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DREDGED MATERIAL RESEARCH PROGRAM

TECHNICAL REPORT [illegible]

METHODOLOGY FOR DESIGN OF FINE-GRAINED DREDGED MATERIAL CONTAINMENT AREAS FOR SOLIDS RETENTION

by

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U. S. [illegible]

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DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180

IN REPLY REFER TO: WESEV

15 June 1979

SUBJECT: Transmittal of Technical Report D-78-56

TO: All Report Recipients

1. The report transmitted herewith is the result of a work unit initiated as part of Task 5C (Disposal Area Reuse Research) of the Corps of Engineers' Dredged Material Research Program (DMRP). Task 5C was part of the Disposal Operations Project of the DMRP and among other items included developing design procedures for reusable disposal areas. Although the work was conducted as part of Task 5C, the methods developed are also applicable to the more general Task 2C (Containment Area Operations).

2. Confining dredged material on land is a disposal alternative which few specific design or construction improvement investigations addressed prior to the DMRP. Because of the dramatic increase in the last several years in the amount of land needed for disposal, a significant portion of the work in the DMRP was aimed toward identifying ways of increasing the capacities of containment areas and designing them in such a manner that return of solid particles in the effluent would be minimized. A literature review revealed gaps in research concerning the use of existing procedures for designing containment areas for fine-grained dredged material to meet standards for effluent suspended solids level. This study (Work Unit 5C11) was conducted to provide a rational procedure for the design of confined containment areas to meet effluent quality standards.

3. Although the literature review revealed gaps in the research, it did provide the basis for developing laboratory and field investigations and for evaluating results. Samples of channel sediments and dredged material were collected at four active dredging sites for use in conducting laboratory tests, determining suspended solid levels of dredged discharges and containment area effluents, and developing profiles of suspended solids versus depth for the containment areas. Dye tracer studies were used to investigate the short-circuiting and mixing properties of containment areas.

4. Procedures are presented for designing new containment areas for suspended solids retention and for determining the suspended solids retention potential of existing areas. Design methods for saltwater

and freshwater sediments are included. The design procedures are based on gravity sedimentation of suspended solids. With proper design and operation of containment areas, the sedimentation process would normally provide removal of solids down to levels of 1 and 2 g/ℓ in the effluent for saltwater and freshwater sediments, respectively. Dye tracer studies indicated that a correction factor of about 2.25 should be applied to design area and to retention times to compensate for the deviation from ideal or plug flow conditions.

5. The results of this study were incorporated into the final recommended design procedures outlined in Technical Report DS-78-10. The final design procedure provides guidance on sizing containment areas to ensure that volume requirements are met as well as requirements for solids retention.

John L. Cannon
JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

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A literature review revealed gaps in research concerning the use of existing procedures for designing containment areas for fine-grained dredged material to meet standards for effluent suspended solids levels. The literature review did provide the basis for developing laboratory and field investigations and for evaluating results.

Four active dredging projects were used as sites to obtain samples of → cont'

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20. ABSTRACT (Continued).

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channel sediments and dredged material for laboratory tests, determine suspended solids levels of dredge discharges and containment area effluents, and to develop profiles of suspended solids versus depth for the containment areas. Dye tracer studies were used to investigate the short-circuiting and mixing properties of containment areas.

It was found that grab samples taken from channel bottom sediments are adequate for performing sediment characterization and settling tests. Sediment organic contents were generally less than 10 percent for all the sites except one. In general the organics were considered to be too low to be a significant factor in evaluating the settling properties of the dredged material.

Settling tests performed in an 8-in.-diam column were found to be satisfactory for defining dredged material settling behavior within a containment area. Settling behavior in the freshwater environment was best described by a flocculent settling test, while behavior in a saltwater environment was best described by a zone settling test. The same settling columns were used for both tests with only minor procedural changes.

Procedures are presented for designing new containment areas for suspended solids retention and the suspended solids retention potential of existing containment areas. Design methods for saltwater and freshwater sediments are included. The design procedures are based on gravity sedimentation of suspended solids. With proper design and operation of the containment area, the sedimentation process will normally provide removal of solids down to levels of 1 and 2 g/ℓ in the effluent for saltwater and freshwater sediments, respectively. If the required effluent standards are lower than these levels, the designer must provide for additional treatment of the effluent; e.g., flocculation or filtration. Dye tracer studies indicated that a correction factor of about 2.25 should be applied to design area and detention times to compensate for the deviation from ideal or plug flow conditions.

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SUMMARY

This report provides procedures for designing fine-grained dredged material containment areas to provide adequate retention of suspended solids so that required effluent suspended solids levels can be met.

A search of the literature revealed major gaps in the research concerning use of existing procedures for designing such containment areas. No major research effort had investigated the settling properties of suspensions having solids concentrations in the range of dredged material slurries. The literature did, however, provide good guidance for developing the field and laboratory investigations for the study and for evaluating the results.

Field studies were performed to obtain samples of channel sediment and dredged material for laboratory tests, determine suspended solids levels of dredge discharges and containment area effluents, and develop profiles of suspended solids versus depth for the containment areas. Dye tracer studies were performed to investigate the short-circuiting and mixing properties of containment areas. Four active dredging projects were used as field study sites.

It was found that grab samples taken from the channel bottom are sufficient for performing sediment characterization and settling tests. Such samples are also relatively easy and inexpensive to obtain. Sediment organic contents were generally less than 10 percent for all the sites except one. In general, the organics were considered to be too low to be a significant factor in evaluating the settling properties.

It was also found that settling tests performed in an 8-in.-diam column are satisfactory for defining dredged material settling behavior within a containment area. Settling behavior in the freshwater environment is best described by a flocculent settling test, while behavior in a saltwater environment is best described by a zone settling test. The same settling column can be used for both tests with only minor procedural changes.

Methodology is presented for fine-grained dredged material containment area designs for meeting effluent suspended solids requirements

based on determination of a surface area or detention time required to accommodate a continuous dredged material disposal operation. The designs call for suspended solids removal by the process of gravity sedimentation allowing discharge of carrier water from the containment area. Suspended solids removal efficiency for freshwater sediments depends on the ponding depth as well as the properties of the particles.

The sedimentation process, with a proper design and operation, will normally provide removal of fine-grained sediments down to a level of 1 to 2 g/ℓ or less in the effluent. However, because of the influence of factors at the site, removal below these levels cannot be predicted from the design procedures. It is possible, however, that a saltwater containment area will accomplish removal to a level less than 1 g/ℓ, but a freshwater containment area will generally provide removal down to a level of only about 2 g/ℓ.

Ideal flow or plug flow never exists in an actual containment area because flow is always accompanied by a certain amount of mixing and short-circuiting. Consequently, the design areas and detention times must be increased by a correction factor to compensate for deviation from plug flow. The dye tracer studies indicate that a correction factor of about 2.25 should be applied to the designs.

Ponding depths should be as great as possible to provide longer detention times and reduce the effects of short-circuiting. A minimum ponding depth of 2 ft is recommended for sedimentation of solids during a continuous disposal activity.

PREFACE

This study was conducted as Work Unit 5C11 of the Dredged Material Research Program for the Office, Chief of Engineers, U. S. Army, at the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss. This work unit was part of the Disposal Operations Project, Mr. Charles C. Calhoun, Jr., Manager.

The study was conducted by the Environmental Engineering Division (EED) of the Environmental Laboratory (EL) at WES, under the general supervision of Dr. John Harrison, Chief, EL, Dr. Roger T. Saucier, Special Assistant, EL, and Mr. A. J. Green, Chief, EED.

The research is the basis for the dissertation research of Dr. Raymond L. Montgomery, who performed the field and laboratory data analyses. SP5 José L. Llopis made significant contributions toward the successful accomplishment of the field and laboratory investigations. Mrs. Jean M. Bishop and Mrs. Patricia B. Hopkins were instrumental in preparation of the data for reporting. The report was written by Dr. Montgomery.

The Director of WES during the study was COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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

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

Multiply	By	To Obtain
acres (U. S. survey)	4046.856	square metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
gallons (U. S. liquid)	3.785412	litres
gallons (U. S. liquid) per minute	3.785412	litres per minute
inches	2.54	centimetres
miles (U. S. statute)	1.609344	kilometres
miles (U. S. statute) per hour	1.609344	kilometres per hour
ounces (U. S. fluid)	29.57353	cubic centimetres
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square feet	0.09290304	square metres
square inches	6.4516	square centimetres
tons (2000 lb mass)	907.1847	kilograms
yards	0.9144	metres

METHODOLOGY FOR DESIGN OF FINE-GRAINED DREDGED MATERIAL CONTAINMENT AREAS FOR SOLIDS RETENTION

PART I: INTRODUCTION

Background

1. Confinement of dredged material on land has been a major disposal alternative used by the Corps of Engineers for a number of years. In more recent years this practice has increased, and added requirements have been placed on the solids retention capability of confined disposal areas. The confined disposal (containment) areas used for both retention and disposal of dredged material are simply sedimentation basins.

2. Sedimentation has been used far more widely than any other major process for the removal of suspended matter from water; no doubt it is the oldest process which has remained in continued use. The settling behavior of suspensions has always been the key to the design of effective sedimentation basins, and this factor has consequently captured the interest of researchers in a number of fields. Extensive literature is available on the subject.

3. Despite the importance of this process and the long years of experience in its use in wastewater and water treatment, application of the principles involved has been so limited in the area of dredged material disposal that procedures have not been developed for designing fine-grained dredged material containment areas. Stricter requirements for effluent suspended solids are now in force, and as a result procedures are needed for designing containment areas for high suspended solids removal efficiencies.

4. The containment areas currently being used for separating and retaining dredged material solids range in size from less than 10 acres*

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 11.

to about 2500 acres. The dimensions of most of these have been fixed on the basis of available land or volume needed for multiyear storage of dredged material.

5. Dredged material containment areas are slightly different from the sedimentation basins used in water and wastewater treatment in that the former must provide for sedimentation to achieve acceptable effluent quality while providing storage volume for several years of material dredged from local waterways. In most cases, the amount of dredged material storage required is the controlling factor in sizing a conventional disposal area. Nevertheless, the large areas now in existence often have problems meeting the effluent requirements for suspended solids. This shortcoming can be attributed to the (a) nonuniform lateral distribution of flow and (b) short-circuiting currents that occur in most dredged material containment areas. As a result of short-circuiting currents, one section of flow is subjected to a different flow-through rate than another.

6. The major problem is that very little is known about the actual sedimentation process in dredged material containment areas. The hydrodynamic problem of one particle falling through a fluid has been solved (Stoke's Law), and formulas have been developed by researchers to determine the fall speed when the particle density is very small and the distance between particles is much greater than their diameter. In practice, dredged material is discharged into containment areas at concentrations averaging about 145 g/ℓ. Because of this high concentration, it is believed that sedimentation occurs under either flocculent or zone settling processes.

7. High-density slurries have been observed near the surface of dredged material containment areas, indicating that hindered settling occurs in a significant portion of the water column. The velocity for hindered settling is less than that predicted by theories based on discrete settling because of the increase in drag occasioned by the presence of other particles. A review of present practices indicates that many dredging-disposal operations cannot be undertaken on a continuous basis and still maintain acceptable suspended solids removal

levels. Where strict effluent suspended solids limits are enforced, periods of interrupted dredging are commonly used to reduce the loading rate and provide time for particle settling. These interrupted dredging operations usually result in increased overall operational costs.

Purpose and Scope

8. The purpose of this study was to investigate dredged material settling characteristics, dredged material sedimentation processes, applicability of prevailing theories on sedimentation to dredged material, and influence of existing disposal operational practices on sedimentation. These results were then to be used in developing guidelines for design and operation of dredged material containment areas. The design and operation guidelines were to be aimed at producing dredged material containment areas that can accommodate continuous flow while meeting effluent suspended solids requirements.

Approach

9. The approach used in this study was to perform field and laboratory investigations of dredged material slurry characteristics, settling characteristics of solids, and sedimentation processes in disposal areas and to identify containment area operational practices affecting sedimentation. A literature review was conducted to determine the applicability of existing sedimentation theories to the design of dredged material containment areas. The information gained from the field and laboratory investigations and literature review was used to develop a design approach for fine-grained dredged material containment areas.

Related Studies

10. For a containment area to perform the solids removal and storage functions, its weir(s) must be properly designed and its shape

must promote efficient flow through the area. Walski and Schroeder[1] evaluated the relationship between weir design and effluent suspended solids and developed a procedure for designing weirs with effective lengths. The design procedure was developed on the basis of a field study program in which several sites were investigated to provide data for mathematical models. The authors found that models were available to predict the depth of the withdrawal zone (the required ponding depth) and the velocity profile for weirs.

11. Data collected at the field sites were also used as input for evaluation and verification of these available models. Information collected included velocity, concentration, and density profiles; flow rates; depth; weir length; head and velocity of flow over the weir; and grain size, specific gravity, and angle of repose of the dredged material. With the exception of concentration and density profiles representative of dredged material containment areas, much of this information was available in the literature. Concentration profiles for different dredged material and site conditions were determined for all field sites.

12. The selective withdrawal model developed at the U. S. Army Engineer Waterways Experiment Station (WES) by Bohan and Grace[2] was found appropriate for use. The design approach for weir sizing was developed using this model and verified with a limited amount of field data.

13. A study by Brian J. Gallagher and Company[3] provided more insight into effective containment area shape and operational procedures. The investigation included an extensive literature review, interviews with key personnel from various Corps Districts, field studies, and development of computer models for synthesizing flow patterns in disposal areas. Model studies were used in estimating overall hydraulic efficiencies of various containment shapes, inflow/outflow locations, and spur dike configurations. All of this information was then integrated to produce recommendations for design of containment areas to obtain maximum hydraulic efficiency.

14. The relative locations of the inflow pipe and the outflow

weir were found to have significant effects on the hydraulic efficiency of the containment area by directly influencing the effective area and the occurrence and degree of short-circuiting.

15. Consideration was given to the use of spur dikes to increase the length-to-width ratio and improve hydraulic efficiency in a disposal area. Flow patterns were determined for various spur dike configurations. Short-circuiting was reduced for all configurations, but the effect was greater for longer spur dikes. However, to avoid excessive flow concentration and increased flow velocities through the spur dike openings, it was determined that the length of the spur dikes should be approximately 0.75 times the length of the parallel side of the containment area. One or two spur dikes should usually be sufficient and three or four should be the maximum number used. A minimum length-to-width ratio of approximately 5 should be provided for the flow pattern if possible. A spur dike should not be located close to the weir as it will have a detrimental effect on the hydraulic efficiency of the containment area because higher flow velocities will occur and there will be a possible resuspension of bottom sediment in the vicinity of the weir.

Literature Review

16. A dredged material containment area performs both clarification and thickening functions. Clarification is essentially the same function as that covered in sanitary engineering literature, but the thickening function is different in that no concentrated underflow slurry can be withdrawn from the containment area. The dredged material containment area must provide adequate storage volume for the thickened dredged slurry during the disposal activity. The influent suspended solids concentrations of dredged slurries vary between about 42 and 300 g/ℓ and average about 145 g/ℓ. (See Part IV.)

17. An extensive search was conducted to gather pertinent literature on known sedimentation theories. The literature was reviewed for information on settling theories and for research on testing procedures and equipment used to determine settling velocities for slurries with

suspended solids in the range mentioned above for dredged material. Literature on prevailing design procedures was also collected.

18. A review is given in the following paragraphs of available information on the work leading to the development of the existing theories for discrete, flocculent, and zone settling. The literature on discrete particle and ideal settling is included mainly because the only work to date on the development of design procedures for dredged material containment areas used the ideal settling approach.[4-6]

19. In 1904, Hazen[7] presented the fundamental proposition that every particle of suspended matter moves downward through the water column at a velocity that depends on its size and weight and the viscosity of the water. He proposed that each particle settles as if no other particles are present. From his work he concluded that sedimentation in a basin would depend on the area of bottom surface exposed to settling particles and that sedimentation of these particles would be independent of basin depth. For best results, he recommended that mixing be minimized in the basin. He discussed short-circuiting as an important factor in reducing basin efficiency.

20. Coe and Clevenger[8] defined four distinct settling zones to describe the sludge thickening mechanism. These zones are as follows:

- a. Zone of clarified water.
- b. Zone of uniform concentration which settles at a constant rate.
- c. Transition zone in which the solids concentration increases from that of zone b to that at the top of zone d.
- d. Compression zone in which the particles rest upon each other (the term "consolidation zone" is used in this report).

They were the first to make the distinction between hindered settling, in which the settling rate depends on concentration, and settling compression, in which elimination of fluid is a function of time. This has become a fundamental principle of thickening theory. They also introduced the concept of each concentration of a suspension having a certain capacity to discharge its solids. It was explained that, if a layer has a lower solids handling capacity than the overlying layer, it will not be able to discharge solids as fast as they are received and will necessarily increase in thickness. Coe and Clevenger prescribed a series of batch settling tests at various concentrations to identify the solids handling capacity of the limiting layer. Designs were then based on providing sufficient area to assure that solids would be applied at a rate less than the solids handling capacity of the limiting layer. From this work originated the concept of surface area requirements and scaling up from batch tests. They also developed design equations based on the assumption that, for a given slurry, settling velocity is a function only of the solids concentration.

21. Camp[9] expanded on Hazen's work and developed the "ideal" basin concept. He proposed a rational theory of clarification based on the following assumptions for the "ideal" basin:

a. The direction of flow is horizontal, and both direction and velocity are the same in all parts of the basin.

b. The concentration of suspended particles of each size is the same at all points in the vertical plane perpendicular to the direction of flow at the basin inlet.

c. All suspended particles maintain their shape, size, and individuality during settling and settle without interference. Hence, each particle is assumed to settle at a constant velocity.

d. A particle is removed when it strikes the bottom.

22. This work by Camp is limited in application to cases where each suspended particle maintains its individuality and settles at a constant velocity. In such cases, settling velocities can be determined by application of Stoke's Law. For ideal conditions, the removal of solids is independent of basin depth for a given discharge; for particles which settle at velocities less than the overflow rate, the removal is directly proportional to the surface area of the basin for a given discharge or inversely proportional to the tank overflow rate. Camp also stated that since removal is independent of depth for a given discharge it is also independent of the detention period. These conditions only apply where each suspended particle maintains its individuality and settles at a constant velocity. Camp agreed that in an actual basin conditions could differ greatly from these assumed conditions.

23. Camp was the first to recognize that gentle mixing promotes flocculation and more rapid clarification. In cases where flocculation occurs, Camp recommended that settling velocity analyses be made using column tests with concentrations being determined with time and at constant depth intervals along the column.

24. Kynch[10] developed a mathematical approach for analysis of the thickening operation on the basis that "at any point in a dispersion the velocity of fall of a particle depends only on the local concentration of particles." This means that for each type of suspension there is a unique curve relating velocity of fall and local concentration. The Kynch analysis permits the determination of settling velocity for any concentration from data obtained in only one batch test. Many researchers feel that the work of Kynch could well have preceded the 1916 work of Coe and Clevenger[8] since the limiting solids handling capacity promoted by Coe and Clevenger is a logical outgrowth of Kynch's work. Kynch presumed that all particles were of the same size and shape and that they were uniformly distributed in the horizontal plane. He did not discuss flocculent particles or the applicability of the theory to compressible materials. However, in contrast to the suspension assumed by Kynch, dredged material is comprised of nonrigid flocculent particles. The flocs may combine into aggregate particles whose size is not necessarily uniform or spherical and is subject to change.

25. Kynch's work has been applied to design procedures in sanitary engineering by Talmage and Fitch[11] and others. Kynch's procedure was considered to have great promise for some time and was used in sanitary engineering texts as the basis for establishing a required area for thickeners. Dick and Ewing[12] and others have found that Kynch's work is inapplicable for flocculent materials, such as biological sludges. Fitch,[13] although originally applying the Kynch analysis for design purposes, has in recent years stated that the procedure has very limited application and should not be used for design.

26. Yoshioka et al.[14] developed a graphic procedure for analysis of the sedimentation of suspensions. This graphic approach eliminates the labor involved in the repetitive solution of the equations developed

by Coe and Clevenger[8] yet produces the same results as the Coe and Clevenger equations. A modified version of the Yoshioka graphic procedure for use in designing containment areas for saltwater sediments is presented in Part V of this report.

27. McLaughlin[15] developed an analytical and experimental approach for evaluating the settling properties of suspensions of particles in fluid and outlined the use of these properties in predicting the sedimentation of the particles. He divided the factors affecting the settling of suspended particles into two groups. The first group was called conditions of flow, and the second was called the settling properties of the slurry. These terms refer to how the particles behave under a given set of flow conditions. He states that, for some specified temperature, pressure, fluid velocity, and turbulence, the particles of a slurry will settle, flocculate, or be diffused in some manner. This behavior will vary for each slurry or sludge and must be determined experimentally. McLaughlin presented a method for use in determining when hindered settling and flocculation occur in column tests and when these factors do not affect settling.

28. Fitch[13] stated that the Kynch analysis of a batch test had not proven as useful in design as originally hoped. The Kynch approach was not completely valid over the entire zone settling regime, and it was not valid at all in the compression regime. In the zone settling regime, although the particles were more or less locked into a zone, they could still move. In the more dilute ranges of this regime, there could be significant classification during the batch settling test, which concentrates slow settling material next to the interface. The subsidence rate of the interface then would no longer correspond to the settling rate of the original solids. He recommended using the Coe and Clevenger technique for design.

29. Dick and Ewing[16] reviewed the prevailing theories for determining the required area of thickeners and concluded that the theories were based on the assumption that settling velocity in a suspension depends only on the local concentration of particles. They showed that this was not a valid assumption for activated sludge and stated that

the prevailing theories were not strictly applicable to the design of final settling tanks or separate thickeners for activated sludge. They assumed that interparticle forces accounted for the deviation from prevailing theory and recommended that the extent of the deviation be evaluated by the retardation factor and ultimate settling velocity. Although they were concerned with activated sludge, their approach in evaluating settling properties appears sound and provided good guidance for developing an approach for evaluating the settling properties of dredged material.

30. Vesilind[17] evaluated the area design methods for designing thickeners and recommended a direct method for calculating area based on experimental determination of an expression relating settling velocity with slurry concentration. He stated that the methods available for determining thickener area requirements were essentially restatements of the Coe and Clevenger equation. This equation is based on the assumption that the settling velocity of the slurry in a small batch cylinder is a true indicator of the settling characteristics in a large continuous thickener. Vesilind showed that settling velocity of sludge is a function of not only concentration but also of initial depth, cylinder diameter, and the amount of flocculation attained by the sludge. He recommended that, if design is to be based on the Coe and Clevenger method, the laboratory tests should be designed to minimize the influence of settling columns on the settling velocities determined. Vesilind concluded that reproducible results, in terms of settling velocities, are possible with quiescent batch settling tests. The sludge must agglomerate, however, and agglomeration is enhanced by low solids concentrations, large diameter test columns, and long filling times. He investigated the effects of stirring and concluded that slow stirring does not benefit settling velocity in large diameter test columns. However, slow stirring did enhance agglomeration, improve reproducibility, and allow the use of smaller diameter test columns and higher sludge concentrations in batch settling tests.

31. Mallory and Nawrocki[4] conducted a study to develop concepts for design of dredged material containment areas. They proposed using

the ideal settling approach and designing fine-grained containment areas using Stoke's Law. Nothing was presented that proved that settling occurs in this manner in a dredged material containment area. The work on settling was a restatement of Camp's work with no effort devoted to investigating true settling properties of fine-grained dredged material.

32. Krizek, FitzPatrick, and Atmatzidis[5] investigated effluent filtering systems for use at dredged material containment areas. In their review of the literature on sedimentation, they concluded that no model or methodology, theoretical or empirical, was available for use in predicting the sedimentation regime in dredged material containment areas with confidence. They presented a design approach based on theories developed by Hazen[7] and modified and extended by Camp[9] to describe sedimentation in an ideal regime of horizontal laminar flow. They suggested that this approach be used for a first-order approximation of sedimentation in a dredged material containment area in the absence of any documented methodologies.

33. Migniot[18] performed a study on fine-grained sediments to investigate their physical properties and evaluate their behavior under hydrodynamic action. He found in this research that a suspension of fine-grained material in water, within certain limits, would flocculate better, the smaller the individual particles, the higher their concentration in the suspension, and the greater the content of flocculent salts in the medium. He also found that very small amounts of seawater were sufficient to promote flocculation. In the concentration range of dredged material (145 g/ℓ), settling rates were not greatly affected by salinity of the water. However, at slurry concentrations of about 2 g/ℓ, Migniot found that settling rates increased until salinity reached 2 ppt salt concentration; then they were constant through higher salinity concentrations.

Summary of Literature

34. The review of literature revealed that the classic laws of sedimentation apply to the settling of discrete, nonflocculating particles in dilute suspension. However, these laws cannot be applied to

dredged material slurries with their high solids concentrations although some researchers have used them for rough approximations of dredged material settling properties.

35. Sedimentation of flocculating particles is a function not only of the settling properties of the particles but also of the flocculating characteristics of the suspension. In this case, sedimentation is dependent both on the settling rate and depth. There is no satisfactory formula available for evaluating the flocculation effect on sedimentation. It is necessary to perform a column settling test in order to measure this effect.

36. The literature, with the exception of Migniot,[18] covered only freshwater suspensions and generally at concentrations less than about 30 g/ℓ. No major research effort has investigated the settling properties of suspensions having solids concentrations in the range of those generally listed for dredged material slurries.

37. Dredged material slurries can contain either fresh or salt water depending on the dredging environment. No major research has investigated the settling properties of highly concentrated saltwater dredged material slurries. However, Migniot worked with the settling of soil sediments to some extent in his study.[8]

38. Dredged material containment areas must provide for both clarification and storage of solids with no provisions made for removal of concentrated slurry during the dredging process. Dredged material containment is both a treatment and a disposal process. Thus, containment areas differ greatly from the clarifiers, thickeners, and sedimentation basins covered in the literature.

39. There are major gaps in the literature as it relates to the problems of designing dredged material containment areas. However, the literature provided good guidance for developing the field and laboratory investigations for this study and for evaluating the results. The works of Coe and Clevenger,[8] Dick and Ewing,[12] Yoshioka et al.,[14] McLaughlin,[15] and Vesilind[17] had the most significant input to this study.

PART II: FIELD INVESTIGATIONS

General

40. The objectives of the field studies were to:

- a. Obtain samples of channel sediment and dredged material for laboratory tests.
- b. Determine dredge discharge suspended solids levels and containment area effluent suspended solids levels.
- c. Develop profiles of suspended solids versus depth for the containment areas.
- d. Perform dye tracer tests to gain information on containment area flow-through characteristics.

The four field sites investigated are shown in Figure 1. These sites were selected because they were less than 100 acres in size, had been built to contain fine-grained dredged material, and were the only acceptable sites identified that would be active during the time frame of the scheduled field studies. Small sites (<100 acres) were necessary to provide the data required to develop the design methodology for sedimentation. These sites were also selected because they involved different dredging environments. It was important that the disposal activities provide an adequate period of continuous dredged material disposal so that the sedimentation processes could be investigated. Only two sites, Yazoo River and Fowl River, were operated to permit the collection of data on sedimentation processes and other data to meet the field study objectives. The other two sites, Mobile Harbor and Brunswick Harbor, were used to collect samples of channel sediments and dredged material for laboratory tests. No tests were performed inside the containment areas at these sites.

Sediment Investigations

41. Samples of the channel sediments to be dredged were taken for use in laboratory testing. A sufficient number of samples were taken over the dredging reach to ensure that the samples would be

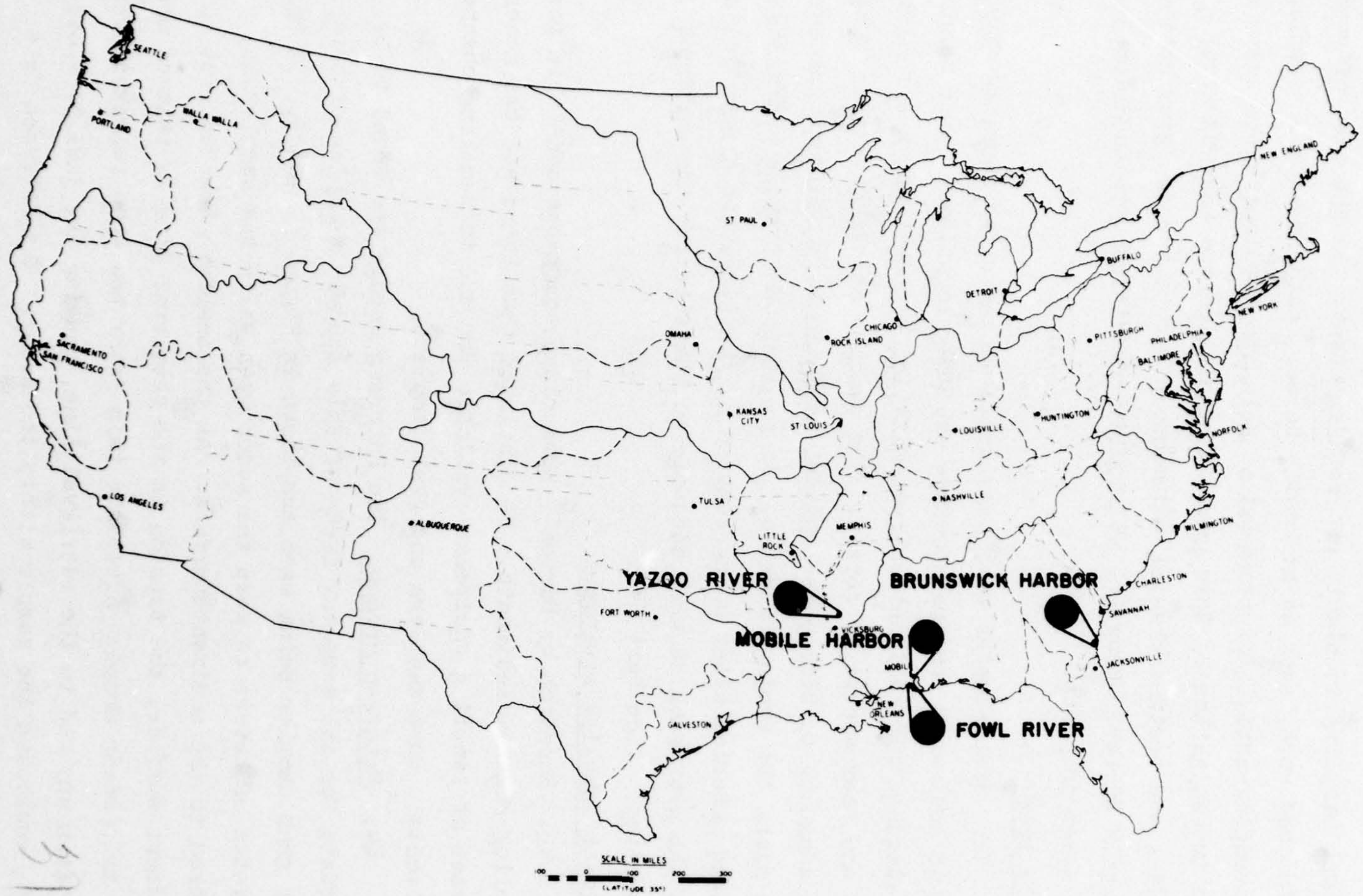


Figure 1. Field study sites

31

representative of the material to be dredged and placed in the containment area. It was found that the level of effort required for channel sediment sampling is highly project-dependent. In the case of routine maintenance work, such as at Mobile Harbor, data from prior samplings and dredging activities provided a basis for developing the scope of field investigations. This general conclusion was reached after sampling and testing channel sediments prior to two dredging activities in Mobile Harbor. However, it should be verified with additional data from other projects.

Sample type

42. Grab samples were considered adequate for sampling fine-grained sediments from maintenance dredging locations. Such samples are adequate for sediment characterization purposes and are relatively easy and inexpensive to obtain. The samples obtained in this study were adequate to define the spatial variations in sediment characteristics along the project reaches. An evaluation of these sediments as dredged material after being removed by the hydraulic dredge indicated that the grab samples were adequate to characterize the sediment properties. (See Part IV.)

Sediment sampling equipment

43. Research by Bartos[19] summarized equipment available for sampling channel sediments. He concluded that there are two general classes of sampling equipment available for use in sampling channel sediments: tube samplers and grab samplers.

44. Petersen dredge. The Petersen dredge was found to be adequate for the sampling needs of this study. Examples of this type grab sampler being used are shown in Figures 2 and 3. It has a system of levers to keep the scoop open while the sampler is lowered to the sediment surface. As the sampler comes to rest on the sediment surface, the tension in the retrieval line is relaxed and the trip lever drops. After the trip lever has been released, tension is again applied to the retrieval line, causing the jaws to slowly shut, enclosing the sample within the scoop. The Petersen is a versatile sampler; it will sample a wide range of bottom textures,

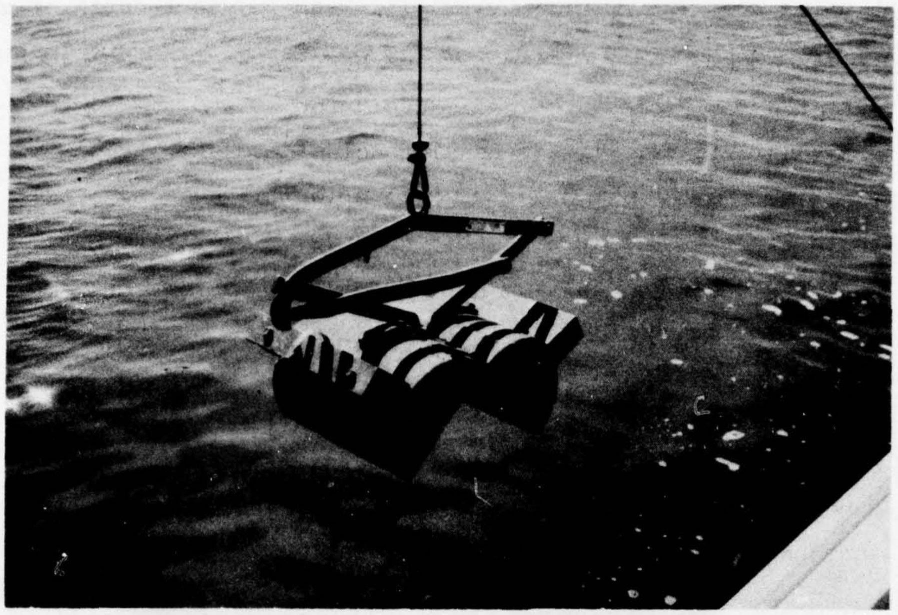


Figure 2. Petersen dredge

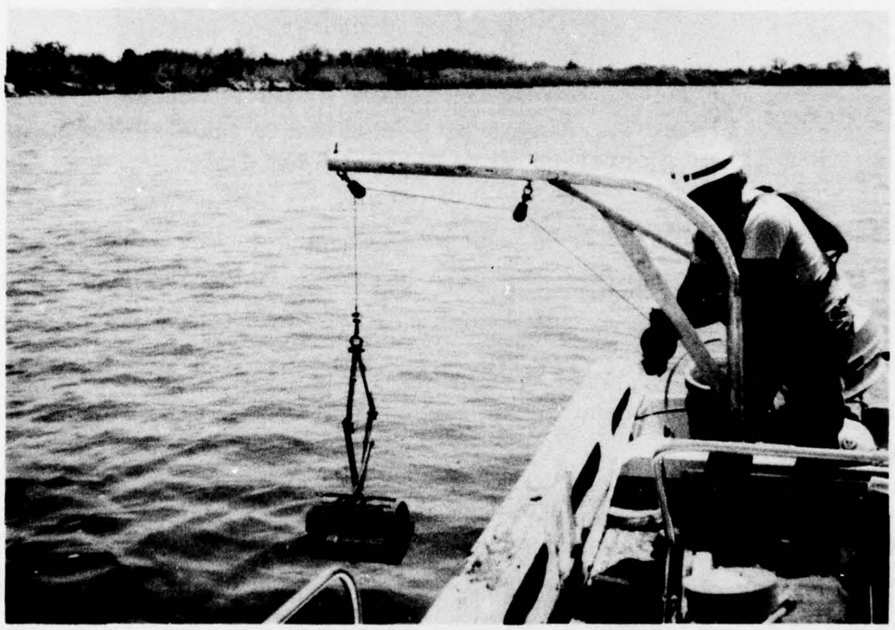


Figure 3. Petersen dredge being used to sample Mobile Harbor sediments

from fine-grained clays to sands. The sampler weighs 39 lb empty (out of water), with additional weights available to provide a total weight of 93 lb. The Petersen samples 144 sq in. to a depth of about 12 in., depending on the texture of the sediment. Figure 4 is presented

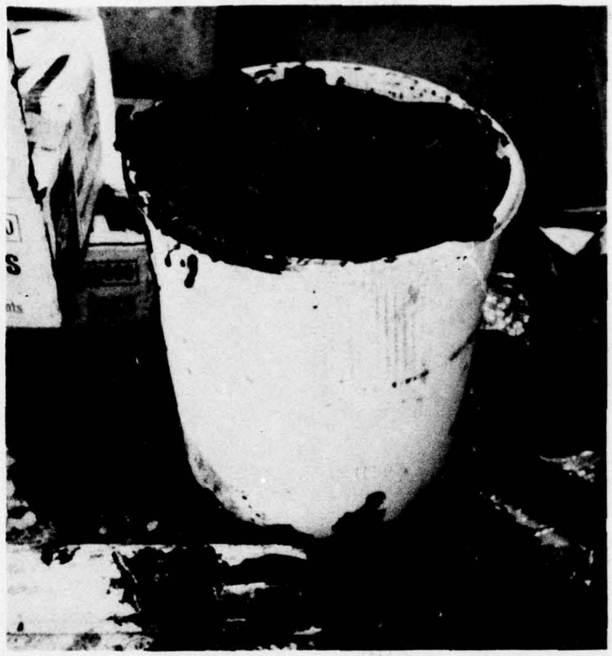


Figure 4. Sample of Mobile Harbor sediment obtained with Petersen sampler

to illustrate the fine-grained texture of the sediments sampled using the Petersen sampler in Mobile Harbor. It can be seen in Figure 3 that the sampler closes tightly, minimizing the loss of sediment and water upon retrieval. The samples obtained with this type grab sampler were considered to be at representative in situ moisture contents.

45. Phleger tube sampler. Figure 5 illustrates an attempt to use the Phleger tube sampler in Mobile Harbor. Although it has been widely used for obtaining samples from the upper portion of underwater sediments, the materials in this location were too soft to be retained in the sampler tube. The sampler was not equipped with a flap in the barrel to retain the soft material. If it had been, sampling

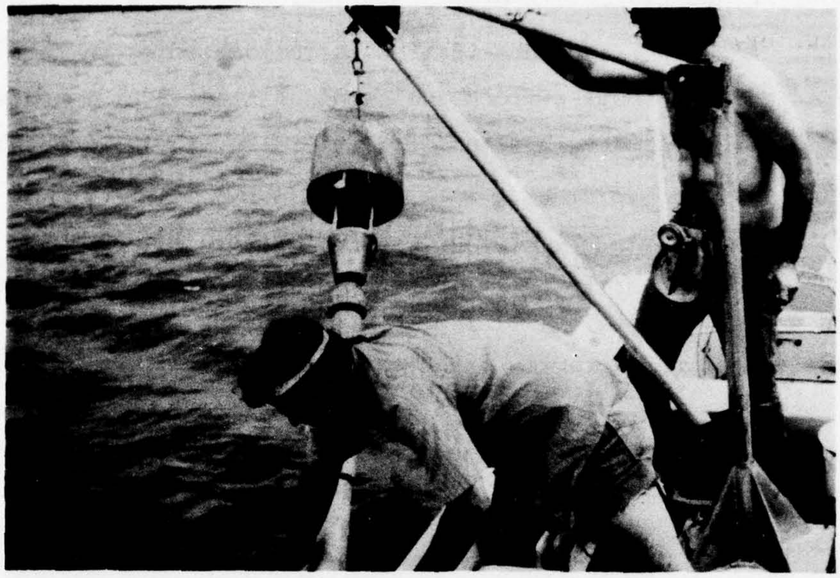


Figure 5. Phleger tube sampler

attempts would likely have been more successful.

