry A. Wechsler and Dr. David R. Cogley) | To determine the amount of turbidity that a given sediment is likely to produce when subjected to a dredging operation by evaluating those sedimentary/hydrologic factors causing and/or controlling turbidity. |
| Field Investigation of the Nature, Degree, and Extent of Turbidity Generated by Open-Water Pipeline Disposal Operations | State University of N. Y. at Stony Brook<br>Stony Brook, N. Y.<br>(Drs. J. R. Schubel and H. H. Carter) | To investigate the nature, degree, and three-dimensional extent of plumes of suspended solids and associated dissolved chemical constituents generated by open-water pipeline disposal operations. |
| Fluid Mud Research | | |
| Field Study of Fluid Mud Dredged Material: Its Physical Nature and Dispersion | Virginia Institute of Marine Science<br>Gloucester Pt., Va.<br>(Drs. Maynard M. Nichols and Richard W. Faas) | To determine the significance of fluid mud in the dispersal of dredged material and in generating turbidity at dredging and disposal operations by measuring the nature, extent, and thickness of fluid mud layers with respect to their source, hydrologic parameters, and behavior as a function of time. |
| Laboratory Investigation of the Dynamics of Mudflows Generated by Open-Water Pipeline Disposal Operations | JBF Scientific Corp.<br>Wilmington, Mass.<br>(Mr. George Henry) | To improve the basic understanding of the dynamics of fluid mud dispersion by evaluating possible controlling factors such as sediment composition, bottom slope and roughness, discharge velocity, salinity, and currents and waves. |
| | Control of Dredged Material Dispersion | |
| Investigation of Techniques for Reducing Turbidity Associated with Present Dredging Procedures and Operations | John Huston, Inc.<br>Corpus Christi, Tex.<br>(Mr. John Huston) | To evaluate new and existing operational techniques with respect to their turbidity-reduction potential, cost, effect on production, and ease of implementation. |
| Analysis of the Functional Capabilities and Performance of Silt Curtains | JBF Scientific Corporation<br>Wilmington, Mass.<br>(Mr. Edward E. Johanson) | To inventory silt curtain specifications, evaluate deployment methods and systems, and determine silt curtain effectiveness as it relates to factors such as size, shape, and design of the enclosed area; the curtain material used; the sediment being dredged; and limiting environmental conditions. |
| Evaluation of the Submerged Discharge of Dredged Material Slurry During Pipeline Dredge Operations | JBF Scientific Corporation<br>Wilmington, Mass.<br>(Mr. Robert W. Neal and Mr. George Henry) | To evaluate the technical, operational, and economic feasibility of using submerged pipeline discharge of dredged material slurry as one disposal alternative within a designated open-water disposal area to minimize the dispersion of the dredged material slurry into the water column. |
| Assessment of Chemical Flocculants and Friction-Reducing Agents for Application in Dredging and Dredged Material Disposal | Mississippi State University<br>Starkville, Miss.<br>(Dr. Donald O. Hill) | To perform a state-of-the-art review and assessment of the potential utilization of flocculants for turbidity control in dredging and disposal operations and friction-reducing (wetting) agents for increasing the efficiency of the pipeline transport of dredged material slurry. |

or bulk density. Relatively low levels of suspended solids characteristic of turbidity plumes are expressed in milligrams per litre or grams per litre indicating the weight of dry solids in a litre volume of sample. Intermediate levels of suspended solids characteristic of dredged material slurry and fluid muds are usually given in grams per litre or percent solids by weight. Percent solids by weight is calculated by dividing the dry weight of solids in a sample by the total weight of the sample (including both the solids plus water) and converting the fraction to a percentage. Bottom sediments with relatively high solids content are usually described in terms of bulk density or the wet weight of a volume of sediment. Units of bulk density are in grams per cubic centimetre. Appendix A shows the relationship between the three methods of expressing solids content.

7. In contrast to the above system, dredgers usually describe a slurry in terms of percent solids by volume where the volume of in situ sediment (including both the solids plus water) excavated during an operation is divided by the volume of slurry pumped; this fraction is then converted to a percentage. In some instances, percent solids is based on apparent volume where the volume of settled solids in a container is divided by the total volume of the settled solids plus the water in the container. In most cases this latter percentage provides an erroneous indication of the solids content, as described by dredgers, since the bulk density of the settled sediment will normally be less than its in situ bulk density before dredging.

### Water-column turbidity

8. Turbidity is commonly used to describe the cloudy or muddy appearance of water. In the strictest sense, turbidity describes an optical property of a particular liquid medium, in this case water, that causes light to be scattered and absorbed rather than transmitted through the water. Scattering and absorption are caused by the dissolved and suspended organic and inorganic substances in the water. The amount of scattering and absorption is controlled by the concentration of suspended particles as well as their shape, size distribution, refractive index, color, and absorption spectra.[8]

9. In addition to the varied definitions of turbidity, there are also many techniques and instruments (turbidimeters) that have been and are used to evaluate or "quantify" turbidity.[9] Turbidity measurements were originally made in the early 1900's with the Jackson candle turbidimeter, calibrated in Jackson Turbidity Units (JTU's) or Jackson Candle Units (JCU's), to approximate the concentration of suspended solids in terms of parts per million (ppm) of a suspension of Fuller's or diatomaceous earth. Turbidimeters were later calibrated with Formazin, a solution of hydrazine sulfate and hexamethylenetetramine, in terms of Formazin Turbidity Units (FTU's). The Jackson candle meter has been replaced by a myriad of turbidimeters that usually measure turbidity in terms of light transmission (transmissometers) or scattering (nephelometers) where the amount of light that is transmitted through or scattered by a particular sample is measured relative to the initial intensity of a light beam. Nephelometers are often calibrated using a scale of Nephelometric Turbidity Units (NTU's). Unfortunately, suspensions of different types of material with the same turbidity reading (in FTU's, NTU's, or JTU's) may have similar optical properties, but do not necessarily contain the same concentration of suspended solids. Furthermore, different types of turbidimeters, although calibrated with the same standard suspension, may indicate different turbidity levels for the same sample.[10]

10. The turbidity levels of water samples collected around dredging and disposal operations for all of the 6C research studies were quantitatively evaluated with turbidimeters or by measuring the concentration of suspended material in water samples. By simultaneously measuring both the turbidity and concentration of total suspended solids over a range of values, a correlation curve was developed showing the relationship (which may not necessarily be linear) between turbidity (expressed in NTU's, FTU's, JTU's, or percent transmission) and total suspended solids. Using an empirical correlation curve for each field site, all the turbidity readings were converted to levels of total suspended solids. These levels were then used to compare suspended solids concentrations at different locations. All turbidity levels in this

report are therefore expressed in terms of milligrams or grams per litre.

11. The turbidity plumes generated by dredging and disposal operations are usually caused by low concentrations of silt and clay-size particles (with diameters of less than 0.03 mm)* or small flocs (i.e., masses of agglomerated particles) that settle independently at very slow rates through the water column. Although solids concentrations in the upper water column in the vicinity of dredging and disposal operations usually do not exceed several hundred milligrams per litre, the particles/flocs continue to settle independently until the solids concentration near the bottom exceeds approximately 10 g/ℓ.[11,12] Therefore, in this discussion, the term turbidity will be used to describe suspensions in the water column where the solids concentration ranges from 0 to 10 g/ℓ (Table 2). Factors controlling the settling rates of these

Table 2

*DREDGED MATERIAL SUSPENSIONS*

| QUALITATIVE DESCRIPTOR | PROCESSES | | SOLIDS CONCENTRATION (g/ℓ) AVERAGE (RANGE) | BULK DENSITY (g/cc)* AVERAGE (RANGE) CENTER |
|---|---|---|---|---|
| | ↑ | | 0 g/ℓ | 1.000 |
| TURBIDITY | SEDIMENTATION | INDEPENDENT SETTLING | ↕ | ↕ |
| | | ///// | 10 g/ℓ (5-20) | 1.006 (1.003-1.012) |
| LOW DENSITY | | HINDERED OR ZONE SETTLING | ↕ | ↕ |
| FLUID MUD | ↓ | ///// | 200 g/ℓ (175-225) | 1.125 (1.109-1.140) |
| HIGH DENSITY | ↑ | | ↕ | ↕ |
| "TYPICAL" BOTTOM SEDIMENT | SELF-WEIGHT CONSOLIDATION | | 400 g/ℓ (300-500) | 1.249 (1.187-1.311) |
| | ↓ | | | |

*ASSUME SOLIDS = 2.65 g/cc
AND WATER = 1.00 g/cc

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* For convenience, factors for converting the metric (SI) to U. S. customary units of measurement are given on page 12.

particles, which in turn directly affect the characteristics of turbidity plumes, are discussed in Part III.

## Fluid mud dredged material

12. Naturally occuring fine-grained sediment that accumulates in rivers, estuaries, and dredged channels as well as dredge-induced near-bottom suspensions of dredged material slurry often form layers of fluid mud overlying more dense bottom sediment.[13] Since there is no universally accepted definition of fluid mud, in this report fluid mud has been classified as low- or high-density fluid mud, based on its solids concentration. The solids concentration marking the transition zones between turbid water, low- and high-density fluid mud, and "typical" bottom sediment varies depending on the texture and composition of the dredged material suspension. Table 2 gives typical average values and ranges associated with each transition zone.

13. Low-density fluid mud. The concentration of suspended solids in a turbidity plume generally increases exponentially with depth. At the relatively well-defined interface between turbid water and the surface of the fluid mud layer, the solids concentration increases very rapidly to levels of several tens of grams per litre. This turbid water/fluid mud interface is approximated by a concentration of 10 g/ℓ, although the exact concentration may vary from 5 to 20 g/ℓ. Low-density fluid mud is characterized by randomly oriented particles or flocs that settle at "hindered" rates; the fluid mud layer settles as a mass as the interstitial water (between the particles) migrates upwards toward the surface of the mud layer. This sedimentation process is called "hindered" or "zone" settling.[11] Low-density fluid mud may be stationary or may freely flow outward, away from the discharge point of an open-water pipeline disposal operation, like syrup poured on a platter, or downslope as a mudflow. At solids concentrations of 175 to 225 g/ℓ the hindered settling process apparently ends and self-weight consolidation begins.[11,12,14] Therefore, an approximate solids concentration of 200 g/ℓ generally indicates the transition zone between low- and high-density fluid mud.

14. High-density fluid mud. When the solids concentration within the fluid mud layer exceeds 200 g/ℓ, the degree of particle contact increases. Because of the high solids concentration and this high degree of particle interaction, high-density fluid mud possesses a certain degree of rigidity and will not normally flow freely as low-density fluid mud may.[12] During this process, the interstitial water is squeezed out under the weight of the overlying material, the bulk density of the material increases, and the randomly oriented particle structure and/or flocs probably begin to break down.[11] Although this high-density fluid mud does not flow freely, it may be subject to sudden failure or creeping.

## Factors Controlling Dredged Material Dispersion

15. The nature, degree, and extent of dredged material dispersion around a dredging or disposal operation are controlled by many factors, including: the characteristics of the dredged material, such as its size distribution, solids concentration, and composition; the nature of the dredging or disposal operation, such as dredge type and size, discharge/cutter configuration, discharge rate, solids concentration of the slurry, and the operational procedures being used; and the characteristics of the hydrologic regime in the vicinity of the operation, including salinity and hydrodynamic forces (i.e., waves, currents, etc.). The relative importance of the different factors may vary significantly from site to site. These factors are discussed in more detail in subsequent chapters of this report dealing with the dispersion of dredged material at dredging and open-water pipeline disposal operations (in that order).

# PART II: PREDICTION AND CONTROL OF TURBIDITY: DREDGING OPERATIONS

16. Under a given set of environmental conditions, different types of dredges will generate different levels of turbidity. While the dredging equipment certainly has a large effect on the amount and concentration of sediment that is resuspended, the techniques for operating this equipment are also important. Although operator training and performance may be one of the most important factors controlling turbidity generation, it is often difficult to evaluate the various parameters of a dredge's operation that reflect the skills of the operator. Unfortunately, in most of the literature cited in this chapter, turbidity levels were measured with little regard to the operation of the dredges or their rates of production (i.e., cubic metres of material dredged per hour).

17. With this in mind, the following discussion examines the levels of turbidity generated by different types of conventional dredges as well as possible methods for minimizing the generation of turbidity by modifying existing equipment and operational procedures. This discussion also includes a brief description of an improved overflow system for hopper dredges, watertight clamshell buckets, and several unconventional dredges that are not widely used in the United States, but appear to have some potential for minimizing turbidity generation.

## Grab/Bucket/Clamshell Dredges

18. The grab, bucket, or clamshell dredge consists of a bucket or clamshell operated from a crane or derrick mounted on a barge.[15] It is used extensively for removing relatively small volumes of material (i.e., a few tens or hundreds of thousands of cubic metres) particularly around docks and piers or within other restricted areas. The sediment is removed at nearly its in situ density; however, production rates (relative to a cutterhead dredge) are low, especially in consolidated material. The material is usually placed in barges or scows for transportation to the disposal area. Although the dredging depth is

practically unlimited, the deeper the depth the lower the production rate. In addition, the clamshell dredge usually leaves an irregular, cratered bottom.

Sources of turbidity

19. The turbidity generated by a typical clamshell operation can be traced to four major sources. Most of this turbidity is the result of sediment resuspension occurring when the bucket impacts on and is pulled off the bottom. Also, because most buckets are not covered, the "surface" material in the bucket and the material adhering to the outside of the bucket are exposed to the water column as the bucket is pulled up through the water column. When the bucket breaks the water surface, turbid water may spill out of the bucket or may leak through openings between the jaws. In addition to inadvertent spillage of material during the barge loading operation, turbid water in the barges is often intentionally overflowed (i.e., displaced by higher density material) to increase the barge's effective load.

Field measurements

20. There is a great deal of variability in the amount of material resuspended by clamshell dredges due to variations in bucket sizes, operating conditions, sediment types, and hydrodynamic conditions at the dredging site.

a. During a channel deepening project using a 16.5-cu m bucket in San Francisco Bay, California, turbidity levels in the water column 50 m downstream from the operation were generally less than 200 mg/ℓ and averaged 30 to 90 mg/ℓ relative to background levels outside the plume of approximately 40 mg/ℓ. Suspended solid levels decreased with increasing distance from the dredging operation due to dilution and settling of the suspended material. The visible plume was about 300 m long at the surface and approximately 450 m long at a bottom depth of 10 m.[16]

b. During a "new work" channel deepening operation on the lower Thames River, Connecticut, maximum suspended solids concentrations of 68, 110, and 168 mg/ℓ at the surface, middepth (3 m), and near bottom (10 m), respectively, were noted within 100 m downstream of a 12.8-cu m clamshell dredging and barge loading operation. These maximum concentrations decreased very rapidly to background levels of 5 mg/ℓ within 300 m at the surface and 500 m near the bottom.[17]

c. Suspended solids levels 22 m downstream from a 16.5-cu m clamshell operation performing maintenance work in the Brewerton Cut-Off Angle, Patapsco River, Maryland, were about 30 mg/ℓ at near-bottom depths of 10 m relative to background water column suspended solids concentrations of approximately 10 mg/ℓ or less. These higher near-bottom concentrations persisted for about 90 m downstream from the dredge, whereas visual surface traces usually persisted for less than 460 m.[18]

d. According to Japanese measurements made in the vicinity of a 1-cu m clamshell operation dredging fine-grained material from a depth of 3.5 m, maximum suspended solids concentrations in the water column 7 m downstream from the dredging operation ranged from 150 to 300 mg/ℓ relative to background levels of less than 30 mg/ℓ.* These levels decreased by about 50 percent at a distance of 23 m. Generally speaking, the turbidity levels in the upper water column were usually somewhat less than those levels at middepth or near the bottom.[19]

21. Based on these limited measurements, it appears that, depending on current velocities, the turbidity plume downstream of a typical clamshell operation may extend approximately 300 m at the surface and 500 m near the bottom. Maximum concentrations of suspended solids in the surface plume should be less than 500 mg/ℓ in the immediate vicinity of the operation and decrease rapidly with distance from the operation due to settling and dilution of the material. Average water-column concentrations should generally be less than 100 mg/ℓ. The near-bottom plume will probably have a higher solids concentration, indicating that resuspension of bottom material near the clamshell impact point is probably the primary source of turbidity in the lower water column. The visible near-surface plume will probably dissipate rapidly within an hour or two after the operation ceases.

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* These suspended solids concentrations are unverified estimates based on a conversion of turbidity to milligrams per litre (Figure 3.14, Yagi et al.[19]) from a different test site in Japan.

Turbidity control using watertight buckets

22. To minimize the turbidity generated by a typical clamshell operation, the Port and Harbor Research Institute, Japan, developed a watertight bucket with edges that seal when the bucket is closed (Figure 1). In addition, the top of the watertight bucket is covered so that the dredged material is totally enclosed within the bucket. Available sizes range from 2 to 20 cu m. According to the manufacturer, Mitsubishi Seiko Company, Ltd. (Box 48, Nippon Building, 2-6-2 Otemachi, Chiyoda-ku, Tokyo, Japan), these buckets are best adapted for dredging fine-grained, soft mud.

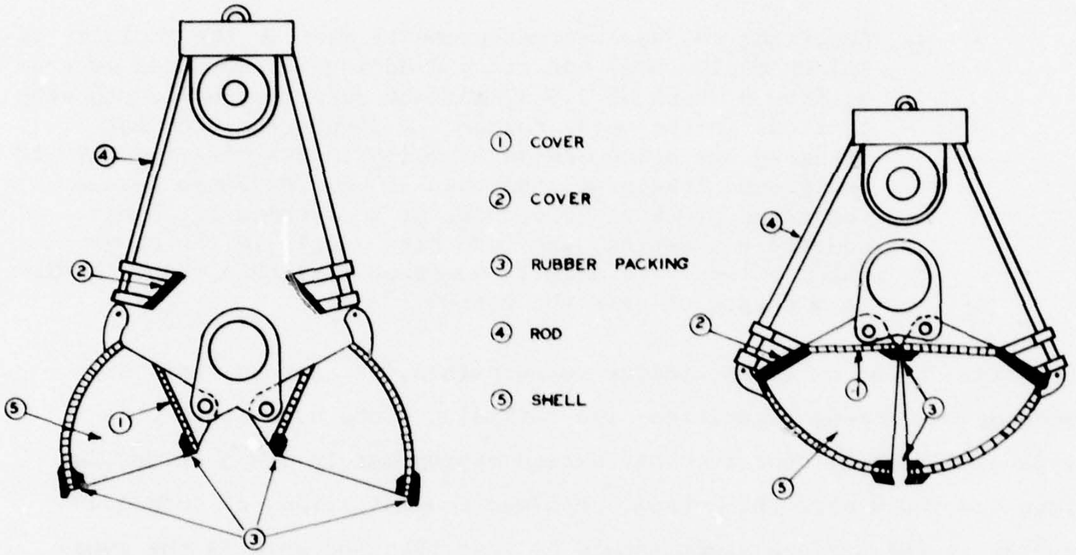

Figure 1. Open and closed positions of the watertight bucket

23. A direct comparison of 1-cu m typical and watertight clamshell operations indicates that watertight buckets generate 30 to 70 percent less turbidity in the water column than the typical buckets. This reduction is probably due primarily to the fact that leakage of dredged material from watertight buckets is reduced by approximately 35 percent.[19] Other measurements made approximately 10 m downstream from a 4-cu m watertight clamshell dredge excavating fine-grained material from a depth of 8 m indicated that maximum suspended solids

concentrations were approximately 500 mg/ℓ or less throughout the water column relative to background levels of 50 mg/ℓ or less. Turbidity levels decreased very rapidly with increasing distance from the operation and approached background levels several tens of metres downstream from the dredge.[20] Near-bottom and midwater column suspended solids levels were greater than surface levels,[19,20] indicating that resuspension of bottom material near the clamshell impact point is probably responsible for most of the material suspended in the lower portion of the water column.

## Cutterhead Dredges

24. The cutterhead dredge (Figure 2) is the most commonly used dredge in the United States. With this type of dredge a rotating cutter 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 15 cm (6 in.) to 112 cm (44 in.)* pipeline as a slurry with a typical solids content of 10 to 20 percent by weight. The nominal size of the dredge is usually defined by the diameter of its discharge pipeline. For conventional

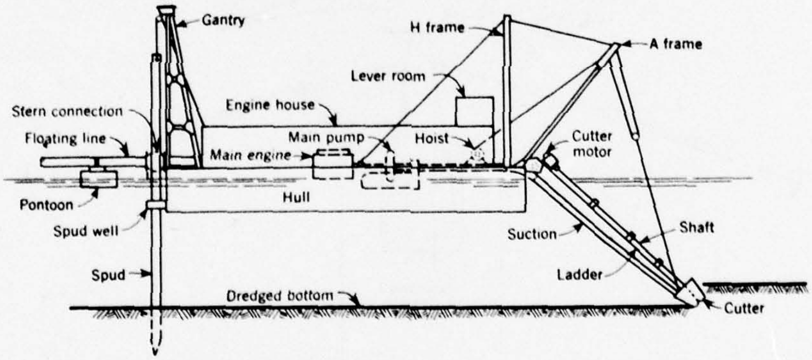

Figure 2. Typical cutterhead dredge (Reprinted by permission from Hydraulic Dredging, by J. W. Huston, 1970. Cornell Maritime Press, Inc.)

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* Pipeline sizes are given in terms of centimetres and inches for the convenience of the reader.

cutterhead dredges the diameter of the cutter is approximately three to four times the diameter of the suction pipe. The typical cutterhead dredge is swung in an arc from side to side by alternately pulling on port and starboard swing wires connected to anchors through pulleys mounted on the ladder just behind the cutter. Pivoting on one of two spuds at the stern, the dredge "steps" or "sets" forward (Figure 3). Although the cost of mobilizing a cutterhead dredge is relatively high, its operation is nearly continuous and production rates (i.e., cubic metres of material dredged per hour) are generally high.[15,21]

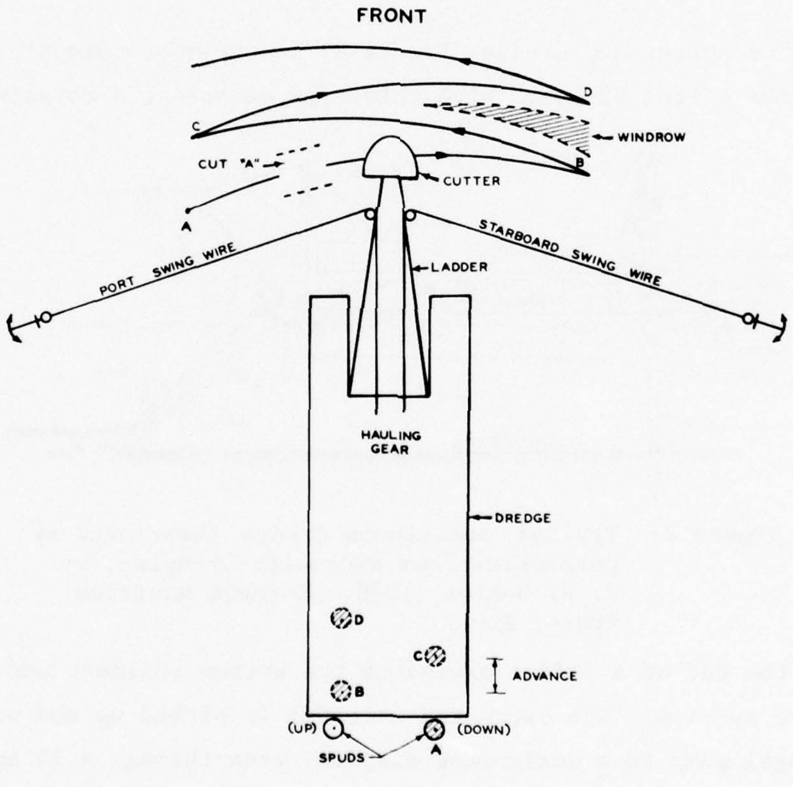

Figure 3. Typical (stabbing) method for operating a cutterhead dredge (Adapted from Reference 27. Used courtesy of Symcon Marine Corp. and WODCON Assn.)

## Sources of turbidity

25. Most of the turbidity generated by a cutterhead dredging operation (exclusive of disposal) is usually found in the vicinity of the cutter.[22] The levels of turbidity 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 swing rate of the dredge (i.e., the horizontal velocity of the cutter moving across the cut). The ability of the dredge's suction to pick up this bottom material determines the amount of cut material that remains on the bottom or suspended in the water column. In addition to the dredging equipment used and its mode of operation, turbidity may also be caused by sloughing of material from the sides of vertical cuts, inefficient operational techniques, and the prop wash from the tenders (tugboats) used to move pipeline, anchors, etc., in the shallow water areas outside the channel. These factors will be discussed in more detail in the following paragraphs.

## Field measurements

26. Although a properly designed cutter will efficiently cut and guide the bottom material toward the suction, the cutting action and 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.

