DREDGED MATERIAL RESEARCH PROGRAM

TECHNICAL REPORT D-77-4

STATE-OF-THE-ART APPLICABILITY OF CONVENTIONAL DENSIFICATION TECHNIQUES TO INCREASE DISPOSAL AREA STORAGE CAPACITY

by

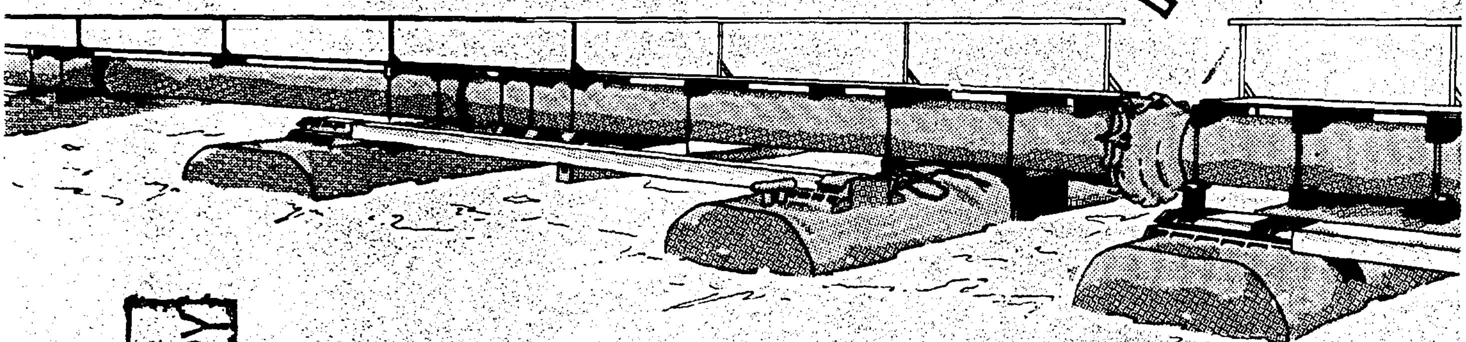
Stanley J. Johnson, Robert W. Cunny
Edward B. Perry, Leslie Devay

Soils and Pavements Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

April 1977

Final Report

Approved For Public Release; Distribution Unlimited



Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under DMRP Work Unit No. 5A03

Monitored by Environmental Effects Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

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

IN REPLY REFER TO: WESYV

29 April 1977

SUBJECT: Transmittal of Technical Report D-77-4

TO: All Report Recipients

1. The report transmitted herewith represents the results of a study of dredged material dewatering concepts evaluated as part of Task 5A (Dredged Material Densification) of the Corps of Engineers' Dredged Material Research Program (DMRP). This task, included as part of the Disposal Operations Project of the DMRP, is concerned with developing and/or testing promising techniques for dewatering or densifying (i.e., reducing the volume of) dredged material using mechanical, biological, and/or chemical techniques prior to, during, and after placement in containment areas.

2. Rapidly escalating requirements for land for the confinement of dredged material, often in the midst of urbanized areas where land values are high, have dictated that significant priority within the DMRP be given to research aimed at extending the life expectancies of existing or proposed containment facilities. While increased life expectancies can be achieved to some extent by improved site design and operation and to a greater extent by removing dredged material for use elsewhere, the attractive approach being considered under Task 5A is to densify the inplace dredged material. Densification of the material would not only increase site capacity but also would result in an area more attractive for various subsequent uses because of improved engineering properties of the material.

3. The technical objective of this study (Work Unit 5A03) was the evaluation of techniques for dewatering/densifying dredged material before and/or after placement in confined disposal sites. The study included conventional techniques used in soil mechanics and foundation engineering and by industries such as phosphate and aluminum processors to dewater/densify large containment areas. The evaluations were made on an engineering judgment basis by experts from the WES Soils and Pavements Laboratory and without laboratory or field research. The purpose of the study was to provide information for use in the overall development and field evaluation of promising dewatering/densifying techniques for dredged material.

4. The study included (a) a comprehensive review of existing conventional treatment methods for maintenance dredging of soft and compressible sediments, (b) evaluation of the technical applicability of various conventional techniques that could be applied before and after dredged material has been placed in the containment area, and (c) approximate evaluation of relative economics of the various techniques. The methodologies considered included conventional stabilization techniques used in soil mechanics and foundation engineering such as surcharge loading, vertical drains, underdrainage, and internal drainage systems; chemical additives; and mechanical working of material. An effort was also devoted to the establishment of the characteristics and properties of dredged material in existing disposal areas.

5. It was concluded that dredged material in disposal areas is similar to material successfully treated by conventional foundation and engineering practice, but the practicability of using these techniques to increase disposal area capacity depends more on economic and other factors than on technical considerations. It was concluded that seepage consolidation and underdrainage with and without vacuum pumping offers significant potential and should be investigated. Desiccation of dredged material placed in relatively thin layers is especially attractive both in cost and quantity of additional storage capacity achieved even though the concept may have limited application. Recommendations are also made for laboratory and field research. Results of this theoretical study should be considered tentative pending completion of the applied research.

6. Major field studies on dewatering techniques are now in progress in Mobile, Alabama. The techniques being evaluated were selected on the basis of the results from this study and other feasibility studies conducted as part of Task 5A. The studies in Mobile include the underdrainage and desiccation studies recommended in this report. Definitive information on the feasibility of these techniques will be provided in guidance in the synthesis reports within Task 5A.

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

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report D-77-4	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) 6 STATE-OF-THE-ART APPLICABILITY OF CONVENTIONAL DENSIFICATION TECHNIQUES TO INCREASE DISPOSAL AREA STORAGE CAPACITY.		5. ~~TYPE OF REPORT & PERIOD~~ COVERED Final repert.
		6. ~~PERFORMING ORG.~~ REPORT NUMBER
7. AUTHOR(s) 10 Stanley J. Johnson, Robert W. Cunny Edward B. Perry, Leslie Devay		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Soils and Pavements Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DRMP Work Unit No. 5A03
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE 11 April 1977
		13. NUMBER OF PAGES ~~148 plus microfiche~~
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) U. S. Army Engineer Waterways Experiment Station Environmental Effects Laboratory P. O. Box 631, Vicksburg, Miss. 39180		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

12 213p.

Approved for public release; distribution unlimited.

14 WES-TR-D-77-4

JUN 16 1977

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

In many localities

18. SUPPLEMENTARY NOTES

[redacted]

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Densification
Dewatering
Dredged material disposal
Soil stabilization
Waste disposal sites

(for dredged materials)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Dredging to maintain or increase project depths in navigable channels and harbors often requires confined dredged material disposal areas. In many localities it is difficult to find suitable confined disposal areas, and even where available, environmental constraints may prevent or restrict their use. This study sought
Restrictions may be placed on allowable heights of retaining dikes and depths of dredged material placed in disposal areas.

The purpose of this study was to determine if conventional stabilization-
(Continued)

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

038100

To increase disposal area storage capacity.

20. ABSTRACT (Continued) (Cr 1473A)

techniques can be used to densify/dewater dredged material as a means ~~for increasing the storage capacity of disposal areas~~. ~~This was done on a judgment basis, and without laboratory or field research.~~ Coarse-grained dredged material was not included in this study, ~~which~~ was restricted to clays and silty clays, which have high water contents after placement in disposal areas.

It was concluded that conventional stabilization techniques can be used to increase disposal area capacity but ~~that~~ economic constraints may restrict their use. ~~in some areas.~~ ~~It was found that~~ the water content, density, and Atterberg limits of fine-grained dredged material in existing disposal areas are inadequately known, and a large-scale but relatively low-cost sampling program is recommended to investigate existing disposal areas of various ages containing various depths and types of dredged material.

A variety of conventional stabilization techniques were evaluated. It was concluded that seepage consolidation and underdrainage with vacuum pumping offer significant potential and should be investigated. Desiccation of dredged material placed in thin layers is especially attractive both in regard to cost and quantity of additional storage capacity achieved, even though the concept may have limited application.

Selected research is recommended and is considered essential. This includes construction of simple but large-scale sedimentation consolidation test devices to investigate fundamental aspects of stabilization processes and benefits of various stabilization techniques.

The increase in storage capacity available from densification treatments should be compared with the alternative of raising the height of retaining dikes and placing greater thicknesses of dredged material in disposal areas. The latter is generally more economical, but may not be possible in some localities because of environmental constraints or because weak foundations are a limiting factor for small disposal areas. Where disposal area foundation consolidation and/or thickness of dredged material is large, densification treatment is especially beneficial.

Appendixes include a description of river sediments, a general description of conventional densification techniques, and calculations for the economic evaluation of densification techniques. ([redacted])

THE CONTENTS OF THIS REPORT ARE NOT TO BE USED FOR ADVERTISING, PUBLICATION, OR PROMOTIONAL PURPOSES. CITATION OF TRADE NAMES DOES NOT CONSTITUTE AN OFFICIAL ENDORSEMENT OR APPROVAL OF THE USE OF SUCH COMMERCIAL PRODUCTS.

EXECUTIVE SUMMARY

The objective of this study was to evaluate conventional techniques for densifying dredged material by dewatering to increase disposal area storage capacity and to improve the engineering characteristics of the material. The report includes a comprehensive review of conventional treatment methods and technical and economic evaluation of surcharge loading, vertical sand drains, underdrainage, chemical additives, and mechanical working techniques for densifying dredged material.

A significant effort was devoted to the establishment of the characteristics and properties of dredged material in existing disposal areas. When pumped into a disposal area, dredged material commonly may have a dry solid content ranging from 7 to 25 percent by weight or water contents ranging from about 1300 to 300 percent. After a period of time (ranging from months to years), depending on the character of the dredged material and the nature of the disposal area, a crust may form below which the material may have a water content approximately equal to 80 to 140 percent of the liquid limit.

Potential costs for dewatering and densifying dredged material are illustrated for an assumed initial condition of material in the disposal area as follows: a developed surface crust 2 ft thick, groundwater at a depth of 2 ft, 10-ft thickness of dredged material, initial water content below water table equal to liquid limit, and liquid limits ranging from 50 to 200. Treatment methods considered included: temporary surcharge fills up to 10 ft high; temporary surcharge fill with vertical sand drains (20 ft of dredged material assumed for this treatment method only); water ponded surcharge up to 16 ft deep with membrane, sand blanket, and collectors; surface vacuum mat with membrane, sand blanket, collectors, and vacuum pumping for 5 yr; underdrainage with collectors and sand blanket; underdrainage with sand blanket, collectors, and vacuum pumping; seepage consolidation with underdrainage sand blanket, collectors, and ponded water surcharge (no membrane); and desiccation by placing in thin layers, surface drainage, and nominal trenching. Costs ranged from $11.80 per cu yd of increased storage capacity for vertical sand drains with 10-ft surcharge on dredged material with a liquid limit of 50 to $0.33 per cu yd for desiccation of dredged material with a liquid limit of 200.

Chemical flocculating agents currently used by the phosphate and aluminum industries accelerate sedimentation of slurries, but unless other treatment methods are used, the end product has a water content of about 200 to 600 percent; this is greater than that desired for densified dredged material. Other chemical agents such as calcium hydroxide and calcium carbide, while capable of dewatering dredged material, are very costly and are relatively ineffective for creating a reduction in volume because the chemical reaction with water produces a chemical residue of significant volume.

It is concluded that dredged material in disposal areas is similar to materials successfully treated by conventional foundation engineering practice, but the practicability of using conventional densification techniques to increase disposal area capacity depends more on economic and other factors rather than technical considerations. For dredged material with water contents equal to liquid limits ranging from 50 to 200 percent, volume changes of from 10 to 60 percent can be produced depending on treatment method used. Desiccation of thin layers was the most effective means for increasing disposal area capacity and was the least costly. A choice of other methods can be made on the basis of time available for dewatering and availability of underdrainage, which generally must be provided prior to disposal operations.

Surface drainage and surface drying should be promoted during densification to reduce water contents to the liquid limit prior to special treatment. The foundation consolidation may result in substantial additional disposal area capacity and should be estimated when evaluating possible use of densification treatment to increase capacity. Dike raising is the lowest cost alternative for increased storage capacity, where permissible.

The study found that the following laboratory research is necessary:

a. Determine the sedimentaion-consolidation characteristics of dredged material.

b. Evaluate a variety of new drainage materials and proposed techniques (large-scale laboratory testing is necessary to avoid technical objections to previous small-scale tests and to investigate proposed densification techniques before undertaking relatively expensive field tests).

The following field investigation is also recommended:

a. Determine in situ conditions of dredged material in disposal areas.

b. Test proposed drainage techniques including pumped underdrainage with induced vacuum and seepage consolidation with and without pumped underdrainage and induced vacuum.

c. Test the efficacy of desiccation by vegetation.

d. Determine techniques for efficiently introducing flocculants into dredged material slurries.

The effects of earthquakes were not considered. Where earthquakes are possible and the effects of dike failure and loss of dredged material may be objectionable, separate studies are required. In such studies dredged material should be considered liquefaction susceptible.

Supplemental information in the appendixes includes a description of river sediments, a general description of conventional densification techniques, and calculations for the economic evaluation of densification techniques.

PREFACE

The study reported herein was made by the Soils and Pavements Laboratory, U. S. Army Engineer Waterways Experiment Station (WES), under the direction of Mr. James P. Sale, Chief, as part of the Corps of Engineers Dredged Material Research Program (DMRP), Disposal Operations Project, DMRP Work Unit No. 5A03. Parts I and V through VIII were prepared by Mr. Stanley J. Johnson. Part IV was prepared by Mr. Robert W. Cunny, and Parts II and III were prepared jointly by Dr. Edward B. Perry and Mr. Johnson. Dr. Perry prepared Appendix A, Mr. Leslie Devay prepared Appendix B, and Mr. Johnson prepared Appendix C. Portions of the report were discussed with Mr. Walter C. Sherman, Jr., who also made several of the visits to District offices.

The DMRP is assigned to the Environmental Effects Laboratory, under the general supervision of Dr. John Harrison, Chief; the Disposal Operations Project of the DMRP is managed by Mr. Charles C. Calhoun, Jr.; and Dr. T. Allan Haliburton, DMRP Geotechnical Engineering Consultant, was manager for the work unit.

The Directors of WES during the work and publication of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONTENTS

[redacted].

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
mils	0.00254	centimetres
inches	2.54	centimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
square feet	0.09290304	square metres
acres	4046.856	square metres
cubic feet	0.02831685	cubic metres
cubic yards	0.764555	cubic metres
gallons (U. S. liquid)	0.003785412	cubic metres
pounds (mass)	453.59237	grams
tons (short)	907.1847	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force)	4.448222	newtons
pounds per square inch	6894.757	pascals
pounds per square foot	4.882428	kilograms per square metre
tons per square foot	95.76052	kilopascals
atmospheres (normal)	101.325	kilopascals
feet per minute	0.00508	metres per second
kilowatt-hour	3600000.0	joules
horsepower (550 foot-pounds per second)	745.6999	watts
foot-pounds (force)	1.355818	joules
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

STATE-OF-THE-ART APPLICABILITY OF CONVENTIONAL DENSIFICATION TECHNIQUES TO INCREASE DISPOSAL AREA STORAGE CAPACITY

PART I: INTRODUCTION

Objectives

1. Task 5A of the Dredged Material Research Program (DMRP) of the Corps of Engineers (CE) has as its objective the developing and testing of promising techniques for dewatering or densifying dredged material using physical, biological, and/or chemical methods.

2. The work described in this report is a subtask under Research Task 5A and has as its primary technical objective the evaluation of techniques for dewatering/densifying dredged material after placement in confined disposal sites. The subtask involves an engineering evaluation of the applicability of conventional techniques used in soil mechanics and foundation engineering and by industry to dewater/densify large containment areas. The principal reason for densifying dredged material placed in containment areas is to increase disposal area storage capacity. A secondary objective, occasionally important, is to improve the engineering characteristics of disposal areas to make them suitable for subsequent development or to make the dredged material suitable as a source of borrow.

3. An ultimate objective of work described herein is to minimize the number of new disposal areas required to contain dredged material and to enhance the environmental impact of land disposal by providing sites which can be utilized for beneficial purposes. An associated benefit is to produce significant cost savings in disposing of dredged material.

Scope

4. This study evaluates the feasibility of densifying dredged material placed in confined disposal areas. The work included: (a) a

comprehensive review of existing conventional treatment methods for maintenance dredging of soft and compressive subsoils (dredging of new works sometimes contains clay balls or lumps of clay in a matrix of soft clay, but the treatment of these materials is excluded from this study); (b) evaluation of the technical applicability of various conventional techniques that could be applied before or after dredged material has been placed in confined disposal areas; and (c) approximate evaluation of relative economics of various techniques.

5. The scope of work involves application of conventional techniques to both active and inactive confined disposal sites. The methodologies considered included conventional stabilization techniques used in soil mechanics and foundation engineering such as surcharge loading, vertical drains, underdrainage and internal drainage systems, chemical additives, and mechanical working of material.

6. The scope of work also included a literature review. It generally excluded densification concepts of an innovative or unproved nature or the conduct of field tests of the applicability of conventional soil mechanics and foundation engineering techniques. As part of the work done, visits were made to the New York Port Authority (NYPA), the Norfolk, Seattle, and San Francisco Districts of the CE, and various private firms.

General Technical Considerations

7. The simplest method of confining dredged material employs low dikes and large disposal areas, but this method is not always possible because of land cost and use restrictions. An alternative is to restrict the size of the disposal area and to gradually increase the height of retaining dikes and thickness of material placed in the disposal area. While merely increasing the height of retaining dikes and thickness of dredged material ultimately becomes undesirable for technical and aesthetic reasons, land creation is a low-priority use in DMRP compared to space creation.

8. Conventional techniques used in soil mechanics and foundation

engineering to stabilize (i.e., dewater and densify) soft materials involve consideration of ultimate results together with the time rate at which desired benefits can be achieved. Some applications of conventional techniques do not require special means to accelerate the rate of densification. Under other circumstances, the desired results cannot be obtained in the time desired, and additional provisions are made to accelerate the rate of densification. For example, a surcharge load will densify underlying materials, but if the thickness of soft materials is large, the time required may be several decades. Where this is the case, vertical drains can be provided that decrease the length of drainage paths and accelerate the rate of consolidation. Since the drains increase the cost substantially, they are not provided unless required. Where disposal areas are large and the rate of placement of dredged material is slow, adequate time may be available for densification without installing special provisions for accelerating the rate of densification. In other locations, this will not be the case and added money must be expended to obtain the desired results within the time available.

9. The time factor is, therefore, a major consideration when evaluating densification techniques. This makes it essential that planning, engineering, and operation consider long-range utilization of disposal areas so that time requirements for the most economical techniques can be anticipated. Unless planning is done sufficiently early, some low-cost alternatives may be precluded because certain construction work was not undertaken before the disposal area was placed in operation. For example, underdrainage layers cannot be added after the disposal area is filled. Planning factors relating to disposal area management are listed in Table 1.

10. After initiation of this study, it was found that relatively little definitive information was available on the condition of dredged material after sedimentation in disposal areas. Since this is the starting point for studying densification treatment, considerable effort was expended to find data relating to in situ conditions of dredged material placed in disposal areas.

Economic Considerations

11. The cost of techniques used in soil mechanics and foundation engineering for densifying soft materials differs enormously. Since the availability of dredged material disposal sites varies greatly, it is impossible to generalize on the economic burden that can be assigned to disposal of dredged material.

12. In some areas, as in the Norfolk District, CE, large disposal sites are available that cost as little as $0.04* per cubic yard** of storage capacity. This prohibits use of even the simplest densification technique. In many areas, tolerable disposal area costs vary from $1.00 to $3.00 per cubic yard,† which is sufficient to permit various conventional densification techniques to be considered. Occasionally, the cost of providing a disposal site may approach $5.00 to $10.00 per cubic yard,† and almost all conventional techniques used in soil mechanics and foundation engineering can be considered.

13. The evaluation of individual treatment methods depends greatly upon site conditions, and detailed studies should be made comparing various alternatives. The methods discussed in this report are intended to illustrate approaches that can be used to evaluate alternatives in light of local and technical factors.

14. Specific techniques will be discussed individually, but the most efficient use of disposal areas may involve either the concurrent or staged use of more than one approach. The most efficient use of confined disposal sites will be achieved by early and continuous planning and comparison of technical and economic aspects of available techniques, followed by field instrumentation to determine results being obtained. Technical evaluation of various alternatives must be considered as a process starting when a disposal area is first being planned and continuing throughout its operation. This entails: (a) detailed investigation

---

* Tom Lawless, personal communication with R. W. Cunny, 10 June 1975.

** A table of factors for converting U. S. customary units of measurement to metric (SI) is given on page 8.

† Personal communication, Roger Saucier to Stanley Johnson.

of materials to be dredged; (b) laboratory tests to determine their physical properties, such as grain size, Atterberg limits, and consolidation characteristics; (c) detailed consolidation and densification treatment analyses, considering all alternatives; and (d) field instrumentation and continuing analyses.

Arrangement of Report

15. The main text presents only essential discussions; supplemental information that amplifies or substantiates the text is given in the appendixes. A general description of conventional densification techniques is given in Appendix A.

PART II: ENGINEERING PROPERTIES OF DREDGED MATERIAL

General

16. The small amount of data currently available regarding the types and physical conditions of dredged material placed in disposal areas made it advisable to supplement this data by whatever relevant information that could be obtained. Materials to be dredged were deposited in a sedimentary environment generally similar to that found in disposal areas. For this reason, data from field and laboratory testing of in situ materials requiring dredging have been reviewed. These are summarized in Appendix A.

Properties of Dredged Material Placed in Confined Disposal Areas

Placement of dredged material and formation of crust

17. When dredged material is pumped into a confined disposal area, the dry solids content may range from 7 to 25 percent by weight.[1] If the material is allowed to remain undisturbed for a few hours to a few weeks, sedimentation will occur and free water can be decanted through a sluice. The surface of dredged material exposed to the atmosphere will begin to dry and a crust will form. The depth of the crust will increase with time of exposure generally at a rapidly decreasing rate.[2] The ultimate thickness of the crust will depend upon underdrainage, vegetation, and climatic conditions.

18. Little definitive information is available regarding engineering properties of the crust.[2,3] Available information generally concerns the movement of men or equipment on the surface of the crust. In describing the condition of the surface crust at Penn 7, a confined disposal area near Toledo Harbor, Krizek and Salem[3] noted there was a period of time during early crust formation when the disposal area was inaccessible. Later it was possible to walk on the disposal area surface using plywood mudshoes. Still later the crust was capable of supporting an individual.

19. Bishop and Vaughan[2] described the condition of surface crusts at disposal areas in England. At Marchwood it was just possible to walk on the surface after 1 yr. After 3-1/2 yr, a firm crust capable of supporting cattle extended down about 1 ft. The effects of surface drying extended down to about 3 ft. At Rainham, the surface could be walked on after 6 months. At Teesmouth, a surface crust of 500-psf average undrained strength and 2.5-ft thickness had developed after 7 yr.

20. At the "Navy Area," Port Newark, N. J., the NYPA found that after 5 months portions of a dredged material disposal area had developed a crust capable of supporting personnel, but no crust had formed in low areas.

Effect of organic matter

21. Organic matter in dredged material may be in the form of sanitary sewage, industrial waste, petroleum products, agricultural wastes, and fibrous material from vegetation growth during dormant periods when no dredging occurs.[4] As shown in Figure 1, an increase in the amount of organic matter results in a decrease in the maximum dry density and an increase in the optimum moisture content for an illitic soil.[5] Similar effects also occur in sedimented soils containing organic matter. The influence of temperature on the behavior of organic soils is discussed by Habibagahi.[6] The presence of organic matter in dredged material may generate gasses which could cause expansion under low-intensity loadings.[3]

Engineering properties - Delaware River

22. Engineering properties of dredged material in confined disposal areas along the Delaware River are given in Table 2.[7] This material was sampled and tested several years following placement in the disposal area. The average dry unit weight was 51.6 pcf. The average ratio of water content to liquid limit (LL)* was 0.80. The average liquidity index (LI) was 0.65. The Atterberg limits are plotted in Figure 2 and fall practically on the A-line. Relationships involving the

* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix D).

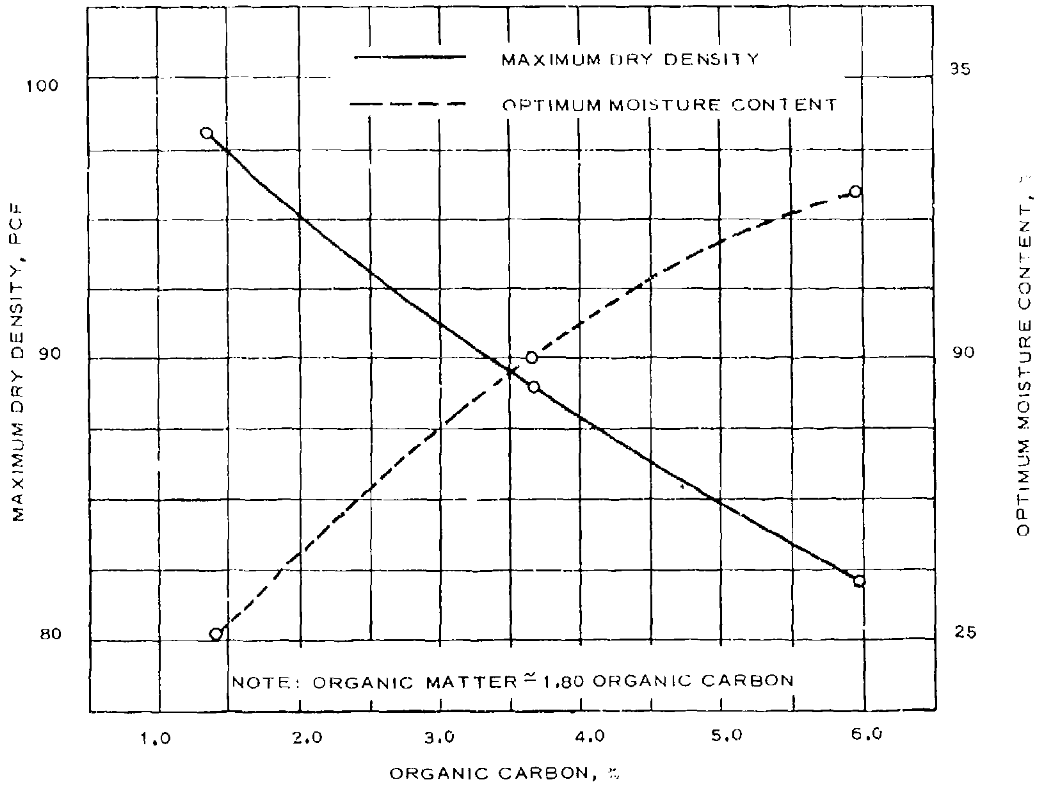


Figure 1. Influence of organic carbon content on compaction characteristics of illitic soil (from Schmidt[5])

Ll, water content, and percent solids are given in Figure 3 for soils plotting along Casagrande's A-line on the plasticity plot.

Engineering properties - Toledo Harbor

23. Krizek and co-workers[3,8-14] conducted extensive investigations into the engineering properties of dredged material placed in confined disposal areas near Toledo Harbor. Results of these investigations on maintenance dredging from the freshwater environment of the Great Lakes should not be indiscriminately applied to dredged material from saline environments. Since these investigations were unusually extensive and represent the largest source of engineering data on freshwater disposal sites, they are reviewed in detail. The four disposal areas are shown in Figure 4. All four areas are nearly rectangular in plan and enclosed by dikes ranging from about 12 to 20 ft in height.

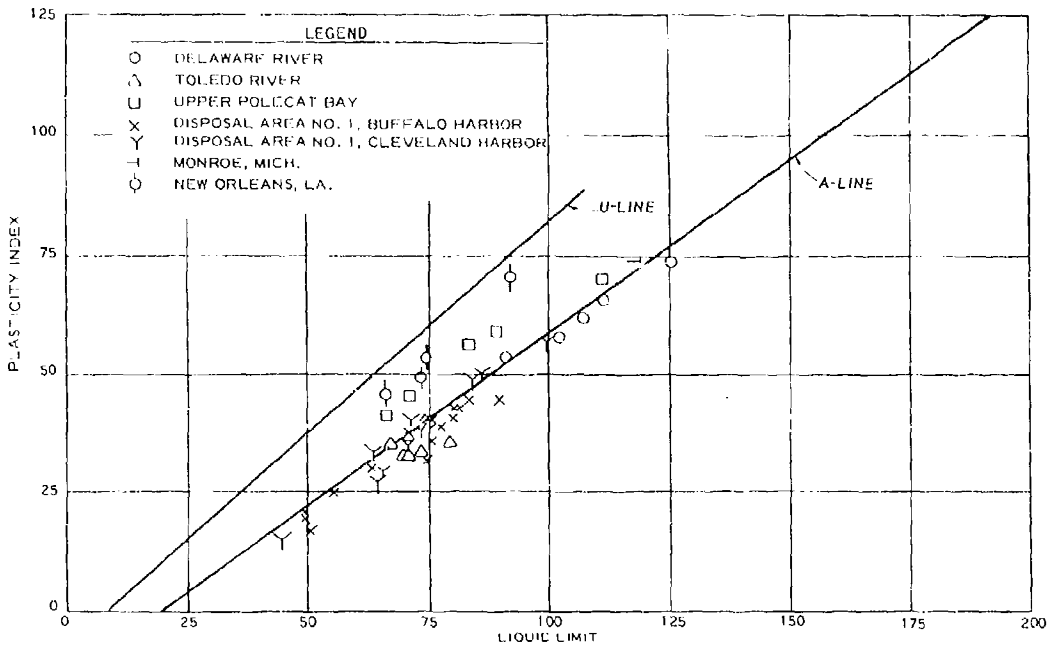


Figure 2. Plasticity plot for material in confined disposal areas

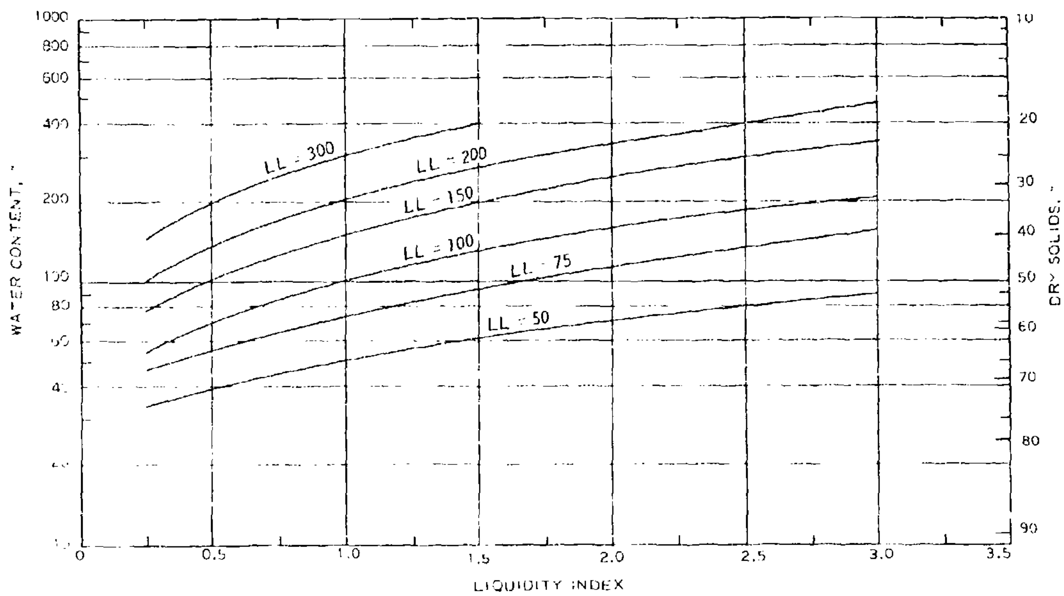


Figure 3. Relationship between water content, LI, and percent solids for soils plotting on A-line of plasticity chart

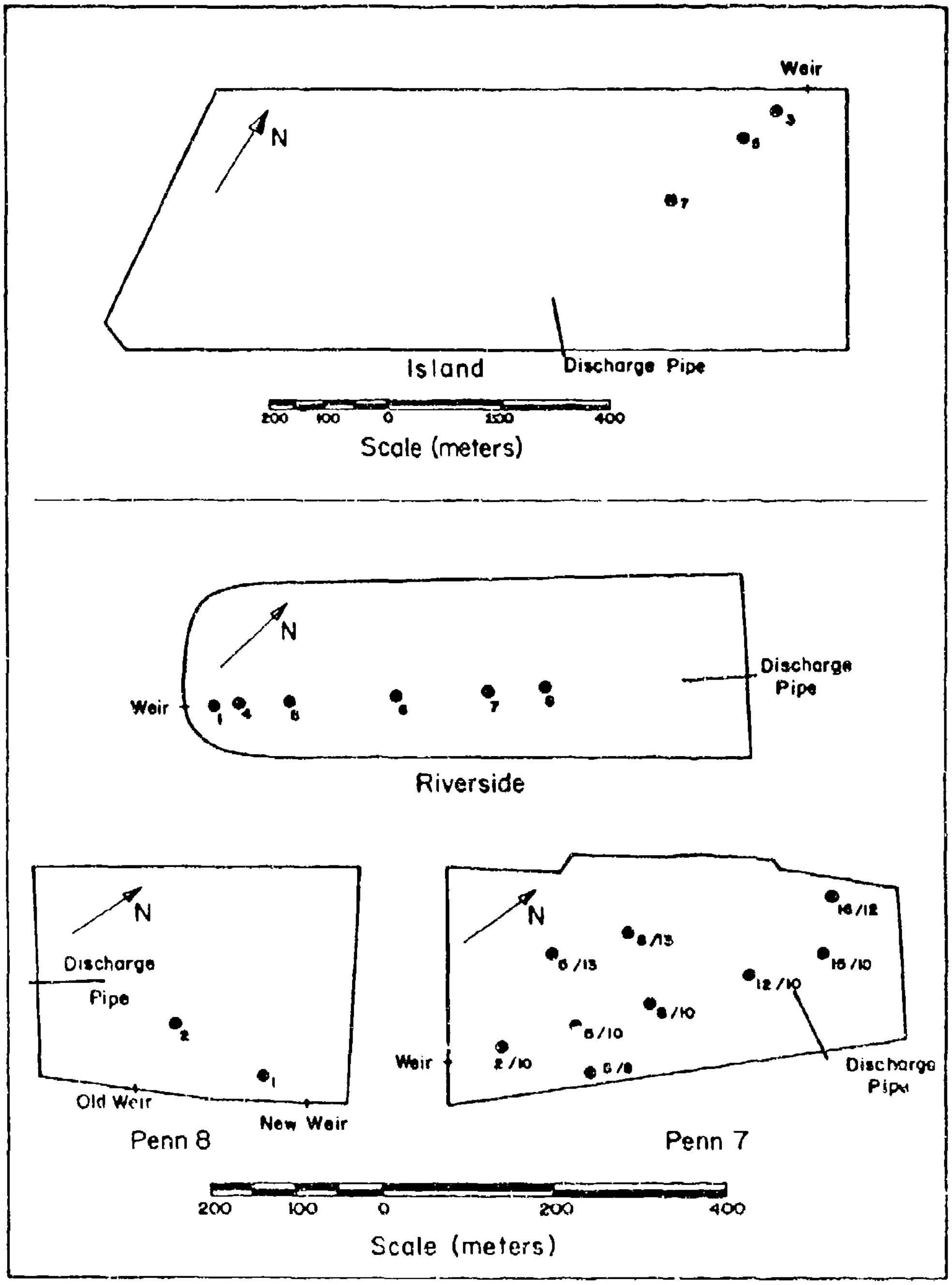


Figure 4. Disposal sites at Toledo Harbor (from Krizek and Salem[15])

The island site is located at the mouth of the Maumee River at the entrance to the bay. The other three sites are located along the north bank of the Maumee River near its mouth. About 9 million cu yd of dredged material was deposited in these four containment areas during the period 1964-1974. The cumulative volume of dredged material deposited in the Toledo Harbor disposal areas is shown in Figure 5. Engineering properties of dredged material in the various confined disposal areas are given in Table 3.[3] Based on the results of classification tests, it was found that the characteristics of dredged material deposited in the four sites listed in Table 3 were essentially the same, thereby enabling data from the different sites to be synthesized and interpreted as representative of one large site spanning a period of about 8 yr.[3]

24. Sampling. Krizek[8] and Hummel[16] presented information on sampling techniques developed. Most of the sampling was done after formation of a desiccated crust firm enough to allow access by foot. It was necessary to use custom-designed, lightweight, hand-operated sampling equipment. The materials sampled were mostly fine-grained OH soils with a water content slightly below the LL. A 3-in. piston sampler was used to obtain undisturbed samples. Thin tubing was used as liners in the core barrel to minimize sample disturbance during extraction, handling, and storage. An air vent connected the hollow stem of the rod to the cutting tip to reduce suction and facilitate sample retrieval. Sample recovery in the soft materials was nearly 100 percent.

25. Water contents, limits, and densities. The average ratio of the water content to the LL (Table 3) was 1.08 1 yr after deposition. For times of 3 to 8 yr after deposition, this ratio was about 0.85. LI values for corresponding times were 1.14 and about 0.65, respectively. The plasticity relationships for the dredged material are given in Figure 6 according to Krizek et al.[3,9] Atterberg limits listed in Table 3 are plotted in Figure 2 and are close to the A-line.

26. The rapid increase in dry unit weight with time is shown in Figure 7.[13] The average organic matter present in the dredged material was about 5 percent.