Water samples

46. Water samples were taken at the same time as channel sediment samples. The water samples were taken from near the water-sediment interface and used to determine the salinity of the sediment environment. As will be seen in Parts III and IV, salinity levels play an important role in the way sediments settle. (Salinity is also discussed by Migniot.[18])

Quantity of sediment samples

47. The quantity of sediment required was based on the amount needed for the laboratory tests outlined in Part III. Enough sediment to perform the necessary characterization tests and provide material for the column settling tests was collected from each established sampling station. Five-gallon containers were used to hold the sediment samples. These containers were about the largest that could be handled efficiently. Small samples were collected and placed in 8-oz watertight jars for water content and specific gravity tests. Care was taken to collect the small sediment sample that appeared to be most representative of the entire sample. Sampling was performed from a

small motorboat as shown in Figure 3.

48. After the characterization tests identified in Part III were performed on grab samples from each sampling station, the container samples were combined to obtain sufficient material for the column settling tests.

Sample preservation

49. Samples were placed in air- and watertight containers and then in a cold room (6° to 8°C) within 24 hours after sampling. The organic content was determined for each sample, and, if less than about 10 percent, it was not considered necessary to have the samples remain in the cold room. Below this organic content level, it was assumed that little biological activity could occur that would affect subsequent testing.

Dredged Material Investigations

50. Early in this study, considerable time and effort were devoted to sampling dredged material discharged from the hydraulic dredge pipeline into the containment area. This was done to eliminate some of the confusion in present practice concerning the influent solids concentrations. It was found that a major point of confusion is not the concentration itself but rather the method of reporting it. Concentration is routinely reported in terms of grams per litre, percent solids by weight, percent solids by volume, and percent solids by apparent volume. This fact led to concern early in the study because the influent solids level would be of critical importance in the performance of laboratory column tests and the subsequent development of a design methodology.

Dredged material sampling

51. Samples were taken at regular intervals from dredging activities at all the field sites except Brunswick Harbor to determine the means and distributions of suspended solids concentrations from the hydraulic dredge pipelines. The method of sampling is illustrated in Figures 6-8. The samples were taken from the midpoint of the dredge

Figure 6. Sampler used for sampling pipeline discharge

Figure 7. Sample being taken at midpoint of discharge

Figure 8. Pipeline sampling operation

discharge pipeline to obtain representative slurry concentrations.

Field Study Sites

52. One of the major problems in this study was locating suitable field study sites. The ideal site would have been a containment area of less than 50 acres in surface area, with flat topography inside and sound dikes for ponding about 2 ft of water during the disposal operation, and operated on a continuous disposal basis for the duration of the field study. Although none of the sites selected (Figure 1) were completely satisfactory according to the above requirements, each provided valuable input to this study.

Brunswick Harbor

53. The initial field investigations for this study were performed in Brunswick Harbor. This site was only used to obtain channel sediment and dredged material samples for laboratory testing. The containment area was too large (about 500 acres) and the dredging quantity too small to provide a good field testing site. The samples taken from this site were valuable in development of the laboratory experiments for the other sites.

Mobile Harbor

54. Mobile Harbor, which is dredged annually, provided good laboratory samples of fine-grained channel sediments and fine-grained material from maintenance dredging. The containment area in use was the Lower Polecat Bay disposal area. It also proved to be too large to be a good field testing site, and water was never ponded to a depth that would permit meaningful investigations in the containment area.

55. Two separate maintenance dredging-disposal operations were monitored in Mobile Harbor during the period of study. Samples of sediment and dredged material from this site provided good material for the laboratory testing. A 24-in. hydraulic pipeline dredge performed the dredging in both operations. Samples were taken from the pipeline at regular intervals during two 24-hour periods and analyzed for suspended solids levels. The results are reported in Part IV.

Yazoo River

56. The Yazoo River dredging project was the only one investigated in a freshwater environment. The operation of this site was carefully controlled by the Vicksburg District to ensure an effective and efficient disposal operation. The disposal area is shown in Figure 9. The main (upper) basin was about 450 by 1800 ft; a 100-ft weir

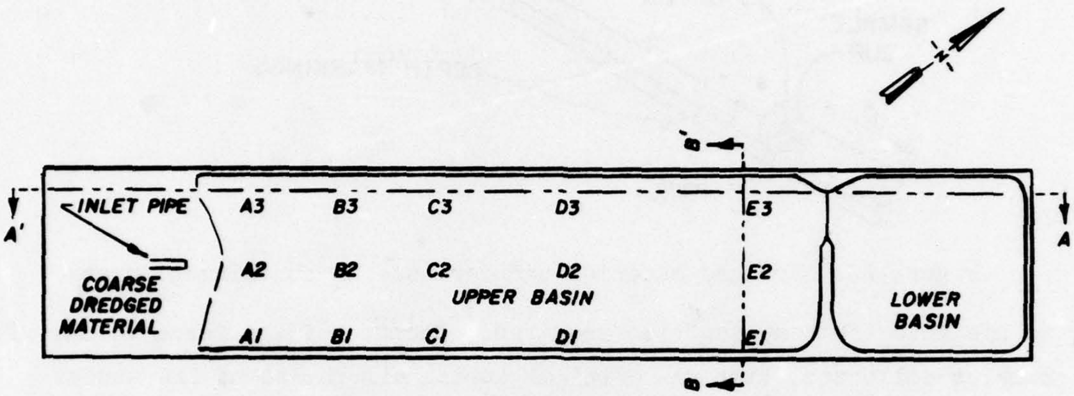


Figure 9. Yazoo River containment area

led into a smaller basin. Only the upper basin was investigated in this study. Field investigations included the following:

- a. Pipeline influent suspended solids determinations.
- b. Effluent suspended solids determinations.
- c. Suspended solids versus depth determinations at the sampling stations in the upper basin.
- d. Dye tracer tests.
- e. Aerial photographs of the tracer tests.

57. The suspended solids concentrations in the upper basin were monitored by sampling at various times during disposal. The researcher was unable to find, in the literature, a suspended solids sampler for use inside the containment area that would fill all the needs for this research. Consequently, the sampler shown in Figure 10 was specially designed and built. Based on the experience gained during field sampling, the sampler proved to be effective and efficient. It is essentially made of PVC pipe and is light enough that one man can use it to collect samples. However, two men were used for the sampling during this study

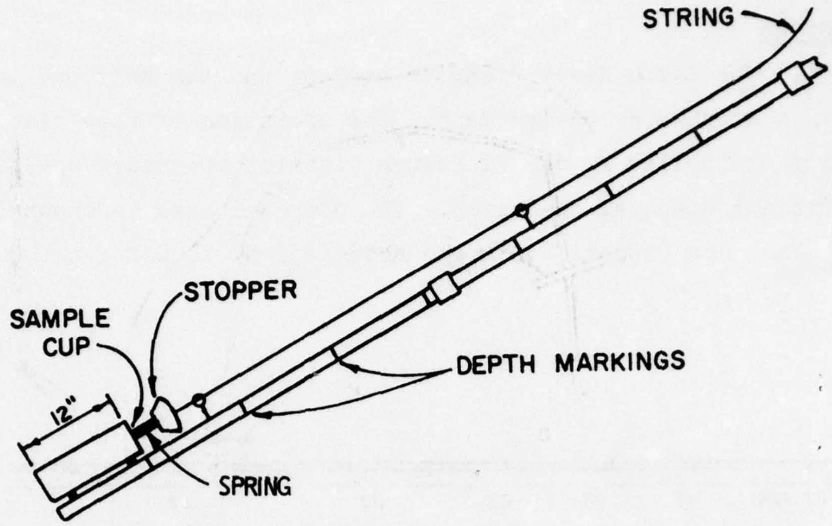


Figure 10. Dredged material sampler used in containment areas

to minimize the sampling time required. Because of the large volume of samples collected, time was critical during all phases of the study.

Fowl River

58. Fowl River flows into the Mobile Bay about 20 miles south of Mobile, Ala. The 12.8-acre containment (Figure 11) was equipped with one 8-ft weir to accommodate the flow from the 16-in. dredge used for the maintenance dredging at the time of this site investigation. The Fowl River containment area is located in a saltwater environment. However, during periods of high water in Fowl River, the inflow of fresh water pushes out the saltwater wedge and the site is under freshwater conditions.[20] During the field investigations, the salinity of the sediment carrier water sampled from the hydraulic dredge pipeline was about 1 ppt.

59. Channel sediment and dredged material samples were taken for laboratory tests. Suspended solids were determined at sampling stations within the containment area. Dye tracer tests were performed using Rhodamine WT dye.

Dye Tracer Tests

60. Dye tracer tests were performed at the Yazoo River and Fowl River field sites to determine the short-circuiting and mixing

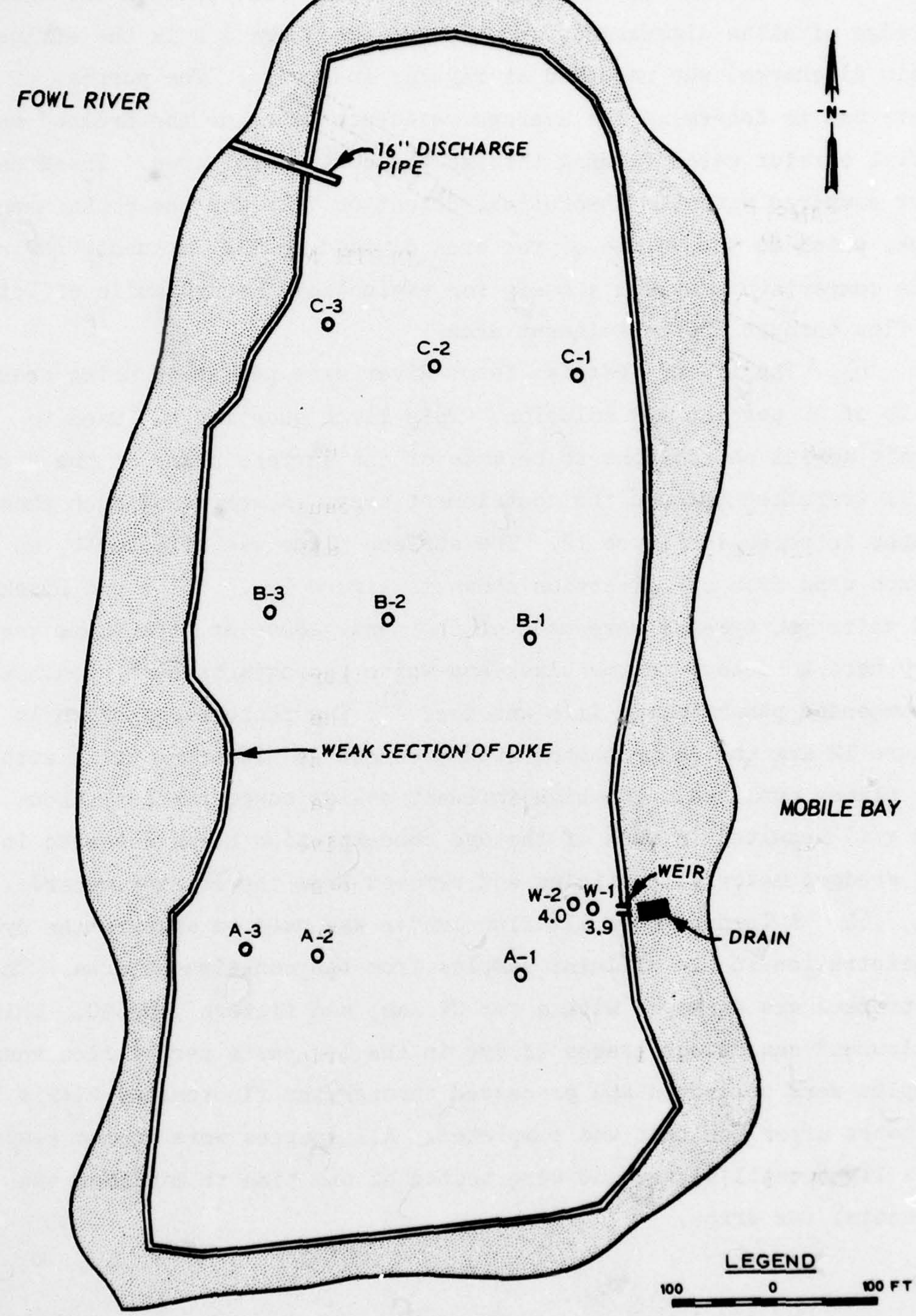


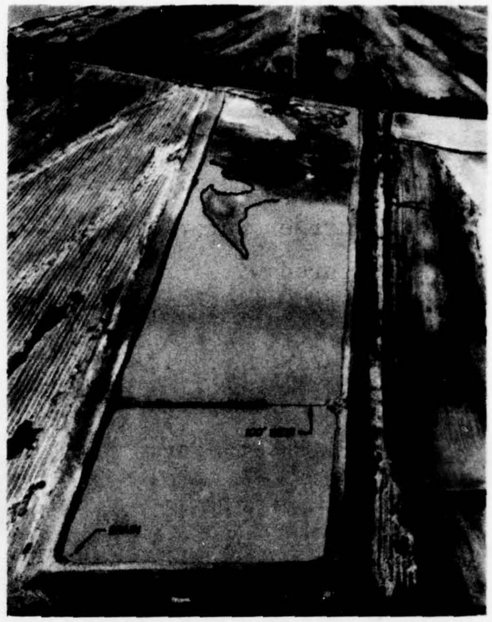
Figure 11. Fowl River containment area

characteristics of the containment areas. A quantity of Rhodamine WT dye was injected instantaneously at the containment area in the influent (dredge pipeline discharge), and the dye concentration in the effluent (weir discharge) was recorded at regular intervals. The purpose of these tests was to determine the average residence time for the dredged material carrier water flowing through the containment area. These data were compared with the theoretical detention time for the containment area, which is the volume of the area divided by the influent flow rate. This comparison provided a basis for evaluating the hydraulic efficiency of flow through the containment area.

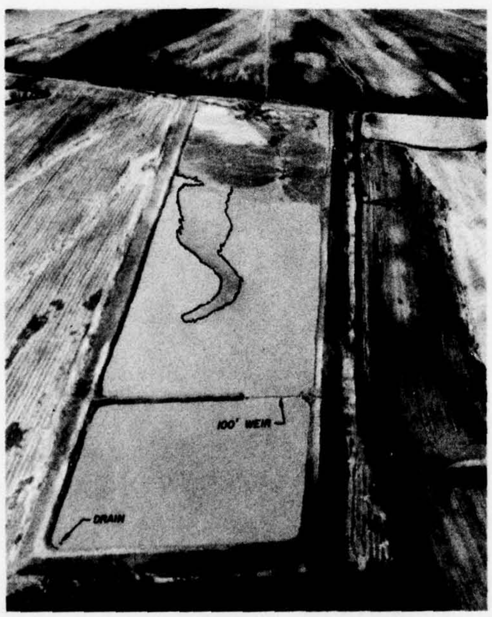
61. The tracer tests at Yazoo River were performed using about 75 lb of 20 percent dye solution. This large quantity was used to permit aerial photographs to be made of the surface plume of the dye as it travelled through the containment area. A series of such photographs is shown in Figure 12. The surface plume was affected by an 18-mph wind from the direction shown in Figure 12a. Color and black and white photographs were made of the test. However, the plume was very hard to detect in the black and white photographs even though the recommended panchromatic film was used.[21] The photographs shown in Figure 12 are the color photographs produced in black and white with the plumes outlined. The high influent solids concentration (about 132 g/ℓ) resulted in much of the dye concentration being adsorbed in the dredged material particles and removed from the carrier water.

62. A Turner Model 111 fluorometer was used to measure the dye concentration in the effluent samples from the containment area. The instrument was equipped with a far UV lamp and filters 546/590. This instrument can detect traces of dye in the low parts per billion range. Samples were collected and processed through the fluorometer within 24 hours after the test was completed. All samples were stored away from light until tested and were tested at one time to minimize the potential for error.

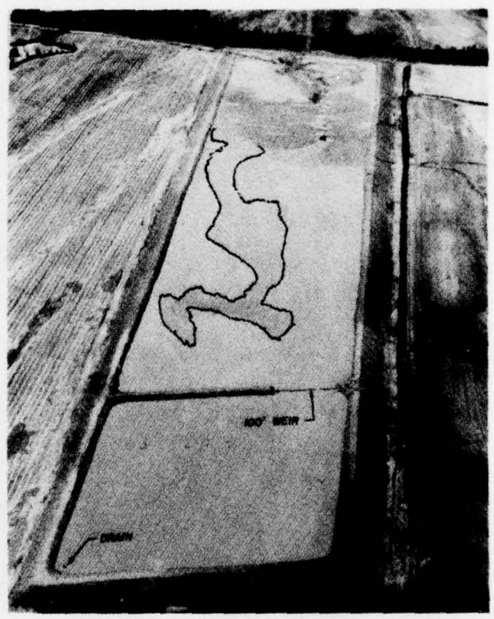
a. 30 min after start of test



b. 1.0 hour after start of test



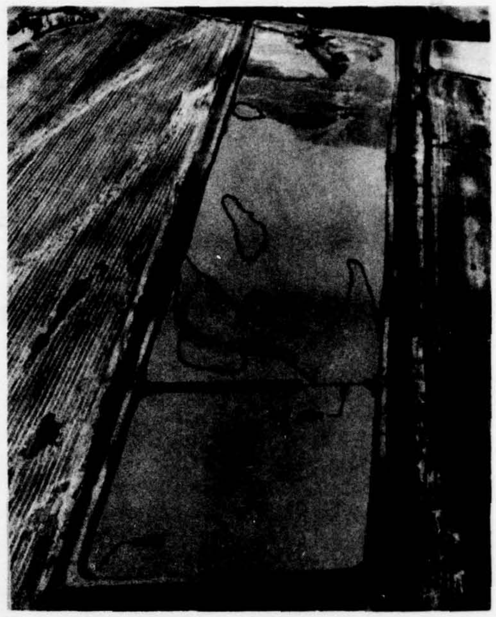
c. 1.5 hours after start of test



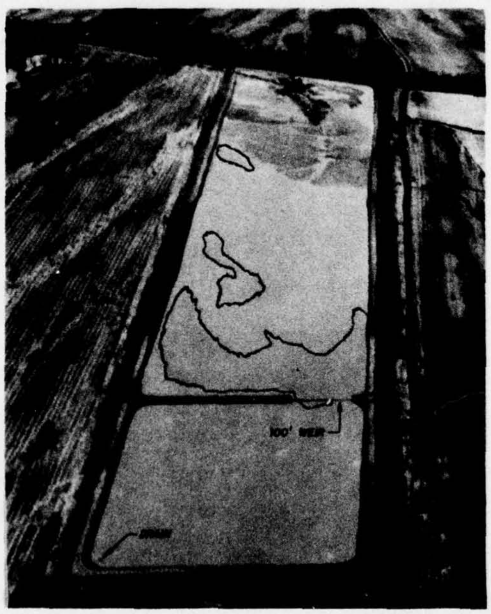
d. 2.0 hours after start of test

Figure 12. Surface plume from dye tracer test at Yazoo River containment area (sheet 1 of 2)

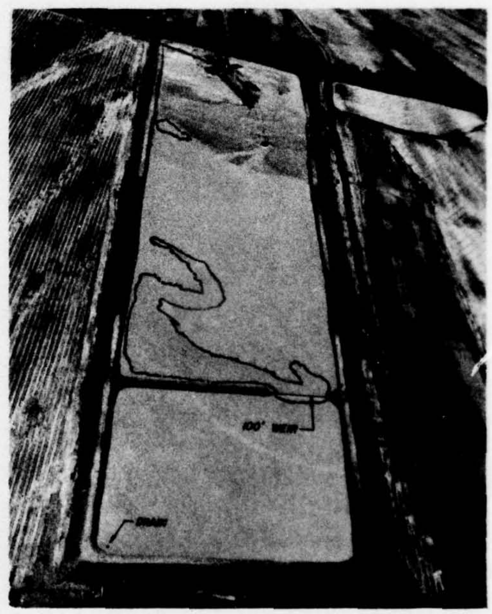
e. 2.5 hours after start of test



f. 3.0 hours after start of test



g. 3.5 hours after start of test



h. 4.0 hours after start of test

Figure 12 (sheet 2 of 2)

PART III: LABORATORY INVESTIGATIONS

63. Extensive laboratory investigations were performed to characterize physical and settling properties of the sediments and dredged material. First, however, it was necessary to determine the range of suspended solids in the slurry discharged from the dredge pipeline. The laboratory tests were aimed at answering the basic question of whether sampling and testing channel sediment could provide data representative of the same material after it had been dredged and transported through a hydraulic dredge pipeline. Simple column zone settling tests were performed to establish whether the data from sediment tests would be adequate for containment area design purposes. Once this question was satisfied, tests were performed to determine the best procedures and equipment for performing settling tests. Tests were performed in the range of suspended solids concentrations determined from dredge pipeline samples to evaluate the effects of column depth and column diameter on test results. Early in the study, the researcher was aware of the significance of salinity as it affects the settling process, so the sediments were tested for salinity and handled as either freshwater or saltwater sediments. Later, this distinction became a significant factor in the design methods developed for sizing dredged material containment areas.

Sediment Characterization Tests

64. Before the sediment or dredged material was characterized, water samples from the environment of the materials were tested for salinity. These data dictated the laboratory procedures for the following tests.

Grain size analyses

65. Early in the study, a number of hydrometer analyses[22] were performed to determine the grain size distribution of the fine-grained material being studied. Hydrometer tests were performed with and without a dispersing agent to characterize the sediment particles.

Performing these tests without the dispersing agent was considered to be more representative of the dredged material flocculated particles. As testing continued, it was realized that, since dredged material slurry is generally pumped into a containment area at a solids concentration averaging about 145 g/ℓ, grain size analyses were unimportant to the design approach. At this concentration, the fine-grained particles would not settle individually. Therefore, there was no further need to perform grain size analyses on the fine-grained sediments (<No. 40 U. S. standard sieve).

Plasticity analyses

66. Plasticity analyses were performed on all of the dredged material and sediment samples, primarily for classification and comparative purposes. A detailed explanation of the test procedures and apparatus used can be found in Appendix III of Engineer Manual EM 1110-2-1906.[22]

Organic content

67. Organic contents were determined for all samples to identify the need for special sample storage measures prior to the settling tests. Special sample storage measures were necessary for the Brunswick samples because organics were found at high levels (see Table 2). The need for special storage in a cold room was not considered necessary for the other samples, although most of the samples remained in the cold room until tests were complete. The following dry combustion test procedure was used to determine the organic content expressed as the percentage of weight lost on ignition:

a. Dry a 40-g specimen at 105°C until there is no further weight loss (usually 1 or 2 hours).

b. Place in desiccator to cool (for 15 min).

c. Weigh specimen and place in 440°C oven for 4 hours.

d. Place in desiccator to cool for 15 min.

e. Weigh and determine organic content by dividing the weight lost by the specimen while in the 440°C oven by the total weight of the specimen at the time it was placed in the 440°C oven.

Specific gravity

68. These tests were performed on the samples to provide data

for use in design calculations. Procedures for performing the specific gravity test are given in Appendix IV of EM 1110-2-1906.[22]

USCS classification

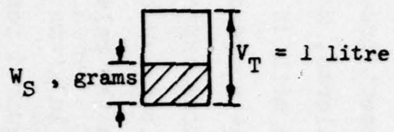
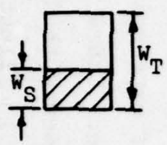
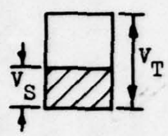
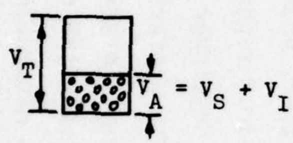
69. All sediment and dredged material samples were classified using the Unified Soil Classification System (USCS). The classifications provided an initial basis for comparison of material from different sites. It will be helpful in the future if all Corps Districts adopt a policy to classify sediments to be dredged according to this system. This policy would permit better interpretation of data exchanged among Districts relative to dredged material disposal activities. Additional information concerning the USCS classification is found in Reference 23.

Solids Concentration Tests

70. The most frequently used laboratory test during this study was that for suspended solids concentration. This test was necessary for evaluating column settling tests and field tests of influent (pipeline discharge) and effluent (weir discharge) solids and dredged material buildup and distribution inside the containment area. As discussed earlier, there is much confusion in present practice concerning the method of reporting suspended solids. Palermo, Montgomery, and Poindexter[24] developed a table which compares the methods being used (Table 1). The preferred method of expressing the suspended solids concentration is in grams per litre. Concentrations expressed in grams per litre provide the design engineer with data that can be readily used in the design methodology. Figure 13 illustrates the relationship between percent solids by weight and concentration in grams per litre. Since in this study suspended solids would be required for both saltwater and freshwater slurries, the procedures used for testing suspended solids would have to consider the total and dissolved solids. Dissolved solids were not a significant factor in the freshwater slurries. The centrifugation and filtration methods discussed later were used if the slurries were from a saltwater environment (>3 ppt). The 3-ppt level was used to define freshwater and saltwater sediments based on research

Table 1

Methods of Reporting Suspended Solids (After Palermo, Montgomery, and Poindexter[24])

Method of Reporting Suspended Solids	Weight-Volume Relationship	Method of Computation	Remarks
		Preferred Method	
grams per litre or milligrams per litre		$S = \frac{W_S}{V_T}$	Common method for reporting dissolved chemical concentrations. Best method for engineering purposes
		Other Methods	
percent by weight		$S = \frac{W_S}{W_T} 100$	Easy to determine by laboratory test. Does not require value for specific gravity
percent by volume		$S = \frac{V_S}{V_T} 100$	Easy to determine by laboratory test. Requires determination of percent by weight and value for specific gravity
percent by apparent volume		$S = \frac{V_A}{V_T} 100$	Apparent volume determined by settled solids for a bottle or flask. No standardized procedure available. Void ratio of settled solids varies with type of sediment. Can lead to errors because of nonstandard test. Not recommended. Value is meaningless in engineering calculations

Note: W_S = ovendry weight of solid particles
V_T = total volume
W_T = total weight
V_S = volume of solid particles
V_A = apparent volume of settled solids
V_I = volume of interstitial water

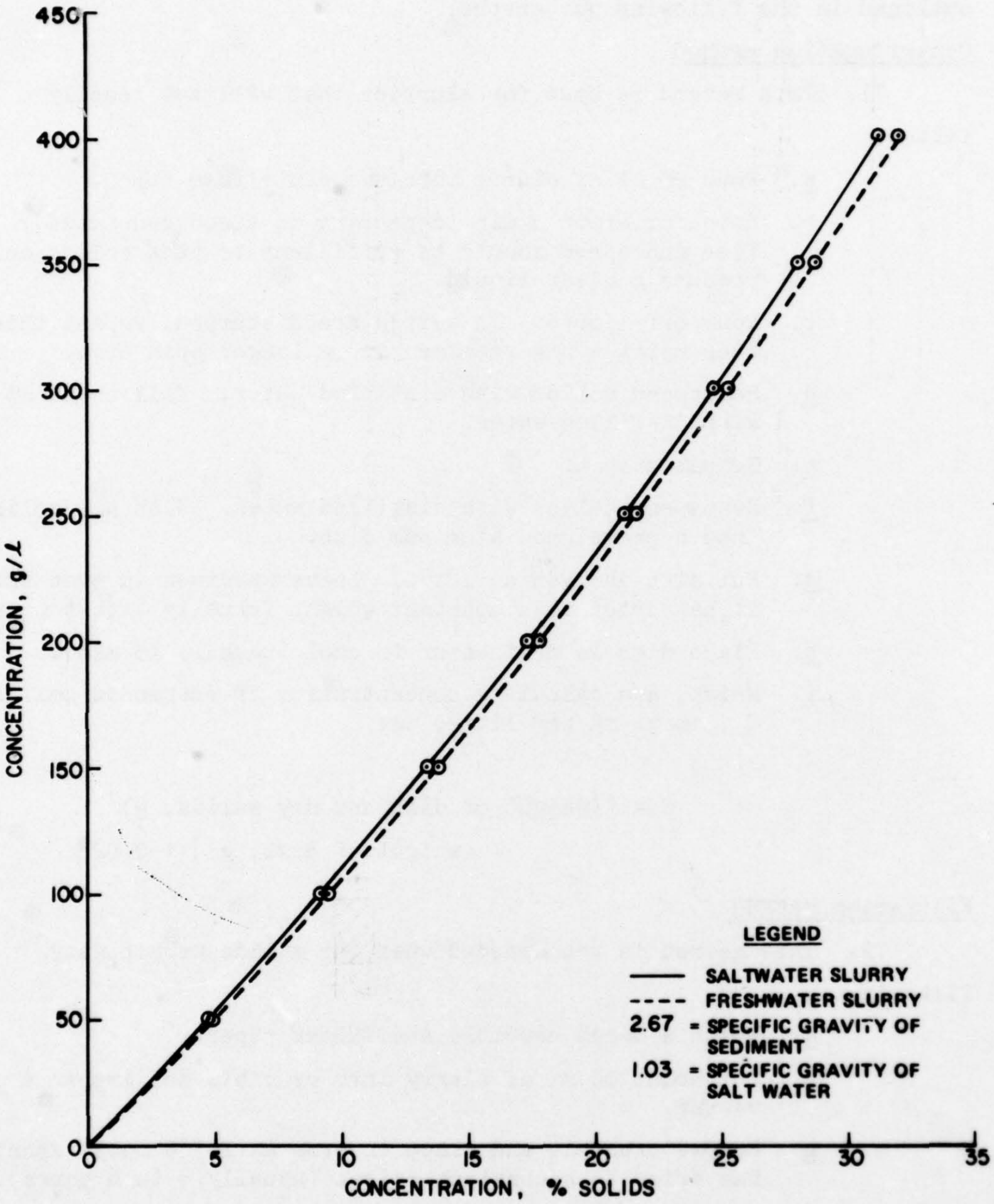


Figure 13. Relationship between concentration in percent solids by weight and concentration in grams per litre

by Migniot[18] and preliminary testing in this study. The total solids method was used for freshwater slurries. The detailed procedures are outlined in the following paragraphs.

Centrifugation method

71. This method is best for slurries that will not readily filter.

a. Pour 20 mℓ of slurry into two centrifuge tubes.

b. Spin for about 3 min (depending on speed generated). Time and speed should be sufficient to pack solids and produce a clear liquid.

c. Pour off liquid. If solids are disturbed, repeat this step using a new specimen and a longer spin time.

d. Resuspend solids with distilled water. Fill to 20 mℓ with distilled water.

e. Repeat step b.

f. Resuspend solids with distilled water. Wash all solids into a preweighed aluminum dish.

g. Put dish in oven at 105°C. Leave specimen in oven until it has dried to a constant weight (usually 4 to 6 hours).

h. Place dish in desiccator to cool (usually 15 min).

i. Weigh, and calculate concentration of suspended solids C, in grams per litre, as:

$$C = [(\text{weight of dish and dry solids, g}) - (\text{weight of dish, g})] \div 0.02 \qquad (1)$$

Filtration method

72. This method is recommended when the solids permit easy filtering.

a. Weigh a Gooch crucible and filter paper.

b. Put about 10 mℓ of slurry into crucible and impose a vacuum.

c. Remove crucible and place in oven at 105°C until specimen has dried to a constant weight (usually 4 to 6 hours).

d. Cool in desiccator for 15 min and weigh.

e. Calculate concentration of suspended solids, in grams per litre, as:

$$C = [(\text{weight of crucible, filter paper, and dry solids, g}) - (\text{weight of crucible and filter paper, g})] \div 0.01 \quad (2)$$

Total solids method

73. If the sediment or dredged material is obtained from a freshwater environment, the dissolved solids are not likely to be significant. In this case, determination of the concentration of total solids will be sufficient.

a. Obtain a tare weight.

b. Put specimen into dish and weigh.

c. Place in oven at 105°C until specimen has dried to a constant weight. Cool in desiccator for 15 min and weigh.

d. Calculate solids concentration %S , in percent solids by weight, as follows:

$$\%S = [(\text{weight of dry specimen and dish} - \text{dish weight}) \div (\text{weight of wet specimen and dish} - \text{dish weight})] \times 100 \quad (3)$$

e. Use Figure 13 to convert concentration in percent solids by weight to concentration in grams per litre.

Characterization of Dredged Material Sedimentation Processes

74. Sedimentation as applied to dredged material disposal activities refers to those operations in which the dredged material slurry is separated into a clarified fluid and a more concentrated slurry. For dredged material containment areas, the production of effluent with a low concentration of suspended solids is as important as providing storage volume for the dredged solids. Laboratory sedimentation tests must provide data for designing the containment area to meet these two requirements. These tests are based on gravity separation of solid particles from the transporting fluid.

75. The important factors governing sedimentation of dredged material solids are initial concentration of the slurry, flocculating properties of the solid particles, and salinity of the fluid. Salinity

of the fluid enhances the flocculation of the dredged material particles. Figure 14 illustrates the approximate effect of the initial

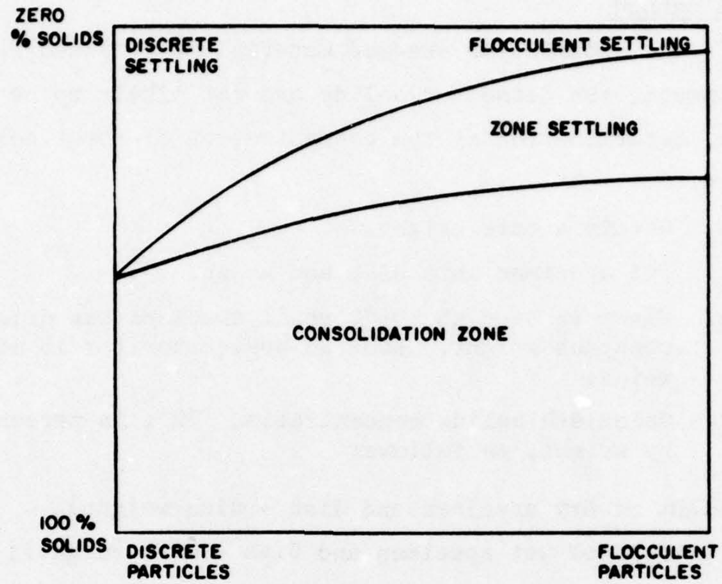


Figure 14. Types of sedimentation

concentration and flocculation properties on the different ways particles can settle out of suspension.

76. There are three basic types of sedimentation:

a. Discrete settling in which the particle maintains its individuality and does not change in size, shape, or density during the settling period.

b. Flocculent settling in which particles agglomerate during the settling period and undergo changes in physical properties and settling rate.

c. Zone settling in which the flocculent suspension forms a more complex structure and settles as a mass, exhibiting a distinct interface during the settling process.

Generally, discrete settling describes the sedimentation of sand particles and fine-grained sediments at concentrations much lower than those found in dredged material containment areas.

77. A number of laboratory tests were performed to identify the proper procedures and equipment needed to adequately characterize the type of sedimentation that would occur in the containment area. These

tests primarily involved characterizing the settling and long-term sedimentation properties.

78. Because the sediments and dredged material included both fresh and salt water, both freshwater and saltwater environments were simulated in the laboratory tests. Ordinary tap water was used for fresh water, and a solution of tap water and a salt additive was used to simulate the salt water. This simulation of salt water was considered adequate for the purposes of this research.

79. Experiments were developed using column settling tests to identify the best procedures and equipment for providing design data. Column settling tests were performed using various slurry concentrations, column depths, and column diameters to identify their effects on zone settling velocities. These tests are referred to as multiconcentration, multiheight, and multidiameter tests, respectively. During the experiments, all other factors were held constant to permit an evaluation of the effect of column depth, column diameter, or slurry concentration on the settling velocity.

80. A number of the tests were performed at a column height of 1.12 ft which is the height of 1000 mℓ in a 1-litre graduated cylinder. This was done for a specific purpose. Much of the early literature reported on zone settling tests which were performed in 1-litre graduated cylinders. This, of course, has been condemned in later studies,[12,17] but some researchers and designers have continued to use 1-litre graduated cylinders for such tests. The depth and diameter of the 1-litre graduated cylinder were used in the experimental phase of this study to provide a basis for comparison of depth and diameter effects. The researcher feels that the purposes of the multiconcentration tests were fulfilled even though most of the tests were performed at an initial slurry depth of 1.12 ft.

Multiconcentration tests

81. The multiconcentration tests were performed at slurry concentrations ranging from 26 to 366 g/ℓ. Columns 4 in. in diameter were used for all these tests. Slurry was filled to a depth of 1.12 ft for most of the tests. However, some of the Fowl River sediments were

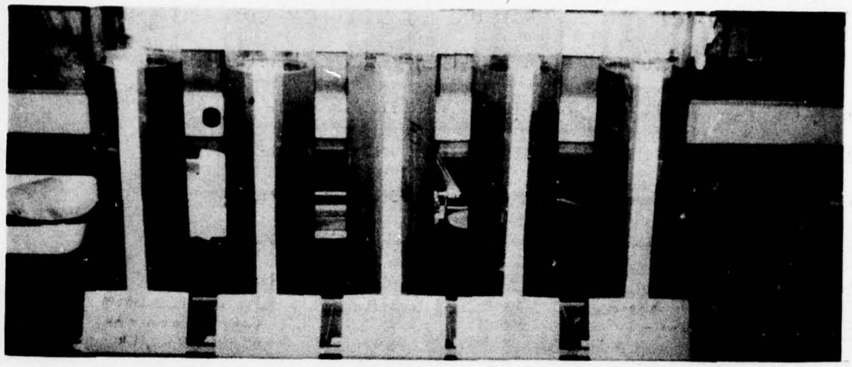
tested at a depth of 4 ft. Figure 15 illustrates this test for Mobile Harbor sediments. It shows the slurry interfaces at three different times during the test. The multiconcentration tests were performed to provide a basis for establishing the variations of zone settling velocities with various slurry concentrations. These tests were also used to provide data for comparing settling properties of channel sediments with those of the same sediments after being dredged and discharged into the containment area.