- a. Turbidity levels around a 61-cm (24-in.) cutterhead dredge excavating fine-grained maintenance material from Mobile Bay ship channel were elevated above background levels of 25 to 30 mg/ℓ only within 1.5 m of the bottom. Near-bottom levels of up to 125 mg/ℓ occurred approximately 300 m in front of the cutterhead; a value of 336 mg/ℓ was recorded 30 m behind the cutter.*

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* Personal Communication, 7 October 1977, Maynard M. Nichols, Associate Professor, Virginia Institute of Marine Science, Gloucester Point, Va.

b. Near-bottom suspended solids levels within 2 m of the cutter of a 69-cm (27-in.) cutterhead dredge widening a portion of the Corpus Christi ship channel (i.e., new work) ranged from background concentrations to 580 mg/ℓ relative to "background" levels of 39 to 209 mg/ℓ measured 73 m to the side of the dredge.[22]

c. Levels of suspended solids under low current conditions (i.e., less than 5 cm/sec) near the cutter of a 61-cm (24-in.) cutterhead dredge excavating fine-grained (new work) material from depths of 6 to 12 m in Yokkaichi Harbor ranged from 2 mg/ℓ to 31 g/ℓ, 1 mg/ℓ to 16 g/ℓ, and 1 mg/ℓ to 4 g/ℓ at distances of 1, 2, and 3 m above the cutter, respectively, relative to background levels of 1 to 18 mg/ℓ. Average turbidity levels appeared to decrease exponentially from the cutter to the water surface. In addition, 60 m in front of the cutter turbidity levels in the near-surface water ranged from 1 to 17 mg/ℓ, whereas near-bottom levels ranged from 5 to 205 mg/ℓ.[23]

27. Based on these limited field data collected under low current conditions, 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. Within 3 m of the cutter suspended solids concentrations are highly variable, but may be as high as a few tens of grams per litre; these concentrations decrease exponentially from the cutter to the water surface. Near-bottom suspended solids concentrations may be elevated to levels of a few hundred milligrams per litre at distances of a few hundred metres from the cutter. This led Yagi et al.[23] to conclude that "in the case of steady dredging of a thin sedimented mud layer, the effect of dredging on turbidity was found to be almost imperceptible at locations several tens of metres distance from the cutter."

### Turbidity generation vs. operational conditions

28. As previously indicated, 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 in Yokkaichi Harbor indicates that as the amount of this

residual material increases, the turbidity levels around the cutter apparently increase exponentially.[23] According to calculations made by Yagi et al.,[23] the amount of residual material increases as the swing rate increases. Further examination of these data (by this author) also indicates that in most cases the amount of 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. There is also a similar relationship between turbidity generation and the rate of cutter rotation.[22]

29. The levels of turbidity in the vicinity of the cutter are apparently not only dependent on the operation of the dredge during a particular cut, but are also related to the amount of material remaining in suspension from the previous cut(s). In fact, during the first four swings of the dredging operation monitored by Yagi et al.,[23] the levels of turbidity around the cutter increased with each successive cut. This trend of increasing levels of suspended solids around the cutter probably continues until a quasi-steady state condition is reached when the amount of material resuspended by the cutter is equal to the amount of material that settles to the bottom.

30. Because the production rate of a dredge is so closely linked with its operation (i.e., thickness of the cut, swing rate, cutter rotation rate, etc.), the levels of turbidity around the cutter may be directly related to the dredge's production rate. This relationship is supported by data (from Yagi et al.[23]) plotted for fine-grained material in Figure 4 showing the levels of suspended solids 1 m from the cutter of a 61-cm (24-in.) cutterhead dredge vs. the production of the dredge (relative to its apparent maximum production rate) during the fourth cut on 26 test runs. Although the scatter in the data is great, there is a general trend showing increasing turbidity levels 1 m from the cutter with increasing rates of relative production. However, there is apparently no well-defined upper limit to the amount of turbidity that the cutter can generate. Yet, the data within the shaded region

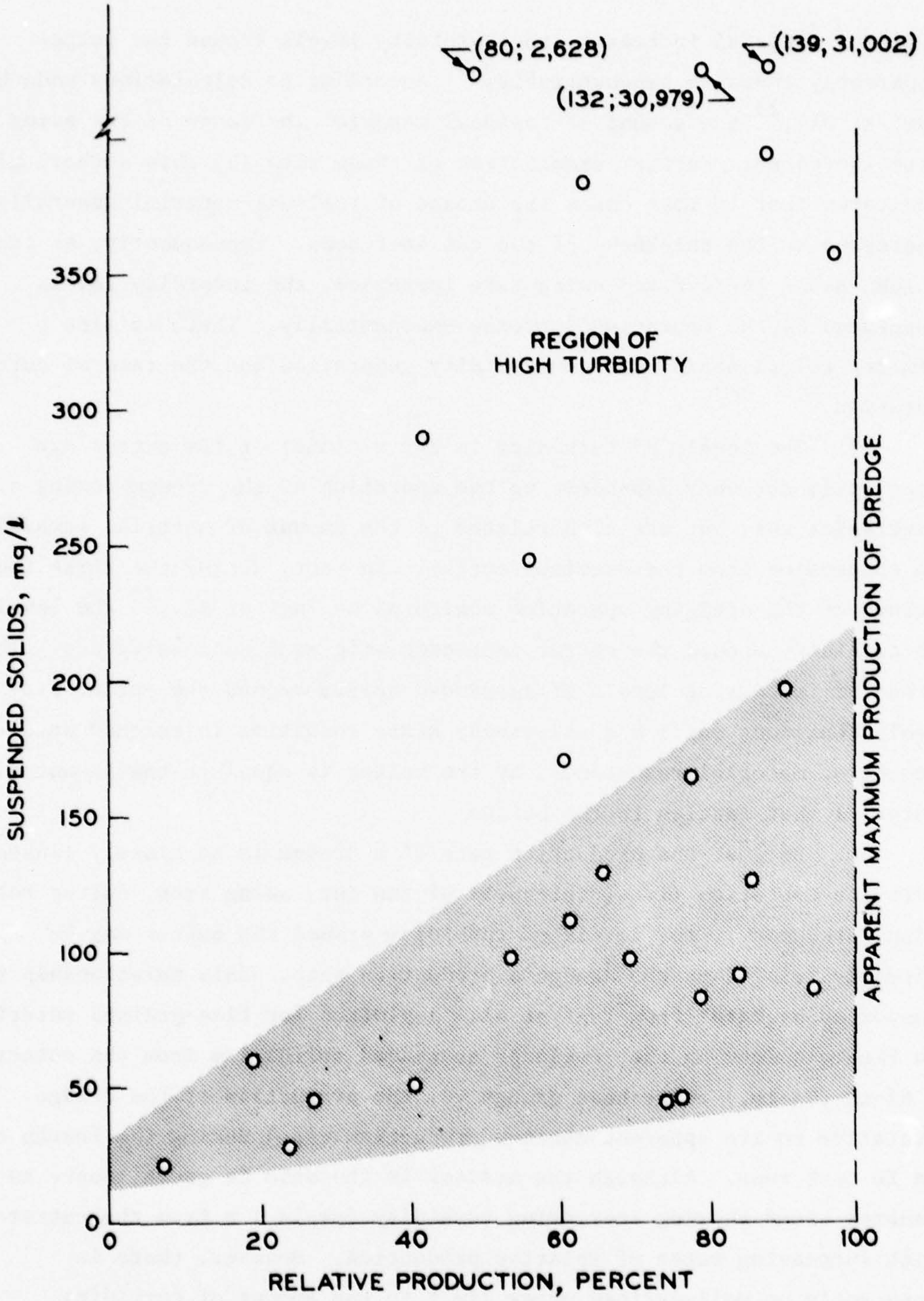

Figure 4. Relationship between the concentration of suspended solids 1 m from the cutter and the relative production of a 61-cm (24-in.) cutterhead dredge

(Figure 4) indicate that it is possible to increase the rate of a dredge's production up to its maximum rate (dotted line, Figure 4) without generating excessive levels of turbidity. Using high swing rates, large cuts, or high cutter rotation rates not only resuspends large amounts of dredged material, but also may lead to high levels of solids in the slurry, which may plug the pipeline.

31. To summarize, the turbidity generated around the cutter of a cutterhead dredge apparently increases exponentially as the thickness of the cut, rate of swing, and cutter rotation rate increase. Although suspended solids levels around the cutter also increase with increasing rates of production, it is possible to maximize the production rate of the dredge without resuspending excessive amounts of bottom sediment. These general relationships should be characteristic of all cutterhead dredging operations; however, the levels of turbidity generated will, of course, depend on the size and characteristics of the dredge, the sediment type, and the environmental and operational conditions.

### Turbidity control

32. Cutter design. The design of a cutter depends primarily on the characteristics of the dredge on which it is used, the effective dredging depth, and the type of material being excavated. Among the various factors that must be considered when selecting a cutter are the number of cutter blades, the twist or curl of the blades, and the shape of the cutter relative to the length of the ladder and the depth of the project. For example, a cutter designed to dig at 10 m will not be as effective at 20 m, if used on the same ladder. Using an improperly designed cutter often requires thicker cuts to provide the suction with an adequate supply of material, thereby generating excessive levels of turbidity. Therefore, the cutter should be selected based on the requirements of a particular project.[22]

33. In an effort to maximize the efficiency of the cutter, several United States and foreign dredge manufacturers are developing and refining new cutter designs. In particular, the Canadian Government has developed a conical cutter, which apparently has a lower rim speed relative

to the typical basket cutter and may reduce the levels of cutter generated turbidity. Additional analyses of turbidity generation as a function of dredge production are now being performed.*

34. Cutter removal. In some cases where the material will flow naturally (i.e., noncohesive materials), the efficiency of the dredging operation can be increased by removing the cutter altogether. Since the suction can then be placed closer to the loose material, the suction's pickup capability increases and the dredge's production rate should improve; the amount of turbidity generated would also be reduced because there is no rotating cutter.[22]

35. Suction. The dredge's suction (Figure 2), which picks up the material that has been cut, can be partially responsible for turbidity generation around the cutter if the energy (i.e., head) provided to the suction by the dredge pump is not great enough to pick up all of the material disturbed by the cutter. In this situation, water-jet booster systems or ladder-mounted submerged pumps can be installed on cutterhead (or hopper) dredges at a considerable cost to increase the energy available for carrying the material and maintaining an adequate slurry velocity in the suction. This will enhance the dredge's pickup capability, increase the slurry density and potential production rate, and should decrease the generation of turbidity.[23,24]

36. Cutter-suction combination. On a typical cutterhead dredge, the cutter is turned by the cutter shaft; the suction pipe is mounted below the shaft. With this arrangement, the cutter must have a diameter that is approximately three to four times the diameter of the suction pipe. However, a new dredge may be designed so that the cutter is attached directly to the suction pipe and turned by the rotation of the suction pipe instead of the cutter shaft. According to Huston and Huston,[22] this system has several advantages. The size of the cutter can be reduced to about twice the diameter of the suction. This not only will increase the amount of force on the cutter blades without any

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*Personal Communication, 18 May 1978, C. G. Benckhuysen, Chief, Marine Equipment, Marine Directorate, Public Works, Canada, Ottawa, Ontario, Canada.

increase in the horsepower of the cutter motor, but also will reduce the distance between the suction mouth and the material being dredged. In addition, the shape of the suction will more closely approximate the ideal bell-shaped mouth, thereby reducing the amount of energy lost as the material enters the suction mouth. Finally, the cutter will more effectively feed material into the suction from the top, sides, and bottom rather than just from the bottom. Although all of these factors tend to enhance the pickup efficiency of the dredge and thereby reduce the amount of material subject to resuspension during an operation, the cutter-suction combination is rarely incorporated into new dredge designs.

37. Dredge production and efficiency. The profitability of a dredging operation depends largely on the production rate of the dredge itself; high production rates mean higher profits. However, where turbidity generation may be a potential problem, those operational parameters (e.g., cutter rotation rate, swing rate, and thickness of cut) affecting the generation of turbidity must be controlled relative to the dredge's production. Unfortunately, it is difficult to instantaneously measure a dredge's rate of production. Normally, the dredge operator or leverman can get some indication of production rate from the dredge's vacuum and pressure gauges. But these readings do not indicate slurry density or velocity, both of which are needed to determine the production rate of the dredge. By installing a production metering system,[25,26] production rate can be closely monitored relative to the dredge's operation. In addition, the manufacturers claim that these metering systems can improve production rates by 10 to 30 percent depending on the skill and experience of the leverman.

38. The method of swinging the dredge can also affect the dredge's production rate. Using a simple "stabbing" method (Figure 3), the dredge swings to the right with the starborad spud down and the port spud raised off the bottom. At the end of the cut, the port spud is lowered, the starborad spud raised, and the dredge swings to the left. In this manner the dredge swings from side to side and advances down the channel cutting a zigzag pattern of arcs leaving some areas undredged (i.e., windrows, Figure 3), and covering other areas twice at the end of

the swing. This method of advancing the dredge can be modified and the production rate increased substantially by using a spud carriage system (Figure 5)[27] or Wagger system (Figure 6),[28] which allow the dredge to advance to the end of each cut, thereby sweeping the cutter in a pattern of concentric arcs over the dredging site. With the spud carriage system the working spud is not permanently fixed to the dredge, but is mounted on a hydraulically powered carriage that moves along a slot at the stern of the dredge. The dredge advances as the working spud moves from position A to D (Figure 5); the walking spud at the stern is then dropped and the working spud is raised and repositioned at A. The Wagger system (Figure 6), developed by Daleeter Corporation, Lansing, Mich.,* consists of two pontoons linked by a steel truss and anchored by three spuds. A second truss that is connected to the stern of the dredge slides back and forth on top of the truss/pontoon section. By expanding and contracting the Wagger with hydraulic rams, the dredge advances over the dredging area. The point of connection between the upper truss and the dredge acts as a pivot point around which the dredge swings. The Wagger also eliminates the need for swing wires.

39. The efficiency of an operation can also affect its profitability. An inefficient operation can result in lower production rates, longer dredging operations, as well as excessive levels of turbidity. In addition to a well-designed dredging system, the efficiency of an operation can be improved by using other accessory equipment that has been developed over the last several years. Among these is the Hofer system that maintains the slurry velocity in the suction when the solids content becomes excessive. This prevents plugging of the pipeline and the costly delays that often result.[22] The efficiency and production of a dredge can also be enhanced by installing a gas removal system on the suction to remove any naturally generated gas from the dredged material slurry before it reaches the main pump.[15] Swell compensators and articulated ladders are also available for maintaining

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* For more information contact Mr. Lee Smith, Lee Power Equipment, Inc., Remus, Mich., 49340, 517-561-2270

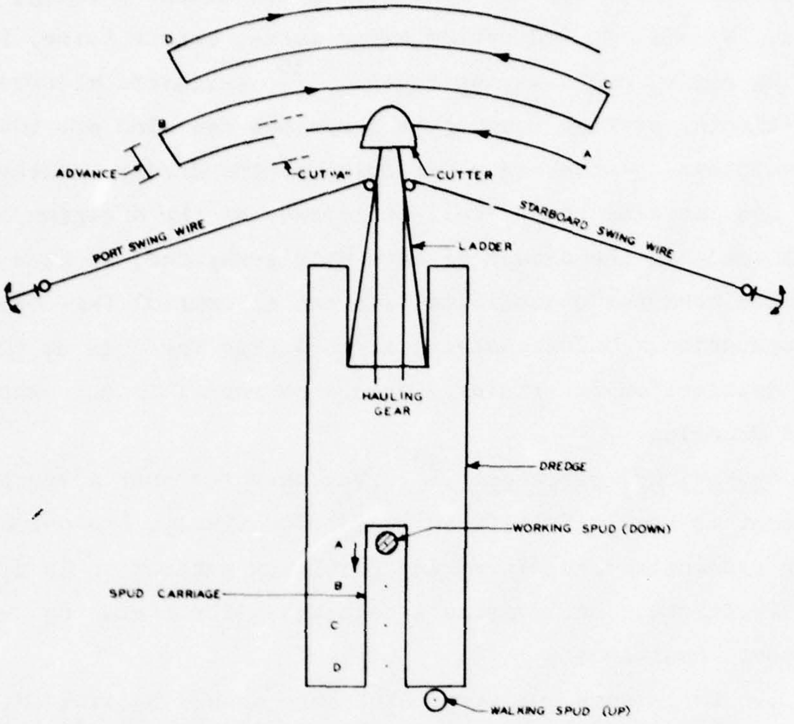

Figure 5. Cutterhead dredge with a spud carriage system (Adapted from Reference 27. Used courtesy of Symcon Marine Corp. and WODCON Assn.)

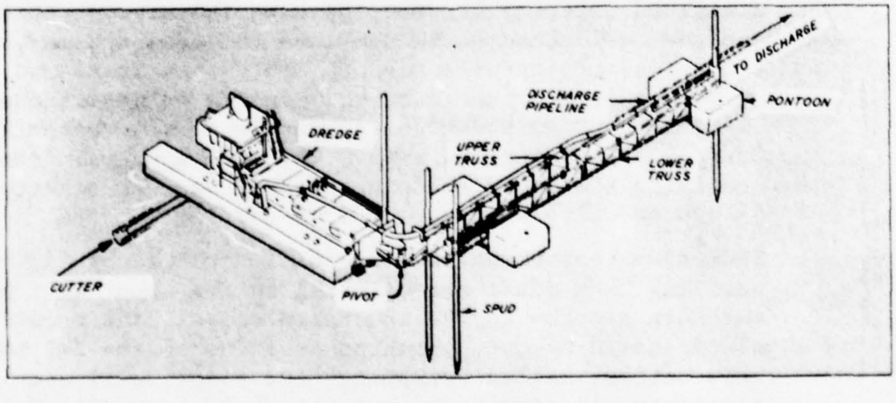

Figure 6. Wagger system. (Patent rights owned by Lee Power Equipment, Inc. Figure used through courtesy of Mr. Leward N. Smith.)

cutter contact with the bottom sediment in rough water. Electronic systems are also available for controlling the dredge's swing, cutter speed, etc., as well as indicating swing force, cutter force, ladder angle, swing angle, and dredging depth.[29,30] Automatic microwave or laser positioning systems[31] and gyro compasses can also provide assistance in maintaining accurate positioning of the dredge. Although this equipment can increase the overall efficiency of the dredging operation and aid in reducing the amount of turbidity generated, it does not eliminate the need for a qualified leverman to control the overall dredging operation. Unfortunately, at this time there is no formal course of instruction for training dredge personnel in the practical aspects of dredging.

40. Operational procedures.[22] Even when the most advanced dredging equipment is used, if it is not used effectively, its potential for increasing production and minimizing turbidity generation is greatly reduced. Therefore, the leverman's techniques for operating a dredge are of utmost importance:

a. Large sets and very thick cuts should be avoided, since they tend to bury the cutter and may cause high levels of turbidity 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 minimizes the formation of windrows or ridges of partially disturbed material between the cuts (Figure 3); 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. The specified slope should be cut by making a series of smaller boxes. This method, called "stepping" the slope, will not eliminate all sloughing, but will help to 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 prop wash 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 only be used where resuspension of the remaining material will not create serious problems.

f. The prop-wash 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 prop-wash cannot be eliminated, oversized tenders should not be used in shallow water areas.

g. In addition to prop-wash, significant resuspension of bottom material often occurs when the anchors used in support of the operation are dragged along the bottom when the dredge is 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.

## Hopper Dredges

41. In those areas characterized by heavy ship traffic or rough water, a self-propelled hopper dredge will probably be used. During a hopper dredge operation, as the dredge moves forward, the bottom sediment is hydraulically lifted from the channel bottom through a draghead, up the dragarm (i.e., trailing suction pipe), and temporarily stored in hopper bins in the ship's hull. Most modern hopper dredges have one or two dragarms mounted on the side of the dredge and have storage capacities ranging from several hundred to over 9000 cu m. The hoppers are either emptied by dumping the dredged material through doors in the bottom of the ship's hull or by direct pumpout through a pipeline.[15,21]

### Sources of turbidity

42. Resuspension of 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 prop wash, overflow of turbid water during hopper filling operations, and dispersion of dredged material during open-water disposal. This latter source of turbidity is discussed in great detail in the DMRP report entitled "Field Study of the Mechanics of the Placement of Dredged Material at Open-Water Disposal Sites."[7] Only the turbidity generated during the dredging operation will be discussed here.

43. The most obvious source of near-surface turbidity is the overflow water. During the filling operation dredged material slurry is often pumped into the hoppers after they have been filled in order to maximize the amount of higher density material in the hopper. The lower density, turbid water at the surface of the filled hoppers overflows and is usually discharged through ports located near the waterline of the dredge. Distributions of suspended solids in these overflow plumes are primarily dependent on the nature of the sediment being dredged; the design and operation of the dredge (such as forward speed and pumping rate); the nature, concentration, and volume of overflowed material; the locations of the overflow ports; and the hydrologic characteristics of the dredging site (such as water depth, salinity, and current direction and velocity). Although there may be no increase in the hopper load achieved by continued pumping of fine-grained sediment into filled hoppers,[32,33] overflowing is a common practice.

### Field measurements

44. Measurements of suspended solids concentrations in the vicinity of the hopper dredge CHESTER HARDING during a maintenance operation in San Francisco Bay indicated that a near-bottom turbidity plume of suspended dredged material extended up to 700 m downcurrent from the dredge.[16] In the immediate vicinity of the dredge a well-defined, upper plume was generated by the overflow process and a near-bottom plume by draghead resuspension; 300 to 400 m behind the dredge the two plumes merged into a single plume (Figure 7). As the distance from the

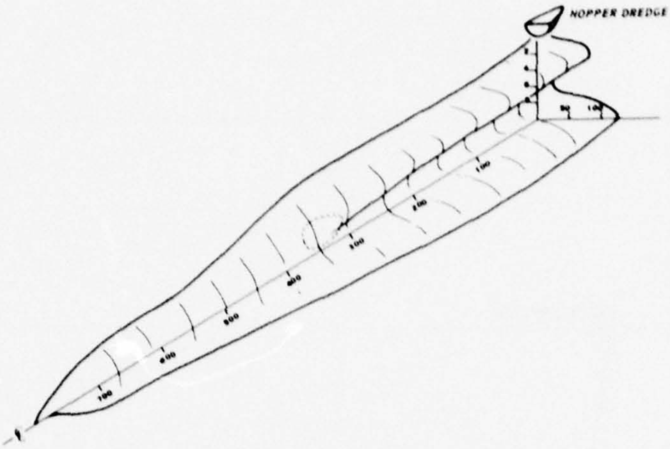

Figure 7. Hypothetical suspended solids plume downstream of a hopper dredge operation with overflow in San Francisco Bay. All distances in metres

dredge increased, the suspended solids concentrations in the plume generally decreased and the plume became increasingly limited to the near-bottom waters, although some surface discoloration was often evident along the entire length of the plume. Suspended solids concentrations in the upper and midwater column rarely exceeded several hundred milligrams per litre (relative to background concentrations of 31 to 35 mg/ℓ) except directly adjacent to the hopper dredge overflow ports where concentrations were as high as several grams per litre. Near-bottom plume concentrations were usually less than a few grams per litre relative to background concentrations of 38 to 123 mg/ℓ.

45. Near-surface suspended solids concentrations were also measured in the overflow plumes generated during maintenance operations by the MARKHAM in Saginaw Bay ship channel, Lake Huron,[34] and the GOETHALS in the Thimble Shoal Channel, Chesapeake Bay.[35] These plume measurements are summarized in Figure 8. In addition to the obvious exponentially decreasing levels of suspended solids with increasing distance from the dredge, the width of the near-surface plume behind the GOETHALS

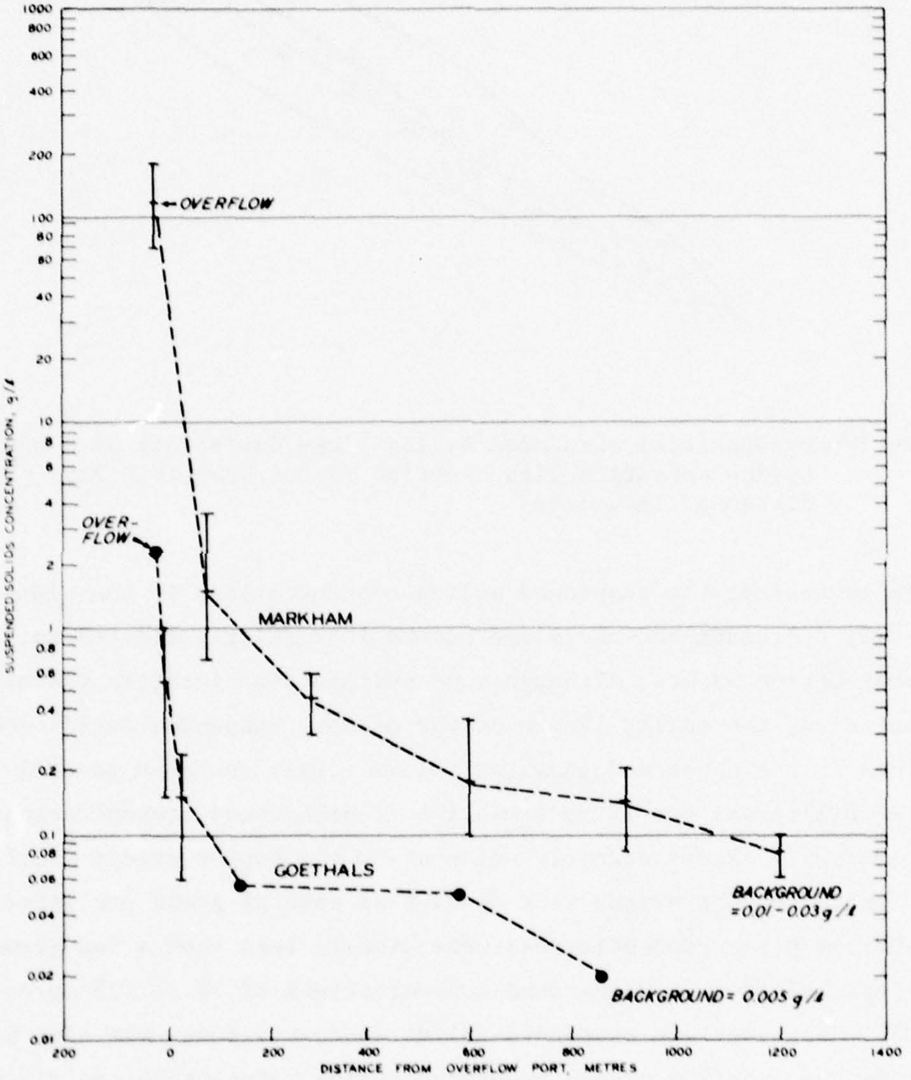

Figure 8. Relationship between concentration of suspended solids in the near-surface overflow plume and the distance (in metres) downstream of the overflow ports

increased with increasing distance from the dredge. This surface pattern resulted from lateral dispersion of the dredged material and attained a half-width of approximately 75 m at a distance of 900 m behind the dredge.