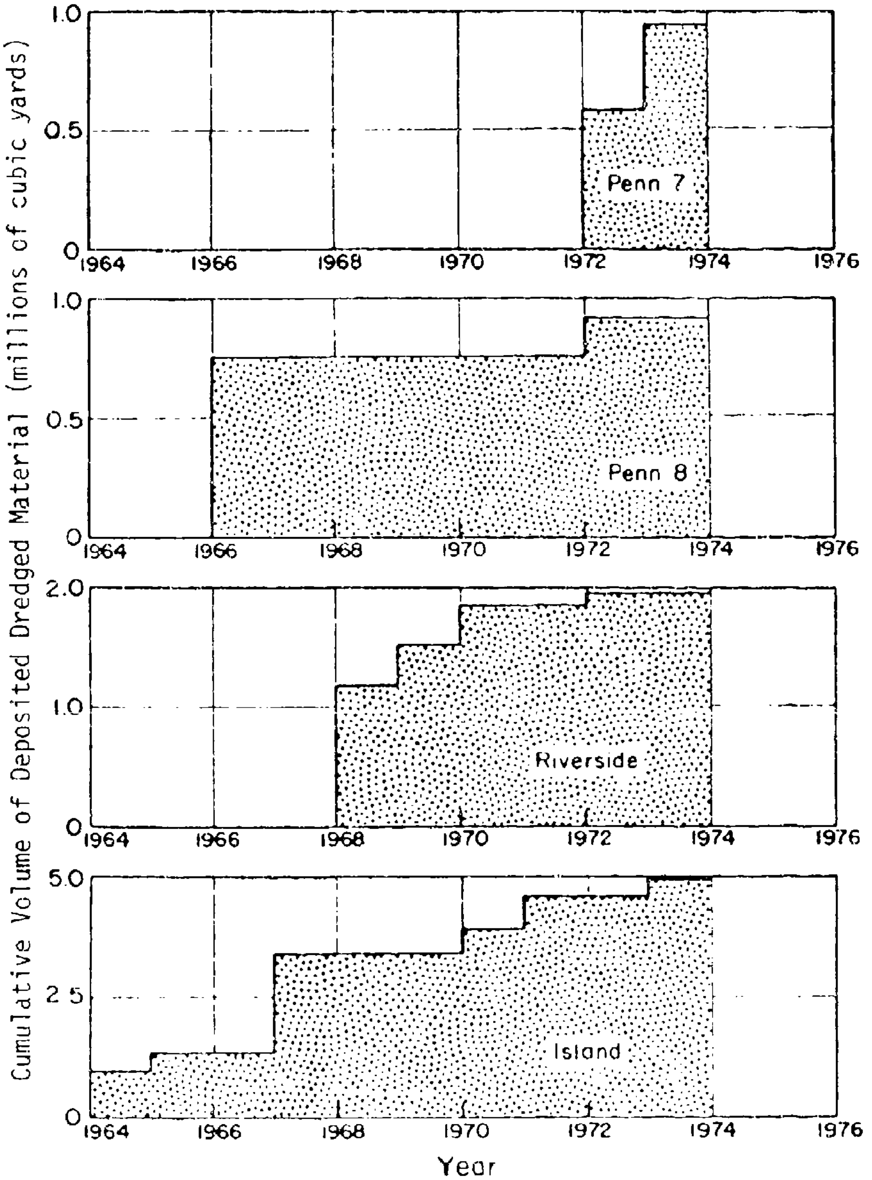


Figure 5. Cumulative volume of dredged material deposited in Toledo disposal sites (from Krizek and Salem[15])

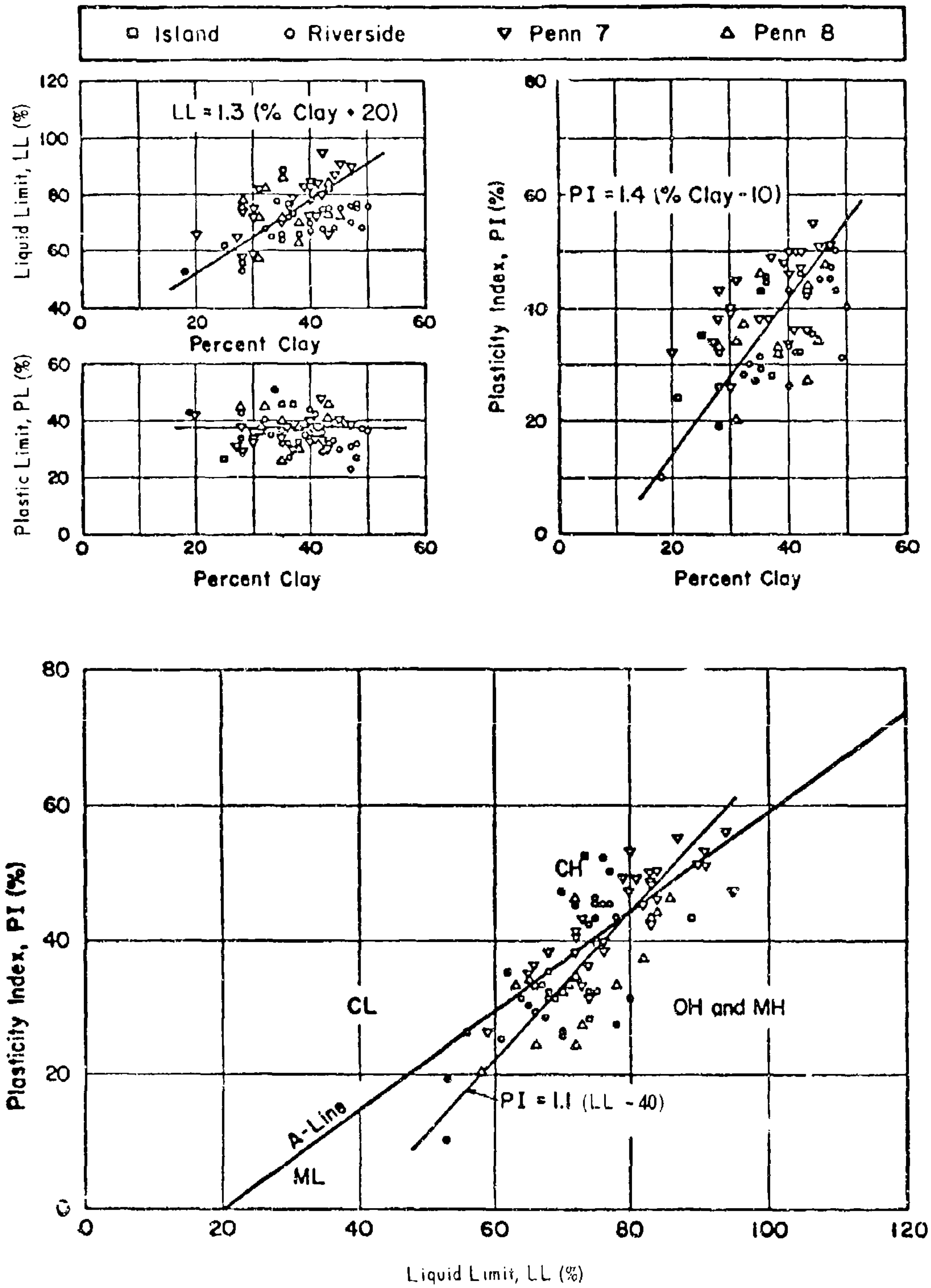


Figure 6. Plasticity relationships for dredged material from disposal areas near Toledo Harbor (from Krizek et al.[3,9])

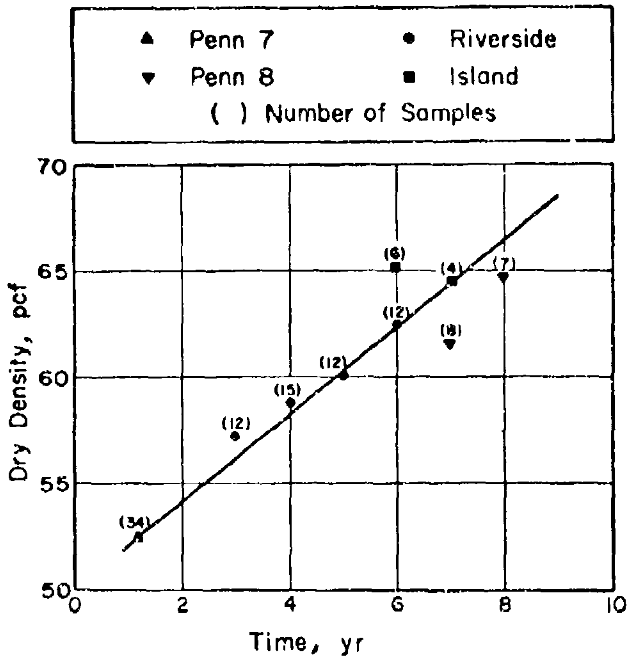


Figure 7. Increase in dry density with time for dredged material deposited in diked disposal areas near Toledo Harbor (from Krizek and Giger[13])

27. Effect of distance from inlet pipe. As shown in Figure 8, borings were located to enable the determination of dredged material properties versus distance from the inlet pipe or overflow weir.[3] The variation in average grain characteristics versus distance from the inlet pipe for Penn 7 disposal area is shown in Figure 9.[3] The effective particle size, D_{10}, decreases from about 0.3 to 0.0015 mm in a distance of about 30 m. In the following 300 m, D_{10} fluctuates with no definite trend. A gradual decrease is noted from about 0.001 to 0.0005 mm in the vicinity of the overflow weir where surface water normally covered the site. The percent fines (<0.074 mm) increase from zero near the inlet pipe to 90 percent in 160 m. Any sands present in the dredged material tend to drop and displace underlying soft materials near the end of the pipe.

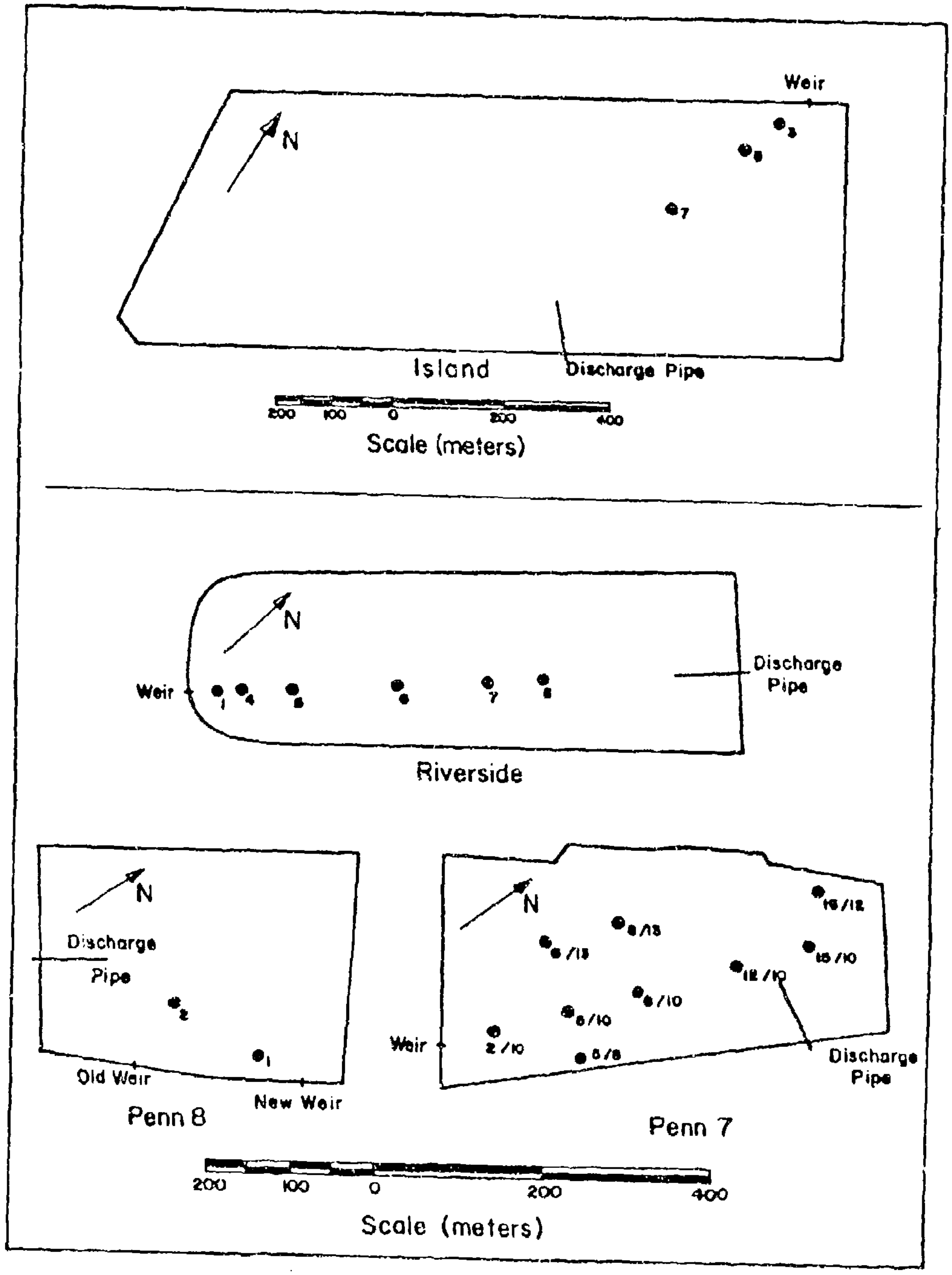


Figure 8. Location of borings at disposal areas near Toledo Harbor (from Krizek and Salem[15])

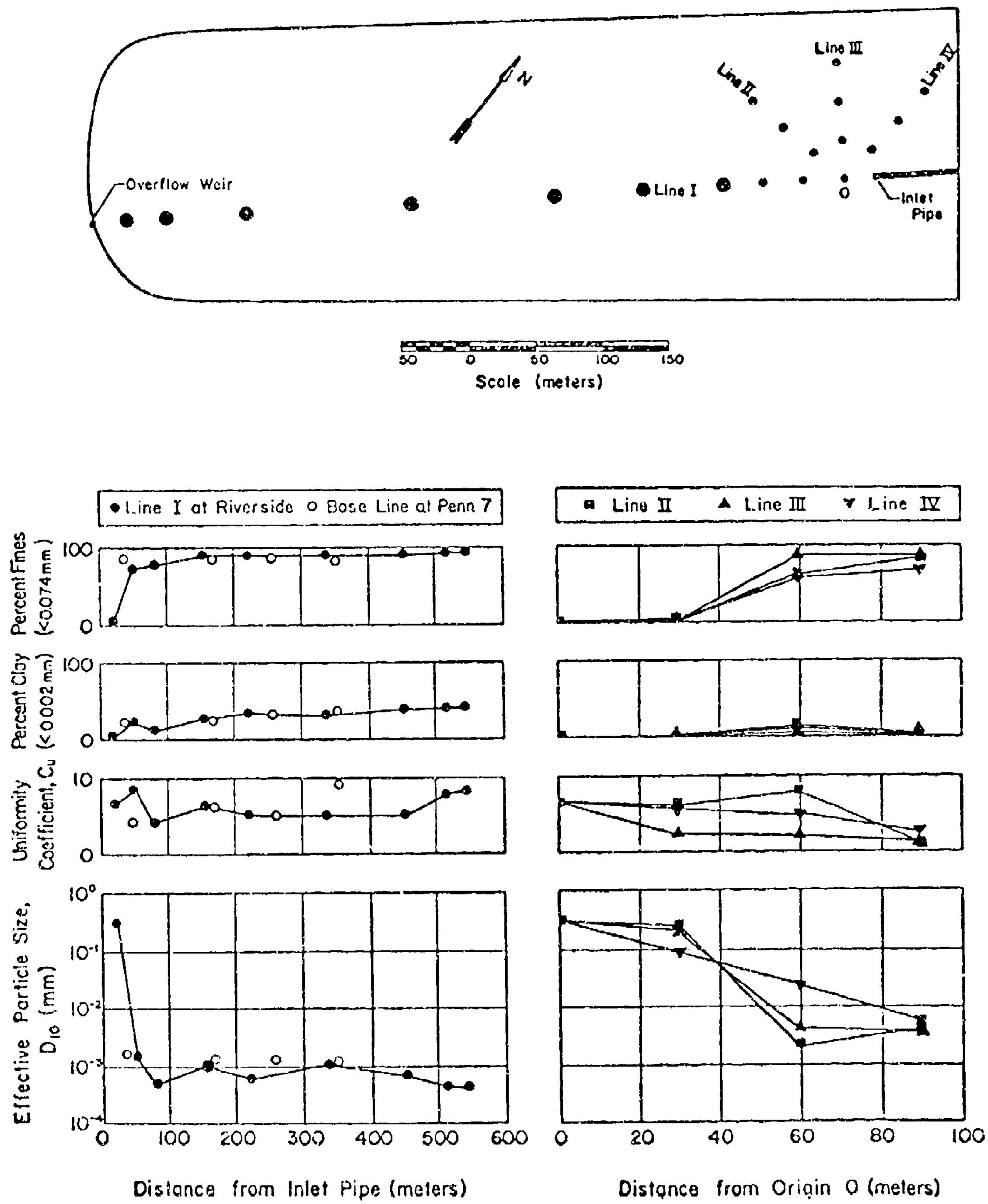


Figure 9. Variation of average grain characteristics versus distance from inlet pipe for Penn 7 disposal area near Toledo Harbor (from Krizek and Salem[15])

28. Decrease in permeability with decrease in void ratio. As shown in Figure 10, the coefficient of permeability decreased from about 10^{-4} to about 10^{-9} cm/sec as the void ratio decreased from approximately 10 to 1.[17] Most permeability values for the firmer materials, which had void ratios between 1 and 2, were in the range of 10^{-6} to 10^{-8} cm/sec. Two field infiltration tests yielded permeabilities approximately three orders of magnitude higher than those obtained from laboratory tests on undisturbed samples.

29. The influence of salinity of depositional environment on the structure of clay is that high salinity causes a more dispersed structure.[18,19] Increased permeabilities may occur in dredged material deposited in saline environments compared to permeabilities measured in freshwater deposits in the Great Lakes region.

30. Consolidation characteristics. The results of slurry consolidation tests on dredged material yielded the empirical equation:[20-22]

$$C_c = 0.02(LL - 22) \qquad (1)$$

where C_c = compression index. However, the range of LL values (60 to 76 percent) was relatively small. This equation gives considerably higher C_c values than given by other correlations for LL more than 40.

31. An increase in void with time during consolidation at low intensity of loading was believed to have resulted from gas generation. Analysis of a gas sample revealed 3.6 percent oxygen, 15.7 percent carbon dioxide, 16.8 percent methane, and 63.9 percent nitrogen.

32. The initial water content w_o also has a significant influence on consolidation behavior at low-intensity loading.[23] Secondary compression was found to be significant and was generally more than one-half of the total settlement[24] under low loads. The secondary compression tended to increase in a linear manner with the logarithm of time for a considerable period of time, after which the rate of secondary compression increased significantly reaching a maximum and then decreasing. The influence of temperature on the secondary compression of organic soils is discussed by So.[25] The relative importance of secondary compression will be considered further in Part V.

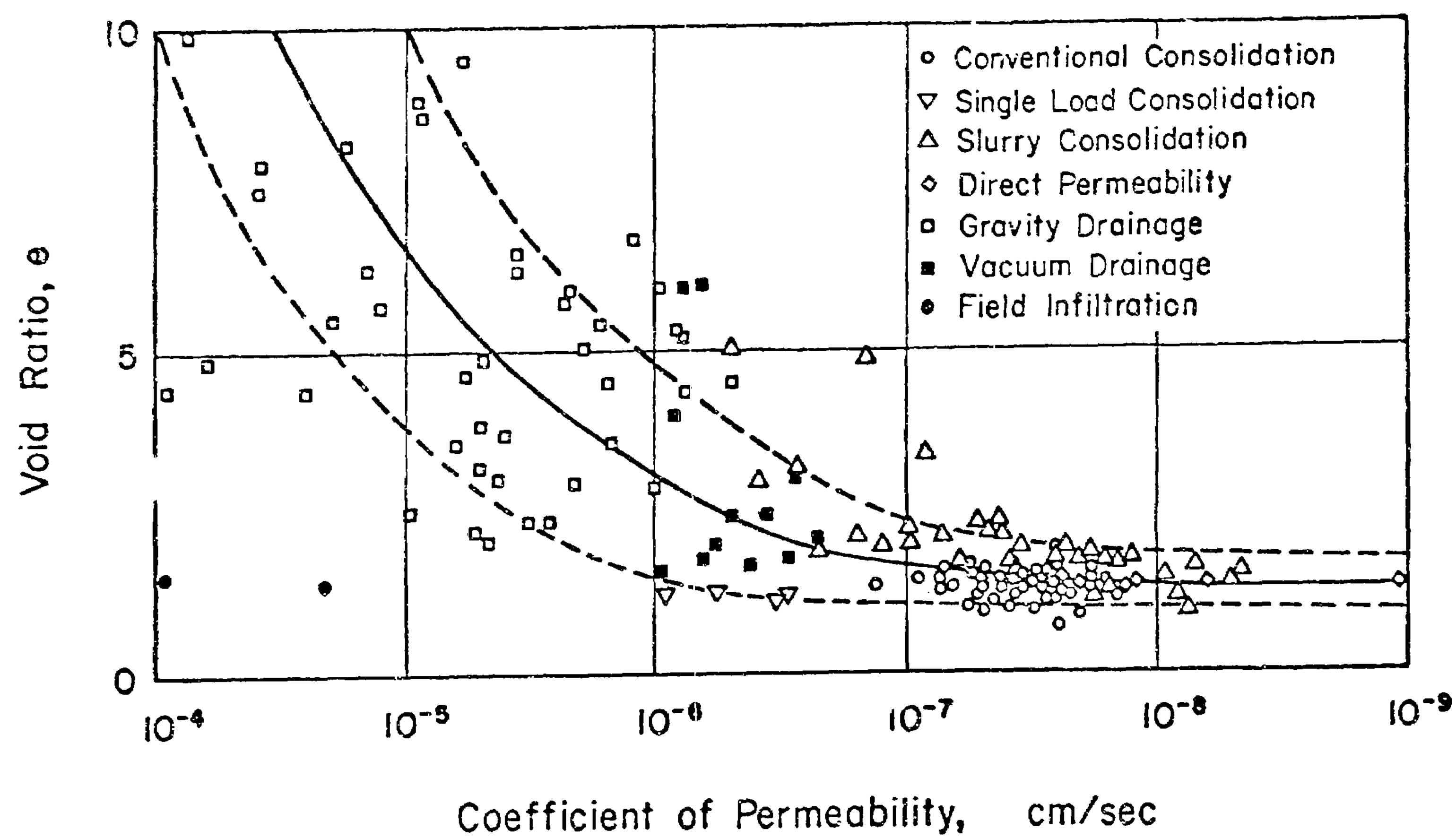


Figure 10. Coefficient of permeability versus void ratio for dredged material disposal areas near Toledo Harbor (from Krizek and Salem[15])

33. Field settlements. Field settlements measured at Penn 7 confined disposal area are compared with settlements predicted using the Casteleiro one-dimensional mathematical model[3,10] in Figure 11. This model accounts for bottom-drainage conditions, nonhomogeneous material properties, and consolidation and desiccation of successive layers of dredged material periodically placed in a disposal area.

34. Shear strength. The relationship between undrained shear strength and water content, dry unit weight, and LI are shown in Figures 12-14, respectively.[3] The strength characteristics of the dredged material were found to be comparable to those associated with fine-grained organic soils of comparable water content. As shown in Figure 15, the average field vane shear strength was found to increase with horizontal distance from the overflow weir.[15] This variation is due in part to the grain-size distribution. Coarse particles tend to settle near the inlet pipe and fine particles tend to settle closer to the overflow weir. The coarse material would drain and consolidate faster than fine material, thereby developing greater strength in a given period of time.

35. Figure 16 shows the average field vane shear strength versus age of landfill.[3] Since the placement of material at a given site took place intermittently during several dredging seasons, an equivalent zero time, corresponding to the placement of one-half of the final volume of dredged material in a site, was arbitrarily assumed. As shown in Figure 16, the shear strength increased consistently and rapidly with time.

36. Sensitivity. The relationship between sensitivity and water content, dry unit weight, and LI is shown in Figures 17-19, respectively.[3] The sensitivity of freshwater dredgings, as shown in Figure 17, increases with a decrease in water content. The sensitivity of marine clays increases with an increase in water content.[26] The sensitivity of freshwater dredgings, as shown in Figure 19, increases with a decrease in LI. The sensitivity of marine clays increases with an increase in LI.[26]

Engineering properties - Buffalo Harbor

37. The U. S. Army Engineer District, Buffalo, conducted studies[27]

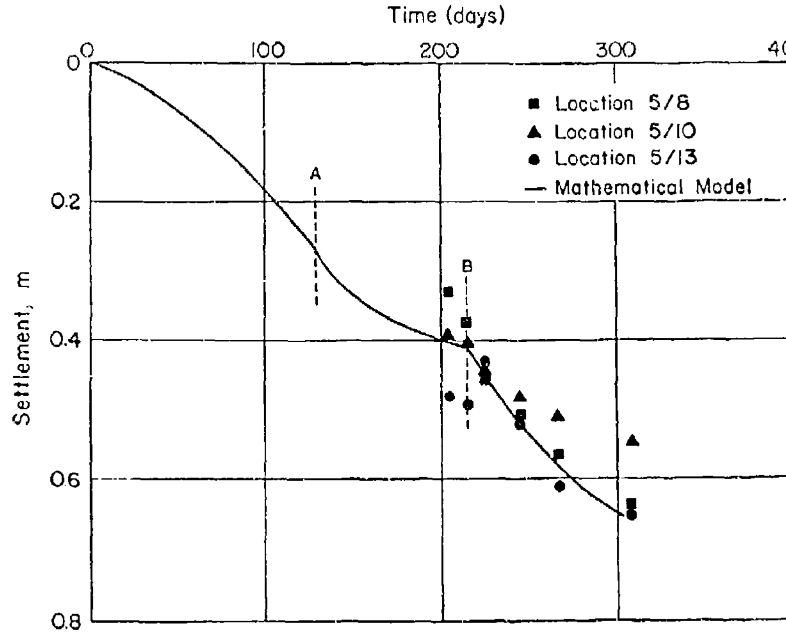


Figure 11. Comparison between measured settlements at Penn 7 disposal area near Toledo Harbor and prediction of Casteleiro's one-dimensional mathematical model (from Krizek and Salem[15])

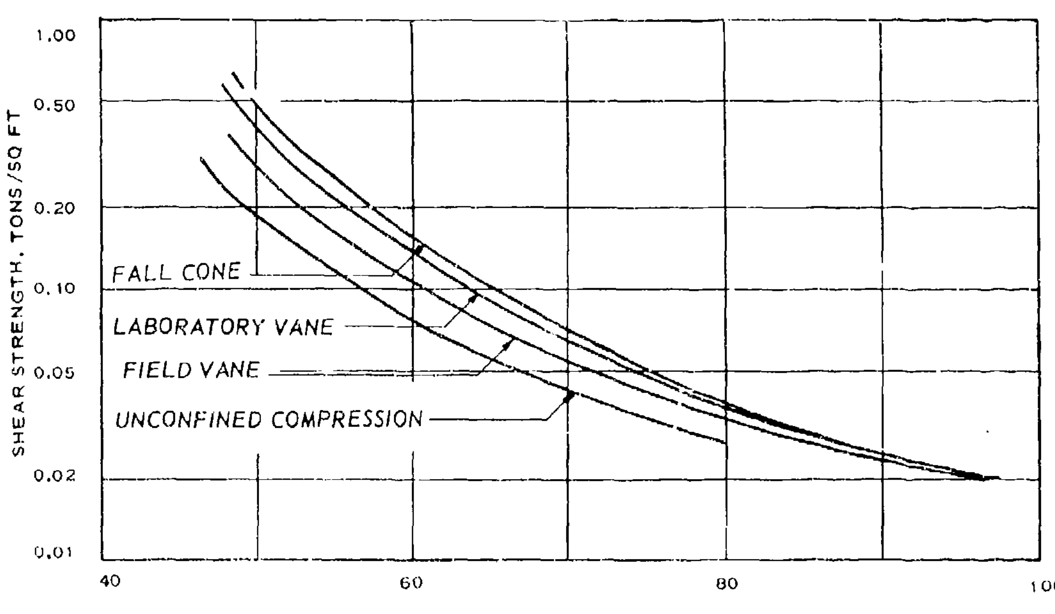


Figure 12. Shear strength versus water content for dredged material disposal areas near Toledo Harbor (from Krizek and Salem[15])

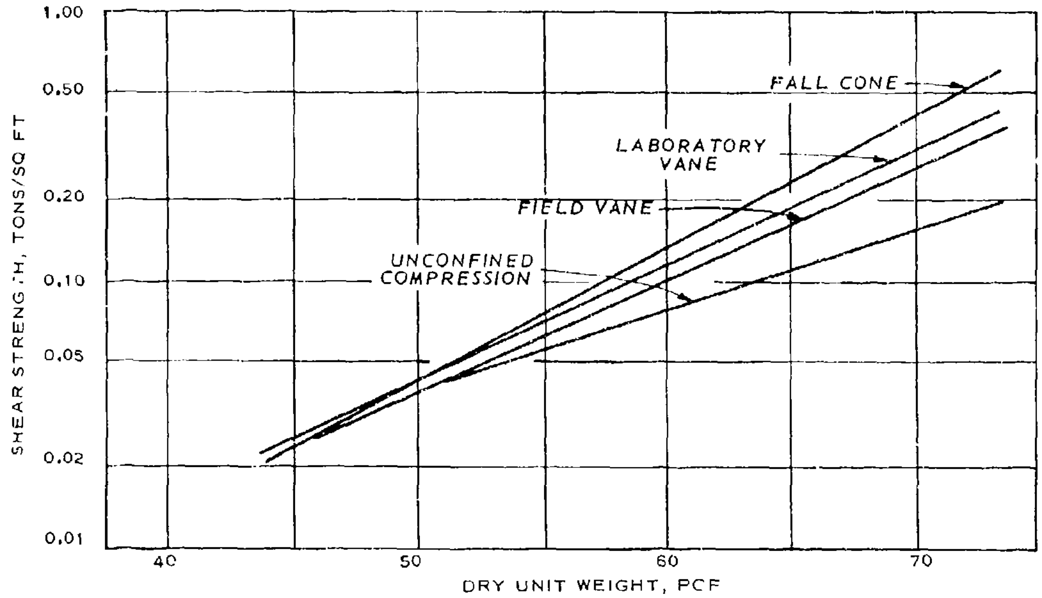


Figure 13. Shear strength versus dry unit weight for dredged material disposal areas near Toledo Harbor (from Krizek and Salem[15])

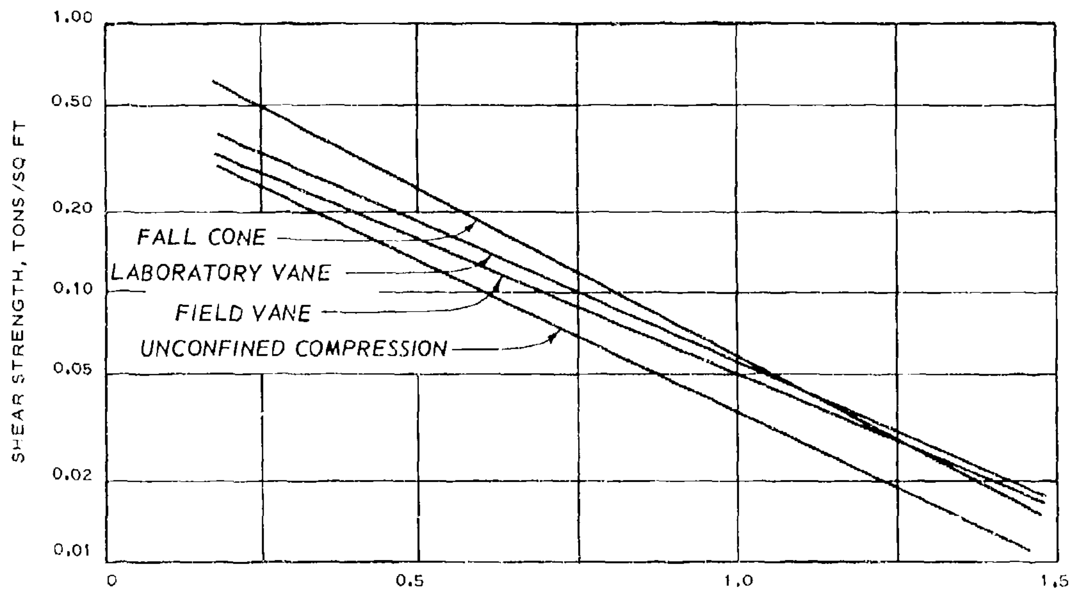


Figure 14. Shear strength versus LI for dredged material disposal areas near Toledo Harbor (from Krizek and Salem[15])

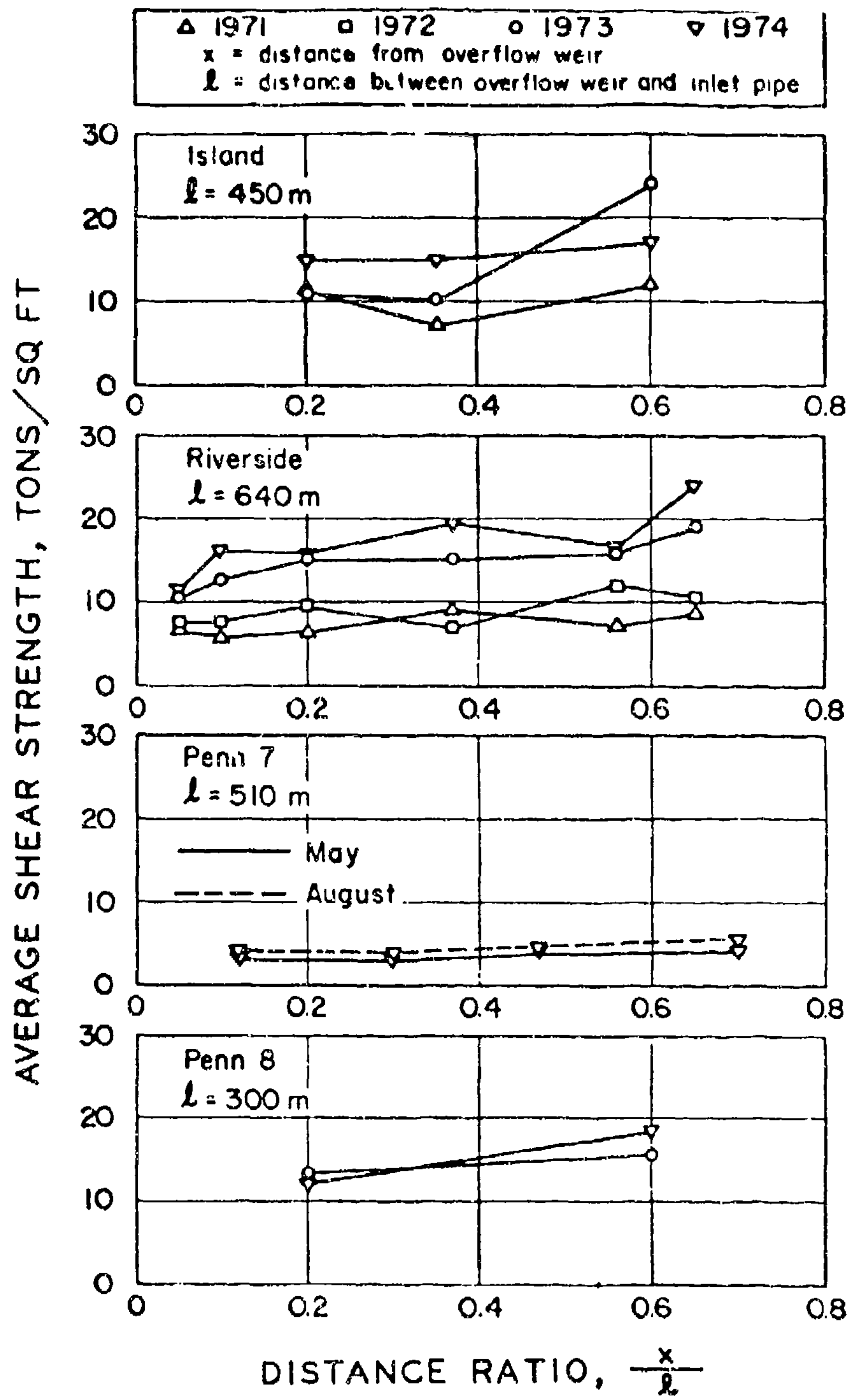


Figure 15. Average field vane shear strength versus distance from overflow weir for dredged material disposal areas near Toledo Harbor (from Krizek and Salem[15])

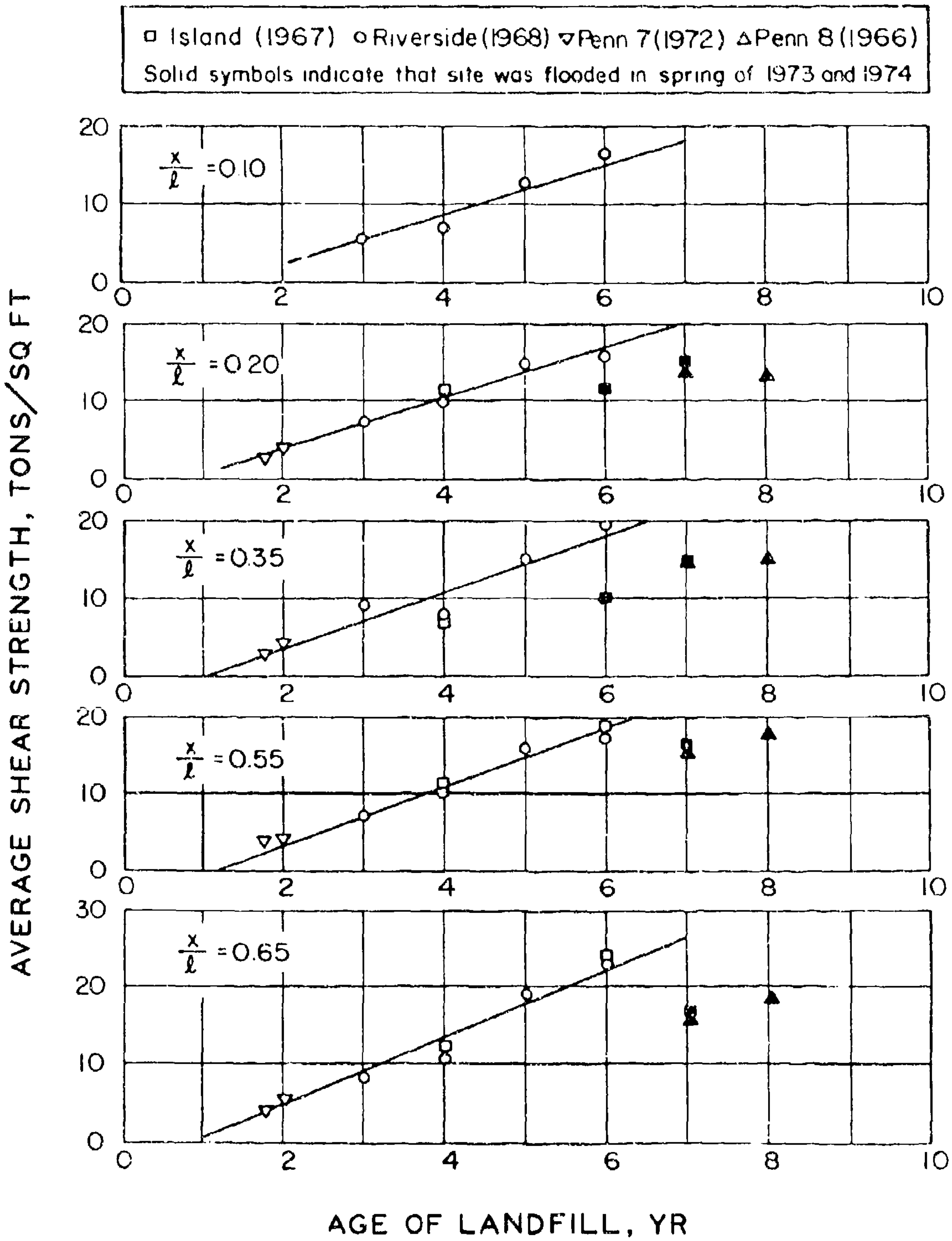


Figure 16. Average field vane shear strength versus age of landfill for dredged material disposal areas near Toledo Harbor (from Krizek and Salem[15])