Multiheight tests

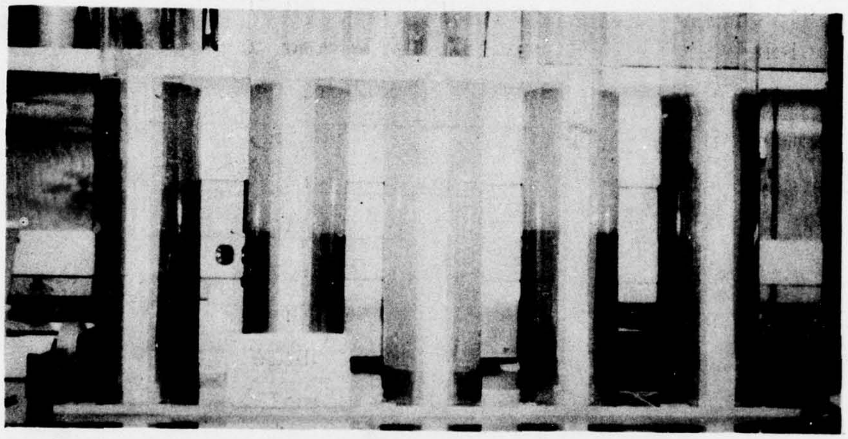
82. Multiheight tests were performed on samples from Mobile Harbor, Fowl River, and Brunswick Harbor. In these tests, the slurry concentrations were held constant and allowed to settle in 4-in.-diam columns at depths varying from 1.12 to 4 ft. A schematic of the multiheight test experimental equipment is shown in Figure 16. All columns were Plexiglas. Examples of a test in progress are shown in Figure 17. Slurry was mixed to the desired suspended solids concentration in a 55-gal container and pumped into the columns in rapid succession. Air was bubbled into the columns to ensure that material remained in suspension during filling. However, the bubbled air was not needed because the columns were filled rapidly (usually in less than 5 min) and the zone settling rates of the dredged material slurry were slow. These tests provided a means of evaluating the effects of column depth on zone settling velocities.

Multidiameter tests

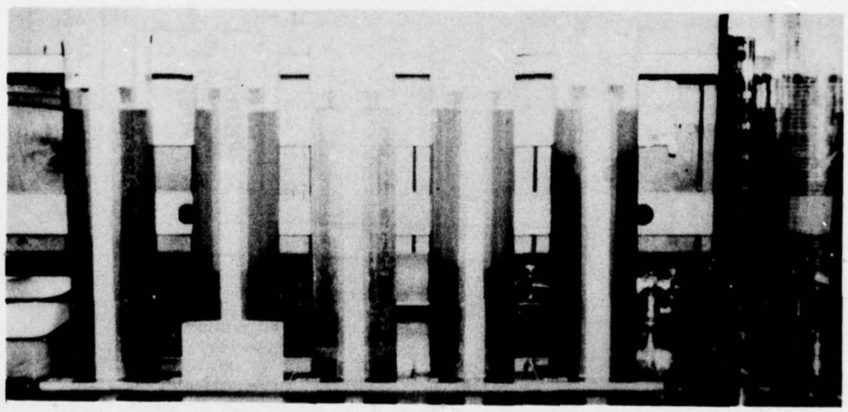
83. Experimental equipment was developed to evaluate the effects of column diameter on zone settling velocities for dredged material slurries within the range of suspended solids concentrations of containment area influents. These tests were aimed primarily at dredged material disposal activities from hydraulic pipeline dredges. A schematic of the experimental equipment used in the multidiameter tests is shown in Figure 18. This phase of the study was designed around the fact that 1- and 2-litre graduated cylinders were being used in practice to gain data on zone settling velocities. For this reason, these types of graduated cylinders were used for the multidiameter tests



a. After 1 hour



b. After 6 hours



c. After 21 hours

Figure 15. Multiconcentration test on Mobile Harbor sediments

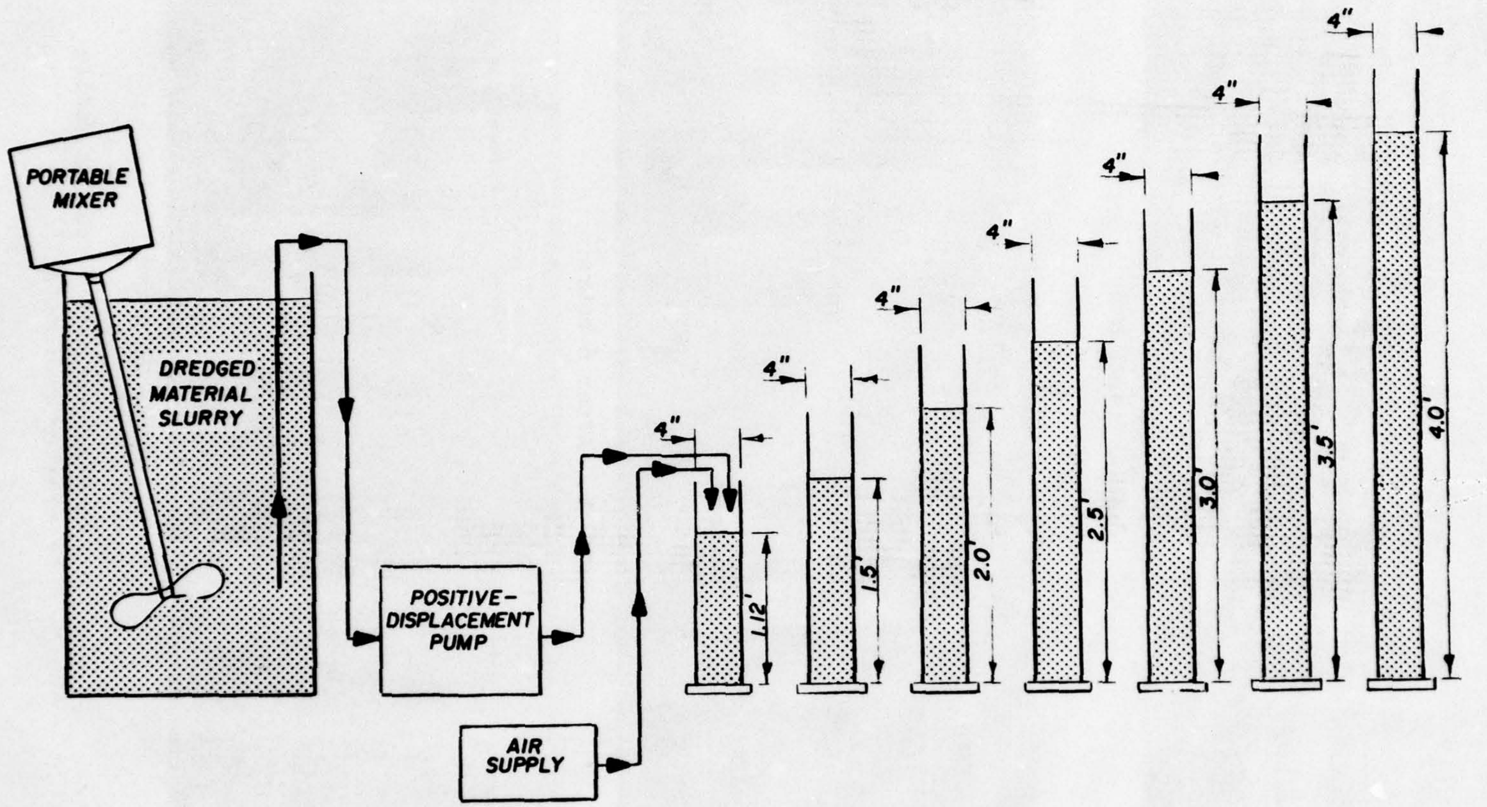
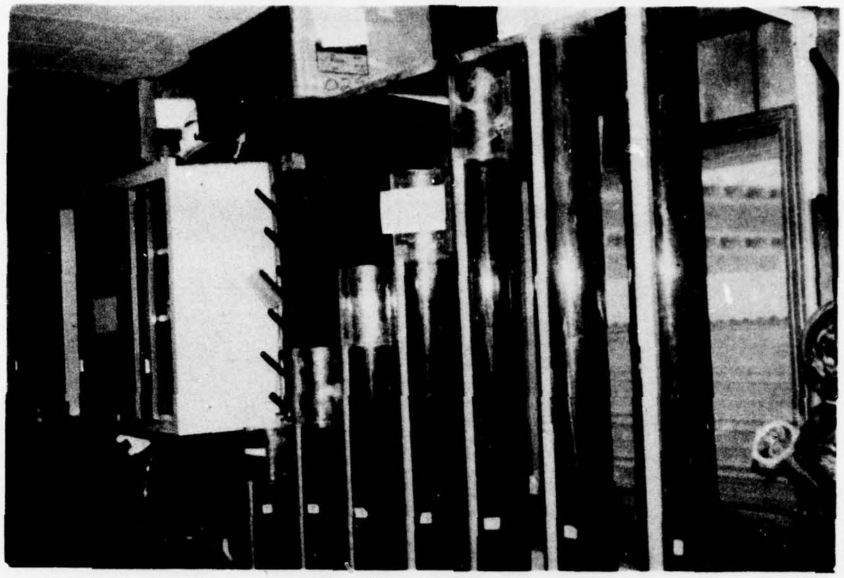
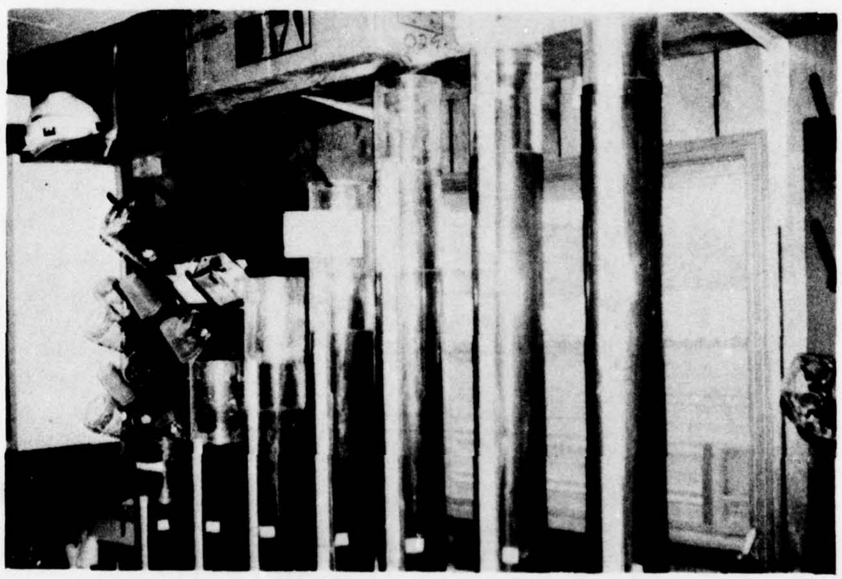


Figure 16. Schematic of multiheight test experimental equipment



a. During early stages



b. After a period of settling

Figure 17. Multiheight test on Mobile Harbor sediments

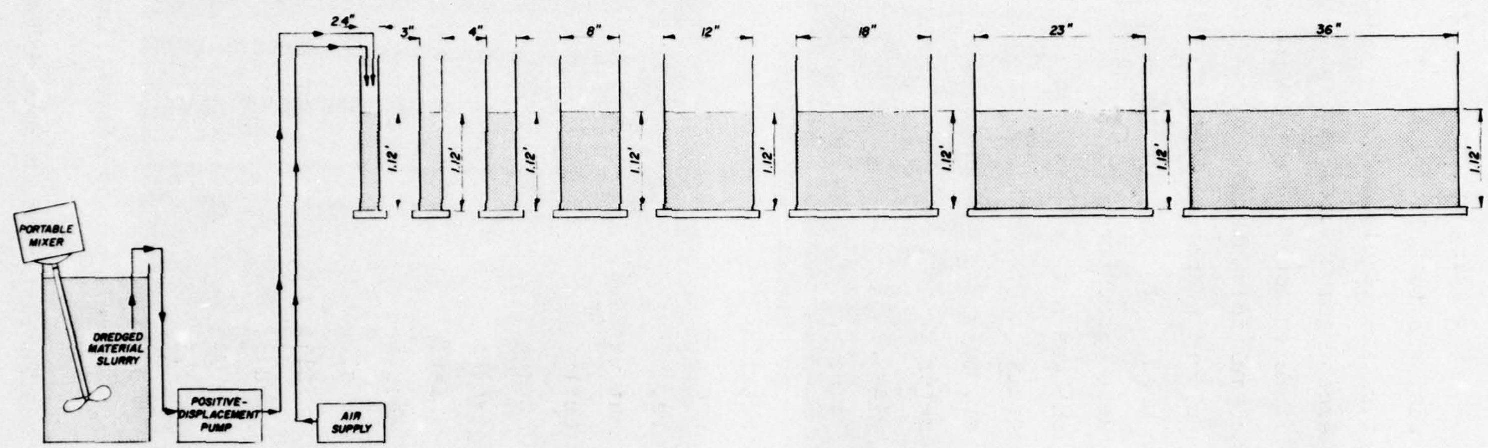


Figure 18. Schematic of multidiameter test experimental equipment

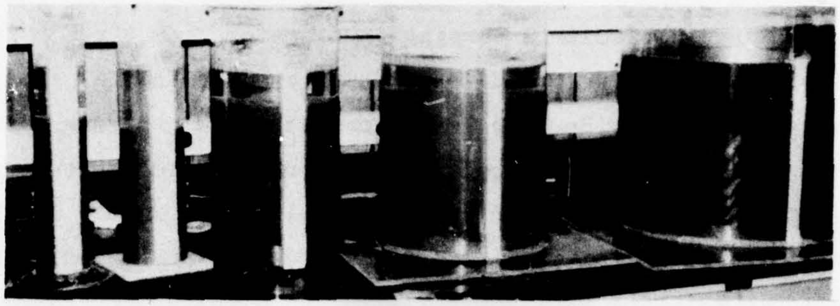
along with Plexiglas columns varying in diameter from 4 to 36 in. The initial slurry height was held to 1.12 ft, and the initial slurry concentration was set at the same level for each column during each series of tests. Everything except column diameter was held constant so that the effects of column diameter could be evaluated. Figure 19 shows photographs of an actual multidiameter test being performed on Mobile Harbor sediments. The slurry preparation and filling procedures used were the same as those used in the multiheight tests and discussed previously. Problems were encountered in obtaining a 36-in.-diam Plexiglas column, and one was not available during all of the laboratory testing phase. As a result, only a minimum of tests were performed in this column. However, this factor was not considered to be detrimental to the multidiameter test objectives.

Flocculent settling tests

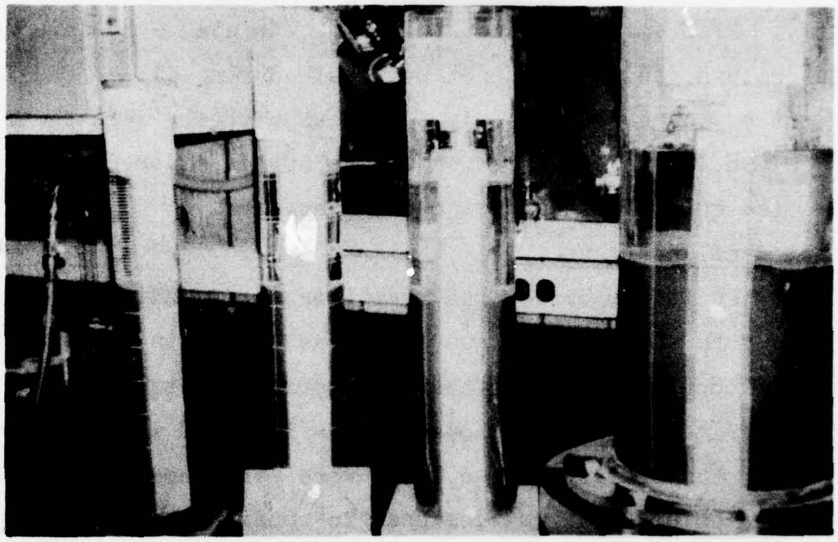
84. When it was discovered that freshwater sediments did not necessarily form an interface and settle as a mass in the settling columns, a flocculent settling test procedure was used. The flocculent settling experiments were developed on the basis of work by Camp,[9] McLaughlin,[15] and others. These tests were performed in an 8-in. Plexiglas settling column that was designed to consider the possible needs of this study but was built and used earlier by Palermo, Montgomery, and Poindexter.[24] A schematic of the flocculent settling test experimental equipment is shown in Figure 20. A porous stone was built into the bottom of the Plexiglas column for the purpose of bubbling air through the column to keep the slurry mixed during column filling. Mixing and placement of the slurry were accomplished as discussed for the previous tests. Column filling times were generally less than 2 min. Sample ports were provided at 1-ft increments along the column. The column was constructed in 2-ft sections for ease in removing the contents after completion of tests.

Column sedimentation tests

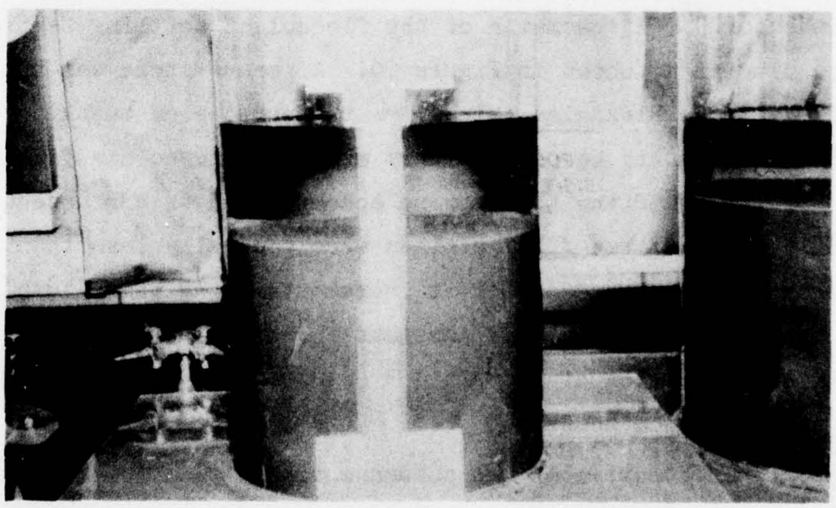
85. The objective of the column sedimentation test was to provide data for estimating the concentration of the dredged material in the containment area at the end of the disposal activity. This test



a. 3- to 18-in.-diam test columns



b. 2.4- to 8-in.-diam test columns



c. 18-in.-diam test column

Figure 19. Multidiameter test on Mobile Harbor sediments

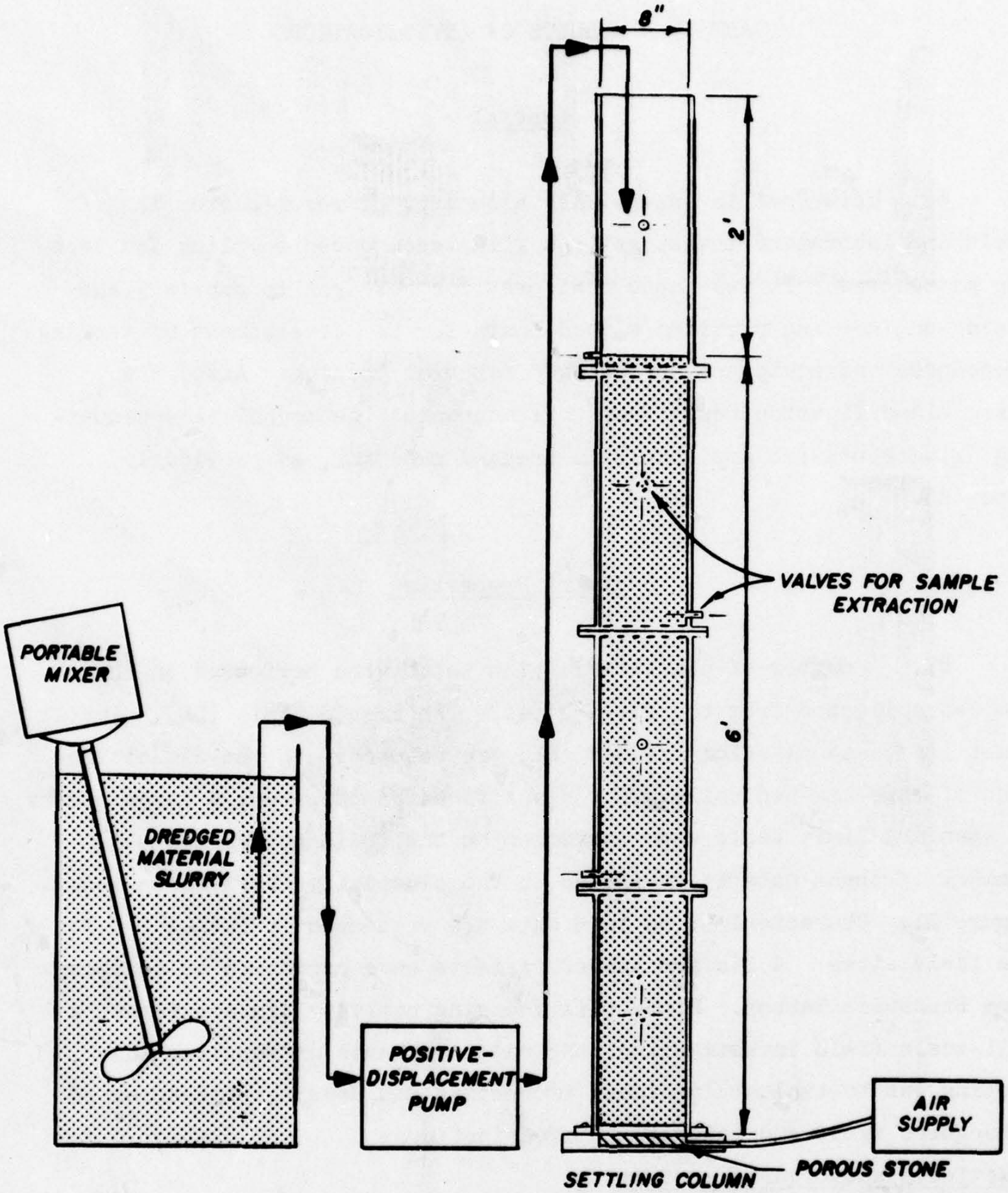


Figure 20. Schematic of flocculent settling test experimental equipment

was performed using the settling column shown in Figure 20. Essentially the slurry was mixed to the desired concentration and allowed to consolidate in the settling column for a long period. Then concentration was calculated with time and plotted.

PART IV: RESULTS OF INVESTIGATIONS

General

86. This Part is essentially a summary of results from the field and laboratory investigations with recommended sampling and testing procedures. It was found that previous research in sanitary and mining engineering provided a good basis for the development of testing procedures and equipment for dredged material testing. Also, the basic classification tests from soil mechanics (geotechnical engineering) literature are applicable to dredged material, as previously reported.[19]

Sediment Properties

87. A number of characterization tests were performed on the samples collected from the field sites. The liquid limit (LL), plastic limit (PL), and plasticity index (PI) are necessary in the classification of fine-grained soils. For classification purposes, a large number of standard limit tests were performed on the sediment samples. A summary of these data is presented in the plasticity chart shown in Figure 21. Characterization test data are presented in Tables 2-5 for the field sites. A limited number of tests were performed on sediments from Brunswick Harbor. Since this dredging activity did not permit a full-scale field investigation, the major emphasis on sampling and testing was to evaluate sediment properties and develop procedures for subsequent field and laboratory investigations.

Plasticity and organic content

88. The data plotted on the plasticity chart (Figure 21) show the differences in plasticity of sediments from each of the field sites. The Yazoo River sediments were classified as lean clays with low plasticity. The plasticity of the Brunswick Harbor sediments was high, and these sediments were classified as organic clays, even though they plot above the A-line on the plasticity chart.

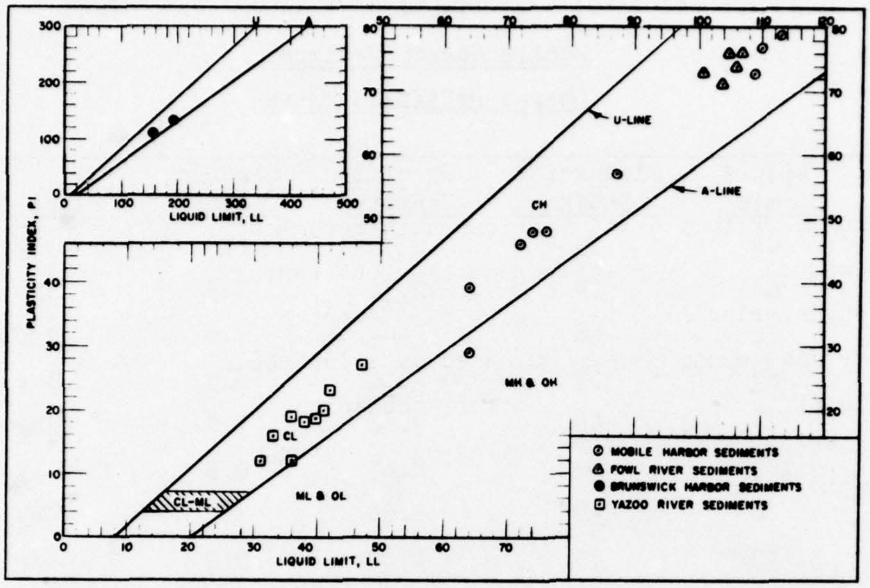


Figure 21. Plasticity chart

Table 2

Brunswick Harbor Sediment

Characterization Tests

Plasticity

Sample No.	1	2
Liquid Limit, LL	192.0	156.0
Plastic Limit, PL	58.0	43.0
Plasticity Index, PI	134.0	113.0
Soil Classification	Organic Clay (OH)	Organic Clay (OH)

Specific Gravity (G_s)

Sample No.	1	2	3	4	5	6	7
G_s	2.55	2.53	2.51	2.57	2.52	2.55	2.53

Organic Content

Sample No.	1	2	3	4	5
Percent organic	11.59	12.76	13.15	12.44	14.40

Table 3

Mobile Harbor Sediment

Characterization Tests

Sample No.	Liquid Limit	Plasticity Index	Specific Gravity	Organic Content	Soil Classification
1	64	39	2.74	6.8	Clay (CH)
2	64	29	2.70	7.9	Silt (MH)
3	72	46	--	7.0	Clay (CH)
4	87	57	2.68	8.5	Clay (CH)
5	74	48	2.66	7.7	Clay (CH)
6	109	73	2.67	9.9	Clay (CH)
7	76	48	2.68	7.9	Clay (CH)
8	113	79	2.60	9.7	Clay (CH)
9	110	77	2.71	12.6	Clay (CH)
10	77	44	2.68	6.0	Clay (CH)
11	76	47	2.69	5.0	Clay (CH)
12	81	48	2.70	6.0	Clay (CH)
13	80	51	2.69	6.0	Clay (CH)
14	82	49	2.69	6.0	Clay (CH)
15	70	41	2.70	4.0	Clay (CH)

Table 4

Yazoo River Sediment

Characterization Tests*

Sample No.	Liquid Limit	Plasticity Index	Specific Gravity	Soil Classification
1	38	18	--	Clay (CL)
2	42	23	2.67	Clay (CL)
3	33	16	--	Clay (CL)
4	41	20	--	Clay (CL)
5	36	12	--	Clay (CL)
6	31	12	--	Clay (CL)
7	36	19	--	Clay (CL)
8	47	27	--	Clay (CL)
9	40	19	--	Clay (CL)

* Characterization tests were only performed on the fine-grained sediments.

Table 5

Fowl River Sediment

Characterization Tests

Sample No.	Liquid Limit	Plasticity Index	Specific Gravity	Organic Content	Soil Classification
1	105	76	2.72	7.98	Clay (CH)
2	104	71	2.73	7.96	Clay (CH)
3	107	76	2.68	8.15	Clay (CH)
4	106	74	--	--	Clay (CH)
5	101	73	--	--	Clay (CH)

Researchers[25] have found that organic soils may plot slightly above the A-line in some cases. The organic content ranged from 11.59 to 14.40 percent for the Brunswick sediments (Table 2). Because of the high organic content, these samples were stored in a cold room to minimize changes due to biological activity prior to and during laboratory testing.

89. The Mobile Harbor and Fowl River sediments were classified as clays of high plasticity. They plot below the Brunswick Harbor sediments and above the Yazoo River sediments in Figure 21. The sediments selected are ideal for the purposes of this study. They cover a wide plasticity range, and each sediment has its range of plasticity that is generally different from the others. Therefore, according to plasticity properties, the sediments were clays having distinctly different plasticity properties.

90. Organic contents were generally less than 10 percent for all the sediments except those from Brunswick Harbor. Organics were considered to be too low to be a significant factor in evaluating the settling properties of all but the Brunswick Harbor sediments. Special precautions were taken in storing these samples to minimize changes caused by the organics.

Specific gravity

91. The specific gravity of the solid particles in the sediment samples varied within small limits for inorganic samples (<10 percent organics). The values reported in Tables 2-5 generally fall between 2.60 and 2.74 except for the organic sediments from Brunswick Harbor. They varied between specific gravities of 2.51 and 2.57. Specific gravity usually lies between 2.64 and 2.72 for most soil minerals;[26] therefore, for inorganic fine-grained sediments, it may often be approximated at a value of about 2.7 with reasonable accuracy.

Sampling During Disposal Activities

92. Samples were taken during disposal into the containment area. The purpose of this sampling was to determine average suspended solids

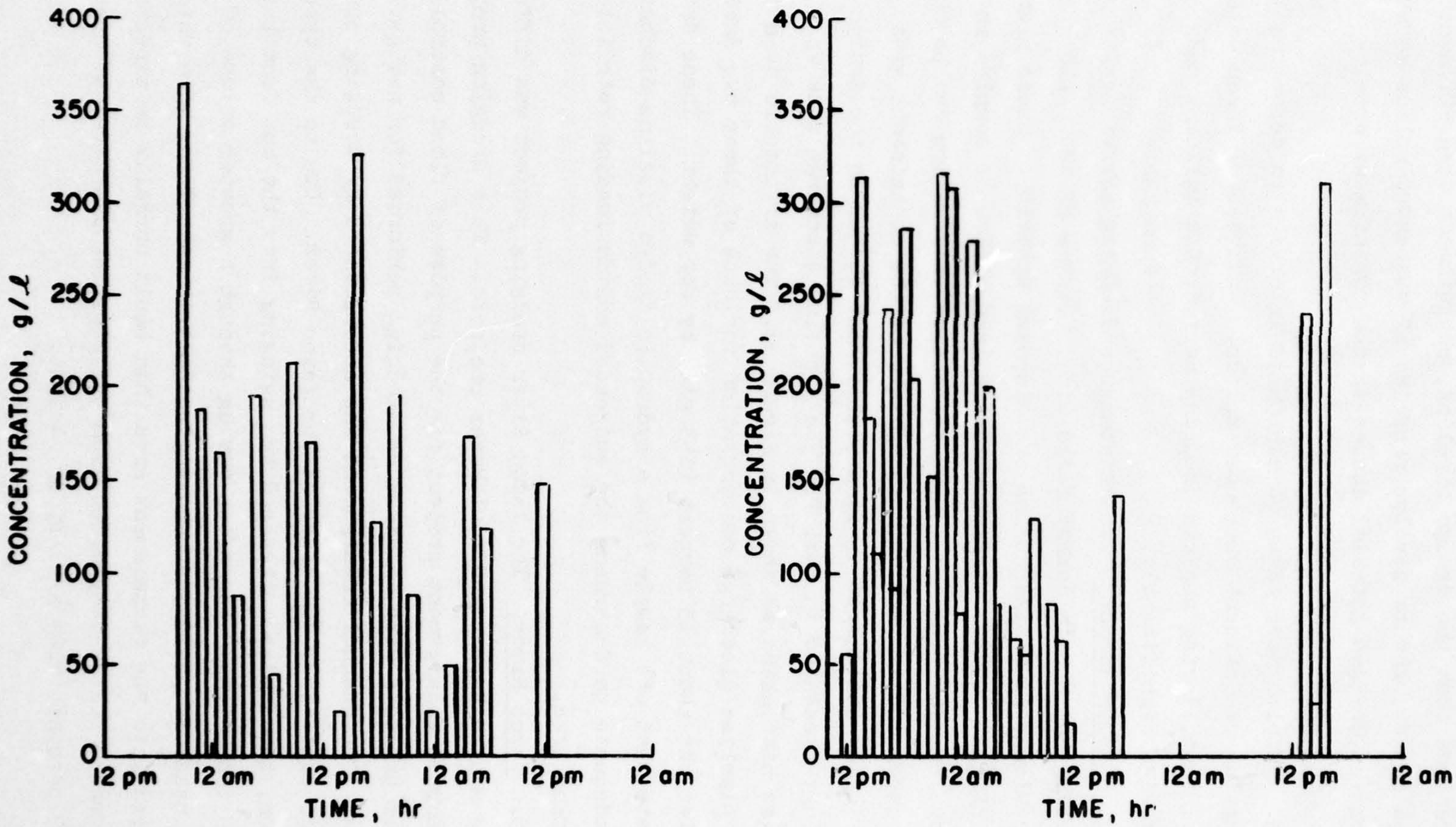
concentrations from the dredge pipeline, containment area effluent suspended solids, and to develop profiles of suspended solids versus depth for the dredged material stored in the containment area.

Pipeline discharge

93. Samples were taken at scheduled intervals to determine the concentration of influent suspended solids. Analyses of these data indicated that, during a given dredging period, the influent suspended solids varied significantly.

94. Mobile Harbor. Two maintenance dredging activities were sampled from the Mobile Harbor field site. Figure 22 shows plots of concentration versus time during the disposal activity. These plots are significant because they show that a long series of samples is necessary from the pipeline before definitive information can be obtained concerning the solids loading rate of the containment area. The average inflow concentration is a significant factor in the design methodology presented in Part V. The pipeline discharge data were also plotted as histograms as shown in Figure 23. The arithmetic mean or average pipeline discharge concentration for each of these two dredging activities was about 13 percent (145 g/ℓ) by dry weight. These data illustrate that one sample from a hydraulic dredge pipeline discharge is not adequate to determine the suspended solids loading rate into a containment area.

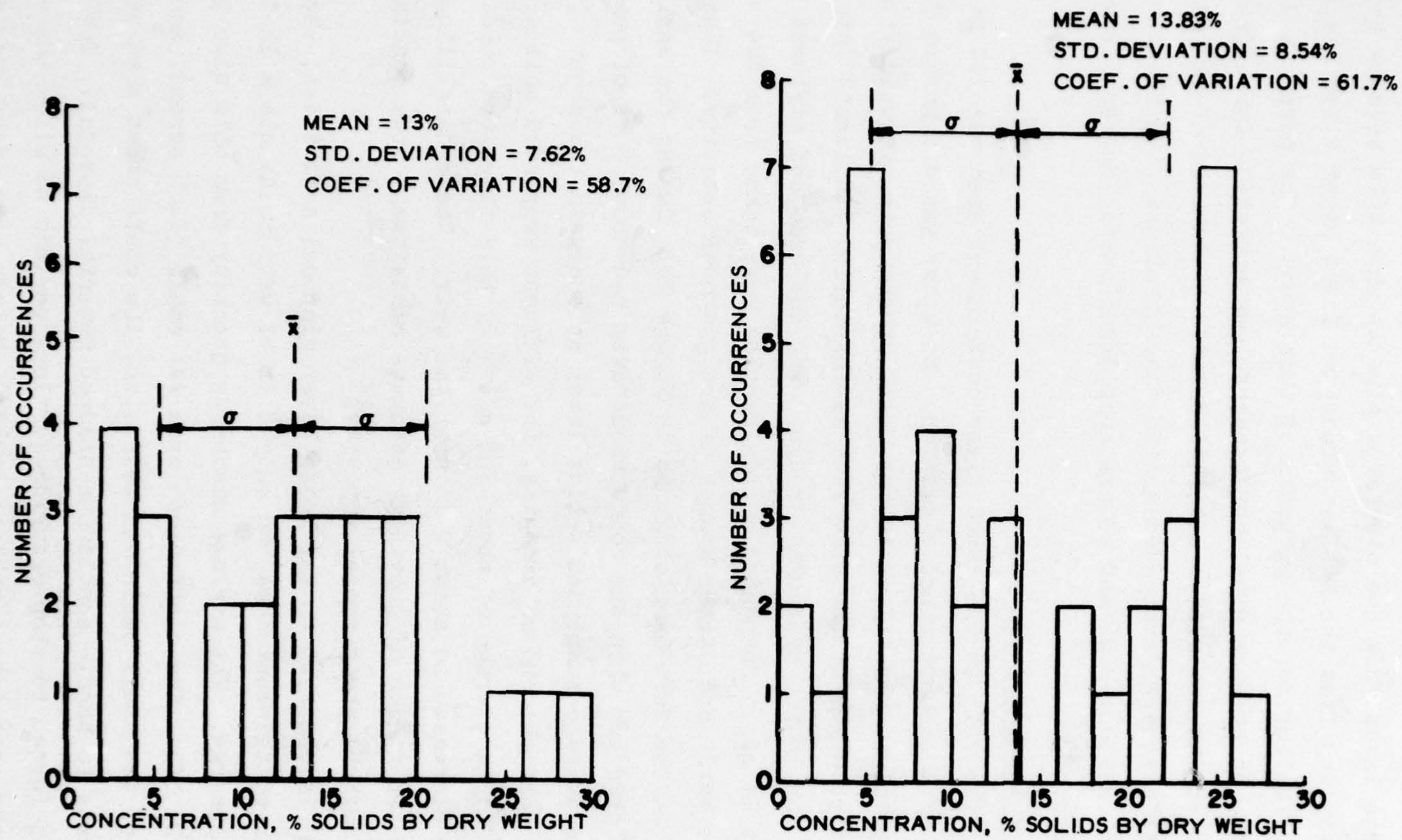
95. Yazoo River. The Yazoo River dredging project was different from the Mobile Harbor and Fowl River projects. This dredging project was a channel enlargement project for the purpose of flood control. The other projects were maintenance dredging performed for navigation purposes. The channel enlargement was accomplished by dredging consolidated soils from the sides of the Yazoo River. Due to the type operation, the dredge cutterhead was swinging into the cut from the side and consequently was often moving through a greater volume of water than is usual for maintenance dredging activities. Thus, more water was pumped into the containment area than would normally be expected. The suspended solids determined from the pipeline discharge averaged about 10 percent (≈109 g/ℓ) by dry weight.



a. MOBILE HARBOR DREDGING, NOVEMBER 1976

b. MOBILE HARBOR DREDGING, MAY 1977

Figure 22. Pipeline discharge concentrations versus time, Mobile Harbor



a. **SOLIDS CONCENTRATION HISTOGRAM FOR 24-INCH DREDGE, MOBILE HARBOR DREDGING, 4-6 NOVEMBER 1976**

b. **SOLIDS CONCENTRATION HISTOGRAM FOR 24-INCH DREDGE, MOBILE HARBOR DREDGING, 17-19 MAY 1977**

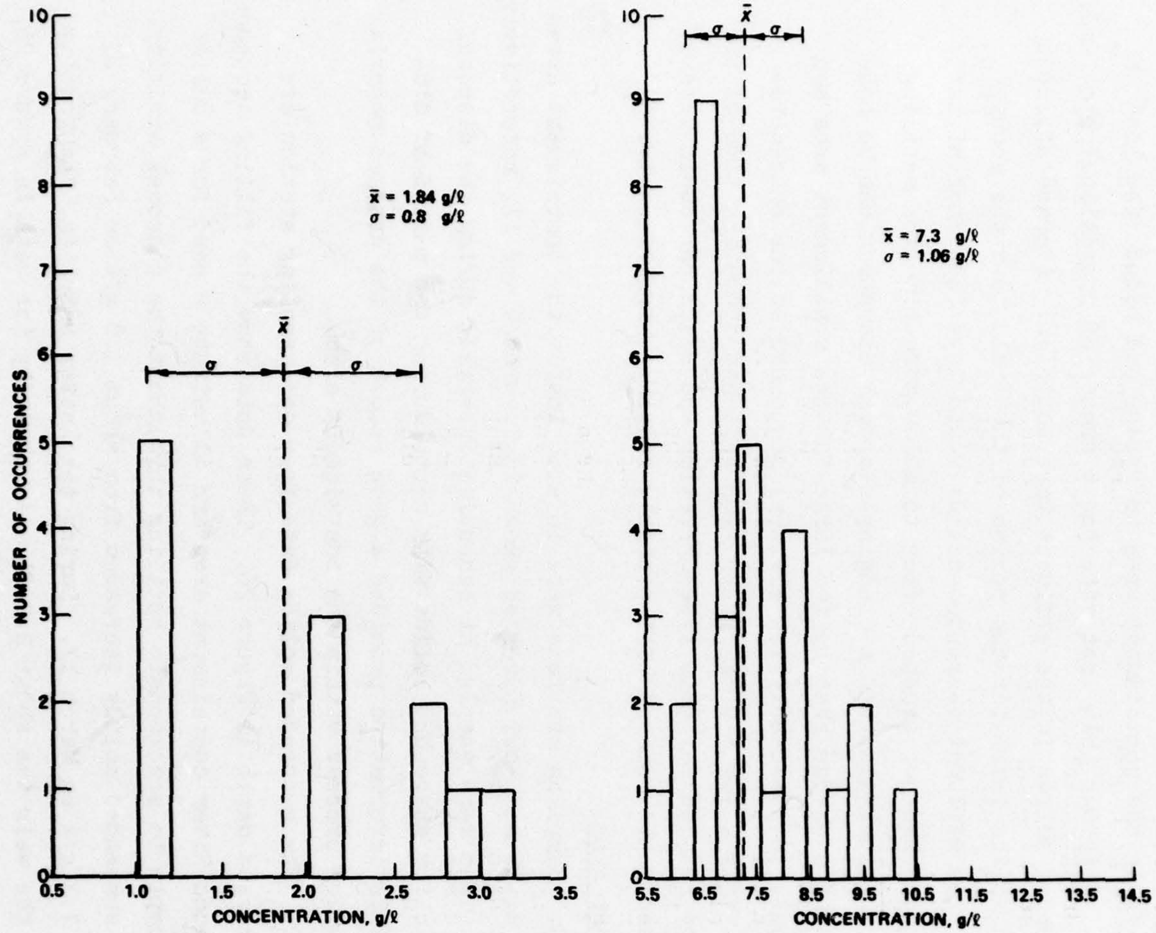
Figure 23. Histograms of 24-in. dredge pipeline discharge solids, Mobile Harbor

96. Fowl River. The suspended solids sampled from the pipeline discharge averaged about 14 percent (151.5 g/ℓ) by dry weight. Fewer samples were taken from the discharge pipe at this site because the extensive sampling from the Mobile Harbor and Yazoo River sites was considered sufficient for the purposes of this study. The purposes were to determine an average pipeline discharge concentration for hydraulic pipeline dredging activities and to determine the degree of variation in pipeline discharge suspended solids concentrations with time. The data shown in Figures 22 and 23 are considered sufficient to illustrate these points.