46. These data indicate that the suspended solids levels generated by a hopper dredge operation are primarily caused by hopper overflow in the near-surface water and draghead resuspension in near-bottom water. Suspended solids concentrations may be as high as several tens of grams per litre near the discharge port and as high as a few grams per litre near the draghead. Turbidity levels in the near-surface plume appear to decrease exponentially with increasing distance from the dredge due to settling and dispersion, quickly reaching concentrations less than 1 g/ℓ. However, plume concentrations may exceed background levels even at distances in excess of 1200 m.

### Turbidity control

47. Operational procedures. Examination of Figure 8 suggests that the levels of suspended solids in a plume generated by typical hopper dredge overflow can be decreased by reducing the solids concentration of the overflowed material. This can be accomplished by reducing the flow rate of the slurry being pumped into the hoppers during the latter phases of the hopper filling operation.[33] By using this technique, the solids content of the overflow can be decreased substantially (e.g., from 200 to 100 g/ℓ or less by weight[34]), while the loading efficiency of the dredge is simultaneously increased.

48. Flocculant injection. There have been several attempts made to increase the rate at which dredged material settles in the hoppers and simultaneously decrease the solids content of the overflow by injecting flocculants into the slurry prior to discharge into the hoppers or spraying flocculants into the filling hoppers.[36,37] Whereas these techniques are ineffective due primarily to the high solids content of the slurry, the settling rate of the suspended material in the overflow water may be increased somewhat by injecting polyelectrolytes (flocculants) into the overflow water before it is discharged overboard. During tests in Saginaw Bay ship channel, Lake Huron, polyelectrolytes were used to treat the overflow from the hopper dredge MARKHAM that had

a typical solids content of 100 g/ℓ or less. Average near-surface suspended solids concentrations in the plume at a distance of 1350 m from the dredge's overflow ports averaged 58 mg/ℓ (relative to average background concentrations of 24 mg/ℓ) and 36 mg/ℓ (relative to background values of 29 mg/ℓ) for untreated and treated conditions, respectively. Based on these data, treatment of the overflow may provide a marginal increase in the settling rate of the solids suspended in the overflow plume, thus reducing the levels of near-surface turbidity during hopper dredge overflow. For the dredging operation described above, the cost of flocculant addition per 10 cu m of overflow was approximately $0.24.[34]

### Submerged overflow system

49. To minimize the dispersion of the discharged overflow the Ishikawajima-Harima Heavy Industries Company, Ltd., Japan, in cooperation with Tokushu-Shunsetsu Company, Ltd., Japan, has developed a relatively simple submerged discharge system for hopper dredge overflow.[38] The overflow collection system in the dredge was streamlined to minimize the 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.

50. This modified overflow system has been successfully used on three Japanese trailing hopper dredges with capacities ranging from 2000 to 4000 cu m without generating any significant near-surface turbidity in the vicinity of the dredge. Suspended solids concentrations around a 2000 cu m hopper dredge with a conventional overflow system ranged from 10 to 1990 mg/ℓ above average ambient concentrations of 8 mg/ℓ, whereas with the submerged system solids concentrations were at most only 5 mg/ℓ above ambient levels of 7 mg/ℓ. The system can be incorporated into existing hopper dredges, hopper barges, and scows through simple modification of existing overflow systems. Symcon Marine Corporation (P.O. Box 1800, San Pedro, Calif. 90733) currently has the marketing franchise for this antiturbidity system in the United States.

## Agitation Dredging

51. Agitation dredging is often used in some parts of the country to deepen shallow channels or clean out low-density material from slips in harbor areas.[39] When this "dredging" technique is used, the bottom material is intentionally resuspended by prop wash,[40] dragging the bottom,[41] continuous hopper dredge overflow, or sidecasting.[42] The material is then transported downstream with the river current or outgoing tidal flow. Although this type of operation can be quite effective and economical, its use should be restricted to those areas where short-term exposure to high levels of suspended solids will not be detrimental.

## Unconventional Dredging Systems

52. Over the last few years several unconventional dredging systems have been developed in the United States and overseas to pump dredged material slurry with a high solids content and/or to minimize the generation of turbidity. Although an evaluation of their potential for reducing the generation of turbidity was beyond the scope of this study, seven unconventional systems are briefly described. Most of these systems are not intended for use on typical maintenance operations; however, they may provide alternative methods for unusual dredging projects (e.g., chemical "hot spots") when the capabilities of a particular system provide some advantage over conventional dredging equipment.

### Mud Cat

53. The Mud Cat (Mud Cat Division, National Car Rental System, Inc., P. O. Box 16247, St. Louis Park, Minn. 55416) is a relatively small, portable hydraulic dredge designed for projects where a 38- to 92-cu m/hr discharge rate is sufficient. Instead of the conventional cutter the Mud Cat has a horizontal cutterhead equipped with cutter knives and a spiral auger that cuts the material and moves it laterally toward the center of the auger where it is picked up by the suction (Figure 9).

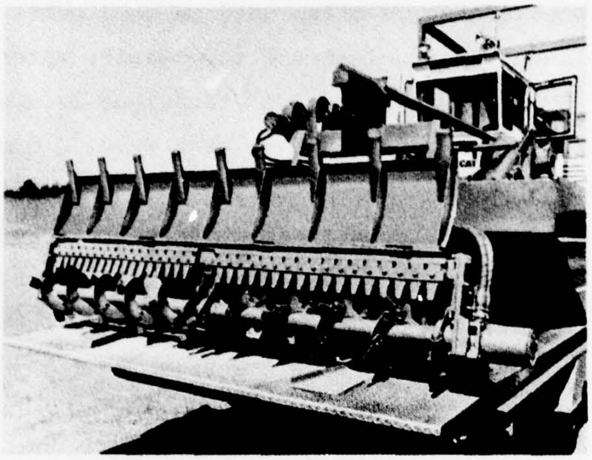

Figure 9. Horizontal cutterhead of the Mud Cat dredge showing cutter knives and spiral auger (Courtesy of MUDCAT Division National Car Rental Systems, Inc.)

This cutter can remove a layer of material 2.4 m wide and 0.4 m thick from water depths of 0.6 to 4.5 m leaving the dredged bottom flat and free of the windrows that are characteristic of the typical cutterhead dredging operation.

54. By covering the cutter/auger combination with a retractable mud shield the amount of turbidity generated by the Mud Cat's operation can be minimized. During one operation near-bottom suspended solids concentrations 1.5 m from the auger were usually slightly greater than 1 g/ℓ, relative to near-bottom background concentrations of 500 mg/ℓ. Surface and middepth concentrations measured 1.5 to 3.0 m in front of the auger were typically less than 200 mg/ℓ above background values of 40 to 65 mg/ℓ. In general, the turbidity plume was confined to within 6 m of the dredge.[43]

### Waterless dredge

55. Waterless Dredging Company (124 North 15th Street, Mattoon, Ill. 61938) has recently developed a dredging system where the cutter and a submerged centrifugal pump are enclosed within a half-cylindrical shroud. By forcing the cutterhead into the material, the cutting blades remove

the material near the front of the cutterhead with little entrainment of carrier water. According to the manufacturer, this system apparently is capable of pumping slurry with a solids content of 30 to 50 percent by weight with little generation of turbidity. Dredge (pipeline) sizes range from 15 to 30 cm.*

Delta dredge

56. *Delta Dredge and Pump Corporation* (11743 Lackland Road, St. Louis, Mo. 63141) has also developed a small portable dredge that apparently removes material at a high solids concentration using a submerged 30-cm (12-in.) pump coupled with two counter rotating, low speed, reversible cutters (Figure 10). According to the manufacturer, this equipment is capable of making a relatively shallow 2.3-m-wide cut without disturbing the surrounding material. For this reason, turbidity levels in the vicinity of the cutterhead are apparently low.[44]

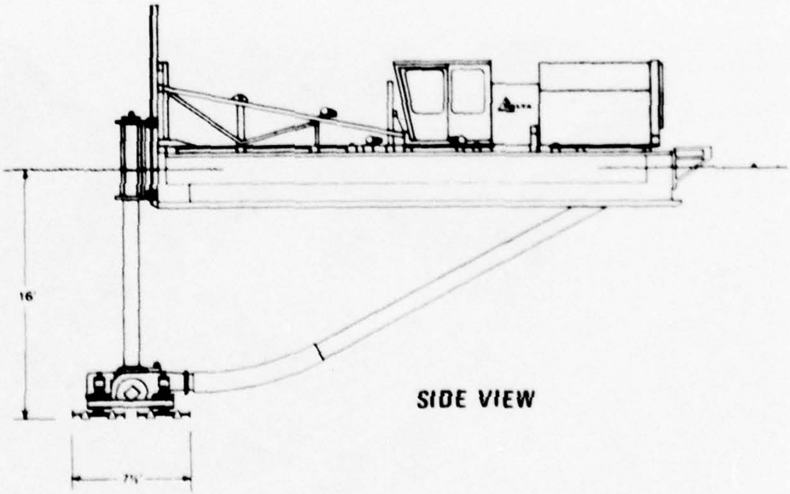

Figure 10. Delta dredge (Taken from Reference 44. Used courtesy of Symcon Marine Corp. and WODCON Assn.)

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* Personal Communication, 17 October 1977, Don Searles, Waterless Dredging Company, Mattoon, Ill.

Bucket wheel dredge

57. Ellicott Machine Corporation (Baltimore, Md.) has recently developed a unique bucket wheel excavator (Figure 11) as a means of improving the efficiency of the cutting operation. Because the cutting force is concentrated on a much shorter cutting edge, the bucket wheel has the capability of efficiently digging highly consolidated material. In addition, the material is force fed to the suction as the wheel turns, making it possible to control the solids content of the dredged material slurry by varying the rotation speed of the wheel. Theoretically, this bucket wheel not only accurately digs to a prescribed level, but also maximizes the pickup of the excavated material.[27]

Pneumatic pumping systems

58. Pneuma. The Pneuma system,[45,46,47] developed by SIRSI (Italian Corporation for the Research of Water Use), Florence, Italy, was the first dredging system to use compressed air instead of centrifugal motion to pump slurry through a pipeline. Although it has been used extensively on European and Japanese dredging projects, the Pneuma system has only been available in the United States since 1975 (through Pneuma North America, Inc., 823 Commerce Drive, Suite 230, Oak Brook, Ill.

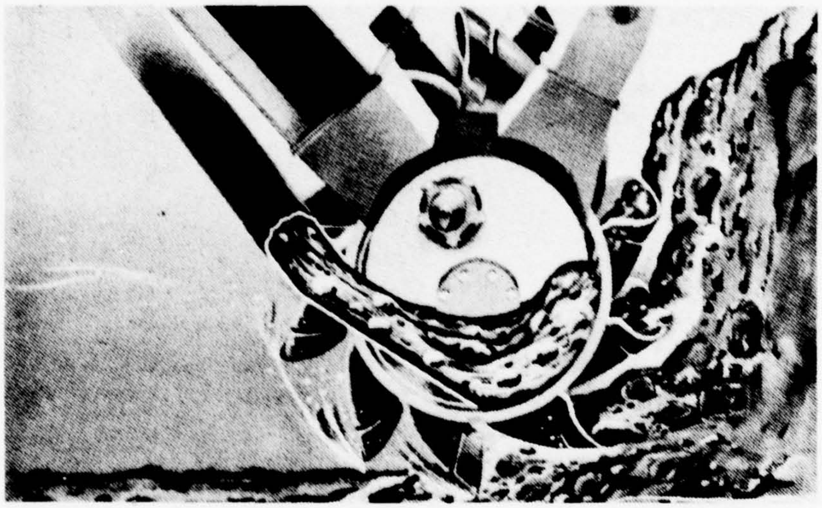

Figure 11. Bucket wheel dredge (Taken from Reference 27. Used courtesy of Symcon Marine Corp. and WODCON Assn.)

60521). According to the literature published by the manufacturer, this system can pump a slurry with a relatively high solids content with little generation of turbidity.

59. The Pneuma system consists of a pump body (composed of three cylinders), compressor, shovel, and a distributor system that automatically controls the supply of compressed air to the cylinders. When the pump is submerged, sediment and water are forced into one of the empty cylinders through an inlet valve (Figure 12). After the cylinder is filled, compressed air is forced into the cylinder closing the inlet valve and simultaneously forcing the material out of an outlet valve and into the discharge line. When the cylinder is empty, the air pressure is reduced to atmospheric pressure, the outlet valve closes, and the inlet valve opens. The two stroke cycle is then repeated. The distributor system controls the cycling phases of all three cylinders so there is always one cylinder operating in the discharge mode.

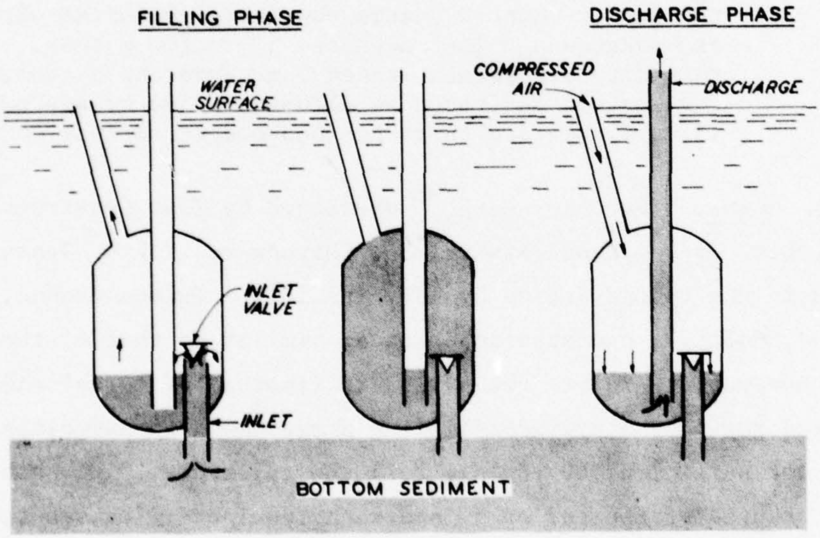

Figure 12. Operating principle of the pneumatic pump (Courtesy of Pneuma North America, Inc.)

60. Depending on the material being dredged and the mode of operation, the three cylinders of the Pneuma system can be arranged in various ways with different shovel attachments. The frontal shovels are

normally equipped with cutting grills that facilitate penetration into compact bottom sediment. The system has been used in water depths of 50 m; however, 100- to 200-m depths are theoretically possible. Depending on the size of the particular Pneuma pump used, production rates can range from 40 to 2000 cu m/hr. The pump can be deployed from a land-based or floating crane, pulled through the sediment in a trailing position, or attached to a dredging ladder.

61. According to unpublished data, the amount of resuspension generated by the Pneuma system is also apparently minimal.

a. 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 the bottom, respectively, approximately 5 m in front of a 300/60 Pneuma pump mounted on a ladder. Turbidity levels 30 m from the system appeared to remain within the general background range of 1 to 3 mg/ℓ.

b. During a second maintenance operation at Kita Kyushu City, Kokura, 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 turbidity measurement taken 1 m above the bottom, 5 m from the system, indicated an elevated value of approximately 13 mg/ℓ relative to background concentrations of 6 mg/ℓ.

62. Oozer. The Oozer pump,[48] developed by Toyo Construction Company, Ltd. (3-7-1 Kanda Nishikicho, Chiyoda-ku, Tokyo, Japan, and marketed in the United States by TJK, Inc., 7407 Fulton Avenue, N. Hollywood, Calif.), operates in a manner similar to that of the Pneuma 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. 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 (i.e., the thickness of 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. Based on production records, the larger Oozer system has an approximate dredging capacity ranging

from 300 to 500 cu m/hr. During one operation suspended solids levels within 3 m of the dredging head were all within background concentrations of less than 6 mg/ℓ. Dredging costs (excluding disposal) using the Oozer system are approximately $6 to $7/cu m.*

63. Mudlark. The Mudlark is another type of pneumatic pump that has been developed to transport dredged material. Similar to the Oozer, it has two chambers that are alternately phased; however, with this system compressed air drives a piston that pumps the slurry.

### Clean Up system

64. To avoid the sediment resuspension typical of a cutterhead dredge, TOA Harbor Works (TOA Kensetsu Kogyo Company, Ltd., 5 Yobancho, Chiyoda-ku, Tokyo, Japan) has also developed a unique Clean Up system for dredging highly contaminated sediment.[49,50] The Clean Up head consists of a shielded auger that collects sediment as the dredge swings back and forth and guides it toward the suction of a submerged centrifugal pump (Figure 13). To minimize sediment resuspension, the auger is shielded and a movable wing covers the sediment as it is being collected by the auger. Any gas that is released from the sediment is trapped by a shroud and vented to the surface where it is collected. Sonar devices on both sides of the head indicate the elevation of the bottom in front of and behind the head; an underwater television system also indicates the amount of material being resuspended during a particular operation. During one dredging operation suspended solids concentrations around the Clean Up head ranged from 1.7 to 3.3 mg/ℓ at the surface and 1.1 to 7.0 mg/ℓ 3 m above the suction equipment relative to background near-surface levels of less than 4 mg/ℓ.

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* Personal Communication, 15 December 1977, Hyman Fine, Civil Engineer U. S. Army Engineer District, Norfolk, Norfolk, Va.

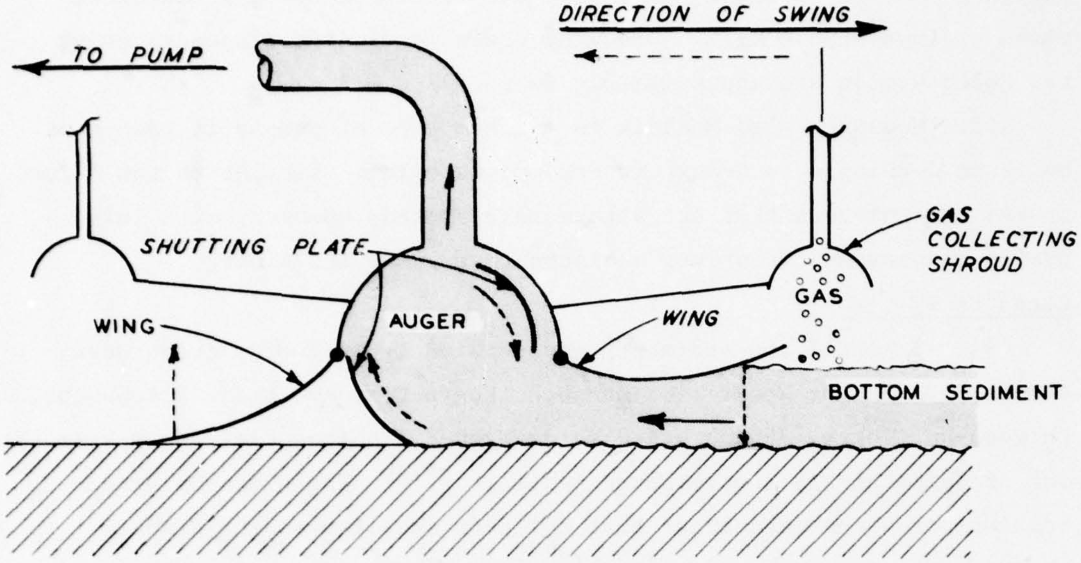


Figure 13. Cross-sectional view of the cutterhead of the Clean Up system (Redrawn from References 49 and 50. Used courtesy Symcon Marine Corp. and WODCON Assn.)

## Dredge Selection

65. When considering an upcoming dredging operation, the project engineer may be faced with the problem of selecting the "best" dredge based on the cost and availability of different dredges, the operating conditions at the project site, the material to be dredged, the job specifications, and various environmental considerations.[51] According to a comparison of conventional dredges by Wakeman, Sustar, and Dickson,[52] "the cutterhead dredge seems to have the least effect on water quality during the dredging operation. This is followed by the hopper dredge without overflow. The clamshell dredge and hopper dredge during overflow periods both can produce elevated levels of suspended solids in the water column." Although this may be true under a given set of environmental conditions, the variability between different sites, material types, dredge sizes and capabilities, as well as perator performance and training makes it difficult to compare different types of dredges.

66. Unfortunately, since each dredging/disposal project is site specific, a dredge that may be ideal in one situation may not be suitable for another. The production rate of a given dredge relative to the levels of turbidity that may be generated, the duration of the project, and the background conditions should all be considered when evaluating the potential impact of different sizes and types of dredges. It is also important to remember that a sophisticated and expensive dredging system will not necessarily eliminate all environmental impacts associated with dredging operations. In addition, it is imperative to concurrently consider the compatibility of all the components of the dredging operation, including excavation, transportation, treatment, and disposal, as a total integrated system and not as separate components. The relative impact of each operation must be objectively evaluated relative to its cost and overall benefits.

## PART III: PREDICTION OF DREDGED MATERIAL DISPERSION: OPEN-WATER PIPELINE DISPOSAL OPERATIONS

67. During the maintenance dredging of channels located in rivers and estuaries, fine-grained dredged material is typically disposed within designated open-water or side-channel disposal areas located 300 to 1,000 m from the channel in water depths of 1 to 6 m. On most large maintenance operations, a cutterhead dredge may be used to excavate the sediment, which is subsequently pumped as a slurry through a pontoon-supported pipeline at velocities of 4 to 6 m/sec to a disposal area adjacent to the channel (Figure 14). Due to the variability in depth of cut, rate of swing, and stepping technique used on a particular operation, the dredged material slurry will usually have a highly variable solids content ranging from 0 to 40 percent solids by weight; 15 percent solids by weight is a typical average value. Dissolved oxygen levels in the fine-grained slurry are essentially zero. The end of the pipeline may be either above water or submerged at an angle of 0 to 90 deg relative to the water surface and may be equipped with a

Figure 14. Typical channel maintenance dredging operation with open-water pipeline disposal

deflector plate. As the dredge advances down the channel the discharge point is usually moved periodically to other disposal areas adjacent to the channel. The dredging operation is normally continuous, but may be interrupted by mechanical breakdown, ship traffic, or bad weather.

## Modes of Dredged Material Dispersal

68. The discharged dredged material slurry is generally dispersed in three modes. Any coarse material, such as gravel, clay balls, or coarse sand, will immediately settle to the bottom of the disposal area and usually accumulate directly beneath the discharge point. The vast majority of the fine-grained material in the slurry also descends rapidly to the bottom where it forms a low gradient circular or elliptical fluid mud mound.[13] A small percentage (1 to 3 percent) of the discharged material is stripped away from the outside of the slurry jet as it hits the water surface and descends through the water column[53] and remains suspended in the water column as a turbidity plume. These latter two forms of dredged material dispersal will be evaluated in more detail in the following discussion.

## Turbidity Plumes

### Plume characteristics[13,53]

69. The levels of suspended solids in the water column above the fluid mud layer generally range from a few tens of milligrams per litre to a few hundred milligrams per litre. Concentrations rapidly decrease with increasing distance downstream from the discharge point (Figure 15) and laterally away from the plume center line due to settling and horizontal dispersion of the suspended solids. Since solids concentrations in the plume often increase with increasing depth, the plume boundaries may be more distinct in the near-bottom portions of the water column. Under tidal conditions, the plume will extend inland during the incoming (flood) tide and seaward during the outgoing (ebb) tide. The plume length will usually be only slightly longer than the maximum distance of

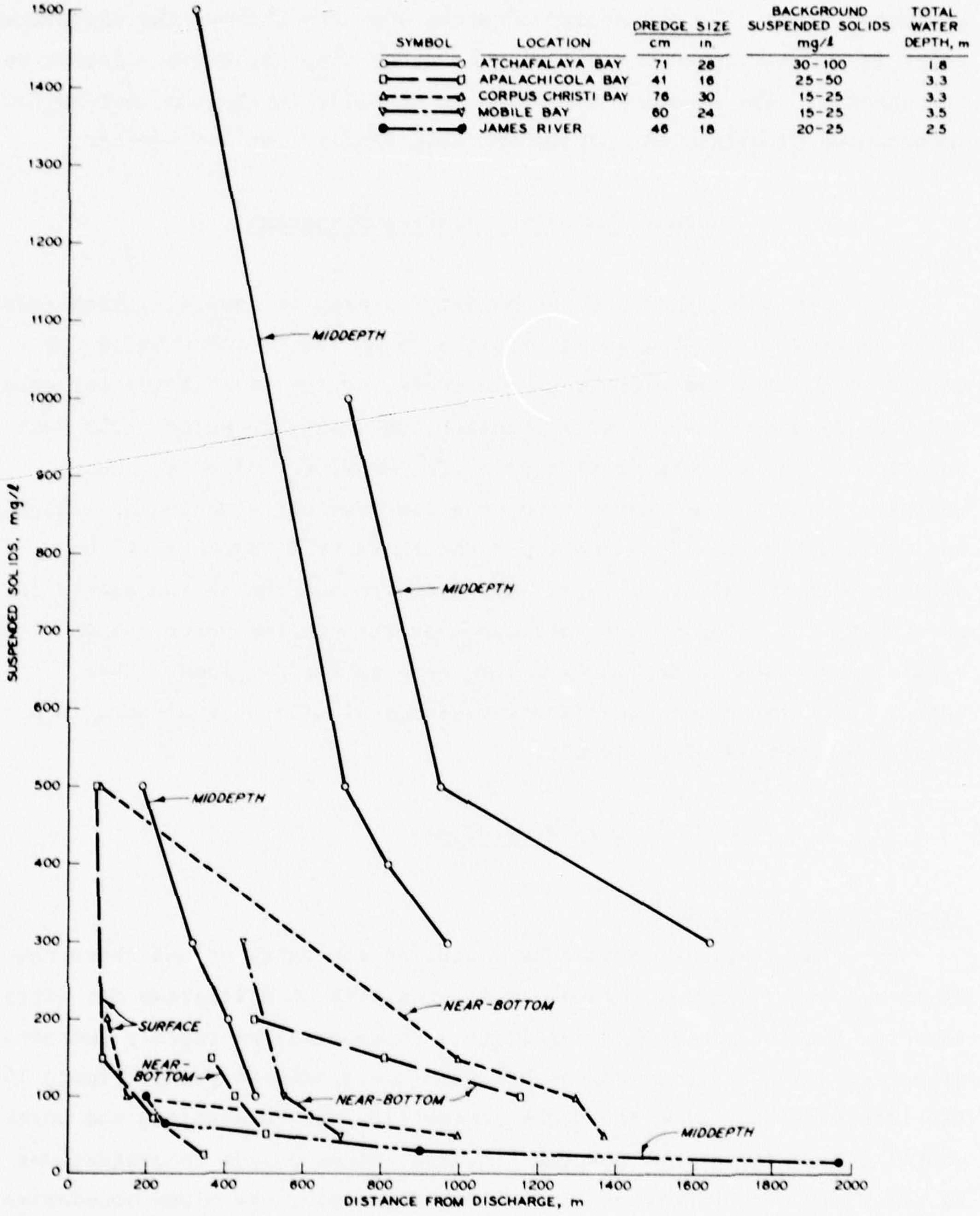


Figure 15. Relationship between suspended solids concentration along the plume center line and distance downcurrent from several open-water pipeline disposal operations measured at the indicated water depths

one tidal excursion (i.e., the distance that the suspended sediment is transported during an ebb or flood tide). In other words, as the tide changes direction a new plume will form downcurrent from the discharge point and will be superimposed on the older plume formed during the last tidal cycle; the new plume will continue to grow until the tide again changes direction. In rivers where the flow is unidirectional, the plume length is controlled by the strength of the current and the settling properties of the suspended material. In both estuarine and riverine environments the natural levels of turbulence and the fluctuations in the rate of slurry discharge will usually cause the idealized teardrop-shaped plume to be distorted by gyres or eddylike patterns (Figure 16).