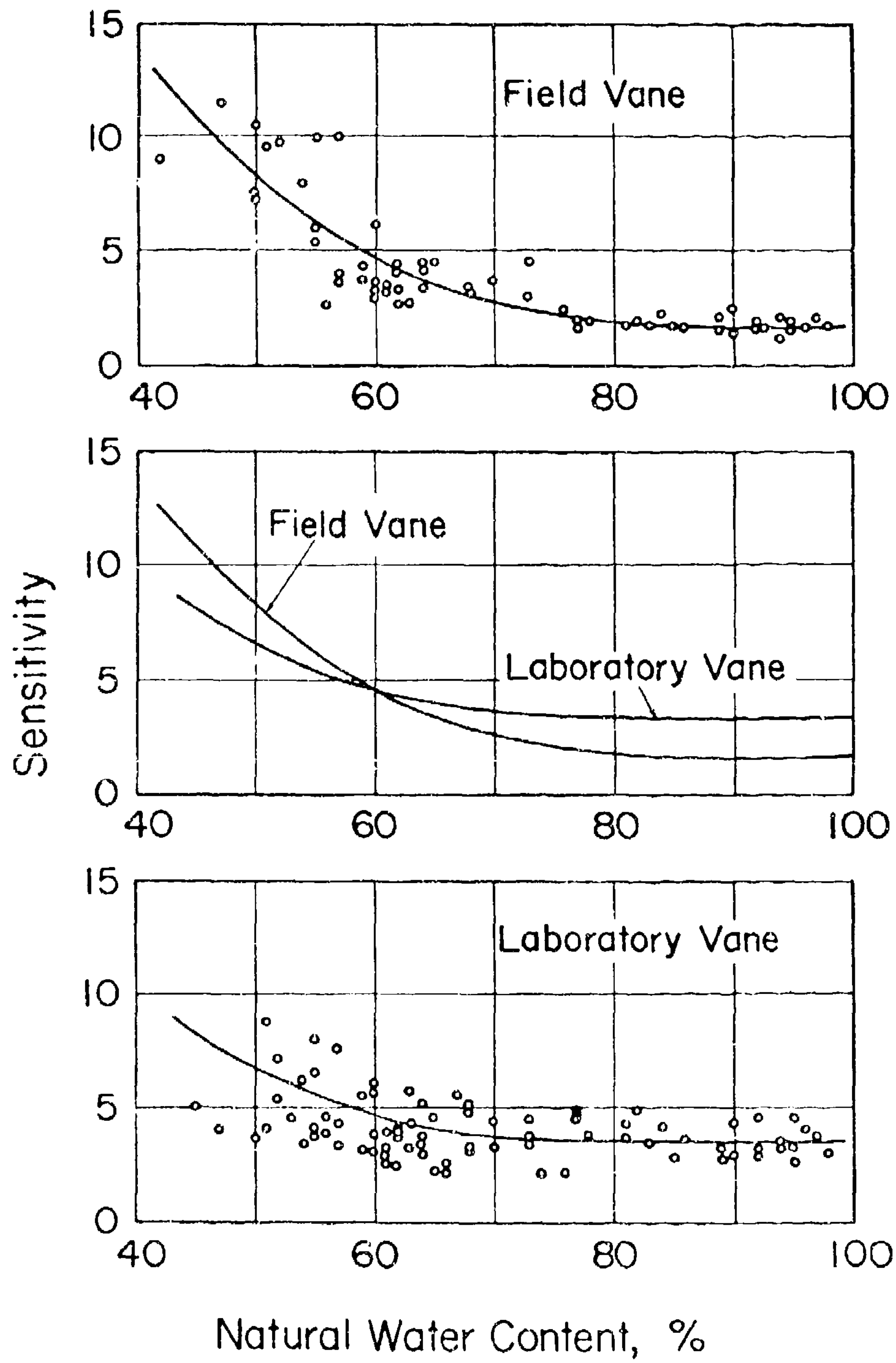


Figure 17. Sensitivity versus water content for dredged material disposal areas near Toledo Harbor (from Krizek and Salem[15])

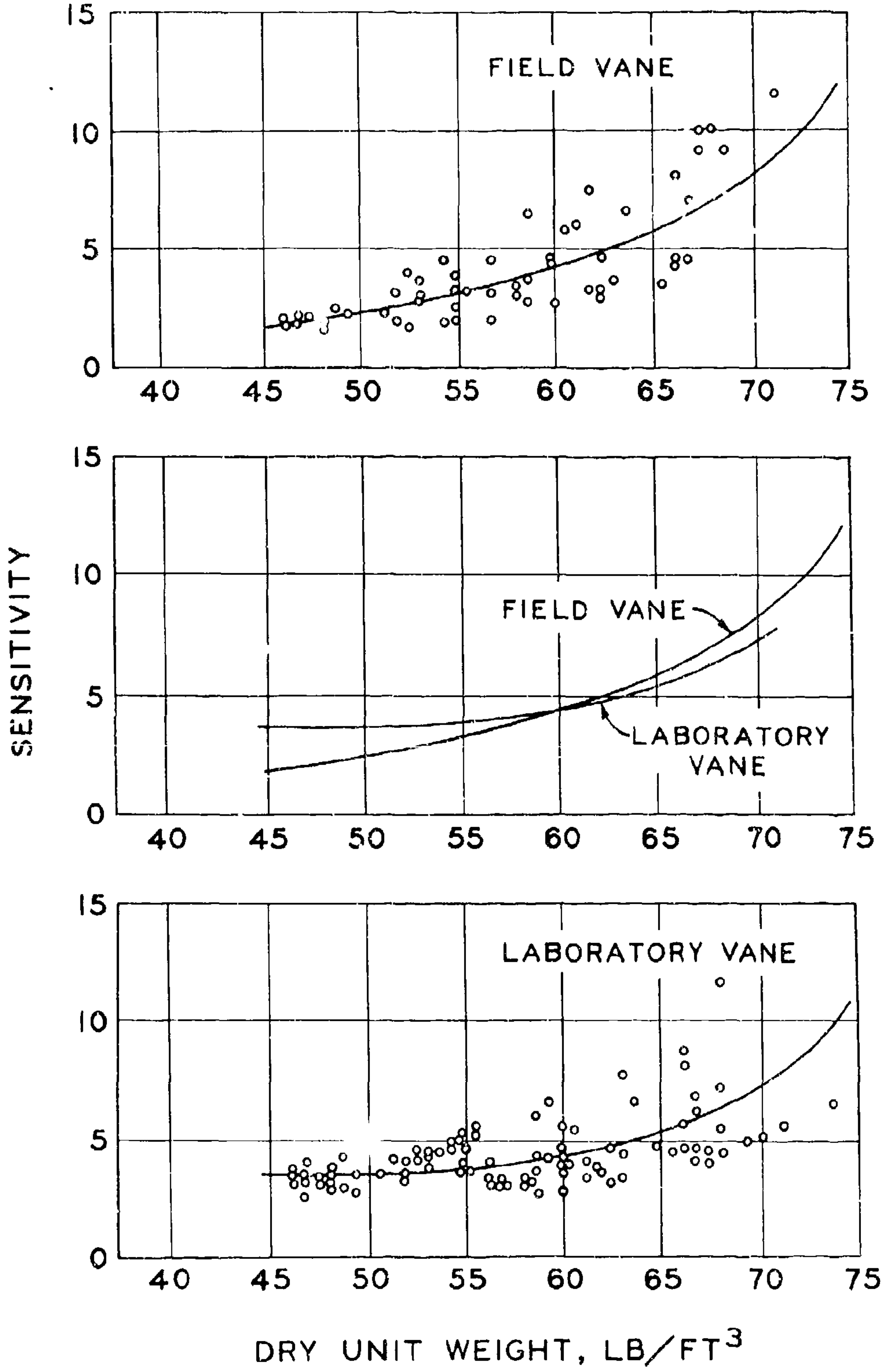


Figure 18. Sensitivity versus dry unit weight for dredged material disposal areas near Toledo Harbor (from Krizek and Salem[15])

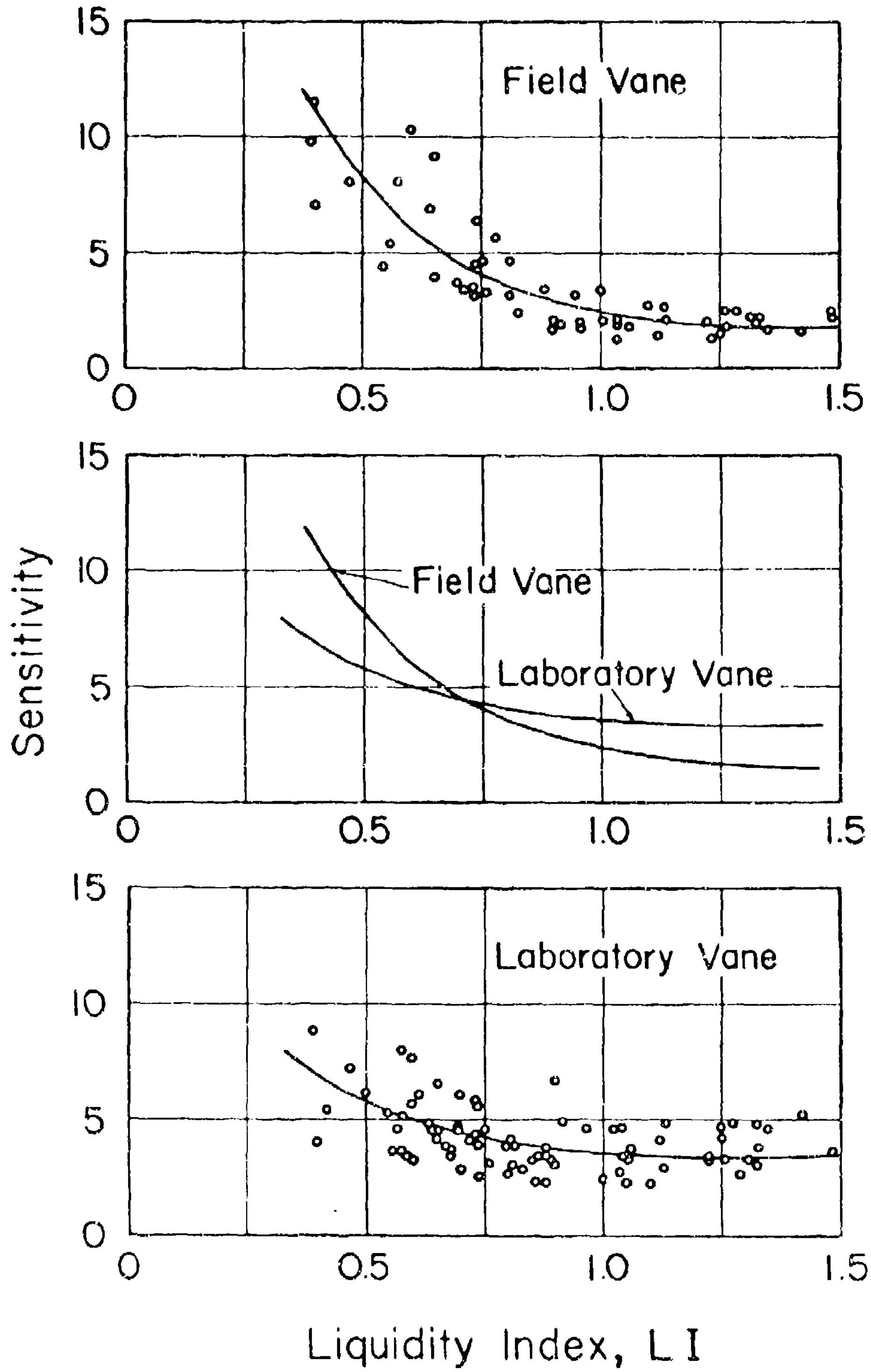


Figure 19. Sensitivity versus LI for dredged material disposal areas near Toledo Harbor (from Krizek and Salem[17])

to determine the engineering properties of dredged material in confined disposal areas in Buffalo Harbor. Table 4 lists these properties for Diked Disposal Area No. 1. Atterberg limits are plotted in Figure 2 and fall close to and slightly below the A-line. This disposal area was completed in November 1967 and used through 1971. Undisturbed sample borings were made in October 1971. The depth of the dredged material when sampled ranged from 11.6 to 14.5 ft and the age ranged from 1 to 4 yr. The water contents averaged 1.04 times the LL and 13 of the 15 test values were between 0.84 and 1.11 times the LL.

Engineering properties -
Cleveland Harbor

38. The Buffalo District, CE, made an investigation at Cleveland Harbor[28] that was similar to that made at Buffalo Harbor. Table 5 gives engineering properties in Diked Disposal Area No. 1. The Atterberg limits are plotted in Figure 2 and fall close to the A-line. Water contents averaged 1.10 times the LL and ranged between 0.93 and 1.37 times the LL. This disposal area was completed in December 1967. Placement of dredged material into the disposal area started in the spring of 1968 and continued through the fall of 1969 with undisturbed sample borings being made in September 1971. The depth of dredged material when sampled ranged from 23.5 to 25.3 ft.

Engineering properties -
Mobile Harbor (Upper Polecat Bay)

39. The engineering properties of Upper Polecat Bay disposal area near Mobile Harbor are given in Table 6. Dredged material was placed in this disposal area in 1971 and 1973. The dredged material was sampled and tested in 1975. Between the surface and a depth of 6 ft, the water content was about 1.4 times the LL, while from 6 to 10 ft, the water content was about equal to the LL. The Atterberg limits fall close to and above the A-line (see Figure 2). Additional laboratory tests are in progress at the U. S. Army Engineer Waterways Experiment Station (WES) to determine the gradation, vane shear strength, and consolidation characteristics from undisturbed soil samples from this disposal area.

Engineering properties -
New Orleans, La.

40. The New Orleans District, CE, investigated dredged material from the Mississippi River Gulf Outlet after it had been placed in a disposal area in 1960 and 1964. Information on limits and water contents is given in Table 7.* Atterberg limits are plotted in Figure 2 and fall well above the A-line, higher than for all other areas, but below the U-line. The water contents ranged between 0.6 and 1.0 times the LL.

Summary and Discussion of Properties of Dredged Material in Confined Disposal Areas

41. The water content of dredged material in disposal areas at the time of densification treatment is of paramount importance in evaluating the efficacy of densification alternatives. If dredged material is placed in a disposal area and remains underwater, it will, for a short time, be in a condition generally similar to that existing in sedimentation tests. The water content in the upper foot might be 4 or 5 times the LL, while below this depth, the water content might be 2 or 3 times the LL. The material would be so weak that densification by surcharge loading would be impossible because the shear resistance would be too small for the dredged material to support any loading.

42. Conditions in dredged material disposal sites are, however, considerably different than in laboratory sedimentation tests. While the laboratory tests are useful, they relate to actual disposal sites only for a short time period following placement of dredged material. With time, surface and base drainage effects some lowering of the groundwater level; a surface crust forms from desiccation; secondary compression effects develop; and consolidation occurs as the effective weight of soil above the lowered groundwater level increases from its submerged weight to its saturated weight, which may be up to 5 to 10

* Personal communication, 1975, Crum Cannon, New Orleans District, New Orleans, La.

times greater than the slurry. After a year or two, the disposal area has reached a more stable condition and densification can be initiated. Great care should be taken because the materials beneath the crust are still extremely weak.

43. Since conventional densification treatments are practicable only after some drainage has occurred and a crust has developed, the water contents at this stage are those relevant to densification analyses. The benefits of densification treatments must be related to volume changes caused by the treatments; any volume and water content decreases that occur before the start of densification treatment should not be credited to the treatment. Water contents relevant to densification analyses cannot be obtained from sedimentation tests but can be obtained from tests on samples recovered from borings made in disposal areas. This is why much attention has been focused on conditions found in actual disposal areas at times when densification treatment might be initiated.

44. To some extent, the condition of recent channel fillings that must be removed during maintenance dredging approximates the condition of dredged material placed in disposal areas. Consequently, and because of the paucity of data from disposal sites, information concerning material to be dredged is also relevant to densification analyses. Nevertheless, differences between natural material in situ and when dredged and placed in disposal areas may be substantial. As reviewed, materials in disposal areas undergo water content decreases and densification that do not occur in situ in natural river bottom deposits. Hence, sediment should be in a more adverse condition than material in disposal areas.

45. Information previously presented on dredged material in disposal sites and on typical materials that are dredged is summarized in Table 8. Values for the LI and water content-liquid limit ratios are listed in Table 9. It appears that, with few exceptions, water contents in disposal areas are less than 1.5 times the LL and it is possible that in freshwater areas the water content is about equal to the LL. The average value for all disposal sites is about 1.0. LI values are generally similar (Table 9). Water content-liquid limit ratios and LI

ratios are significantly higher for in situ materials typical of locations where dredging is required. For reasons given, these are believed too high to use in densification analyses. Liquid limits of dredged material are generally less than 200 (Table 8), with most values between 50 and 100. For practical purposes, the Atterberg limits can be assumed to plot on the A-line (Figure 2). Typical specific gravities are about 2.60 to 2.65. Many sites contain organic matter, as discussed for individual sites.

Comparison of Dredged Material with Soils Stabilized by Conventional Techniques

46. Stabilization of soft soils is a frequent necessity in soil mechanics and foundation engineering, and a large amount of experience is available on the performance of various stabilization techniques. The most frequently used stabilization technique is surcharge loading with or without vertical drains to accelerate the rate of consolidation. This type of work is reviewed in detail in References 29-34. The relevancy of such work to dredged material is discussed in Bishop and Vaughan.[2] References 29 and 30 contain extensive references to stabilization case histories.

47. Engineering properties of some typical soils stabilized by precompression techniques are listed in Table 10. According to this table, much experience exists in stabilizing soft, highly compressible soils with water contents in the range of 0.9 to 1.4 times the LL. Since this is about the same water content range as most dredged material (Table 9), conventional engineering experience appears applicable to densification of dredged material. Shear strengths and compressibilities have not been discussed, but similar findings apply.

48. While the above comparisons and conclusions are believed valid for reasons cited, more direct justification is available for considering conventional stabilization techniques for densification of dredged material. Dredged material was stabilized for the Philadelphia International Airport[35] that had water contents close to the LL, and work done by the NYPA is especially relevant because of the innovative

techniques that were used for construction.

49. The NYPA had an area at Port Newark, N. J., the so-called Navy Area, into which dredged material (glacial till) was placed hydraulically in 1972 to an average depth of 20 ft. The plasticity index (PI) ranged between 6 and 24. After placement, the dredged material was too soft (water content was equal to or slightly greater than the LL, which ranged from about 29 to 43) to support a man, but after about 5 months a crust formed over part o the area. Sand fill was placed (causing local soil displacements), vertical sand drains of the displacement type were installed (1974), and the area is now (October 1975) under surcharge loading. The sand fill was placed hydraulically using end discharge and a deflector, but any future filling work would probably be done under water to obtain more uniform distribution of the sand fill. This case illustrates that conventional stabilization techniques can be used but require special construction expedients.*

50. The conclusion that densification of dredged material placed in disposal areas can be analyzed using presently available knowledge and experience is not intended to suggest that special problems and shortages of data and knowledge do not exist when analyzing densification for dredged material in disposal areas. These limitations will be discussed subsequently.

---

* Donald York, personal communications to S. J. Johnson, 21 October 1975, also communication to R. W. Cunny during visit to NYPA, 16 June 1975.

PART III: DESCRIPTION OF CONVENTIONAL DENSIFICATION TECHNIQUES

Densification Methodologies

51. Dewatering-densification methodologies can be broadly classified as physical, mechanical, chemical, or thermal. Specific treatments may utilize certain features of various methodologies. These methodologies, together with general techniques under each and their status regarding current state of development for subsoil stabilization, are described in Reference 36 and listed in Table 11. A general literature review of conventional subsoil stabilization practices is given in Appendix B. Chemical methodologies are discussed in Part IV. Thermal techniques are in a research stage and are not reviewed, being beyond the scope of this report. Electro-osmosis is an old but seldom used technique and is also beyond the scope of this report and will not be discussed; however, it is being considered for dredged material volume reduction.[36]

Physical Methods for Densification

52. Physical methods group themselves broadly into loading, drainage, and desiccation techniques. These treatment methods are listed and described in Table 12 and are identified in Table 13 according to benefits achieved.

53. The physical methods are used in soil mechanics and foundation engineering to reduce postconstruction settlements and increase shear strengths and bearing capacities of soft soils. When used for these purposes, the objective is to improve the properties of soft soils so a site can be developed for construction purposes. In some cases, the subsoils treated are extremely soft and approach the properties of dredged material after several years in a disposal area. Construction purposes for which stabilized soft soil areas are used include construction of embankments and foundations for buildings, tanks, etc.[29,30]

Loading techniques

54. Various loading techniques, listed in Table 12, are illustrated in Figure 20.[29,30] As generally used in conjunction with loading techniques, vertical drains to accelerate consolidation serve only to decrease the time required for densification. Vertical drains dissipate excess pore water pressures developed by loading techniques.

55. Surface ponding of water with a membrane on the surface of the material to be densified (Figure 20) was used by the NYPA. A sand blanket and collector pipe system are required beneath the membrane for this technique. Surface ponding without a membrane could densify soft soils if downward flow could be induced by drainage beneath or in the soft materials, i.e., seepage pressure consolidation. This method will be examined in Part V in detail since it is not described in available technical literature.

56. Surface loading by atmospheric pressure was ı oposed by Kjellman in 1952 (Reference 37 and Figure 20). For su .arging large areas, vacuum pumps and collector pipes in the sand blanket beneath the membrane would be required to avoid excessive head losses and facilitate removal of water forced into the sand blanket.

Drainage techniques

57. Various treatment methods to secure dewatering and densification by improving drainage are listed in Table 12 and are shown schematically in Figure 21. Drainage techniques can increase the settlement of dredged material, thereby increasing the storage capacity of the disposal area. Drainage can also accelerate the rate of consolidation, i.e., stabilization, of dredged material. The various types of vertical drains that have been used or proposed for dewatering soft soils function in the same manner as conventional vertical sand drains. Figure 22 shows two types of paper drains developed by the Swedish Geotechnical Institute. One such drain was reported by Kjellman[38] and was later adopted for use in Japan. The Kjellman type of vertical drain was called a cardboard wick, but this term is a misnomer in the sense that a wick implies capillary action, whereas Kjellman's drain did not function as a capillary device. Kjellman's cardboard drains (wicks)

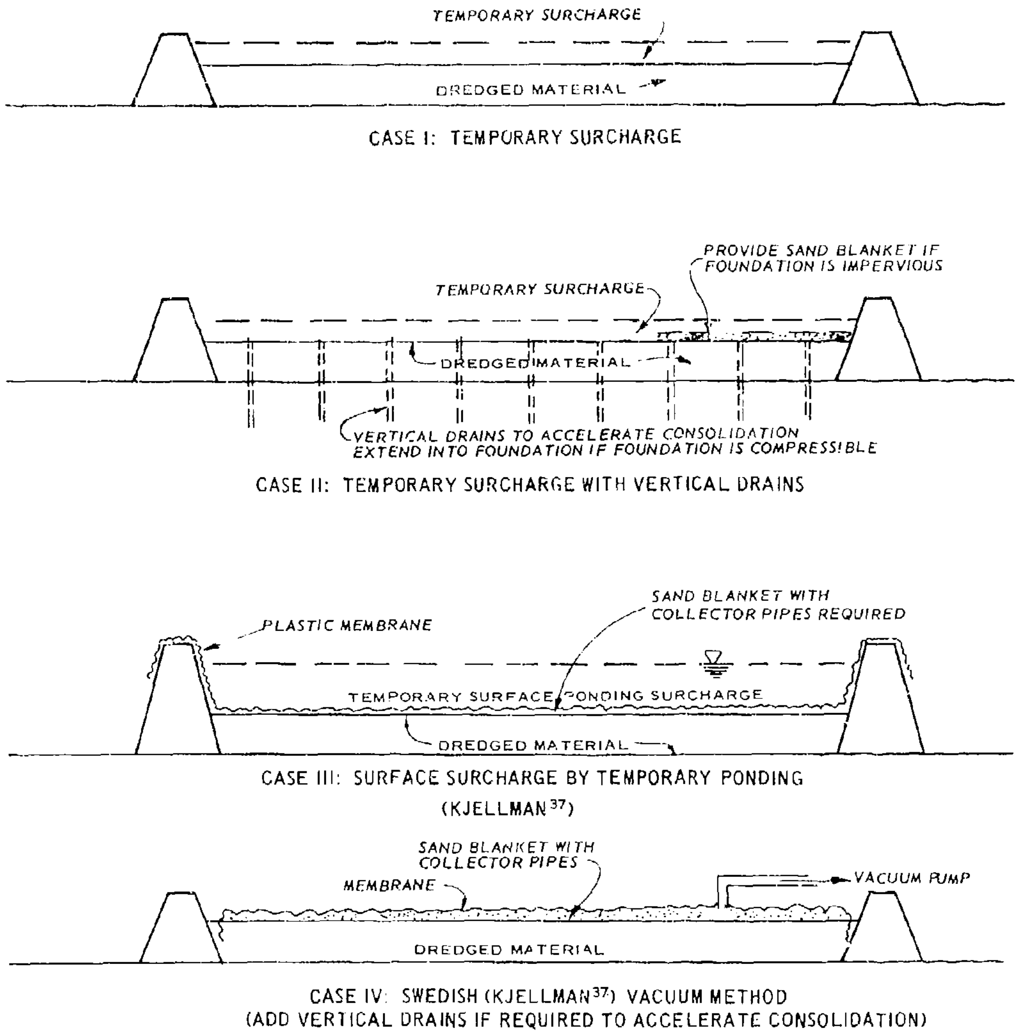


Figure 20. Loading techniques used to increase densification

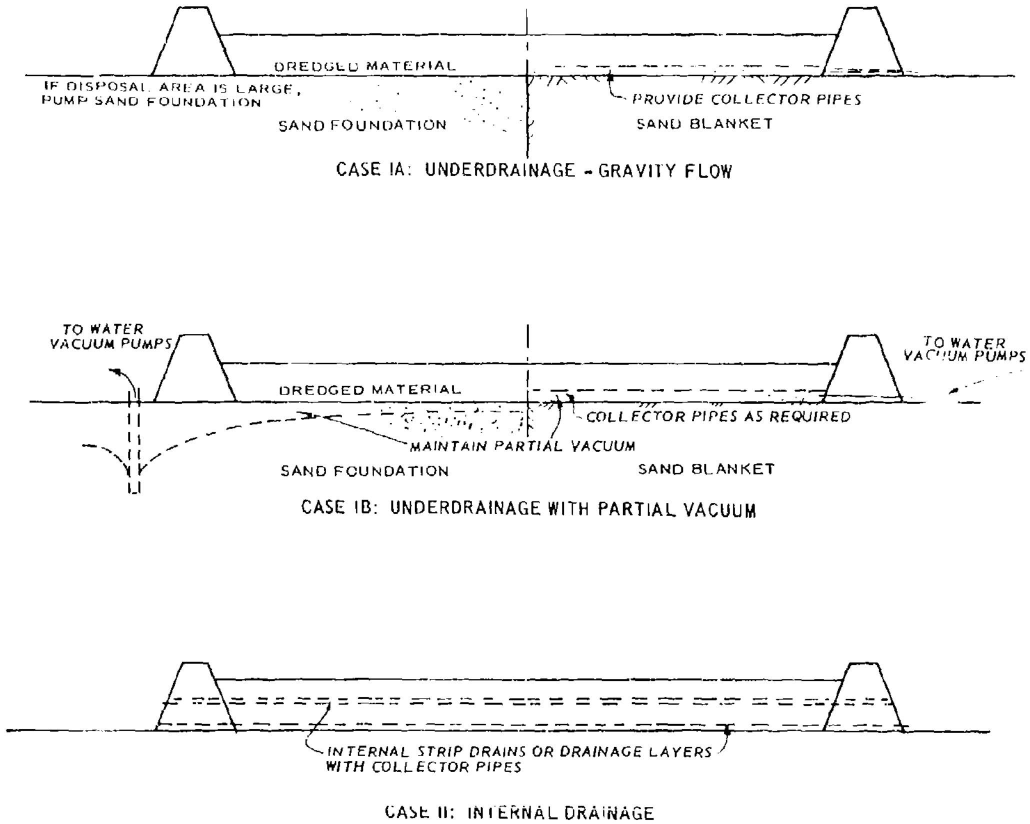


Figure 21. Drainage techniques used to increase densification

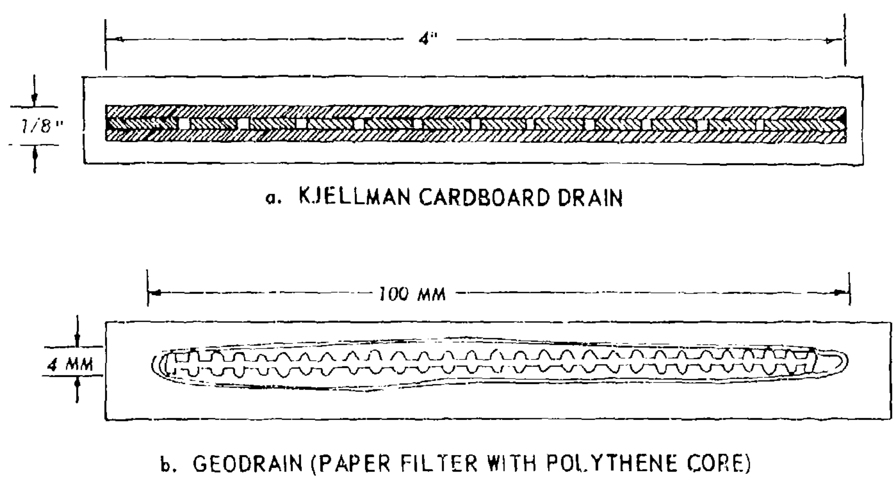


Figure 22. Paper drains developed by the Swedish Geotechnical Institute

consist of a cardboard sleeve having small open channels that conduct water under pressure vertically to a drainage layer. The cardboard serves as its own filter.

58. A drain generally similar in concept to Kjellman's cardboard wick was recently developed at the Swedish Geotechnical Institute and is called a Geodrain (Figure 22b). This device utilizes an inner piece of plastic with grooves that conduct water and is surrounded by an outer heavy paper that serves as a filter. Geodrains are not capillary devices. They appear to be potentially useful in lieu of vertical sand drains or as horizontal drains.

59. Underdrainage by lowering the groundwater level has been used to effect consolidation of soft soils. The effect is increased if a partial vacuum is maintained in the underlying material in which the groundwater level is lowered (Figure 21 and Reference 35).

Desiccation by vegetation

60. Desiccation techniques are attractive and imply relatively low-cost treatment methods. These treatment techniques (Table 12) are generally applicable to disposal areas to varying degrees.

61. The use of vegetation to secure dewatering-densification by the water demand of root systems is attractive on the basis of engineering experience. It is known that some types of vegetation in swamp and marsh areas reduce the soil moisture content and increase the preconsolidation stress. In some areas where normally consolidated soils were expected, subsoils were found to be preconsolidated by as much as 500 psf. This is a major benefit and a systematic investigation of desiccation by vegetation is obviously of substantial importance to engineering studies of disposal area densification. The effects of vegetation are being investigated separately in the DMRP, WES.

Desiccation by capillary wicks

62. Capillary wicks (Table 12) have never been used for stabilizing soft soils and must be regarded as completely experimental. They were only recently proposed by Dr. James Spotts,* and are currently

* Personal communication, Dr. James Spotts, civil engineer, Soils and Pavements Laboratory, WES, April 1975.

being evaluated for possible use in stabilizing dredged material. The concept is attractive, but its potential cannot be assessed until necessary research has been performed. It will not be discussed herein.

Mechanical Methods for Densification

63. Mechanical methods for densifying dredged material include surface drainage, surface trenching, and reworking to accelerate desiccation. These techniques involve, therefore, drainage and desiccation concepts and could also be listed under other methodologies. Less information is readily available on mechanical methods and are, therefore, reviewed in some detail.

Laboratory tests on effects of mixing

64. Greeley and Hansen (reported by Krizek et al.[8]) conducted laboratory evaporation tests on dredgings from the Calumet River in Chicago, Ill. The program consisted of drying dredgings, which were placed at depths of 2, 4, 8, and 12 in., with and without mixing at a temperature of 74°F and relative humidity of 58 percent. The 2-in. samples were mixed at 1-hr intervals, 4- and 8-in. samples three times a day, and there was no mixing of the 12-in. samples. As shown in Figure 23, nearly linear relationships were obtained for the reduction in water content with time. The rate of drying increased with mixing but was influenced more by a decrease in thickness of dredged material.

65. A laboratory study at WES is under way to quantify the rates of water loss so that field operations with regard to agitation frequencies and duration can be optimized for various types of dredged material slurry. Another laboratory study is being conducted to determine the benefit of agitation on reduction in moisture content under controlled foundation conditions. It is evident that controlled tests are necessary to separate mixing benefits from those caused by normal surface desiccation and downward drainage.

66. The mechanism of mixing effects is not clearly understood. Traditionally, tilling, or breaking up the surface of a cultivated agricultural area, is done partially to interrupt capillary channels and

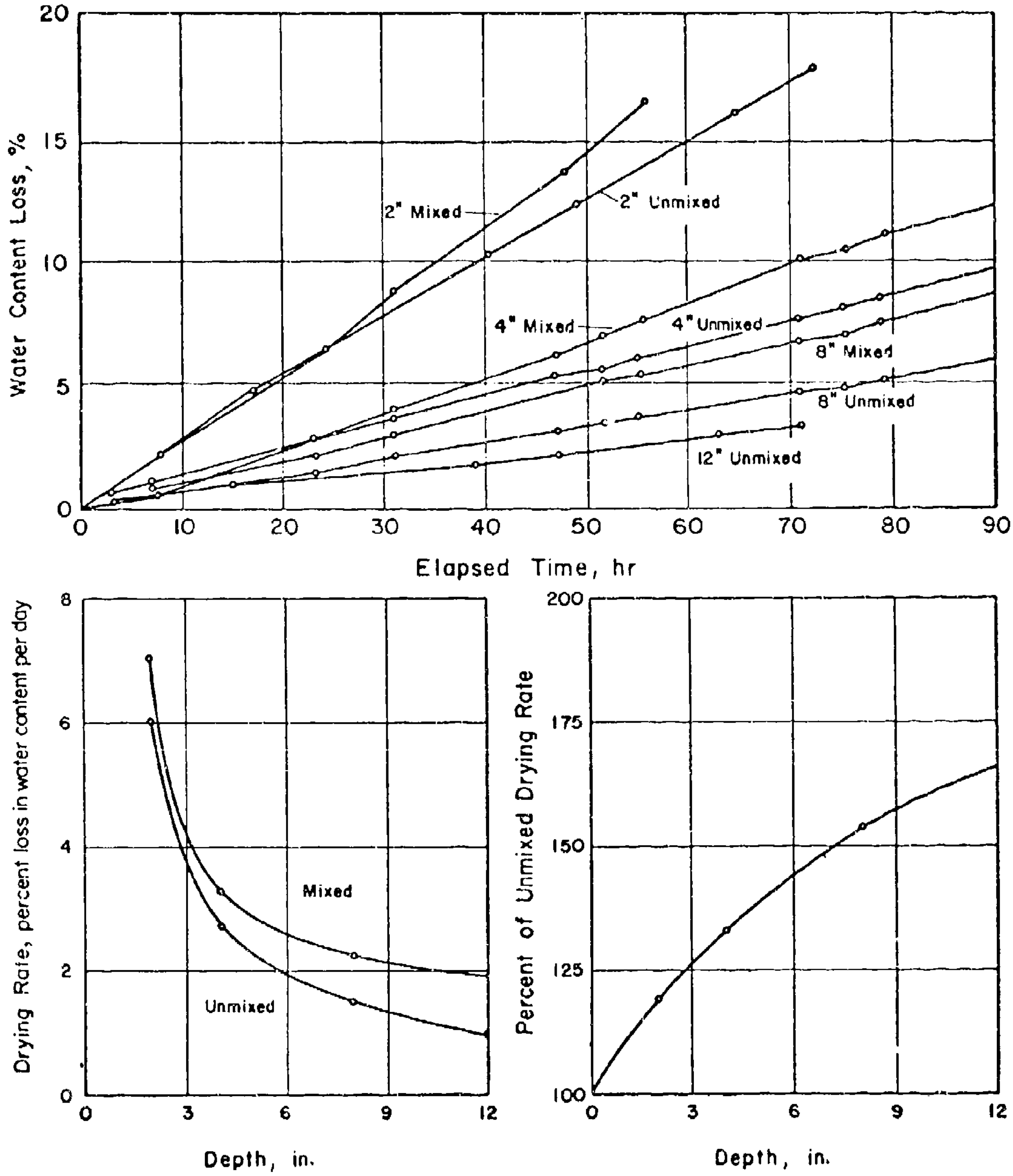


Figure 23. Greeley and Hansen laboratory study of evaporation tests of dredged material from Calumet River, Chicago (from Krizek, Karadi, and Hummel[8])

reduce surface evaporation. From this viewpoint surface agitation and mixing would appear to be of limited or questionable benefit. The tests under way should clarify this aspect.

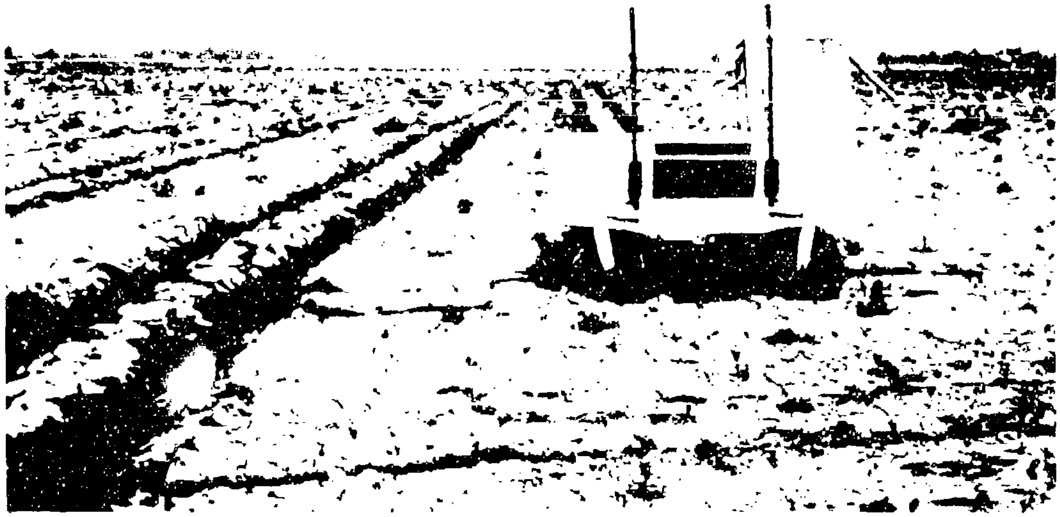
Dutch method

67. The Dutch have developed a method to increase the speed of "ripening" (biological and chemical process by which dredged material is converted to earth containing animal and plant life) of dredged material from Rotterdam Harbor.[2,39-41] The dredged material is pumped into confined disposal areas which are surrounded and subdivided into compartments by dikes. Following sedimentation and decanting of the free water, the dredged material is about 1 m thick.