Containment area effluent

97. The weir at the Yazoo River containment area was 100 ft long and fixed at a predetermined elevation. No water was discharged from the area until it was filled to the level of the weir, at which time the weir discharged at the same rate as the inflow (influent) into the area from the 18-in. hydraulic dredge. The influent and effluent rates were about 27 cfs. Suspended solids samples were taken from the weir during the early and latter stages of the disposal activity. These data are shown in the form of histograms in Figure 24. During the early stages of dredging when the containment area had about 8 ft of ponding depth, the average suspended solids level at the weir was about 1.8 g/ℓ. Near the end of dredging, the effluent suspended solids increased to an average of about 7.3 g/ℓ. By this time, the ponding depth had decreased to about 2 ft near the weir. These data illustrate the importance of providing adequate containment area ponding depth throughout the disposal activity.

98. In contrast to the Yazoo River disposal activities, the Fowl River containment area had only 8 ft of weir to handle a 16-in. dredge discharge. The average discharge quantity from this size dredge is about 21 cfs. The containment area was small (12.8 acres), and, as a result of the small basin and weir size, the containment area was not adequate to handle continuous dredged material disposal. The dredge was forced to stop dredging for long periods to allow the water level in the containment area to recede. Boards were added and taken



SOLIDS CONCENTRATION HISTOGRAM FOR WEIR DISCHARGE YAZOO RIVER BASIN 5 23-25 FEBRUARY 1977

SOLIDS CONCENTRATION HISTOGRAM FOR WEIR DISCHARGE YAZOO RIVER BASIN 5 16-17 MARCH 1977

Figure 24. Histograms of weir discharge solids, Yazoo River

out of the weir as required to maintain a low level of effluent suspended solids. The effluent suspended solids measured from this dredging project are plotted in Figure 25. The gaps in the data indicate periods when the dredge was inactive. The dredge was also stopped to allow the water level in the containment area to recede and reduce the load on the dike. Although this test site had a number of operational problems, the suspended solids in the effluent were not high. Average effluent suspended solids level for the period of the field test was about 2.1 g/ℓ. The effluent suspended solids would have been much higher if the dredge had not stopped often to allow more time for settling. These data illustrate that a dredging-disposal operation can be conducted using a dredge that is too large for the containment area and still result in reasonably low effluent suspended solids concentrations. However, the average production rate and operating time of the dredge are reduced for this type operation and costs per cubic yard of in situ sediments removed will probably increase significantly.

<u>Containment area</u>

99. Sampling stations were located inside the containment areas at Yazoo River and Fowl River as shown in Figures 9 and 11, respectively. These stations were sampled at scheduled intervals during the disposal activities for suspended solids with depth during the period of disposal. This information provided a good record of the dredged material sedimentation process within the containment area.

100. The suspended solids data from one sampling station are plotted versus depth in Figure 26. These data show the filling sequence of the Yazoo River containment area and illustrate a need for a design ponding depth to accommodate settling throughout the disposal activity. Effluent suspended solids increased from about 1.8 g/ℓ on February 23 to about 7.3 g/ℓ on March 17. During the latter sampling, the ponding depth at the weir was about 2.0 ft. As shown by the data in Figure 26, it was considerably less than 2.0 ft in other parts of the containment area. Walski and Schroeder[1] describe research on the effects of ponding depths in containment areas.

101. The data indicate that the dredged material interface (mud

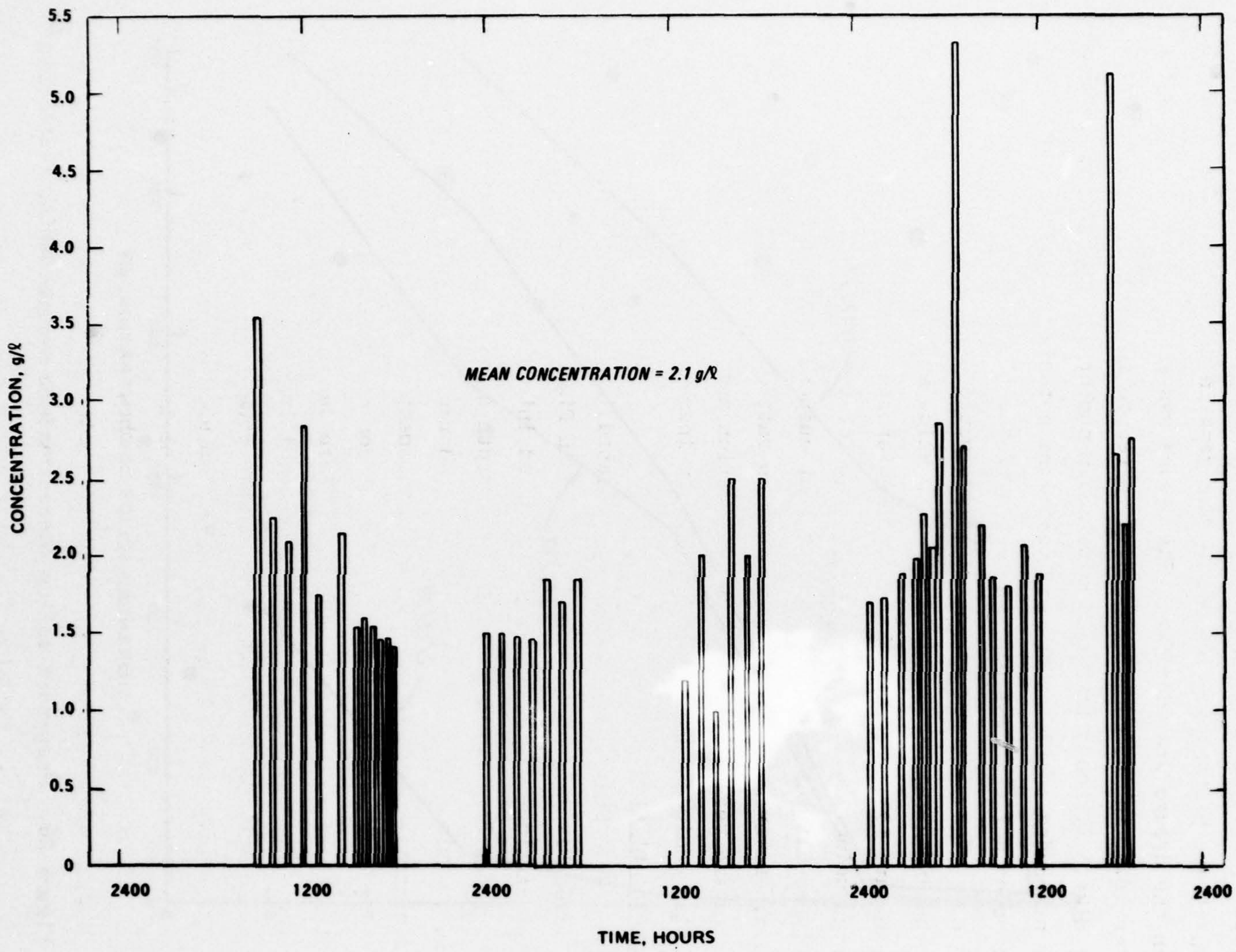


Figure 25. Suspended solids concentrations versus time measured at weir, Fowl River

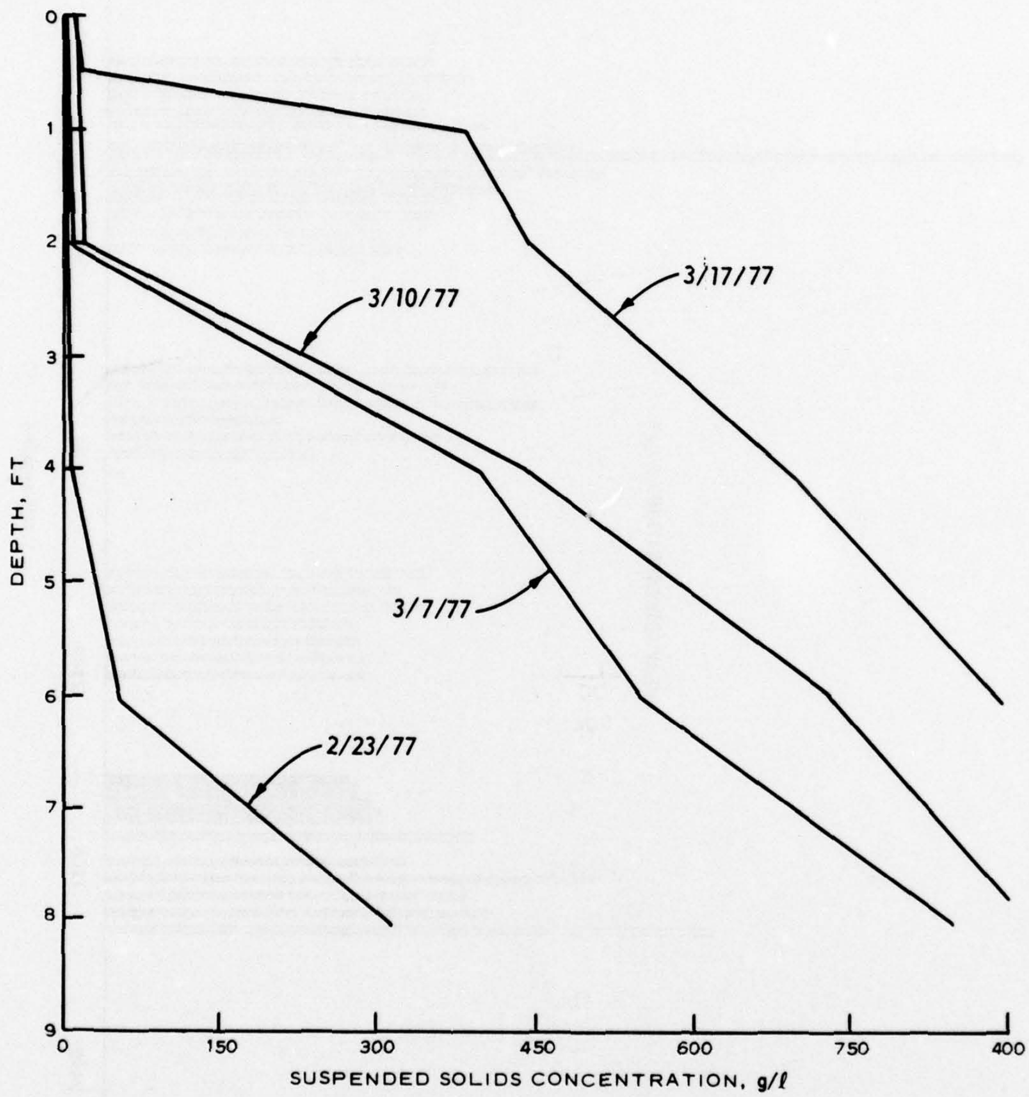


Figure 26. Suspended solids concentrations versus depth, Yazoo River

line) in the containment area slopes from the dredge discharge pipe to the weir. This fact is illustrated in Figure 27. Sampling station C-1

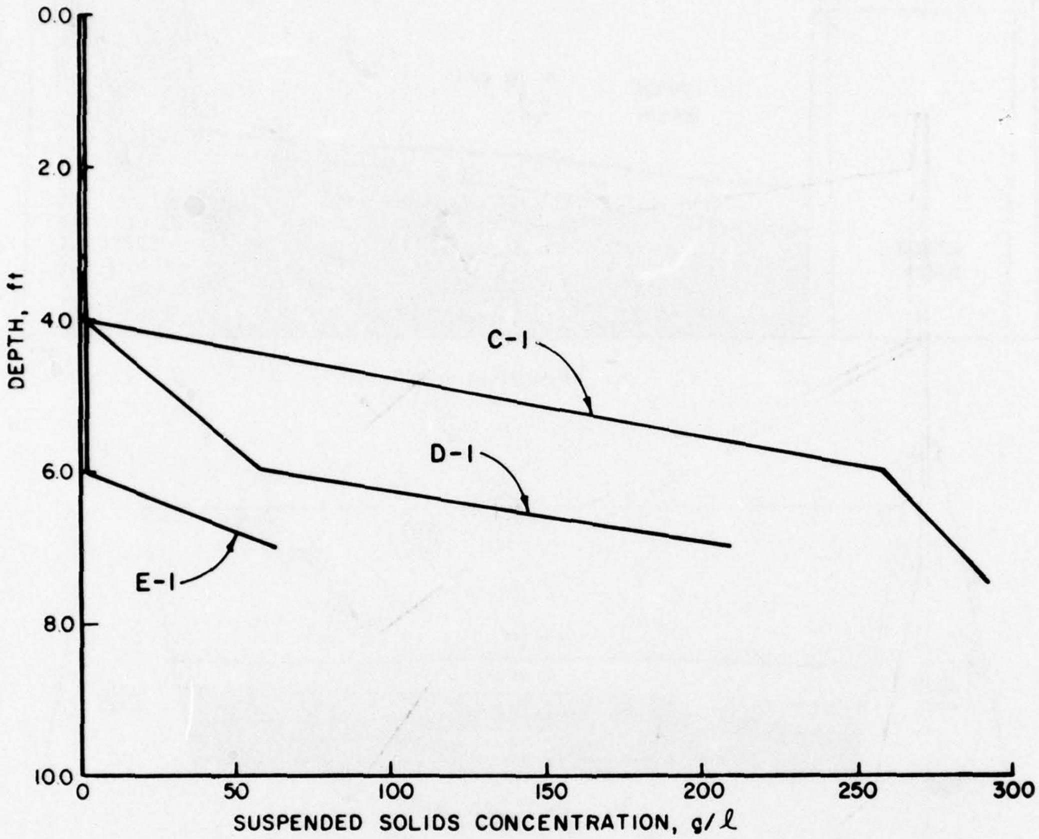
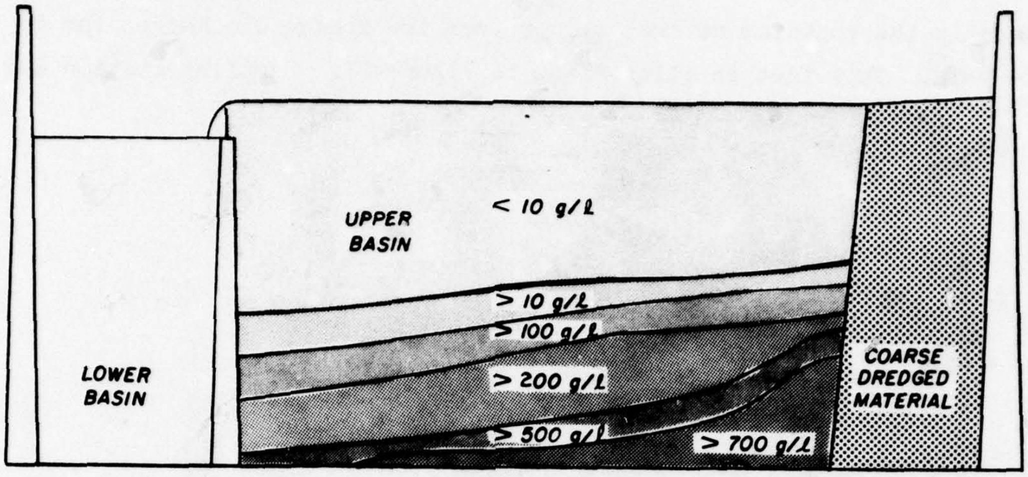


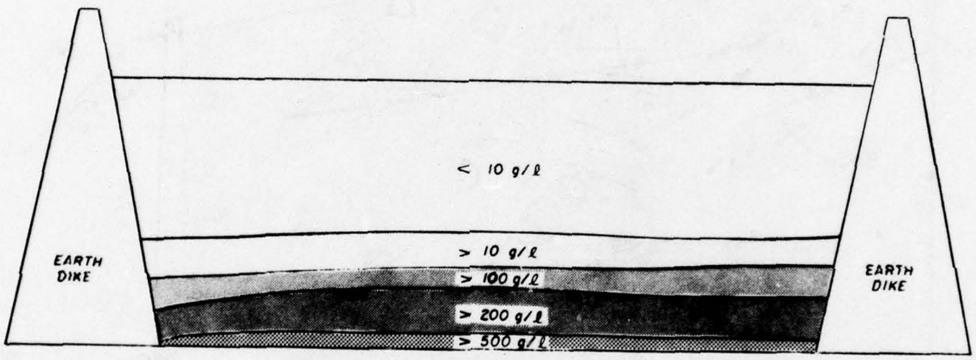
Figure 27. Suspended solids concentrations versus depth on 23 February 1977 at 3 sampling stations, Yazoo River

was located the greatest distance from the weir. The sloping dredged material interface and concentration increase with depth are illustrated more clearly in the generalized suspended solids profiles shown in Figures 28 and 29. Figure 28 shows the suspended solids concentration profile along two sections of the containment area during the early stages of disposal. Figure 29 shows the same type profile near the end of disposal. The slope of the dredged material interface at the Yazoo River containment area was about 0.005.

102. The coarse-grained dredged material settled rapidly near the dredge pipeline discharge as shown in Figures 28 and 29. The



a. Section A-A'



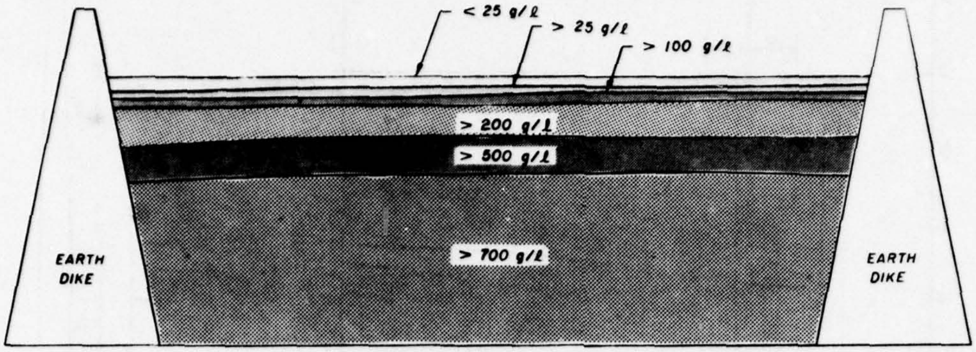
b. Section B-B'

Figure 28. Sections (see Figure 9) of Yazoo River containment area during early stages of disposal

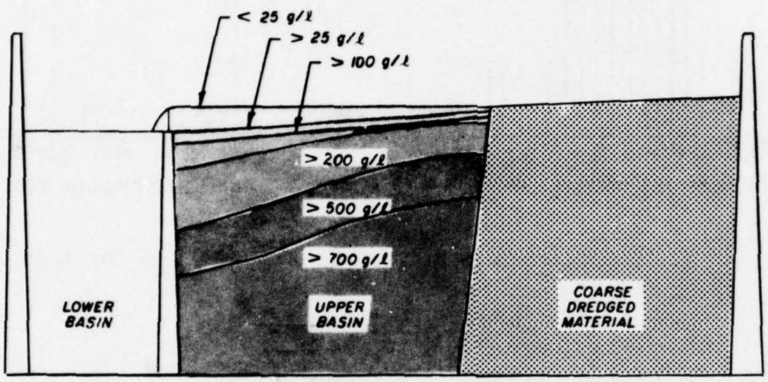
fine-grained dredged material settled slower and was displaced by the coarse-grained material as disposal continued. The fine-grained material filled the remaining portion of the containment area and was found to be generally homogeneous with distance from the pipeline discharge.

Dredge Production Rates

103. Data were collected from a maintenance dredging job to evaluate the rate of dredging of in situ fine-grained dredged material.



a. Section A-A'



b. Section B-B'

Figure 29. Sections (see Figure 9) of Yazoo River containment area near end of disposal

The data came from daily inspector reports maintained in the Corps office responsible for the dredging job. These data are plotted in the form of histograms in Figure 30. The average amounts of in situ sediment removed by dredges A and B were 1217 and 806 yd^3/hr, respectively. The only significant difference between the two dredges was the greater dredge horsepower of dredge A. This type information is available in Corps records of dredging activities and should be evaluated for use in planning future dredging and designing containment areas.

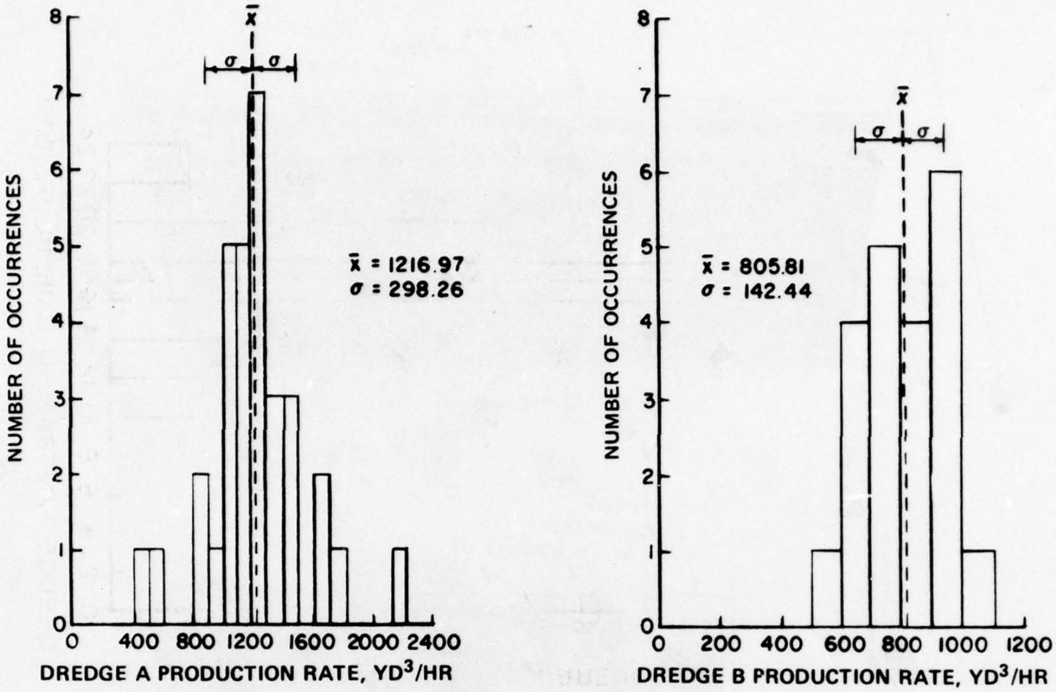


Figure 30. Histograms of production rates for dredges A and B

Dredge Operating Times

104. Most dredging activities are scheduled as round-the-clock operations. However, there is a certain amount of downtime required for moving pipeline, routine maintenance, etc., and there is lost time due to equipment problems. Dredges A and B were evaluated to determine average times of actual dredging during a 24-hour period. The data collected from the Corps office are shown in the histograms in Figure 31. During the period of evaluation, dredge A averaged dredging about 15 hours per day, while dredge B averaged about 17 hours per day. Operating time is a significant factor in estimating containment area solids loading rate for design purposes. Actual operating or dredging time is highly dependent upon the condition of the dredge, dredging environment, distance to containment area, etc., and is hard to estimate with any degree of certainty. Best estimates will likely be made from records of past dredging activities.

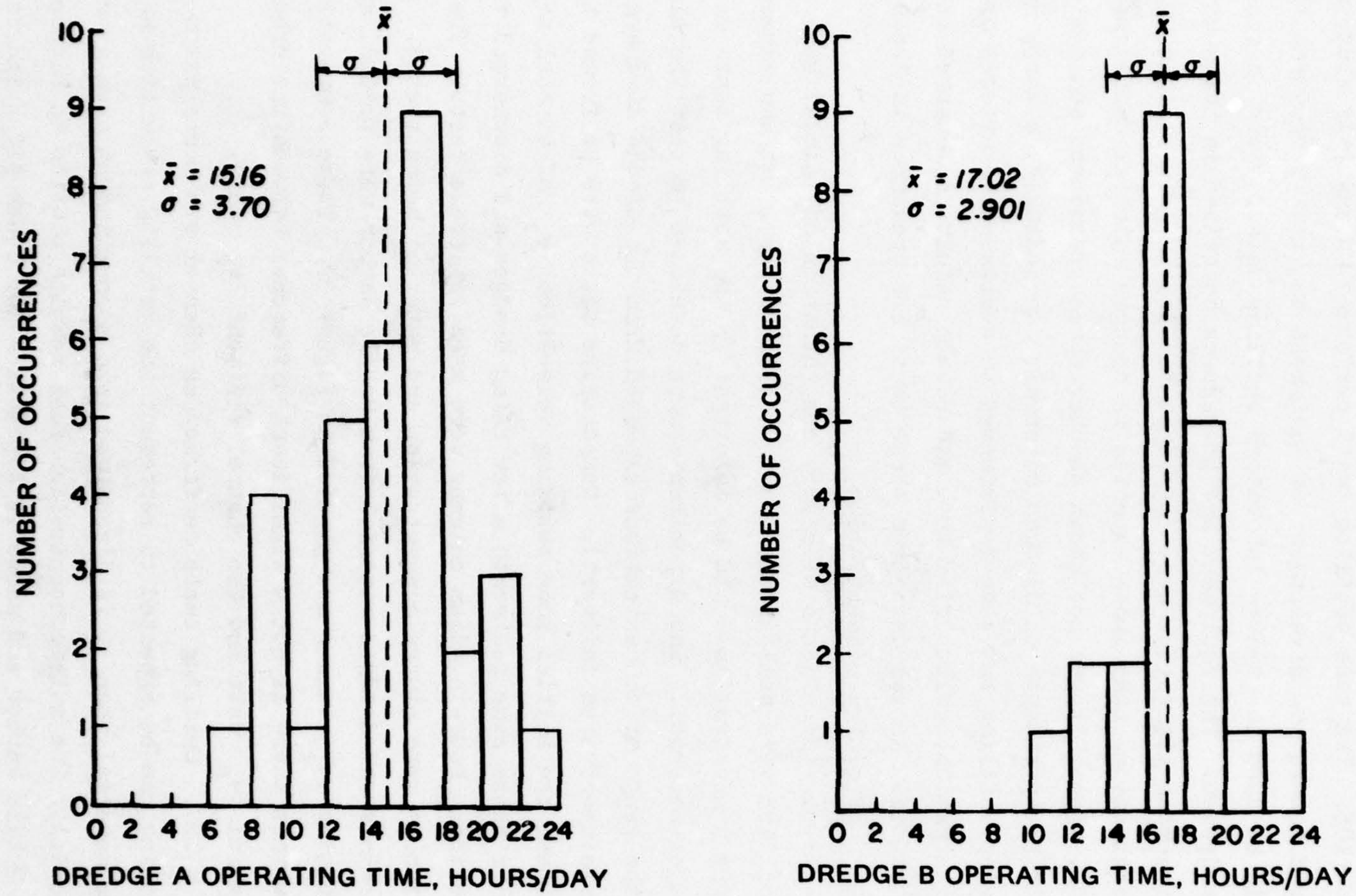


Figure 31. Histograms of operating times for dredges A and B

Zone Settling Tests

105. The zone settling tests performed during this study were geared toward the development of equipment and test procedures that could be used to produce laboratory settling data for use in containment area design. The equipment and procedures described in the sanitary engineering literature were developed for testing slurries at much lower concentrations than those expected in dredged material containment areas. Thus, it was not known whether these procedures and equipment would be applicable to dredged material. Accordingly, a large number of zone settling tests were performed to evaluate the effects of slurry concentration, column diameter, and column height on measured settling velocities. Actual data from these tests are presented in Appendix A.

Effects of slurry concentration

106. The effects of slurry concentration on initial zone settling velocities were well documented in the literature. It was expected that slurry concentration would be important in the settling tests on dredged material. The experiments were developed to test the slurries at the range of concentrations expected from the dredge discharge pipe (containment area influent). Comparative tests were performed to evaluate the initial zone settling velocities v_s of channel sediments and of those same sediments after being dredged and discharged from the pipeline. Four-in.-diam columns were used for these tests. The only variables were slurry concentration and material being tested. Channel sediments and dredged material from Mobile Harbor were tested, and the resulting v_s values are plotted in Figure 32. These comparative tests show that there is not a significant difference between the dredged material v_s data and the channel sediment v_s data.

107. Settling tests performed on channel sediments prior to dredging can be expected to represent the settling properties of that same material when it is discharged into a containment area as dredged material. The multiconcentration test results plotted in Figure 32 for Mobile Harbor and shown in Appendix A for other sites indicate that v_s decreases with increased slurry concentration. Therefore, it is

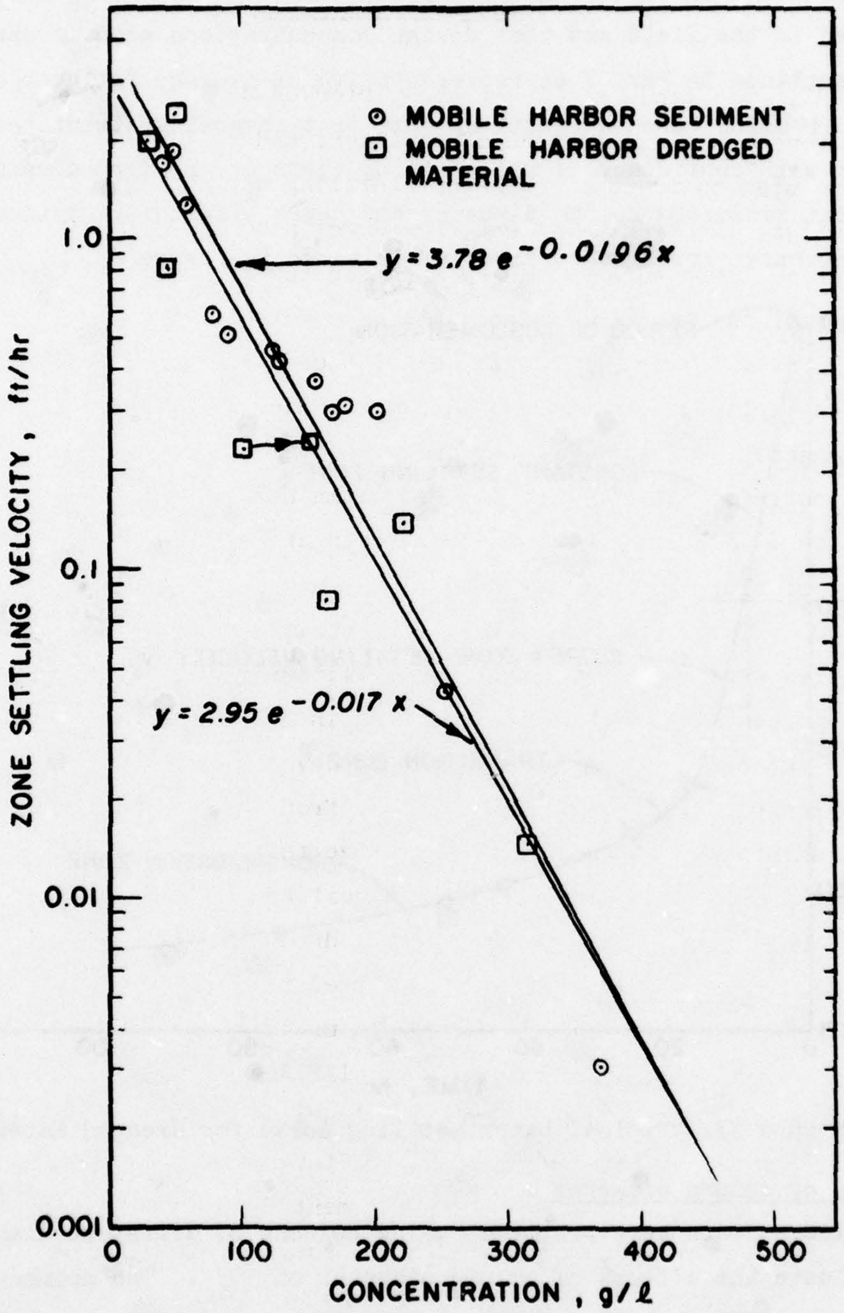


Figure 32. Zone settling velocity versus concentration

important that the settling tests cover the range of concentrations expected in the field and that design concentrations used in the methodology outlined in Part V be representative of average influent concentrations. Designs based on settling data from channel sediment tests can be made with confidence if the settling tests are performed using equipment that minimizes column diameter and depth effects. A typical zone settling curve for dredged material is shown in Figure 33.

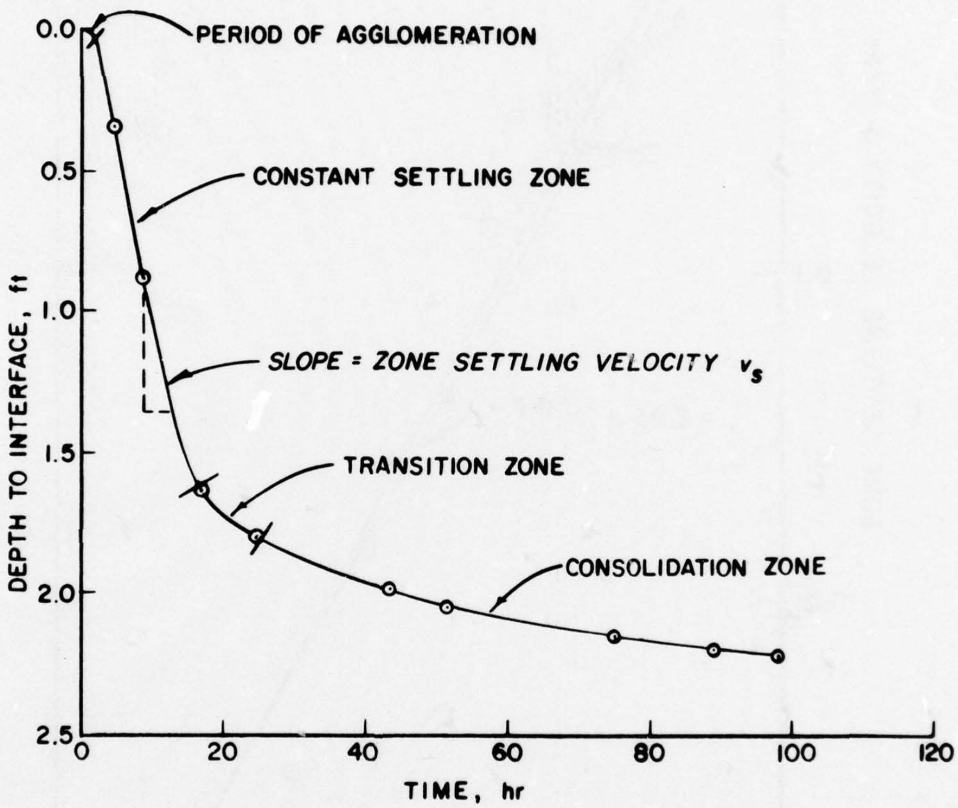


Figure 33. Typical batch settling curve for dredged material

<u>Effects of column diameter</u>

108. Tests were performed using columns of different diameters to evaluate the effects of column diameter on v_s . The columns used are shown in Figures 18 and 19. Height in these tests was maintained at that of a 1-litre graduated cylinder so that this vessel could be used in the tests. In practice, this vessel has often been used to perform the zone settling tests, and the accuracy of settling data

from such tests has been questioned.

109. The "wall effect" is probably more pronounced in tests of dredged material than in tests of slurries for sanitary engineering purposes because of the high concentrations required. This effect is illustrated in Figure 34: small diameter columns can cause an increase

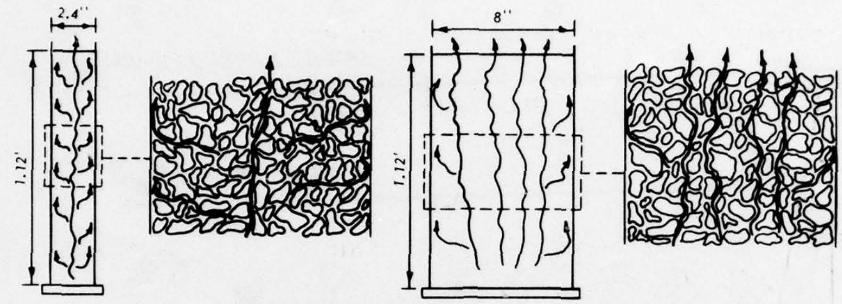


Figure 34. Illustration of wall effects in settling columns

in v_s measurements as a result of "bridging" against the column walls. The rate of fall of the solids interface v_s increases because the water that is displaced by the subsidence of solids encounters less resistance flowing upward along the wall than the more difficult route between particles. Results of five multidiameter column settling tests are shown in Figure 35. These data indicate that the wall effect becomes significant at concentrations greater than about 53 g/ℓ. Column diameters less than 8 in. resulted in increased v_s for the tests with concentrations >53 g/ℓ. These data lead to the conclusion that columns less than 8 in. in diameter should not be used for zone settling tests for the purpose of designing dredged material containment areas. Data gained using 1-litre graduated cylinders as settling columns are not reliable.