### Factors controlling plume characteristics

70. The large degree of variability characteristic of most turbidity plumes can be traced to several major factors: the discharge rate, character of the dredged material slurry, water depth, hydrodynamic regime, and discharge configuration. The first four factors will be discussed below and used as input for a relatively simple plume model; the discharge configuration and its affect on slurry dispersal will be discussed in Part IV.

71. Particle settling rates. The nature and persistence of turbidity plumes are controlled largely by the settling rates of the material suspended in the water column. Low concentrations of silt and clay (with diameters of less than 0.03 mm) settle very slowly causing large, persistent turbidity plumes. Under certain conditions clay particles may collide to form aggregates or flocs with diameters of 0.1 to 2 mm. If the suspended particles are coarse-grained or composed of large flocs, they will settle relatively rapidly; the suspended solids concentrations in the resulting plume will be relatively low and decrease very rapidly with distance from the discharge point.

72. Turbidity plumes will be relatively persistent in fresh water, because fine-grained particles at low concentrations do not readily form flocs.[54] However, the degree of flocculation increases very rapidly as salt concentrations increase from 0 to 10 g/ℓ and remains essentially

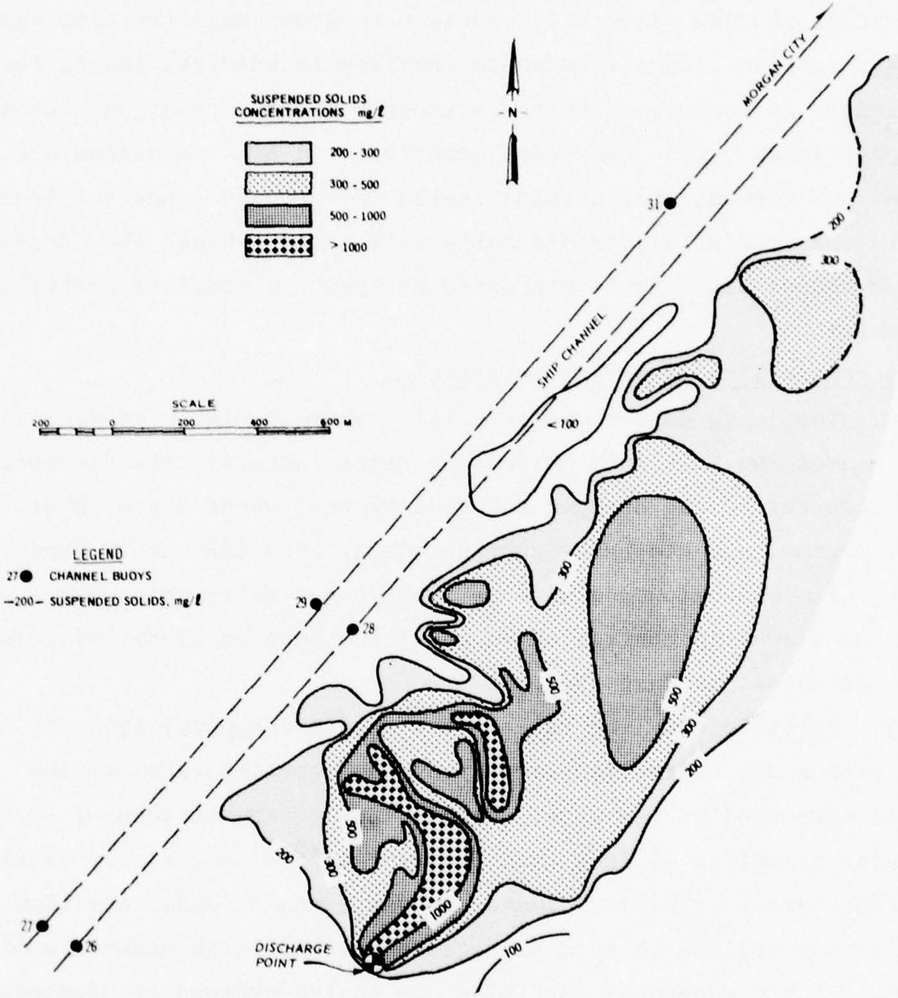


Figure 16. Middepth (0.9 m) turbidity plume generated by a 71-cm (28-in.) pipeline disposal operation in the Atchafalaya Bay. Current flow is generally toward the northeast

constant between concentration of 10 g/ℓ and seawater concentrations of 35 g/ℓ.[12] The clay mineralogy of the dredged sediment may exert a subtle influence on settling behavior but its importance is relatively small due to the presence of naturally occurring organic material which apparently coats the clay particles. In fact, in salt water the settling rate of the suspended material generally increases as the organic content increases.[54] Regardless of the sediment/water composition, settling rates generally increase with increasing solids concentrations up to approximately 10 to 20 g/ℓ;[11,12,54] at higher solids concentrations the particle settling rates are "hindered" or reduced due to contact with adjacent sediment particles or flocs.

73. Effect of various factors on plume characteristics. The particle settling rates, slurry discharge rate, water depth, current velocities, and the diffusion velocity (describing horizontal dispersion) all interact to control the characteristics of the turbidity plume during the disposal operation.[53] As the current velocity increases, the plume (as defined by a specified level of suspended solids in excess of background) will grow longer. With increasing depth of water in the disposal area, the average concentration of suspended solids in the plume will tend to decrease. As the dredge size increases or particle settling rates decrease, the plume size and suspended solids concentrations will tend to increase. In addition, as the diffusion velocity increases for a given current velocity, the plume becomes longer and wider, while the solids concentrations in the plume decrease. (However, if there is no resuspension of bottom sediment, the total amount of solids in the plume will remain the same.) Finally, with a decrease in diffusion velocity or particle settling velocity, or an increase in water depth, the length of time required for the plume to dissipate after the disposal operation has ceased will increase.

### Turbidity plume model[53]

74. A simple method for predicting plume characteristics has been developed based on a theoretical hydraulic model. This model has subsequently been verified and empirically refined using field data collected around three typical open-water pipeline disposal operations in estuarine

environments. Only six input parameters are necessary: the size of the dredge, water depth and average current velocity in the disposal area, mean diameter or settling velocity of the sediment being dredged, an estimate of the diffusion velocity, and the "age" of the plume. The model will provide an approximate "worst case" prediction of the shape and dimensions of the plume, the corresponding average excess concentration of suspended solids (above background) along the plume center line as a function of distance from the discharge point, and the persistence of the plume after the disposal operation has ceased. Factors such as discharge configuration, waves, and wind, although important, are not considered in the model due to their complex and quantitatively unpredictable effect on the plume characteristics.

75. *Procedure*. The following stepwise procedure indicates how the six input parameters are used to calculate several nondimensional variables that are plotted on the accompanying nomographs. The nondimensional numbers are then converted to physical units of metres and milligrams per litre using distance and concentration scaling factors, respectively.

*a*. *Determine the amount of material that will remain suspended in the water column (q)*: q is at most 5 percent of the total quantity of material discharged by the dredge (Q) where:

$$Q(\text{g/sec}) = \underset{\text{area}}{\text{pipeline}}\ (\text{cm}^2) \times \underset{\text{velocity}}{\text{flow}}\ (\text{cm/sec}) \times \begin{array}{l}\text{solids con-}\\ \text{tent of}\\ \text{slurry }(\text{g/cm}^3)\end{array} \qquad (1)$$

$$\text{Therefore:}\quad \begin{array}{l} q(\text{g/sec}) = 0.05 \times Q(\text{g/sec}) \\ \text{Convert } q \text{ to mg/sec.}\end{array} \qquad (2)$$

If the silt/clay content is less than 5 percent, use that fractional amount instead of 0.05.

*b*. *Determine the average vertical thickness of the plume (D)*:

D(cm) = one-half the average depth of the water in the disposal area for depths less than 8 m.

*c*. *Determine the rate of horizontal spread of the plume*: This rate is controlled by the diffusion velocity ($\omega$), which is estimated based on the following average values:

| Environment | $\omega$ (cm/sec) |
|---|---|
| Lakes and rivers | 0.3 |
| Medium estuaries<br>(e.g., Corpus Christi Bay) | 1.0 |
| Large estuaries<br>(e.g., Chesapeake Bay) | 1.4 |

d. Determine the mean particle settling velocity ($v_s$). A size analysis of a typical sediment sample from the dredging site should be performed using disposal site water; no dispersing agent should be used. From the size data determine the mean diameter of the sediment. The mean particle settling velocity $v_s$ (cm/sec) can then be approximated using Figure 17.

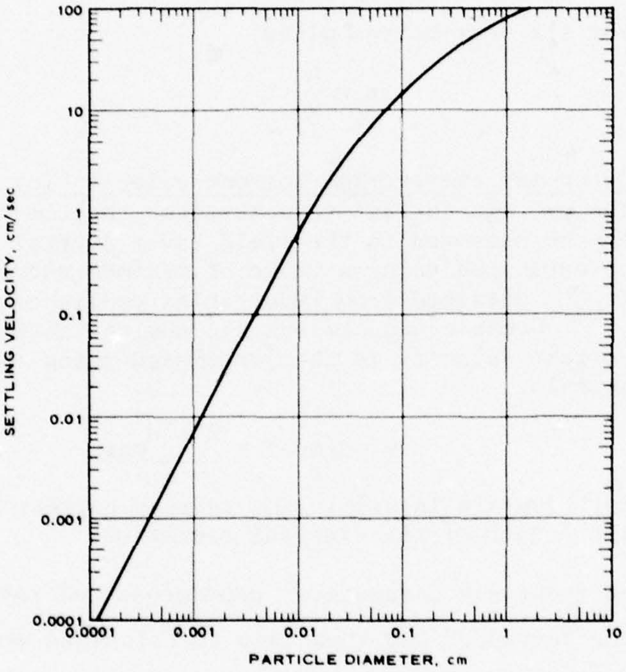


Figure 17. Settling velocity versus mean particle diameter

e. Determine the age of the plume (t): The age of the plume is the time (t) that is required for the plume to reach its maximum length. In an estuary, where the current reverses direction, this will occur at the end of an ebb or flood tide. In those estuaries where there are two high and two low tides/day the age of the plume is:

$$t(\text{sec}) = 6\ \text{hr} = 2.16 \times 10^4\ \text{sec} \approx 2 \times 10^4\ \text{sec} \quad (3)$$

Where there is one high and one low tide per day:

$$t(\text{sec}) = 12\ \text{hr} \approx 4 \times 10^4\ \text{sec} \quad (4)$$

In rivers the flow is unidirectional; therefore, plume age is defined as the length of time that is required for a particle with a settling velocity ($v_s$) to settle a specified vertical distance relative to the depth of water (D). The surface plume will probably not be visible after the suspended particles have settled approximately 10 cm below the surface; therefore, for the surface plume:

$$t = \frac{10\ \text{cm}}{v_s} \quad (5)$$

For the near-bottom plume:

$$t = \frac{D}{v_s} \quad (6)$$

f. Determine the average current velocity (u): For estuaries the everage current velocity over the time interval t can be measured in the field (over several tidal cycles) or estimated using a value of maximum current velocity ($u_{max}$) obtained from tide tables published by the National Oceanic and Atmospheric Administration. The average current velocity is then estimated using the following formula:

$$u(\text{cm/sec}) = \frac{2 \times u_{max}}{\pi} \quad (7)$$

For rivers u is simply the average current velocity over the length of the disposal operation.

76. Knowing these six parameters, nondimensional ratios and scaling factors can be developed and then used to calculate worst case estimates of vertically averaged suspended solids concentrations (above background) along the plume center line as a function of distance from the discharge point.

a. Determine the value of $\frac{\omega}{u}$.

b. Determine the value of $\gamma$ where:

$$\gamma = \frac{v_s t}{D} \quad (8)$$

and round off to 0.1, 1, 3.2, or 10.

c. Determine the Distance Scaling Factor (DSF):

$$\text{DSF(cm)} = ut \qquad (9)$$

d. Determine the Concentration Scaling Factor (CSF):

$$\text{CSF(mg/cc)} = \frac{q}{\pi\omega^2 Dt} \qquad (10)$$

e. Enter Figure 18 at the calculated value of $\omega/u$, move up to the appropriate $\gamma$ curve, and then over to the left-hand (vertical) scale to obtain the value of

$$\frac{\text{Concentration (mg/}\ell\text{) at distance ut}}{\text{CSF}}$$

Knowing this value and CSF, the concentration at distance ut can then be calculated.

f. To determine the distance X (cm) downstream of the discharge point where the plume center line concentration will be a specified Y (mg/ℓ), above background,

(1) Calculate:

$$\frac{\text{Y (mg/}\ell\text{)}}{\text{Concentration at distance ut (Step e)}};$$

(2) Using this ratio enter Figure 19, 20, 21, or 22, depending on value of $\gamma$, along the left-hand scale.

(3) Move horizontally to the $\omega/u$ curve closest to the value calculated in Step a and down to the lower scale. Obtain a value for $\frac{\text{Distance X}}{\text{DSF}}$ where the average concentration will be Y (mg/ℓ).

(4) This value of $\frac{\text{Distance X}}{\text{DSF}}$ multiplied by the DSF is equal to Distance X.

g. To determine the concentration Y (mg/ℓ) above background at a specified distance X (cm) downstream from the discharge point,

(1) Calculate: $\frac{\text{Distance X}}{\text{DSF}}$

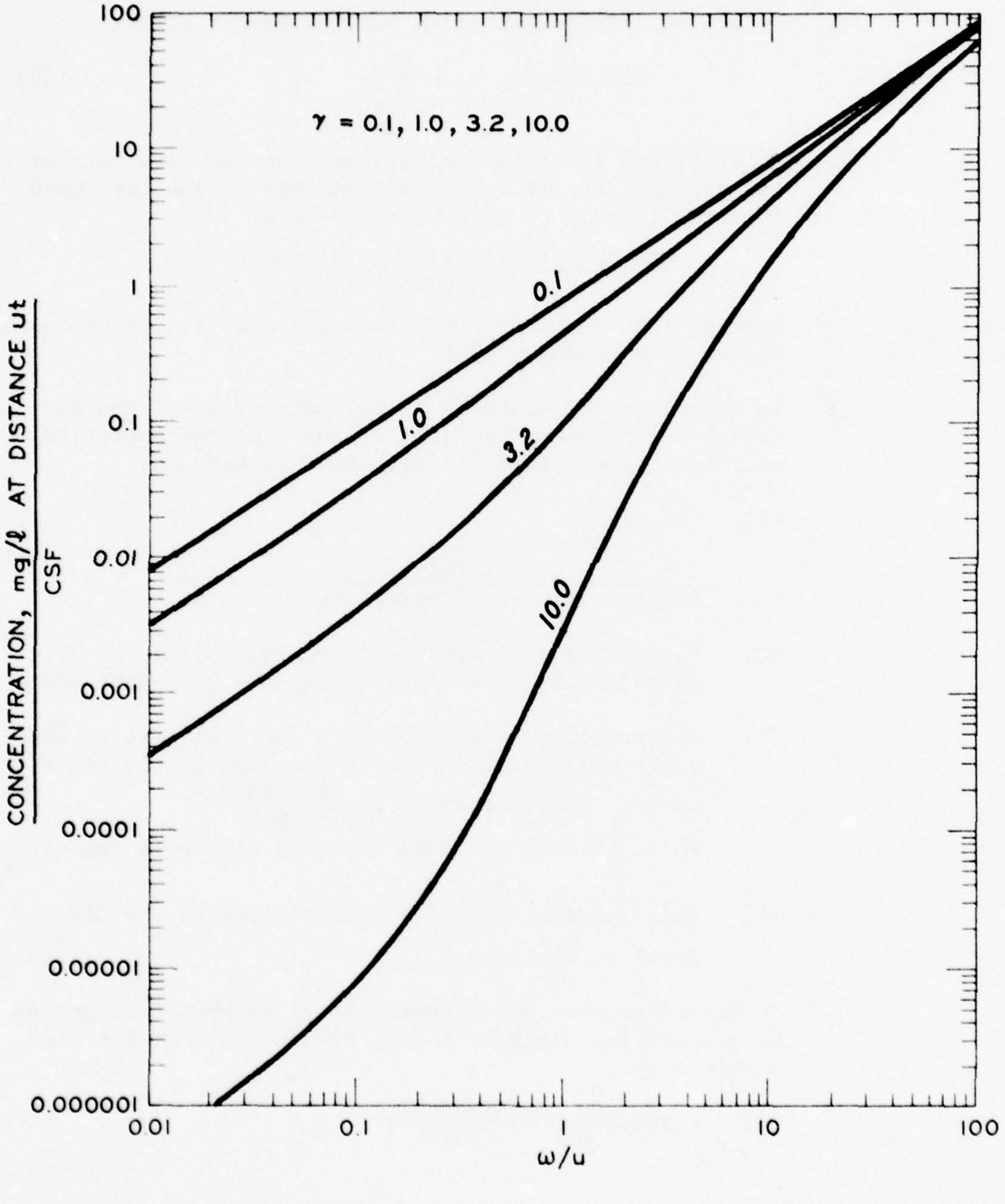


Figure 18. Relationship between ω/u and $\frac{\text{Solids concentration at distance ut}}{\text{CSF}}$ for γ = 0.1, 1, 3.2, and 10

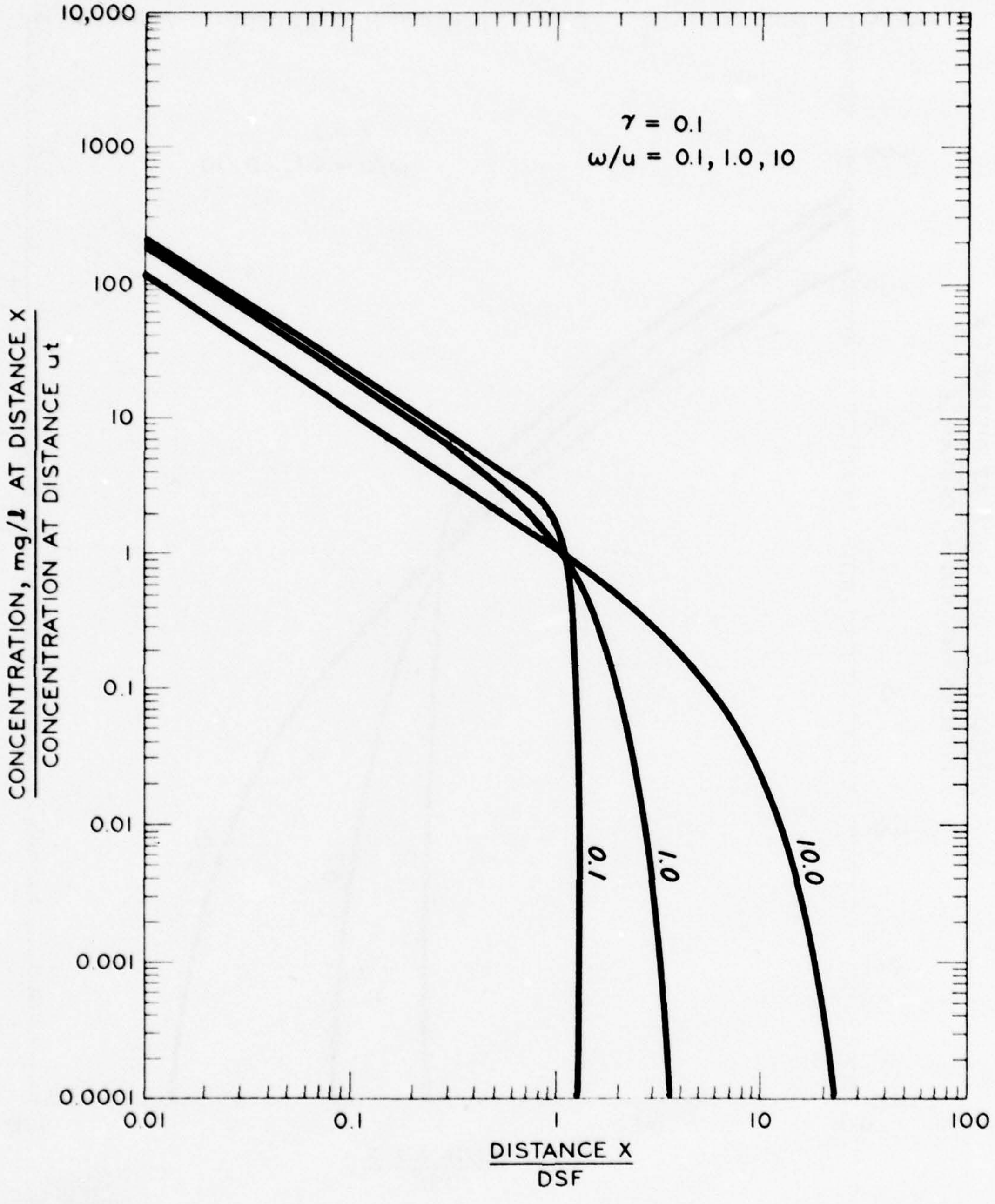


Figure 19. Relationship between $\frac{\text{Distance X}}{\text{DSF}}$ and $\frac{\text{Solids concentration at distance X}}{\text{Solids concentration at distance ut}}$ for ω/u equal to 0.1, 1, and 10 and $\gamma = 0.1$

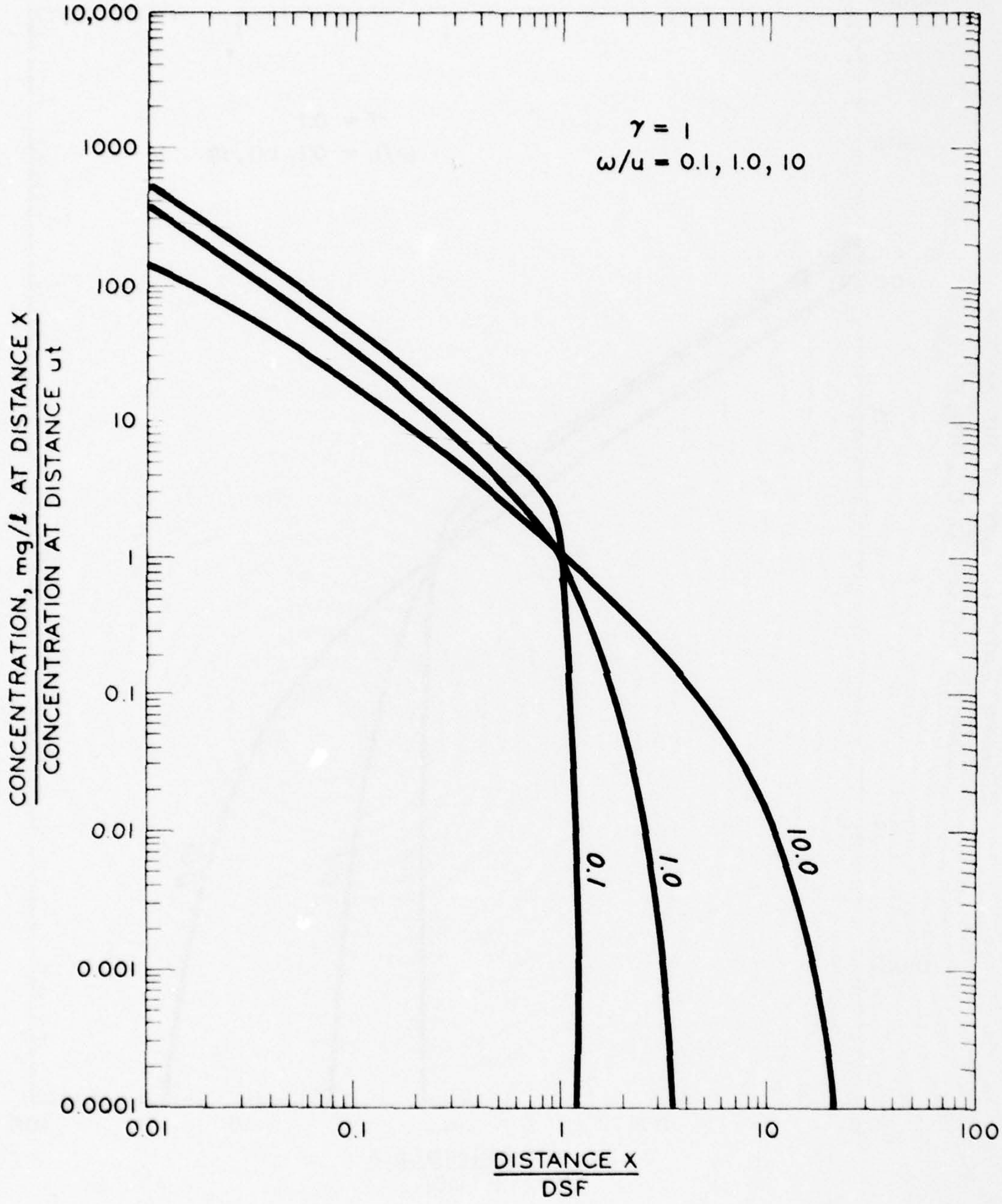


Figure 20. Relationship between $\frac{\text{Distance X}}{\text{DSF}}$ and $\frac{\text{Solids concentration at distance X}}{\text{Solids concentration at distance ut}}$ for ω/u equal to 0.1, 1, and 10 and γ = 1