68. About 2 months after filling, a vehicle known as the Amphirol is brought into the area, leaving ditches about 10 cm deep. Figure 24 shows the Amphirol and the Riverine Utility Craft (RUC), a similar type vehicle used at Upper Polecat Bay disposal area near Mobile Harbor. The Amphirol is supported by two cylinders that provide near buoyancy. The vehicle is propelled by rotating the cylinders, which have a spiral cutting edge to cut small furrows in the wall of the ditches, which initiates cracking and ripening of the soil.

69. Two months later the ditches are deepened by the Amphirol pulling a pair of small disk wheels (2.5 m in diameter) through the original ditches. Before the third stage, again 2 months later, a good growth of swamp weeds has developed. A large disk wheel (3.4 m in diameter) is pulled by tractors located on the dikes. A pattern of ditches about 0.5 m deep and 10 m apart results. When the first layer of dredged material has sufficiently ripened, the process is repeated until the final height is reached. Underdrains have been used in some cases to promote consolidation. The thickness of the dredged material layer after ripening will decrease to 60 to 80 percent of the freshly deposited layer. A seven-layer deposit, with 1-yr consolidation and ripening time for each layer, will yield a 4-m final thickness in about 10 yr. Grass is sown in desiccation cracks in each lift to dewater and form a vegetative mat.

a. Riverine utility craft (RUC)



b. Amphirol

Figure 24. Screw mobile vehicles used in dredged material disposal areas

PART IV: CHEMICAL DENSIFICATION TECHNIQUES

Phosphate and Aluminum Industry Techniques

Survey conducted

70. As part of the effort for evaluating potential methods for dewatering and densification of dredged material, contacts were made with the phosphate and aluminum industries to determine what chemical treatments are being used to dewater their waste slimes and to evaluate the potential application of these procedures to dredged material. Visits were made to the U. S. Bureau of Mines, Tuscaloosa Metallurgy Research Laboratory, Tuscaloosa, Ala.; Florida Phosphatic Clays Research Project, Lakeland, Fla.; Andco, Inc., Buffalo, N. Y.; and Kaiser Aluminum and Chemical Corp., Gramercy, La.

Phosphatic clay slimes

71. Phosphorus in America is obtained from phosphate rock ore called matrix, which contains approximately equal parts of phosphate minerals, sand, and clay. Over 100 million tons of ore is mined annually in central Florida. The ore is mined with large draglines, slurried, and pumped to washer plants where it is washed, sized, and subjected to various benefication methods to produce phosphate rock used principally for production of fertilizer.[42]

72. Phosphatic clay slurry produced by the washing process is a waste product called slime. The slimes must be disposed of, but they cannot be deposited into nearby streams because of the pollution problem and instead are stored in ponds for reasons of economy. The average solids concentration of slimes discharged from a plant usually ranges from 2 to 6 percent by weight. The suspension is pumped into extensive settling ponds constructed in the mined-out areas. However, because the volume of stored slimes exceeds the volume of mined-out matrices, the dams used for impounding the slimes extend above the ground to heights up to 40 or 50 ft. The industry reuses supernatant water released from the suspension as settling progresses, but the combination of very slow settling and large volumes of slurry requires very large settling ponds.

73. The mineralogical and engineering properties of the slimes are summarized in Reference 42. The slimes are primarily a suspension of clay particles in water. The particles are of colloidal size (0.001 mm and smaller), and tend to form a gel and remain in suspension. Settling is slow because of the resistance of the gel to compression and the upward flow of entrapped water. A plot of solids content versus depth for six Florida settling ponds ranging in age from 1 to 60 yr is shown in Figure 25. The solids content for slimes less than 10 yr old and more

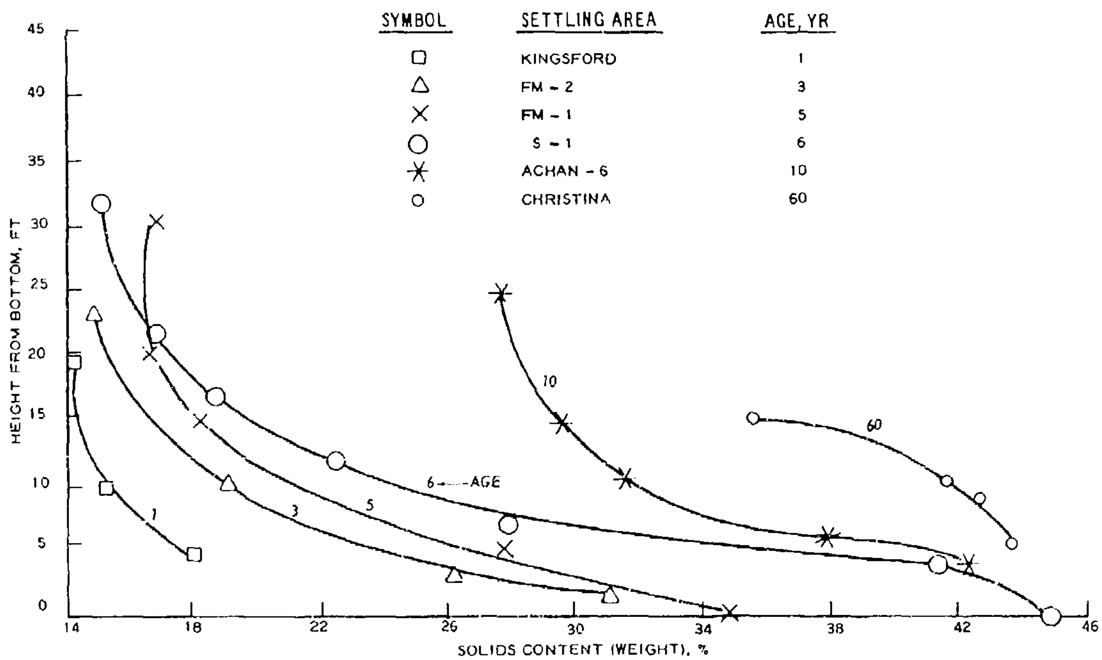


Figure 25. Solids content of phosphatic slimes from six Florida impoundment areas[43]

than 10 ft above the bottom generally ranged from 14 to 24 percent (this is equivalent to water contents of 610 to 320 percent). The higher solids near the bottom are attributed to drainage of water from the slimes into pervious underlying material.

Potential volume decrease

74. The phosphate industry is highly motivated to find rapid and economical methods for dewatering slime not only because of public pressure to eliminate the potential environmental hazard of dike failures

and slime spills but also because the slimes retain a significant amount of water that must be replaced for continued plant operations. An estimate of the potential volume change that might be brought about by dewatering can be obtained by inspection of Figure 26, which shows the relationship between percent volume decrease and change in percent solids. As an example, if slimes at an initial solids content of 20 percent by weight could be dewatered to 35 percent solids, a volume decrease of almost 50 percent would result. This volume decrease is significant to the phosphate industry. As has been shown in Figure 25,

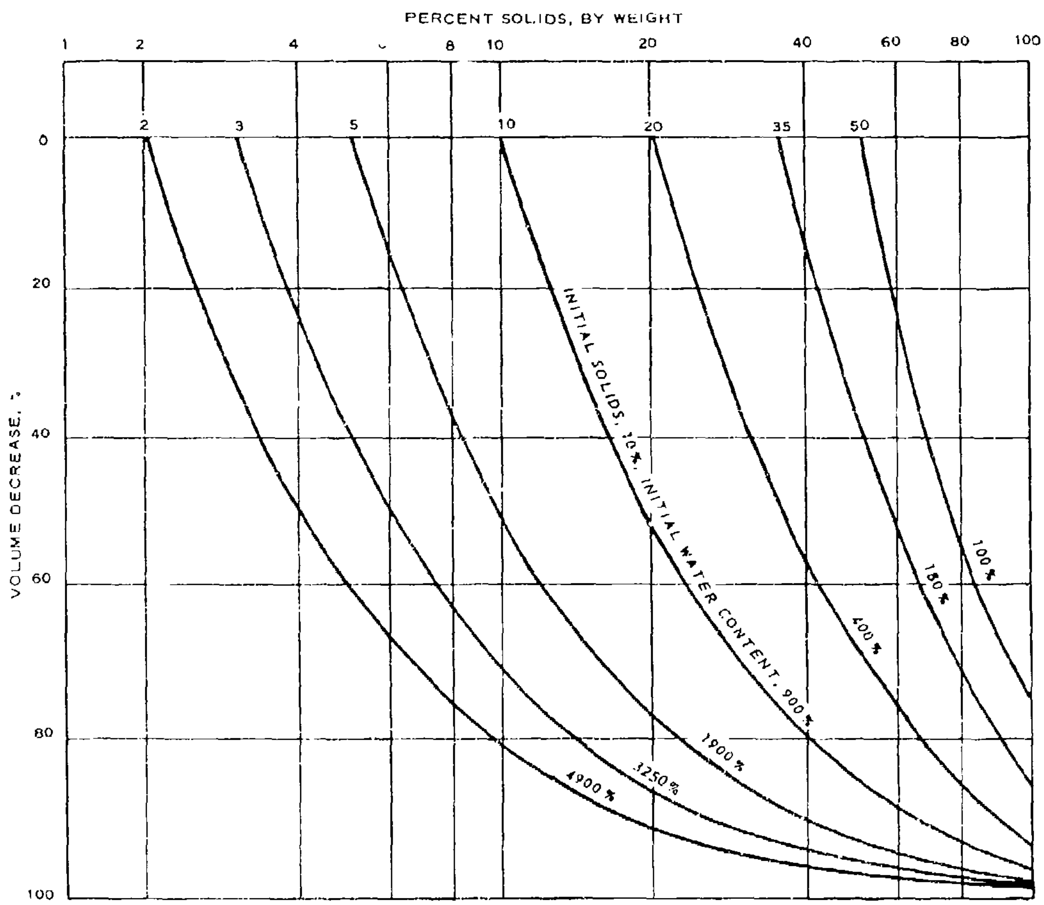


Figure 26. Volume decrease potential as a function of percent solids

slimes less than 10 yr old are generally in a condition of about 20 percent solids. If the slime solids could be increased to 35 percent, all slimes and sand tailings could be placed back into the pits from which the phosphate ore had been mined. Elevated settling ponds would not be required and the potential of dike failure and slime spills would be eliminated.

Phosphate slimes research
by Tennessee Valley Authority

75. The phosphate industry has been studying ways to dewater slimes more rapidly for many years. In the late 1940's and early 1950's, the Tennessee Valley Authority (TVA) conducted an extensive study of a wide variety of methods that might be used to dewater slimes.[44] These methods included filtration, centrifugation, drying, electrophoresis, flocculation, ultrasonic irradiation, freezing, weighing, and stirring. Their studies found that although it is technically feasible to dewater the slime suspension to 50 percent solids by several different methods, the expense of applying any of the processes is significantly greater than that of storing the material in ponds. However, they also noted that thickening of the suspension by sedimentation is expedited by the use of minimum amounts of water and dispersing and flocculating agents in the hydraulic classification operation. They also noted that dewatering of the suspension by filtration would be facilitated by lining storage basins with a properly constructed filter bed, and that provisions for drainage of surface water from ponds that had been filled would permit drying of the mud by evaporation and by transpiration from ensuing plant growth.

76. As part of their investigation of chemical agents, the TVA studied the effect of (a) amount of reagent, (b) type of flocculant, (c) type of dispersant, and (d) depth of suspension. For these tests a standard slurry of 5 percent solids by weight was used. Sodium hydroxide was the standard dispersant, calcium sulfate the standard flocculant, and both were used for evaluating other reagents. These tests indicated an optimum amount of dispersant and flocculant above which slower and decreased sedimentation occurs. Generally, 0.5 to 3 lb of dispersant

and 3 to 7 lb of flocculant per ton of solids was used for these experiments. For the slurry tested, calcium sulfate was the most effective flocculant for the first 7 hr, but sulfuric acid and calcium chloride each were more effective after 24 hr. Suspensions that were dispersed with sodium hydroxide and sodium silicate and later reflocculated with calcium sulfate settled more rapidly than those dispersed with ammonium hydroxide or sodium oxalate.

77. None of the 32 different dispersants, 34 different flocculants, and 40 modifiers produced marked improvement in settling. The depth of suspension appeared to have no effect on the settling for short-period tests in the laboratory; however, the tendency of different suspensions to form incompressible gels at different times subsequent to agitation makes it difficult to evaluate the effect of depth. In all of these laboratory tests it is important to note that the best flocculants produced a sediment with about 25 percent solids after a period of 17 to 24 months.

Florida Phosphatic Clays Research Project

78. More recently, the Florida Phosphatic Clays Research Project[43,45,46] initiated a study for the finding of the most economical flocculants for use with clay slurries found in Polk County, Fla. Flocculants that produce strong aggregations (large flocs, rapid dewatering) to as much as 35 percent solids or more are desired and chemical plus operating costs for treatment of the slurries hopefully will not exceed $1.00 per ton of solids. The investigation is still going on but conclusions based on testing conducted to date indicate that the most significant variable influencing flocculant effectiveness is the mineralogy of the clay. Slime lacking in attapulgite could be flocculated at levels of 0.3 to 0.4 lb per ton of solids with the best flocculants, but about 3 lb of some flocculants were required for a sample with a relatively large amount of attapulgite. Different flocculants work best for different slimes (i.e., no one flocculant gives the lowest dosage level for all slimes tested). However, of more than 100 products tested,

about 10 appear consistently to give the best results.* Many of the flocculants cost about $1.05 to $1.15 per pound. If the required dosage is 0.5 lb per ton of solids, the cost for the flocculant is about $0.50 per ton of solids for the treated material. Since other costs for treating the material are about $0.50 per ton of solids, it appears that the phosphate industry will successfully reach its objective of finding a satisfactory treatment process that costs no more than about $1.00 per ton of solids.

79. In the past 10 yr or so there have been no really new flocculants produced. Advancements made have been primarily in modification of existing flocculants to improve settlement times and reduce cost. Many of the better flocculants are polyacrylamides that have different molecular weights and ionic conditions. Based on experience with phosphatic slimes, it appears that different types of dredged material will flocculate best with different flocculants. However, it is believed that it would not be too difficult to determine what flocculant from a group of approximately 100 would be best for a particular material, and it was estimated that this could be done for about $200 per sample.

80. Studies of the Florida Phosphatic Clays Research Project also involve determination of the most practical and effective means for introducing flocculants into the slurry. Techniques which are currently being studied include the addition of flocculants to the slurry with and without prior mixing with sand tailings. Based on field experiments, it has been determined that the flocculant should be added about 25 to 50 ft from the end of the discharge pipe. At lesser distances insufficient mixing occurred and at greater distances degradation of the polymer-type flocculant appeared to occur. When flocculant was added without sand tailings the average solids content of the flocculated slimes at the end of 5 months was about 25 to 27 percent by weight. This was significantly better than the nonflocculated slimes, which averaged about 15 percent by weight. When flocculant was added with

* Personal communication, Fred E. Woodward, Surface Chemists of Florida, to R. W. Cunny, 1 April 1975.

sand tailings, the solids content of the slimes 1 week after deposition ranged from 20 to 40 percent with an average of 27 percent; the rapid dewatering of these slimes was aided by the sand tailings, which separated from the flocculated clay and provided some sort of drainage system for the clay.

81. Based on tests currently being conducted, it appears that flocculants will be found useful to the phosphate industry in that they will make possible the rapid dewatering of the slimes to a solids content of 35 percent by weight or more. This will satisfy the requirements of the phosphate industry since, at this solids content, all the slimes and sand tailings will fit back into the mine pits. However, it is to be noted that 35 percent solids is equivalent to a water content of 186 percent, and this is more water than considered acceptable for dewatered dredged material.

<u>Bauxite residue treatment</u>

82. Bauxite residue, also called red mud or slurry, is a waste product resulting from the production of alumina. At the Kaiser Aluminum and Chemical Plant in Gramercy, La., alumina is made from Jamaican bauxite, and residue is produced more or less continuously at the rate of approximately 1400 gallons per minute (gpm) with a solids content ranging from 15 to 20 percent by weight. In the past this waste has been discharged into the Mississippi River, but in 1971 an agreement was made to discontinue this practice and since November 1974, the residue has been impounded in a storage pond.[47]

83. A substantial portion of residue has a particle size in the range of 1 μ, and the slurry is highly caustic. To permit the recovery of soda values from the slurry, starch is added, thereby flocculating the solids to an average size of about 10 μ. The resultant slurry at 15 to 20 percent solids by weight still has poor settling characteristics and without additional processing would settle and consolidate to a solids content of only 28 to 30 percent (equivalent to a water content of 260 to 230 percent).

84. To obtain increased consolidation of the residue and minimize land area required for storage, the following additional processes were

studied: (a) a mechnical filtration/filter cake distribution; (b) decantation and evaporation of water (DEW process); and (c) drainage, decantation, and evaporation of water (DREW process). Pilot filtration experiments were conducted with a 4- by 3-ft rotary drum filter, and it was found that the solids contents could be increased to about 40 percent by weight. The 40 percent mud was pumped at a rate of 8 gpm to an impoundment area where, within 2 months, it further dewatered to 70 percent solids, its estimated shrinkage limit. Pilot tests of decantation and evaporation in a 100- to 200-acre pond indicated that, with rainfall that occurs in south Louisiana, only a maximum of 37 percent solids could be expected.

85. The third method, called the DREW process, involved the addition of a sand bed to the bottom of the storage pond. Two DREW processes, shallow and deep, were studied. The shallow DREW process involved repetitive distribution of an average 4-in. layer of slurry over the sand bed. Pilot tests for this process indicated that a 4-in. layer of slurry at 15 to 20 percent solids by weight would be dewatered to the shrinkage limit in about 15 days on the average, depending on rainfall and time of year. Based on these results, it was estimated that a minimum of 600 acres of sand beds would be required to handle the bauxite residue from the Gramercy plant.

86. The deep DREW process involves the continuous distribution of slurry from a feed point infrequently rotated around or within a sand bed impoundment area to ultimate depths of 18 ft or greater. Pilot tests for this process indicated that 50 percent solids by weight can be obtained in about 10 months. During feeding, 65 percent of the liquid extracted was removed by decantation and evaporation, and 35 percent was removed via the bottom sand bed. After feeding stopped, surface cracks developed. Rainfall was removed primarily by decantation although some rain penetrated through the mud into the drains. If rainwater was not removed by subsurface drainage, it was believed that dewatering past 37 percent solids would not be possible. However, it was also believed that evaporation was necessary for the bed to reach an ultimate solids

content of 50 percent, and after the tenth month it became the principal dewatering mechanism.

87. Of the several alternative methods studied, the deep DREW process was selected for dewatering the bauxite residue. The basis for this selection was: (a) stable land with 50 percent solids by weight or greater could be obtained; (b) minimum land area required; (c) lowest capital and operating costs; and (d) storage area apparently can be converted to usable land or raw material sources after pond is filled. Cost for construction, operation, and maintenance of the storage pond has been estimated to be about $1.00 to $1.20 per ton of solids.

Discussion

88. Experience in and status of the use of flocculants by the phosphate industry in Florida and the Kaiser Gramercy plant have been described in the preceding sections. Both used flocculants to increase the rate of sedimentation of slurries composed of clay-size particles. The Kaiser group at Gramercy has found that their bauxite residue can be flocculated and dewatered to a condition of 28 to 30 percent solids by weight by the use of starch alone and that by the addition of underdrains and surface evaporation an average condition of 50 percent solids can be obtained at a cost of approximately $1.00 per ton of solids. The phosphate industry investigators are currently searching for the least costly flocculants and are developing techniques for efficiently introducing the flocculants into the phosphate slimes to increase the solids content from about 5 to 35 percent in a period of weeks or months rather than years, and at a total cost of about $1.00 per ton of solids. Similar experience might be anticipated with dredged material. However, solids contents of either 50 or 35 percent are equivalent to water contents of 100 or 186 percent and these are still relatively high; this appears to be the lowest water contents that should be expected if dredged material was treated only with flocculants.

89. Caution must be taken when dealing with flocculants. As a result of laboratory experience, it has long been recognized that flocculants greatly accelerate the settlement of soil suspensions and this is of interest to the dredged material disposal business. However,

laboratory experience has also shown that, while flocculants accelerate initial settlement, after a period of time untreated material will settle to void ratio less than that for the treated material. This is illustrated by a test reported by Bishop and Vaughan[2] and shown in Figure 27. This figure shows that in the laboratory a 400-mm high,

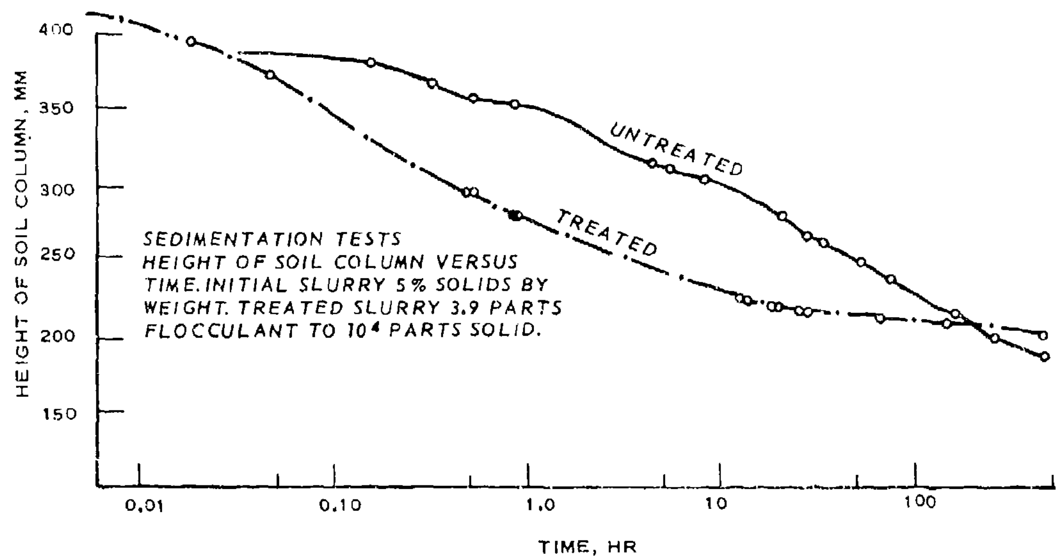


Figure 27. Comparative laboratory sedimentation tests on Thames black mud untreated and treated with polyacrylamide

5 percent solids by weight, suspension of Thames black mud treated with polyacrylamide initially settled much faster than the untreated mud. Settlement of the treated mud was virtually complete after 1 day, but the untreated mud continued to settle. After 8 days the untreated mud had settled more than the treated mud.

90. It is not known whether the above test reported by Bishop and Vaughan should be considered typical of dredged material treated with flocculants. At least one aspect of the Bishop and Vaughan test appears to be nontypical and that is that after 3 weeks the solids content of the treated mud had increased only from 5 to 10 percent by weight. In a test conducted by Andco, Inc., flocculant was added to a slurry of Mobile Bay mud and in a matter of moments the solids content had increased from about 21 to about 35 percent. Also field tests

conducted on attapulgite phosphatic slimes in Florida indicated that after 26 days and at depths of 2 to 8 ft the solids content of treated slimes averaged 14.8 percent whereas the solids content of untreated slime averaged 10.2 percent. It is also possible that the salt content of the liquid phase of the dredged material could have a significant effect on the efficiency of the particular flocculant being used. This factor should be carefully considered in the evaluation of different flocculants. However, in Florida the laboratory phenomenon is generally not duplicated in the field and it is thought that this is because gravity forces are very important. At depths greater than those obtained in laboratory flasks, it is believed that effective stresses caused by the weight of the overlying material are sufficient to overcome the interparticle shear strength of flocculated material and then, because of other characteristics, the flocculated material is compressed to a degree greater than that possible for the untreated material (at least during the time frame of interest).

Conclusions from review
of industrial practice

91. Based on the experience of the phosphate and aluminum industries, it appears that flocculants could be used to expedite the initial sedimentation of clay-size dredged material that would otherwise settle only very slowly. Solids contents of 25 to 30 percent by weight for treated dredgings up to 18 ft thick can be anticipated in less than 1 yr. With the addition of underdrains, surface drainage, and evaporation, a solids content of about 50 percent is a reasonable expectation.

92. Cost for effective flocculant appears to be approximately $0.50 per ton of solids treated. For claylike materials with a natural water content of 100 to 300 percent, cost for the flocculant will range from $0.30 to $0.15 per cu yd of measured material in the disposal area. Other costs associated with the flocculant treatment might be $0.15 to $0.10 per cu yd with the total costs ranging from $0.25 to $0.45 per cu yd of material treated. If the volume decrease resulting from using flocculants was 63 percent, the cost of the flocculants would be about

$0.21 per cu yd of additional storage volume obtained. These benefits would not be realized if the solids drop out of suspension without undue delay.

Other Chemical Treatments

Types of treatment

93. In addition to various uses of flocculants to accelerate sedimentation, other chemical treatments have been used to stabilize soils. It is appropriate, therefore, to consider the potential application of these techniques for dewatering and reducing the volume of high-water-content dredged material. The most common treatment of this type is the application of quicklime which reacts with water to produce a material with a lowered water content. Another chemical of this type is calcium carbide, which the University of California at Berkeley has suggested might be added to dredged or other material to produce a desirable construction material and at the same time produce acetylene gas which could possibly be recovered and sold to recoup at least part of the treatment cost. A patent application for these and other uses has been prepared. Chemical grouting has been used to stabilize soils but is not considered applicable for reducing the volume of dredged material placed in disposal areas. Chemical grouting could be used to increase shear strengths but the high cost eliminates its consideration even for this purpose.

94. Quicklime. When quicklime (CaO) is added to a high-water-content soil, the immediate reaction is for the quicklime to combine with the water (H_2O) to produce calcium hydroxide ($Ca(OH)_2$) and heat. Over a longer time period the calcium hydroxide (slaked lime) reacts with some minerals in the soil to produce a soil with improved drainage and strength characteristics. However, from the point of view of dewatering and densification, interest centers on the immediate reaction as it relates to volume change resulting from loss of water due to the formation of calcium hydroxide and heat.

95. The chemical equation for the reaction of quicklime and water is as follows:

$$CaO + H_2O \rightarrow Ca(OH)_2 + \approx 16{,}000 \text{ cal} \qquad (2)$$

The comparable equation with molecular weights is

$$56.07 + 18.02 \rightarrow 74.09 \qquad (3)$$

Thus, for each 56.07 g of quicklime added to a wet soil, 18.02 g of water is consumed and 74.09 g of calcium hydroxide and approximately 16,000 cal of heat are produced. Since the specific gravities of water and calcium hydroxide are 1.0 and 2.08, respectively, the net volume change of such a reaction in the absence of any vaporization of water is an increase of 17.6 cc and not a decrease.

96. To examine the potential for vaporization of water, it will be helpful to run through a sample calculation. Assume that 1 cu yd (0.76 m^3) of dredged material with a water content of 200 percent is to be treated with 430 lb (195 kg) of quicklime. If the specific gravity of solids of the dredged material is 2.50, each cubic yard will contain 702 lb (318 kg) of solids and 1400 lb (635 kg) of water. The 430 lb of quicklime will consume 138 lb (63 kg) (2.2 ft^3) of water and will produce 568 lb (258 kg) (4.4 ft^3) of calcium hydroxide and 5.58×10^7 cal of heat. The specific heat of water is 1.0 cal/g and if it is assumed that the specific heat of solids is 0.2, the temperature will be increased 81°C if 100 percent of the liberated heat is uniformly utilized. If the initial temperature was 19°C, all the water would be at the boiling point, but none would have vaporized; and the net volume change would have been an increase of 8 percent.

97. If an additional 100 lb (45 kg) of quicklime was added to the dredged material, an additional 0.50 ft^3 (0.014 m^3) of volume increase would result from the production of additional calcium hydroxide, but since the heat of vaporization of water is 540 cal/g, the extra heat would vaporize 0.90 ft^3 (0.026 m^3) of water. Thus, the volume of water lost by vaporization is greater than the volume increase from calcium hydroxide. However, it would take an additional 540 lb (245 kg)

of quicklime to reduce the volume to the original. Thus, with the addition of a total of 970 lb (440 kg) of quicklime, there would have been no volume decrease and the material would be more lime than soil; but the water content would have been reduced to about 40 percent. Based on 1975 prices, the cost of the quicklime would have been about $20, and it is quite apparent that, volumewise, nothing would have been gained by this expenditure of effort.

98. Calcium carbide. Calcium carbide (CaC_2) is another chemical agent that reacts with water and thus potentially might be useful for dewatering purposes. When calcium carbide is added to water, acetylene gas (C_2H_2), calcium hydroxide (slaked lime), and heat are produced. The chemical reaction and molecular weight equations are as follows:

$$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2 + \approx 30{,}000 \text{ cal} \tag{4}$$

$$64.07 + 36.04 \rightarrow 26.02 + 74.09 \tag{5}$$

The above equations indicate that for each 64.07 g of calcium carbide added to a wet soil, 36.04 g of water will be consumed, 26.02 g of acetylene gas will be released, 74.09 g of calcium hydroxide will be produced, and approximately 30,000 cal of heat will be liberated. Using the specific gravities of water and calcium hydroxide, the net volume change of such a reaction in the absence of any vaporization of water is a net volume decrease of 0.44 cc.

99. To examine the potential for vaporization of water it again will be helpful to use a sample calculation. Assume that the same 1 cu yd (0.76 m^3) of dredged material as in the previous example is to be treated, but this time 250 lb (113 kg) of calcium carbide is added. The chemical reaction consumes 141 lb (64 kg) (2.2 ft^3) of water, produces 289 lb (131 kg) (2.2 ft^3) of calcium hydroxide, releases 102 lb (46 kg) of acetylene gas to the atmosphere, and liberates 5.31×10^7 cal. Assuming the same specific heats as before, the temperature of the dredged material would be increased by 80°C if 100 percent of the liberated heat is uniformly utilized. If the initial temperature was 20°C, all the water would be at the boiling point, but none would have vaporized;

and the net volume change would have been negligible.

100. If an additional 250 lb (113 kg) of calcium carbide was added to the dredged material, the additional heat would vaporize 216 lb (98 kg) (3.5 ft^3) of water. Thus, with the addition of a total of 500 lb (227 kg) of calcium carbide, the volume would have been decreased 13 percent and the water content reduced from 200 to about 71 percent. Based on 1974 prices, the cost of the calcium carbide would have been about $46, and it is apparent that only a relatively small volume decrease would result from a relatively costly expenditure. It is possible that some of the acetylene gas could be recovered from this operation; and while the value of the acetylene gas produced apparently is somewhat greater than the cost of the calcium carbide, the cost for collection and distribution of the gas and thus the cost benefit from such a recovery operation is not known.

Discussion

101. In the examples described above, it was assumed that 100 percent of the heat liberated by the chemical reactions was utilized to increase the temperature of the dredged material and to vaporize water. In actual practice, this, of course, would not be the case. The actual efficiency of heat utilization would depend on the process used and most likely would not exceed 70 percent, probably being much less. Thus, the volume changes that might be obtained in a full-scale operation would be less than that calculated, and it is apparent that the potential for obtaining significant dewatering and volume reduction by addition of commonly known chemicals to dredged material is minimal.

102. While only quicklime and calcium carbide were considered in the above analyses, it is possible that other more effective chemical compounds may exist. However, no survey of the chemical industry was made for this study, and it is believed unlikely that more effective and less expensive chemical dewatering compounds would be found if such a survey were conducted. Unfortunately, the cost of even inexpensive chemicals is relatively high.

PART V: TECHNICAL ANALYSIS AND COMPARISONS

Methods of Analysis

Basic concepts

103. Because dredged material placed by hydraulic means in disposal areas is essentially saturated, increased disposal area capacity can be achieved only if the water content of the dredged material is decreased. Procedures for computing volume decreases associated with moisture content decreases utilize methods developed in soil mechanics and foundation engineering and are widely used for analyzing effects of conventional stabilization techniques. Computations for amount and rate of volume decrease can be made considering the (a) characteristics and thickness of dredged material; (b) type of densification treatment, if any; and (c) opportunities for natural moisture content decreases from drainage into foundation soils beneath the disposal area.

104. While disposal areas may have relatively firm and incompressible foundation soils, such materials also may be soft and highly compressible since disposal areas are generally located along rivers or harbors. Where foundation soils are thick and highly compressible, the weight of dredged material may cause substantial foundation consolidation and result in increased disposal area storage. In some cases, the increase in storage capacity from the weight of dredged material and effects of densification treatment may largely result from foundation settlement. It is necessary, therefore, when analyzing effects of densification treatment, to evaluate the effect of treatment on the disposal area foundation as well as on the dredged material. While this can be done by methods to be discussed, this report will consider only the effects of densification treatment on dredged material.

Magnitude of volume decrease

105. The volume decrease which can be achieved by densification treatment, i.e., the storage capacity increase, depends on the initial water content of the dredged material after sedimentation has occurred. Sandy soils placed in disposal areas have low moisture contents after

sedimentation, and little storage volume can be obtained by attempting to dewater such soils. This is not true for fine-grained dredged material because it has high water contents and undergoes large volume decreases if the moisture contents can be reduced. It is this type of material that is of primary interest.

106. The nature of fine-grained dredged material can most easily be described by the Atterberg limits and water content. For convenience, Atterberg limits, i.e., the LL and plastic limits (PL), are normally plotted on a plasticity chart, as was done, for example, in Figures 2 and 28. Clayey soils generally plot above the A-line whereas silty

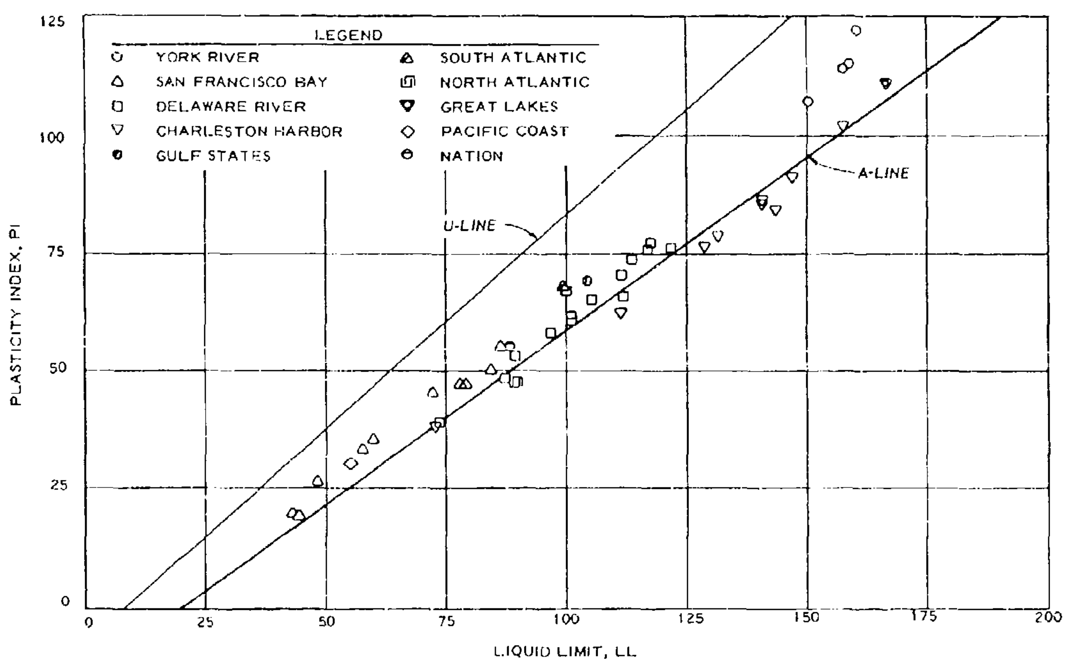


Figure 28. Plasticity plot for material to be dredged

and organic soils plot below the A-line. From Figures 2 and 28 it is evident that materials encountered in most dredging work plot along the A-line. This is convenient because soil property correlations and volume changes are somewhat simpler if only the LL and water content are controlling factors.

107. The equations for volume decrease of a normally consolidated fine-grained soil are:

$$\frac{\Delta V}{V} = \frac{\Delta H}{H} = \frac{\Delta e}{1 + e_o} = \frac{C_c}{1 + e_o} \log \frac{\bar{p}_o + \Delta\bar{p}}{\bar{p}_o} \quad (6)$$

where

ΔV = decrease in volume

V = original volume

ΔH = decrease in dredged material thickness

H = thickness of dredged material

Δe = decrease in void ratio

e_o = initial void ratio

$\bar{p}_o$ = initial effective stress

$\Delta\bar{p}$ = increase in effective stress

The effective stress increase causing volume decrease $\Delta\bar{p}$ can be caused by surcharge, drainage, or by desiccation. The effective stress before application of $\Delta\bar{p}$ is $\bar{p}_o$. The value of $C_c/(1 + e_o)$ is a measure of the compressibility of a soil and can be correlated with LL and w_o. Various correlations have been developed (Reference 29 and Appendix C), and the following conservative values are selected and used in the illustrative computations made subsequently.

LL	$C_c/(1 + e_o)$
50	0.16
75	0.22
100	0.25
150	0.29
200	0.31

The above values assume that the initial void ratio e_o corresponds to a water content equal to the LL and the specific gravity is 2.6.

108. The volume decrease of dredged material can be related to a decrease in water content w as follows:

$$\frac{\Delta V}{V} = \frac{\Delta H}{H} = \frac{\Delta e}{1 + e_o} \quad (7)$$

Since, for saturated materials $e = wG$ and $\Delta e = G\Delta w$

$$\frac{\Delta V}{V} = \frac{\Delta H}{H} = \frac{G\Delta w}{1 + Gw_o} \tag{8}$$

in which e is the void ratio, Δw is the decrease in water content, and G is specific gravity. For reference purposes, the water content of dredged material having an initial moisture content of twice the LL, which might exist shortly after sedimentation in the disposal area, has been plotted versus corresponding volume changes in Figure 29. Moisture contents of natural soils generally fall between the LL and PL. At the LL, soils are soft, have low shear strengths, and can undergo large volume changes if loaded. At the PL, soils are relatively strong and can carry significant loads without undergoing large volume changes. Soft soils stabilized by conventional techniques have LI values generally in the range of 50 to 100 percent. These soils, stabilized by techniques such as surcharging, undergo relatively small decreases in water content.

109. Volume changes associated with moisture content decreases plotted in Figure 29 are summarized in Table 14. It is evident that it becomes increasingly difficult to secure an added increment of volume decrease as the moisture content decreases. For example, it is relatively easy to secure moisture content decreases from initial values of twice the LL down to the LL, since this almost occurs naturally (according to data presented in Part II). Further decreases in moisture content, to LI values of 0.75, 0.50, 0.25, or 0.00, are increasingly more difficult to obtain. The upper portion of Table 14 shows incremental volume decreases expressed in percent of an initial volume corresponding to a water content equal to twice the LL. The lower portion of this table shows similar incremental volume changes for a disposal area in which the water content at the time of possible densification treatment is at the LL.