Effects of slurry depth

110. The equipment developed to evaluate the effects of initial slurry depth on zone settling velocity is shown in Figure 16. Photographs of actual tests are shown in Figure 17. Results of two series of multiheight tests are shown in Figure 36. The data in Figure 36a are from tests at initial concentrations of 43 g/ℓ. Depth had little

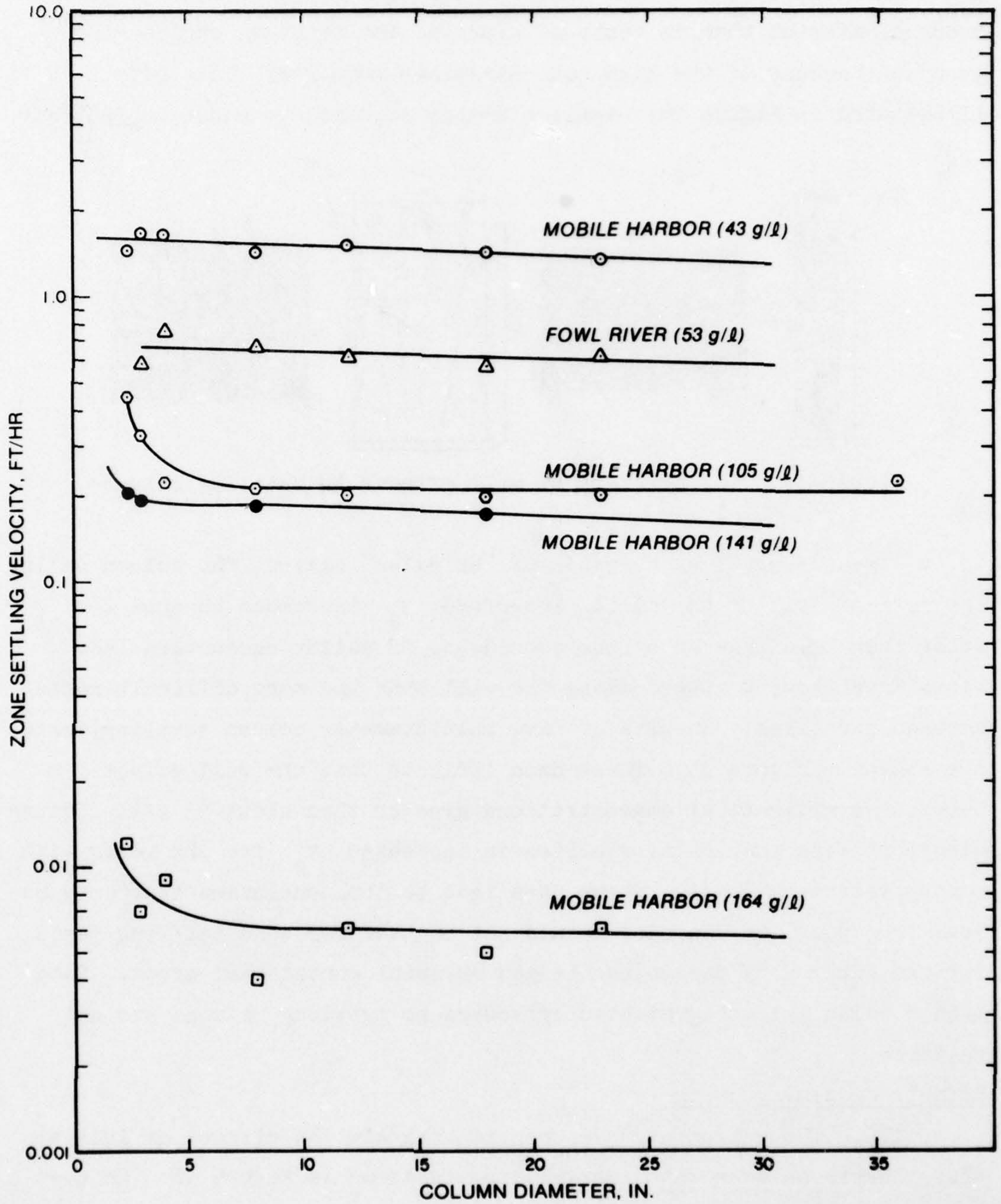
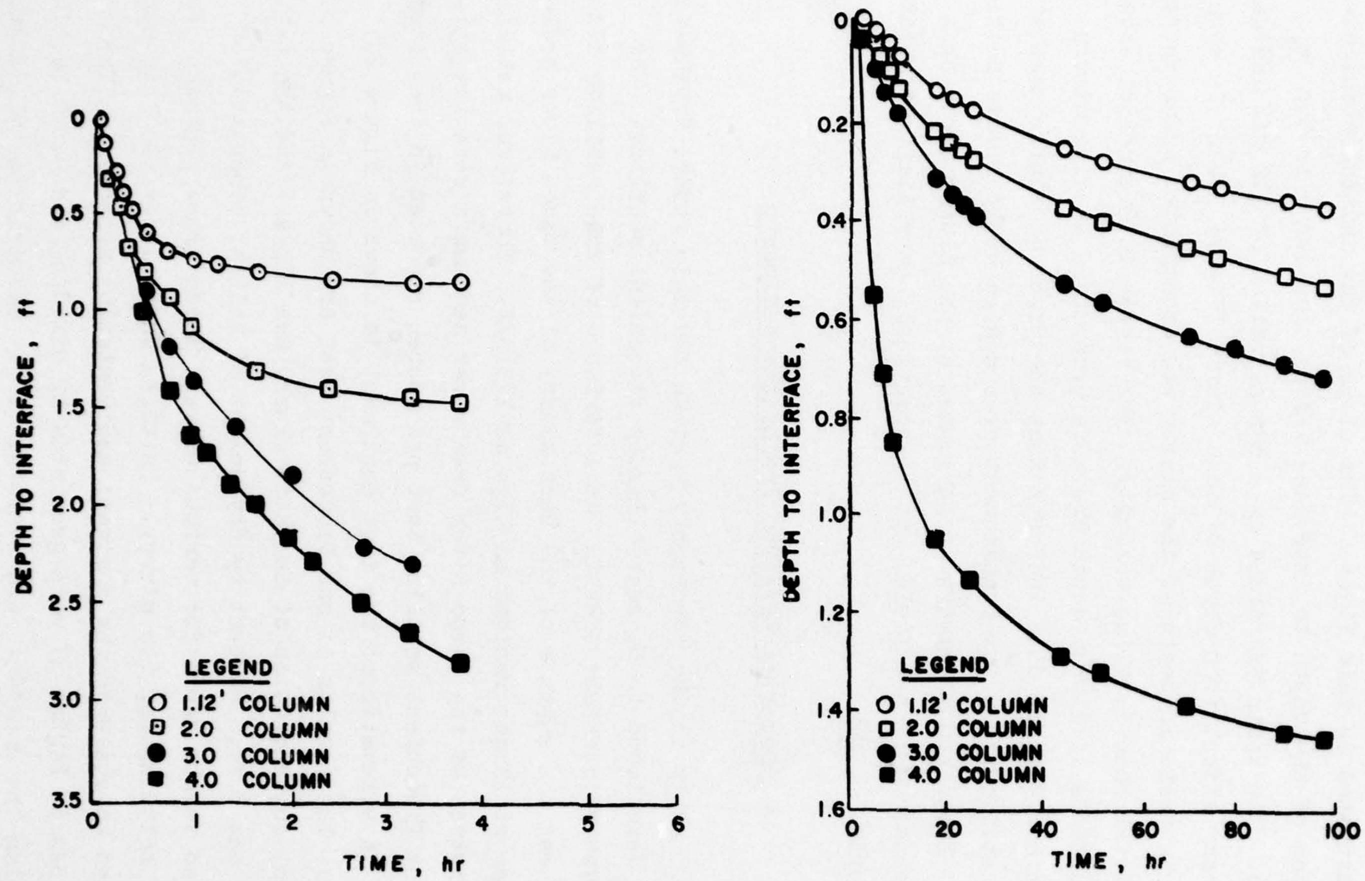


Figure 35. Zone settling velocities versus column diameter



a. 43-g/ℓ slurry concentration

b. 172-g/ℓ slurry concentration

Figure 36. Results of multiheight settling tests

effect at this level of solids concentration on the settling velocity. The initial zone settling velocity v_s is determined from plots like those illustrated in this figure. The slope of the initial straight-line portion of the depth to interface versus time curve is the v_s (see Figure 33). The tests performed at a concentration of 172 g/ℓ indicate a significant effect from depth of test slurry (Figure 36b). In each case, the increase in depth of the slurry was accompanied by an increase in the initial zone settling velocity. The curves in Figure 36b show that the effects of slurry depth are more pronounced at high slurry concentrations. These data indicate that the depth of slurry used in the zone settling test for containment area design would always be significant. Tests should always be performed at the slurry depth that would be expected in the field, with a practical upper limit of about 6 ft of depth.

Settling Tests on Freshwater Sediments

111. Early in the laboratory testing for this study, freshwater sediments were found to be controlled by flocculent settling. The sediment-water interface that is characteristic of zone settling did not form near the surface of the test slurry of the Yazoo River sediments, even at concentrations as high as 175 g/ℓ. Therefore, settling characteristics of the Yazoo River freshwater sediments were investigated using flocculent settling test procedures reported in the literature.[9,15] A schematic of the test equipment is shown in Figure 20.

112. The results of one flocculent test are shown in Figure 37. The initial concentration of the test slurry was 175 g/ℓ and the depth of slurry was 8 ft. Percent by dry weight of initial concentration was plotted versus depth for various times. These times represent the period of settling for the slurry. Settling data plotted in this manner can be used to evaluate the dominant sedimentation process.[15] The dashed lines in Figure 37 were generated by dividing the depth by time and plotting the constant d/t values. It is possible to tell directly from this plot that flocculation is causing the particles to settle

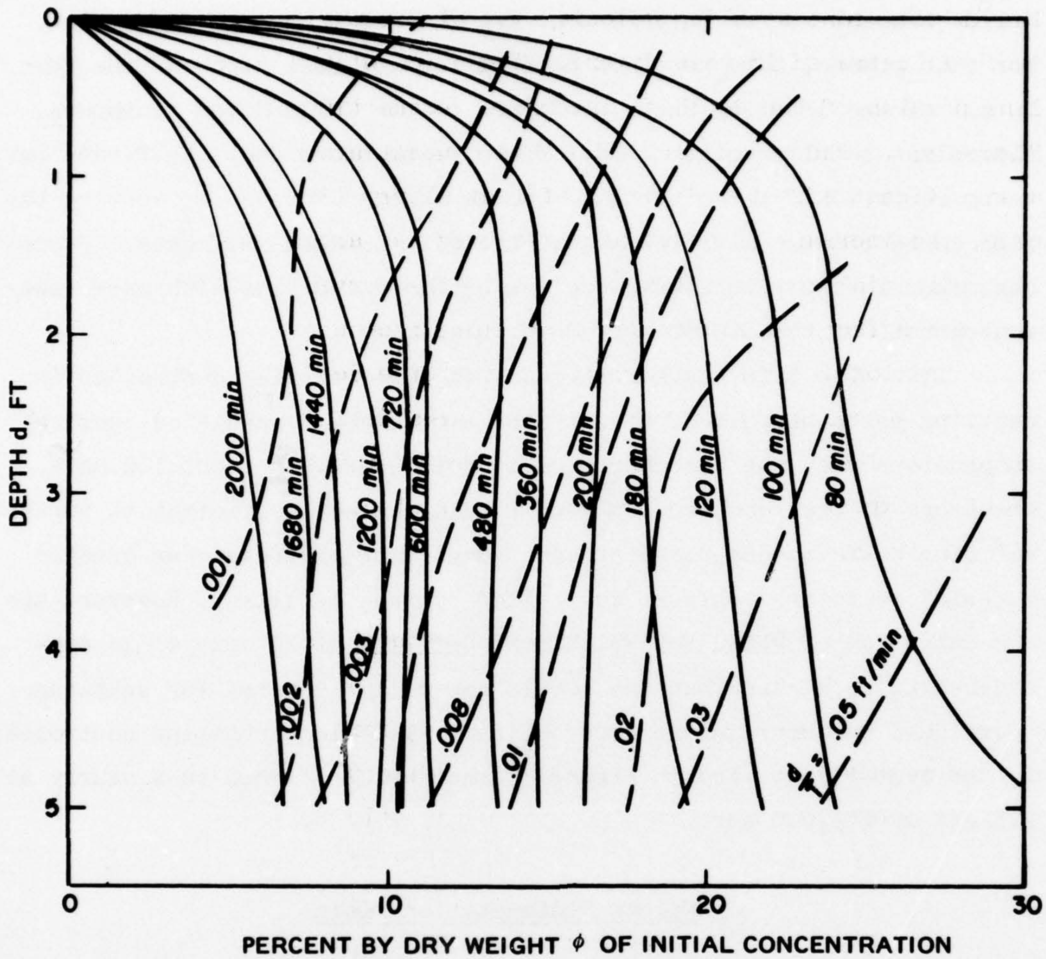


Figure 37. Depth versus percent by dry weight of initial solids concentration for Yazoo River. (Initial concentration = 175 g/ℓ)

more rapidly.[15] This result is indicated by the fact that the dashed lines (d/t) slope toward the d-axis. When neither zone settling nor flocculation occurs, the dashed lines will be straight and parallel to the d-axis. When zone settling slows the particles down more than flocculation can speed them up, the dashed lines will slope away from the d-axis.

113. Zone settling did control in the lower portion of the flocculent settling columns. However, because the withdrawal zone in a

containment area is generally limited to the upper 2 to 3 ft, suspended solids removal values in this zone are the data required for design. For this reason, data were not plotted for the full depth of the test. In all of the settling tests performed on the Yazoo River sediments, flocculent settling controlled. These tests prove that the flocculent tests reported in the literature can be adapted for use in testing the high concentration slurries associated with dredged sediments. Tests described in the literature were performed on slurries with much lower concentrations than those tested in this study.

114. The literature reported that zone settling controlled in settling tests performed in activated sludge and flocculated chemical suspensions when the concentration of solids exceeds about 500 mg/ℓ. The scope of the research reported herein was not sufficient to pursue settling tests to determine at what concentration freshwater dredged material sediments would be controlled by zone settling. However, the concentration of solids at which zone settling would control is considered to be higher than the levels generally required for settling tests used for containment area design. Flocculent settling controlled in the test illustrated in Figure 37 that was performed on a slurry at 175 g/ℓ or 175,000 mg/ℓ.

Column Sedimentation Tests

115. To provide adequate design volume, the average concentration of the dredged material pumped into the containment area must be estimated from laboratory tests. The average concentration of the dredged material at the end of disposal activities can be estimated from the column sedimentation tests described in Part III using the equipment shown in Figure 20. Tests were performed using this equipment, and the test data were compared with column sedimentation data from a field test basin used in research on densification of fine-grained dredged material (see Figure 38).[27] The upper basin shown in Figure 38 was filled with dredged material to a depth of about 5 ft and allowed to settle and consolidate, without drainage, for more than a year's time. This 30- by

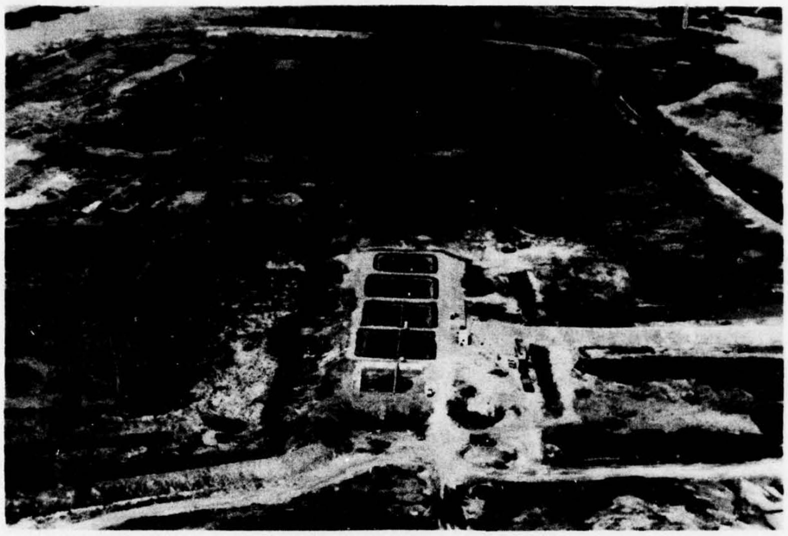


Figure 38. Test basins used in densification study[27]

30-ft test basin was used to evaluate the laboratory column sedimentation data because it was considered to be more representative of the actual sedimentation experienced in dredged material containment areas.

Methods used for data analysis

116. Coulson and Richardson,[28] Roberts,[29] and Michaels and Bolger[30] all assumed that the rate of consolidation of a slurry can be expressed by a first-order rate expression. This previous research was modified to give the following expression relating concentration changes with time in the consolidation zone:

$$\frac{dC}{dt} = K\,(C_\infty - C) \qquad (4)$$

where

C = Concentration ($C = C_o$ when $t = 0$), g/ℓ

t = time at C , hours

K = first-order rate constant, hours^{-1}

C_∞ = ultimate concentration in sedimentation environment, g/ℓ

Separation of variables in Equation 4 gives

$$\int_{C_o}^{C} \frac{dc}{C_\infty - C} = \int_{o}^{t} Kdt \qquad (5)$$

where C_o is the concentration of dredged material at $t = 0$. The resulting expression for concentration as a function of time is

$$\ln\left(\frac{C_\infty - C_o}{C_\infty - C}\right) = Kt \qquad (6)$$

Equation 6 can be rearranged and expressed as

$$C = C_\infty - (C_\infty - C_o)e^{-Kt} \qquad (7)$$

Equation 7 can be used to generate a concentration versus time curve based on a series of data points from the sedimentation tests.

117. There were several models described in the literature for determining the ultimate concentration C_∞ and rate constant K using the data from the column sedimentation tests. The Thomas[31] and least squares[32] methods were used in this study.

Comparison of data

118. A comparison of data from the field test basin and from laboratory column sedimentation tests is shown in Figure 39. Equation 7, using ultimate concentrations and rate constants determined from the Thomas and least squares methods, was used to extend the concentration versus time curves. Data from a 30-day sedimentation test were used in the two models. Column sedimentation tests of shorter periods resulted in poor comparisons. The models used for the comparison of data in Figure 39 were considered to be unsatisfactory because they required that the laboratory tests be performed for excessive periods.

119. In an attempt to reduce the time required for the column sedimentation tests, other plots of the data were investigated. It was found that the concentration versus time data plotted in straight-line form on log-log plots. A comparison of the test basin data with data from a 15-day column sedimentation test is shown in Figure 40. This

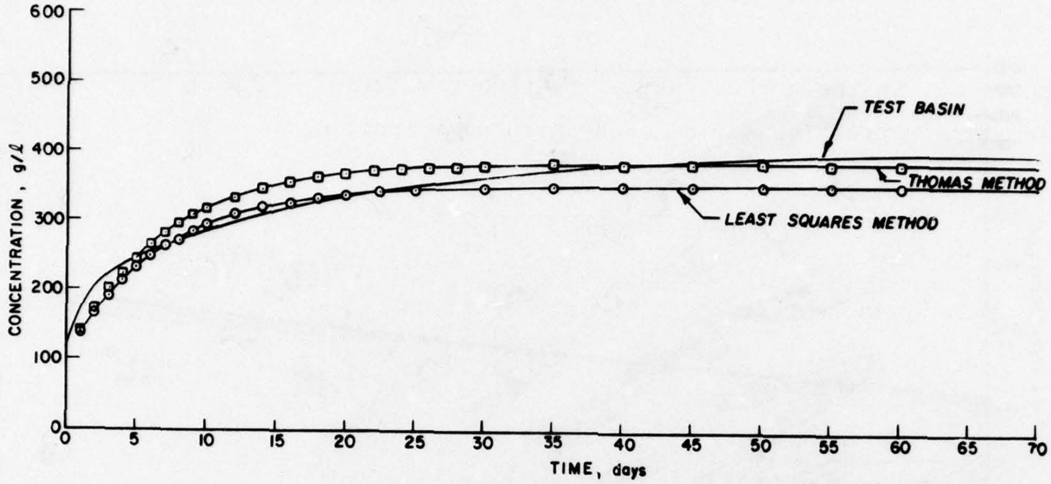


Figure 39. Comparison of model generated data (30-day test results) with test basin data

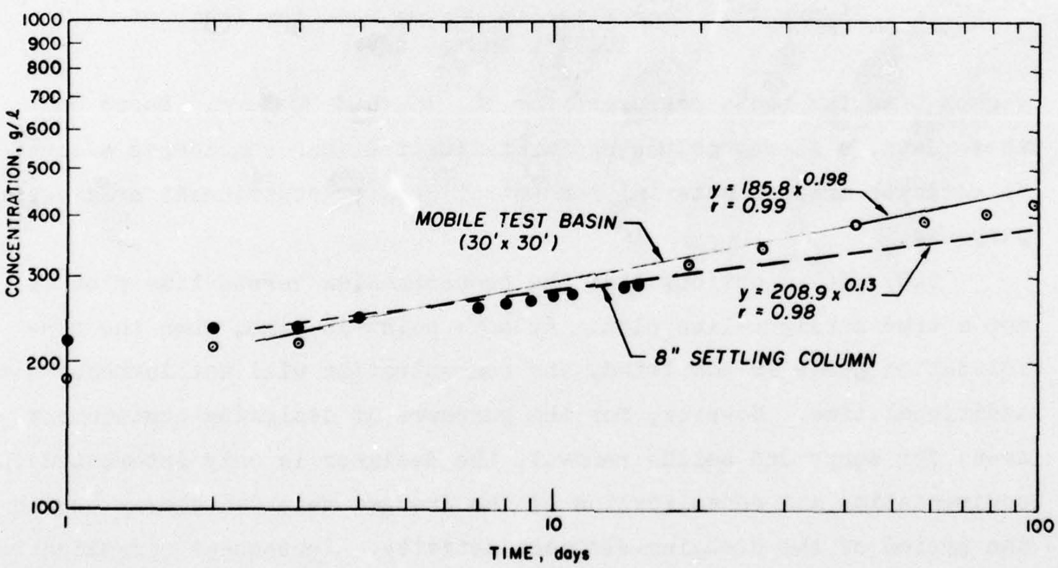


Figure 40. Comparison of 15-day test results with test basin data

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figure indicates that the column sedimentation test described in Part III can be used to obtain reliable data for design purposes when plotted in a log-log form. Figure 41 shows log-log plots of concentration

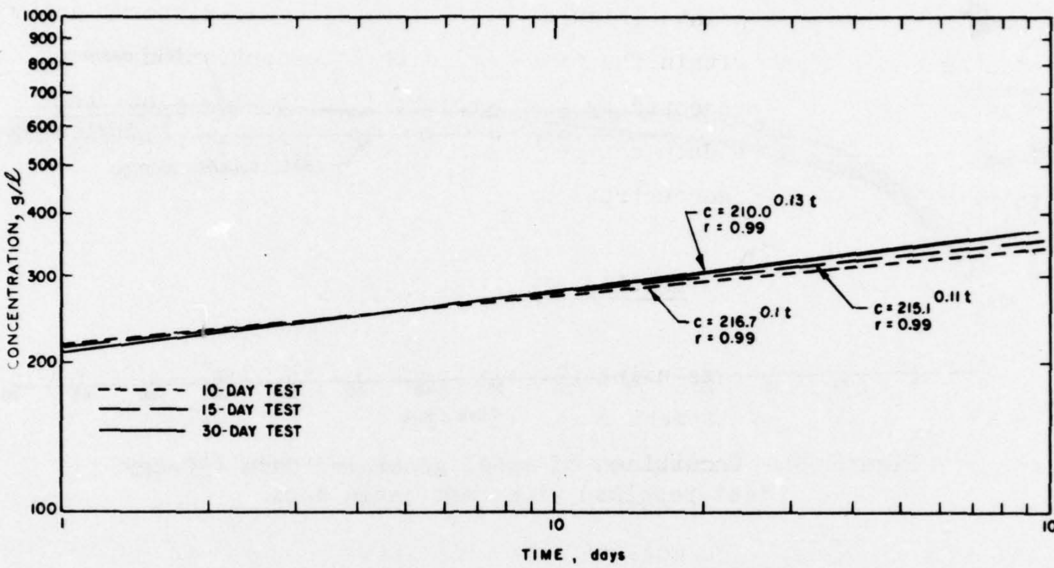

Figure 41. Concentration versus time for tests of 10, 15, and 30 days

versus time for tests performed for 10, 15, and 30 days. Based on these data, a 15-day column sedimentation test was considered adequate to estimate dredged material concentrations for containment area design purposes.

120. It is obvious that the concentration versus time plot is not a true straight-line plot. At some point in time, when the consolidation phase is completed, the concentration will not increase with additional time. However, for the purposes of designing containment areas for suspended solids removal, the designer is only interested in sedimentation and consolidation of the dredged material slurry during the period of the dredging-disposal activity. Subsequent consolidation of the dredged material is important for long-term storage volume requirements but has no bearing on the design of the containment area for a particular disposal activity.

121. The data measured from the field test basin indicate that

a straight-line fit is reasonable for a log-log plot of the concentration versus time data within the time period of 1 to 100 days. The correlation coefficient for the regression analysis on these data was 0.99, which indicates that the straight-line log-log plot has a good correlation of data points (Figure 40). Since dredging-disposal activities generally fall within the time period that concentration versus time data can be represented by the straight-line log-log plot, the log-log plot of these data can be used with confidence to estimate containment area design concentrations.

Results of Tracer Studies

122. Tracer tests using a fluorescent dye (Rhodamine WT) were performed in the containment areas at Yazoo River and Fowl River to characterize short-circuiting and dispersion. Short-circuiting is related to the amount of deviation from ideal plug flow through the containment area. For the most effective removal of suspended solids, flow in the dredged material containment area should approach plug flow. However, plug flow never exists in actual containment areas. Flow in these areas is always accompanied by a certain amount of mixing and short-circuiting. Therefore, flow in containment areas falls somewhere between plug flow and completely mixed flow.

123. Plug flow is defined as the flow condition under which fluid passing through the containment area is retained for a time equal to the containment area volume V divided by the influent (dredge discharge) rate Q. If the flow is not plug flow, some fluid will be short-circuited and will be held for a time less than V/Q. A completely mixed containment area is one in which the influent is mixed immediately with the entire content of the containment area resulting in a high release of suspended solids. It is easy to see that neither plug flow nor completely mixed flow will ever be completely realized in containment area disposal activities. Since laboratory data provide a basis for designing the containment area for plug flow conditions, the design must be increased by some factor to compensate for the fact that

actual flow falls somewhere between plug flow and completely mixed flow.

124. Tracer tests performed during this study were used to determine the design modifications necessary to account for containment area short-circuiting and mixing. Data from these tests were compared with the results of an investigation on containment area efficiencies.[3]

Yazoo River tracer tests

125. Tracer tests were performed in the containment area shown in Figure 9 during the early stages of disposal and again near the end of disposal when the average depth in the containment area was about 2.0 ft. Data from these tests are plotted in Figure 42. During the

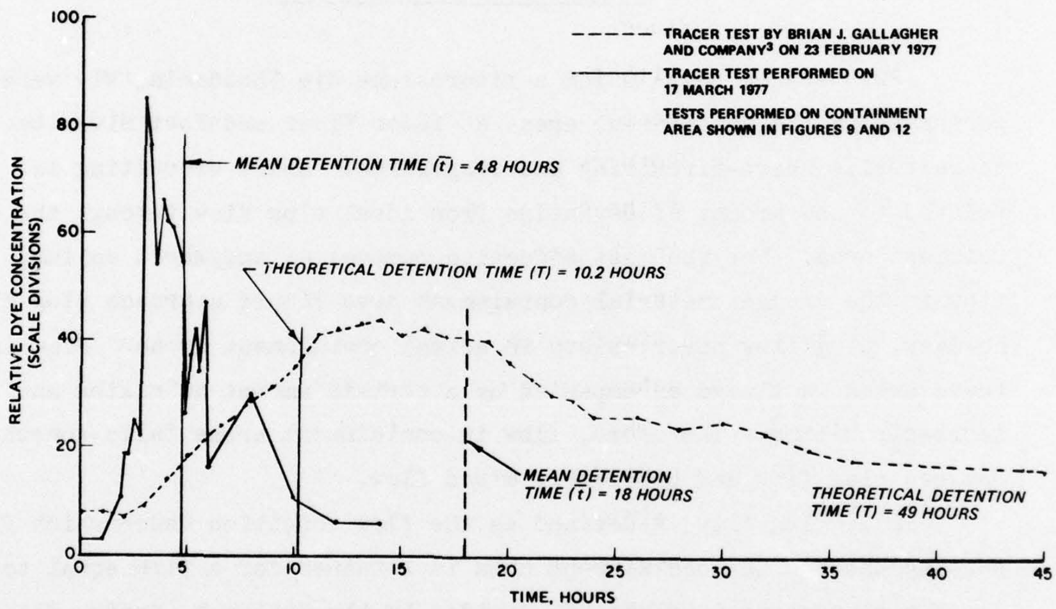

Figure 42. Dye flow-through curves for tracer test at Yazoo River

period of these two tests, the volume in the containment area decreased from about 4,695,000 to 974,700 ft^3, and the average depth decreased from about 7.4 ft to 2.0 ft. These numbers were computed from the data obtained during containment area sampling for suspended solids determinations with depth. The bottom of the containment area was assumed to be at the depth where the suspended solids were greater than 200 g/ℓ.

126. The curves in Figure 42 show the changes in detention times as the containment area was filled with dredged material. During the

early stages of disposal, the theoretical detention time V/Q was 49 hours, and the mean detention time determined from the tracer curve was 18 hours. This indicates that the actual detention time was only about 37 percent of the theoretical.

127. The surface plume of a tracer test performed during the last stages of disposal is shown in Figure 12. The photographs in this figure show the surface plume of the dye at various times after injection into the containment area. The dye flow-through curve is shown in Figure 42 as the tracer test performed on 17 March 1977. The photographs show that the surface plume of dye arrived at the weir about 2.5 hours after dye was injected into the containment area at the point of dredged material influent. This time corresponds to the time of peak concentration measured with the fluorometer as shown in Figure 42. The 18-mph wind during the test had a significant effect on the dye plume, as can be seen in the photographs. The wind caused a dead zone of dye to remain in a corner of the containment area. It was difficult to identify the dye plume in the aerial photographs after about 4 hours.

128. The tracer test performed near the end of disposal indicated that the mean detention time had decreased from 18 to 4.8 hours. At this point, the actual detention time was about 47 percent of the theoretical detention time. This compares with the 37 percent of theoretical detention time calculated from the first tracer test. This difference indicates that the efficiency of the containment area, as indicated by the deviation from theoretical detention time, remained essentially the same during the disposal period covered by the tracer tests when the average depth decreased from about 7.4 to 2.0 ft.

Fowl River tracer tests

129. Tracer tests performed at Fowl River were not as successful as those performed at the Yazoo River site. Because of problems with seepage through the dikes and the fact that the weir was small for the dredge being used, the flow conditions were never ideal for performing a tracer test. On 12 April 1977, the dredge operated on a continuous basis for about 9 hours, which was enough time to obtain the data for the flow-through curve shown in Figure 43. However, data for the

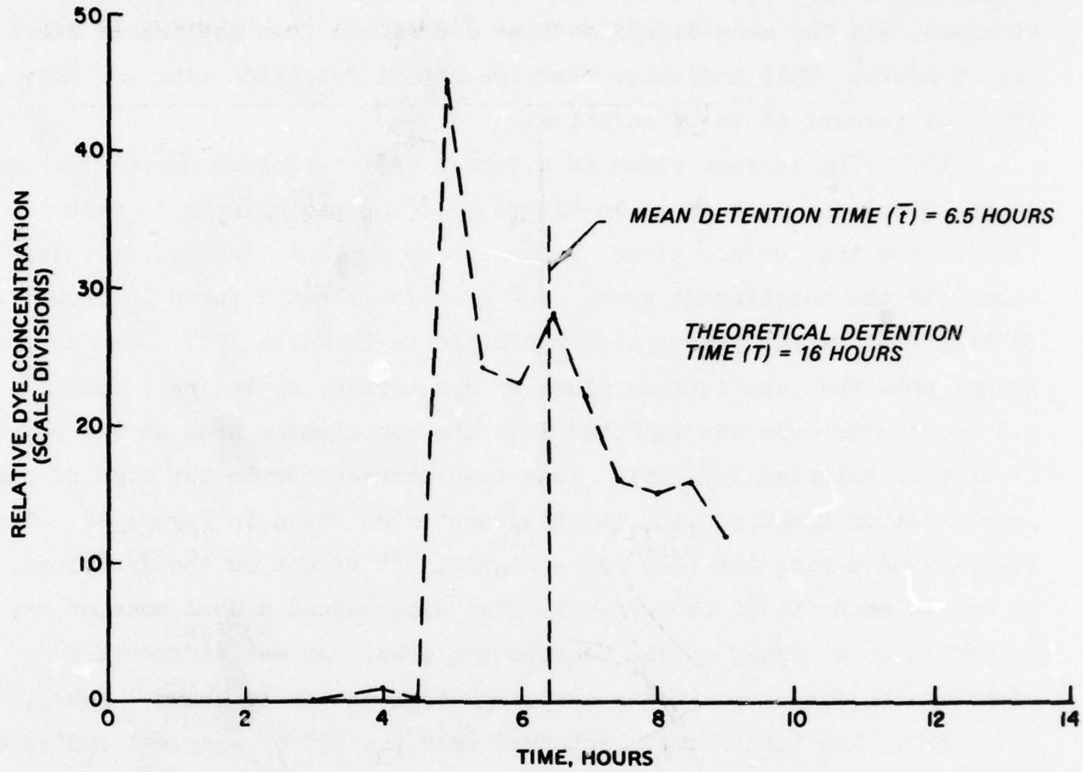

Figure 43. Dye flow-through curve for tracer test at Fowl River

complete curve could not be developed because the dredge stopped pumping 9 hours after the dye was injected into the containment area. A smooth curve was drawn through the available data points and extrapolated to provide a complete dye flow-through curve.

130. The Fowl River basin had an average depth of about 2.2 ft during the time of the test and a volume of about 1,207,372 ft^3. The mean detention time calculated from the tracer curve was 6.5 hours, and the theoretical detention time was 16 hours. The efficiency of this containment area, based on detention time, was 41 percent.

Analyses of containment area mixing

131. The three tracer tests discussed previously were used to evaluate the extent of mixing or dispersion occurring during the disposal activities. A dispersion model presented by Levenspeil[33] was used to calculate the dispersion number (D_d/v_xL_c) for each containment area

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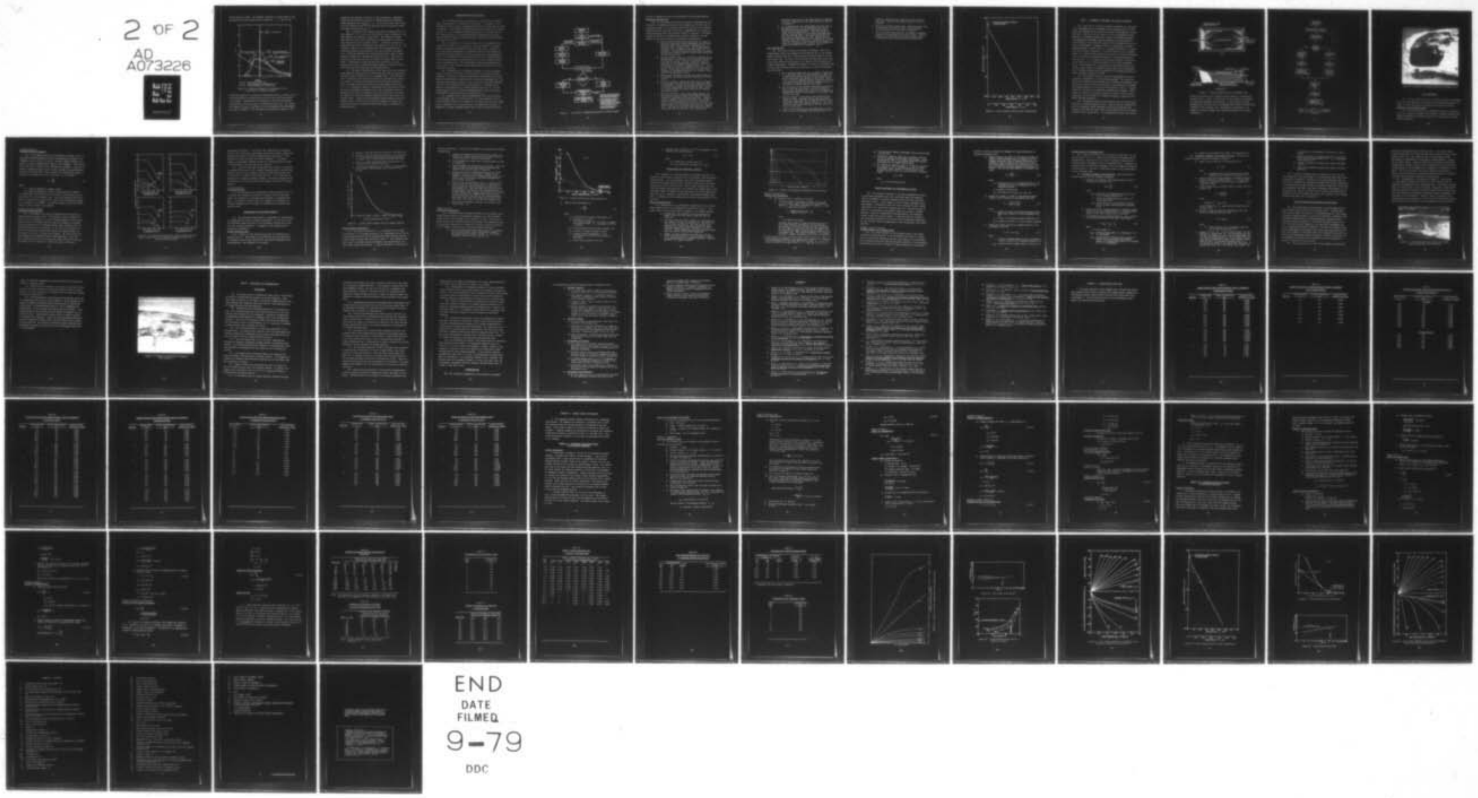

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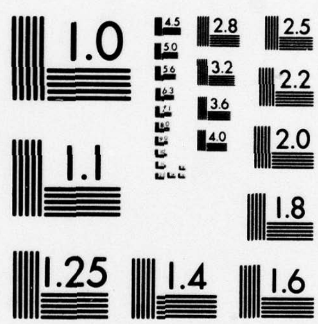

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tested using the tracer. The effluent responses to a pulse input of dye are plotted for each disposal area in Figure 44. A C curve is the

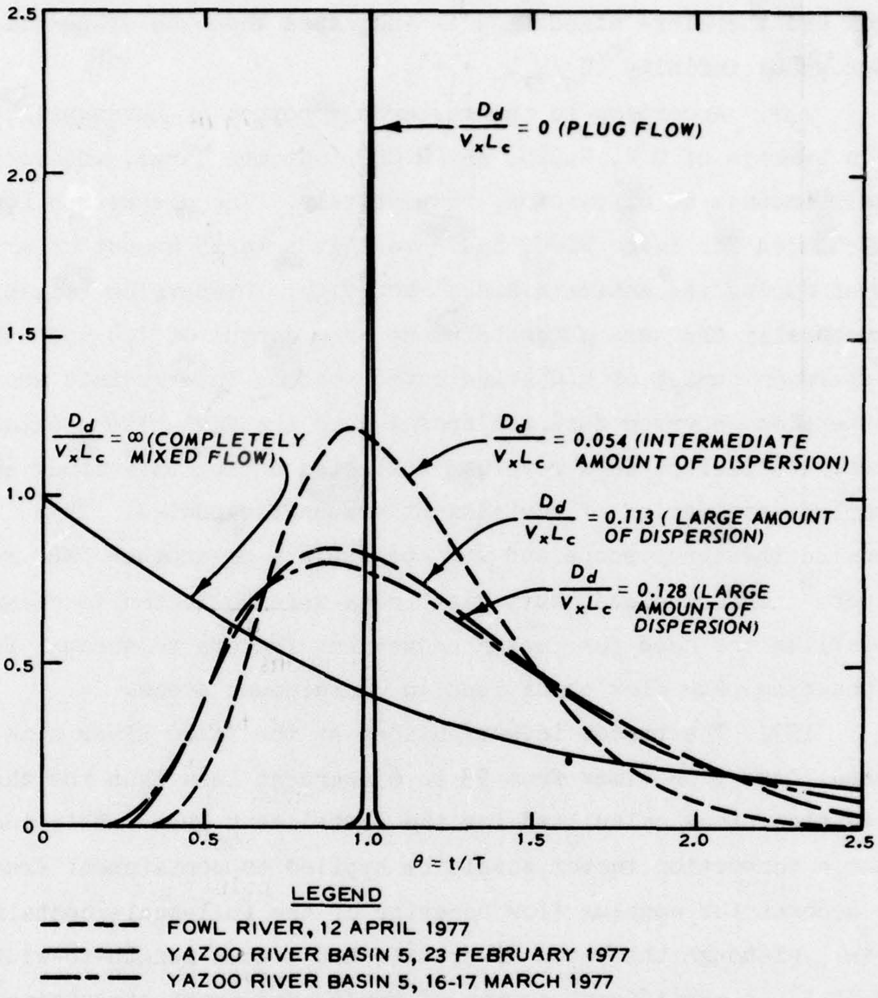

Figure 44. Effluent response to a pulse input of dye predicted by a dispersion model[33]

normalized response to an idealized instantaneous pulse of tracer on the stream entering the containment area with no tracer initially present in the system. Normalization was performed by dividing the measured concentration by the area under a concentration-time curve. The dispersion numbers ($D_d/v_x L_c$) calculated for the containment areas investigated are shown in Figure 44. The containment area dispersion number is the parameter that measures the extent of axial dispersion. Negligible dispersion and therefore plug flow is indicated when the dispersion number approaches zero ($D_d/v_xL_c \rightarrow 0$). On the other hand, large dispersion and therefore mixed flow is indicated when the dispersion number approaches infinity ($D_d/v_xL_c \rightarrow \infty$).