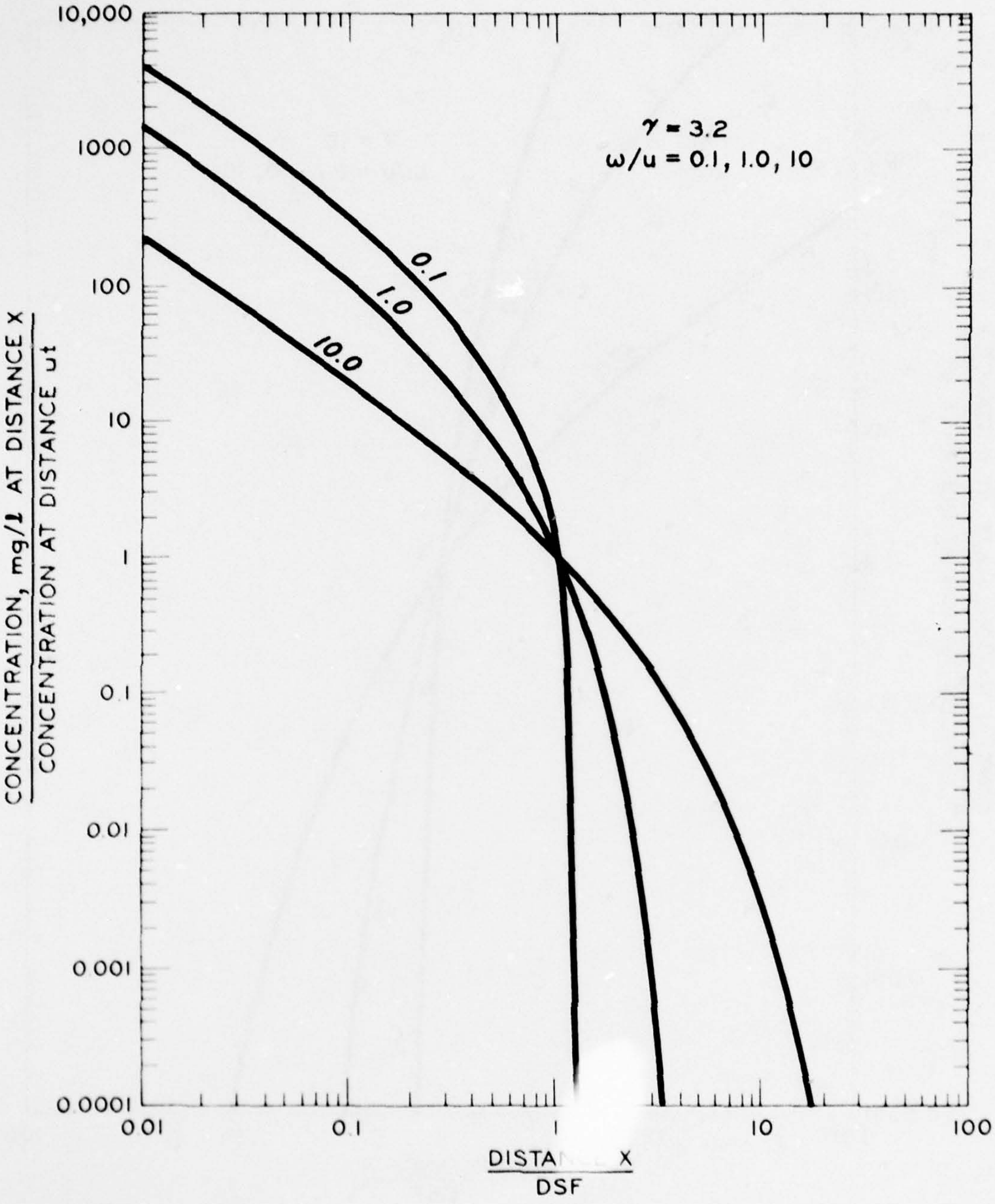


Figure 21. Relationship between $\frac{\text{Distance X}}{\text{DSF}}$ and $\frac{\text{Solids concentration at distance X}}{\text{Solids concentration at distance ut}}$ for ω/u equal to 0.1, 1, and 10 and γ = 3.2

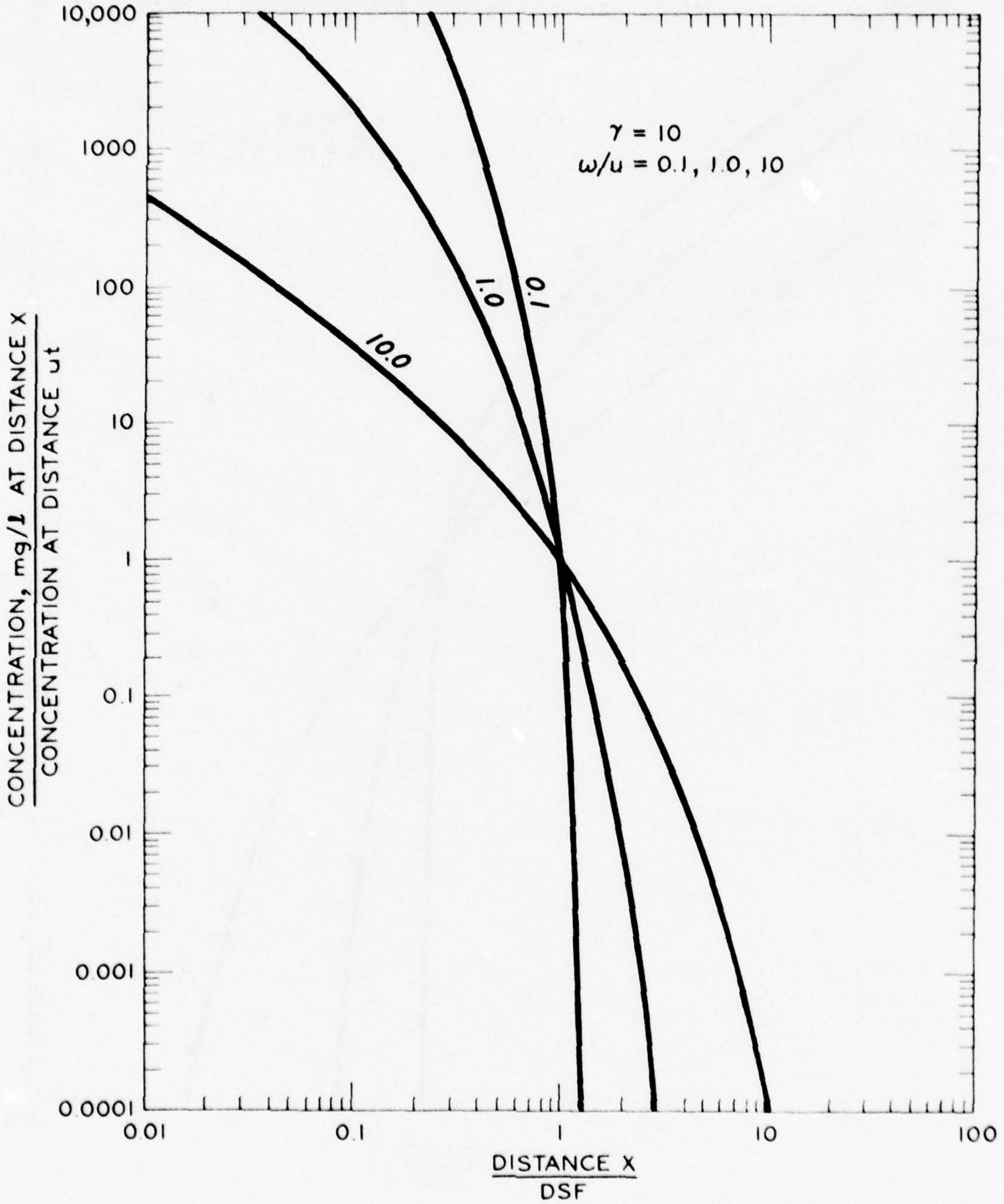


Figure 22. Relationship between $\frac{\text{Distance X}}{\text{DSF}}$ and $\frac{\text{Solids concentration at distance X}}{\text{Solids concentration at distance ut}}$ for ω/u equal to 0.1, 1, and 10 and γ = 10

(2) Using this ratio enter Figure 19, 20, 21. or 22, depending on the value of $\gamma$, along the horizontal axis.

(3) Move vertically upward to the appropriate $\omega/u$ curve, then horizontally across to the vertical axis. Obtain a value for $\frac{\text{Concentration at distance X}}{\text{Concentration at distance ut}}$.

(4) This ratio multiplied by the concentration at ut (Step e) gives the average center line concentration at distance X.

h. To determine the approximate maximum width of the plume (which occurs at an approximate distance ut) as specified by a solids concentration above background, multiply the center line length of the plume (as defined by that concentration) by the appropriate factor listed below for the respective $\omega/u$ values.

| $\omega/u$ | Width factor |
|---|---|
| 0.1 | 0.25 |
| 0.3 | 0.6 |
| 1.0 | 1.3 |

i. Idealized plume shapes generated by the model are shown in Figure 23 for various hydrodynamic conditions. For values of $\omega/u$ less than 0.1 the plume width will be less than 0.25 times the length. As $\omega/u$ increases beyond 1.0 the plume will approach a circular "patch" shape centered on the discharge point. Plume shapes are similar for different values of $\gamma$.

77. Example. To illustrate the use of this model the following example is given.

a. Operation : (1) 61-cm (24-in.) pipeline with a radius = 30 cm

(2) Velocity = 549 cm/sec (18 ft/sec)*

(3) Solids content = 15 percent solids by weight*

$$Q = \pi(30)^2 \times 549 \times 0.15 = 2827 \text{ cm}^2 \times 549 \times 0.15 = 232{,}803 \text{ g/sec}$$

$$q = 232{,}803 \times 0.05 = 11{,}640 \text{ g/sec} = 11.6 \times 10^6 \text{ mg/sec}$$

---

* These approximate values may be used if better estimates are not available.

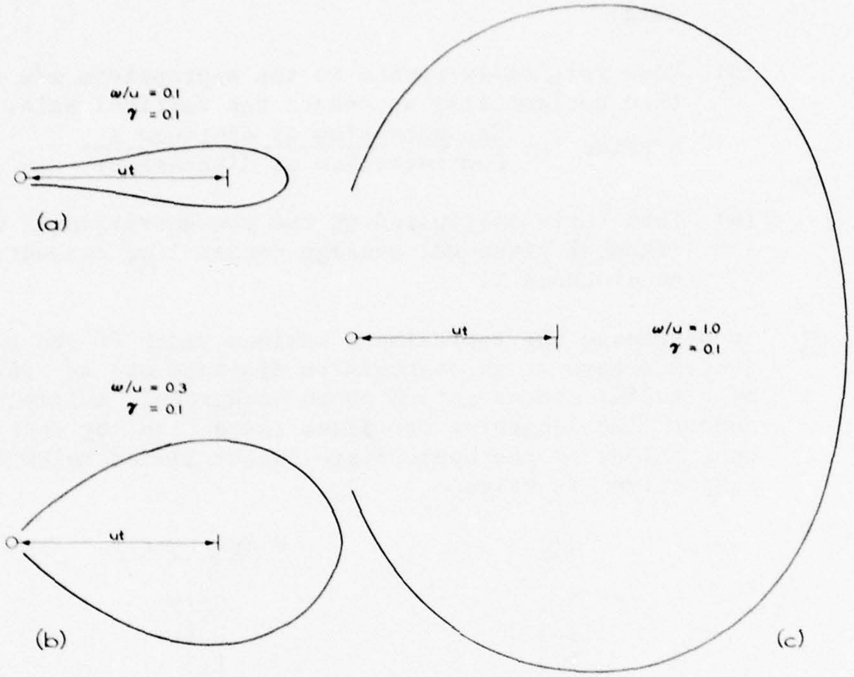


Figure 23. Idealized plume shapes generated by the model

b. D: 4 m = 400 cm (For a water depth of 8 m)

c. Medium size estuary: $\omega \approx 1$ cm/sec

d. Mean grain diameter: $4 \times 10^{-4}$ cm; $v_s = 0.001$ cm/sec

e. Tidal half-cycle = 6 hr $\times\ 3600\ \frac{\text{sec}}{\text{hr}} = 2.16 \times 10^4$ sec $\approx 2 \times 10^4$ sec

f. Maximum current velocity: 25 cm/sec $u = \frac{2 \times 25 \text{ cm/sec}}{\pi} =$ 16 cm/sec

g. $\omega/u = 1/16 = 0.06$

h. $\gamma = \frac{(1 \times 10^{-3})(2 \times 10^{4})}{(4 \times 10^{2})} = 0.05$ Round to 0.1

i. DSF = (16 cm/sec) $(2 \times 10^{4}$ sec) $= 32 \times 10^{4}$ cm (or 3.2 km)

j. $\text{CSF} = \frac{11.6 \times 10^{6} \text{ mg/sec}}{\pi\ (1 \text{ cm/sec})^{2} (400 \text{ cm})(2 \times 10^{4} \text{ sec})} = 0.46$ mg/cc

k. Follow dotted line in Figure 24a for $\omega/u = 0.06$ ("A") and $\gamma = 0.1$; $\frac{\text{Concentration (mg/}\ell\text{) at ut}}{\text{CSF}} = 0.05$

Concentration at 3.2 km = 0.05 × CSF = (0.05) (0.46) = 0.023 mg/cc = 23 mg/ℓ

l. To determine the distance X (cm) downstream of the discharge point where the plume center line concentration will be 50 mg/ℓ,

(1) $\frac{50 \text{ mg/}\ell}{23 \text{ mg/}\ell} = 2.17 \approx 2.2$

(2) Enter Figure 24b (for $\gamma = 0.1$) along left-hand scale at 2.2 ("C")

(3) Move horizontally to the $\omega/u = 0.1$ curve and down to the lower scale ("D")

$$\frac{\text{Distance X}}{\text{DSF}} = 0.9$$

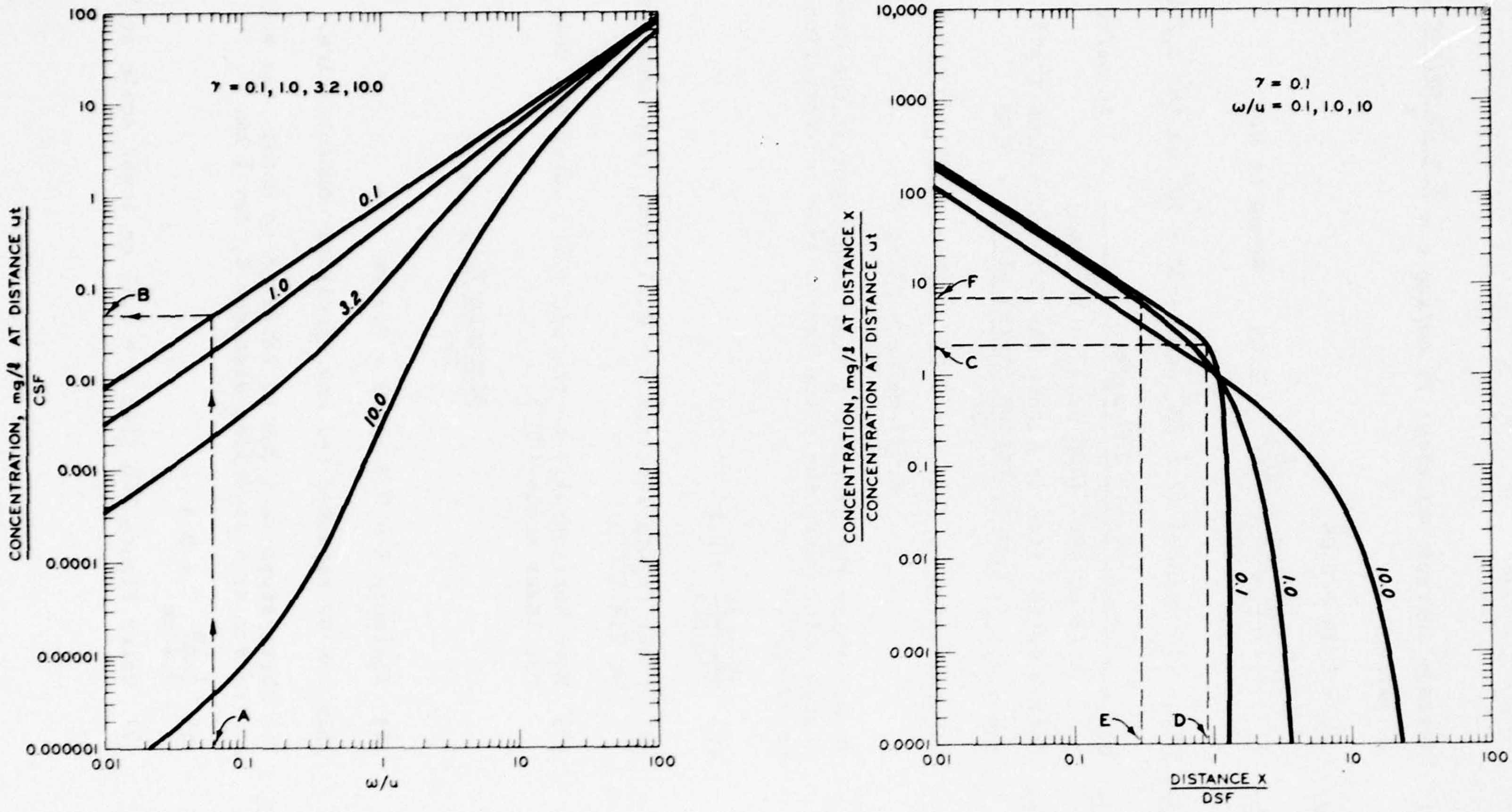
(4) Distance X = 0.9 × 3.2 = 2.9 km

This can be repeated for any specified concentration.

m. The above steps in l can be reversed to obtain the solids concentration at a specified distance X, say 1 km.

(1) $\frac{1 \text{ km}}{3.2 \text{ km}} = 0.3$

(2) Enter Figure 24b (for $\gamma = 0.1$) on lower scale at "E"



(a) (b)

Figure 24. Nomographs used in example problem

(3) Move vertically up to the $\omega/u = 0.1$ curve and over to the left-hand scale to "F"

$$\frac{\text{Concentration (mg/}\ell\text{) at 1 km}}{23 \text{ mg/}\ell} = 7$$

(4) Concentration at 1 km = $7 \times 23 = 161$ mg/ℓ

n. The concentration of excess suspended solids in this case was 23 mg/ℓ at a distance of 3.2 km from the discharge point. With $\omega/u$ less than 0.1 the maximum width of the plume as defined by the 23 mg/ℓ contour will be less than $0.25 \times 3.2$ km = 0.8 km.

o. The shape of an idealized plume under these conditions will approximate the shape shown in Figure 23a.

78. The average center line concentration for this operation as a function of distance from the discharge point is:

| Distance, km | Concentration, mg/ℓ |
|---|---|
| 0.5 | 368 |
| 1.0 | 161 |
| 2.0 | 71 |
| 3.0 | 37 |
| 3.2 | 23 |
| 3.5 | 1.5 |

79. After the disposal operation has ceased, the suspended material in the plume will settle ($v_s$) and diffuse laterally ($\omega$). The visual near-surface plume will usually disperse within a period of 1 to 2 hr (Equation 3);[13,55] however, the subsurface plume may theoretically persist for a few days depending on the water depth, settling velocity of the suspended particles, and the diffusion velocity. A method for estimating the rate of decrease in the plume concentrations due to settling and/or diffusion is given by Schubel et al.[53]

## Fluid Mud Dispersion

80. Whereas a small percentage of the fine-grained dredged material slurry discharged during open-water pipeline disposal operations is dispersed in the water column as a turbidity plume,[53] the vast majority rapidly descends to the bottom of the disposal area where it

accumulates under the discharge point in the form of a low gradient fluid mud mound overlying the existing bottom sediment.[13] If the discharge is moved as the dredge advances, a series of mounds will develop. The majority of the mounded material is usually high-density (nonflowing) fluid mud that is covered by a surface layer of low-density (flowing or nonflowing) fluid mud. The short- and long-term dispersion characteristics of the discharged slurry depend on many factors, including the nature and rate of slurry discharge, the discharge configuration, and the hydrodynamic regime and bottom topography in the disposal area. These factors will be evaluated in more detail in the following discussion of fluid mud accumulation and dispersion.

### Dispersion of low-density fluid mud

81. At a typical open-water pipeline disposal operation, an estimated 97 to 99 percent[53] of the fine-grained dredged material slurry descends rapidly through the water column and impacts on the bottom. During the descent and impact phases, the slurry usually entrains water and may initially flow radially away from the discharge point over the bottom or surface of the existing mound as a fragmented flow of low-density fluid mud.[13] The fluid mud front propagates in the form of a near-bottom headwave[56,57] (Figure 25). Under quiescent conditions more

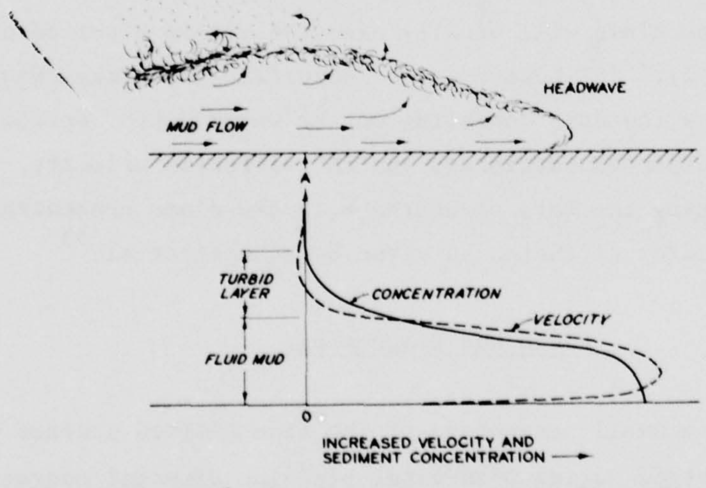


Figure 25. Velocity/sediment concentration distribution within the headwave of a low-density fluid mudflow. (Redrawn from Reference 56 and used through courtesy of the Pacific Section SEPM, P. O. B[illegible]0344, Ambassador Station, Los Angeles, Calif. [illegible].)

than 98 percent of the sediment in the mudflow remains in the fluid mud layer at concentrations greater than 10 g/ℓ, while the remaining 2 percent is resuspended in a turbid layer behind the headwave by turbulence and upward mixing of the sediment suspended at the upper surface of the mud layer.[57] High sediment concentrations and flow velocities characterize the lower levels within the low density fluid mud, whereas relatively low solids concentrations and velocities are present in the overlying turbid layer.[56,57] Areal and temporal fluctuations in this flow of low-density fluid mud are probably caused in part by pulses of higher density dredged material slurry discharged from the pipe.[13]

82. Material characteristics. The size distribution of the discharged material will strongly influence its flowing/mounding behavior. Very coarse sand, gravel, and clayballs from "new work" dredging projects will rapidly settle out at the discharge point independently of any fine-grained material. However, in slurries of fine-grained material containing less than 30 percent medium to fine sand, the sand apparently does not settle out, but tends to flow with the slurry. As the sand content increases above 30 percent, the fluid mud will tend to flow less and mounding will increase.[12] The relative percentages of silt, clay, and organics may have a marginal effect on the behavior of the fluid mud; however, no such relationship has been documented.

83. Neither laboratory nor field data indicate any obvious differences between the flow characteristics of freshwater and estuarine fluid mud.[13,57] Under similar flume test conditions freshwater and saltwater sediments appeared to generate mudflows of similar thickness and flow velocity; however, the overlying turbid layer generated above saltwater fluid mudflows may be somewhat thinner due to flocculation of fine-grained material.[57]

84. Bottom slope.57 The slope of the bottom probably has the greatest influence on the flow characteristics of low-density fluid mud. Mudflows propagating uphill decelerate very rapidly due to increased settling of the suspended sediment. However, if the bottom has a sufficient downslope, the velocity of the flowing mud will increase until it reaches a constant terminal velocity. For slopes less than

2 deg (1:30), the terminal velocity generally increases as both the solids concentration of the fluid mud and the slope increase. Under quiescent flume conditions, the minimum critical downslope angle at which a channelized (i.e., nonexpanding) headwave will maintain a constant velocity is approximately 0.75 deg (1:76). Under field conditions, this critical angle may be less than 0.75 deg depending on the pipeline configuration at the discharge, the slurry discharge rate, and the hydrodynamic regime in the disposal area. In other words, if fine-grained dredged material slurry is discharged in open water where the bottom slopes are greater then 0.75 deg, the fluid mud material will flow downslope at velocities of approximately 0.1 to 0.3 m/sec as long as that slope is maintained. At slopes of less than 2 deg the thickness of the fluid med layer remains approximately the same regardless of the slope; however, the thickness of the turbid layer overlying the fluid mud layer tends to increase as the downslope angle increases.