110. At the present time, the relatively little information available suggests that initial moisture contents of dredged material at the time of densification will range from 1 to 1.5 times the LL. There is some evidence that dredged material extracted from salt water

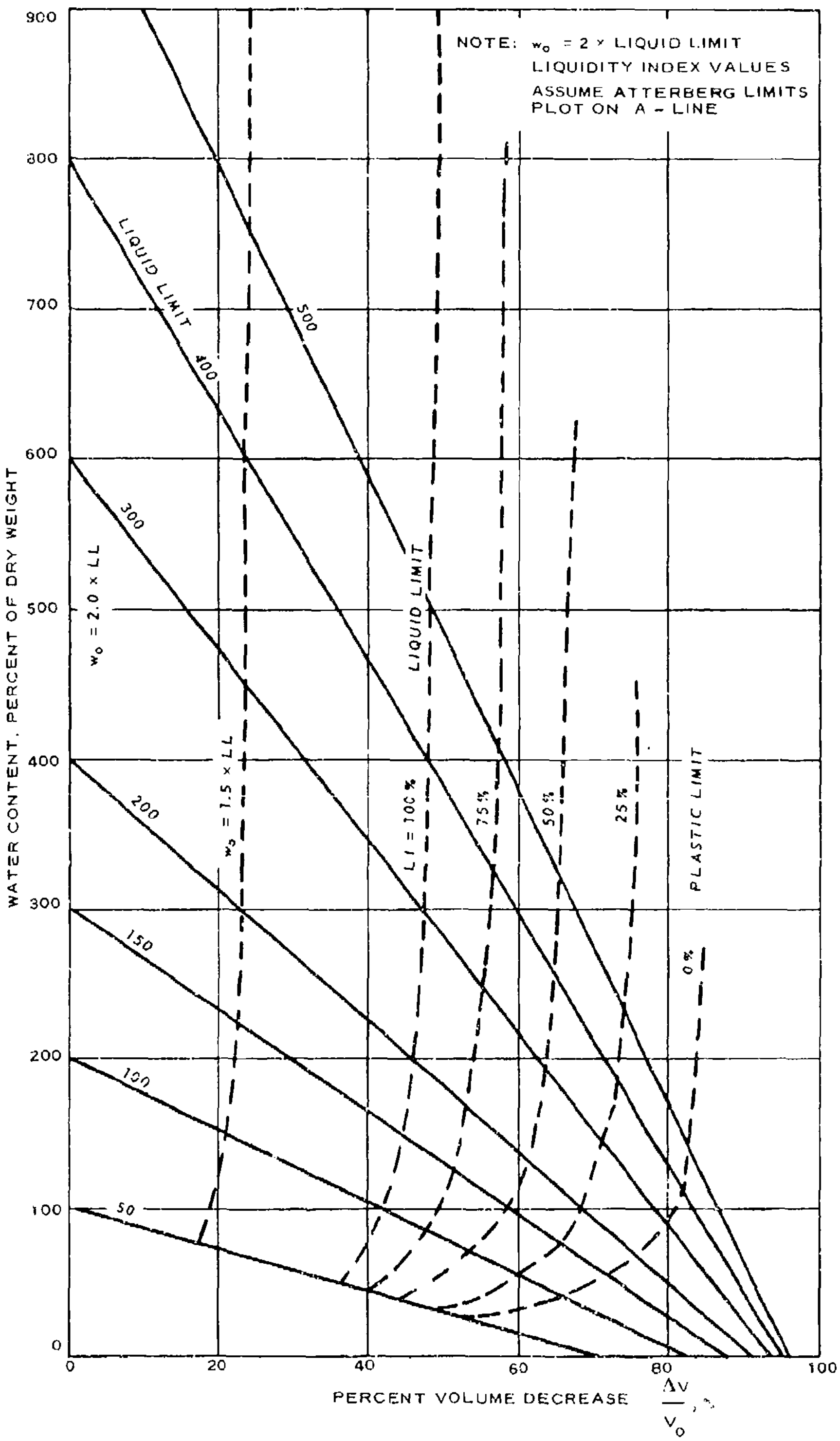


Figure 29. Volume changes with moisture content creases

has higher water contents than dredged material from tidal marsh or freshwater deposits. For conservatism, benefits of densification treatment will be computed assuming initial water contents equal to the LL. This is consistent with the data examined in Part II.

Time required for densification by consolidation

111. Basic concepts. The time required to obtain densification by consolidation can be estimated using Terzaghi's method for one-dimensional consolidation. While there have been many modifications to this approach, it is convenient and sufficiently accurate for estimating the time required and illustrating concepts involved. When a soil is loaded, excess pore water pressures are developed which dissipate with time as pore water is squeezed from the interior of a soil deposit to the exterior or drainage boundaries. The time required to reach a given percent consolidation is dependent on a time factor T_v; the thickness squared H^2 of the soil deposit, where H is the length of one-way drainage path; and the coefficient of consolidation c_v of the soil, which is considered a soil property although it depends also upon effective stress. These factors are related to the time t required to reach a given percent consolidation by the equation:

$$t = \frac{T_v H^2}{c_v} \tag{9}$$

112. The effects of time, thickness of soil deposit, and degree of consolidation achieved are illustrated in Figure 30 for a soil having a c_v of 0.01 sq ft/day. If the soil is underlain by impervious material and water must flow to the surface to escape during consolidation, the thickness H is taken as the total thickness of dredged material. Alternatively, if the dredged material is underlain by free-draining soil so that water can be squeezed from the dredged material to the surface and also to underlying material, the thickness H is one-half the total thickness of dredged material. The curves shown in Figure 30 illustrate that the thickness of disposal material has a great effect on the time required to achieve consolidation. Values for

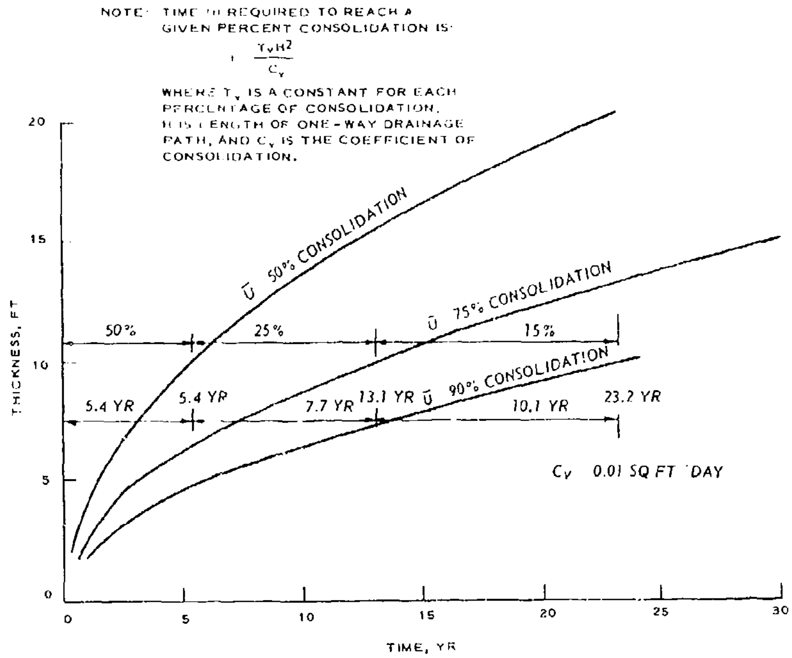


Figure 30. Effect of thickness on consolidation of dredged material

a 10-ft-thick layer are summarized in Table 15. While the first 50 percent consolidation may be achieved fairly rapidly (Table 15 and Figure 30), succeeding increments of consolidation require substantially more time.

113. Figure 30 illustrates that thin layers consolidate rapidly even for the low value of coefficient of consolidation used for this example, which is, incidently, that for a high LL dredged material. This figure illustrates that if the one-way drainage path is 5 ft or less, or the two-way drainage path is 10 ft or less, the rate of consolidation may be so rapid that treatment methods are unnecessary to accelerate consolidation.

114. Radial flow to vertical drains. The general concepts illustrated in Figure 30 also apply to radial flow of vertical drains. A theory for such flow was fully developed by Barron and is reviewed in Reference 30. Consolidation by radial flow depends on the length of flow path in the same manner as illustrated for vertical flow. The

time factors have different values for vertical and radial flow and values for these cases can be obtained from numerous references.[30] The coefficient of consolidation for radial flow can be determined from laboratory tests and from field permeability tests, but precautions must be observed in using the results of field tests.[30]

115. Combined vertical and radial flow. The theory for combined vertical flow to drainage layers and radial flow to vertical drains was also developed by Barron and is reviewed in Reference 30. It is evident that if the length of radial drainage path is long, vertical flow will dominate even if vertical drains are installed. Drains cannot be spaced more than the thickness of soil being treated.

Means to accelerate densification

116. Since the time required to achieve a given percent consolidation depends on the square of the length of drainage path for either vertical or radial flow, an effective means for accelerating the rate of densification is to decrease the length of flow path. This can be done by placing intermediate drainage layers within the dredged material or by adding vertical drains. Because of the large size of disposal areas, drainage layers must be provided with collector pipes surrounded by suitable filter materials. Also, vertical drains must discharge into drainage layers which in turn must have collector pipes. An exception to this occurs where vertical drains discharge into underlying pumped drainage layers. Vertical drains accelerate the rate of consolidation but do nothing to promote an increased degree of densification or additional storage area capacity. This is not the case, however, with intermediate drainage layers which can result in increased settlements and, hence, more storage.

Secondary compression effects

117. Clay-type dredged material obtained in maintenance dredging undergoes volume changes as a result of primary consolidation, which involves the dissipation of excess pore water pressures. However, a secondary type of volume change occurs as a consequence of shear stresses in the soil. These secondary compression effects can proceed under small excess hydrostatic pressure differentials. Because they

occur slowly, pore pressures associated with secondary compression effects are, for practical purposes, negligible. Secondary compression effects are small for overconsolidated soil and are at a maximum for normally consolidated soils, especially for stress increases only slightly greater than the existing overburden stress.

118. The practical significance of secondary compression depends upon the use of a given area of soft soils. For example, if soft soils are to be densified so they can be loaded by buildings or other similar structures, secondary compression effects normally must be considered and measures taken so that stabilization treatment minimizes postconstruction effects.[29] Alternatively, if the purpose of densification treatments is to secure more storage capacity in a disposal area, secondary compression effects have little practical importance. For example, if increased storage capacity is being obtained by surcharge loading treatments or the equivalent, the ratio of storage volume obtained by secondary compression effects to that obtained by primary consolidation would be in the range of 3 to 10 percent. In other words, the effects of secondary compression on available storage capacity are not sufficiently large to be considered when evaluating storage capacities increases which can be achieved by treatment methods.

119. The practical significance of secondary compression effects is sometimes evaluated by expressing settlements from secondary compression as a fraction of settlements from primary consolidation. This is satisfactory provided care is exercised to obtain meaningful comparisons. For example, if small increments of added effective stresses $\Delta\bar{p}$ are used to estimate settlements from primary consolidation, the settlements from secondary compression may be a substantial percentage of primary consolidation settlements. From a practical viewpoint, this does not demonstrate the importance of secondary compression, because neither type of settlements is large. If this procedure is repeated with larger increments of effective stress, it becomes evident that secondary compression is not a significant factor in determining disposal area storage capacity.

Practical considerations

120. Pore pressures beneath disposal areas. The weight of dredged material placed in disposal areas in which the subsoil profile consists of silt or clay overlying sand (Figure 31) causes water to

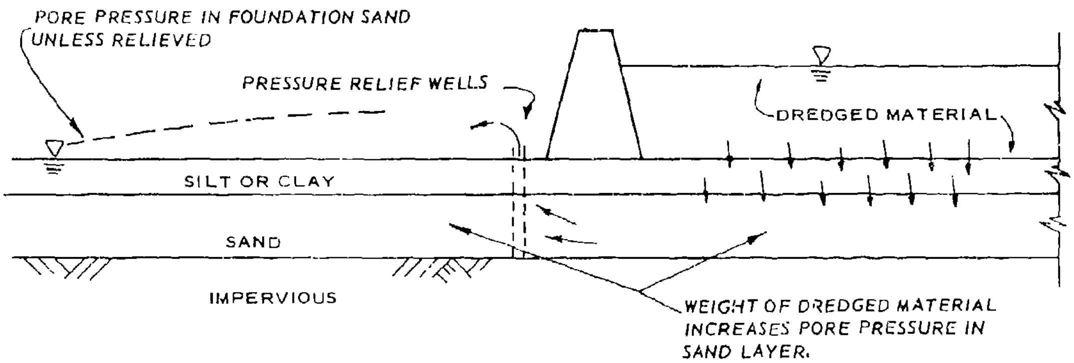


Figure 31. Pore pressures beneath disposal areas

be squeezed from the silt or clay strata into the underlying sand. In addition, the pore pressure in the underlying foundation sand is increased because of the high water level in the dredged material. The pore pressure in the foundation sand may be further increased if the dredged material is subjected to a temporary surcharge. Outside the retaining dike the pore pressures in the underlying foundation sand can be high, thereby preventing the sand layer from functioning as a drainage layer and impairing retaining dike stability. To some extent, this situation can be alleviated by installing free-flowing pressure-relief wells outside the retaining dikes. While this may assure stability of the retaining dikes, it may not make this layer effective in providing underdrainage for the dredged material. Where studies on any specific disposal area show this is the case, the pore pressures in the foundation sand can be decreased by pumping the wells. Also, it may be necessary to install wells within the interior of the dredged material disposal area because of the large size.

121. Horizontal drainage layers. Where sand layers are provided as underdrainage in dredged material disposal areas, or as layers at various intermediate elevations within the dredged material, they will

normally develop such large pore water pressures as to render them ineffective as drainage layers unless collector pipes are provided. The design of required collector pipe systems has been developed in connection with conventional stabilization procedures for soft soils. The increased pore water pressures within drainage layers are similar to that illustrated in Figure 31.

122. Placement of temporary surcharge loads. The practical aspects of placing temporary surcharge loads to secure densification assumes great importance due to the difficulty of placing a surcharge fill in thin layers without locally building up accumulations of fill that overstress the extremely soft dredged material. This can be done by using small draglines to cast thin layers of material in advance of the fill. Another procedure is hydraulic placement, but open-end pipes cannot be readily used because of the rapid accumulations of coarse material at the end of the pipe. This accumulation causes an overstressing of soft dredged material and the development of large mud waves. Underwater fill placement may be beneficial in these cases.

123. Types of vertical drains. Vertical drains have, until recently, consisted of vertical columns of sand of a suitable gradation.[30] Various methods have been used to install such columns as jetting, augering, displacement mandrels, and subsequent ejection of sand by compressed air, etc.[30] Vertical cardboard drains were developed by Kjellman, and a drain of this type in plastic was recently developed by the Swedish Geotechnical Institute and is being marketed under the tradename Geodrain.

124. The extremely soft and weak dredged material tends to favor the simplest possible installation technique, and it seems possible that vertical drains could be installed to limited depths by hand or simple light equipment. From this viewpoint, the Geodrain appears to be worth investigation and use in preliminary feasibility tests where vertical drains are desirable. A Geodrain is self-filtering and installation techniques should be extremely simple. Jetted or displacement drains would be satisfactory from technical viewpoints but require heavy equipment for installation.

125. Pumped drainage techniques. Drainage techniques combining pumping with large vacuum pumps appear promising and probably can be developed into an automatic system requiring a minimum of labor, particularly since the consequences of a malfunction would not be significant. It seems practicable to design the systems so that dewatering pumps would operate as required while vacuum pumps would function continuously or could operate within predetermined limits of desired vacuum.

126. Pumped drainage and vacuum drainage techniques appear most practicable where the quantity of water required to be pumped is not large. Because of the very large size of dredged material disposal areas, the volume of water would probably be relatively small on a unit area basis compared to conventional dewatering projects. For this reason, pumped drainage techniques might be practicable where normally they would be considered too expensive. The concept of vacuum pumping is especially attractive and should be considered seriously as a treatment technique for certain conditions.

127. Pumped wells with large vacuum pumps to secure vacuum in underlying drainage layers appear practicable. However, based on conventional usage, pumped wellpoints installed only in the disposal material do not appear to be a viable alternative because the spacing of the wellpoints would have to be so close as to make installation costs excessive. However, where an underlying sand layer exists in the foundation and the wellpoints are installed into the underlying sand, a pumped wellpoint would be essentially a pumped vacuum system in the underlying sand; and this would require a relatively small number of wellpoints or deep wells sealed at the upper surface. This appears to be a viable alternative to pumped wellpoints of the vacuum type installed only in the dredged material.

Analysis for Densification Effects

Concepts of densification

128. The reduction in water content and volume of dredged material is necessarily associated with an increase in the effective stress,

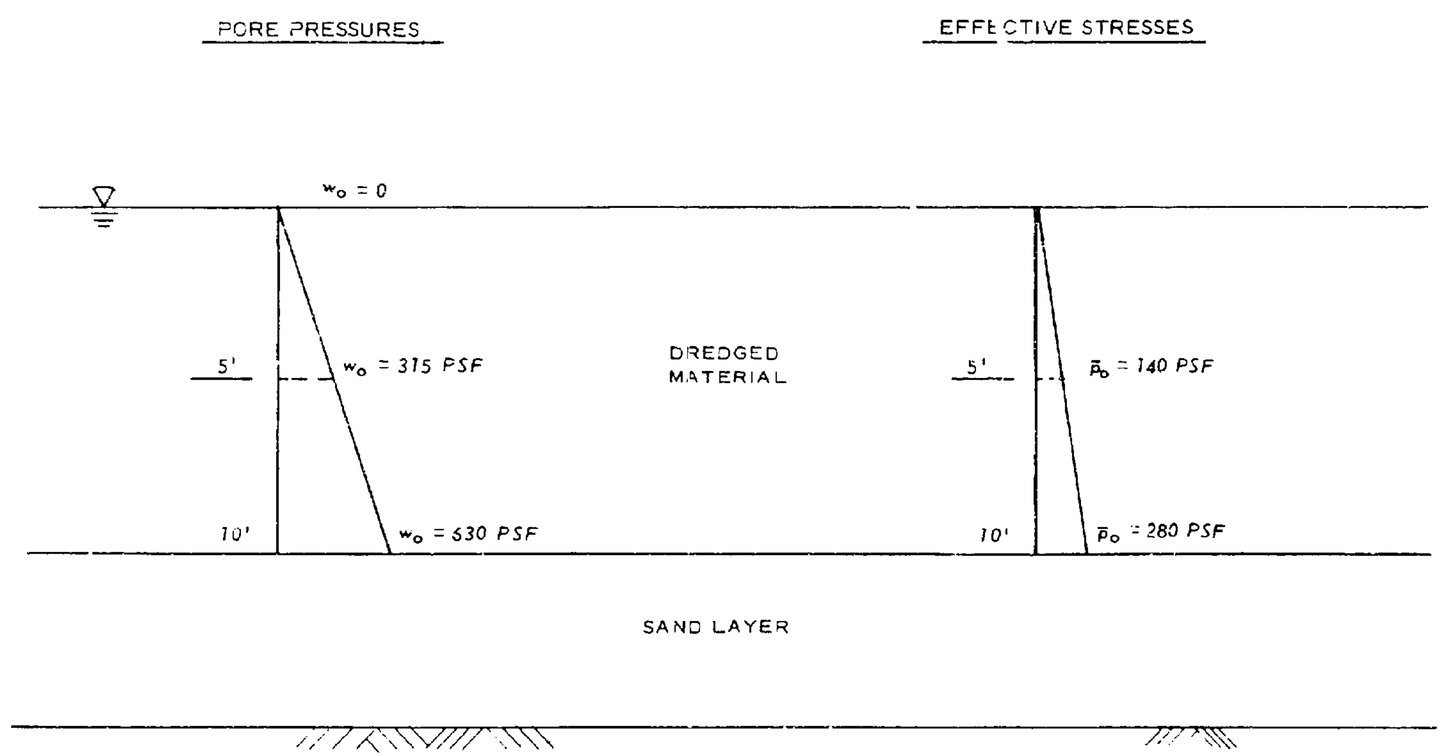
i.e., the grain-to-grain contact pressure in the dredged material. This is the case for any nonchemical method of densification and includes treatment methods such as surcharge loading, drainage, or desiccation. A simple and convenient means for comparing different treatment techniques, therefore, is to compare effective stresses produced in the soil by the treatment being considered. Such comparisons apply when excess pore water pressures have been fully dissipated, i.e., at the end of the treatment method. The effective stresses to be discussed are ultimate or maximum possible values, which may in some cases require long time periods to develop. The effect of time will be considered separately.

Effective stresses
for loading techniques

129. Effective stresses in the dredged material with the groundwater level at the surface are shown in Figure 32. Similar stresses when the groundwater level has dropped about 2 ft and a surface crust has developed are shown in Figure 33. Capillary stresses in the surface crust could be large and exceed 1 ton/sq ft. Effective stresses possible from surcharge loading are indicated in Figure 34 and are summarized in Table 16. While effective stresses developed from desiccation in the surface crust may be rather large, the use of surcharge loading may result in effective stresses at the surface which exceed the desiccation stresses. In this event, for surcharge loading treatment methods, the benefits of a crust are primarily as an aid to construction operations. An advantage of surcharge loading techniques is that even thick layers of dredged material would be benefited.

Effective stresses
for drainage treatments

130. Effective stresses developed by various drainage techniques are illustrated in Figures 35-38 and are summarized in Table 17. Underlying drainage layers are quite effective and can consist of natural sandy or silty soils occurring in the disposal area or may consist of sands placed in the disposal area prior to placement of dredged material. If the groundwater level is initially at the top of the dredged material and is gradually lowered to the top of the underlying drainage layer,



NOTE: SUBMERGED UNIT WEIGHT OF DREDGED MATERIAL = 28 PCF

Figure 32. Disposal area without densification

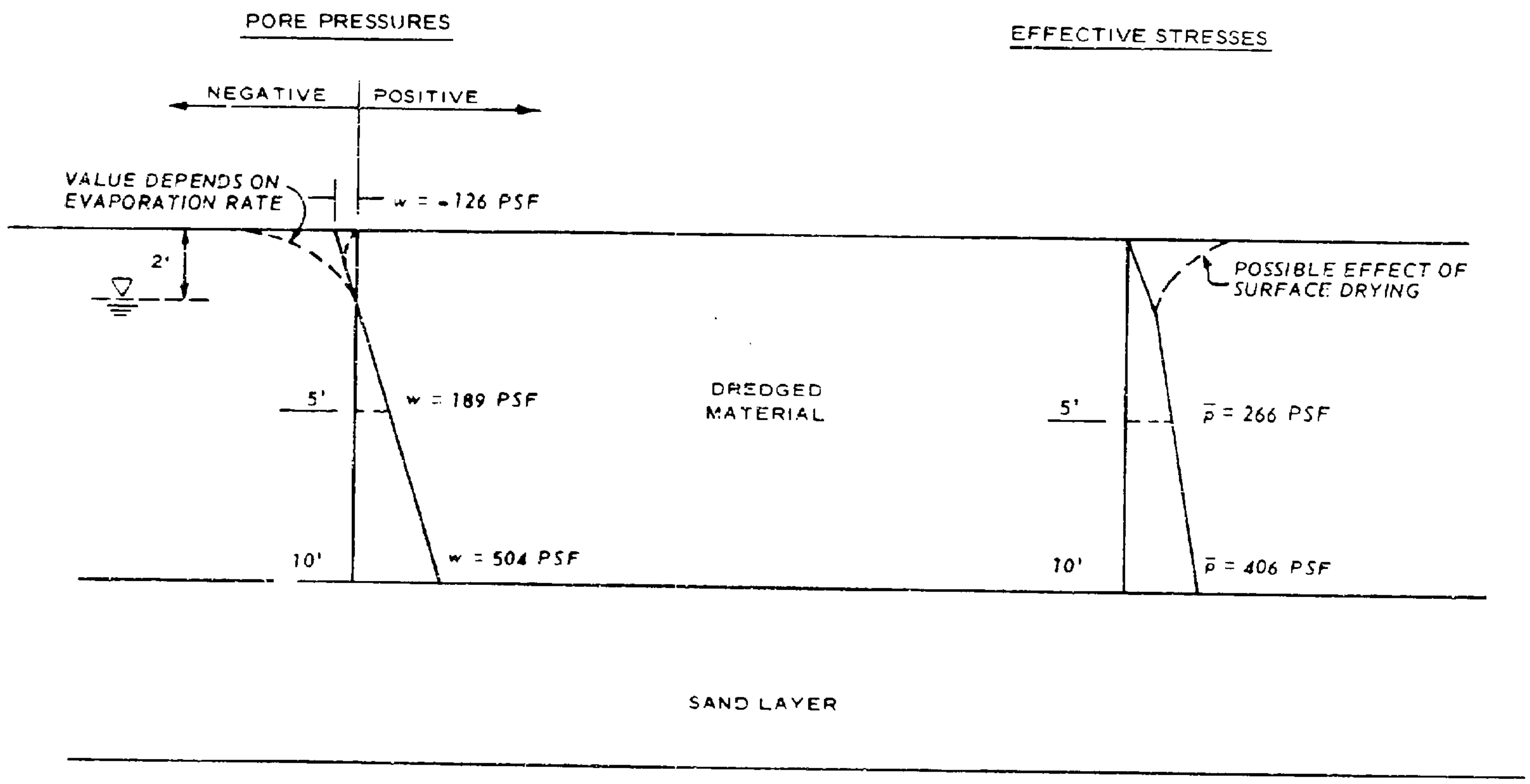


Figure 33. Disposal area with surface drying

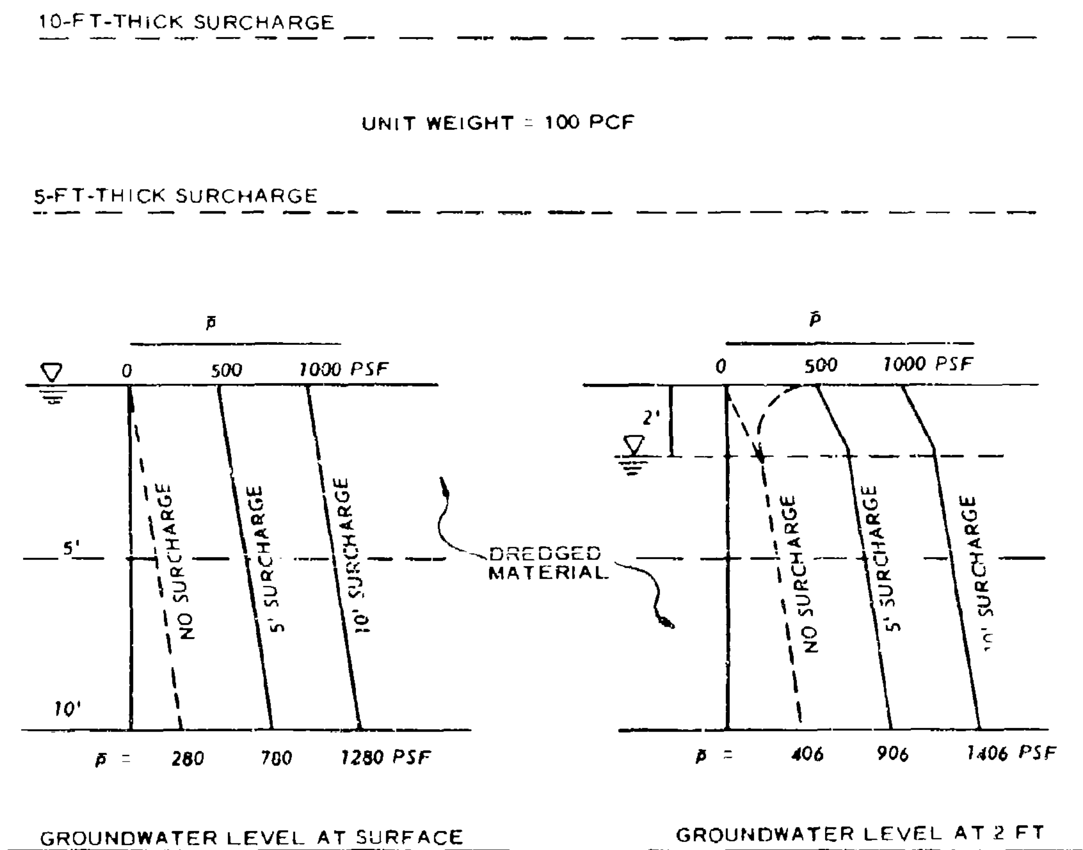


Figure 34. Effective stresses from surcharge loading

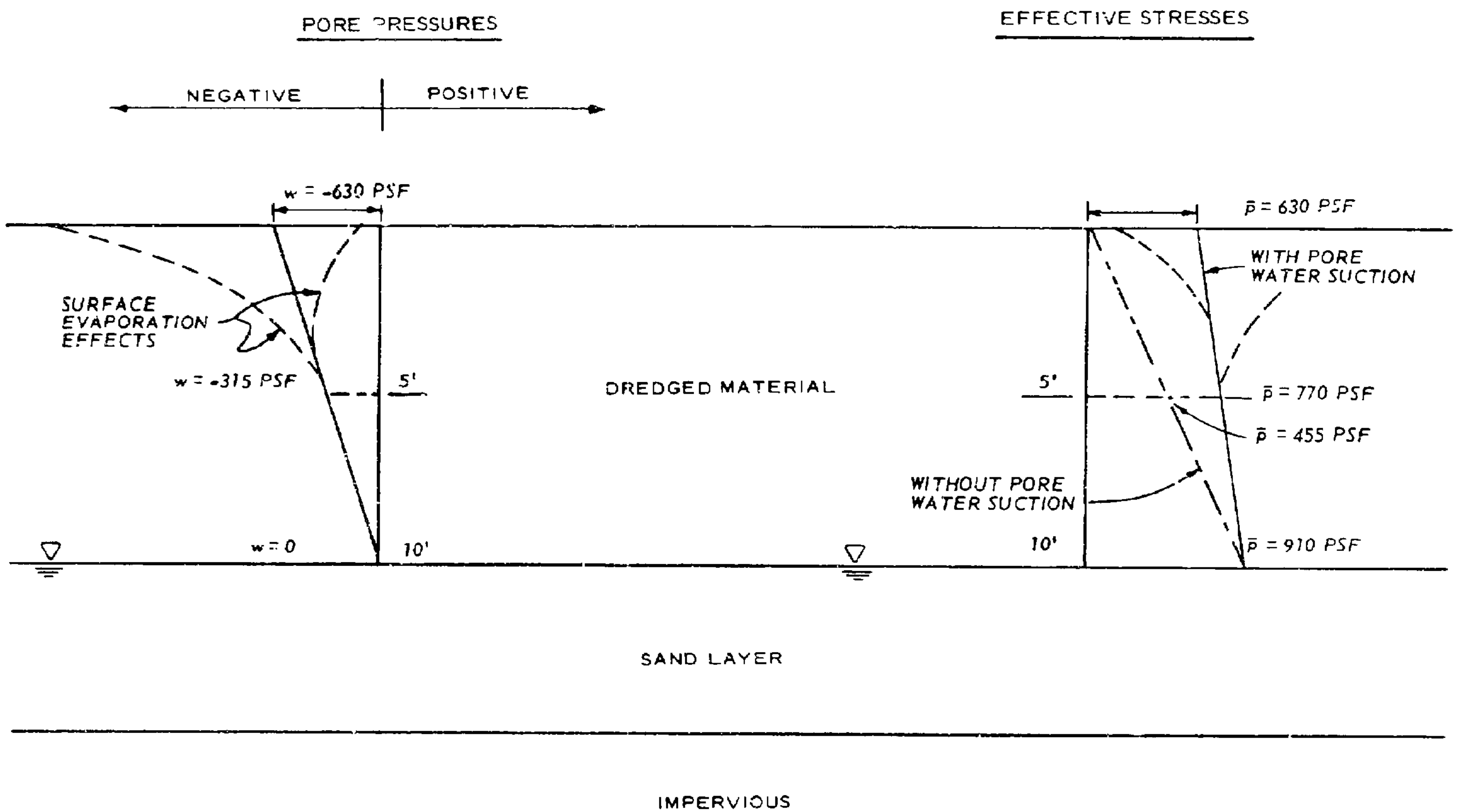


Figure 35. Disposal area with underlying drainage layer (groundwater level lowered to base of dredged material)

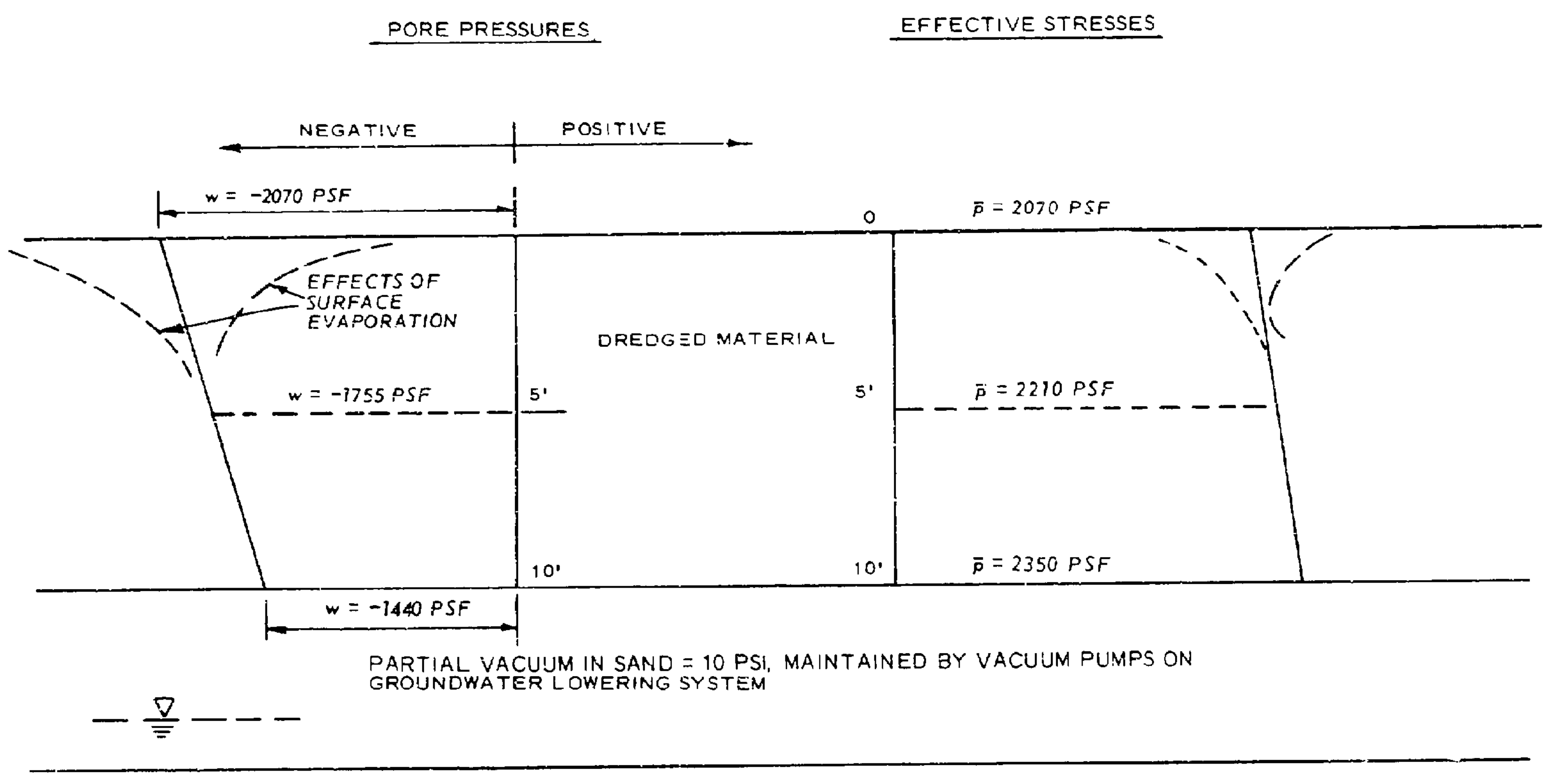


Figure 36. Disposal area with underlying drainage layer pumped by dewatering pumps fitted with large vacuum pumps

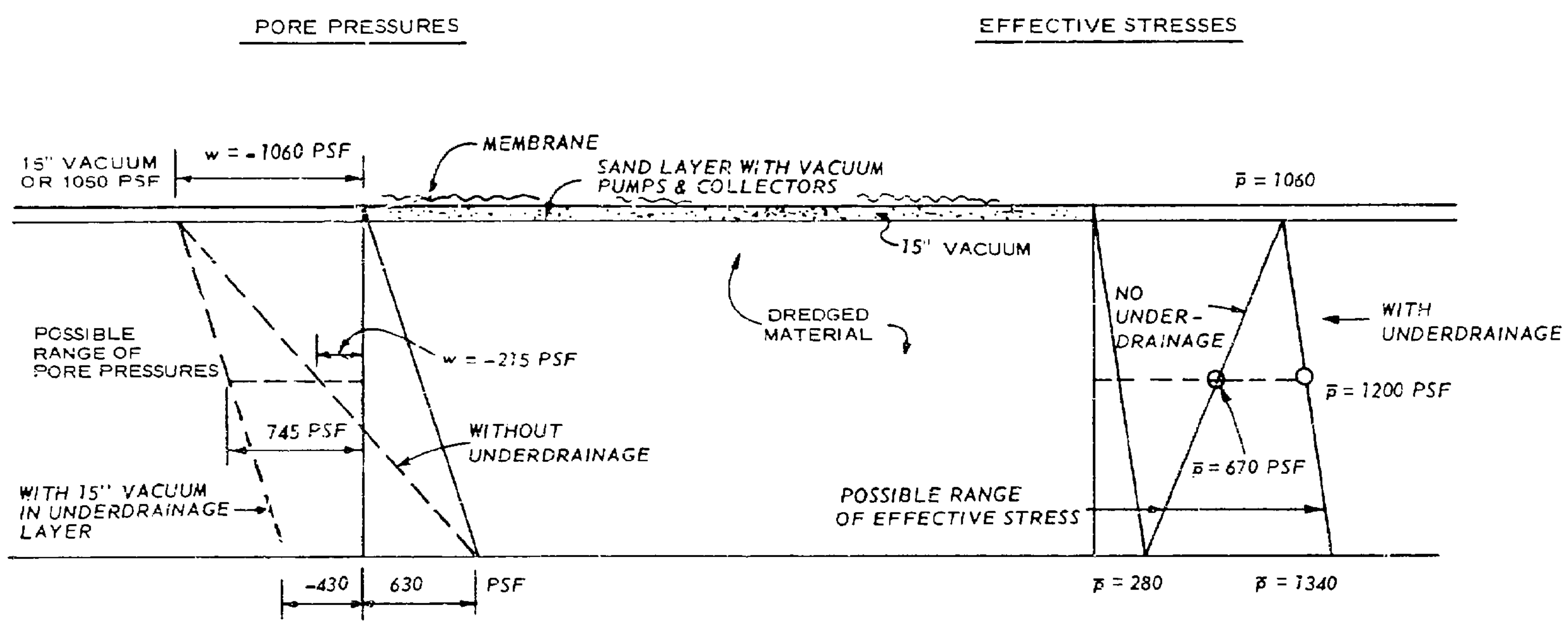
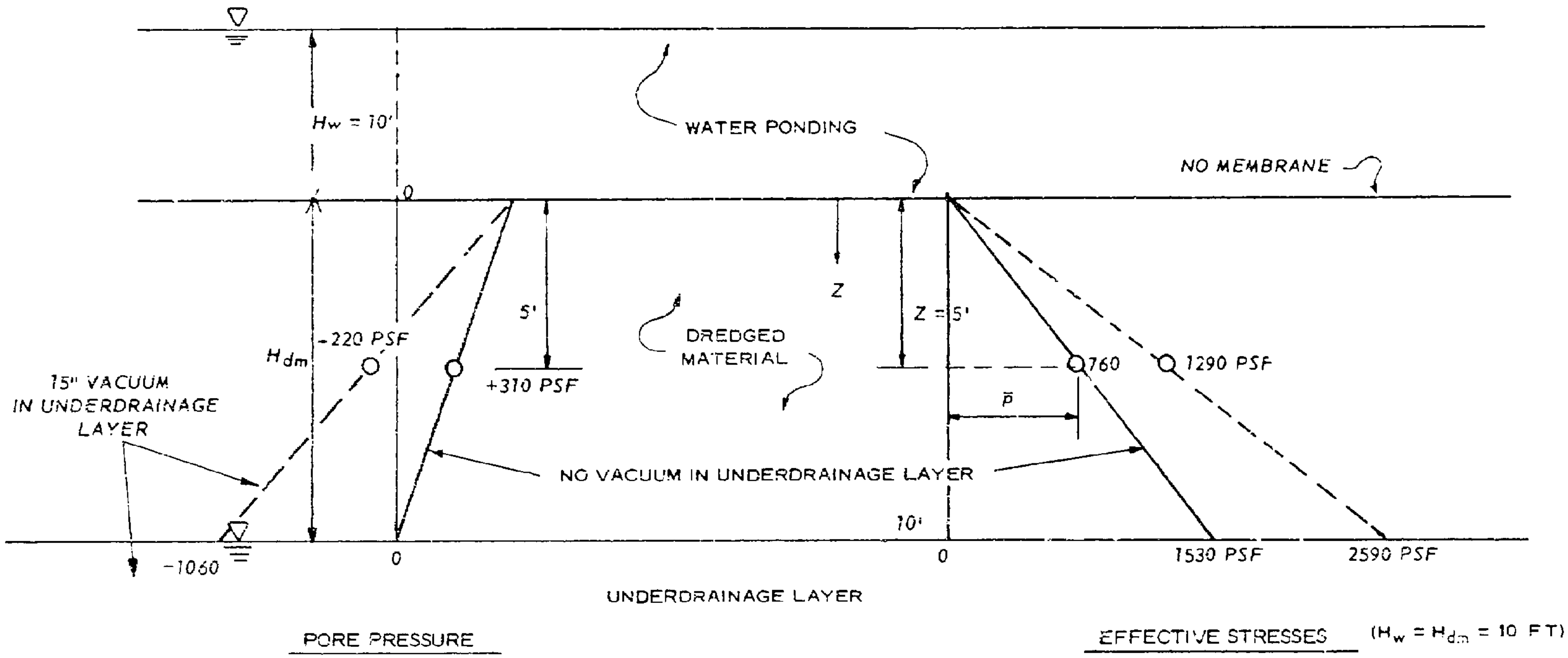


Figure 37. Disposal area with surface sand layer, membrane, and vacuum-dewatering system



SEEPAGE GRADIENT $= \dfrac{H_w + H_{dm}}{H_{dm}}$ OR $i = 1 + \dfrac{H_w}{H_{dm}}$, FOR $\dfrac{H_w}{H_{dm}} = 1$, SEEPAGE FORCE $= i\gamma_w$

OR SEEPAGE FORCE = 125 PSF / FT, $\bar{p} = Z\gamma_{sub} + Z\gamma_w \left(1 + \dfrac{H_w}{H_{dm}}\right)$

Figure 38. Seepage consolidation with underdrainage with and without vacuum pumping in underdrainage layer (no surface membrane)

negative pore water pressures will develop in the dredged material and these will increase the effective stresses. This is shown in Figure 35, which shows effective stresses both with and without pore water suction or negative pressures. In addition, for a case such as shown, desiccation may substantially increase effective stresses in near-surface materials.