132. According to the research reported by Levenspeil,[33] dispersion numbers of 0.2, 0.025, and 0.002 indicate large, intermediate, and small amounts of dispersion, respectively. The dispersion numbers calculated for Yazoo River indicate that a large amount of mixing occured during the entire disposal activity. Dispersion (mixing) was essentially the same at containment area depths of 7.4 and 2.0 ft. The dispersion number of 0.054 indicated that an intermediate amount of dispersion occurred during disposal into the Fowl River containment area. Sufficient data were not collected during this study to make a complete evaluation of containment area efficiencies. This item was outside the study scope and was the subject of another DMRP research study.[3] Nevertheless, sufficient data were collected to clearly establish the need for design adjustment factors to account for deviations from plug flow conditions in containment areas.

133. The tracer investigations at the Yazoo River site indicated actual detention times from 53 to 65 percent less than the theoretical detention times calculated for the containment area. This indicated that a correction factor should be applied to containment area designs to account for nonplug flow behavior of the full-scale containment area. Although the Yazoo River site had a good length-to-width ratio (4 to 1), a significant amount of mixing and short-circuiting occurred. The field investigations indicate that, after containment areas are designed on the basis of laboratory data, the design must be modified to consider the actual performance characteristics of full-scale containment areas. Increasing the calculated design detention times and design areas by a factor of 2.25 should be adequate to account for scale-up and actual performance factors that cannot be obtained from laboratory tests.

Recommended Testing Procedures

134. Laboratory tests are necessary to characterize the sediment and to provide data for containment area design. A flowchart of the laboratory testing program recommended for providing design data is shown in Figure 45. The sediment characterization test procedures are outlined in Part III. The recommended laboratory procedures discussed here are for characterization of the dredged material sedimentation processes. They are based on results from the extensive laboratory testing program discussed in Part III.

135. The objective of running settling tests on sediments to be dredged is to define, on a batch basis, settling behavior in a large-scale continuous flow dredged material containment area. Results of tests must allow determination of numerical values for the design criteria which can be projected to the size and design of the containment area. It is important that the characteristics of the sediment slurry in the settling column be representative of the slurry characteristics in the containment area. This requirement becomes increasingly difficult to meet as the sediment slurry becomes more flocculent and as concentrations increase.

136. Sedimentation of freshwater sediments at slurry concentrations as high as 175 g/ℓ can be characterized by flocculent settling properties. However, as slurry concentrations are increased, the sedimentation process may be characterized by zone settling properties. The settling column shown in Figure 20 can be used with procedural modifications for both flocculent and zone settling tests. Salinity >3 ppt enhances the agglomeration of dredged material particles.[18] The settling properties of all saltwater dredged material tested during this study could be characterized by zone settling tests.

137. Samples used to perform sedimentation tests should consist of fine-grained (<No. 40 sieve) material. If coarse-grained (>No. 40 sieve) material present in the sample is less than 10 percent (dry weight basis), separation is not required prior to sedimentation testing. A composite of several sediment samples may be used to perform the tests

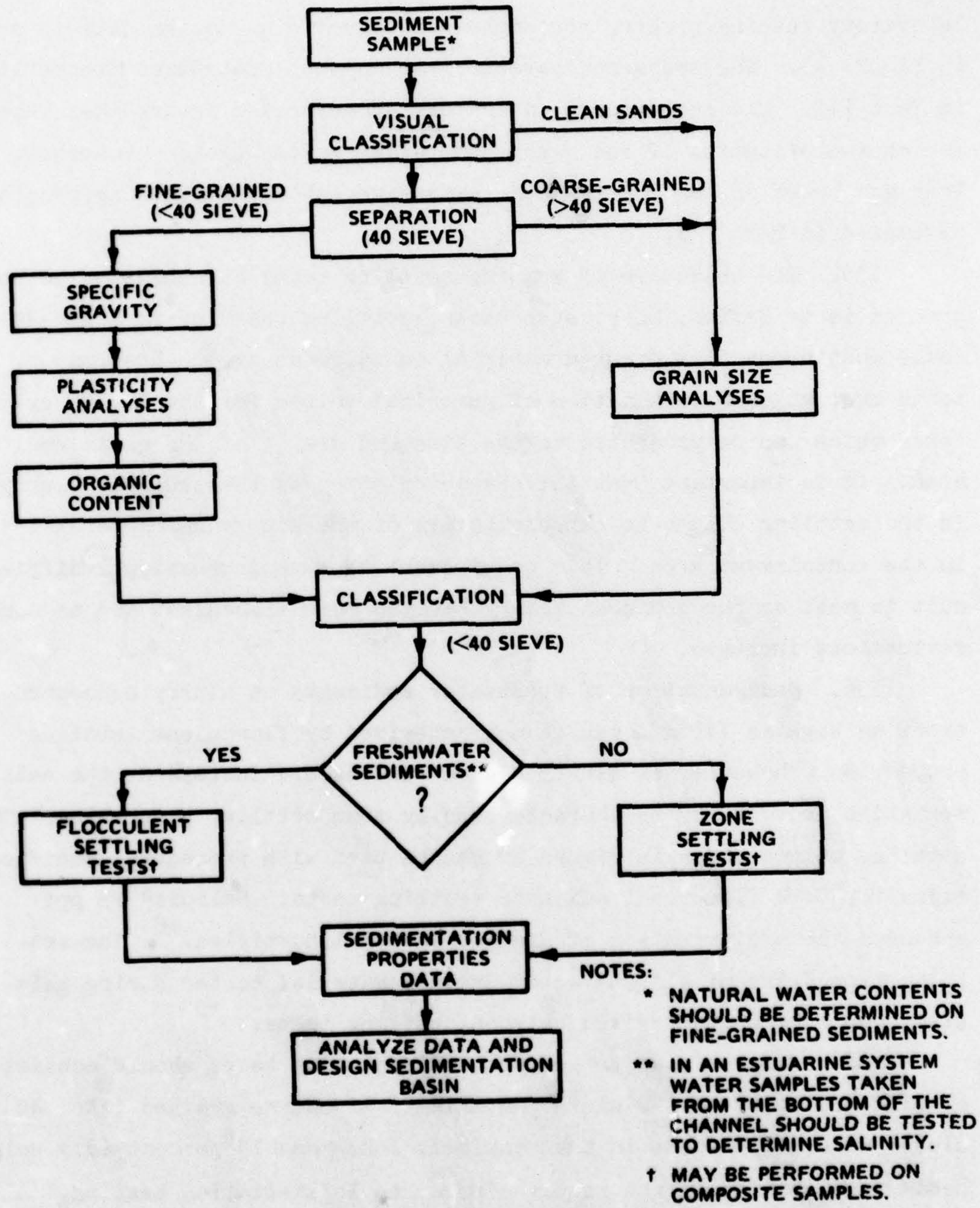

Figure 45. Flowchart of recommended laboratory testing program

if this is thought to be more representative of the dredged material.

Flocculent settling test

138. The flocculent settling test consists of measuring the concentration of suspended solids at various depths and time intervals in a settling column. If an interface forms near the top of the settling column during the first day of the test, sedimentation is governed by zone settling and that test procedure should be initiated. Information required to design a containment area in which flocculent settling governs can be obtained using the procedure described below.

a. Use a settling column such as that shown in Figure 20. The test column depth should approximate the effective settling depth of the proposed containment area. A practical depth of test is 6 ft. The column should be at least 8 in. in diameter with sample ports at 1-ft intervals. The column should have provisions to bubble air from the bottom to keep the slurry mixed during the column filling period.

b. Mix the sediment slurry to the desired suspended solids concentration in a container with sufficient volume to fill the test column. At least two tests should be performed at the concentration selected to represent concentration of influent dredged material C_i . Use the average detention time computed from these tests for design. Field studies indicate that, for maintenance dredging in fine-grained material, the disposal concentrations average about 145 g/ℓ.

c. Pump or pour the slurry into the test column using air to maintain a uniform concentration during the filling period.

d. While the column is completely mixed, draw off samples at each sample port and determine the suspended solids concentration. Average these values and use the result as initial concentration at the start of test. After the initial samples are taken, stop the air bubbling and begin the test.

e. Allow the slurry to settle then withdraw samples from each sampling port at regular time intervals and determine the suspended solids concentrations. Sampling intervals depend on the settling rate of the solids: usually at 30-min intervals for the first 3 hours and then at 4-hour intervals until the end of the test. The sampling times can be adjusted after the first complete test. Continue the test until the interface of solids can be seen near the bottom of the column and the

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suspended solids level in the fluid above the interface is <1 g/ℓ. Tabulate the test data as shown in Table B1 of Appendix B.

f. If an interface has not formed within the first day on any previous tests, run one additional test with a suspended solids concentration sufficiently high to induce zone settling behavior. This test should be carried out according to the procedures outlined below for zone settling tests. The exact concentration at which zone settling behavior occurs depends upon the sediment being tested and cannot be predicted. The data from this test will be used to estimate the volume required for dredged material storage. The procedure for volume determinations is outlined in Part V.

Zone settling test

139. The zone settling test consists of placing a slurry in a sedimentation column and reading and recording the fall of the liquid-solids interface with time. These data are plotted as depth to interface versus time. The slope of the constant settling zone of the curve is the zone settling velocity which is a function of the initial test slurry concentration. Information required to design a containment area in which zone settling governs can be obtained by using the procedure described below.

a. Use a settling column such as that shown in Figure 20. It is important that the column diameter be sufficient to reduce wall effects and the test be performed at a slurry depth near that expected in the field. Therefore, a 1-litre graduated cylinder should never be used to perform a zone settling test for sediment slurries representing dredging-disposal activities.

b. Mix the slurry to the desired concentration and pump or pour it into the test column. Test concentrations should range from about 60 to 200 g/ℓ. Air may not be necessary to keep the slurry mixed if the filling time is less than 1 min.

c. Record the depth to the solid-liquid interface with respect to time. Readings must be taken at regular intervals to gain data for plotting the depth to interface versus time curve shown in Figure 33. It is important to take enough readings to clearly define this curve for each test.

d. Continue the readings until sufficient data are available to define the maximum point of curvature of the depth to interface versus time curve (Figure 33) for each test. The tests may require from 1 to 5 days to complete.

e. Perform a minimum of eight tests. Data from these tests are required to develop the zone settling velocity versus concentration curve shown in Figure 46.

f. One of the above tests should be performed on sediment slurries at a concentration of about 145 g/ℓ. The test should be continued for a period of at least 15 days to provide data for estimating volume requirements.

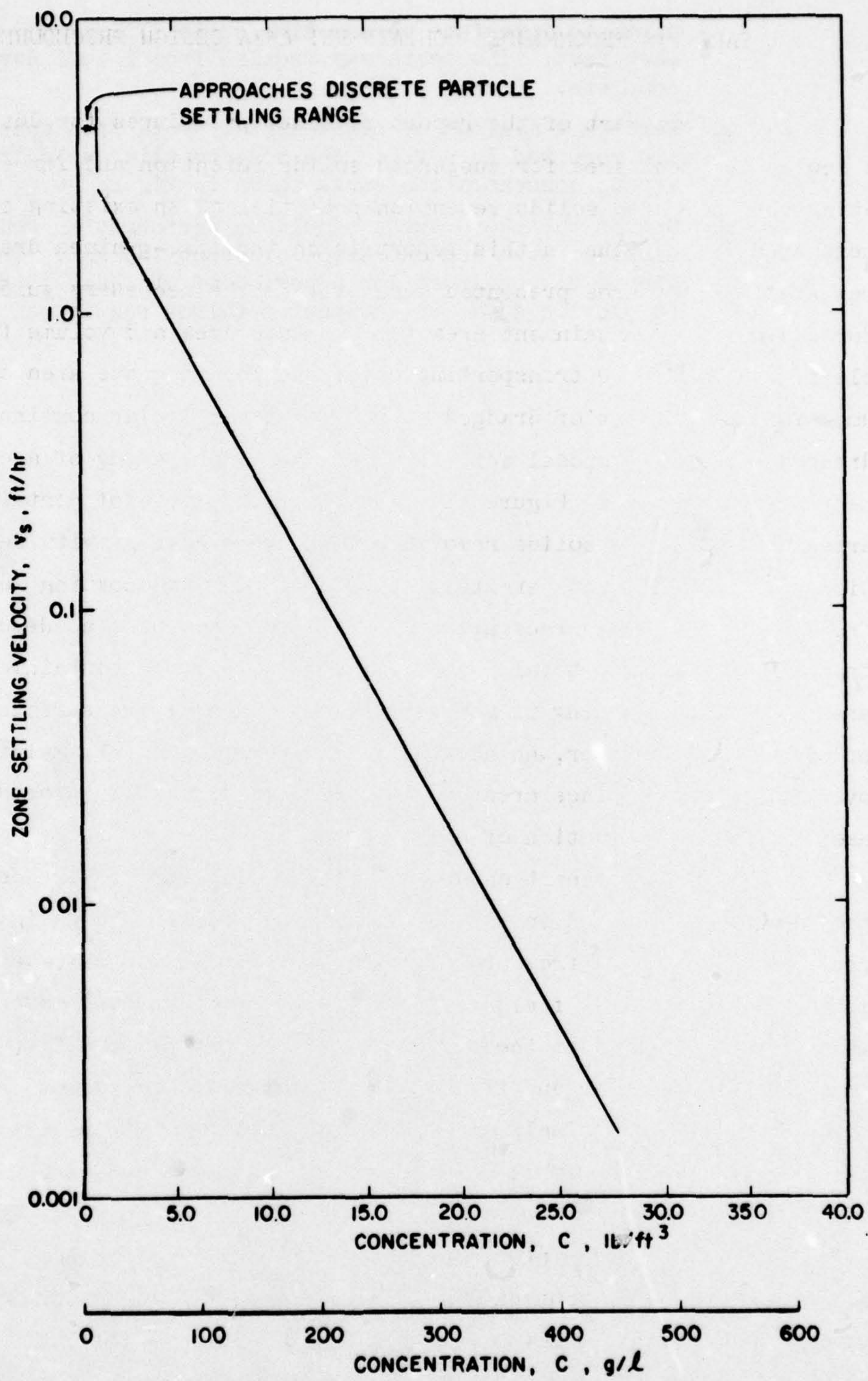


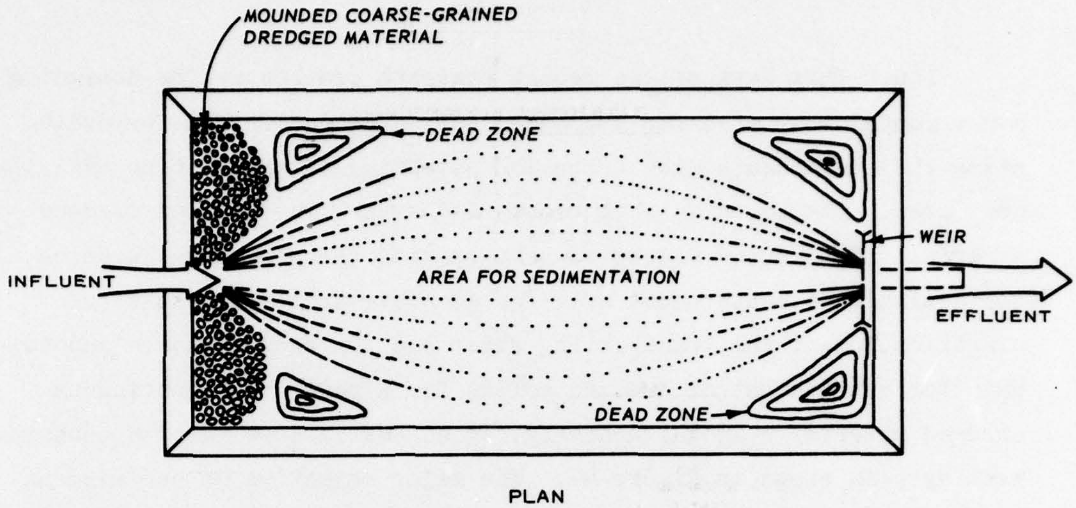
Figure 46. Zone settling velocity versus concentration

PART V: RECOMMENDED CONTAINMENT AREA DESIGN PROCEDURES

140. This Part of the report presents procedures for designing a new containment area for suspended solids retention and for evaluating the suspended solids retention potential of an existing containment area. The focus in this report is on the fine-grained dredged material. Procedures presented here provide the necessary guidance for designing a containment area for adequate area and volume for clarification of the transporting water and for adequate area and volumes for containment of dredged solids for a particular continuous dredged material disposal activity. A schematic drawing of a containment area is shown in Figure 47. The major objective of containment areas is to provide solids removal by the process of gravity sedimentation to the level that permits discharge of the transporting water from the area. It is recognized that design procedures as described in this Part are not totally applicable to very large containment areas. Because ponding is not feasible over the entire surface area of such sites, however, an adequate ponding depth must be maintained over the design surface area as determined by the design procedures to assure adequate retention of solids.

141. The flowchart shown in Figure 48 illustrates the design procedures recommended in the following paragraphs. The design procedures were adapted from procedures used in water and wastewater treatment and are based on field and laboratory investigations on sediments and dredged material at the field sites discussed in Part II. Design methods for saltwater and freshwater sediments are presented. Essentially the method for saltwater sediments is based on zone settling properties, and the method for freshwater sediments is based on flocculent settling properties.

142. The design procedures presented here are for gravity sedimentation of dredged suspended solids. However, gravity sedimentation will not completely remove suspended solids from containment area effluent since wind and other factors can resuspend solids and increase effluent solids concentration. The sedimentation process, with proper



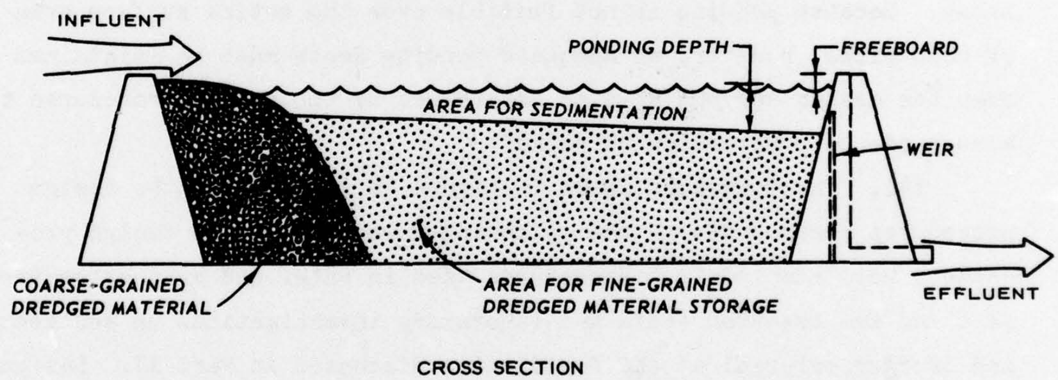


Figure 47. Typical dredged material containment area

design and operation, will normally provide removal of fine-grained sediments down to levels of 1 and 2 g/ℓ in the effluent for saltwater and freshwater sediments, respectively. If the required effluent standards are lower than this, the designer must provide for additional treatment of the effluent, e.g., flocculation or filtration. An example of a poorly designed and operated containment are is shown in Figure 49.

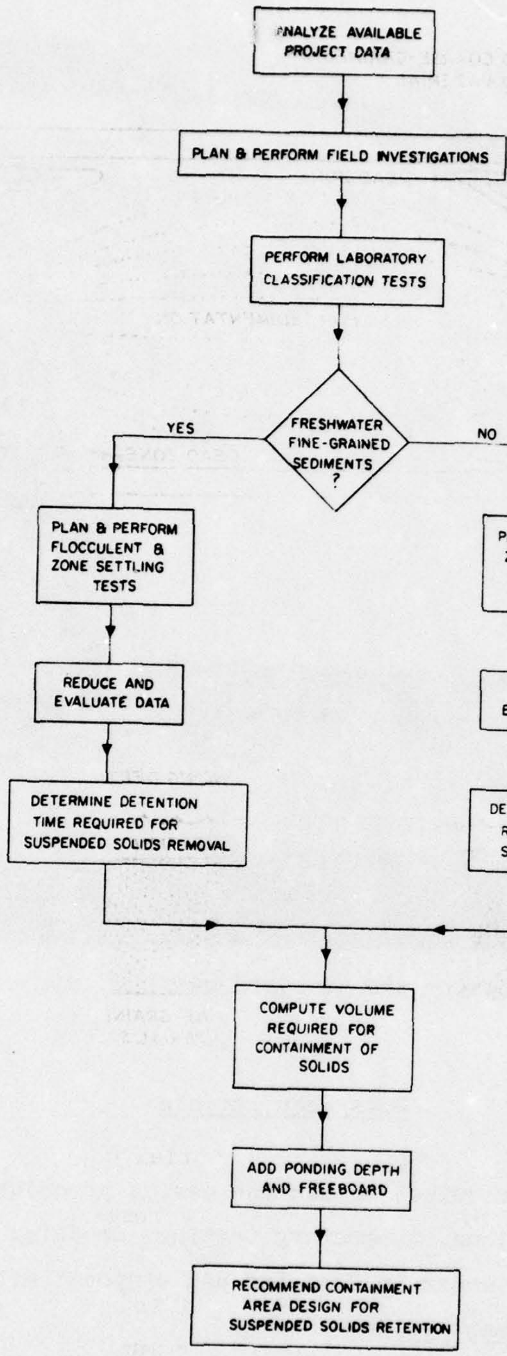


Figure 48. Flowchart of recommended design procedures for fine-grained sediments

Figure 49. Turbidity from dredged material containment area

Data Requirements

143. The data required to use the design procedures are obtained from field investigations, laboratory testing, dredging equipment designs, and past experiments in dredging and disposal activities.

Estimate in situ sediment volume

144. The initial step in any dredging activity is to estimate the in situ volume of sediment to be dredged. Sediment quantities are usually determined from channel surveys on a routine basis by Corps District personnel.

Determine physical
characteristics of sediments

145. Field sampling should be accomplished according to Part II, and sediment characterization should be accomplished according to the laboratory tests in Parts III and IV. Adequate sample coverage is required to provide representative samples of the sediment. Also required are in situ water contents of the fine-grained sediments. Care must be taken in sampling to ensure that the water contents are representative of the in situ conditions. Water contents of representative samples w are used to determine the in situ void ratio e_i as follows:

$$e_i = \frac{wG_s}{S_d} \tag{8}$$

where

G_s = specific gravity of sediment solids

S_d = degree of saturation (equal to 100 percent for sediment)

A representative value from in situ void ratios is used later to estimate volume for the containment area. Grain size analyses must be performed to estimate the quantities of coarse- and fine-grained material in the sediment to be dredged. Procedures outlined in EM 1110-2-1906[22] should be used for grain size analysis.

Obtain and analyze proposed
dredging and disposal data

146. The designer must obtain and analyze data concerning the dredged material disposal rate. For hydraulic pipeline dredges, the type and size of dredge(s) to be used, average distance to the containment area from the dredging activity, depth of dredging, and average solids concentration of the dredged material when discharged into the containment area must be considered. If the size of the dredge to be used is not known, the designer must assume the largest dredge size that might be expected to perform the dredging. The time required for the dredging can be estimated based on past experience. Data from past dredging activities can be plotted as shown in Figure 50 and used to estimate the time required to dredge the volume of sediments

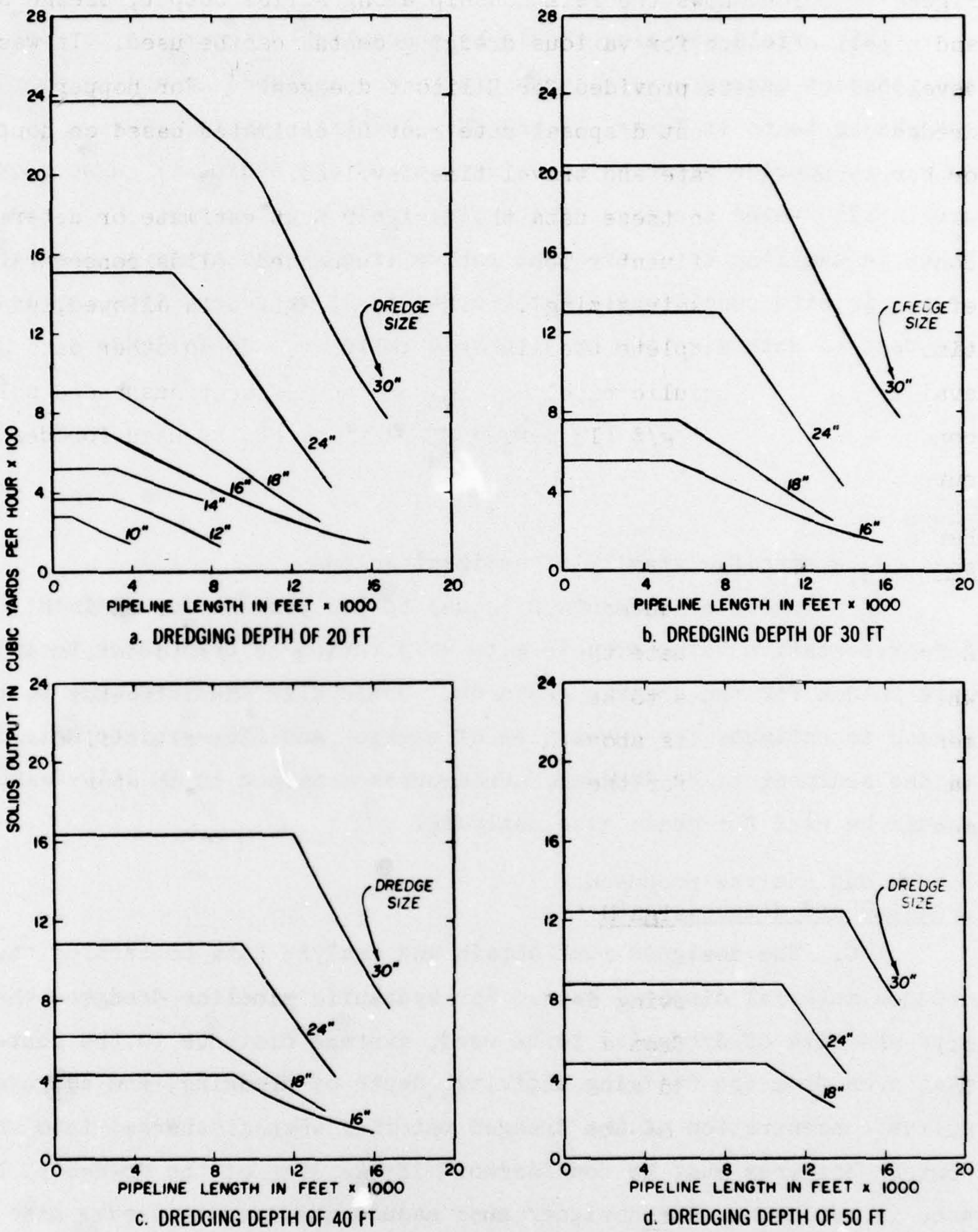


Figure 50. Relationships among solids output, dredge size, and pipeline length for various dredging depths (developed from data provided by Turner[34])

identified for removal. If no data on past experience are available, Figure 50 which shows the relationship among solids output, dredge size, and pipeline length for various dredging depths can be used. It was developed from data provided for Ellicott dredges.[34] For hopper dredges, an equivalent disposal rate must be estimated based on hopper or barge pump-out rate and travel time involved.

147. Based on these data the designer must estimate or determine containment area influent rate, influent suspended solids concentration, effluent rate (for weir sizing), effluent concentration allowed, and time required to complete the disposal activity. If no other data are available, for hydraulic pipeline dredges, an influent suspended solids concentration of 145 g/ℓ (13 percent by weight) can be used for design purposes.

Perform laboratory sedimentation tests

148. The procedures for sedimentation tests are given in Part IV. A designer must evaluate the results of salinity tests to determine whether the sediments to be dredged are freshwater or saltwater sediments. If salinity is above 3 ppt, the sediments are classified as saltwater sediments for the purpose of selecting the laboratory sedimentation test.

Design Method for Saltwater Sediments

149. The following design method is recommended for sedimentation of dredged material from a saltwater environment. It can also be used for freshwater dredged material if the laboratory settling tests indicate zone settling properties. An example of this design method is presented in Appendix B.

Analyze laboratory data

150. A series of zone settling tests must be conducted as detailed in Part IV. The results of the settling tests are correlated to determine zone settling velocities at the various suspended solids concentrations. The procedure is as follows:

a. Develop a settling curve for each test (see Figure 33).

b. Calculate the zone settling velocity v_s as the slope of the constant settling zone (straight-line portion of curve). The velocity should be in feet per hour.

c. Plot v_s versus suspended solids concentration on a semilog plot as shown in Figure 46.

d. Use the plot developed in c to develop a solids loading versus solids concentration curve as shown in Figure 51.

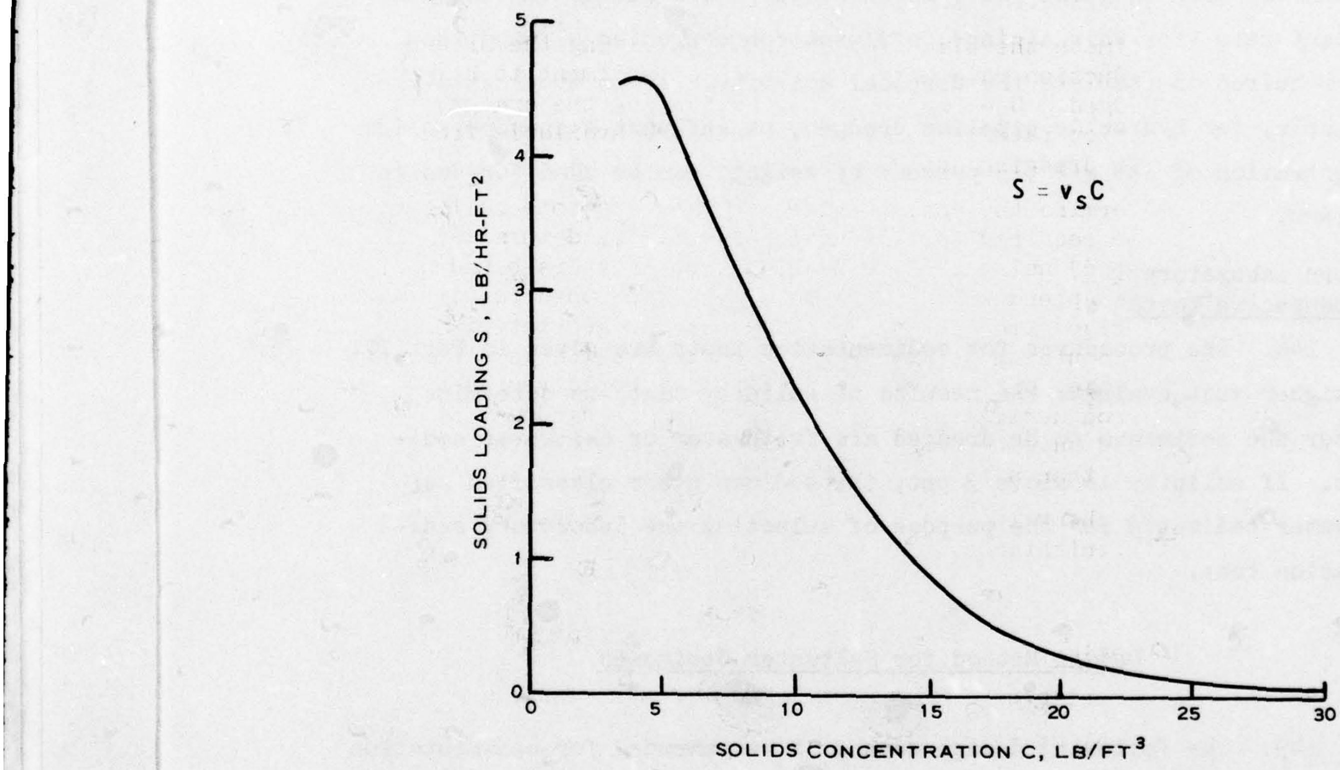


Figure 51. Typical solids loading curve for dredged material

Compute design concentration

151. The design concentration C_d is defined as the average concentration of the dredged material in the containment area at the end of the disposal activity and is estimated from data obtained from the 15-day column settling tests described in Part IV. The following steps can be used to estimate average containment area concentrations for each 15-day column settling test. It may be desirable to perform more

than one 15-day test. If so, use an average of the values as the design concentration.

a. Compute concentration versus time for the 15-day settling test. Assume zero solids in the water above the solids interface to simplify calculations.

b. Plot concentration versus time on log-log paper as shown in Figure B7.

c. Draw a straight line through the data points. This line should be drawn through the points representing the consolidation zone as shown in Figure 33.

d. Estimate the time of dredging by dividing the dredge production rate into the volume of sediment to be dredged. Use Figure 50 for estimating the dredge production rate if no specific data are available from past dredging activities.

e. Determine the concentration at time t (one half the time required for the disposal activity determined in step d) using the figure developed in steps b and c (see Appendix B). This time should be used to give an average time of residence for the dredged material in the containment area. Since concentration is a function of time, one half the dredging time would represent a period during which one half of the dredged material would have been in the area longer and the other half less than a time equal to one half the dredging time.

f. Use the value computed in step e as the design solids concentration C_d.

Compute area required for sedimentation

152. Containment areas designed according to the following steps should provide removal of fine-grained sediments such that suspended solids levels in the effluent do not exceed 1 to 2 g/ℓ. The area required for the zone settling process to concentrate the dredged material to the design concentration is computed as follows, using the Yoshioka et al.[14] graphic solution to the Coe and Clevenger procedure.[8]

a. Use the design concentration and construct an operating line from the design solids concentration tangent to the loading curve as shown in Figure 52. The design loading is obtained on the y-axis as S_L.

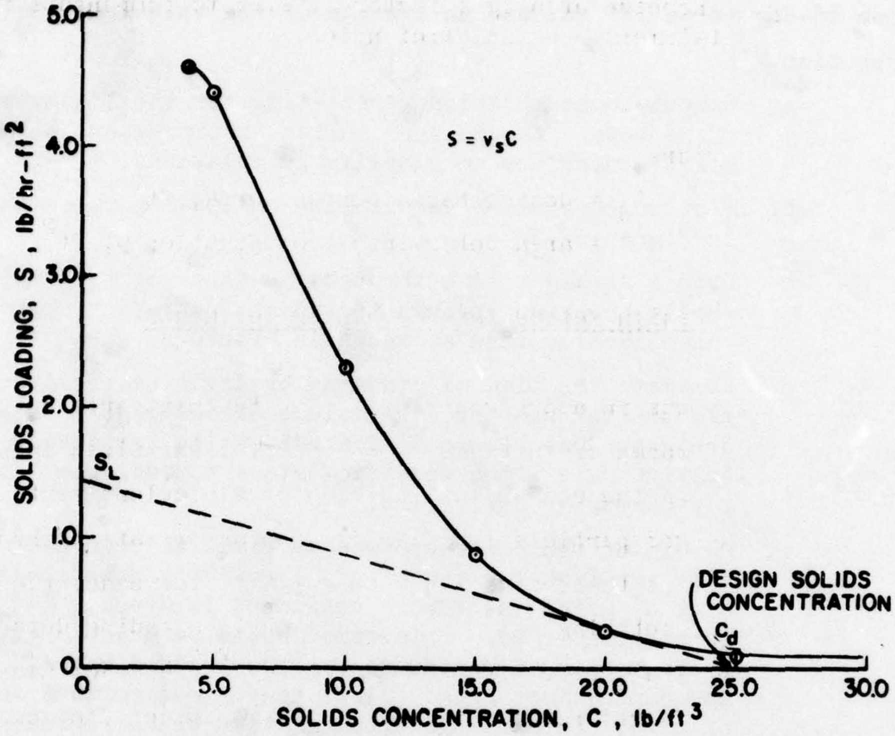


Figure 52. Solids loading curve showing design line

b. Compute area requirements as

$$A = \frac{Q_i C_i}{S_L} \tag{9}$$

where

A = containment area surface requirement, ft^2

Q_i = influent rate, ft^3/hr
($Q_i = A_p V_d$; assume $V_d = 15$ ft/sec in absence of data and convert Q_i calculated in ft^3/sec to ft^3/hr)

A_p = cross-sectional area of dredge pipeline, ft^2

V_d = velocity of dredge discharge, ft/sec

C_i = influent solids concentration, lb/ft^3
(use 145 g/ℓ or 9.2 lb/ft^3 if no data are available)

S_L = design solids loading, $lb/hr\text{-}ft^2$

c. Increase area by a factor of 2.25 to compensate for containment area inefficiencies.

$$A_d = 2.25A \tag{10}$$

where

A_d = design basin surface area, ft^2
A = area determined from Equation 9, ft^2

Design Method for Freshwater Sediments

153. Sediments in a dredged material containment area are comprised of a broad range of particle flocs of different sizes and surface characteristics. In the containment area under flocculent settling conditions the larger particle flocs settle at faster rates, thus overtaking finer flocs in their descent. This contact increases the floc sizes and enhances settling rates. The greater the ponding depth in the containment area, the greater is the opportunity for contact among sediments and flocs. Therefore, sedimentation of freshwater dredged sediments is dependent on the ponding depth as well as the properties of the particles.