85. Discharge rate.[57] The flow characteristics of fluid mud also depend in part on the discharge rate of the dredged material slurry. High discharge velocities produce maximum levels of dispersion, both areally and throughout the water column. As the size of the dredge and discharge rates increase, the thickness of both the fluid mud and turbid layers increase; however, the thickness does not appear to be significantly dependent on the solids concentration of the discharged slurry.

86. Currents. Under laboratory flume conditions the flow characteristics of low-density fluid mud are not significantly affected by currents up to velocities as high as 3 cm/sec; however, the thickness of the overlying turbid layer will tend to increase when current velocities exceed 1.8 cm/sec.[57] Under field conditions dominated by low current velocities, this turbid layer is relatively thin with concentrations increasing from 1 to 10 g/ℓ within a vertical interval of 5 to 10 cm; at current velocities of 50 cm/sec the same transition zone may extend over an interval of approximately 50 cm.[13] This indicates that resuspension and subsequent downcurrent movement of some material at the surface of the low-density fluid mud layer may occur during periods dominated by

high currents. However, significant resuspension and upward mixing of fluid mud throughout the upper water column apparently does not occur.

87. Waves.[57] Waves generated by weak to moderate winds interfere very little with the overall motion or velocity of low-density fluid mudflows. In fact, the near-bottom orbital motions induced by waves are damped significantly by the presence of a fluid mud layer. However, when orbital velocities exceed 1.8 cm/sec, the thickness of both the fluid mud and turbid layers will tend to increase. The amount of resuspension and the height to which fine-grained sediment is suspended depends primarily on the depth of water, wave size, and length of time that the fluid mud is exposed to wave activity. As these factors increase in magnitude, so does the degree of sediment resuspension. In most cases, typical tidal current velocities (e.g., 5 to 10 cm/sec) are much greater than wave-induced velocities except during periods of high winds and/or wave activity when dredging activities usually cease.

### Fluid mud mound characteristics

88. If the bottom slopes are not steep enough to maintain low-density fluid mudflows, the sediment suspended in the fluid mud layer will tend to settle and the flow velocity of the headwave will decrease.[57] When suspended sediment concentrations exceed 200 g/ℓ, the fluid mud is no longer capable of flowing freely, but instead will accumulate under the discharge point in the form of a low gradient (e.g., 1:500) circular or elliptical fluid mud mound.

89. Solids concentrations.[13] At the water column/fluid mud interface, the solids concentrations increase very rapidly from approximate levels of a few hundred milligrams per litre to 200 g/ℓ. Below the 200 g/ℓ concentration level the solids concentration within the high-density fluid mud increases at a slower rate with increasing depth. Fluid mud layers may be stratified in sublayers of 20 to 30 cm thick with each layer becoming increasingly more dense with depth in the fluid mud mound. Concentrations at the base of the mound may be as high as 500 g/ℓ depending on the thickness of the mound and its state of consolidation.

90. Flow characteristics. As the disposal operation continues, the thickness and radius of the mound will increase due to the addition of dredged material slurry and the settling of the dredged material suspended in the water column; however, the rate of expansion of the mound decreases exponentially with time. Flow velocities at the water column/fluid mud interface generally range from zero to a few centimetres per second indicating that recently discharged slurry may flow away from the discharge point along the surface of the existing mound as a fragmented sheet of low-density fluid mud. Velocities decrease rapidly with depth as the bulk density of the fluid mud increases. This pattern indicates that high-density fluid mud within the mound probably moves away from the discharge point by a very slow creeping process[13] or occasional sudden failure (that was not detected by the field measurements) when the slope of the mound exceeds a critical angle and/or the fluid mud loses its strength due to rapid deposition of sediment and consequent generation of excess pore pressures.

91. Mound slopes. The slopes on the fluid mud mound are controlled primarily by the dispersive characteristics of the discharged dredged material slurry. During the disposal operation typical mound slopes may average about 1:500;[13,55] however, the surface of the mound close to the discharge point may be pocked with conical hills and scour pits with maximum slopes of 1:50 and a relief of approximately 0.5 m.[13] If the slurry is widely dispersed, mound slopes will probably range from 1:500 to 1:2,000. With a low degree of dispersion, the fluid mud mound will have slopes ranging from 1:100 to 1:500.[13] Unfortunately, the dynamic nature of open-water environments, the high degree of variability associated with the disposal operation itself, and the lack of extensive fluid mud field data make it very difficult to accurately predict the mounding characteristics of the discharged dredged material. However, the amount of slurry dispersion can be controlled by using various pipeline configurations at the discharge point; this is discussed in Part IV.

92. Mound shapes. The areal and cross-sectional shape of a fluid mud mound on a nonsloping bottom depends primarily on the strength

and predominant direction of the current and the configuration of the discharge.[13] For a vertical discharge in an environment without significant currents, the fluid mud mound will have a conical shape with the apex centered on the discharge point (Figure 26a). Where current velocities are greater than a few centimetres per second the mound will be skewed in the direction of the predominant current. Mound slopes on the downcurrent side will also be less than those facing the predominant current direction (Figure 26b). Under low current conditions a similarly skewed mound will result if the discharge is oriented at a low angle relative to the water surface (Figure 26c). The degree of mound elongation is controlled by the discharge configuration and the strength of the currents, both of which affect the dispersion of the fluid mud (Figure 26d).

93. Mound consolidation. When the solids concentration of the fluid mud exceeds 200 g/ℓ, the material will begin to undergo self-weight consolidation. During this process, the bulk density of the sediment increases, the height and slopes of the mound decrease, and the rate of consolidation decreases. In high energy environments the thickness of the mound may also be reduced significantly by resuspension and erosion of low-density fluid mud at the surface of the mound by waves and currents.

94. The time that is required for the mound to reach its ultimate state of consolidation depends primarily on the characteristics of the material and the thickness of the deposit. As the thickness of the mound increases, the amount of time that will be required for the material to reach its final state of consolidation will increase; doubling the thickness of the layer will decrease the rate of consolidation by as much as four times. However, the thicker the layer, the higher will be the final bulk density of the material after it has undergone consolidation. Depending on the sedimentation/consolidation characteristics of the dredged sediment, complete consolidation of a fluid mud mound may continue from one to several years.[58,59,60]

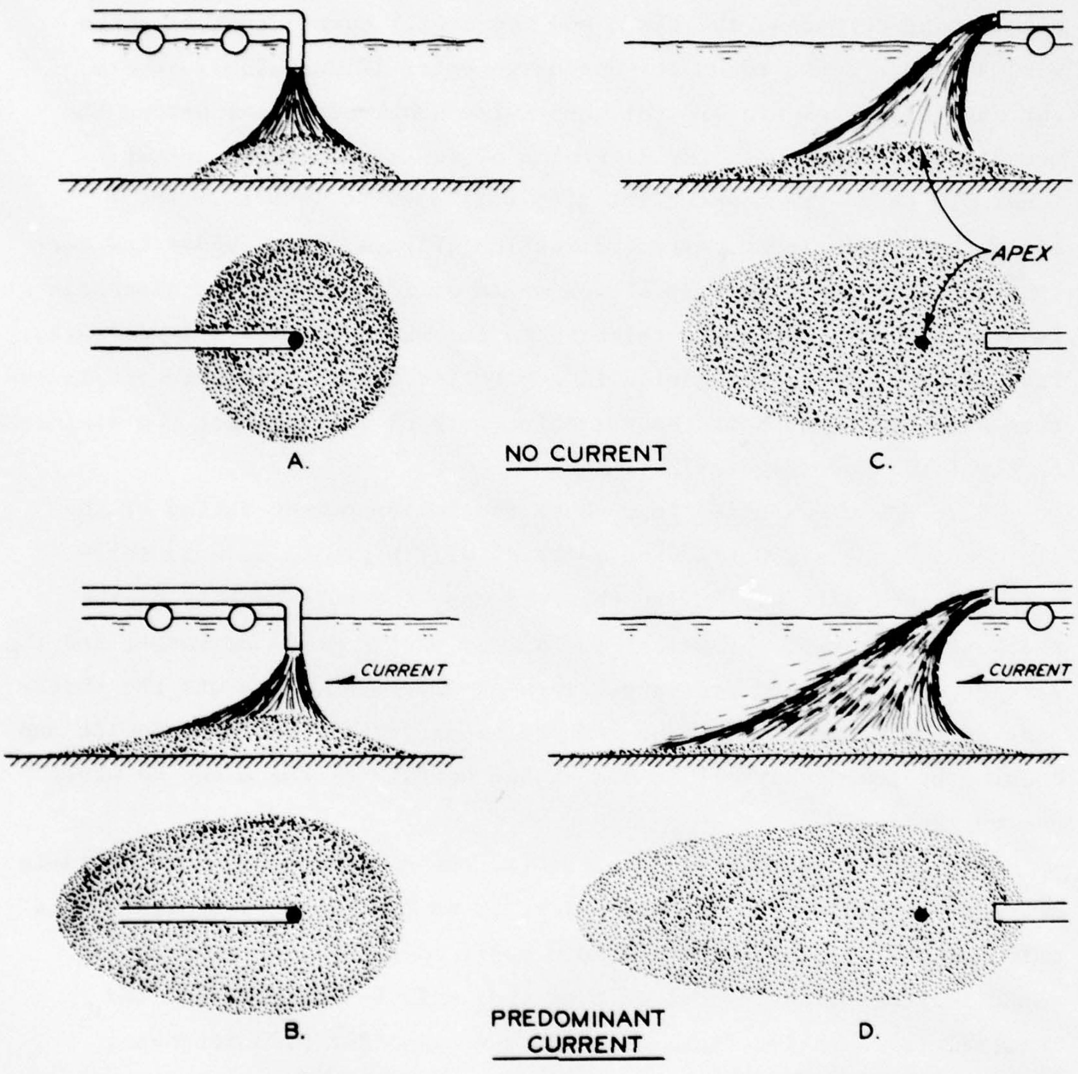


Figure 26. Effect of discharge angle and predominant current direction on the shape of a fluid mud mound

# PART IV: METHODS FOR CONTROLLING DREDGED MATERIAL DISPERSION: OPEN-WATER PIPELINE DISPOSAL OPERATIONS

95. Probably the most promising method for controlling the dispersion of dredged material slurry at open-water pipeline disposal operations involves modifying the pipeline configuration at the discharge point. In addition, under certain circumstances silt curtains may be used to control the dispersion of water-column turbidity by modifying the current flow patterns in the vicinity of certain types of dredging and disposal operations. Flocculants may be injected into the pipeline to increase the settling rate of the fine-grained material, but this technique is not recommended.

## Pipeline Discharge Configurations[13,53,55,57,61]

### Dredged material dispersal

96. Of all the environmental and operational factors affecting the dispersion of dredged material slurry during open-water pipeline disposal operations, the configuration of the pipeline at the discharge point appears to be the only parameter that, from a practical point of view, can be varied to effectively control the characteristics of dispersion. The pattern of dredged material dispersal is apparently controlled by the configuration of the pipeline at the discharge point as well as the angle and height of the discharge relative to the water surface (for above water discharge) or bottom (for submerged discharge).

97. Generally speaking, pipeline configurations that minimize water-column turbidity tend to produce fluid mud mounds with steep side slopes, maximum thickness, and minimal areal coverage. Conversely, those configurations that generate maximum levels of water-column turbidity produce relatively thin fluid mud mounds of maximum areal extent. As shown in Table 3, as the height of the mound decreases by a factor of two, the areal coverage increases by a factor of two. But as the mound height decreases, the amount of wave-induced resuspension of the surface material will also decrease. This relationship between mound

Table 3

Fluid Mud Mound Characteristics (Mound Volume: 250,000 cu m)

| Height, m | Areal coverage, sq m | Slope |
|---|---|---|
| 4 | 187,500 | 1:61 |
| 2 | 375,000 | 1:173 |
| 1 | 750,000 | 1:489 |
| 0.5 | 1,500,000 | 1:1382 |

height and areal extent/resuspension potential should be considered when evaluating the potential short- and long-term impact of a particular disposal operation. Unfortunately, there is no "best" pipeline configuration; the design chosen should be based on the desired dispersal of dredged material in the water column and on the bottom.

Typical configurations

98. The dispersal characteristics of several typical discharge configurations (Table 4) are described below the table.

Table 4

Effect of Pipeline Configuration on Dredged Material Dispersion

| TYPICAL PIPELINE CONFIGURATIONS* | WATER COLUMN TURBIDITY | | FLUID MUD MOUND | | | |
|---|---|---|---|---|---|---|
| | SURFACE | MID-DEPTH | HEIGHT | SLOPE | AREA COVERED | RATE OF CONSOLIDATION |
| DIFFUSER-SUBMERGED | LOW | LOW | HIGH | HIGH | LOW | LOW |
| 90° ELBOW WITH CONICAL EXPANSION SECTION-SUBMERGED | LOW | LOW/MEDIUM | ↓ | ↓ | ↓ | ↓ |
| 90° ELBOW-SUBMERGED | LOW | MEDIUM | ↓ | ↓ | ↓ | ↓ |
| 90° ELBOW WITH SPLASHPLATE | LOW | HIGH | ↓ | ↓ | ↓ | ↓ |
| 0° WITH SPLASHPLATE-SUBMERGED | MEDIUM | HIGH | ↓ | ↓ | ↓ | ↓ |
| 0° WITH SPLASHPLATE-ABOVE | MEDIUM | HIGH | ↓ | ↓ | ↓ | ↓ |
| 20° OPEN END-SUBMERGED | MEDIUM | HIGH | ↓ | ↓ | ↓ | ↓ |
| 0° OPEN END-SUBMERGED | HIGH | HIGH | ↓ | ↓ | ↓ | ↓ |
| 0° OPEN END-ABOVE | HIGH | HIGH | LOW | LOW | HIGH | HIGH |

* PIPELINE ANGLE RELATIVE TO WATER SURFACE.

a. With a simple open-ended pipeline discharging slurry at 4 to 6 m/sec parallel to the water surface, the high momentum levels cause a great deal of entrainment of disposal site water as the slurry jet descends through the water column and impacts on the bottom. Turbidity levels are generally high and the fluid mud layer is relatively thin and widely dispersed.

b. Submerging the discharge just below the water surface may reduce the degree of slurry dispersion; however, based on the field data, it is difficult to determine how significant this reduction may be. If the discharge pipe is submerged to a sufficient depth below the surface, a visible plume may not be apparent.

c. At low discharge angles a significant reduction in the slurry momentum can be achieved with a deflector or splashplate mounted at the end of the pipe perpendicular to the slurry flow. Although this tends to disperse the slurry as it is discharged, the momentum loss is apparently significant enough to cause the dispersed slurry to settle to the bottom relatively quickly, thereby generating less water-column turbidity.

d. The amount of water-column turbidity generated by a simple submerged discharge decreases as the angle of the pipeline increases from 0 to 90 deg. With a simple 90-deg elbow on the end of the pipeline, the slurry is discharged vertically towards the bottom with less entrainment of disposal site water. Upon impact on the bottom, the vertical motion of the slurry is translated into a horizontal flow, which spreads radially from the impact point. In areas where current velocities are less than 10 cm/sec, this configuration produces near-surface turbidity plumes that are very diffuse, with occasional "puddles" of higher solids concentrations at varying distances from the discharge point.

e. By adding a splashplate to the simple 90-deg elbow, the amount of slurry dispersion can be increased. With the end of a 69-cm (27-in.) pipeline discharging at a depth of 1 m against a splashplate positioned at a depth of 2 m, the slurry is dispersed at the depth of the splashplate with traces of surface turbidity visible only within 100 m of the discharge point.[55] *

f. By adding a 15-deg conical section at the end of the simple 90-deg elbow, the effective velocity of the discharged slurry can be reduced by a factor of 2 or 3 (without affecting the dredge's production rate). This will tend to decrease the levels of water-column turbidity and increase the mounding tendency of the fluid mud.

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* Personal Communication, 3 January 1978, William B. Cronin, Research Scientist, Cheasapeake Bay Institute, Baltimore, Md.

### Submerged diffuser system[61]

99. The amount of water-column turbidity generated by an open-water pipeline disposal operation can probably be minimized most effectively by using a submerged diffuser system (Figure 27) that has been developed through extensive laboratory flume tests. (Unfortunately, the diffuser system has not been field tests.) This system has been designed to eliminate all interaction between the slurry and upper water column by radially discharging the slurry parallel to and just above the bottom at a low velocity. The entire discharge system is composed of a submerged diffuser and an anchored support barge attached to the end of the discharge pipeline that positions the diffuser relative to the bottom. As it is presently designed, the diffuser/barge system can be used in water depths up to 9 m.

100. The primary purpose of the diffuser (Figure 28) is to reduce the velocity and turbulence associated with the discharged slurry. This is accomplished by routing the flow through a vertically oriented, 15-deg axial diffuser with a cross-sectional area ratio of 4:1 followed by a combined turning and radial diffuser section that increases the overall area ratio to 16:1. Therefore, the flow velocity of the slurry prior to discharge is reduced by a factor of 16, yet the dredge's discharge rate (i.e., slurry flow velocity × the pipeline cross-sectional area) is not affected in any way by the diffuser. The conical and turning/radial diffuser sections are joined to form the diffuser assembly, which is flange mounted to the discharge pipeline. An abrasion-resistant impingement plate is supported from the diffuser assembly by 4 to 6 struts. The parallel conical surfaces of the radial diffuser and impingement plate slope downward at an angle of 10 deg from the horizontal so that stones and debris can roll down the sloped surface and automatically clear the diffuser. The radial discharge area of the diffuser can be adjusted by changing the length of the struts supporting the impingement plate. In this manner both the thickness and velocity of the discharged slurry can be controlled. The strut length, which determines not only the slurry discharge velocity, but also the maximum diameter of an object that will pass through the diffuser, should be

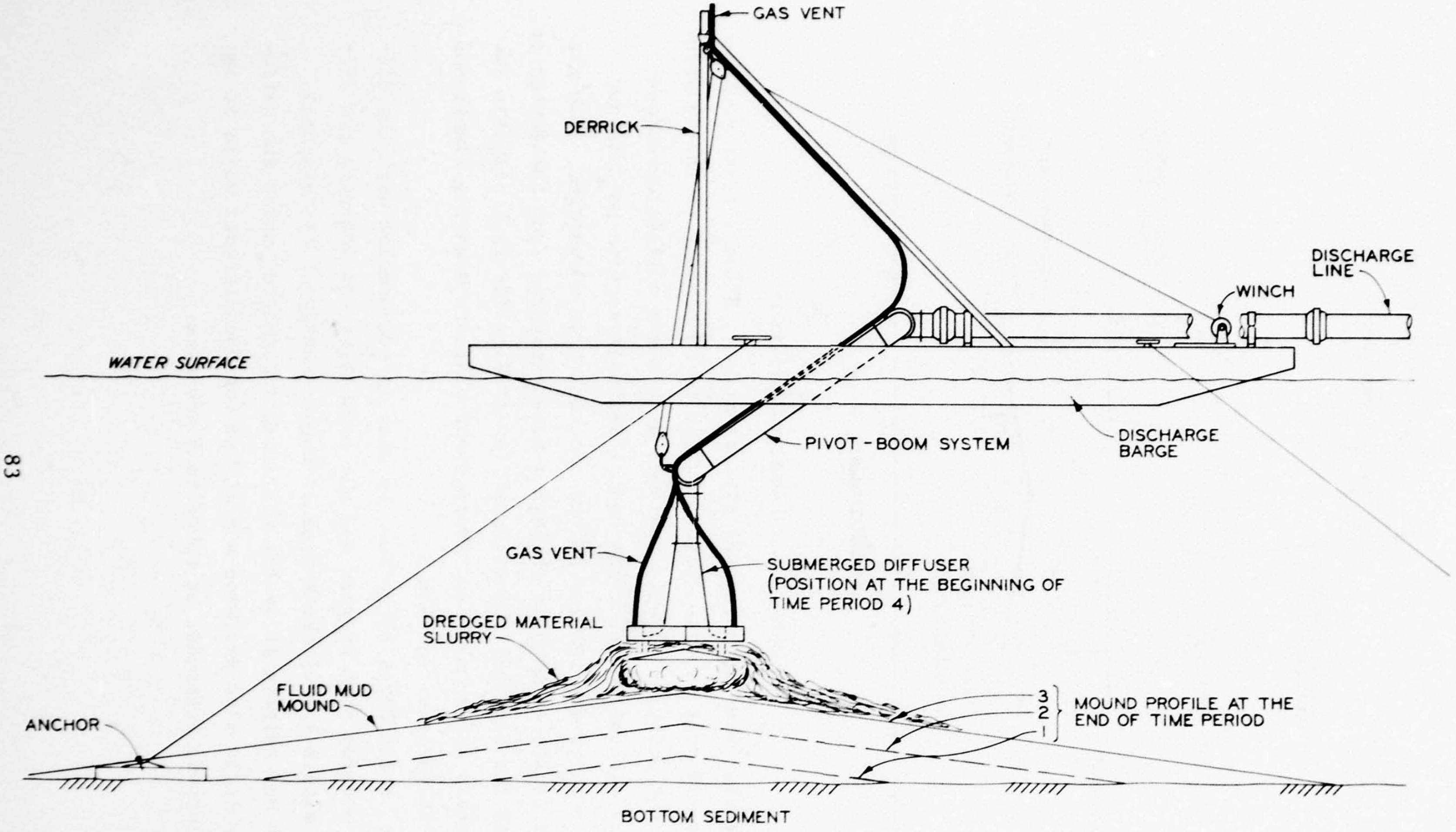

Figure 27. Submerged diffuser system, including the diffuser and discharge barge. (The length of the respective time periods is given in Table 5, page 86)

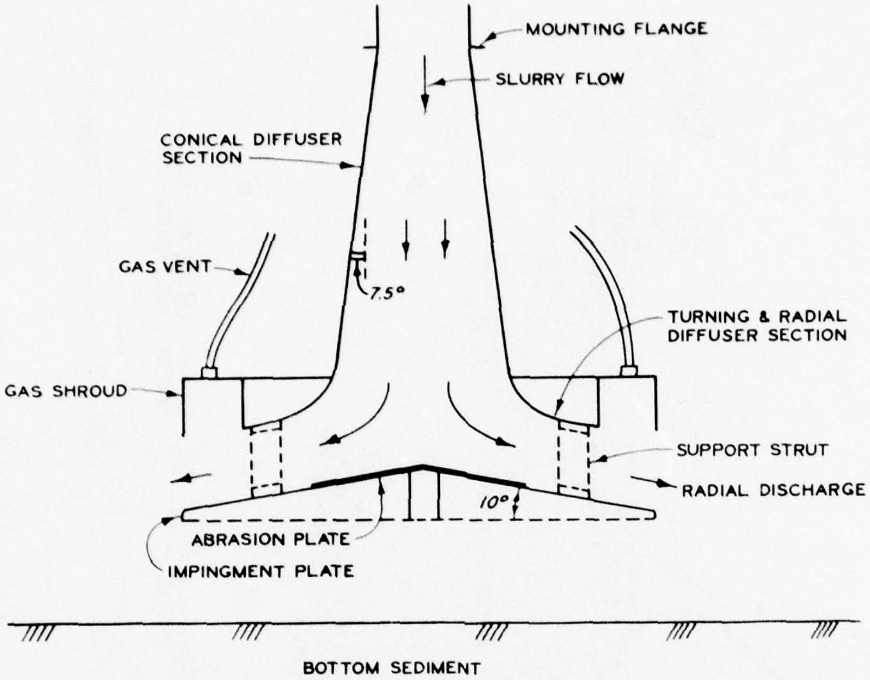

Figure 28. Submerged diffuser

approximately five-sixths of the pipe diameter. Since the gas content of bottom sediment is often high (e.g., 5 to 30 percent of the in situ volume), the diffuser is also equipped with a gas collection shroud around the circumference of the radial diffuser section to trap any sediment-covered gas bubbles before the slurry is discharged. The gas is vented to the atmosphere through a hose extending from the shroud to the top of the derrick. The diffuser for a 46-cm (18-in.) pipeline is approximately 2.4 m tall from impingement plate to mounting flange and 2.4 m in diameter at its base.

101. A discharge barge must be used in conjunction with the diffuser to provide both support and the capability for lowering the diffuser to within 1 m of the bottom at the beginning of the disposal operation and raising it as the fluid mud accumulates under the diffuser. The barge also provides a platform for the diffuser while it is being adjusted, serviced, or moved to a new site.