131. The effectiveness of underlying drainage layers can be substantially increased if the water level in them is lowered and if a partial vacuum in the drainage layer is maintained by vacuum pumps attached to or operated in conjunction with the groundwater lowering system (Figure 36). This type of technique has been successfully used in connection with conventional stabilization techniques,[35] and partial vacuums of 15 to 20 in. of mercury have been obtained and maintained. This results in greatly increased effective stress in the soil, as indicated in Figure 36. From a technical standpoint, it is immaterial if the drainage layer occurs naturally in the foundation of the disposal area or if it is provided by placing sand materials on the surface of the drainage area prior to storage of dredged material. A thin sand layer placed prior to use of the disposal area would require collector pipes.

132. The concept of using atmospheric pressure in conjunction with sand layers in which a vacuum is induced was introduced by Kjellman[37] and has been applied several times. This concept is illustrated in Figure 37. While the case shown is only for a sand layer on the surface of the dredged material, it is also possible to place such sand layers, in which partial vacuums are maintained, at intermediate depths in the dredged material. Obviously, a membrane must protect the surface sand layer and the edges of all sand layers must be sealed so that partial vacuums can be maintained by a practicable amount of pumping.

133. The underlying drainage layers illustrated in Figures 35 and 36 and the overlying sand layer illustrated in Figure 37 must be provided with collector pipes for removal of water from the drainage layers. If collector pipes are not used, the head losses within the drainage layers would be excessive and the drainage layers would not function as intended.

134. An alternative that has never been considered, to the authors' knowledge, is seepage consolidation stabilization. In this technique, water would be ponded on the surface of the dredged material and underdrainage would be provided at the base of the dredged material. Downward seepage gradients would act as a consolidating force causing densification (Figure 38). This concept would require increased height of dikes, and possibly interior dikes to minimize wave effects in large disposal areas. After stabilization, surface drainage and surface drying could be used to increase effective stresses in the upper part of the dredged material.

135. Effect stresses possible from the various drainage techniques are summarized in Table 17. By comparing Tables 16 and 17, it is evident that drainage treatments can produce effective stresses as great as those produced by 5 to 10 ft of temporary surcharge loading. From this standpoint, drainage treatment concepts are efficient means of increasing effective stresses in dredged material, which is necessary to cause densification.

Effective stresses
for desiccation treatments

136. When the rate of evaporation exceeds the rainfall, soil located above the groundwater level will undergo drying, which induces negative pore water pressures in the soil and, consequently, positive effective stresses in excess of those caused by the weight of the material. This is illustrated in Figure 33. In fine-grained materials large negative pore water pressures can develop and associated effective stresses are also large. Pore water suctions from a few atmospheres to as large as 10 or 15 atmospheres can develop in soil exposed to drying. If a disposal area is drained so that surface waters are removed, the drying effects in areas where evaporation exceeds rainfall would be expected to gradually lower the groundwater level, providing that high pore water pressures do not exist in underlying soils. The drying effect and lowering of the water level would, of course, be greatly facilitated by trenching and other surface drainage techniques.

137. Drying of dredged material could also be effected by plant

root systems, and it has been observed in engineering prectice that certain types of vegetation have deep root systems capable of inducing sufficient drying to cause preconsolidation stresses as high as 500 psf. Desiccation effects combined with even slight lowering of the groundwater level, which may occur either as a result of trenching or as a consequence of desiccation processes, have a beneficial effect on material below the groundwater level. This results because the effective weight of soil above the groundwater level is changed from initially submerged weight to a moist or saturated weight. Thus, the material above the groundwater level has an effect similar to that of a small surcharge. Moisture content, shear strength, and preconsolidation stress changes resulting from desiccation have received only limited attention in conventional engineering practice although these effects have been observed and measured. Nevertheless, this area is one that merits much more investigation, combining soil engineering studies with the study of root systems of various types of vegetation.

Water content decrease

138. The effect of increases in effective stresses is to cause densification and water content decreases. The water content decrease and corresponding LI are listed in Table 18 for soils of various LL and increases in effective stress. This table was prepared assuming: (a) initial water contents equal to the LL, (b) Atterberg limits plotting along the A-line, and (c) values of $C_c/(1 + e_o)$ from correlations previously given. Water content decreases are also plotted in Figure 39.

Volume decrease from densification

139. Effective stress increases for various types of densification treatments are listed in Table 19 and afford a means for comparing results from various densification treatments. Underdrainage assuming pore water suction, a 500-psf surcharge, seepage consolidation, and a surface vacuum mat without underdrainage would each result in an ultimate effective stress increase of about 500 psf at a 5-ft depth. A surface vacuum mat combined with underdrainage, seepage consolidation with 15-in. vacuum in the underdrainage layer, and a 1000-psf surcharge would cause an ultimate effective stress increase of about 1000 psf

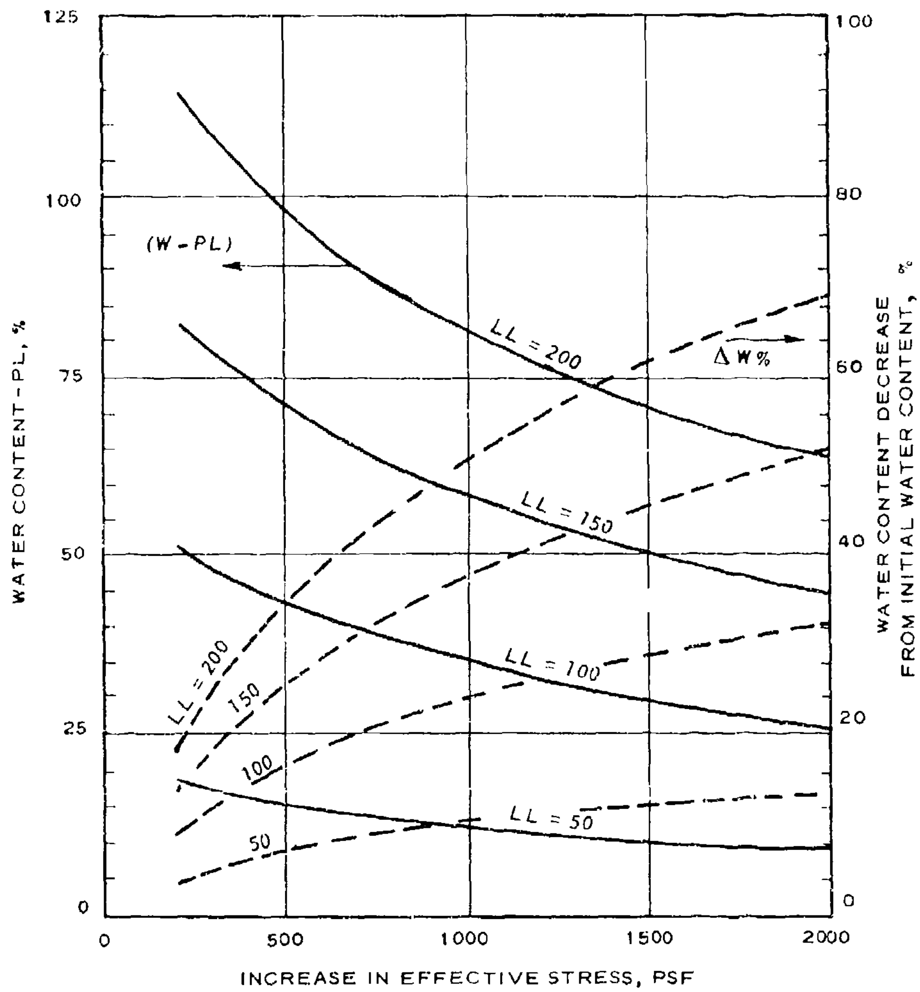


Figure 39. Water content versus effective stress

at the same depth and would be exceeded only by an underlying drainage layer with vacuum pumping, which would cause an effective stress increase of nearly 2000 psf.

140. Volume changes induced by increases in effective stresses are plotted in Figure 40 for various LL. These were computed on the same basis as water content decreases previously discussed and presented in Table 18 and Figure 39. The volume decrease depends on the increase in effective stress and on the LL, especially for LL less than 100, as shown in Figure 40. Since dredged material generally has a LL less

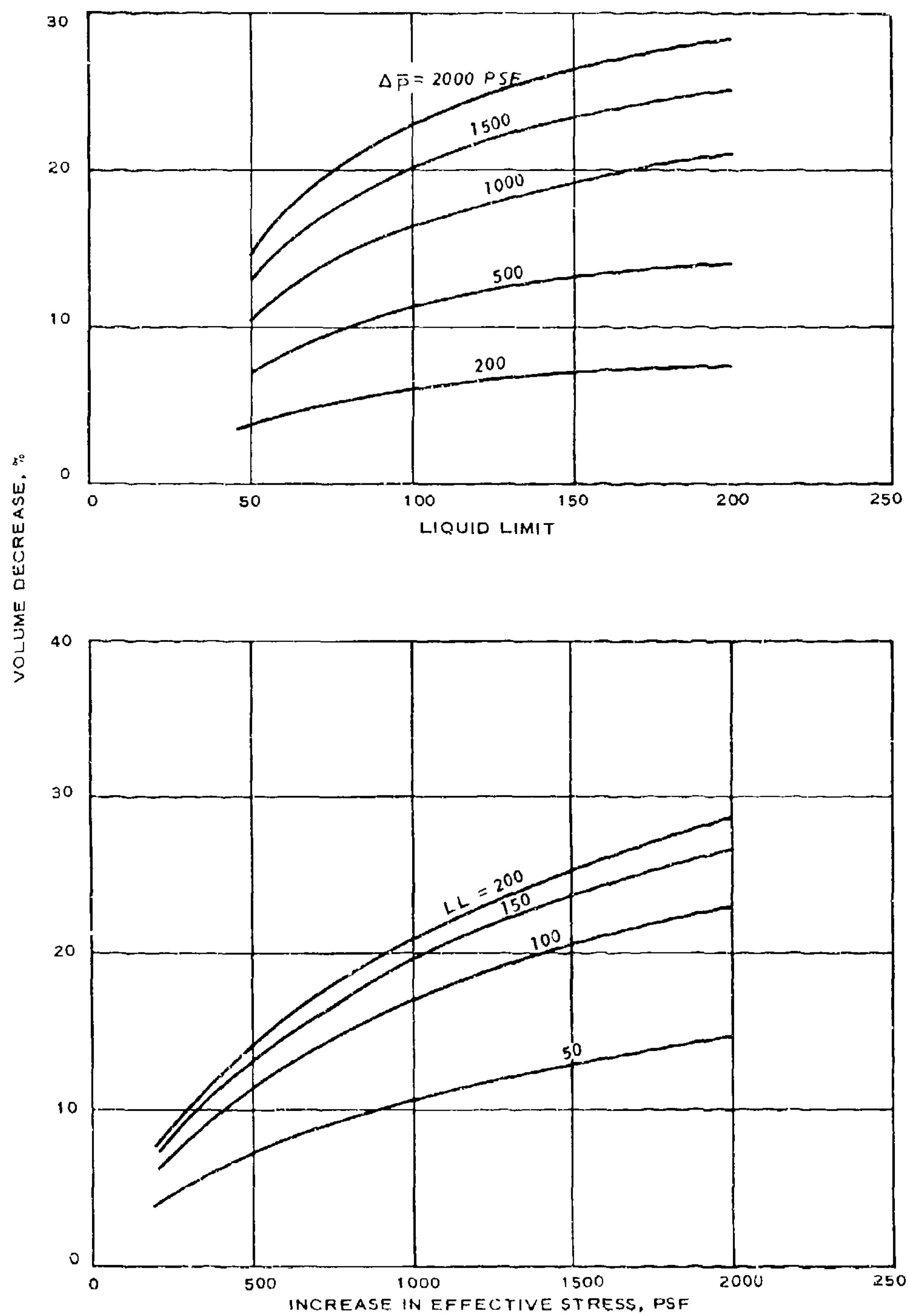


Figure 40. Volume decrease from densification

than 100, volume decreases (i.e., additional storage volume) from densification will be less than about 15 to 20 percent of the volume of dredged material. For high LL (i.e., 200), storage volume increases would not exceed 20 or at most 30 percent. For lower LL (i.e., 50), storage volume increases would not exceed about 10 to 15 percent.

Volume decrease from desiccation

141. An important exception to the above summary is the case where dredged material is placed in thin layers and each layer is subjected to severe desiccation. Drying can lower water contents to the shrinkage limit, which is close to the PL. (This would cause soils having water contents initially at the LL to undergo volume decreases of 25 to 60 percent, or substantially more than could be achieved by any drainage or loading technique.) While drainage at the bottom of the dredged material is significant (Table 19), recent work by Krizek and Casteleiro[10] has shown that the evapotranspiration potential dominates the rate of consolidation after desiccation at the surface has begun. Combined effects of vegetation and evaporation resulted in a 30- to 70-percent increase in relative settlement (Figure 41). Ditching is important in draining confined disposal areas,[48] but transpiration by vegetation is highly effective for accelerating the consolidation of dredged material in the thickness of material subject to desiccation. The use of vegetation with high transpiration rates and the ability to grow in saline wet soils provides a potential for accelerating the consolidation rate of limited thicknesses of dredged material and thereby increasing the available disposal storage. A field test sponsored by the DMRP is being conducted at the Grassy Island disposal site in the Detroit District to study dredged material drying by use of vegetation (the reed Phragmites communis).

Dredged material as borrow

142. The suitability of densified fine-grained dredged material for use in embankments or for other borrow purposes can be examined by considering water contents after densification. High LL soils, like fine-grained dredged material, are not good fill material for many purposes, but might find uses where borrow is scarce.

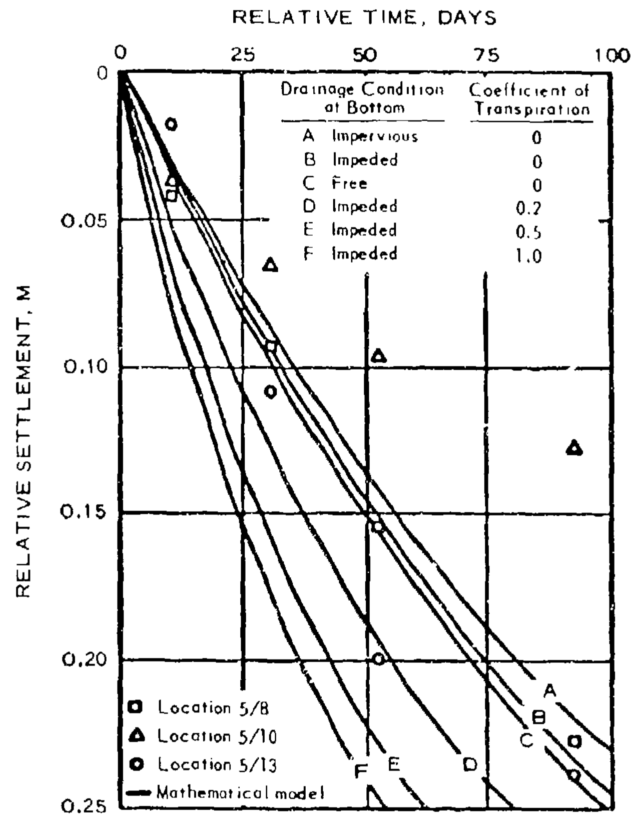


Figure 41. Effect of bottom drainage and vegetation on the settlement of Penn 7 disposal area near Toledo Harbor by Casteleiro's one-dimensional mathematical model (from Krizek and Casteleiro[10])

143. For dredged material to be useful as borrow, the water contents would have to be reduced to 10 percentage points or less above the PL, with a maximum of 5 desirable. As can be seen in Figure 39, the requirement could not be met by loading or drainage treatments.

144. Placing dredged material in thin lifts and allowing drying to occur could reduce water contents to near the PL, as previously discussed. This would make dredged material suitable for borrow where high-LL, fine-grained soils would be acceptable.

Discussion of Densification

145. The various examples are intended to illustrate means for examining effects of densification treatment. The computations made are believed conservative, in that actual volume decreases that could be achieved might be greater, especially where initial water contents at time of densification are more than the LL.

146. The benefits of densifying soils in disposal areas so water contents are about equal to the LL are substantial and are considered to be achievable by simple means. Additional storage volume is more difficult to obtain, and the practicability of densification for this purpose must be compared with the alternative of raising dikes surrounding the disposal area. The latter may be a preferred alternative, where possible.

147. It is evident that many alternatives exist for densifying dredged material. This makes it desirable to analyze actual conditions at a disposal area, since these may govern selection of appropriate methods. Properly designed densification treatments are technically feasible, but this is a rather time-consuming effort that requires experience and judgment as well as borings and laboratory tests. In the ultimate analysis, selection of the most appropriate densification treatment will probably be governed by economic factors.

PART VI: ECONOMIC COMPARISONS

Basis for Cost Comparisons

148. The cost of densifying dredged material depends, to a large extent, upon local conditions at a site, such as foundation compressibility, time available for treatment, and flexibility for scheduling storage of dredged material in different sections of the disposal area. These can be considered in a specific manner when comparing the cost of various treatment alternatives for a disposal area and may govern choice of the most appropriate method. Cost comparisons of alternative treatment methods presented in this section neglect the effects of local conditions. Consequently, data presented are intended only to provide order of magnitude of densification costs and to illustrate factors involved.

149. One of the principal factors influencing the cost of dredged material treatment is the time available for densification, i.e., how soon will added storage capacity in the disposal area be required? Some treatment methods may produce the desired densification but require a long time. Where necessary, added drainage can be provided to accelerate the rate of densification, but this benefit is secured only at a significant cost increase. If planning for densification is made when a disposal area is first developed, minimum cost treatments can be selected. Alternatively, if only a few years are available to obtain densification and added storage capacity, some low-cost alternatives will be precluded.

150. In general, it appears desirable to anticipate the need for increased storage capacity from dredged material densification at least 10 yr prior to the time added capacity will be needed, and even this time period may be insufficient. Unless increased storage capacity from densification of dredged material is anticipated when the disposal area is first opened, underdrainage layers that may result in minimum cost cannot be installed. In addition, to preclude the necessity for expensive installations solely to accelerate the rate of consolidation,

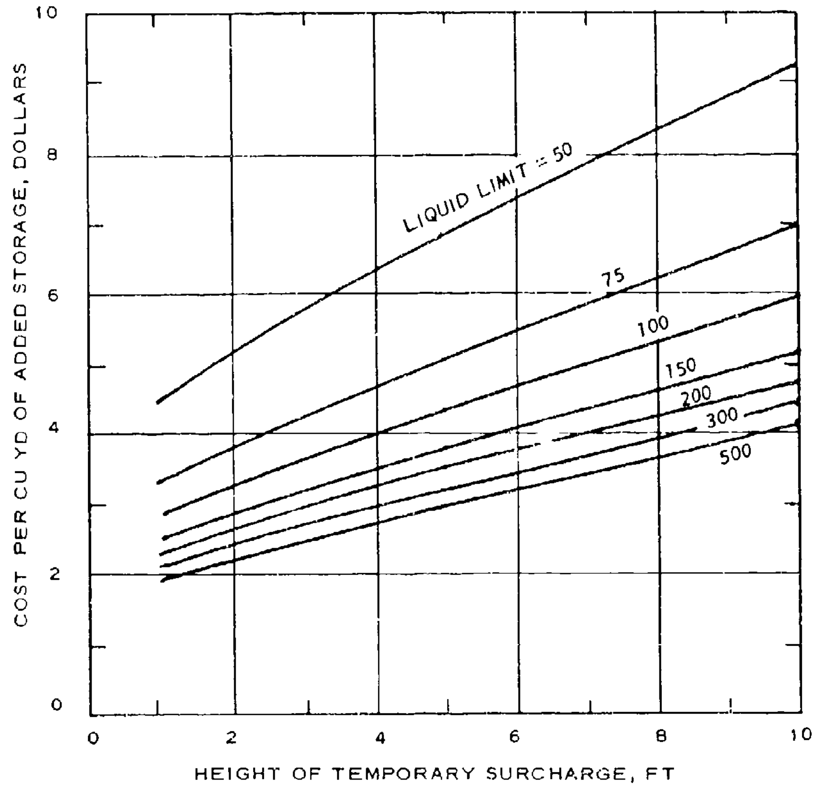
anticipation times for desired storage capacity increase should preferably be from 10 to 30 yr.

Densification by Loading

Temporary earth surcharge

151. The placement of a temporary surcharge on the surface of a disposal area is virtually impossible until after a surface crust has formed. Thus, for economic comparison purposes, it will be assumed that the disposal area has been drained and that an approximately 2-ft-thick surface crust has developed, so that light construction operations can be performed in the disposal area. It will be assumed also that the groundwater level is 2 ft below the surface and that soils are consolidated below this depth only by their own weight and by the weight of the crust.

152. The basis for the settlement and cost estimates is shown in Appendix C. The settlements were estimated assuming soils are fine-grained silty clays and clays plotting on the A-line of the plasticity plot. Various correlations were used between compressibility and soil properties (Part V and Appendix C). The cost of added storage volume obtained for various thicknesses of temporary surcharge fill is shown in Figure 42 for soils having various LL and for a 10-ft thickness of dredged material. The costs shown in this figure are approximately inversely proportional to the thickness of dredged material since the temporary surcharge fill would cause constant effective stress increases regardless of thickness of dredged material. Thus, if a 20-ft thickness of dredged material was being loaded, the costs shown in this figure would be reduced by at least one-half. Figure 42 illustrates that the cost of treating soils of low plasticity (i.e., relatively low LL such as 50) is high because the soils are not highly compressible and the additional storage volume that can be obtained is small. In contrast, treatment cost for soils having high LL (100 or higher) drops sharply because of the added consolidation obtained by the same amount of surcharge fill.



NOTE: COST ESTIMATE BASED ON SURCHARGE FILL COST OF $1/CU YD FOR 10-FT THICKNESS OF DREDGED MATERIAL.

Figure 42. Cost of added disposal storage using temporary surcharge fill

153. The added storage capacity, expressed in cubic yards per acre, for dredged material having various LL and heights of temporary surcharge fill is summarized in Table 20. This table also shows the cost of densification treatment per cubic yard of storage and also per acre of disposal area. As indicated, these costs were estimated assuming a placement and removal charge of $1.00 per cubic yard of temporary surcharge fill. In any specific instance, the cost could be substantially different.

154. When using a surcharge fill and computing fill costs for a

specific site, it can be assumed that the disposal area is divided into sections and that the temporary surcharge fill is placed in one section and, after densification is achieved, is moved to successive sections so that the fill is reused a number of times. The placement and removal of fill in each section would be the principal charge, together with the initial cost of the fill divided by the expected number of reuses. The cost of additional storage, per cubic yard and per acre of disposal area, is inversely proportional to the cost of the surcharge fill. In many geographical locations it will be possible to sell a sand surcharge fill when it is no longer required. This would have to be evaluated on a site-per-site basis.

155. The computations and data summarized in Table 20 are approximate and neglect factors that would be included when making computations for a specific site. For example, a site analysis would consider: (a) possible submergence of surcharge fill below the groundwater level, therefore decreasing its effective weight; (b) actual thickness of dredged material being treated, which would influence the amount of settlement obtained; and (c) consolidation of underlying compressible natural foundation soils, which would add to the storage volume available from treatment of dredged material. The time required to secure densification (discussed in Part V) for dredged material thicknesses more than 10 ft may be so long that means to accelerate the rate of consolidation may be necessary.

Temporary surcharge
<u>fill with vertical drains</u>

156. Where the thickness and/or consolidation characteristics of homogeneous dredged material and time available for densification require vertical drains to accelerate the rate of consolidation, the drains must be installed with fairly close spacings; otherwise, consolidation will be dominated by vertical flow and the drains will serve no useful purpose. An exception arises if intermediate horizontal sand layers exist in the dredged material, either accidentally or deliberately. This case can be considered on its merits by separate computations as an exception to the general situation.

157. The cost estimate using vertical drains assumed that 20 ft of dredged material had been placed in a disposal area and that a crust had developed. Underlying soils were considered normally consolidated under the weight of overlying materials. For illustrative purposes, a c_v of 0.02 sq ft/day was assumed and it was stipulated that 90-percent consolidation be achieved in 5 yr. As before, the dredged material was assumed to plot along the A-line on the plasticity plot. The computations are presented in Appendix C, page C4, for a case where vertical drains cost $1.00 per linear foot, a collector pipe system costs $1200 per acre of treated area, and sand surcharge fill costs $1.00 per cubic yard. Obviously, these cost figures would have to be adjusted for specific locations. The cost of vertical drains at $1.00 per linear foot for vertical sand drains is comparatively low since a short installation time would be anticipated for drains in soft materials. Other type drains could be used, but costs are believed generally similar.

158. The added storage that could be obtained, expressed as cubic yards per acre of disposal area, is summarized in Table 20 for soils having various LL and subjected to surcharge fill thicknesses of 1, 5, and 10 ft. The cost of densification per cubic yard, the added storage capacity obtained, and the cost per acre of disposal area are also summarized in Table 20. It can be seen that a high premium must be paid for vertical drains. This added cost was incurred because of the requirement imposed that 90-percent average consolidation be achieved in 5 yr. As illustrated in Figure 30, for a fill thickness of 20 ft having one-way drainage, 50-percent consolidation would be achieved in about 22 yr without drains. Obviously, it is beneficial to make long-range plans in an effort to avoid the cost for vertical drains to accelerate consolidation.

Ponded water surcharge

159. This alternative would generally follow work done by NYPA and would consist of 20-mil unreinforced PVC membrane, a sand drainage layer immediately beneath the membrane, and collector pipes in the sand drainage layer. The total cost is approximately $12,700 per acre (Appendix C, page C7).

160. The added storage available in cubic yards per acre for soils having various LL is tabulated in Table 20 for water depths of 8 and 16 ft, corresponding to surcharge loads of 500 and 1000 psf, respectively. The cost of densification treatment per cubic yard of added storage is also shown in this table. The cost figures shown do not reflect the added height of retaining dikes required to confine the ponded water. Neither do the cost figures include wave protection, which might be necessary if large disposal areas were subjected to water ponding. The use of interior dikes could reduce wave heights and reinforced PVC could protect dikes. While these costs might total appreciable amounts, they were not included because the effect on average cost per cubic yard of additional storage obtained would be largely dependent on the configuration and size of the disposal area and would not be expected to govern selection of a treatment method.

Surface vacuum mat

161. The Kjellman type of vacuum mat used to apply surface loading by atmospheric pressure was assumed to consist of a membrane, sand blanket with collectors and water, and vacuum pumping. A vacuum of about 15 in. of mercury or about 1000 psf was assumed (Appendix C, page C8). The cost estimate assumed a pumping time of 5 yr with automatic pumps. Storage available and cost per cubic yard of increased storage are summarized in Table 20.

Densification by Drainage

Underdrainage

162. The use of an underdrainage layer to effect densification is illustrated in Figure 35. The sand layer shown in this figure can be a naturally occurring foundation layer or one placed on the bottom of the disposal area prior to placing dredged material. Consolidation of overlying dredged material would develop pore pressures in a sand blanket, which could be reduced by a collector pipe system in the sand layer. Such a collector pipe system would probably be required even if the foundation consisted of sands because of the large size of disposal

areas. As previously discussed, this results in large pore pressures in sand layers and renders them inefficient for use as drainage layers unless collector pipes are used

163. To be conservative, the cost estimate presented in Appendix C, page C10, assumed that pore water suctions in dredged material did and did not develop. The results are summarized in Table 20 for the conservative assumption that suction pressures did not develop in the dredged material. If such suctions developed, and there is good reason to believe this would be the case, the volumes of additional storage would be approximately twice the values shown in Table 20 and the cost per cubic yard of additional storage would be approximately one-half. These computations were made for a 10-ft thickness of dredged material.

Pumped underlying
drainage layer with vacuum

164. The conditions for this case (Figure 36) could be developed by pumping from an underlying drainage layer with a high vacuum maintained by vacuum pumps. In computing benefits from such a system, it was assumed that a crust had formed to a depth of 2 ft and that underlying soils were normally consolidated. Pumping of water and development of a vacuum in an underlying drainage layer would cause additional settlement. Cost estimates (Appendix C, page C11) assume that pumping and maintenance of a vacuum would be necessary for a 5-yr period on the premise that this would result in 50-percent consolidation of the dredged material. This time (Figure 30) applies for one-way drainage, a 10-ft length of drainage path, and a coefficient of consolidation of the dredged material of 0.01 sq ft/day.

165. If the foundation material of the disposal area contained pervious sands, the only cost would be the pumping involved. Costs per cubic yard of additional storage obtained are summarized for this case in Table 20. If the pumping period could be reduced substantially, as would be the case if the coefficient of consolidation of the dredged material were higher, the cost would be reduced correspondingly.

166. In the event that the disposal area did not have pervious

foundation sands, this treatment method could be used by placing a 1-ft sand layer on the surface of the disposal area, together with collector pipes embedded in the sand, as shown in Figure 37. The addition of a sand layer and collector pipes would increase costs shown in Table 20 by approximately 40 percent. If consolidation proceeded more rapidly, the available storage volume would be correspondingly increased and the cost per cubic yard of storage obtained would be decreased. Actual costs for this treatment technique are largely dependent on local site conditions and figures shown should be interpreted to illustrate order of magnitude costs for this technique.

Seepage consolidation
<u>with ponded water surcharge</u>

167. If dredged material is placed on an underdrainage layer in which the water level is maintained at the top of the layer, water will drain out of the dredged material into the drainage layer and will exert a seepage pressure on the dredged material. If water is ponded above the dredged material, the seepage gradient and seepage forces through the dredged material will increase, tending to consolidate the dredged material (Figure 38). This alternative was evaluated assuming that a drying crust had formed to a depth of 2 ft and the added storage obtained would be in addition to that resulting from consolidation of dredged material under the weight of a 2-ft crust. This is consistent with evaluation for other techniques.

168. Computations for this case are presented in Appendix C, page C13, and assume that evaporation and rainfall are in balance over a 1-yr period so that maintenance of the pond would not be significant. It was further assumed that an effective natural underdrainage layer did not exist and that it would be necessary to provide an artificial layer with embedded collector pipes. A 10-ft thickness of dredged material was assumed with water ponded to a depth of 10 ft. For these conditions, the quantity of added storage that would result for various dredged material is summarized in Table 20 together with the cost per cubic yard of additional storage obtained.

169. If a site had an existing underdrainage layer capable of

conducting seepage away, the cost for stabilization would be only the cost of raising the retaining dikes and pumping in water. Neglecting the cost of the dikes, which would have to be estimated in accordance with the size of the area and height required, the cost for pumping only would amount to only $0.10 to $0.15 per cubic yard of additional storage volume obtained, which would be exceedingly inexpensive.

170. The section shown in Figure 38 assumes a homogeneous thickness of dredged material. This could be expected if the dredged material was placed continuously. In the event that dredged material was placed intermittently, a drying crust would develop on the surface of each lift. These crusts would have reduced permeabilities and would serve as partial barriers to downward seepage. The effect would be to decrease consolidation of material above a crust and increase consolidation of material beneath a crust. This is not necessarily an argument against permitting crust development during intermittent deposition of dredged material in the disposal areas because the development of a crust automatically entails a volume reduction and, hence, increased storage capacity. Detailed studies might show, however, that the permeability reduction resulting from formation of a crust would be undesirable and that better overall results would be achieved if crust development were not permitted. This aspect should be investigated by additional studies.

171. No instance is known where water ponding without a membrane has been used. However, seepage pressures do exist and would cause increased effective stresses in the dredged material. Hence, the concept of this treatment alternative is considered sound although the technique itself is regarded as experimental.

Densification by Desiccation

Incremental placement of dredged material

172. If dredged material is placed in increments of 1 to 3 ft and allowed to dry, the water content can be reduced to about the PL if drying conditions are favorable. This type of disposal area operation

might be feasible if the area available is large enough to be divided into sections, some of which are drying while others are receiving dredged material.

173. The cost of this alternative was estimated assuming that nominal labor and equipment costs would be incurred to maintain good surface drainage (Appendix C, page C15). The costs and increased storage for this treatment are summarized in Table 20 for volume benefits that correspond to a water content reduction from the LL to the PL. Volume reduction from the placement water content to the LL was not credited, considering that it would develop with nominal maintenance, as done for the other treatment alternatives.

Other desiccation techniques

174. Capillary wicks and internal thermal treatments are regarded as being in a research stage and not amenable to cost analyses. The cost for treatment by capillary wicks might be relatively low, but this cannot be expected for internal thermal treatments.

Evaluation of Densification Benefits

Increased disposal area storage capacity

175. The data shown in Table 20 are arranged in Table 21 according to the amount of added storage, expressed in cubic yards per acre of disposal area. This facilitates examination of treatment alternatives where the amount of added storage which can be obtained is the paramount consideration. The data shown are for a 10-ft thickness of dredged material being subjected to densification treatment. Some techniques would produce added benefits in approximately direct proportion to the thickness of dredged material being treated, but associated questions such as time for consolidation might become paramount and would have to be determined on an individual site basis.

Cost of increased storage capacity

176. For many locations, the feasibility of densification treatment will depend on the cost per cubic yard of added storage capacity.

For this reason, the data summarized in Table 20 are listed in Table 22 according to the cost of densification per cubic yard of storage. The cost data shown, as previously stressed, are extremely approximate and are intended to indicate only the order of magnitude. It is evident that densification treatment to obtain added storage is an expensive process, except for desiccation by placing in thin layers and for some drainage techniques.

177. The principal limitation of the volume and cost estimates shown in Tables 20-22 is that foundation settlement is ignored. At some sites, this will equal or exceed dredged material settlement and may drastically alter conclusions reached by considering only the dredged material. Another limitation of data shown on these tables is that only a 10-ft thickness of dredged material is assumed.

Raising retaining dikes

178. The information shown in Tables 20-22 can also be evaluated by comparing treatment results with the volume and cost of additional storage obtained by raising the retaining dikes. The cost of retaining dikes, expressed in terms of cost per acre of disposal area, is heavily dependent on foundation conditions, the size of area, and other factors. Nevertheless, to obtain the general order of magnitude of what is involved, estimates were made for retaining dikes having a crown width of 5 ft (Appendix C, page C17). For one-on-four side slopes, the added volume of dike, expressed in terms of volume of dikes per acre of a 1000- by 3000-ft disposal area, is shown in Table 23 together with the added storage volume obtained by raising the dikes. The added volume is also expressed in terms of cubic yards per acre of storage area. The added storage volume that can be obtained per acre by raising the height of dikes in increments is shown in Table 23 for dikes having side slopes of one-on-four and a crown width of 5 ft.

179. Comparing this added storage volume with the additional storage shown in Table 22 for various dredged material treatment techniques shows that increased storage capacity can most easily be obtained merely by raising the height of dikes slightly. As summarized in Table 24, raising the dikes no more than 2 ft is the equal of all

treatments listed in Table 21 except for the desiccation technique, and raising the dikes 3 ft is the equal of all treatments considered. If the thickness of dredged material is more than about 10 ft, the added storage that can be obtained from densification treatme' ' will be increased, and equal storage capacity without treatment would require higher dikes. In terms of the cost per cubic yard of additional storage, it is evident (Table 23) that the approximate cost of p: ..iding a.lded storage capacity by raising t'e dikes, $0.25 per cubic yard, is substantially less than for any dens ication technique, including desiccation by placing in thin layers, dr ·ing, and trenching.