Analyze laboratory data

154. Evaluation of the sedimentation characteristics of a freshwater sediment slurry is accomplished as discussed in Part IV. The design steps are as follows (refer to Appendix B for example problem):

a. Arrange data from laboratory tests illustrated in Table B1 into the form shown in Table B2 (see Appendix B).

b. Plot these data as shown in Figure 53. The percent by dry weight of initial concentration for each depth and time is given in Table B2. The solid curved lines represent the concentration depth profile at various times during settling (refer to Figure B1 for more details). Numbers appearing along the horizontal depth lines are used to indicate area boundaries.

c. Compute a design concentration using data from the 15-day zone settling test. Follow procedure outlined in the design method for saltwater sediments. Refer to Appendix B for example problem.

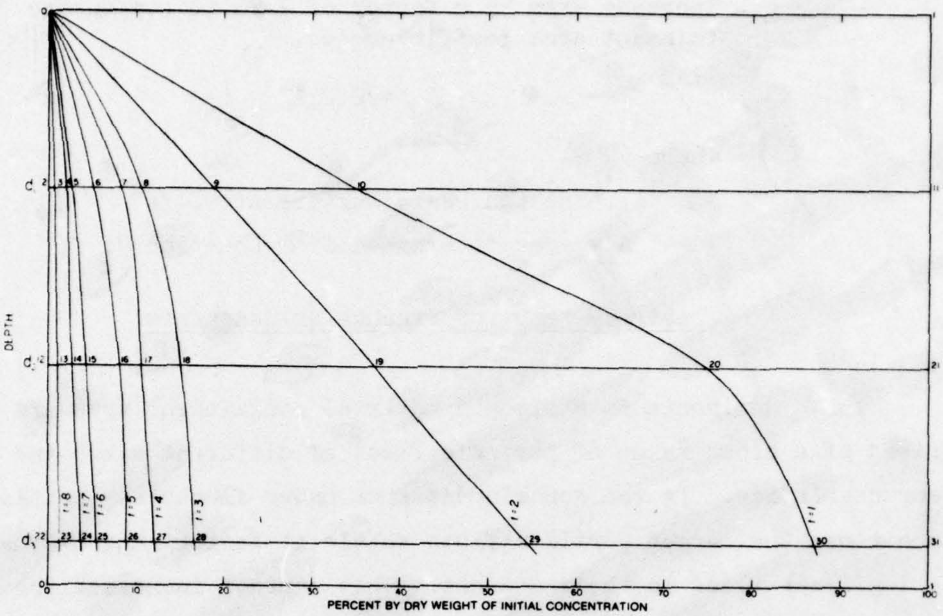


Figure 53. Removal of flocculating dredged material particles

Compute detention time
required for sedimentation

155. The detention time is computed as follows:

a. Calculate removal percentage at depths of 1, 2, and 3 ft for various times using the plot illustrated in Figure 53. The removal percentage for depth d_1 and $t = 1$ is computed as follows:

$$R = \frac{\text{Area } 0, 10, 11, 1^*}{\text{Area } 0, 2, 11, 1} \times 100 \qquad (11)$$

where

R = Removal percentage

Determine these areas by either planimetering the plot or by direct graphic measurements and calculations. This approach is used to calculate removal percentages for each depth as a function of time. The depths used should cover the range of ponding depths expected in the containment area. This report recommends 2 ft of ponding depth. Example calculations are shown in Appendix B.

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* These numbers correspond to the numbers used in Figure 53 to indicate the area boundaries for the total area down to depth d_1 (0, 2, 11, 1) and the area to the right of the $t = 1$ time line (0, 10, 11, 1).

b. Plot the solids removal percentages versus time as shown in Figure B3.

c. Theoretical detention times can be selected from Figure B3 for various solids removal percentages. Select the detention time T that gives the desired removal percentage for the design ponding depth.

d. The theoretical detention time T should be increased by a factor of 2.25 to compensate for the fact that containment areas, because of inefficiencies, have average detention times less than volumetric detention times:

$$T_d = 2.25T \tag{12}$$

where

T_d = design detention time

Volume Requirements for Containment of Solids

156. The procedures outlined in the above paragraphs are aimed at providing containment areas with sufficient areas and detention times to accommodate continuous disposal activities while providing sufficient suspended solids removal to meet effluent suspended solids requirements. Containment areas must also be designed to meet volume requirements for a particular disposal activity. The total volume required of a containment area includes volume for storage of dredged material, volume for sedimentation (ponding depths), and freeboard volume (volume above water surface). Volume required for storage of the coarse-grained material (>200 sieve) must be determined separately as this material behaves independently of the fine-grained (<200 sieve) material.

Estimate volume occupied by dredged material in containment area

157. The volume computed in the following steps is the volume occupied by dredged material in the containment area after the completion of a particular disposal activity. The volume is not an estimate of the long-term needs for multiple-disposal activities. The procedures given below can be used to design for volume required for one disposal

activity or used to evaluate the adequacy of volume provided by an existing containment area.

a. Compute average void ratio of fine-grained dredged material in the containment area at completion of the dredging operation using the design concentration determined in earlier steps as dry density of solids. (Note that design concentration is determined for both the flocculent and the zone sedimentation design procedure.) Use the following equation to determine void ratio:

$$e_o = \frac{G_s \gamma_w}{\gamma_d} - 1 \qquad (13)$$

where

e_o = average void ratio of dredged material in the containment area at the completion of the dredging operation

γ_w = density of water, g/ℓ

γ_d = dry density of solids ($C_D = \gamma_d$), g/ℓ

b. Compute the change in volume of fine-grained channel sediments after disposal in containment area from

$$\Delta V = V_i \left(\frac{e_o - e_i}{1 + e_i} \right) \qquad (14)$$

where

ΔV = change in volume of fine-grained channel sediments after disposal in the containment area, ft^3

V_i = volume of fine-grained channel sediments, ft^3

e_i = average void ratio of in situ channel sediments

c. Compute the volume required by dredged material in the containment area from

$$V = V_i + \Delta V + V_{sd} \qquad (15)$$

where

V = volume of dredged material in the containment area at the end of the dredging operation, ft^3

V_{sd} = volume of sand (compute using 1:1 ratio), ft^3

Estimate depth of containment area

158. Previous calculations have provided a design area A_d and design detention time T_d required for fine-grained dredged material sedimentation. Equations 13-15 are used to estimate volume and corresponding depth requirements for the containment area. Throughout the design process, the existing topography of the containment area must be considered since it can have a significant effect on the average depth of the containment area.

159. Saltwater sediments (zone settling). The following procedure should be used for saltwater sediments:

a. Estimate the thickness of dredged material at end of the disposal operation from

$$H_{dm} = \frac{V}{A_d} \tag{16}$$

where

H_{dm} = thickness of dredged material layer at the end of dredging operation, ft

V = volume of dredged material in basin, ft^3 (from Equation 15)

A_d = design area, ft^2 (as determined from Equation 9 or known surface area for existing sites)

b. Consult with soils design engineers to determine maximum height allowed for confining dikes.[35] Anticipated settlement of the dikes should also be considered.

c. Add ponding depth and freeboard depth to H_{dm} to determine required containment area depth (dike height).

$$D = H_{dm} + H_{pd} + H_{fb} \tag{17}$$

where

D = dike height, ft

H_{pd} = average ponding depth, ft (a minimum of 2 ft is recommended)

H_{fb} = freeboard above the basin water surface to prevent wave overtopping and subsequent damage to confining earth dikes, ft (a minimum of 2 ft is recommended).

d. Compare with allowable dike height (see paragraph 161).

160. Freshwater sediments (flocculent settling). The following procedure should be used for freshwater sediments:

a. Compute volume required for sedimentation from

$$V_B = Q_i T_d \tag{18}$$

where

V_B = containment area volume required for meeting suspended solids effluent requirements, ft^3

b. Consult with soils design engineers to determine maximum height allowed for confining dikes D. In some cases it might be desirable to use less than the maximum allowed dike height.

c. Compute design area as minimum required surface area for storage from

$$A_d = \frac{V}{H_{dm(max)}} \tag{19}$$

where

$$H_{dm(max)} = D - H_{pd} - H_{fb} \tag{20}$$

or set design area A_d equal to known surface area for existing sites.

d. Evaluate volume available for sedimentation near the end of the disposal operation from

$$V^* = H_{pd} A_d \tag{21}$$

where

V^* = volume available for sedimentation near the end of disposal operation, ft^3

e. Compare V^* and V_B. If the volume required for sedimentation is larger than V^*, the containment area will not meet the suspended solids effluent requirements for the entire disposal operation. The following three measures can be considered to ensure that effluent requirements are met: (1) increase the design area A_d, (2) operate the dredge on an intermittent basis when V^* becomes less than V_B or use smaller size dredge, and

(3) provide for posttreatment of effluent to remove solids.

f. Estimate thickness of dredged material at end of disposal operation using Equation 16. A_d is determined using step c above.

g. Determine required containment area depth using Equation 17.

h. Compare with maximum allowable dike height (see paragraph 161).

161. At most containment areas the foundation soils are soft. Such foundations limit the heights of confining earth dikes that can be economically constructed. Therefore, soils design engineers must be consulted to determine the maximum dike heights that can be constructed. If the maximum dike height allowed by foundation conditions is less than the containment area depth requirement determined from Equation 17, the design area A_d must be increased until the depth requirement can be accommodated by the allowable dike height; the thickness of the dredged material layer must also be decreased.

Factors Influencing Containment Area Efficiency

162. The design guidelines presented in the preceding sections require design data obtained from laboratory tests. Although these data provide a basis for design of a containment area for a full-scale, continuous dredging operation, they must be modified to consider actual performance characteristics of dredged material containment areas. A correction factor was applied to the designs presented earlier to account for the "nonideal" behavior of the full-scale containment area (i.e., scale-up and operation problems). This factor was based on dye tracer investigations performed at the field sites discussed in Part II. From these studies, a correction factor of 2.25 applied to area and detention time requirements appears reasonable. However, this factor can be increased or decreased by the designer if data are available to justify a different correction factor.

163. Short-circuiting is by far the most common and significant

problem with dredged material containment areas. The overall effect of short-circuiting is to reduce the effective residence time of a major portion of the flow. This reduction has a serious adverse effect, particularly on sedimentation of freshwater dredged material because of its flocculent nature. Short-circuiting can be caused by insufficient ponding depth, improper location of the dredged material inlet pipeline in relationship to the discharge weir, topography, or vegetation in the basin. All of these factors can cause an improper distribution of velocity vectors resulting in shortened detention periods and increased velocities with resultant scouring of settled solids.

164. Ponding depth is illustrated in Figure 47. Essentially, it is the depth of ponded water above the solids interface that is required for sedimentation in a containment area. Insufficient ponding depth is a major cause of short-circuiting. Basically, ponding depths should be as great as possible to provide longer detention times, minimize flow velocities, and maximize protection against resuspension and discharge of bottom sediments. Figure 54 shows a containment area experiencing short-circuiting as a result of insufficient ponding depth. The inefficient flow patterns in this containment area significantly

Figure 54. Containment area with insufficient ponding depth and resultant short-circuiting

reduce the effective sedimentation area and detention time needed for removal of suspended solids.

165. There has been reluctance in the past to pond water during disposal activities because of concern about potential dike failures. The need for this concern can be eliminated when the dikes are properly designed and constructed.[35]

166. Providing adequate ponding depth during disposal activities is an operational as well as a design function. Proper designs can be negated by improper containment area operation such as insufficient ponding depth. A minimum ponding depth of 2 ft is recommended for sedimentation of solids during a continuous disposal activity. Lesser ponding depths can be tolerated when the dredge is operated on an intermittent basis. Ponding depths greater than 2 ft may be required for efficient weir operation. Figure 55 illustrates short-circuiting caused by insufficient ponding depth and poor location of the dredge discharge pipeline. The effective settling area and volume have been significantly limited by these factors in the containment area shown in the photograph.

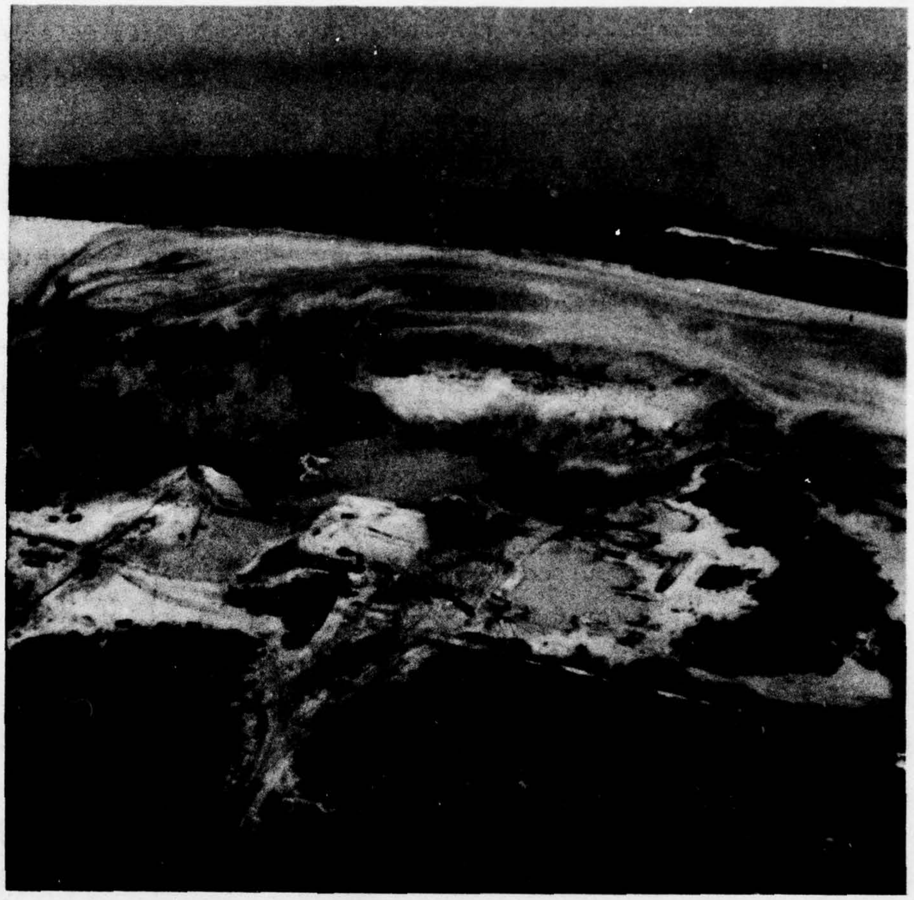

Figure 55. Example of undesirable containment area operation

PART VI: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

167. The classic laws of sedimentation apply only to the settling of discrete, nonflocculating particles in dilute suspension. These laws cannot be applied to the highly concentrated dredged material slurries although some researchers have used them for rough approximations of dredged material settling properties.

168. Sedimentation of flocculating particles is a function not only of the settling properties of the particles but also of the flocculating characteristics of the suspension. Therefore, sedimentation of freshwater dredged material is dependent both on the settling rate and depth. There is no satisfactory formula available for evaluating the flocculation effect on sedimentation, so it is necessary to perform a column settling test to measure the effect.

169. The literature generally covered only suspensions of low concentrations. No previous major research effort has investigated the settling properties of suspensions having solids concentrations in the range of those listed for dredged material slurries.

170. There were major gaps in the literature regarding the problems of designing fine-grained dredged material containment areas. However, the literature provided good guidance for developing the field and laboratory investigations for this study and for evaluating the results.

171. Grab samples were considered adequate for sampling fine-grained sediments from maintenance dredging projects. Such samples are adequate for sediment characterization purposes and are relatively easy and inexpensive to obtain.

172. Organic contents were generally less than 10 percent for all the sediments except those from Brunswick Harbor. In general, the organics were considered to be too low to be a significant factor in evaluating the settling properties.

173. The arithmetic mean or average hydraulic pipeline discharge

concentration was found to be about 13 percent (145 g/ℓ) by dry weight for fine-grained dredged material. In the absence of actual data from past dredging projects, this value can be used for containment area design purposes. Because of the wide variation in suspended solids pumped by a dredge during any period, a number of pipeline samples are required to evaluate solids concentration and containment area loading rate.

174. Sedimentation processes investigated during containment area disposal activities indicated the need for the design ponding depth to be maintained throughout the continuous disposal activity to provide adequate area and volume for sedimentation.

175. The multiconcentration zone settling tests show that the zone settling velocities for dredged material decrease with increased slurry concentrations. Therefore, it is important that the settling tests cover the range of concentrations expected in the field and that design concentrations used in the design procedures be representative of influent concentrations.

176. Settling tests on Mobile Harbor sediments and those same sediments after being dredged and discharged from the dredge pipeline as dredged material showed that there was not a significant difference in the zone settling velocities. Thus, settling tests performed on channel sediments prior to dredging can be used to estimate the settling properties of those sediments as dredged material.

177. The settling column wall effect is probably more pronounced in testing high concentration (145 g/ℓ) dredged material than other slurries of lower concentration. Settling tests using columns less than 8 in. in diameter resulted in increased zone settling velocities for the tests performed with slurry concentrations >53 g/ℓ. These increased settling velocities were considered to be artifacts of the small diameter test equipment and not representative of actual zone settling velocities.

178. Settling tests performed at concentrations representative of field conditions indicated a significant effect from depth of test slurry. Settling tests for the purpose of obtaining containment area

design data should always be performed at the slurry depth expected in the field, with an upper limit of about 6 ft of depth.

179. Sedimentation of freshwater sediments at slurry concentrations as high as 175 g/ℓ was characterized by flocculent settling properties. The settling properties of all saltwater sediments tested during this study could be characterized by zone settling tests because the salinity enhanced the agglomeration of particles into a settling mass.

180. Because of the different sedimentation processes of freshwater and saltwater sediments, two separate design procedures are required for designing dredged material containment areas. However, one settling column, 8 in. in diameter, can be used for the settling tests with minor procedural changes for both freshwater and saltwater sediments.

181. Laboratory data provide a basis for designing the containment area for plug flow conditions. However, plug flow never exists in actual containment areas because flow is always accompanied by a certain amount of mixing and short-circuiting. The designs must be increased by a correction factor to compensate for the fact that actual flow falls somewhere between plug flow and completely mixed flow. The dye tracer investigations indicate that a correction factor of about 2.25 should be applied to the design area and detention time.

182. The sedimentation process, with proper design and operation, will normally provide removal of fine-grained sediments down to a level of 1 to 2 g/ℓ or less in the effluent. However, because of the influence of factors at the site, removal below these levels cannot be predicted from the design procedures. If the required effluent standards are lower than 1 to 2 g/ℓ, the designer must consider treatment of the effluent. It is possible, however, that a saltwater containment area will accomplish removal to a level less than 1 g/ℓ, but a freshwater containment area will generally provide removal down to a level of only about 2 g/ℓ.

Recommendations

183. The following recommendations are presented as guidance

for designing and operating dredged material containment areas:

a. Sediment sampling:

(1) Use a grab type sampler capable of sampling up to a depth of about 12 in. in fine-grained sediments.

(2) Take sediment samples at a sufficient number of locations to adequately define spatial variations in the sediment character.

(3) Collect at least 5 gal of sediment sample at each sampling station.

(4) Collect samples in airtight and watertight containers and place samples in cold room (6 to 8°C) as soon after sampling as possible until organic content of the samples can be determined. If organic content is above 10 percent, the samples should remain in the cold room until testing is complete.

b. Sediment testing:

(1) Perform sediment characterization tests before the initiation of settling tests.

(2) Settling tests should be performed in a column at least 8 in. in diameter, and the column depth should be representative of that expected in the containment area. A practical depth of test is 6 ft.

(3) Zone settling test concentrations should range from about 60 to 200 g/ℓ, and at least eight tests are recommended.

c. Containment area design:

(1) The freshwater and saltwater design procedures presented in this report should be used for containment area design and evaluation depending upon the dredging environment.

(2) Designs should be based on providing sufficient area and volume for effective sedimentation during the last stages of continuous disposal operations.

(3) A minimum ponding depth of 2 ft is recommended to ensure that adequate sedimentation volume is provided during the entire disposal activity.

(4) The designs should be increased by a correction factor of 2.25 to account for nonideal flow in the containment area.

d. Containment area operation:

(1) The weir should be set at a predetermined elevation at the beginning of disposal and left at that

elevation throughout the disposal period unless additional ponding depth is required.

(2) Effluent suspended solids should be monitored during disposal activities to evaluate containment area design and provide records of compliance with effluent requirements.

(3) Efforts should be made to locate the dredge discharge pipeline so that short-circuiting flow through the containment area will be minimized.

REFERENCES

1. Walski, T. M. and Schroeder, P. R., "Weir Design to Maintain Effluent Quality from Dredged Material Containment Areas," Technical Report D-78-18, May 1978, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

2. Bohan, J. P. and Grace, J. L., "Selective Withdrawal from Man-Made Lakes," Technical Report H-73-4, Mar 1973, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

3. Brian J. Gallagher and Company, "Investigation of Containment Area Design to Maximize Hydraulic Efficiency," Technical Report D-78-12, May 1978, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

4. Mallory, C. W. and Nawrocki, M. A., "Containment Area Facility Concepts for Dredged Material Separation, Drying, and Rehandling," Contract Report D-74-6, Oct 1974, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

5. Krizek, R. J., FitzPatrick, J. A., and Atmatzidis, D. K., "Investigation of Effluent Filtering Systems for Dredged Material Containment Facilities," Contract Report D-76-8, Aug 1976, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

6. Raster, T. E. et al., "Development of Procedures for Selecting and Designing Reusable Dredged Material Disposal Sites," Technical Report D-78-22, Jun 1978, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

7. Hazen, A., "On Sedimentation," Transactions of the American Society of Civil Engineers, Vol 53, 1904, pp 45-88.

8. Coe, H. S. and Clevenger, G. H., "Methods for Determining the Capacities of Slime-Settling Tanks," Transac ions, American Institute of Mining Engineers, Vol 55, No. 9, Sep 1916, pp 356-384.

9. Camp, T. R., "A Study of the Rational Design of Settling Tanks," Sewage Works Journal, Vol 8, No. 6, Sep 1936, pp 742-758.

10. Kynch, G. J., "A Theory of Sedimentation," Transactions, Faraday Society, Vol 48, 1952, pp 166-176.

11. Talmage, W. P. and Fitch, E. B., "Determining Thickener Unit Areas," Industrial Engineering and Chemistry Fundamentals, Vol 47, 1955, pp 38-41.

12. Dick, R. I. and Ewing, B. B., Closure of "Evaluation of Activated Sludge Thickening Theories," Journal of the Sanitary Engineering Division, American Society of Civil Engineers, Vol 95, No. SA2, 1969, pp 333-340.

13. Fitch, B., "Sedimentation Process Fundamentals," Transactions, American Institute of Mining Engineers, Vol 223, Jun 1962, pp 129-137.

14. Yoshioka, N. et al., "Continuous Thickening of Homogeneous Flocculated Slurries," Chemical Engineering (Tokyo), Vol 21, 1957, pp 1-10.

15. McLaughlin, R. T., "The Settling Properties of Suspensions," Journal of the Hydraulics Division, American Society of Civil Engineers, Vol 85, No. 12, 1959, pp 9-41.

16. Dick, R. I. and Ewing, B. B., "Evaluation of Activated Sludge Thickening Theories," Journal of the Sanitary Engineering Division, American Society of Civil Engineers, Vol 93, No. SA4, 1967, pp 9-29.

17. Vesilind, P. A., "Design of Thickeners from Batch Tests," Water and Sewage Works, Vol 115, No. 9, 1968.

18. Migniot, C., "A Study of the Physical Properties of Various Very Fine Sediments and Their Behavior Under Hydrodynamic Action," La Houille Blanche, Vol 23, No. 7, 1968, pp 59-620.

19. Bartos, M. J., "Classification and Engineering Properties of Dredged Material," Technical Report D-77-18, Sep 1977, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

20. Schroeder, W. W., "Physical Environment Atlas of Coastal Alabama," MASGP-76-034, 1976, published by Miss-Ala Sea Grant Program, Dauphin Island Sea Lab, Dauphin Island, Ala.

21. Wilson, J. F., "Fluorometric Procedures for Dye Tracing," Techniques of Water Resources Investigations of the United States Geological Survey, Chapter A12, U. S. Government Printing Office, Washington, D. C., 1968.

22. Office, Chief of Engineers, Department of the Army, "Laboratory Soils Testing," Engineer Manual EM 1110-2-1906, Nov 1970, Washington, D. C.

23. U. S. Army Engineer Waterways Experiment Station, CE, "The Unified Soil Classification System," Technical Memorandum No. 3-357, Mar 1953, Vicksburg, Miss.

24. Palermo, M. R., Montgomery, R. L., and Poindexter, M. E., "Guidelines for Designing, Operating, and Managing Dredged Material Containment Areas," Technical Report DS-78-10 Dec 1978, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

25. Seed, H. B. et al., "Fundamental Aspects of the Atterberg Limits," Journal of the Soil Mechanics and Foundation Division, American Society of Civil Engineers, Vol 90, No. SM6, 1965, pp 75-108.

26. Krizek, R. J. et al., "Engineering Characteristics of Polluted Dredgings," Northwestern University Technical Report No. 1 to the Environmental Protection Agency, Evanston, Ill., 1974.

27. Hammer, D. P., "Densification of Fine-Grained Dredged Material by Underdrainage Techniques," Miscellaneous Paper (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

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28. Coulson, J. M. and Richardson, J. F., Chemical Engineering, Vol 2, McGraw-Hill, New York, 1955, p 515.

29. Roberts, E. J., "Thickening - Art or Science?", Mining Engineering, Vol 1, No. 61, 1949.

30. Michaels, A. S. and Bolger, J. C., "Settling Rates and Sediment Volumes of Flocculated Kaolin Suspensions," Industrial and Engineering Chemistry Fundamentals, Vol 1, 1962, pp 24-33.

31. Thomas, H. A., Jr., "Graphical Determination of BOD Curve Constants," Water and Sewage Works, Vol 97, p 123, 1950.

32. Young, H. D., Statistical Treatment of Experimental Data, McGraw-Hill, New York, 1962.

33. Levenspeil, O., Chemical Reaction Engineering, 2d ed., Wiley, New York, 1972, pp 253-283.

34. Turner, T. M., "Dredging Systems and the Basic Dredge Laws," paper presented at Florida Atlantic University, 1972.

35. Hammer, D. P. and Blackburn, E. D., "Design and Construction of Retaining Dikes for Containment of Dredged Material," Technical Report D-77-9, Aug 1977, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

APPENDIX A: COLUMN SETTLING TEST DATA

1. The data presented in this Appendix were obtained from laboratory column settling tests on sediment and dredged material samples from the Brunswick Harbor, Mobile Harbor, and Fowl River field study sites (see Figure 1). The data include results from multidiameter, multiheight, and multiconcentration tests.

Table A1

Column Settling Data from Multiheight Tests on Sediments from Brunswick Harbor

Test No.	Column Depth ft	Solids Concentration g/ℓ	Zone Settling Velocity v_s, ft/hr
1	1.12	105	0.0090
	1.50	105	0.0037
	2.0	105	0.0029
	2.5	105	0.0041
	3.0	105	0.0116
	3.5	105	0.0010
	4.0	105	0.0200
2	1.12	105	0.0018
	1.5	105	0.0023
	2.0	105	0.0026
	2.5	105	0.0031
	3.0	105	0.0120
	3.5	105	0.0090
	4.0	105	0.0185
3	1.12	146	0.0012
	1.5	146	0.0010
	2.0	146	0.00146
	2.5	146	0.00176
	3.0	146	0.0020
	3.5	146	0.00238
	4.0	146	0.0024
4	1.12	70	0.064
	1.5	70	0.209
	2.0	70	0.245
	2.5	70	0.258
	3.0	70	0.272
	3.5	70	0.394
	4.0	70	0.540

Table A2

Column Settling Data from Multidiameter Tests on Sediments from Brunswick Harbor

Test No.	Column Diameter in.	Solids Concentration g/ℓ	Zone Settling Velocity v_s, ft/hr
1	2.4	105	0.0084
	3.0	105	0.0086
	4.0	105	0.0090
	8.0	105	0.0072
	12.0	105	0.0058
	18.0	105	0.0036
	23.0	105	0.0030

Table A3

Column Settling Data from Multiconcentration Tests on Mobile Harbor Materials

Slurry Depth ft	Solids Concentration g/ℓ	Zone Settling Velocity v_s, ft/hr
	Sediments	
1.12	43	1.765
1.12	41	1.714
1.12	55	1.238
1.12	73	0.571
1.12	86	0.571
1.12	118	0.440
1.12	120	0.410
1.12	148	0.360
1.12	163	0.282
1.12	174	0.298
1.12	200	0.287
1.12	243	0.041
1.12	366	0.003
	Dredged Material	
1.12	215	0.133
1.12	42	2.400
1.12	26	2.000
1.12	310	0.014
1.12	143	0.245
1.12	57	0.800
1.12	140	0.240
1.12	159	0.078

Table A4

Column Settling Data from Multidiameter Tests on Sediments from Mobile Harbor

Test No.	Column Diameter in.	Solids Concentration g/ℓ	Zone Settling Velocity v_s, ft/hr
1	2.4	43	1.464
	3.0	43	1.690
	4.0	43	1.644
	8.0	43	1.412
	12.0	43	1.500
	18.0	43	1.412
	23.0	43	1.333
2	2.4	105	0.440
	3.0	105	0.325
	4.0	105	0.222
	8.0	105	0.211
	12.0	105	0.200
	18.0	105	0.200
	23.0	105	0.200
3	2.4	141	0.207
	3.0	141	0.194
	4.0	141	0.057
	8.0	141	0.188
	12.0	141	0.186
	18.0	141	0.171
	23.0	141	0.079
4	2.4	151	0.031
	3.0	151	0.023
	4.0	151	0.013
	8.0	151	0.081
	12.0	151	0.050
	18.0	151	0.054
	23.0	151	0.060
5	2.4	164	0.012
	3.0	164	0.007
	4.0	164	0.009
	8.0	164	0.004
	12.0	164	0.006
	18.0	164	0.005
	23.0	164	0.006

Table A5

Column Settling Data from Multiheight Tests on Sediments from Mobile Harbor

Test No.	Column Depth ft	Solids Concentration g/ℓ	Zone Settling Velocity v_s, ft/hr
1	1.12	42	1.714
	1.5	43	1.744
	2.0	43	1.863
	2.5	43	1.780
	3.0	43	2.117
	3.5	43	2.480
	4.0	43	2.174
2	1.12	110	0.287
	1.5	110	0.292
	2.0	110	0.301
	2.5	110	0.272
	3.0	110	0.265
	3.5	110	0.214
	4.0	110	0.216
3	1.12	150	0.085
	1.5	150	0.187
	2.0	150	0.155
	2.5	150	0.161
	3.0	150	0.158
	3.5	150	0.156
	4.0	150	0.154
4	1.12	157	0.034
	1.5	157	0.071
	2.0	157	0.200
	2.5	157	0.183
	3.0	157	0.176
	3.5	157	0.195
	4.0	157	0.202
5	1.12	172	0.009
	1.5	172	0.012
	2.0	172	0.016
	2.5	172	0.020
	3.0	172	0.021
	3.5	172	0.150
	4.0	172	0.154

Table A6

Column Settling Data from Multiconcentration Tests on Sediments from Fowl River

Slurry Depth ft	Solids Concentration g/ℓ	Zone Settling Velocity v_s, ft/hr
1.12	37	0.984
1.12	48	0.800
1.12	63	0.690
1.12	87	0.512
1.12	116	0.379
1.12	141	0.007
1.12	164	0.009
4.0	38	1.17
4.0	42	0.60
4.0	49	0.39
4.0	89	0.33
4.0	91	0.268
4.0	114	0.300
4.0	125	0.218
4.0	126	0.250
4.0	163	0.058
4.0	173	0.021

Table A7

Column Settling Data from Multiheight Tests on Sediments from Fowl River

Test No.	Column Depth ft	Solids Concentration g/ℓ	Zone Settling Velocity v_s, ft/hr
1	1.12	53	0.738
	1.5	53	0.653
	2.0	53	0.728
	2.5	53	0.646
	3.0	53	0.554
	3.5	53	0.603
	4.0	53	0.394
2	1.12	116	0.0333
	1.5	116	0.0316
	2.0	116	0.0877
	2.5	116	0.2940
	3.0	116	0.3130
	3.5	116	0.5040
	4.0	116	0.3660
3	1.12	165	0.005
	1.5	165	0.0066
	2.0	165	0.008
	2.5	165	0.0074
	3.0	165	0.0052
	3.5	165	0.0055
	4.0	165	0.01
4	1.12	163	0.009
	1.5	163	0.006
	2.0	163	0.0082
	2.5	163	0.006
	3.0	163	0.025
	3.5	163	0.006
	4.0	163	0.054

Table A8

Column Settling Data from Multidiameter Tests on Sediments from Fowl River

Test No.	Column Diameter in.	Solids Concentration g/ℓ	Zone Settling Velocity v_s, ft/hr
1	2.4	53	0.046
	3.0	53	0.586
	4.0	53	0.765
	8.0	53	0.670
	12.0	53	0.610
	18.0	53	0.569
	23.0	53	0.615
2	2.4	116	0.236
	3.0	116	0.039
	4.0	116	0.090
	8.0	116	0.008
	12.0	116	0.008
	18.0	115	0.145
	23.0	116	0.193
3	2.4	165	0.005
	3.0	165	0.005
	4.0	165	0.0047
	8.0	165	0.00447
	12.0	165	0.00549
	18.0	165	0.00745
	23.0	165	0.0043
4	2.4	153	0.005
	3.0	153	0.0051
	4.0	153	0.0051
	8.0	153	0.005
	12.0	153	0.0040
	18.0	153	0.0070
	23.0	153	0.0056

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APPENDIX B: EXAMPLE DESIGN CALCULATIONS

1. This Appendix presents example calculations for containment area designs. The examples are developed to illustrate use of field and laboratory data and include designs for sedimentation and weir design. Weir design is based on the research reported in Walski and Shroeder.[1] Separate examples are developed for saltwater and freshwater sedimentation designs as described in Part V of the main text. Only those calculations necessary to illustrate the procedure are included in the examples.

Example I: Containment Area Design Method for Freshwater Sediments

Project information

2. Each year an average of 300,000 yd^3 of fine-grained channel sediment is dredged from a harbor on Lake Michigan. A new in-water containment area is being constructed to accommodate the long-term dredged material disposal needs in this harbor. However, the new containment area will not be ready for approximately 2 years. One containment area in the harbor has some remaining storage capacity, but it is not known whether the remaining capacity is sufficient to accommodate the immediate disposal requirements. Design procedures must be followed to determine the detention time needed to meet effluent requirements of 4 g/ℓ and the storage volume required for the 300,000 yd^3 of channel sediment. These data will be used to determine if the existing containment area storage capacity is sufficient for the planned dredged material disposal activity. The existing containment area is about 3 miles from the dredging activity.

3. Records indicate that, for the last three dredgings, an 18-in. pipeline dredge was contracted to do the work. The average working time was 17 hours per day, and the dredging rate was 600 yd^3 per hour of in situ channel sediment. The project depth in the harbor is 50 ft.

Results of containment area surveys

4. The existing containment area has the following dimensions:

a. Size: 96 acres.

b. Shape: length-to-width ratio is about 3.

c. Volume: 1,548,800 yd^3 (average depth, from surveys, is 10 ft).

d. Weir length: 24 ft (rectangular weir).

Results of laboratory tests and analysis of data

5. The following data were obtained from laboratory tests as described in the main text:

a. Salinity: <1 ppt.

b. Channel sediment in situ water content w : 85 percent.

c. Specific gravity G_s : 2.69.

d. Observed flocculent settling concentrations as a function of depth (see Table B1).

e. Percent of initial concentration with time (see Table B2). This is determined as follows: Column concentration at beginning of tests is 132 g/ℓ. Concentration at 1-ft level at time = 30 min is 46 g/ℓ (Table B1). Percent of initial concentration = 46 ÷ 132 = 0.35 = 35 percent. These calculations are repeated for each time and depth to develop Table B2.

f. Plot the percent of initial concentration versus depth profile for each time interval from data given in Table B2 (see Figure B1).

g. Concentration as a function of time (15-day settling column data) (see Table B3).

h. Plot concentration versus time from data in Table B3 as shown in Figure B2.

i. Laboratory tests indicate that 20 percent of the sediment is coarse-grained material (>No. 40 sieve); therefore, the volume of coarse-grained material V_{sd} is:

$$V_{sd} = 300{,}000(0.20) = 60{,}000 \text{ yd}^3$$

and the volume of fine-grained material V_i is:

$$V_i = 300{,}000 - 60{,}000 = 240{,}000 \text{ yd}^3$$

Compute detention time
<u>required for sedimentation</u>

a. Calculate removal percentages for depths of 1, 2, and 3 ft:

$t = 30$ min

$d = 1$ ft

$C_i = 132$ g/ℓ

$H_{pd} = 2$ ft

$C_e = 4$ g/ℓ

Calculating the total area down to a depth of 1 ft from Figure B1 gives an area of 100 (scale units). Calculating the area to the right of the 30-min time line down to a depth of 1 ft gives 82.5 (scale units). These areas could also have been determined by planimetering the plot. Compute removal percentages as follows (see Equation 11 in the main text):

$$R = \frac{82.5}{100} \times 100 = 82.5$$

For a settling time of 30 min, 82.5 percent of the suspended solids are removed from the water column above the 1-ft depth.

b. The calculations illustrated in step a are repeated for each depth as a function of time and the results are tabulated in Table B4.

c. Plot the data in Table B4 as shown in Figure B3.

d. Since the average ponding depth H_{pd} is 2 ft, use the 2-ft depth curve shown in Figure B3 and determine the theoretical detention time required to meet the 4-g/ℓ effluent suspended solids requirement:

$$\text{Required Solids Removal} = \frac{C_i - C_e}{C_i}$$

$$= \frac{132 - 4}{132} = 0.97 \text{ or } 97 \text{ percent}$$

e. From Figure B3, $T = 365$ min.

f. Increase theoretical detention time T by a factor of 2.25:

$$T_d = 2.25T \qquad (12\ \text{bis})$$

$$T_d = 2.25(365)$$

design detention time, T_d = 822 min.

<u>Compute volume required for sedimentation</u>

$$V_B = Q_i T_d \qquad (18\ \text{bis})$$

$$Q_i = \frac{\left(\frac{18\ \text{in.}}{12}\right)^2 \pi}{4} \times 15\ \text{ft/sec}$$

$$= 26.5\ \text{ft}^3/\text{sec}$$

$$= 1590\ \text{ft}^3/\text{min}$$

$$V_B = 1590\ (822) \approx 1{,}300{,}000\ \text{ft}^3$$

<u>Compute design concentration</u>

<u>a</u>. Project information:

(1) Dredge size: 18 in.

(2) Volume to be dredged: 300,000 yd^3.

(3) Average operating time: 17 hr/day.

(4) Production: 600 yd^3 per hour.