102. Because the dredged material slurry discharged from the diffuser will form a low-gradient fluid mud mound similar to that formed by any typical open-water disposal operation, a schedule for lifting the diffuser as the mound accumulates has been developed by equating the volume of slurry discharged from the diffuser to the resulting volume of the mound.

$$\text{Volume of solids in the discharged slurry} = \text{Volume of solids in the fluid mud mound}$$

$$\frac{\pi}{4} d^2 \ V \ T \ B_s = \frac{\pi}{3} R^2 \ H \ B_m \qquad (11)$$

where:

$d$ = inside diameter of the pipeline

$V$ = flow velocity of the slurry in the pipeline

$T$ = total length of time of the disposal operation (at the same site)

$B_s$ = solids ratio (by volume) of the slurry

$R$ = radius of the fluid mud mound

$H$ = height of the fluid mud mound

$B_m$ = solids ratio (by volume) of the fluid mud mound

Assuming that the slope (S) of the fluid mud mound ($S = \frac{H}{R}$) is equal to 1/200, the average slurry velocity in the pipeline is 5.5 m/sec, and the solids contents of the slurry and fluid mud mound are equal to 15 and 25 percent (by weight), respectively, Equation 11 can be written as:

$$T = \frac{1}{450} \frac{B_m}{B_s} \frac{H^3}{S^2 d^2 V} = 2008 \frac{H^3}{d^2} \qquad (12)$$

where:

T is expressed in days

H is expressed in metres

d is expressed in centimetres

This formula can be used to develop a schedule for raising the diffuser or moving it to a new site to prevent interference with the mounded material. Table 5 shows a typical schedule for adjusting the height of diffuser above the bottom for several different discharge pipeline sizes. The mound configurations at the ends of the time periods are shown in Figure 27. In most cases the movement of the diffuser to a new site would probably be determined by the advancement of the dredge rather than excessive mounding of dredged material at the disposal site.

Table 5

Submerged Diffuser Movement Schedule

| Time Period | Recommended Height of Diffuser Above Bottom At Beginning of Time Period, m | Total Pumping Time (Days) Elapsed At Disposal Site for Dredge Sizes | | | | | | Mound Height (H) At End of Time Period, m |
|---|---|---|---|---|---|---|---|---|
| | | 30 cm 12 in. | 40 cm 16 in. | 51 cm 20 in. | 61 cm 24 in. | 71 cm 28 in. | 81 cm 32 in. | |
| 1 | 1.0 | 0.4 | 0.2 | 0.1* | 0.1* | <0.1* | <0.1* | 0.6 |
| 2 | 1.5 | 3.8 | 2.1 | 1.3 | 0.9 | 0.6 | 0.5 | 1.2 |
| 3 | 2.1 | 13.0 | 7.3 | 4.5 | 3.1 | 2.3 | 1.7 | 1.8 |
| 4 | 2.7 | 30.8 | 17.3 | 10.6 | 7.4 | 5.5 | 4.2 | 2.4 |

Note: To be conservative all numbers beyond the first decimal place are ignored.

* For pipeline sizes exceeding 51 cm, the diffuser should be initially positioned 1.5 m above the bottom.

103. Mathematical scaling techniques based on flume test data[61] can be used to compare the initial dispersive characteristics of fine-grained dredged material slurry discharged from the diffuser with that of a simple submerged pipeline. For a 61-cm (24-in.) dredge discharging slurry at 5.5 m/sec in 3.7 m of water through a pipe section submerged 1.2 m below the water surface at an angle of 20 deg, the flud mud layer a short distance (30 to 60 m) from the discharge point would be approximately 1.5 m thick and would move away from the discharge point at a velocity of about 0.3 m/sec. A 0.7-m-thick turbid layer might be present above the surface of the fluid mud layer. Using a diffuser system positioned 1 m above the bottom, the slurry would be discharged at a velocity slightly greater than 0.3 m/sec. A short distance from the diffuser the headwave velocity of the flowing mud would probably be less than 0.1 m/sec. The fluid mud layer would be approximately 1 m thick or a reduction of about 33 percent over the 20-deg submerged discharge configuration. The thickness of the turbid layer overlying the fluid mud

layer would probably be about 0.6 m thick so that the total thickness of the fluid mud/turbid water layer would be approximately 1.6 m. In both cases the thickness of the fluid mud/turbid water layer will decrease with increasing distance from the discharge point as the flow expands radially and the bulk density of the fluid mud increases due to settling of the suspended sediment.

104. Although the diffuser has not been field tested, it has a great deal of potential for eliminating turbidity in the water column and maximizing the mounding tendency of the discharged dredged material. The slurry remains in the pipeline/diffuser until it is discharged at low velocity near the bottom, thus eliminating all interaction of the slurry with the water column above the diffuser. This effectively eliminates water-column turbidity as well as any depression of the dissolved oxygen levels in the water column.[53,62] Unfortunately, using the diffuser does not eliminate the impact of the fluid mud on the benthic organisms,[55,63] nor does it eliminate the possible resuspension of low-density material at the surface of the fluid mud mound by waves and ambient currents.

## Silt Curtains[64]

105. One method for physically controlling the dispersion of near-surface turbid water in the vicinity of open-water pipeline disposal operations, effluent discharges from upland containment areas, and possibly clamshell dredging operations in quiescent environments involves placing a silt curtain or turbidity barrier either downcurrent from or around the operation. Silt curtains are not recommended for operations in the open ocean, in currents exceeding 50 cm/sec (1 knot), in areas frequently exposed to high winds and large breaking waves, or around hopper or cutterhead dredges where frequent curtain movement would be necessary.

### General Description

106. Silt curtains (Figure 29) are impervious, floating barriers that extend vertically from the water surface to a specified water

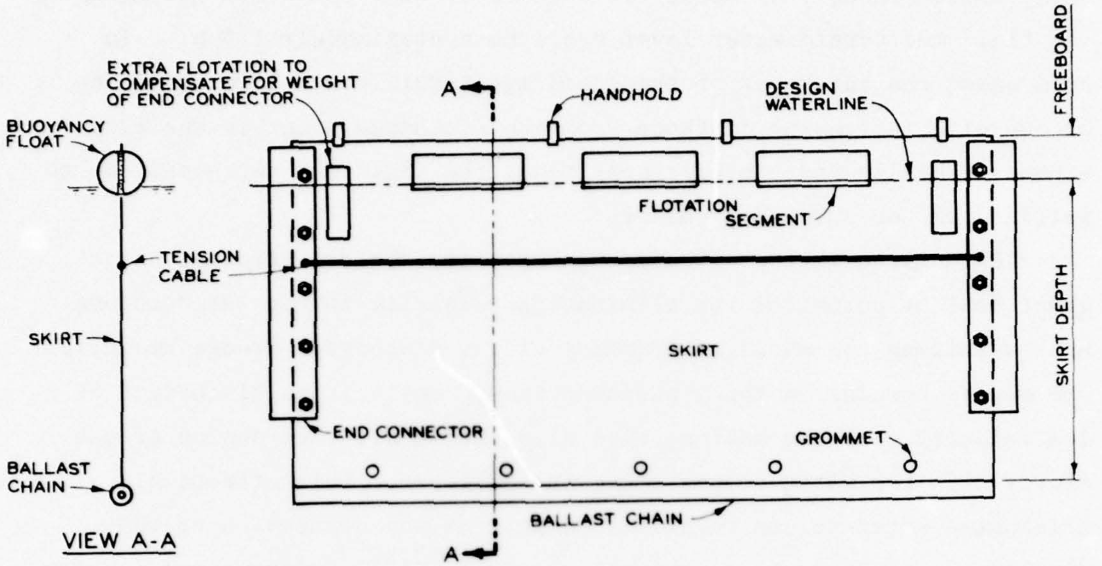

Figure 29. Construction of a typical center tension silt curtain section

depth. 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 along the bottom. A tension cable is often built into the curtain immediately above or below the flotation segments (top tension) or approximately 0.5 m below the flotation (center tension) to absorb stress imposed by currents and other hydrodynamic forces. The curtains are usually manufactured in 30-m sections that can be joined together at a particular site to provide a curtain of specified length. Anchored lines hold the curtain in a deployed configuration that is usually U-shaped or circular.

Processes affecting silt curtain performance

107. 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. In the case of a typical pipeline disposal operation surrounded by a silt curtain (Figure 30), the vast majority (95 to 99 percent) of the fine-grained material descends

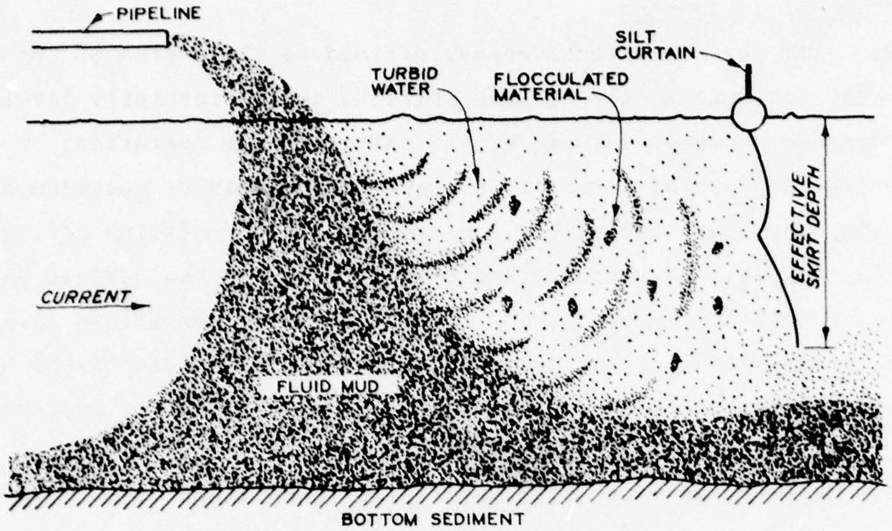

Figure 30. Processes affecting the performance of silt curtains in controlling dredged material dispersion

rapidly to the bottom where it forms a low gradient fluid mud mound. While the curtain provides an enclosure where some of the remaining fine-grained suspended material may flocculate and/or settle, most of the turbid water and fluid mud flow under the curtain. The silt curtain does not indefinitely contain turbid water, but instead diverts its flow under the curtain, thereby minimizing the turbidity in the upper water column outside the silt curtain.

108. Whereas properly deployed and maintained silt curtains can effectively control the flow of turbid water, they are not designed to contain or control fluid mud. In fact, when the accumulation of fluid mud reaches the depth of the ballast chain, the curtain must be moved away from the discharge; otherwise, sediment accumulation on the lower edge of the skirt will pull the curtain underwater and eventually bury it. Consequently, the rate of fluid mud accumulation relative to changes in water depth due to tides must be considered during a silt curtain operation. When bottom slopes exceed 0.75 deg, the fluid mud will not accumulate within the curtained area, but instead will flow downslope under the curtain.

## Silt curtain effectiveness

109. Silt curtain effectiveness, defined as the degree of turbidity reduction outside the curtain relative to the turbidity levels inside, depends on several factors: the nature of the operation; the quantity and type of material in suspension within or upstream of the curtain; the characteristics, construction, and condition of the silt curtain as well as the area and configuration of the curtain enclosure; the method of mooring; and the hydrodynamic conditions (i.e., currents, tides, waves, etc.) present at the site. Because of the high degree of variability in these factors, the effectiveness of different silt curtain operations is highly variable.

110. Under relatively quiescent current conditions (i.e., 5 cm/sec or less), turbidity levels in the water column outside the curtain can be as much as 80 to 90 percent lower than the levels inside or upstream of the curtain. While turbid water may flow under the curtain, the amount of suspended material in the upper part of the water column, as a whole, is substantially reduced. However, the effectiveness of silt curtains can be significantly reduced in high energy regimes where high currents cause silt curtains to flare. For example, in a current of 50 cm/sec the effective skirt depth of a 1.5-m curtain is reduced to approximately 0.9 m. Increased water turbulence around the curtain also tends to resuspend the fluid mud layer and may cause the suspended material flowing under the curtain to resurface just beyond the curtain. Especially where anchoring is inadequate and/or reversing tidal currents cause resuspension of the fluid mud as the curtain sweeps back and forth (over the fluid mud) with changes in the direction of the current, the turbidity levels outside the curtain can be substantially higher than the levels inside the curtain. With respect to overall effectiveness and deployment considerations, a current velocity of approximately 50 cm/sec appears to be a practical limiting condition for silt curtain use.

## Guidelines for selecting and using silt curtains

111. Site survey. Prior to selecting a curtain for a particular project, it is necessary to characterize the deployment site with

respect to current velocity, water depth (relative to tidal range), bottom slope and sediment types, and possibly background levels of turbidity. Maximum surface currents over a tidal cycle (i.e., 12 or 24 hr) should first be established from current measurements or tide tables. In addition, information on current direction and water turbulence may also indicate potential deployment problems and/or the best configuration(s) to use.

112. If the hydrodynamic regime appears to be conducive to silt curtain deployment (i.e., current velocities are less than 50 cm/sec), a survey of the water depths over the entire site and surrounding areas is required so that a curtain with a proper skirt depth can be selected and its initial and future placement geometries determined. At sites where the tidal range (i.e., the difference in depth between high and low tide) is negligible, a simple survey of bottom depths can be performed (preferably with a vessel equipped with a precision navigation system and a fathometer). However, if tide prediction tables (or curves) indicate that the tidal range exceeds approximately 0.3 m over a tidal cycle, the survey data must be adjusted to account for changes in water depth that will occur during the operation. The minimum depths (at the lowest low tide) are then used to determine the necessary skirt depth allowing about 0.5 m clearance between the lower edge of the skirt and the existing bottom. Unfortunately, this 0.5-m gap between the skirt and bottom may be difficult to maintain in very shallow water. The effect of fluid mud accumulation on water depth as well as the proposed schedule for moving the silt curtain to prevent burial should also be considered in selecting the curtain skirt depth.

113. The character of the bottom sediment/vegetation at the proposed deployment site should also be established using a grab sampler or a coring device to determine the type of anchors to use and convenient anchor points on the outer limits of the deployment site. The potential effect of boat traffic and boat-generated waves on the proposed deployment configuration and mooring system should also be considered. Since launching and retrieving the silt curtain will require the use of a large truck and a boat(s), a launching ramp and possibly a crane

should be located as near the site as possible. If an evaluation of silt curtain effectiveness relative to preoperation background conditions is desired, background turbidity levels at various depths must be determined, preferably under a variety of current and wave conditions.

114. Deployment configurations. After the deployment site has been surveyed, the length and geometry of the proposed curtain should be determined based on the type of silt curtain application, the hydrodynamic regime at the deployment site, any environmental policies regulating allowable turbidity levels as a function of distance from the operation, and such factors as boat traffic. Curtain lengths for typical operations might be 150 to 450 m for the U-shaped or semicircular configurations, 300 to 900 m for the circular/elliptical case.

115. In most cases a silt curtain can be deployed in an open-water environment in the form of a maze, semicircle or U-shape, or a circle or ellipse:

a. The maze configuration ("A," Figure 31) has been used on rivers where boat traffic is present, but appears to be relatively ineffective due to direct flow through the gap between the two separate curtains.

b. On a river where the current does not reverse, a U-shaped configuration ("B," Figure 31) is acceptable, but the distance between the anchored ends of the curtain should be large enough to prevent leakage of turbid water around the ends of the U.

c. Where turbidity is being generated by effluent from a containment area or a pipeline disposal operation close to the shoreline, the curtain can be anchored in a semicircular or U-shaped configuration ("C," Figure 31) with the ends of the curtain anchored onshore approximately equidistant from the discharge point. The required radius of the configuration is determined by the type and volume of material being disposed inside the curtain as well as the water depth.

d. In a tidal situation with reversing currents, a circular or elliptical configuration ("D," Figure 31) is necessary. Unfortunately, this latter case requires an extensive mooring system.

116. Silt curtain specifications. The silt curtain can now be selected based on the appropriate deployment geometry and the

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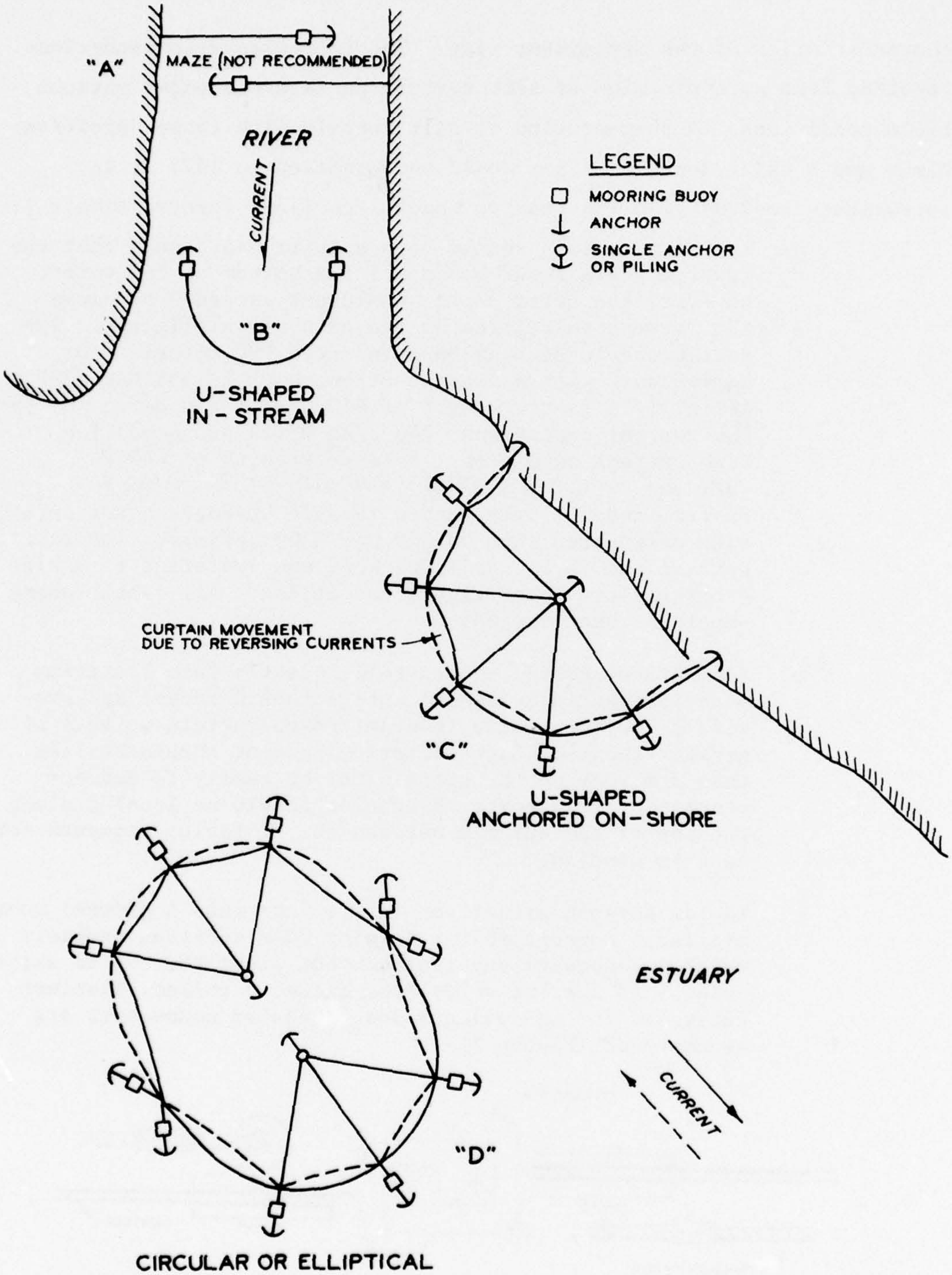

Figure 31. Typical silt curtain deployment configurations

characteristics of the deployment site. The following recommendations resulted from an evaluation of silt curtain performance under various field conditions. A 30-m section of silt curtain with these specifications and a skirt depth of 1.5 m could be purchased in 1977 at an approximate cost of $700 (no tension member) to $1300 (center tension).

a. The silt curtain should have a skirt depth such that the lower edge is about 0.5 m off the bottom at low water; however, the skirt depth should not exceed 3 m unless the current velocities at the site are negligible. The fabric should be a nylon-reinforced PVC material (or equivalent) with a tensile strength of 52,538 N/m (300 lb/in.); a fabric weight of 610 g/sq m (18 oz/sq yd) for low current conditions, 746 g/sq m (22 oz/sq yd) for high current conditions; a tear strength of 445 N (100 lb) or 890 N (200 lb) for 610- or 746-g/sq m fabric, respectively; and a tensile strength after abrasion of greater than 35,025 N/m (200 lb/in.). The fabric surface should be easily cleaned and resistant to marine growth, ultraviolet light, and mildew. All fabric seams should be heat sealed.

b. Segments of solid, closed-cell, plastic foam flotation material should be sealed into a fabric pocket and provide a bouyancy ratio (bouyant force/curtain weight) of greater than 5. Each flotation segment should be less than 3 m long so the curtain may be easily folded for storage or transport. Handholds should be located along the top of the curtain between the flotation segments for ease in handling.

c. In low current situations (i.e., less than 5 cm/sec) most available connectors for joining 30-m sections probably maintain adequate physical contact along the entire skirt joint. If current velocities exceed 5 cm/sec, aluminum extrusion (or equivalent) load transfer connectors are recommended (Figure 32).

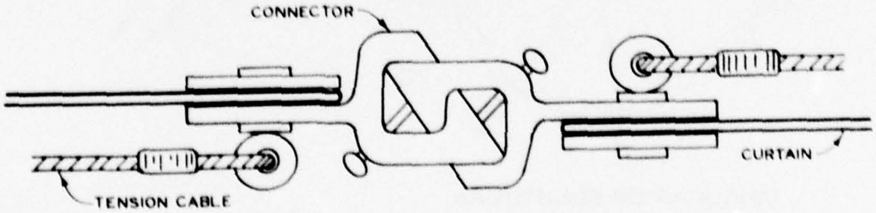

Figure 32. Recommended aluminum extrusion connectors for joining silt curtain sections

d. When current velocities are negligible, no tension member (other than the fabric itself) is necessary. For current velocities between 5 and 50 cm/sec, a galvanized or stainless steel wire rope should be used as a top or center tension member; the center tension curtain provides a somewhat greater effective skirt depth, but requires stronger tension members as well as more effective anchor systems. The noncorrosive, ballast chain should have a weight ranging from approximately 1.5 kg/m (1 lb/lin ft) for a 1.5-m skirt depth up to 3.0 kg/m (2 lb/lin ft) for a 3-m skirt depth.

117. Transportation. When transporting silt curtains from a storage facility to an unloading site, they should be furled (Figure 33), tied with lightweight straps or rope every 1 to 1.5 m, compactly folded accordion style, packaged into large bundles, carefully lifted into the transport vehicle, and transported to the unloading dock. At the unloading dock, the truck is backed down the ramp so that the tailgate is as close to the water as possible; the curtain is then carefully pulled out of the truck (like a string of sausages). After all the 30-m sections have been payed out and joined, the curtain can be towed by boat to the site at speeds of approximately 1 m/sec. The curtain should remain furled except near the end connectors until it has been deployed at the operation site.

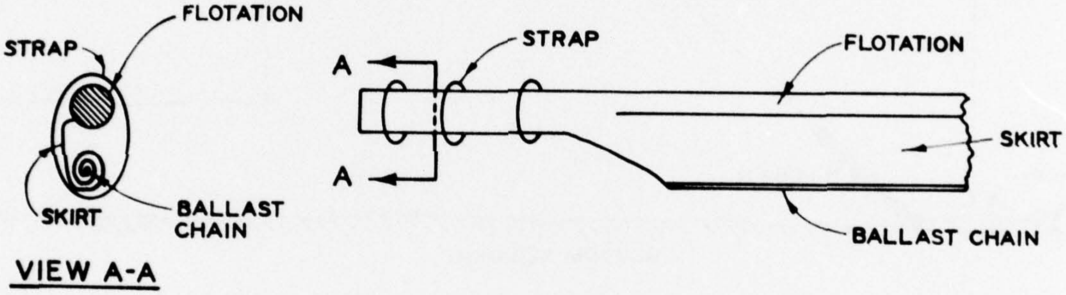

Figure 33. Furling of the curtain skirt for deployment and/or recovery of silt curtains

118. An alternative method involves maneuvering the curtain onto an open-decked workboat or barge, transporting the curtain to the

site, and, finally, off-loading the curtain in sections. The sections are then joined and the curtain deployed.

119. Mooring. Improper and/or inadequate mooring systems typically contribute to silt curtain ineffectiveness and failure. The recommended mooring system (Figure 34) consists of an anchor, a chain, an anchor rode (line or cable), and mooring and crown buoys. It is recommended that the curtain be anchored from the section joints every 30 m in a radial pattern (Figure 31) and on both sides if the curtain is exposed to reversing tidal currents. Half-inch (1.275-cm) polypropylene line used in conjunction with lightweight, self-burying anchors with weights of at least 4.5 kg for sandy bottom sediment and up to 34 kg for firm mud will provide adequate holding power in most situations. However, with increasing current velocities, the anchor weights will also have to be increased.

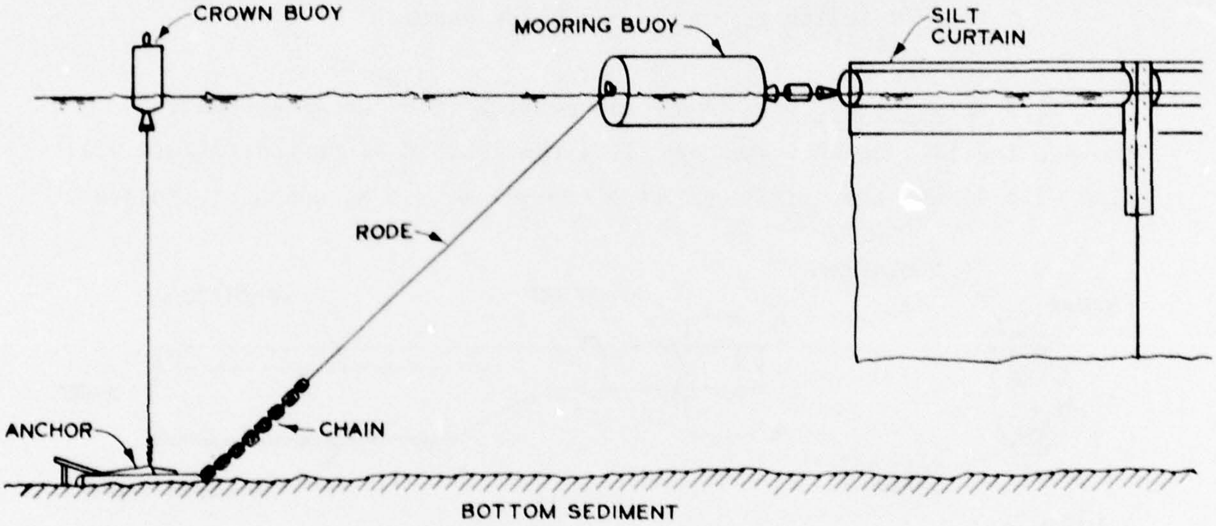

Figure 34. Recommended silt curtain mooring system

120. After the furled curtain has been anchored, it should be checked to ensure that the skirt is not twisted around the flotation. If this is the case, the curtain should be separated at the nearest

connector, untwisted, and rejoined. The curtain in its deployed, untwisted configuration can now be unfurled by simply cutting the furling lines or straps. If the barrier needs to be repositioned during the operation, any curtain with a long skirt depth should be refurled before it is moved.