Conclusions of Densification Treatment

180. It is evident that the densification treatment of dredged material placed in disposal areas is a practical alternative only where raising the dikes is prevented by legal or environmental considerations, or where the cost of dike raising is relatively large because of the small size of the disposal area. Nevertheless, there are cases where dikes cannot be raised. Economic comparisons favor raising dikes as a means of obtaining additional storage capacity at minimum cost.

181. These comparative volume and cost data do not include desiccation by internal thermal treatment of dredged material. This tech- is undeveloped in the United States and meaningful comments concerning its application cannot be made. However, since this type of work has been undertaken in Russia and other countries to varying extents, it may be desirable to consider this subject area for research.

182. The various densification treatment techniques have been discussed solely from the viewpoint of obtaining additional storage volume in disposal areas. Where the eventual development of a disposal area entails construction of buildings or other structures, the efficacy of densification treatment can be evaluated using engineering analyses such as have been discussed in this report and elsewhere.[29,30] It has been adequately demonstrated by work at many locations that soils found in disposal areas are of types that can be densified adequately for many development purposes.

PART VII: RECOMMENDED RESEARCH

183. The presentation of methods of analysis for total and time rate of consolidation settlements and for secondary compression have not emphasized uncertainties involved when using these procedures for high-water-content dredged material. Similarly, comments have not been made regarding limitations of the various densification techniques, nor for recommended research. This was done to make the presentations and evaluations concise, but in some cases, research is desirable.

184. The general concepts of consolidation are reasonably well understood regarding computation of total settlements. In any specific case, laboratory consolidation tests can be performed that determine the consolidation characteristics. However, little is known concerning the combined sedimentation-consolidation of soils under extremely small increments of loading.

Laboratory Research

Sedimentation-consolidation processes

185. When densifying dredged material, the initial conditions of the soil are considerably different than those for which much engineering experience has been accumulated. Consequently, the time rate and amount of consolidation should be researched under extremely small loadings and under small increments of loads. This work should start with typical slurries and simulate prototype conditions through densification treatment. Consolidation properties that are regarded as constant in conventional soils engineering practice are variable when consolidation takes place over a large range in void ratios. Further, initial conditions are inadequately known. Variable soil properties can be considered by available computer analyses but appropriate soil properties input are largely unknown.

186. Dredged material sedimentation and consolidation are a combined and continuous process unlike conditions in conventional engineering practice wherein only the consolidation phase is considered. Some

research has been accomplished in which sedimentation and consolidation have been jointly studied, but the height-to-diameter ratios of equipment used restrict the validity of the work. Research on consolidation test requirements has shown that height-to-diameter ratios are critical, and values of about 0.33 to 1 are generally used in engineering practice. In contrast, height-to-diameter ratios used in sedimentation or slurry consolidation tests have been about 4.5 to 1, or the height has been about 14 times larger than considered appropriate for consolidation tests. This difference would cause large sidewall friction forces to develop and makes the test results questionable, although they are probably correct qualitatively and useful for illustrating concepts and mechanisms. The principal reason why large, instead of small, height-to-diameter ratios have been used is, of course, the practical one of ease of testing.

187. The importance of correctly simulating prototype sedimentation-consolidation processes under controlled conditions warrants construction of a large sedimentation-consolidation device that more closely meets normal criteria for height-to-diameter ratios. For this reason, devices 6 ft high and 4, 8, and 12 ft in diameter are recommended. These devices would be simple to construct and operate, since required loading capacity is small, not over about 2000 psf. The devices should be thoroughly instrumented with piezometers at various levels; side ports for X-rays, samples, pressure cells, etc.; and facilities to simulate underdrainage, surface drainage, desiccation, seepage consolidation, and other treatment techniques. Since these devices would be filled with various typical dredged material slurries placed by pumps, operating costs would be small. If, for example, such devices had to be filled with hand-placed and compacted soil, the cost would be large, but this would not be the case for dredged material.

188. Equipment of the type recommended would be used to investigate the combined process of sedimentation-consolidation followed by various desiccation or densification treatments. Such tests are considered essential for establishing initial conditions of disposal areas at the time densification treatments, including desiccation, might be

undertaken and for establishing the validity of theoretical analyses of disposal area treatment.

Secondary compression research

189. While secondary compression of soils is only partially understood, it may not appear to be sufficiently important to disposal area usage to require additional research. This is probably the case where effects of densification treatment on dredged material of specified initial conditions are being evaluated. Secondary compression is considered relatively unimportant when effective stress increases are large, but is important when effective stress increases are small, as during sedimentation-consolidation. Because secondary compression effects are possibly of major importance in determining the initial conditions of dredged material at the time densification treatment is undertaken, the research with large sedimentation-consolidometers should include study of secondary compression effects. The uncertainty in determining initial conditions of dredged material is of decisive importance in evaluating effects of densification treatment.

190. If a disposal area is to be extensively developed for building construction, further research on secondary compression is highly desirable. Details of recommended research are not presented in this report because development of disposal areas for such purposes has not been assigned a high priority.

Atterberg limits research

191. The utility of Atterberg limits for describing initial conditions in disposal areas and to facilitate computation of total and time rate of settlements has been demonstrated by analyses previously presented. The Atterberg limits used were the Atterberg LL and PL; however, Atterberg also defined an "upper liquid limit" which should be explored further since it relates closely to the placement and subsequent changes in dredged material placed in disposal areas.[49]

192. Atterberg defined the upper LL as the "upper limit of viscous flow; that is, the limit at which a clay slurry retains so much water that it flows almost like water." After various attempts Atterberg states that he obtained the most constant values with the following test procedures:[49]

> The clay powder is mixed in a porcelain dish, with round bottom, with enough water for the sticky limit to be reached.... Only then, water is gradually, with the aid of a wash bottle, added until with constant mixing the mass begins to flow like water. A groove is then made in the slurry with a glass rod. If this groove disappears within half a minute, the limit is reached. If one has gone beyond the limit, one should set the procelain dish over a hot water bath for a while in order to evaporate some of the water, or one can add a little more clay powder to the slurry (less desirable, however). Then one again attempts, by the addition of small amounts of water, to reach the limit. When it has apparently been reached, one lets the slurry pass through a fine sieve so that any small lumps that may be present will be removed. A portion of strained slurry is then weighed and dried at 100 deg C. The loss of weight, calculated on the basis of 100 parts of dry clay, gives the position of the limit.

193. The test values reported by Atterberg appear closely related to properties of dredged material placed in disposal areas. The values given by Atterberg for the upper LL vary between about 1.0 and 2.3 times the LL, with most values between 1.5 and 2.2. There appears to be a generally consistant relationship between the plasticity of the clays and the upper LL. The ratio between the upper LL and the conventional LL appears to be dependent also on the plasticity of the clays. Atterberg's tests were limited in number and were not expressed in current soils engineering terminology. The concept of the "upper limit of viscous flow" appears sufficiently valuable so that it should be related to the condition of material in the disposal area at the time that densification treatment might normally be undertaken.

194. It is extremely important to determine what increase in density will occur in disposal areas. The analyses made have assumed that densification treatment would not be attempted until the soil had reached approximately the LL. This assumes that the volume decrease from placement moisture contents of 2, 3, or 4 times the LL to the LL will occur without specific need for treatment other than draining surface water and normal crust development. This assumption is conservative and appears warranted, but requires further investigation.

Initial Conditions in Disposal Areas

195. Dredged material deposited hydraulically has water contents after sedimentation which are different from those normally encountered in engineering practice. While available data have been examined and summarized in Part II, the data are insufficient for dredged material densification design. For this reason, more investigations of existing conditions in various disposal areas at various times after placement of dredged material are highly recommended. This work is considered to have a high, or urgent, priority. It is recommended that systematic boring and testing programs be undertaken to determine water contents and soil properties in existing disposal areas having various foundation conditions and covering a variety of dredged material.

196. Borings and samplings suitable for determining water contents, Atterberg limits, and grain-size distributions can consist of simple displacement-type fixed piston samples having liner tubes. A diameter of about 1 in. would be sufficient. Samples of this type could be advanced by hand without casing or drilling mud. At the most, a simple tripod rig would be required, but even this would probably be unnecessary because of the softness of dredged material and the small sampler size.

Theoretical Research

197. The process of sedimentation and consolidation has been considered in research sponsored by DMRP, but additional work is necessary. The effects of secondary compression during sedimentation and consolidation before start of densification treatment have not been considered and are believed to be of major importance in determining the initial water content and density of dredged material. In addition, the available analyses need to be compared with results from laboratory and field tests to establish the validity of available theories and to modify them as required.

Densification Treatment Research

198. The benefits and utility of densification treatment have been examined herein but should be verified by field tests under a variety of field conditions having a range of dredged material and of disposal area foundation conditions. The latter should include pervious and impervious soils. The field tests should be instrumented and sampled at intervals.

Densification by loading

199. Conventional engineering techniques involving densification by loading are considered to be understood well enough to be applied to dredged material densification treatment, if desired. Principal uncertainties involve possible construction problems arising because of the extremely soft nature of dredged material requiring densification. Research required can best be accomplished as part of demonstration test uses of various methods. A major problem requiring study is how to place a layer of sand over large disposal areas without permitting local concentrations of sand that result in displacement of the dredged material. Research in this area could consist of underwater placement, use of various spreaders, etc., to secure a uniform thickness of sand fill.

Densification by drainage

200. Seepage consolidation. Seepage consolidation by downward flow of ponded water of dredged material is particularly attractive where foundation conditions underlying the dredged material are sufficiently pervious to prevent pore pressure development in the foundation, since this would eliminate or reduce downward seepage gradients. This possibility of seepage consolidation affords an extremely low-cost method for stabilization where foundation conditions are suitable, but needs research to establish its feasibility.

201. Underdrainage. Underdrainage, especially with vacuum pumping, affords an attractive means for stabilization. However, further studies, both field and analytical, are desirable. Plastic collector pipes that can be unrolled from large coils and have their own plastic

filter cloth should be investigated as underdrainage collectors with and without sand layers.

202. Geodrains. Geodrains offer a possibility for use as horizontal drains and also as inexpensive vertical drains. It is suggested that this possibility be further explored by determining the hydraulic conductivities of Geodrains and their stability as filters in dredged material. A Geodrain may be a simple, vertical drain, substantially less expensive than anything that has been used in previous engineering practice. It may be possible to use very lightweight equipment for economically installing large numbers of Geodrains. Geodrains may also be useful if inserted vertically in desiccation cracks to connect newly deposited dredged material with underdrainage and avoid sealing effects of a desiccation crust.

Densification by desiccation

203. Desiccation appears to offer the most significant opportunity for securing densification of disposal materials at low cost. It is recommended that work currently being done in this area be pursued and intensified. This work should be expanded to include possible use of Geodrains or other vertical drainage through crusts between intermittently placed layers of dredged material. Desiccation achieved by vegetation or by surface drying should be investigated from the viewpoint of engineering characteristics involved. Suction pressures caused by surface drying or by vegetation should be measured, together with changes in water contents and shear strengths. Measurements should be made to determine if surface drying or water demand by root systems can effect deep lowerings of the groundwater level during periods of low rainfall. For example, it can be speculated that surface trenching might lower the groundwater level 2 or 3 ft, whereas suction pressures from deep root systems, or perhaps surface drying, might exist to depths of 5 to 8 ft and, hence, increase loadings on deeper soils. This might develop only during periods of low rainfall, but an intermittent effect could be cumulative.

Densification by chemical treatment

204. Stabilization by chemicals appears to require, and merit,

research only in the manner in which flocculants are dispersed in the dredged material. Available expertise, in the private sector, seems adequate to select flocculants for any case where dredged material settles out of suspension so slowly that the process must be accelerated.

PART VIII: CONCLUSIONS

205. The following conclusions are made on the basis of information presented. They relate primarily to densification for the purpose of providing additional disposal area capacity.

Soil Types in Disposal Areas

206. Dredged material varies from sands to silts and fine-grained plastic silty clays and clays. Sands and silts consolidate rapidly and are not considered troublesome, nor susceptible to densification treatment. Fine-grained silty clays and clays are weak, compressible, and undesirable as fill and borrow materials. Only such materials have been considered in this report.

207. The natural water content of dredged material immediately after sedimentation is several times the LL. After some surface drainage and drying has occurred, the limited data available suggest that water contents are about equal to the LL.

208. Fine-grained dredged material usually has Atterberg limits that plot close to Casagrande's A-line on the plasticity plot. This offers a simple basis for correlating soil properties for preliminary design computations.

Applicability of Conventional Densification Methods

209. Soil types and conditions in dredged material disposal areas are similar to those encountered in some conventional soil mechanics and foundation engineering stabilization applications. However, conventional applications have encountered difficulties when soil types and conditions were as poor as those of dredged material. These difficulties can be avoided if personnel are experienced in soft soil stabilization design.

210. The practicability of using conventional densification techniques to secure increased disposal area capacity depends more

upon economic and other factors than upon technical considerations.

Increased Disposal Area Capacity

211. A large volume decrease occurs when the water content of dredged material is reduced from its initial value after sedimentation to the LL. According to field observations currently available, this reduction in water content can be achieved by simple surface drainage combined with crust development and slight lowering of the groundwater level in the dredged material.

212. A reduction in water content below the LL is achieved with much greater difficulty and results in less volume decrease, and, hence, in less increase in storage capacity. The amount of storage capacity that can be achieved with densification depends on the plasticity characteristics of the dredged material, which are related to compressibility characteristics.

213. The increase in disposal area capacity that can be achieved by densification can be related to the Atterberg limits of the dredged material. Using surcharge and drainage techniques, materials having LL less than 50 undergo volume decreases less than about 5 to 15 percent. If the LL is between 50 and 100, disposal area capacity may be increased from 10 to 20 percent for most densification treatments. If the LL is as high as 200, the increase in capacity may be as much as 20 to 30 percent.

214. Desiccation and seepage consolidation techniques produce the least costly additional storage volume. Desiccation may cause storage volume increases of 25 to 60 percent for LL of 50 to 200. Seepage consolidation and underdrainage with vacuum pumping are attractive.

215. Estimates of increased disposal area capacity from densification have assumed initial moisture contents equal to the LL. This is intended to apply to disposal areas when surface drainage and a surface crust have developed. This assumption should be further examined.

216. Disposal area foundation consolidation from surcharge loading and drainage treatments may be large where foundation soils are soft,

compressible, and thick. Densification treatments may result in substantial increases in disposal area storage capacity under these conditions, and foundation consolidation should always be evaluated.

217. Desiccation can produce the largest storage capacity increase of any of the densification treatments considered, and the cost is less than for other techniques. However, the method may not be readily usable for areas limited in size where flexibility in scheduling storage of dredged material does not exist. It is generally not feasible for treating existing disposal areas where substantial filling has already occurred.

Densification Versus Dike Raising

218. Surface drainage and surface drying should be promoted in all disposal areas to reduce water contents to the LL or lower if possible.

219. Increased storage capacity from densification treatment may be the equivalent of raising the height of retaining dikes only a few feet. Dike raising, where permissible, is the lowest cost alternative for increased storage capacity.

Dredged Material As Borrow

220. Fine-grained plastic clays having high LL are undesirable borrow materials for most purposes where strength and compressibility of the material are important considerations.

221. Dredged material treated by loading or drainage techniques cannot be reduced in water content sufficiently to make it useful as sources of borrow material.

222. Desiccation techniques and placement of dredged material in 1- to 3-ft layers could, under favorable conditions, reduce the water content sufficiently to permit use of the material where high LL borrow material is acceptable.

Upgrading of Disposal Areas

223. Disposal areas located in urban centers are especially attractive for development purposes, often providing an inexpensive and strategically located site.

224. Conventional stabilization techniques can be used to improve disposal areas so they can support substantial one- or two-story buildings without objectionable settlement. Secondary compression effects must be included when this use is anticipated.

225. When used for parks, golf courses, etc., disposal areas can be easily upgraded by conventional densification treatments to avoid objectionable settlements. The dredged material can be landscaped to provide rolling topography when desired.

226. Benefits of placing dredged material in disposal areas in urban centers may be large and the value of land created may pay for virtually any conventional type of densification treatment. This aspect has not been included in this report.

Chemical Treatment

227. Chemical densification treatments do not appear applicable for increasing disposal area storage capacity.

228. Flocculants ordinarily do not appear to be required to expedite settlement of dredged material.

229. Occasionally dredged material may be slow to drop out of suspension in reasonable time periods. In these cases, flocculants can be beneficial. Suitable flocculants must be selected by appropriate tests for specific site conditions. This is within the state of the art, especially in the private sector.

230. The efficient introduction of flocculants may require experimentation on a site, since the manner in which flocculants are introduced may determine if they are beneficial.

231. Flocculants may effectively accelerate sedimentation where

required, but thereafter have no significant effect on the engineering behavior of dredged material.

Recommended Research

232. Further research in the following areas is considered to have a Category I priority:

a. Combined sedimentation-consolidation tests with large test devices, at least 6 ft high and 4 to 12 ft in diameter.

b. Evaluation of Atterberg's "upper liquid limit."

c. Theoretical analyses of the combined sedimentation-consolidation process including effect of secondary compression in the early stages before densification treatment is undertaken.

d. Determination of the condition of dredged material after placement in disposal areas. This should include various types of dredged material and various disposal area foundation conditions. This work can be done simply in a large number of disposal areas using small-diameter displacement samplers with liners. Water contents and Atterberg limits should be determined. The "one-point" LL test will probably be adequate.

e. Field test of drainage techniques such as: (a) pumped underdrainage with induced vacuum, (b) seepage consolidation with normal unpumped underdrainage, and (c) seepage consolidation with pumped underdrainage with induced vacuum.

f. Field tests of desiccation by vegetation and by surface trenching and surface drying should be combined with engineering tests to determine if beneficial effects can be induced to depths substantially greater than currently expected or would be possible by surface trenching. This work should include measurement of soil moisture suctions at various depths and relationship to engineering predictions, water contents, settlements, piezometer pressures, and similar engineering tests. These engineering tests must be combined with associated biological research.

233. Additional research described below, classified Category II, should be undertaken when possible, and is considered desirable:

a. Effects of secondary compression when densification is undertaken for site development purposes.

b. Consolidation of high-water-content soils under small effective stress increments.

c. Various types of collector pipe systems for internal and underdrainage design. These include Geodrains and plastic pipes that can be unrolled from large coils and equipped with plastic filter-cloths.

d. Introduction techniques for flocculants.

e. Thermal densification techniques.

REFERENCES

1. Little, Arthur D., Inc., "A Feasibility Study of Lawn Sod Production and/or Related Activities on Dredged Material Disposal Sites," Contract Report D-75-1, Jan 1975, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

2. Bishop, A. W. and Vaughan, P. R., "Consolidation of Fine-Grained Dredged Material After Hydraulic Deposition," Aug 1972, National Ports Council, London, England.

3. Krizek, R. J. and Salem, A. M., "Behavior of Dredged Materials in Diked Containment Areas," Environmental Protection Agency Grants 15070-GCK and R-800948, Technical Report No. 5, Sep 1974, Northwestern University, Evanston, Ill.

4. Krizek, R. J., Giger, M. W., and Hummel, P. L., "Organic Content and Engineering Behavior of Typical Maintenance Dredgings," presented to the Fourth Southeast Asian Conference on Soil Engineering, Kuala Lumpur, West Malaysia, Apr 1975.

5. Schmidt, N. O., A Study of the Isolation of Organic Matter as a Variable Affecting Engineering Properties of a Soil, Ph. D. Thesis, University of Illinois, Urbana, Ill., 1965.

6. Habibagahi, K., Influence of Temperature on Consolidation Behavior of Remolded Organic Paulding and Inorganic Paulding Soils, Ph. D. Thesis, University of Illinois, Urbana, Ill., 1969.

7. U. S. Army Engineer District, Phildelphia, CE, "Long-Range Spoil Disposal Study; Part II, Substudy 1, Short-Range Solution," Jun 1969, Phildelphia, Pa.

8. Krizek, R. J., Karadi, G. M., and Hummel, P. L., "Engineering Characteristics of Polluted Dredgings," Environmental Protection Agency Grants 15070-GCK and R-800948, Technical Report No. 1, Mar 1973, Department of Civil Engineering, Northwestern University, Evanston, Ill.

9. Krizek, R. J., Roderick, G. L., and Jin, J. S., "Stabilization of Dredged Materials," Environmental Protection Agency Grants 15070-GCK and R-800948, Technical Report No. 2, 1974, Northwestern University, Evanston, Ill.

10. Krizek, R. J. and Casteleiro, M., "Mathematical Model for One-Dimensional Desiccation and Consolidation of Dredged Materials," Environmental Protection Agency Grants 15070-GCK and R-800948, Technical Report No. 3 (in publication), Northwestern University, Evanston, Ill.

11. Krizek, R. J., Gallagher, B. J., and Karadi, G. M., "Water Quality Study for a Dredgings Disposal Area," Environmental Protection Agency Grants 15070-GCK and R-800948, Technical Report No. 4, 1974, Northwestern University, Ill.

12. Krizek, R. J. and Giger, M. W., "Use of Dredgings for Landfill," Environmental Protection Agency Grants 15070-GCK and R-800948, Final Report (in preparation), Northwestern University, Evanston, Ill.

13. _________, "Storage Capacity of Diked Containment Areas for Polluted Dredgings," Proceedings of the Sixth World Dredging Conference, 1974, pp 354-364.

14. Krizek, R. J. and Karadi, G. M., "Disposal of Polluted Dredgings from the Great Lakes Area," Proceedings of the First World Congress on Water Resources, Vol 4, 1973, pp 482-491.

15. Krizek, R. J. and Salem, A. M., "Time-Dependent Development of Strength in Dredgings," 1975, Northwestern University, Evanston, Ill.

16. Hummel, P. L. and Krizek, R. J., "Sampling of Maintenance Dredgings," Journal of Testing and Evaluation, American Society for Testing and Materials, Vol 2, No. 3, May 1974, pp 139-145.

17. Krizek, R. J., Jin, J. S., and Salem, A. M., "Permeability and Drainage Characteristics of Dredgings," Proceedings of the Seventh Dredging Seminar, New Orleans, La., Nov 1974.

18. Englehardt, W. V. and Gaida, K. H., "Concentration Changes of Pore Solutions During the Compaction of Clay Sediments," Journal of Sedimentary Petrology, Vol 33, No. 4, Dec 1963, pp 919-930.

19. Yong, R. N. and Warkentin, B. P., Introduction to Soil Behavior, MacMillan Co., New York, 1966.

20. Krizek, R. J. and Sheeran, D. E., "Slurry Preparation and Characteristics of Samples Consolidated in the Slurry Consolidometer," Contract Report S-70-6, Report 2, Jun 1970, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

21. Salem, A. M. and Krizek, R. J., "Consolidation Characteristics of Dredging Slurries," Journal of the Waterways, Harbors, and Coastal Engineering Division, American Society of Civil Engineers, Vol 99, No. WW4, Nov 1973, pp 439-457.

22. Sheeran, D. E. and Krizek, R. J., "Preparation of Homogeneous Soil Samples by Slurry Consolidation," Journal of Materials, American Society for Testing and Materials, Vol 6, No. 2, Jun 1971, pp 356-373.

23. Skempton, A. W., "Notes on the Compressibility of Clays," Quarterly Journal of the Geological Society of London, Vol C, Parts 1 and 2, No. 397-398, Jul 1944, pp 119-135.

24. Salem, A. M. and Krizek, R. J., "Secondary Compression of Maintenance Dredgings," submitted to the Fifth Panamerican Conference on Soil Mechanics and Foundation Engineering, Buenos Aires, Argentina, Oct 1975.

25. So, R. K.-M., The Influence of Temperature, Carbon Content, and Preloading on Secondary Consolidation of a Clay, M. S. Thesis, University of Missouri at Rolla, 1971.

26. Sangrey, D. A., "Obtaining Strength Profiles with Depth for Marine Soil Deposits Using Disturbed Samples," Underwater Soil Sampling, Testing, and Construction Control, American Society for Testing and Materials Special Technical Publication 501, 1972, pp 106-121.

27. U. S. Army Engineer District, Buffalo, CE, "Summary Report of Tests, Subsurface Explorations of Dredged Diked Disposal Area No. 1, Buffalo Harbor," 31 Jan 1972.

28. U. S. Army Engineer District, Buffalo, "Summary Report of Tests, Subsurface Explorations of Dredged Diked Disposal Area No. 1, Cleveland Harbor," 31 Jan 1972.

29. Johnson, Stanley J., "Precompression for Improving Soils," Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol 96, No. SM1, Jan 1970, pp 111-144.

30. __________, "Foundation Precompression with Vertical Sand Drains," Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol 96, No. SM1, Jan 1970, pp 145-175.

31. Moran, Proctor, Mueser, and Rutledge, Consulting Engineers. "Study of Deep Soil Stabilization by Vertical Sand Drains," Report to the Bureau of Yards and Docks, Department of the Navy, Jun 1958

32. Haley and Aldrich, Consulting Soil Engineers, "Engineering Properties of Foundation Soils, Long Creek-Fore River and Back Cove Area, Portland, Maine," Report No. 1 to Maine State Highway Commission, Oct 1969.

33. Henkel, D. J., "Problems Associated with the Construction of the Ebute Metta Causeway over Soft Clays in Lagos, Nigeria," Paper 3/16, Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering, Montreal, Vol II, Divisions 3-6, University of Toronto Press, Canada, 1965.

34. Margason, E. and Arango, I., "Sand Drain Performance on a San Francisco Bay Mud Site," Proceedings, Specialty Conference on Performance of Earth and Earth-Supported Structures, Soil Mechanics and Foundation Division, American Society of Civil Engineers, Purdue University, Lafayette, Ind., Vol I, Part 1, Jun 1972, pp 181-210.

35. Halton, G. R., Loughney, R. W., and Winter, E. "Vacuum Stabilization of Subsoil Beneath Runway Extension at Philadelphia International Airport," Proceedings, 6th International Conference on Soil Mechanics and Foundation Engineering, Vol 2, 1965, pp 61-65.

36. Dredged Material Research, Notes News Reviews, etc., Miscellaneous Paper D-76-1, Jan 1976, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

37. Kjellman, W., "Consolidation of Clay Soil by Means of Atmospheric Pressure," Proceedings of the Conference on Soil Stabilization, Massachusetts Institute of Technology, Cambridge, Mass., Jun 18-20, 1952, pp 258-263.

38. __________, Discussion of "Consolidation of Fine-Grained Soils by Drain Wells," by Reginald A. Barron, Transactions, American Society of Civil Engineers, Vol 113, 1948, pp 748-751.

39. Calhoun, C. C., Jr., "Trip Report," 29 Aug 1975, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

40. Chadney, R. F., "Preparation of Dredged Spoil Deposit Areas," The Dock and Harbor Authority, Jul 1968, pp 115-117.

41. De Nekker, J. and In's Veld, J. K., "Dredged Rotterdam Harbour Mud: Its Qualities and Use as Soil," Terra et Aqua, No. 8/9, 1975, pp 34-40.

42. U. S. Bureau of Mines, "The Florida Phosphate Slimes Problem; A Review and a Bibliography," Information Circular 8668, 1975.

43. Bromwell, L. G., Progress Report, Florida Phosphatic Clays Research Project, Apr-Jun 1974, 15 Jul 1974.

44. Davenport, J. E., Kieffer, G. W., and Brown, E. H., "Disposal of Phosphate Tailing," Tennessee Valley Authority Report No. 661, 1953, Wilson Dam, Ala.

45. Bromwell, L. G., Progress Report, Florida Phosphatic Clays Research Project, Jan-Mar 1974, 10 Apr 1974.

46. __________, Progress Report, Florida Phosphatic Clays Research Project, Jul-Dec 1974, 4 Feb 1975.

47. Vogt, M. F., "Development Studies on Dewatering Red Mud, Kaiser Aluminum and Chemical Corporation," Gramercy, La., presented at the 103rd Annual Meeting of the AIME, 25 Feb 1974, Dallas, Tex.

48. U. S. Soil Conservation Service, Drainage of Agricultural Land, Water Information Center, Inc., Port Washington, N. Y., 1973.

49. Atterberg, A., "Plasticity of Clays," Draft Translation 413, Sep 1974, U. S. Army Cold Regions Research and Engineering Laboratory, CE, Hanover, N. H.

50. Boyd, M. B., et al., "Disposal of Dredged Spoil; Problem Identification and Assessment and Research Program Development," Technical Report H-72-8, Nov 1972, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

51. Reikenis, R., Elias, V., and Drabkowski, E. F., "Regional Landfill and Construction Material Needs in Terms of Dredged Material Characteristics and Availability," Contract Report D-74-2, Vol I, May 1974, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

52. Johnson, L. E. and McGuinness, W. V., Jr., "Guidelines for Material Placement in Marsh Creation," Contract Report D-75-2, Apr 1975, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

53. U. S. Army Engineer District, Philadelphia, CE, "Long-Range Spoil Disposal Study; Part III, Substudy 2: Nature, Source, and Cause of the Shoal," Sep 1973, Phildelphia, Pa.

54. Oosterbaan, N., "On the PIANC Classification of Soils to be Dredged," Terra et Aqua, No. 5, 1973, pp 29-32.

55. U. S. Army Engineer District, Charleston, CE, "Investigation for Reduction of Maintenance Dredging in Charleston Harbor, S. C.; Part 2, Materials Testing Laboratory Investigation of Properties of Shoals and Materials in Movement," Vol II-2, Feb 1954, Charleston, S. C.

56. U. S. Army Engineer District, Buffalo, CE, "Dredging and Water Quality Problems in the Great Lakes," Vol 8, Appendices C6 to C9, Investigation Reports, Jun 1969, Buffalo, N. Y.

57. U. S. Army Engineer District, San Francisco, CE, "Dredge Disposal Study, San Francisco Bay and Estuary; Appendix J, Land Disposal," Oct 1974, San Francisco, Calif.

58. Rieke, H. H., III and Chilingarian, G. V., Compaction of Agrillaceous Sediments, Developments in Sedimentology 16, American Elsevier Publishing, New York, 1974.

59. Bartos, M. J., Jr., "Classification and Engineering Properties of Dredged Material," (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

60. Mohr, A. W., "Development and Future of Dredging," Journal of the Waterways, Harbors, and Coastal Engineering Division, American Society of Civil Engineers, Vol 100, No. WW2, May 1974, pp 69-83.

61. Mesri, G., and Olson, R. E., "Mechanisms Controlling the Permeability of Clays," Clays and Clay Minerals, Vol 19, No. 3, 1971, pp 151-158.

62. Murphy, W. L. and Zeigler, T. W., "Practices and Problems in the Confinement of Dredged Material in Corps of Engineers Projects," Technical Report D-74-2, May 1974, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

63. U. S. Army Engineer District, Phildelphia, CE, "Long-Range Spoil Disposal Study; Part IV, Substudy 3, Development of New Dredging Equipment and Technique," Jun 1969, Phildelphia, Pa.

64. 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.

65. Skempton, A. W., "The Consolidation of Clays by Gravitational Compaction," Quarterly Journal of Geological Society of London, Vol 125, 1970, pp 373-411.

66. Knill, J. L., et al., "Artificially Simulating the Geological History of Clay," Final Technical Report, Jul 1974, U. S. Army European Research Office, London, England.

67. Freitag, D. R., "Soil as a Factor in Shoaling Processes; A Literature Review," Technical Bulletin No. 4, Jun 1960, Committee on Tidal Hydraulics, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

68. Johnson, L. D., "Mathematical Model for Predicting the Consolidation of Dredged Material in Confined Disposal Areas," Technical Report D-76-1, Jan 1976, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

69. Olson, R. E., "Shearing Strengths of Kaolinite, Illite, and Montmorillonite," Journal of the Geotechnical Engineering Division, American Society of Civil Engineers, Vol 100, No. GT11, Nov 1974, pp 1215-1229.

70. Whitehouse, U. G., Jeffrey, L. M., and Debbrecht, J. D., "Differential Settling Tendencies of Clay Minerals in Saline Waters," Proceedings of the Seventh National Conference on Clays and Clay Minerals, 1960, pp 1-79.

71. Krone, R. B., "Flume Studies of the Transport of Sediment in Estuarial Shoaling Process," Final Report, Jun 1962, Hydraulic Engineering Laboratory and Sanitary Engineering Research Laboratory, University of California, Berkeley.

72. May, E. B., "Environmental Effects of Hydraulic Dredging in Estuaries," Bulletin No. 9, Apr 1973, Alabama Marine Resources Laboratory, Dauphin Island, Ala.

73. Leonards, G. A. and Altschaeffl, A. G., "Compressibility of Clay," Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol 90, No. SM5, Sep 1964, pp 133-155.

74. U. S. Army Engineer District, Wilmington, CE, "Final Environmental Statement, Maintenance Dredging of Basins and Channels at Military Ocean Terminal, Sunny Point, Southport, North Carolina," prepared by Coastal Zone Resources Corporation, Wilmington, North Carolina, May 1972.

75. Department of the Navy, Naval Facilities Engineering Command, "Design Manual, Soil Mechanics Foundations, and Earth Structures," NAVFAC DM-7, Mar 1971, Washington, D. C.

Preceding Page Blank

Table 1

Planning Factors Relating to Disposal Area Densification

Factor	Remarks
Ultimate use of area.	Can property value enhancement be considered when evaluating densification alternatives?
When will increased storage be required?	Is time a factor? Will increased storage be required in 2 yr, 5 yr, 10 yr, etc?
What is practicable cost of densification treatment--in terms of cost/cubic yard of added storage provided by densification?	If additional disposal sites are available for purchase, evaluate cost of buying more sites versus fewer sites with densification treatment.
Required condition of disposal area when maximum desired height is reached.	Will disposal area be required to be essentially stable under its own weight so it can be used as a park area without large maintenance expense for roads or utilities?
	Will disposal area be developed for manufacturing, research park, office buildings, etc., by (a) Federal Government, (b) State or local governments, or (c) private developers.
	Is it under water?
Physical characteristics of disposal area.	Is foundation highly compressible? Will foundation settlement provide added storage? Is there a continuous sand layer in the foundation that could function as an underdrainage layer? Has area been used as a dump area for rock and building debris, i.e., can vertical drains be driven through surface materials?
Physical characteristics of dredged material.	What are grain-size, Atterberg limits, permeability, and consolidation characteristics?
	What variation in materials will occur?
	Do materials to be dredged contain sand? Can sands be obtained when needed and used as underdrainage layers?
	Can required dredging be deepened slightly to provide sands for underdrainage layers, vertical drains, or surcharge loading?

Table 2

Engineering Properties of Dredged Material in Confined Disposal Areas Along Delaware River (from U. S. Army District, Philadelphia[7])

Disposal Site	Filling Period*	Wet Unit Weight pcf	Water Content %	Dry Unit Weight pcf	Specific Gravity of Solids	Liquid Limit %	Plastic Limit %	Plasticity Index %	Void Ratio	Degree of Saturation %	Liquidity Index**	Water Content: Liquid Limit
Edgemoor (Part A)	1911-1967	94.8	93.9	48.9	2.45	111	45	66	2.13	100.0	0.74	0.85
Oldmans No. 1	1946-1963	94.8	83.7	51.6	2.43	125	51	74	1.94	100.0	0.44	0.67
Darby Creek	1956-1967	96.1	84.1	52.2	2.50	102	44	58	1.99	100.0	0.69	0.82
Pigeon Point	1948-1966	94.4	76.4	53.5	2.55	91	38	53	1.97	98.9	0.72	0.84
Average		95.0	84.5	51.6	2.48	107	45	62	2.01	99.7	0.65	0.80

* Laboratory tests made in 1967.
** Liquidity Index = (Water Content - Plastic Limit)/(Liquid Limit - Plastic Limit).

Table 3

Engineering Properties of Dredged Material in Confined Disposal Areas near Toledo Harbor (from Krizek and Salem3)

Disposal Area	Age of Disposal Area yr	Wet Unit Weight pcf	Water Content %	Dry Unit Weight pcf	Liquid Limit %	Plastic Limit %	Plasticity Index %	Organic Matter* %	Liquidity Index**	Water Content: Liquid Limit
Island	6	101.5	54.7	65.6	67	32	35	5.6	0.65	0.82
	7	105.1	59.5	65.9	72	35	37	--	0.66	0.83
Riverside	3	99.5	59.4	62.4	70	33	37	4.8	0.71	0.85
	4	95.2	60.8	59.2	71	39	32	--	0.68	0.86
	5	99.1	58.6	62.5	70	38	32	--	0.64	0.84
Penn 7	1	94.2	85.1	50.9	79	35	44	--	1.14	1.08
Penn 8	7	97.0	63.1	59.5	73	40	33	--	0.70	0.86
	8	100.4	58.4	63.4	70	38	32	--	0.64	0.83

* Organic Matter = 1.80 Organic Carbon.
** Liquidity Index = (Water Content - Plastic Limit)/(Liquid Limit - Plastic Limit).

Table 4

Engineering Properties of Dredged Material in Diked Disposal Area No. 1, Buffalo Harbor*

(from U. S. Army District, Buffalo[27])

Boring No.	Depth ft	Estimated Age of Material When Sampled yr	Wet Unit Weight pcf	Water Content %	Dry Unit Weight pcf	Specific Gravity of Solids	Liquid Limit %	Plastic Limit %	Plasticity Index %	Classification**	Void Ratio	Degree of Saturation %	Cohesion pcf	Liquidity Index †	Water Content: Liquid Limit
U71-2	0.6-1.1	1	93.2	69.4	55.0	2.60	74	42	32	OH	1.95	92.5	--	0.86	0.94
	4.7-5.8	2	93.0	45.5	63.9	2.63	75	40	40	OH	1.57	76.2	--	0.26	0.61
	6.3-8.0	3	92.6	79.4	51.6	2.59	--	--	--	OH	2.13	86.5	145	--	--
	10.5-12.4	4	100.7	55.1	64.9	2.80	55	30	25	OH	1.69	91.3	--	1.00	1.00
U71-3	0.0-1.5	1	92.4	70.8	54.1	2.58	80	39	41	OH	1.98	92.3	--	0.78	0.89
	4.2-5.7	2	91.0	86.4	48.8	2.65	81	38	43	OH	2.39	95.8	--	1.13	1.07
	6.3-8.2	2-3	96.0	72.7	55.6	2.54	63	33	30	OH	1.85	99.8	120	1.32	1.15
	10.5-12-3	4	100.2	56.8	63.9	2.79	50	31	19	OH	1.73	91.6	--	1.36	1.14
	12.6-4.7	4	101.8	55.0	65.7	2.86	51	34	17	OH	1.65	95.5	140	1.24	1.08
U71-4	0.0-1.8	1	94.6	64.3	57.6	2.64	77	38	39	OH	1.86	91.3	--	0.67	0.84
	2.1-3.6	1-2	88.2	89.7	46.5	2.54	89	44	45	OH	2.41	94.5	--	1.02	1.01
	6.3-8.1	3	93.6	77.9	52.6	2.54	76	40	36	OH	2.12	93.3	110	1.05	1.03
	8.4-10.2	3-4	94.1	71.0	55.0	2.64	--	--	--	OH	2.00	93.7	--	--	—
	10.5-11.8	4	95.4	72.5	55.3	2.70	--	--	--	OH	2.05	95.5	--	--	--
U71-5	2.1-2.4	1	98.0	37.8	71.1	2.66	24	24	0	ML	1.33	75.6	--	--	--
	2.4-3.9	1-2	89.9	80.6	49.8	2.66	76	38	38	OH	2.33	92.0	--	1.12	1.06
	6.3-8.1	3	88.5	88.7	46.9	2.58	83	39	44	OH	2.43	94.2	--	1.13	1.07
	10.5-12.3	4	100.3	57.5	63.7	2.79	49	28	21	OL-OH	1.73	92.7	130	1.40	1.17

* Dredged material placed in disposal area 1967-1971. Material sampled and tested in 1971.
** Unified Soil Classification System.
† Liquidity Index = (Water Content - Plastic Limit)/(Liquid Limit - Plastic Limit).