<u>b</u>. Estimate time of dredging activity:

$$\frac{300{,}000\ \text{yd}^3}{600\ \text{yd}^3/\text{hr}} = 500\ \text{hours}$$

$$\frac{500\ \text{hours}}{17\ \text{hr/day}} = 29.4 \approx 30\ \text{days}$$

<u>c</u>. Average time for dredged material consolidation:

$$\frac{30\ \text{days}}{2} = 15\ \text{days}$$

<u>d</u>. Design solids concentration C_d is the concentration shown in Figure B2 at 15 days:

$$C_d = 253\ \text{g}/\ell$$

Estimate volume required for dredged material

a. Compute average void ratio e_o using Equation 13:

$$e_o = \frac{G_s \gamma_w}{\gamma_d} - 1 \qquad \text{(13 bis)}$$

$G_s = 2.69$

$\gamma_w \approx 1000\ g/\ell$

$\gamma_d = 253\ g/\ell$

$$e_o = \frac{2.69(1000)}{253} - 1$$

$$e_o = 9.63$$

b. Compute change in volume of fine-grained channel sediments after disposal in containment area using Equation 14:

$$\Delta V = V_i \frac{e_o - e_i}{1 + e_i} \qquad \text{(14 bis)}$$

$$e_i = \frac{wG_s}{S_d} \qquad \text{(8 bis)}$$

$$e_i = \frac{(85/100)(2.69)}{1.00}$$

$$= 2.29$$

$$V_i = 240{,}000\ yd^3$$

$$\Delta V = \frac{9.63 - 2.29}{1 + 2.29} \times 240{,}000$$

$$\Delta V = 535{,}440\ yd^3$$

Estimated volume required by dredged material in containment area

$$V = V_i + \Delta V + V_{sd} \qquad \text{(15 bis)}$$

$$V_i = 240{,}000 \text{ yd}^3$$

$$\Delta V = 535{,}440 \text{ yd}^3$$

$$V_{sd} = \underline{60{,}000 \text{ yd}^3}$$

$$V = 835{,}440 \text{ yd}^3$$

Determine maximum dike height

Foundation conditions limit dike heights to 10 ft.

Determine design area

Design area is equal to existing surface area:

$$A_d = 96 \text{ acres} \times 43{,}560 \text{ ft}^2/\text{acre}$$
$$= 4{,}181{,}760 \text{ ft}^2$$

Evaluate volume available for sedimentation near the end of the disposal operation

$$V^* = H_{pd} A_d$$
$$= 2 \text{ ft}(4{,}181{,}760 \text{ ft}^2)$$
$$= 8{,}363{,}520 \text{ ft}^3$$

Compare V^* and V_B

Since $V^* > V_B$, a 96-acre containment area will meet the suspended solids effluent requirement of 4 g/ℓ for the entire disposal operation.

Estimate thickness of dredged material layer

$$H_{dm} = \frac{V}{A_d} \qquad (16 \text{ bis})$$

$$= \frac{835{,}440 \text{ yd}^3 \cdot 27}{4{,}181{,}760 \text{ ft}^2}$$

$$= 5.4 \text{ ft}$$

Determine required containment area depth

$$D = H_{dm} + H_{pd} + H_{fb} \qquad (17 \text{ bis})$$
$$= 5.4 + 2 + 2$$
$$= 9.4 \text{ ft}$$

Since $D = 9.4$ ft is less than the average basin depth of 10 ft, sufficient volume is available for the project.

Check weir length

Existing effective weir length L_e = weir crest length L for rectangular weirs:

$L_e = 24$ ft

$C_e = 4$ g/ℓ

$Q_i = 26.5$ ft^3/sec

$H_{pd} = 2$ ft

6. With an average ponding depth within the containment H_{pd} of 2 ft, the ponding depth at the weir D_p is estimated to be in excess of 3 ft, accounting for a dredged material surface which slopes toward the weir. Using Figure B4, a 3-ft ponding depth at the weir requires an effective weir length of approximately 13 ft. The existing 24-ft weir length should therefore be adequate, but effluent suspended solids should be monitored periodically.

7. The remaining volume of 1,548,800 yd^3 in the existing containment area is sufficient to accommodate disposal of the 300,000 yd^3 of maintenance channel sediment into the basin under a continuous disposal operation. Since the required basin depth is less than the existing depth, no upgrading will be necessary to accommodate the first dredging operation.

Example II: Containment Area Design Method for Saltwater Sediments

Project information

8. Fine-grained maintenance dredged material is scheduled to be dredged from a harbor maintained to a project depth of 50 ft. Channel surveys indicated that 500,000 yd^3 of channel sediment must be dredged. All available disposal areas are filled near the dredging activity, but land is available for a new site 2 miles from the dredging project. Since this harbor has to be dredged once every 2 years, the containment area must be designed to accommodate long-term disposal needs while

meeting effluent suspended solids levels of 4 g/ℓ. In the past, the largest dredge contracted for the maintenance dredging has been a 24-in. pipeline dredge. This is the largest size dredge located in the area.

Results of laboratory tests

9. The following data were obtained from laboratory tests:

a. Salinity: 15 ppt.

b. Channel sediment in situ water content w : 92.3 percent.

c. Specific gravity G_s : 2.71.

d. Depth to solids interface as a function of time (settling column data) (see Table B5).

e. Zone settling velocity as a function of concentration (see Table B6).

f. Zone settling velocity versus concentration curve (see Figure B5).

g. Calculations of solids loading values: use data given in Figure B5 to develop Table B7.

h. Solids loading versus solids concentration: use data in Table B7 to develop Figure B6.

i. Concentration as a function of time data (15-day settling column data) (see Table B8).

j. Concentration versus time curve (see Figure B7).

k. Representative samples of channel sediments tested in the laboratory indicate that 15 percent of the sediment is coarse-grained material (>No. 40 sieve).

$$V_{sd} = 500{,}000(0.15) = 75{,}000 \text{ yd}^3$$

$$V_i = 500{,}000 - 75{,}000 = 425{,}000 \text{ yd}^3$$

Compute design concentration

a. Project information:

Dredge size: 24 in.
Volume to be dredged: 500,000 yd^3

b. Good records are available from past years of maintenance dredging in this harbor. They show that each time a 24-in. dredge was used, the dredge averaged operating 12 hours per day and dredged an average of 900 yd^3 per hour.

c. Estimate time of dredging activity:

$$\frac{500{,}000\ \text{yd}^3}{900\ \text{yd}^3/\text{hr}} = 556\ \text{hours}$$

operating time per day = 12 hr

$$\frac{556\ \text{hours}}{12\ \text{hours}} \approx 46\ \text{days}$$

d. Average time for dredged material consolidation:

$$\frac{46\ \text{days}}{2} = 23\ \text{days}$$

e. Design concentration is the concentration shown in Figure B7 at 23 days:

$$C_d = 340\ \text{g}/\ell \text{ or } 21.1\ \text{lb/ft}^3$$

Compute area required for sedimentation

a. Construct operating line from design concentration (21.1 lb/ft^3) tangent to the loading curve (Figure B6):

Design solids loading $S_L = 2.95\ \text{lb/hr-ft}^2$

b. Compute area requirement using Equation 9:

$$A = \frac{Q_i C_i}{S_L} \qquad \text{(9 bis)}$$

$$Q_i = A_p V_d$$

$$V_d = 15\ \text{ft/sec}$$

$$C_i = 9.2\ \text{lb/ft}^3$$

$$S_L = 2.95\ \text{lb/hr-ft}^2$$

$$Q_i = \frac{\left(\frac{24\ \text{in.}}{12}\right)^2 \pi}{4} \times 15\ \text{ft/sec}$$

$$= 47.12\ \text{ft}^3/\text{sec}$$

$$= 169{,}632\ \text{ft}^3/\text{hr}$$

$$A = \frac{169,632\ (9.2)}{2.95}$$

$$= 529,022\ ft^2$$

$$= \frac{529,022}{43,560} = 12.14\ acres$$

c. Increase the area by a factor of 2.25 (assumes containment can be constructed with a length-to-width ratio of approximately 3):

$$A_d = 2.25(12.14\ acres)$$

$$A_d = 27.3\ acres$$

Thus, area required for sedimentation is 27.3 or 27 acres.

Estimate volume required for dredged material

a. Compute average void ratio using:

$$e_o = \frac{G_s \gamma_w}{\gamma_d} - 1 \qquad (13\ bis)$$

$G_s = 2.71$

$\gamma_w \approx 1000\ g/\ell$

$\gamma_d = 340\ g/\ell$ = design concentration C_d (Figure B7)

$$e_o = \frac{2.71(1000)}{340} - 1$$

$$e_o = 6.97$$

b. Compute change in volume of fine-grained channel sediments after disposal in containment area using:

$$\Delta V = V_i \frac{e_o - e_i}{1 + e_i} \qquad (14\ bis)$$

Using Equation 8, $e_i = \frac{wG_s}{S_d}$

$$e_i = \frac{(92.3/100)(2.71)}{1.00}$$

$$e_i = 2.5$$

$$V_i = 425{,}000 \text{ yd}^3$$

$$\Delta V = \frac{6.97 - 2.50}{1 + 2.50} \times 425{,}000$$

$$\Delta V = 542{,}785 \text{ yd}^3$$

c. Estimate volume required by dredged material in containment area using:

$$V = V_i + \Delta V + V_{sd} \qquad (15 \text{ bis})$$

$$V_i = 425{,}000 \text{ yd}^3$$

$$\Delta V = 542{,}785 \text{ yd}^3$$

$$V_{sd} = 75{,}000 \text{ yd}^3$$

$$V = 425{,}000 + 542{,}785 + 75{,}000$$

$$V = 1{,}042{,}785 \text{ yd}^3$$

Estimate thickness of dredged material at end of disposal operation

$$H_{dm} = \frac{V}{A_d} \qquad (16 \text{ bis})$$

$$= \frac{1{,}042{,}785 \text{ yd}^3(27)}{27 \text{ acres}(43{,}560)}$$

$$= 23.9 \text{ ft}$$

10. Because of foundation problems, dike heights are limited to 15 ft. Therefore, the area of the disposal area must be increased to accommodate the storage requirements. Use Equation 17 to determine the allowable dredged material height:

$$D = H_{dm} + H_{pd} + H_{fb} \qquad (17 \text{ bis})$$

$$D = 15 \text{ ft}$$

$$H_{pd} = 2 \text{ ft}$$

$$H_{fb} = 2 \text{ ft}$$

$$H_{dm} = D - H_{pd} - H_{fb}$$

$$= 15 - 2 - 2$$

$$= 11 \text{ ft}$$

Compute new area requirement

$$H_{dm} = \frac{V}{A_d} \qquad (16 \text{ bis})$$

$$A_d = \frac{1{,}042{,}785 \text{ yd}^3 (27)}{11}$$

$$= 2{,}559{,}563 \text{ ft}^2$$

$$= 59 \text{ acres}$$

Design for weir

$$Q_i = 47.12 \text{ ft}^3/\text{sec}$$

$$C_e = 4 \text{ g}/\ell$$

11. Using Figure B8, operating lines constructed at $Q_i = 47.12$ ft^3/sec and $C_e = 4 \text{ g}/\ell$ indicate possible combinations of ponding depth and effective weir length required. Assuming that a 1-ft ponding depth at the weir is the minimum that could be allowed, a weir length of 35 ft is required. However, a ponding depth of 2 ft is recommended during the operation to provide a margin of safety. Note that 59 acres is the minimum area required for storage of one dredging of 500,000 yd^3 and will not meet the long-term storage capacity requirement.

Table B1

Observed Flocculent Settling Concentrations with Depth

Time, min	Concentration, g/ℓ, for Cited Depth from Top of Settling Column, ft						
	1	2	3	4	5	6	7
0	132	132	132	132	132	132	132
30	46	99	115	125	128	135	146
60	25	49	72	96	115	128	186
120	14	20	22	55	78	122	227
180	11	14	16	29	75	119	
240	6.8	10.2	12	18	65	117	
360	3.6	5.8	7.5	10	37	115	
600	2.8	2.9	3.9	4.4	14	114	
720	1.01	1.6	1.9	3.1	4.5	110	
1020	0.90	1.4	1.7	2.4	3.2	106	
1260	0.83	1.14	1.2	1.4	1.7	105	
1500	0.74	0.96	0.99	1.1	1.2	92	
1740	0.63	0.73	0.81	0.85	0.94	90	

Note: Data from actual test on freshwater sediments. Although a 6-ft test depth is recommended, an 8-ft depth was used in this test.

Table B2

Variation of Percent by Dry Weight of Initial Concentration with Time

Time T , min	Percent by Dry Weight of Initial Concentration at Cited Depth from Top of Settling Column, ft		
	1	2	3
0	100	100	100
30	35	75	87
60	19	37	55
120	11	15	17
180	8	11	12
240	5	8	9
360	3	4	6
600	2.0	2.2	3.0
720	1.0	1.2	1.4

Note: Initial suspended solids concentration = 132 g/ℓ .

Table B3

Concentration as a Function of Time

Time days	Concentration g/ℓ
1	190
2	217
3	230
4	237
5	240
6	242
7	244
9	249
10	247
15	256

Table B4

Removal Percentages as a Function of Settling Time

	Removal Percentage at Cited Depth from Top of Settling Column, ft		
Time, min	1	2	3
30	82.5	62.0	47.0
60	91.0	81.0	73.0
120	93.7	90.2	88.1
180	95.8	93.1	91.5
240	97.4	95.5	94.2
360	98.0	97.0	96.2
600	98.9	98.4	98.1
720	99.6	99.3	99.1

Table B5

Depth to Solids Interface as a Function of Settling Time

Time hr	Depth to Solids Interface, ft, at Cited Initial Solids Concentration, g/ℓ							
	55	73	120	143	163	215	243	310
0	0	0	0	0	0	0	0	0
0.25	0.230	0.145	0.065	0.050	0.065	0.026	0.010	--
0.50	0.390	0.290	0.165	0.090	0.138	0.050	0.020	0.005
0.75	0.530	0.435	0.270	0.170	0.210	0.075	0.030	--
1.0	0.620	0.535	0.360	0.230	0.276	0.100	0.040	0.009
2.0	0.690	0.635	0.490	0.420	0.430	0.225	0.080	0.020
3.0	0.740	0.680	0.535	0.475	0.467	0.340	0.100	0.025
4.0	0.770	0.700	0.555	0.505	0.495	0.365	0.122	0.035
5.0	0.805	0.710	0.580	0.530	0.510	0.390	0.140	0.050
6.0	0.820	0.730	0.585	0.553	0.515	0.410	0.160	0.070
7.0	0.830	--	--	0.565	--	0.430	0.175	--
8.0	0.840	--	--	0.575	--	0.440	0.188	--
10.0	--	--	--	0.595	--	0.459	0.212	--
20.0	--	--	--	0.655	--	0.522	0.259	0.190
30.0	--	--	--	0.690	--	0.564	0.292	0.250

Table B6

Zone Settling Velocity as a Function of Suspended Solids Concentration

Concentration			Zone Settling Velocity
g/ℓ	%	lb/ft^3	ft/hr
55	5.2	3.4	1.238
73	6.8	4.5	0.571
120	10.8	7.5	0.410
143	12.7	9.0	0.245
163	14.3	10.2	0.282
215	18.5	13.5	0.133
243	20.7	15.2	0.041
310	25.8	19.5	0.015

Table B7

Calculations of Solids Loading Values*

Concentration of Suspended Solids C			Settling Velocity v_s	$S = v_s C$ Solids Loading
%	g/ℓ	lb/ft^3	ft/hr	$lb/hr\text{-}ft^2$
6.1	65	4	1.15	4.60
7.4	80	5	0.88	4.40
14.2	160	10	0.23	2.30
20.0	240	15	0.06	0.87
26.0	320	20	0.02	0.29
31.2	400	25	0.004	0.09

* Developed from curve shown in Figure B1.

Table B8

Concentration as a Function of Time

Time days	Concentration g/ℓ
1	192
2	215
3	219
4	240
5	251
6	272
8	280
10	290
15	320

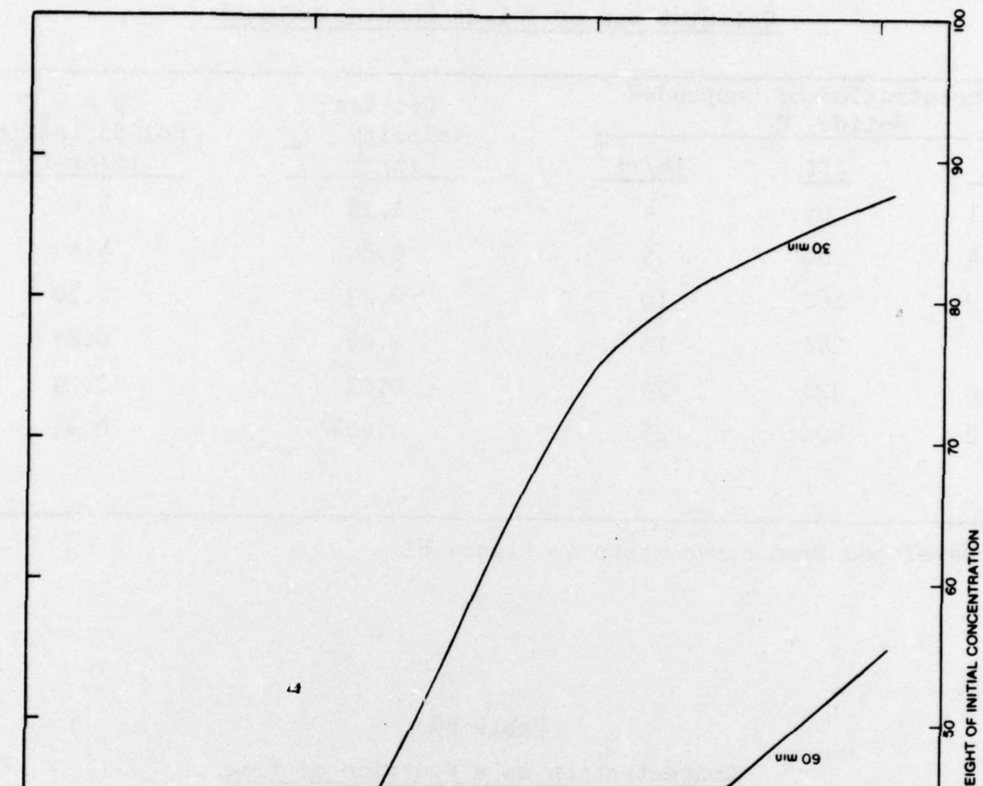

Figure B1. Percent of initial concentration versus depth profile

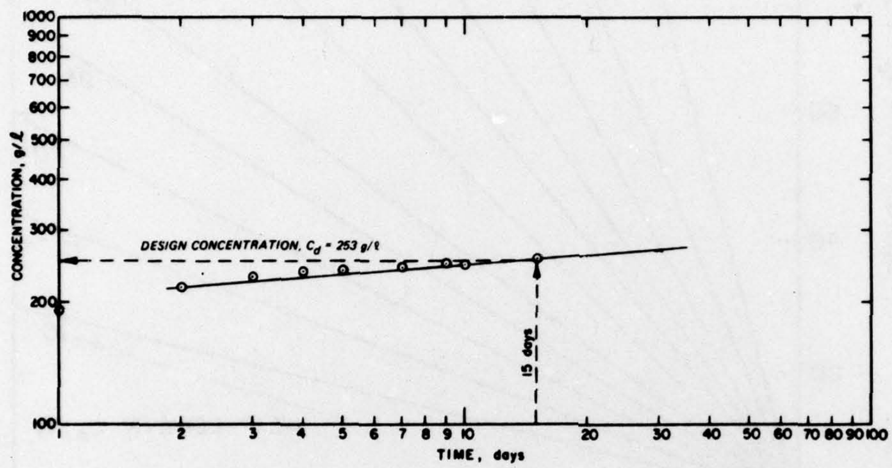

Figure B2. Time versus concentration

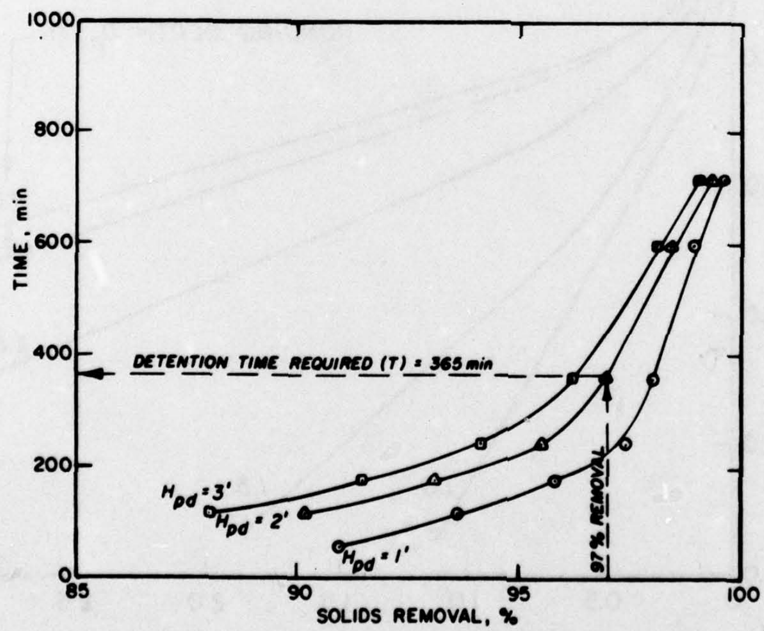

Figure B3. Solids removal versus time as a function of depth

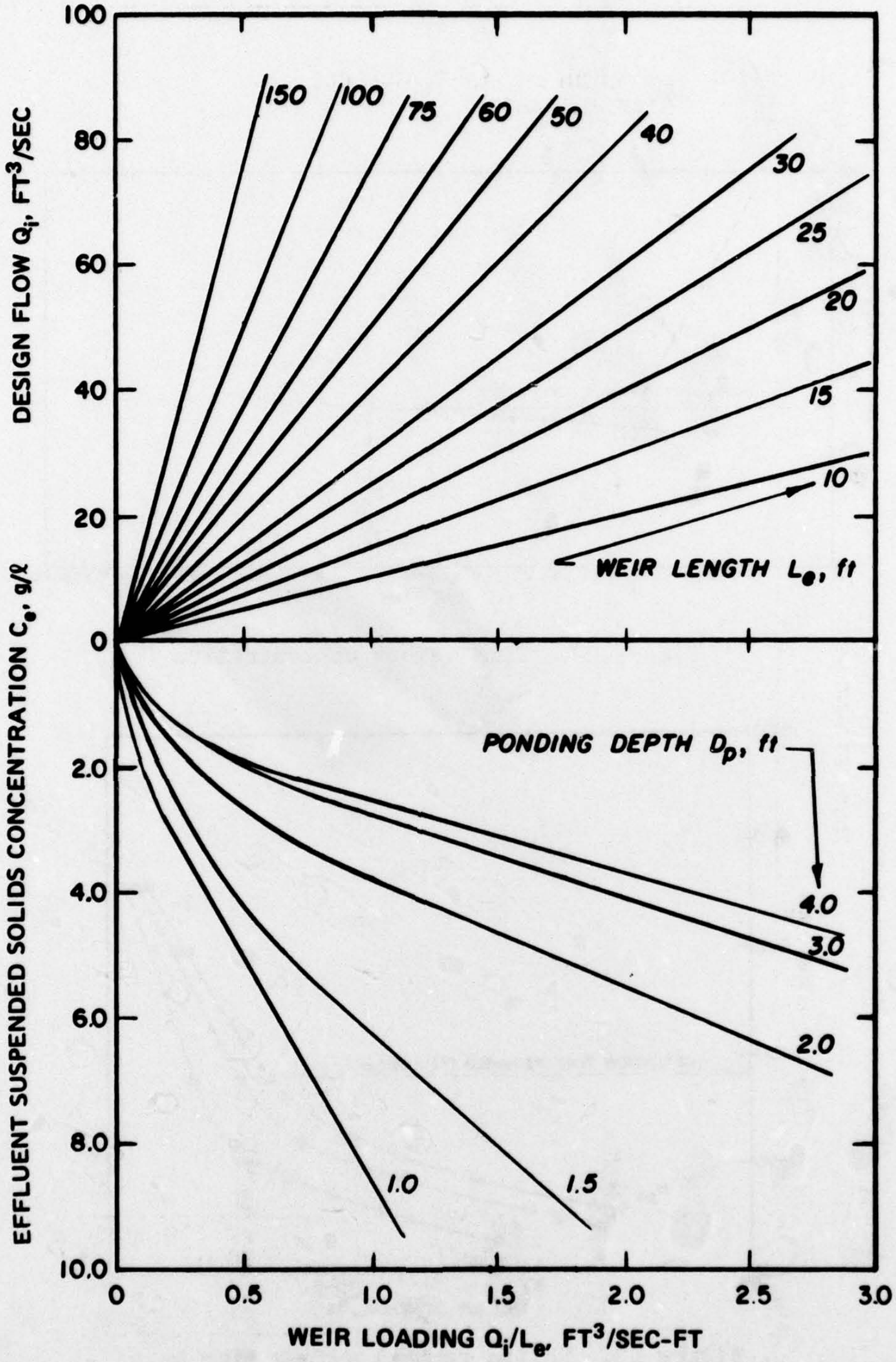

Figure B4. Weir design nomogram for freshwater clays (modified from Walski and Schroeder[1])

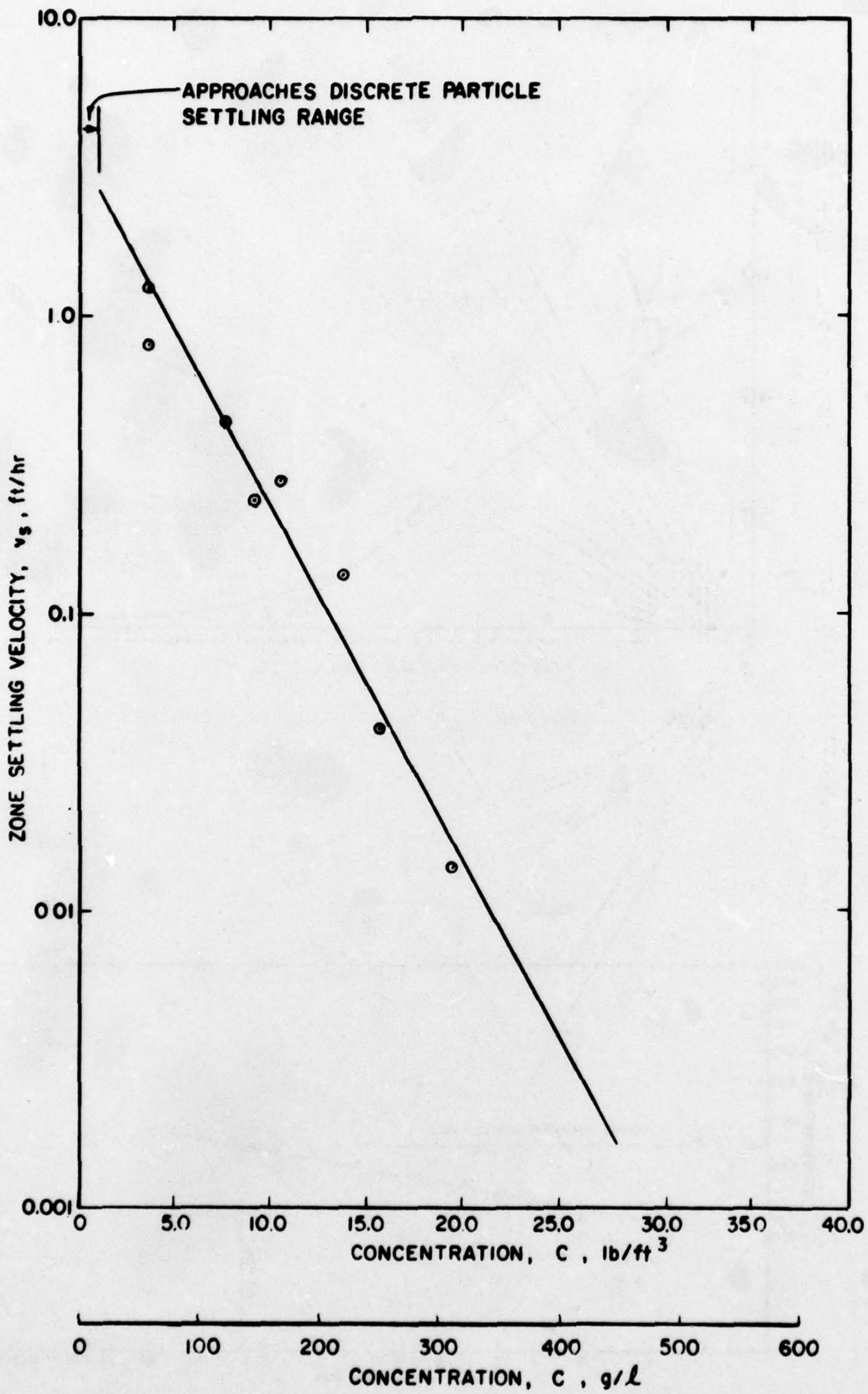

Figure B5. Zone settling velocity versus concentration

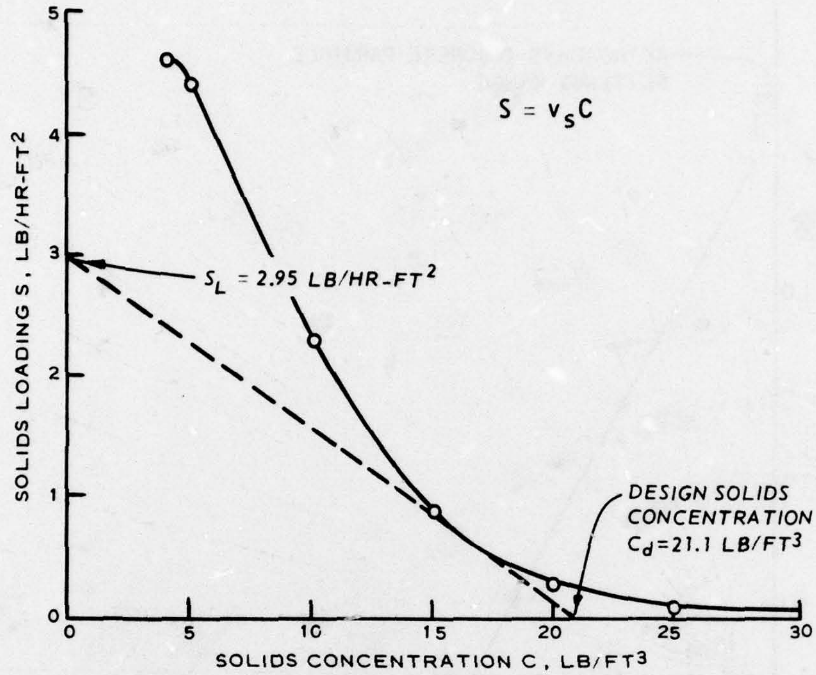

Figure B6. Solids loading versus concentration

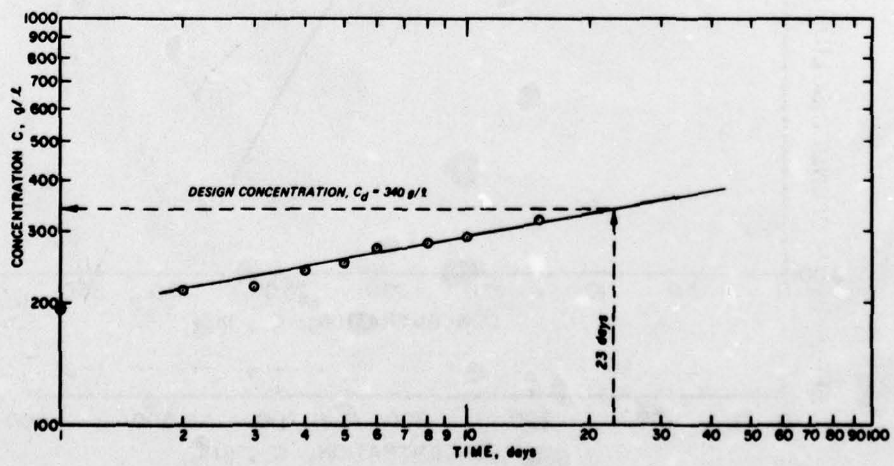

Figure B7. Concentration versus time

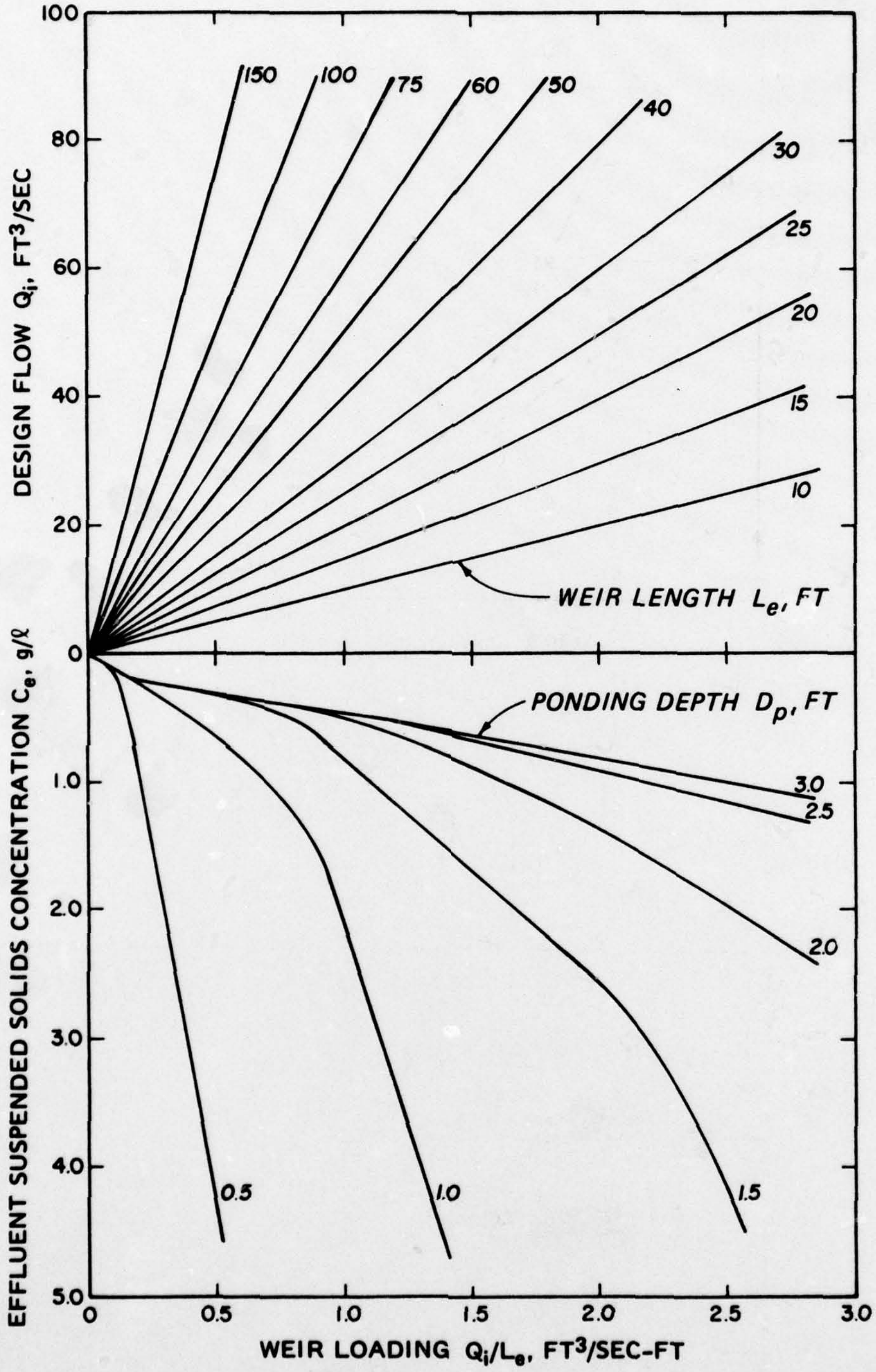

Figure B8. Weir design nomogram for all silts and saltwater clays (from Walski and Schroeder[1])

APPENDIX C: NOTATION

A	Containment surface area requirement, ft^2
A_d	Design surface area, ft^2
A_p	Cross-sectional area of dredge pipe, ft^2
c_i	Dye concentration measured at containment area weir with time, ppb
c_{io}	Input concentration of dye, ppb
C	Suspended solids concentration, g/ℓ or lb/ft^3
C_d	Design solids concentration, g/ℓ or lb/ft^3
C_e	Suspended solids concentration of dredged material influent, g/ℓ or lb/ft^3
C_i	Suspended solids concentration of dredged material influent, g/ℓ or lb/ft^3
C_∞	Ultimate suspended solids concentration in sedimentation environment, g/ℓ or lb/ft^3
C_o	Initial suspended solids concentration, g/ℓ or lb/ft^3
CH	Clay of high plasticity
CL	Clay of low plasticity
d	Depth, ft
D	Required dike height, ft
D_d	Coefficient of dispersion, ft^2/sec
D_p	Ponding depth at weir, ft
e_i	Average void ratio of in situ sediment
e_o	Average void ratio of dredged material at completion of dredging
G_s	Specific gravity of solids
H	Initial thickness of layer, ft
H_{dm}	Thickness of dredged material layer at the end of the dredging operation, ft
H_{fb}	Freeboard, ft
H_{pd}	Ponding depth, ft
K	First-order rate constant, $hours^{-1}$
L	Weir crest length, ft
L_c	Length of containment area, ft
L_e	Effective weir length, ft

LL	Liquid limit of soil
MH	Silt of high plasticity
ML	Silt of low plasticity
OC	Organic content, percent
OH	Organic clay of high plasticity
OL	Organic clay of low plasticity
PI	Plasticity index of soil
PL	Plastic limit of soil
Q	Flow rate, ft^3/sec
Q_e	Clarified effluent rate, ft^3/sec or gal/min
Q_i	Dredged material influent rate, ft^3/sec or gal/min
R	Percent solids removal
S	Solids loading, $lb/hr\text{-}ft^2$
S_d	Degree of saturation (equal to 100 percent for sediment)
S_L	Design solids loading, $lb/hr\text{-}ft^2$
%S	Solids concentration, percent by weight
t	Time, hours
$\bar{t}$	Mean detention time, hours
T	Theoretical detention time, min or hours
T_d	Design detention time, min or hours
v_d	Velocity of dredge discharge, ft/sec
v_s	Zone settling velocity, ft/hr
v_x	Component of mass velocity in x direction, ft/sec
V	Volume of dredged material in basin at end of the dredging operation, ft^3
V^*	Volume available for sedimentation near the end of the disposal operation, ft^3
V_i	Volume of shoal sediment to be dredged, ft^3
V_{sd}	Volume of sand, ft^3
V_A	Apparent volume of settled solids in specimen, litres
V_B	Containment area volume required for meeting suspended solids effluent requirements, ft^3
V_C	Containment area volume for sedimentation, ft^3
V_I	Volume of interstitial water in specimen, litres
V_S	Volume of solid particles in specimen, litres

V_T	Total volume of specimen, litres
w	Water content, percent
W_w	Weight of water in specimen, g
W_S	Ovendry weight of solid particles in specimen, g
W_T	Total weight of specimen, g
$\overline{X}$	Mean
γ	Unit weight, lb/ft^3
γ_d	Dry density of solids, g/ℓ or lb/ft^3
γ_w	Density of water, g/ℓ or lb/ft^3
ΔV	Change in volume of fine-grained channel sediment after disposal in the containment area, ft^3
θ	t/T, dimensionless
σ	Standard deviation
$\emptyset$	Percent by dry weight of initial solids concentration

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Montgomery, Raymond Lowree
  Methodology for design of fine-grained dredged material containment areas for solids retention / by Raymond L. Montgomery. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.
  126, [35] p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; D-78-56)
  Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under DMRP Work Unit No. 5C11.
  References: p. 124-126.

1. Containment areas. 2. Dredged material. 3. Fine grained soils. 4. Sedimentation. 5. Suspended solids. 6. Waste disposal sites. I. United States. Army. Corps of Engineers. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; D-78-56.
TA7.W34 no.D-78-56