121. Deployment model. The length of time that a silt curtain can remain deployed in one configuration before the enclosed area must be enlarged or the curtain moved to a new location to prevent siltation along the lower edge of the curtain depends on the accumulation of fluid mud inside the curtain relative to the deployment geometry, the slurry discharge rate, and the initial bottom gap (i.e., the distance between the lower skirt edge and the bottom sediment at the beginning of the operation) (Figure 35). The size of the enclosure is limited by the total length of the curtain available for the project; as the enclosed area and bottom gap increase, the length of time before the curtain must be moved also increases. Since it may be necessary to move a silt curtain during an operation, the following procedure can be used to develop a general schedule for curtain movement and redeployment.

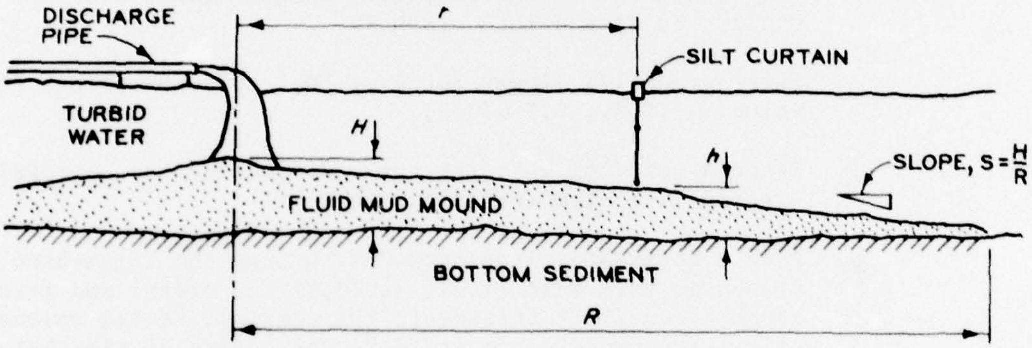

Figure 35. Parameters affecting the schedule for moving and redeploying silt curtains

122. To illustrate the use of the nomograph (Figure 36) used in this procedure, assume that approximately 975 m of curtain with a skirt depth of 1.5 m surrounds an open-water pipeline disposal operation

located in a quiescent nontidal environment with a uniform water depth of 2.7 m. The circular configuration has a radius of approximately 155 m. The dredged material slurry with a solids content of 15 percent (by weight) is discharged from a 46-cm (18-in.) pipeline at a velocity of 5.5 m/sec. To determine when the fluid mud dredged material will build up to the lower edge of the silt curtain:

a. Enter graph I (upper left, Figure 36) at "A" for 152 m radius.

b. Proceed vertically to "B," the planned initial bottom gap (i.e., 1.2 m) between the silt curtain and the existing bottom sediment.

c. Move horizontally through the right-hand axis indicating the approximate volume of the fluid mud dredged material mound (i.e., 0.3 million cu m) to "C" (graph II).

d. Draw a vertical line from "C" through the lower axis indicating the amount of slurry pumped (i.e., 0.57 million cu m) and into graph IV.

e. Enter graph III (lower left) at "D," the appropriate flow velocity (i.e., 5.5 m/sec).

f. Proceed vertically to the curve indicating the appropriate pipeline diameter (i.e., 46 cm).

g. Draw a horizontal line from "E" through the right-hand discharge rate axis (i.e., at 78,974 cu m/day) and into graph IV until it intersects the vertical "total volume of slurry pumped" line at "F." The length of time before the curtain needs to be moved is estimated from the diagonal time line that goes through "F."

123. In this example the operation can probably continue for approximately 7.32 days before the curtain must be moved due to fluid mud accumulation up to the lower skirt edge. Figure 37 shows that the mound will be approximately 2 m thick under the discharge pipe and will extend radially approximately 395 m. If the configuration were semicircular and located in a river (Figure 31B), the above procedure would be performed in the same manner using the radius of the semicircle; however, with a semicircular configuration anchored onshore (Figure 31C) the calculated time is divided in half. Similarly, if the

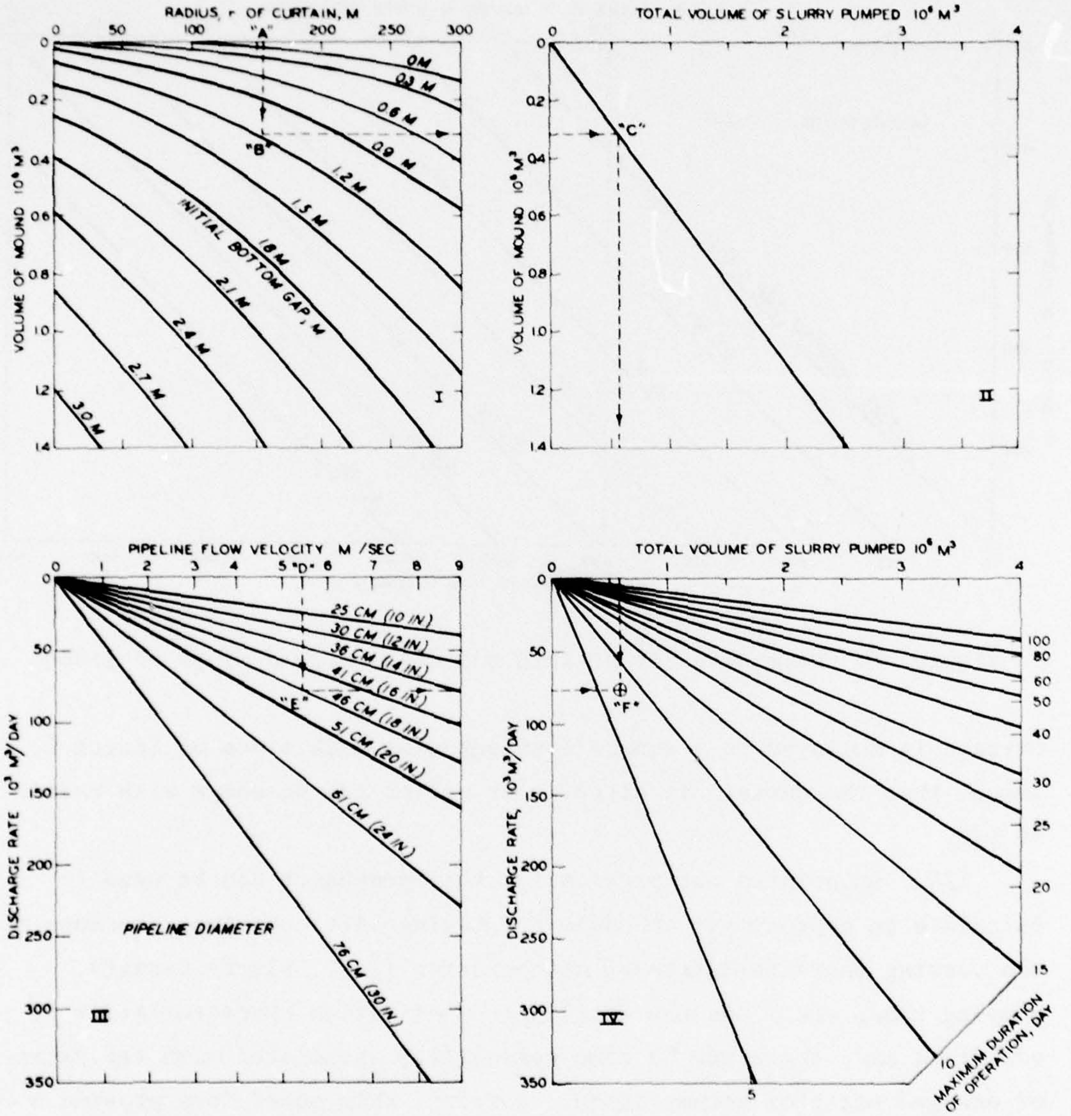

Figure 36. Nomograph depicting the relationship among different parameters that affect the redeployment schedule for silt curtains during an operation. It is assumed that the dredged material slurry is 15 percent solids by weight, the fluid mud is 25 percent solids by weight, and the fluid mud mound has a slope of 1:200. "A"-"F" refer to example in text (paragraph 122)

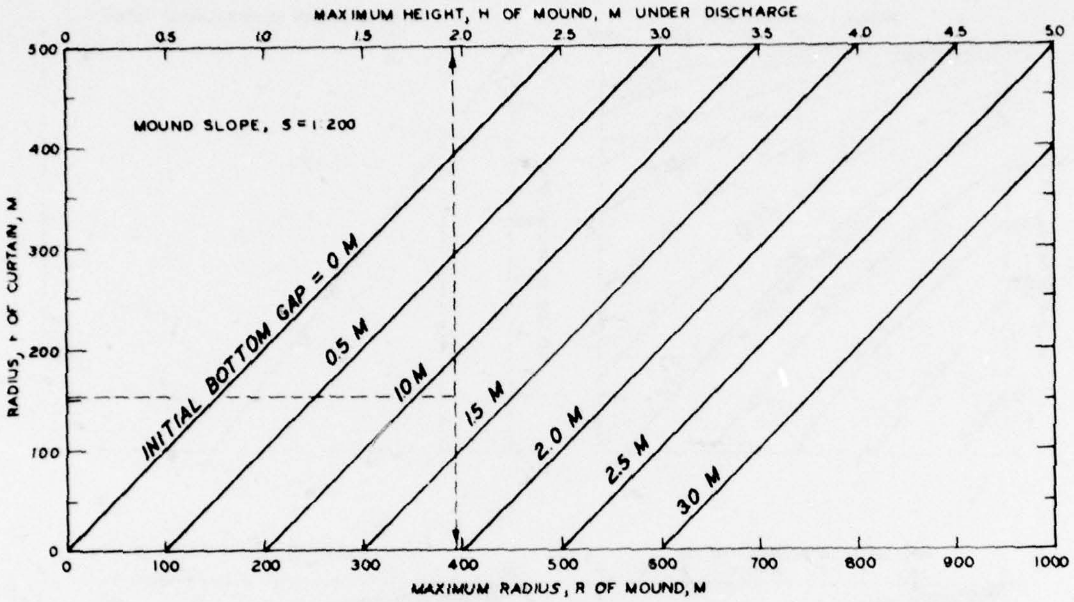

Figure 37. Dimensions of a fluid mud mound with a slope of 1:200

curtain is deployed in a square configuration with sides of length L, assume that the curtain is circular or elliptical in shape with radius of L/2.

124. As pointed out previously, this procedure can be used to calculate an approximate schedule for moving silt curtains. Because of the varying characteristics of an operation (i.e., slurry density, pumping time, etc.) and the settling/consolidation characteristics of the fluid mud, there may be some variability associated with the rates of dredged material accumulation. However, this model does provide a conservative time framework (i.e., a shorter length of time between curtain movements than might be necessary) for planning the silt curtain operation. Additional experience should indicate possible modifications for improving the accuracy of this procedure.

125. Maintenance. To maximize the effectiveness of a silt curtain operation, maintenance is extremely important. This entails moving the

curtain away from the turbidity source just before the fluid mud layer encounters the lower edge of the skirt, replacing worn or broken anchor lines, and maintaining the integrity of the curtain by repairing leaking connectors and/or tears in the curtain fabric. Tears in the flotation pocket can be repaired in the water with a hand type pop rivet gun. Moderate tears in the skirt may be repaired on land with a vinyl/nylon repair kit and VINYLFIX or PVC glue. Because extensively torn sections must be returned to the manufacturer for refurbishing, one or two spare sections should be purchased for immediate substitution in the field. Improper maintenance will not only decrease the curtain's effectiveness on a particular operation, but also increase the cost of reconditioning the curtain for reuse.

126. Recovery. After the operation has been completed, the curtain should be refurled, the anchor/mooring system recovered, and the curtain returned to the launching site for cleaning, repacking, and storage. If properly stored in a location that is unexposed to the elements, the curtain can be maintained in its existing condition for several years and reused on subsequent operations.

## Flocculant Injection

127. It may be possible under certain conditions to marginally increase the settling velocity of the small percentage of dredged material slurry that is suspended in the water column during an open-water pipeline disposal operation by injecting polyelectrolytes (flocculants) into the dredge pipeline before the slurry is discharged. However, the practicality of this technique is probably limited, at best, due to the variability in the solids concentration of the slurry, the high solids concentrations that must be treated, as well as the high cost and many logistical problems associated with handling, mixing, and injecting flocculants into the slurry.[65] Therefore, the use of flocculants to reduce dredged material dispersion at open-water pipeline disposal operations is not recommended.

# PART V: DREDGED MATERIAL DISPERSION: A PERSPECTIVE ON ENVIRONMENTAL IMPACT

128. The ultimate purpose of any environmental assessment is to determine the relative impact of a proposed dredging or disposal operation. Using the information presented in the previous parts of this report, the dispersion of dredged material generated by an operation can be predicted with a reasonable degree of certainty. These predictions can then be interpreted in light of related research results dealing with the biological and chemical impact associated with the suspended dredged material. The following paragraphs first discuss some of the impacts that may be associated with a typical dredging or disposal operation, and then relate these potential effects to natural variations in the environment and other "acceptable" human activities.

## Water-Column Impact

129. There are now ample research results indicating that the traditional fears of water-quality degradation resulting from the resuspension of dredged material during dredging and disposal operations are for the most part unfounded.[6] Although the vast majority of heavy metals, nutrients, and petroleum and chlorinated hydrocarbons are usually associated with the fine-grained and organic components of the sediment,[1] there is no biologically significant release of these chemical constituents from typical dredged material to the water column during or after dredging or disposal operations. Levels of manganese, iron, ammonium nitrogen, orthophosphate, and reactive silica in the water column may be increased somewhat for a matter of minutes over background conditions during open-water disposal operations; however, there are no well-defined plumes of dissolved metals or nutrients at levels significantly greater than background concentrations.[4,6,53]

130. The impact associated with depressed levels of dissolved oxygen has also been of some concern, due to the very high oxygen demand associated with fine-grained dredged material slurry. However, even at

open-water pipeline disposal operations where the dissolved oxygen decrease should be greatest, near-surface dissolved oxygen levels of 8 to 9 ppm will be depressed during the operation by only 2 to 3 ppm at distances of 20 to 40 m from the discharge point. The degree of oxygen depletion generally increases with depth and increasing concentration of total suspended solids; near-bottom levels may be less than 2 ppm. However, dissolved oxygen levels usually increase with increasing distance from the discharge point, due to dilution and settling of the suspended material.[53,62]

131. Unfortunately, there are still many unanswered questions about the chronic and sublethal effects of turbidity on different aquatic organisms.[5,21] In some cases suspended solids may reduce photosynthesis, interfere with respiration or feeding behavior, etc. Other studies show apparently insignificant effects on organisms even after long exposure to high levels of suspended solids. Although there is apparently no significant migration of trace metals and hydrocarbons into soluble phases, these constituents associated with the suspended particulates may have a minor effect on some organisms that may use the particulates as a food source. Although research indicates that even minor impact caused by ingestion of fine-grained suspended sediment is highly unlikely,[4,5] the toxicity of highly contaminated sediment should be evaluated on a case-by-case basis.

132. It has been demonstrated that elevated suspended solids concentrations are generally confined to the immediate vicinity of the dredge or discharge point and dissipate rapidly at the completion of the operation. If the amount of turbidity generated by a dredging or disposal operation is used as a basis for evaluating its environmental impact, it is essential that the predicted turbidity levels are evaluated in light of background conditions. Average turbidity levels as well as the occasional relatively high levels that are often associated with naturally occurring storms, high wave conditions, and/or floods should be considered. For example, in San Francisco Bay, California, suspended solids levels in 1.5 m of water can average 500 mg/ℓ when wind velocities exceed 5 m/sec, which occurs 30 percent of the time.[52] On the Thames River,

Connecticut, if the suspended solids levels generated by a 12.8-cu m clamshell operation are "compared to suspended material variations associated with naturally occurring aperiodic storm events, the dredging related impacts appear negligible."[17]

133. Other activities of man may also be responsible for generating as much or more turbidity than dredging and disposal operations. For example, each year shrimp trawlers in Corpus Christi Bay suspend 16 to 131 times the amount of sediment that is dredged annually from the main ship channel. In addition, suspended solids levels of 100 to 550 mg/ℓ generated behind the trawlers are comparable to those levels measured in the turbidity plumes around open-water pipeline disposal operations.[53] Resuspension of bottom sediment in the wake of large ships, tugboats, and tows can also be considerable.[66] In fact, where bottom clearance is 1 m or less, there may be scour to a depth of 1 m if the sediment is easily resuspended.[67]

## Benthic Impact

134. Whereas the impact associated with water-column turbidity around dredging and disposal operations appears to be for the most part insignificant, the dispersal of fluid mud dredged material appears to have a relatively significant short-term impact on the benthic organisms within open-water disposal areas. Open-water pipeline disposal of fine-grained dredged material slurry may result in a 45 to 70 percent reduction in the average abundance of organisms and a decrease in the community diversity in the area covered by the fluid mud.[63,68] Despite this immediate impact, recovery of the community apparently begins soon after the disposal operation ceases. Assuming that the disposed material is similar to the sediment in the disposal area, total recovery of the disposal area to predisposal conditions has been observed to take from 3 to 18 months. The recovery time depends on factors such as the magnitude of the initial impact, the characteristics and seasonal response of the indigenous organisms to natural stresses, etc. Regardless of the environment, the impact on benthic organisms can be minimized if

the dredged material is disposed on similar sediment. In other words, mud should be disposed on mud, and not on sand.[5]

## Perspective

135. In most cases, the environmental impact associated with the dredging of uncontaminated sediment will be insignificant. However, the impact of fluid mud dispersal at open-water pipeline disposal operations appears to be relatively significant, at least for short time periods (i.e., months). Regardless of the type of dredging or disposal operation, there are certain environments (e.g., spawning grounds, breeding areas, oyster and clam reefs, areas with poor circulation, etc.) and organisms (e.g., coral, sea grasses, etc.) that may be extremely sensitive to high levels of turbidity and/or burial by dredged material.[5,69,70] It is therefore necessary to evaluate the potential impact of each proposed operation on a site-specific basis, considering: the character of the dredged material, the type and size of dredge and its mode of operation, the mode of dredged material disposal, the nature of the dredging and disposal environment and its associated seasonal cycles of biological activity, and the degree and extent of the potential short- and long-term impact relative to background conditions. Although the impacts associated with existing dredging and disposal procedures are proving not to be as severe as previously alleged, by implementing the guidelines given in this report for selecting dredges, improving operational techniques, properly using silt curtains, and selecting appropriate pipeline discharge configurations, any dredging or disposal operation can be conditioned to minimize its environmental impact.

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# APPENDIX A: RELATIONSHIP BETWEEN SUSPENDED SOLIDS CONCENTRATION, BULK DENSITY, AND PERCENT SOLIDS BY WEIGHT

1. Suspended solids concentrations (in grams per litre) can be converted to percent solids by weight or bulk density using the following procedure:

a. $$\frac{\text{Solids concentration (i.e., weight of dry solids)}}{\text{Dry density of solids}} = \text{Volume of solids}$$

b. 1000 cc of suspension - Volume of solids = Volume of liquid

c. Volume of liquid × Density of liquid = Weight of liquid

d. $$\frac{\text{Weight of solids} \times 100}{\text{Weight of solids} + \text{Weight of liquid}} = \text{Percent solids (by weight)}$$

e. $$\frac{\text{Weight of solids} + \text{Weight of liquid}}{\text{1000 cc of sample}} = \text{Bulk density of sample (g/cc)}$$

EXAMPLE: solids concentration = 200 g/ℓ, density of solids = 2.65 g/cc, and density of liquid = 1.03 g/cc.

1. $$\frac{200\ \text{g}}{2.65\ \text{g/cc}} = 75.47\ \text{cc of solids}$$

2. 1000 cc - 75.47 cc = 924.53 cc of liquid

3. 924.52 × 1.03 g/cc = 952.27 g of water

where: density of fresh water = 1.00 g/cc

density of seawater = 1.035 g/cc

4. $$\frac{200\ \text{g} \times 100}{200\ \text{g} + 952.27\ \text{g}} = 17.35\ \text{percent solids by weight}$$

4. $$\frac{200\ \text{g} + 952.27\ \text{g}}{1000\ \text{cc}} = 1.152\ \text{g/cc}$$

2. The relationship among suspended solids concentrations, percent solids by weight, and bulk density is shown in Figure A1.

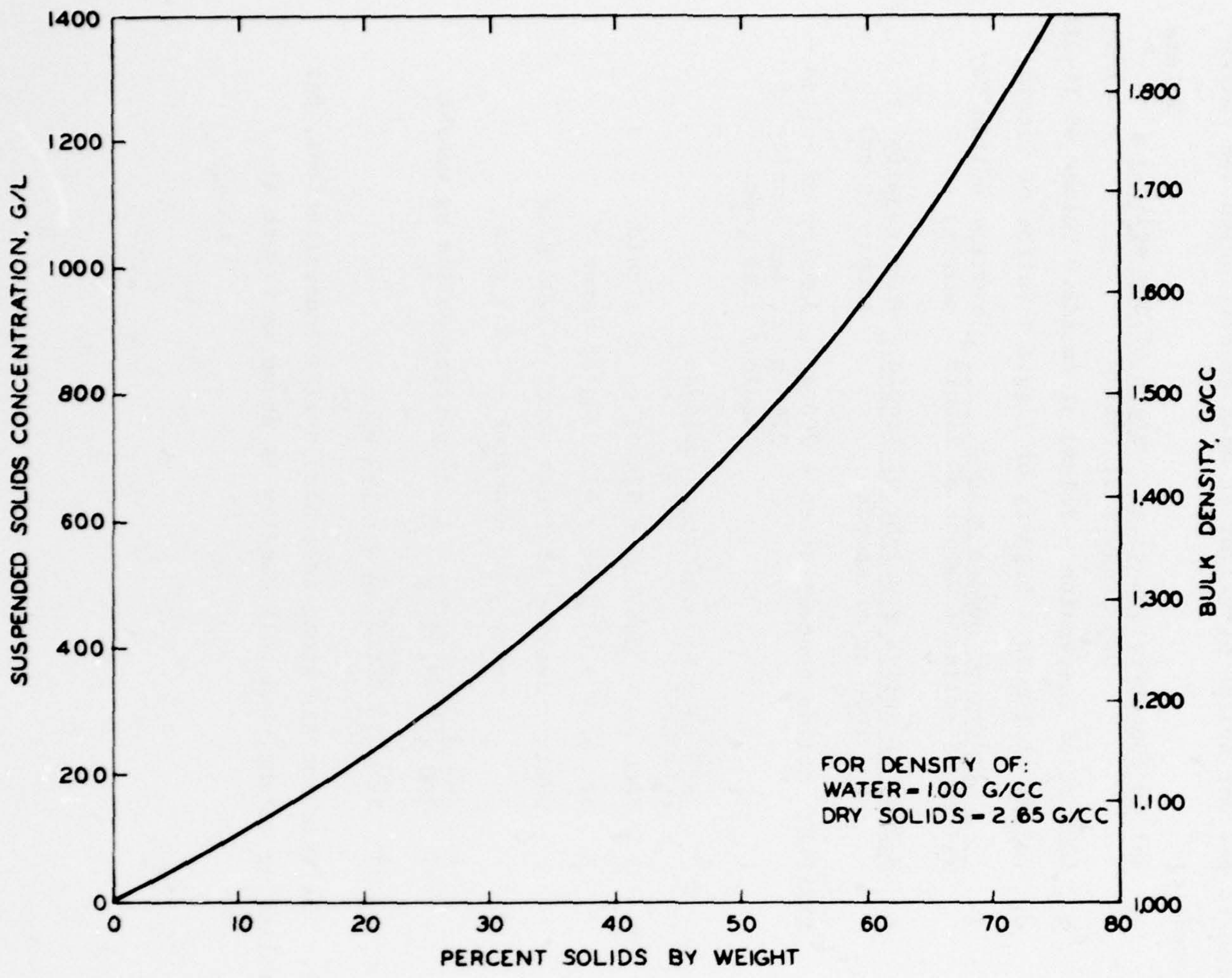

Figure A1. Relationship among suspended solids concentrations, percent solids by weight, and bulk density

**In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.**

Barnard, William D

Prediction and control of dredged material dispersion around dredging and open-water pipeline disposal operations / [by William D. Barnard]. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.

112, 2 p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; DS-78-13)

Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C.

Literature cited: p. 106-112.

1. Dispersion. 2. Dredged material. 3. Dredged material disposal. 4. Dredging. 5. Fluid mud. 6. Open water pipeline disposal. 7. Predictions. 8. Silt curtains. 9. Turbidity. I. United States. Army. Corps of Engineers. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; DS-78-13.

TA7.W34 no.DS-78-13