Table 5

Engineering Properties of Dredged Material in Diked Disposal Area No. 1, Cleveland Harbor*

(from U. S. Army District, Buffalo[28])

Boring No.	Depth ft	Estimated Age of Material When Sampled yr	Wet Unit Weight pcf	Water Content %	Dry Unit Weight pcf	Specific Gravity of Solids	Liquid Limit %	Plastic Limit %	Plasticity Index %	Classification**	Void Ratio	Degree of Saturation %	Cohesion pcf	Liquidity Index†	Water Content: Liquid Limit
U71-2	7.2-9.2	2-2.5	108.2	48.2	73.0	2.80	44	29	15	OL	1.39	96.9	120	1.28	1.10
	11.4-13.2	2-2.5	92.0	78.0	51.7	2.56	84	37	47	OH	2.09	95.5	--	0.87	0.93
	14.9-16.8	2.5-3.5	91.8	74.1	52.7	2.67	70	35	35	OH	2.16	91.5	110	1.12	1.06
	23.3-24.8	2.5-3.5	86.0	84.9	44.1	2.61	99	42	57	OH	2.69	92.0	170	0.93	0.96
U71-3	14.7-16.6	2.5-3.5	90.5	75.3	51.6	2.62	73	35	38	OH	2.17	90.3	190	1.06	1.03
	23.1-25.0	2.5-3.5	96.9	65.0	58.7	2.72	64	37	27	OH	1.84	93.5	140	1.04	1.02
U71-4	10.5-12.3	2-2.5	88.6	89.0	46.9	2.50	86	36	50	OH	2.33	95.6	90	1.06	1.03
	18.9-20.9	2.5-3.5	95.3	71.8	55.5	2.63	66	57	9	OH	1.96	96.5	90	1.64	1.08
	24.1-24.8	2.5-3.5	79.3	90.7	41.6	2.63	66	37	29	OH	2.94	96.4	90	1.85	1.37
U71-5	8.4-10.3	2-2.5	--	88.8	--	2.58	73	33	40	OH	--	--	--	1.40	1.22
	14.7-16.4	2.5-3.5	89.4	85.9	48.1	2.54	72	34	38	OH	2.29	95.2	70	1.37	1.19
	18.9-20.7	2.5-3.5	91.5	75.7	52.1	2.60	63	30	33	OH	2.12	93.0	80	1.38	1.20

* Dredged material placed in disposal area 1968-1969. Material sampled and tested in 1971.
** Unified Soil Classification System.
† Liquidity Index = (Water Content - Plastic Limit)/(Liquid Limit - Plastic Limit).

Table 6

Engineering Properties of Dredged Material in Upper Polecat Bay Disposal Area near Mobile Harbor*

Depth ft	Wet Unit Weight pcf	Water Content %	Dry Unit Weight pcf	Liquid Limit %	Plastic Limit %	Plasticity Index %	Classification**	Liquidity Index†	Water Content: Liquid Limit
0 - 2	72.3	166.8	27.1	111	41	70	CH	1.80	1.50
2 - 4	77.6	127.5	34.1	89	30	59	CH	1.65	1.43
4 - 6	85.1	98.0	43.0	71	26	45	CH	1.60	1.38
6 - 8	90.1	85.7	48.5	83	27	56	CH	1.05	1.03
8 - 10	96.2	70.0	56.6	66	25	41	CH	1.10	1.06

* Dredged material placed in disposal area in 1971 and 1973. Material sampled and tested in 1975.
** Unified Soil Classification System.
† Liquidity Index = (Water Content - Plastic Limit)/(Liquid Limit - Plastic Limit).

Table 7

Mississippi River Gulf Outlet - New Orleans, Dredged Material in Disposal Area*

Liquid Limit %	Plastic Limit %	Plasticity Index %	Water Content %	Liquidity Index %	Water Content: Liquid Limit %
92	21	71	88	0.94	0.96
66	21	45	50	0.64	0.76
73	24	49	47	0.47	0.64
74	21	53	67	0.87	0.91

* Borings U-2A and U-2C, samples above elevation 0.0.

Table 8

Summary of Atterberg Limits and Water Content

Location	Water Content %	Liquid Limit	Plastic Limit	Plasticity Index	Depth ft	Liquidity Index	Water Content:Liquid Limit
			Natural Conditions				
Charleston Harbor, S. C.	63-347	111-166	49-59	62-111		1.1 1.9 2.6	1 (3 tests) 1-1/2 (3 tests) 2 (3 tests)
Marcus Hook Shoal Delaware River	104-151	73-122	34-46	39-77		0.85-1.5 2.6	1.2 (14 tests) 1.8
San Francisco Bay	66-112	43-78	22-32	26-55		1.6-2.2	1.4
York River, Va.	167-220	150-160	38-43	107-122		1.5	1.4
Tilbury Tidal Basin, England*	131-181	152-163	43-149	14-113		0.2-1.2	0.9-1.2
Nine sites reported by Skempton[65]							
Seabed, top 25 cm	68-174	46-111				1.75	1.5
Tidal flats, top 25 cm	33-85	36-64				1.0	1.0
			Materials Placed in Confined Disposal Areas				
Delaware River site	84	107	45	62		0.65	0.80
Toledo Harbor		67-79	32-40	32-44		0.64-1.14	0.82-1.08
Buffalo Harbor, Area No. 1	38-89	50-89	28-44	21-45		0.67-1.40	0.84-1.17 (Mean = 1.04)
Mobile Bay, Upper Polecat Bay	70-167	66-111	25-41	41-70	0-6 6-10	1.7 1.0	1.4 1.0
Cleveland Harbor, Area No. 1	48-90	44-99	29-42	15-57		0.93-1.8	0.93-1.37 (Mean = 1.10)
Lake Ponchartrain, New Orleans	47-88	66-92	21-24	45-71		0.5-0.9	0.6-1.0

* Bishop and Vaughan, Reference 2.

Table 9

Liquidity Index and Water Content - Liquid Limit Ratios

Location	Liquidity Index			Water Content: Liquid Limit		
	Mean	Std Dev	N*	Mean	Std Dev	N*
Typical Dredging Locations						
Charleston Harbor	1.8	0.9	8	1.5	0.5	8
Delaware River	1.4	0.4	15	1.3	0.2	15
San Francisco Bay	1.8	0.3	3	1.4	0.1	3
York River, Va.	1.4	0.3	4	1.3	0.2	4
All Sites	1.5	0.6	32	1.3	0.3	30
In Disposal Areas						
Delaware River	0.6	0.1	4	0.8	0.1	4
Toledo Harbor	0.7	0.2	8	0.9	0.1	8
Buffalo Harbor	1.0	0.3	14	1.0	0.2	15
Cleveland Harbor	1.2	0.3	12	1.1	0.1	12
Mobile Harbor	1.4	0.3	5	1.3	0.2	5
Miss. River Gulf Outlet	0.7	0.2	4	0.8	0.1	4
All Sites	1.0	0.4	47	1.0	0.2	48

* N = number of tests.

Table 10

Engineering Properties of Some Typical Soils Stabilized by Conventional Techniques

(from Moran et al.[31])

Location	Water Content %	Liquid Limit %	Plastic Limit %	Plasticity Index %	Classification*	Liquidity Index**	Water Content: Liquid Limit
San Francisco Bay, Calif.	70	58	30	28	CL	1.43	1.21
Algiers, La.	380	400	265	135	PT	0.85	0.95
	68	83	56	27	CH	0.44	0.82
Point Pleasant, N. J.	76	102	48	54	MH	0.52	0.75
	131	149	83	66	OH	0.73	0.88
LaGuardia, N. Y.	90	95	38	57	CH	0.91	0.95
Yonkers, N. Y.	80	58	35	23	CH-OH	1.95	1.38

* Unified Soil Classification System.

** Liquidity Index = (Water Content - Plastic Limit)/(Liquid Limit - Plastic Limit).

Table 11

Dewatering-Densification Methodologies

Methodology	Technique	Status
Physical	Loading	Applicable
	Drainage	Applicable
	Desiccation	
	Surface drying	Applicable
	Capillary wicks	Proposed-not developed
Mechanical	Surface reworking	In use
	Surface drainage	In use
Chemical	Grouting	Not applicable
	Flocculants	Applicable
Thermal	Internal heating	Potentially applicable

Table 12

Dewatering-Densification by Physical Methods

Technique	Description
Loading	Temporary surcharge on surface of disposal area. Temporary surcharge with vertical drains to accelerate densification. a. Vertical sand drains. b. Kjellman cardboard drains. c. Geodrains. Surface ponding with plastic membranes. Vacuum mats.
Drainage and Drainage Combined with Other Techniques	Underdrainage with lowered water level. a. Natural sand foundation. b. Sand layers with collector pipes placed on disposal area before placement of dredged materials. Seepage pressure consolidation, i.e., surface ponding without surface membranes but with underdrainage. Internal drainage in dredged material after placement in disposal area. a. Horizontal sand layers with collector pipes. b. Sand finger drains with collector pipes. c. Geodrain and other drain strips, horizontal. d. Electro-osmosis. e. Vacuum wellpoints.
Desiccation	Surface evaporation. Surface trenching to increase desiccation depths. Vegetation. Capillary wicks.

Table 13

Conventional Densification Alternatives

(Physical Treatment Techniques)

Technique	Description	Benefits: Increased Settlement	Benefits: Accelerated Settlement	Benefits: Upgrading of Disposal Area
Surcharge loading only	Temporary surcharge fill	yes	yes	yes
	Water ponding on membrane	yes	yes	yes
	Surface vacuum mats	yes	yes	yes
Drainage and drainage combined with other techniques	Vertical drains	no	yes	no
	Underdrainage and internal drainage	yes	yes	yes
	Pumping from underlying sand layers	yes	yes	yes
	Surface trenching	yes	yes	no
	Electro-osmosis	yes	yes	yes
	Normal surface evaporation	yes	yes	no
Desiccation	Surface trenching	yes	yes	no
	Surface sloping	yes	yes	no
	Mechanical agitation	no	yes	no
	Internal heating	yes	yes	yes
	Vegetation	yes	yes	yes

Table 14

Volume Changes Associated with Decrease in Water Content

Water Content Change		Volume Decrease, Percent for LL Shown			
From	To	50	100	150	200
	Initial Water Content Equal to Twice LL				
2 × LL (LI = 2.00)	LL (LI = 1.00)	36	42	44	46
LL (LI = 1.00)	LI = 0.75	4	6	7	8
LI = 0.75	LI = 0.50	4	6	7	8
LI = 0.50	LI = 0.25	4	6	7	8
LI = 0.25	PL (LI = 0)	4	6	7	8
	Initial Water Content Equal to LL				
LL (LI = 1.00)	LI = 0.75	6	10	13	14
LI = 0.75	LI = 0.50	6	10	13	14
LI = 0.50	LI = 0.25	6	10	13	14
LI = 0.25	PL (LI = 0)	6	10	13	14

Note: See Figure 29 for plot of water content versus percent volume decrease.

Table 15

Time Required for Consolidation of a 10-Ft-Thick Layer of Dredged Material (See Figure 30)

Time, Yr			Average Percent of Consolidation	
From	To	Increment	Total	Increment
0	5.4	5.4	50	50
5.4	13.1	7.7	75	25
13.1	23.2	10.1	90	15

Table 16

Effective Stresses Possible from Use of Surcharge Loading

Condition	Maximum Effective Stress, psf Surface	5-ft Depth
Groundwater at surface	0	140
500 psf surcharge	500	640
1000 psf surcharge	1000	1140
Groundwater at 2 ft	large	270
5-ft surcharge	500	770
10-ft surcharge	1000	1300

Table 17

Effective Stresses Possible from Use of Drainage Treatments

Condition	Maximum Effective Stress psf	
	Surface	5-ft Depth
No drainage of disposal area; groundwater level at surface	0	140
Surface drying, groundwater level at depth of 2 ft	Large	270
Drainage layer underlying dredged material; groundwater level at base of dredged material	Large	450-770
Drainage layer underlying dredged material; groundwater level lowered by pumping in drainage layer and partial vacuum maintained in drainage layer by vacuum pumps fitted to dewatering pumps	Large	2200
Surface sand layer, membrane, and vacuum-dewatering; 15-in. vacuum in sand layer	1060	670-1200
Seepage consolidation; i.e., surface ponding and underdrainage (10-ft depth of ponded water)		
a. No vacuum in underdrainage layer	0	760
b. 15-in. vacuum in underdrainage layer	0	1290

Table 18

Water Content Decrease from Increase in Effective Stress

Initial Water Content and Liquid Limit	Water Content Decrease, % for $\Delta \bar{p}$, psf				Liquidity Index for Δp psf			
	200	500	1000	2000	200	500	1000	2000
50	3	6	10	13	0.84	0.70	0.56	0.40
100	8	16	24	32	0.86	0.73	0.60	0.45
150	13	25	37	51	0.86	0.74	0.61	0.47
200	18	34	50	69	0.86	0.74	0.62	0.48

Table 19

Summary of Effective Stress Increases

Condition	Densification Treatment		Effective Stress at 5-Ft Depth psf	
	Loading	Drainage	Total	Increase
Groundwater at 2-ft depth			270	0
Underdrainage, neglecting pore water suction		yes	460	190
Underdrainage assuming pore water suction		yes	770	500
500-psf surcharge	yes		770	500
Seepage consolidation with 10-ft deep surface ponding, no membrane; with underdrainage	yes	yes	760 1290	490 (No vacuum) 1020 (15-in. vacuum)
Surface vacuum loading; membrane, surface layer, and vacuum pumping in sand layer				
a. Without underdrainage	yes		670	400
b. With underdrainage	yes	yes	1200	930
1000-psf surcharge	yes		1270	1000
Underlying drainage layer with vacuum pumping		yes	2210	1940

Table 20

Additional Storage Volume and Cost of Densification Treatment

Treatment	Added Storage in Cu Yd/Acre LL				Cost of Densification Treatment, Dollars/Cu Yd Per Cu Yd of Storage for LL				Cost of Densification Treatment, Dollars/Cu Yd Per Acre of Disposal Area	Remarks
	50	100	150	200	50	100	150	200		
Temporary surcharge fill*										
1-ft-high surcharge	350	560	650	690	4.60	2.90	2.50	2.40	1,600	Fill placement and removal @ $1.00/cu yd
5-ft-high surcharge	1180	1860	2150	2290	6.80	4.40	3.80	3.50	8,100	
10-ft-high surcharge	1740	2730	3160	3390	9.30	5.90	5.10	4.80	16,100	
Temporary surcharge fill with vertical drains, 20-ft dredged material										
1-ft-high surcharge	450	690	820	870	33.00	21.50	18.10	17.10	14,900	
5-ft-high surcharge	1610	2520	2920	3130	13.30	8.50	7.30	6.80	21,400	
10-ft-high surcharge	2480	3990	4520	4820	11.80	7.60	6.50	6.10	29,400	
Water ponding surcharge with membrane and sand blanket collectors*										
8-ft depth of water	1180	1860	2150	2290	10.80	6.80	5.90	5.50	12,700	
16-ft depth of water	1740	2730	3160	3390	7.30	4.60	4.00	3.70	12,700	
Surface vacuum mat: membrane, sand blanket, collectors, and vacuum pumping*	1400	2190	2530	2710	8.60	5.50	4.80	4.50	12,200	

(Continued)

* 10-ft thickness of dredged material.

Table 20 (Concluded)

Treatment	Added Storage in Cu Yd/Acre LL				Cost of Densification Treatment, Dollars/Cu Yd Per Cu Yd of Storage for LL				Per Acre of Disposal Area	Remarks
	50	100	150	200	50	100	150	200		
Underdrainage*										
Foundation collectors	600	940	1100	1160	2.00	1.30	1.10	1.00	1,200	Assumes no suction in pore water
Collectors and Sand Blanket	600	940	1100	1160	4.70	3.00	2.60	2.40	2,810	
Underdrainage layer, pumped and vacuum induced*	1190	1850	2150	2300	6.10	3.90	3.40	3.20	10,100	5-yr pumping assumed with 50% consolidation
Seepage consolidation										
Underdrainage layer with collectors and ponded water surcharge, no membrane*	1220	1900	2210	2360	2.30	1.50	1.30	1.20	2,830	Consolidation from seepage forces only
Desiccation by placing in thin layers, draining and nominal trenching	2580	3870	4520	4840	0.62	0.42	0.36	0.33	1,610	

* 10-ft thickness of dredged material.

Table 21

Additional Storage Volume and Costs According to Added "Volumes Available"

Treatment	Added Storage in Cu Yd/Acre LL				Cost of Densification Treatment, Dollars/Cu Yd: Per Cu Yd of Storage for LL				Cost of Densification Treatment, Dollars/Cu Yd: Per Acre of Disposal Area
	50	100	150	200	50	100	150	200	
Underdrainage, with sand blanket and collectors	600	940	1100	1160	4.70	3.00	2.60	2.40	2,810
5-ft-high temporary surcharge fill	1180	1860	2150	2290	6.80	4.40	3.80	3.50	8,100
8-ft-deep water ponding with membrane, sand blanket, and collectors	1180	1860	2150	2290	10.80	6.80	5.90	5.50	12,700
Underdrainage layer with collectors; vacuum induced by pumping	1220	1850	2150	2300	6.10	3.90	3.40	3.20	10,100
Underdrainage layer with collectors, no membrane, ponded water surcharge, and no pumping; seepage consolidation	1220	1900	2210	2360	2.30	1.50	1.30	1.20	2,800
10-ft-high temporary surcharge fill	1740	2730	3160	3390	9.30	5.90	5.10	4.80	16,100
16-ft-deep water ponding with membrane, sand blanket, and collectors	1740	2730	3160	3390	7.30	4.60	4.00	3.70	12,700
Desiccation-placing in thin layers; draining and trenching	2580	3870	4520	4840	0.62	0.42	0.36	0.33	1,610

Table 22

Additional Storage Volume and Costs According to Cost Per Cubic Yard of Added Storage

Treatment	Added Storage in Cu Yd/Acre LL				Cost of Densification Treatment, Dollars/Cu Yd				
					Per Cu Yd of Storage for LL				Per Acre of Disposal Area
	50	100	150	200	50	100	150	200	
Desiccation-placing in thin layers; draining and trenching	2580	3870	4520	4840	0.62	0.42	0.36	0.33	1,600
Underdrainage layer with collectors, no membrane, ponded water surcharge, and no pumping, seepage consolidation	1220	1900	2210	2360	2.30	1.50	1.30	1.20	2,800
Underdrainage, with sand blanket and collectors	600	940	1100	1160	4.70	3.00	2.60	2.40	2,800
Underdrainage layer with collectors; vacuum induced by pumping	1190	1850	2150	2300	6.10	3.90	3.40	3.20	10,100
5-ft-high temporary surcharge fill	1180	1860	2150	2290	6.80	4.40	3.80	3.50	8,100
16-ft-deep water ponded with membrane, sand blanket, and collectors	1740	2730	3160	3390	7.30	4.60	4.00	3.70	12,700
10-ft-high temporary surcharge fill	1740	2730	3160	3390	9.30	5.90	5.10	4.80	16,100
8-ft-deep water ponding with membrane, sand blanket, and collectors	1180	1860	2150	2290	10.80	6.80	5.40	5.50	12,700

Table 23

Additional Disposal Area Storage by Raising Retaining Dikes

Dikes Raised ft	Added Storage Volume cu yd/acre	Added Dike Volume per Acre of 1000- to 3000-ft Area	Cost per Cubic Yard of Added Storage
0.5	810	190	$0.23
1.0	1610	380	0.24
1.5	2420	590	0.24
2.0	3230	800	0.25
2.5	4030	1020	0.25
3.0	4840	1250	0.26

Table 24

Comparison of Treatment Alternatives

Treatment Alternatives	Added Storage Volume %
Dessication or raise dikes 1.5 to 2.5 ft	15-25
Surcharge loading or raise dikes 1 ft	10
Underdrainage and water surcharge without membrane or raise dikes 0.5 ft	5

APPENDIXES A, B, AND C

of

WES TECHNICAL REPORT D-77-4

STATE-OF-THE-ART APPLICABILITY OF CONVENTIONAL DENSIFICATION TECHNIQUES TO INCREASE DISPOSAL AREA STORAGE CAPACITY

by

S. J. Johnson, et al

APPENDIX A: COMPOSITION OF SEDIMENT

Depositional Environments

1. Depositional environments and types of material generated in maintenance dredging in the United States[50*] are shown in Figures A1 and A2, respectively. Engineering properties of dredged material are determined to a large extent by the depositional environment from which they are obtained. Engineering problems associated with dredged coarse-grained materials from littoral zones are minimal in comparison to problems associated with fine-grained material encountered in routine maintenance dredging associated with commercial port facilities.[51]

Salinity of Soil Pore Water

2. Dredged material taken from soils deposited in a saline environment and subsequently placed in a diked disposal area may exhibit different engineering properties from soils which have been subjected only to a freshwater environment. As shown in Table A1, the majority of maintenance dredging in the United States is performed in saline waters.[50,52] Only on the Great Lakes and interior riverine environments is dredging performed in fresh waters. As shown in Figure A3, a salinity of 1 ppt exists 60 miles above the mouth of the Delaware River.[53] Similar conditions probably exist in other rivers where they discharge into salt water.

Classification and Engineering Properties of Bottom Sediments

3. In 1973, the Permanent Internal Association of Navigation Congress (PIANC) proposed a classification system for soils to be dredged, given in Table A2.[54] In the United States, the Unified Soil

* Raised numbers refer to similarly numbered items in the References at the end of the main text.

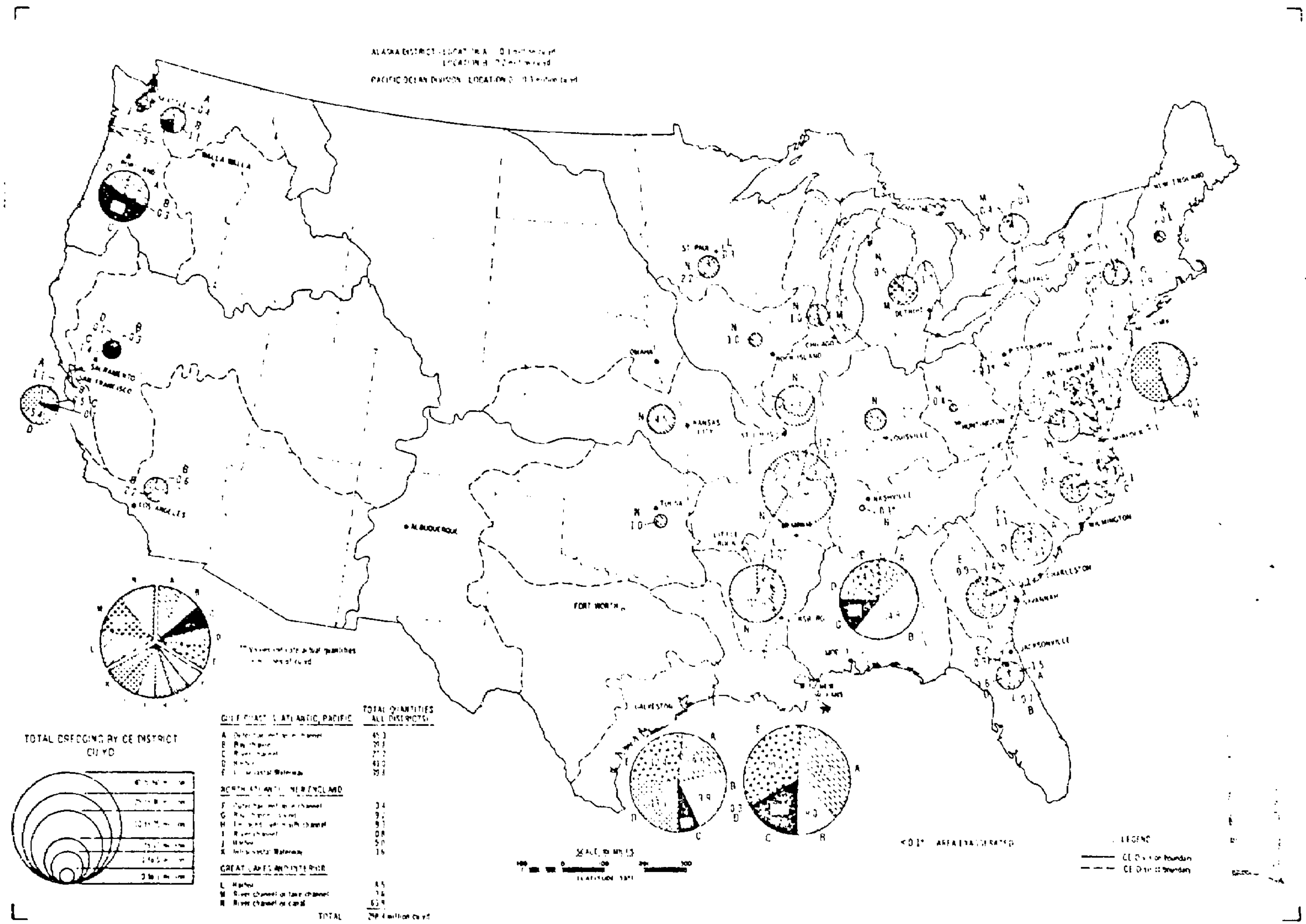


Figure A1. Depositional sedimentary environments and average annual quantities of maintenance dredgings in the United States (from Boyd et al.[50])

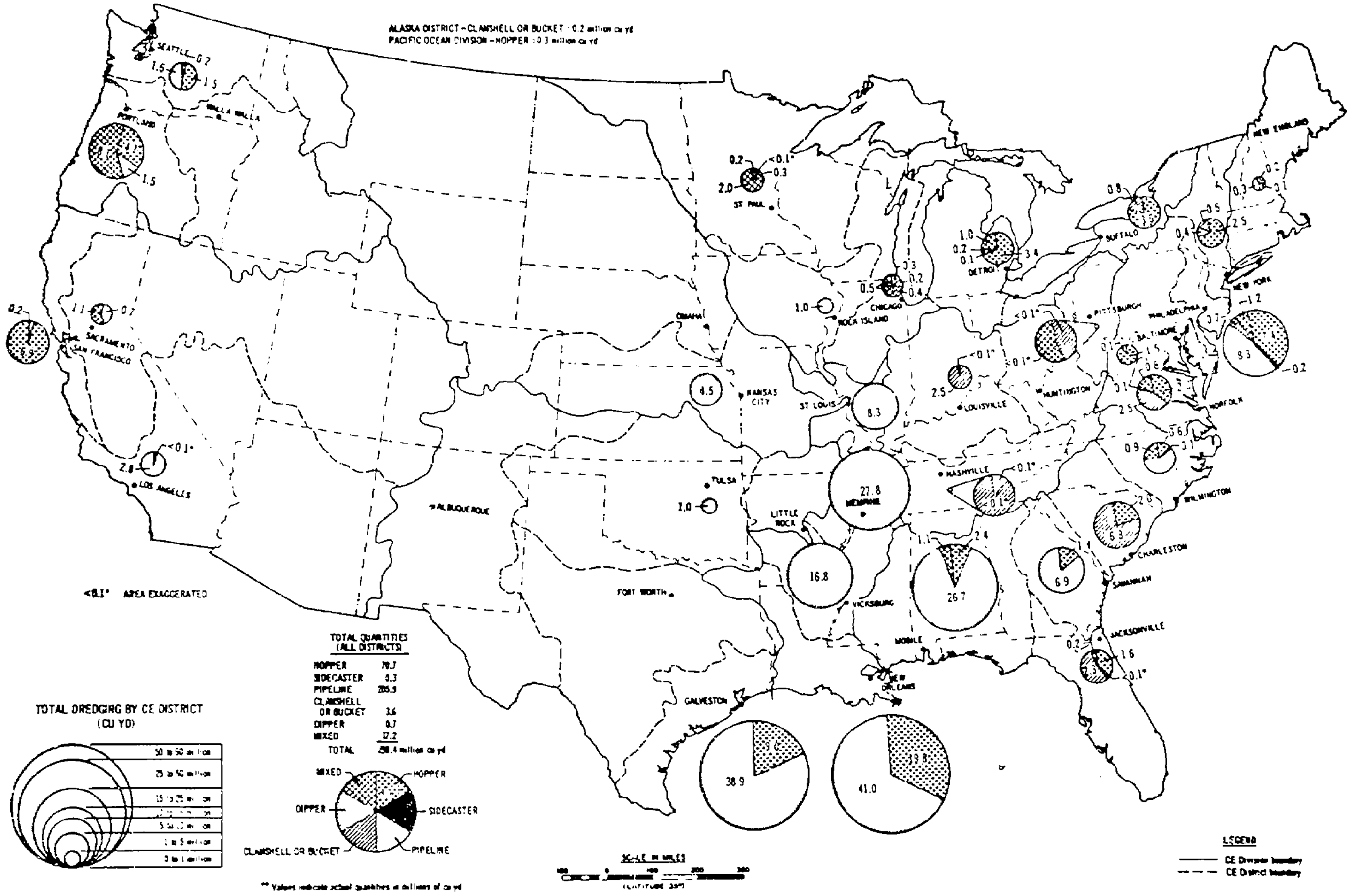


Figure A2. Types of material generated in maintenance dredging in the United States (from Boyd et al.[50])

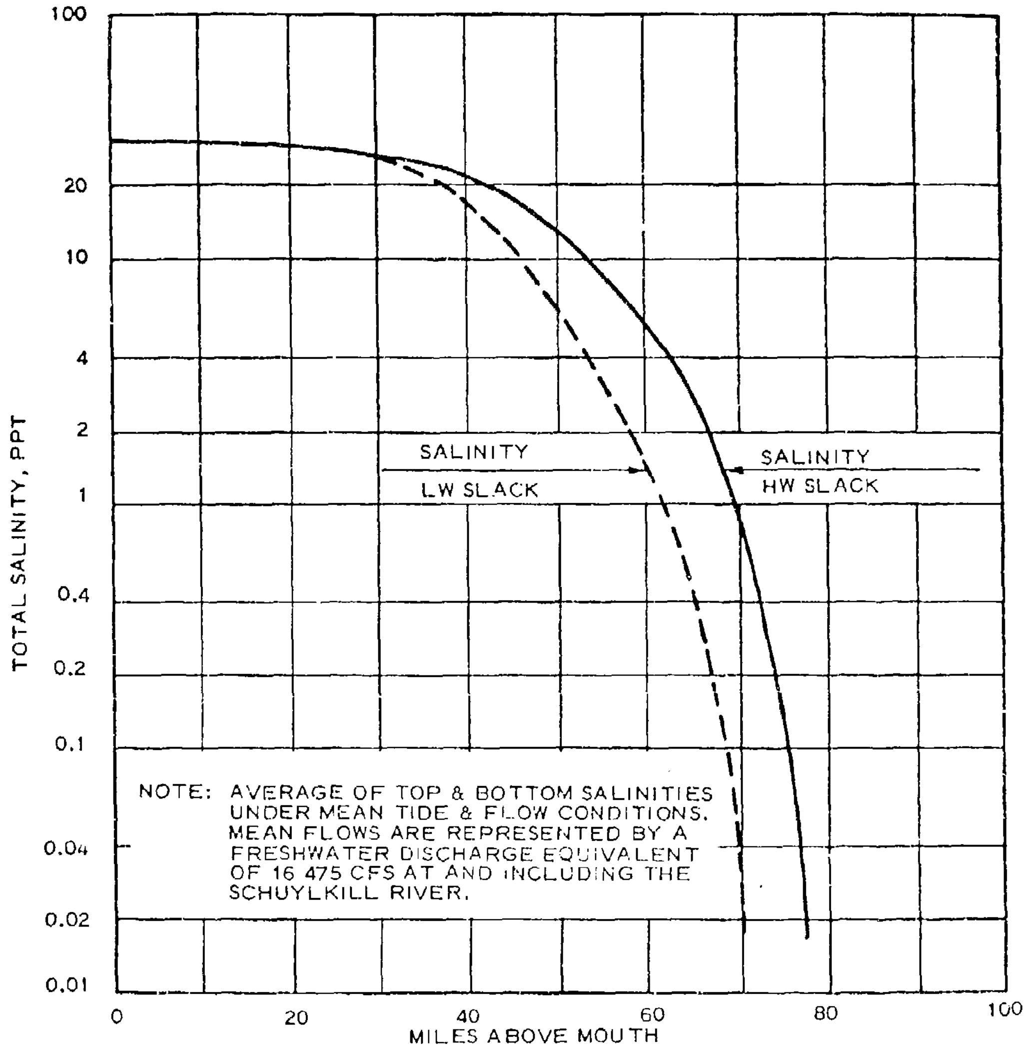


Figure A3. Salinity versus miles above mouth of Delaware River (from U. S. Army Engineer District, Philadelphia[53])

Classification System (USCS) is widely used, not only by the Corps of Engineers (CE), Bureau of Reclamation, and Department of the Navy, but also by numerous other public and private engineering organizations.

Charleston Harbor

4. Engineering properties of shoal material in Charleston Harbor are given in Table A3.[55] As shown in Figure A4, the dry unit weight of shoal material in Charleston Harbor ranges from almost zero at the surface to about 20 pcf at a depth of 6 ft,[55] but most of the increase in density occurred in the upper 2 ft. Figure A5 shows the increase in dry unit weight of shoal material with an increase in sand content.[55] The Atterberg limits are plotted on the plasticity plot (Figure 28 in main text), and plot close to Casagrande's A-line. About one-third of the test values had water contents about at or below the liquid limit (LL), one-third had water contents of about 1.5 LL, and one-third had water contents about twice the LL.

Marcus Hook, Delaware River

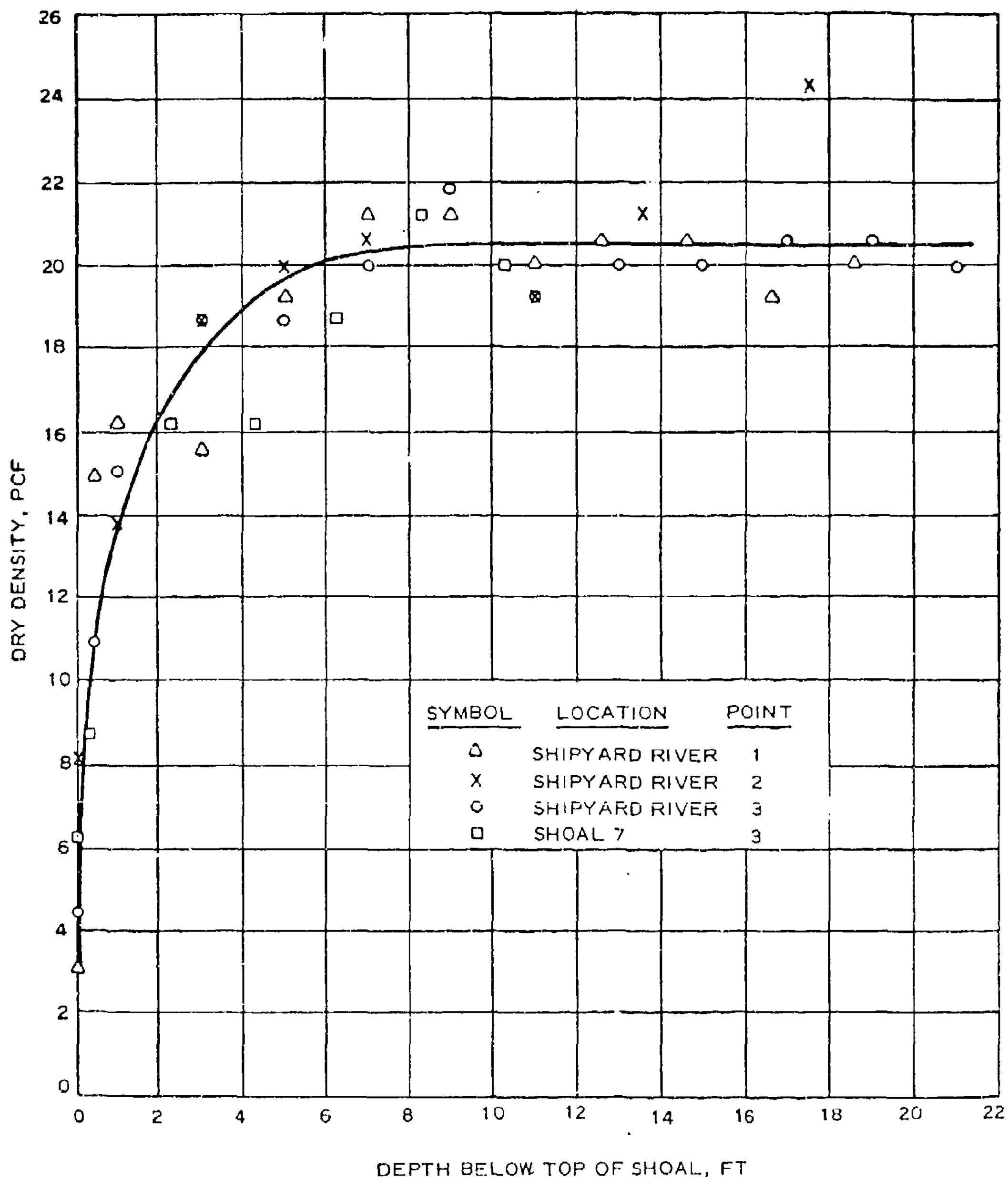
5. Table A4 gives engineering properties of Marcus Hook shoal material in the Delaware River.[56] All except one specimen had water contents about 1.2 LL. Atterberg LL and plastic limits (PL) are plotted in Figure 28 in main text and fall close to Casagrande's A-line.

San Francisco Bay

6. Engineering properties of shoal material from San Francisco Bay are given in Table A5.[57] The water contents average about 1.4 LL. Atterberg limits are plotted in Figure 28 in main text, and fall close to and slightly above the A-line.

York River, Va.

7. Faas[58] measured the variation of engineering properties with depth for bottom sediments in the York River, Va. (Table A6). The liquidity index (LI) was about 1.5 to 1.6, with one value of 1.1 at a depth of about 1.5 ft. The ratio of water content to the LL was about 1.4, except for one value of 1.0 at a depth of about 1.5 ft. The Atterberg limit plot was appreciably above the A-line, but well below the U-line or upper limit of credible test values (Figure 28 in main text).



NOTE: LESS THAN 3 PERCENT OF THE SHOAL MATERIAL RETAINED ON 200 - MESH SIEVE.

Figure A4. Dry density versus depth below top of shoal material in Charleston Harbor, South Carolina (from U. S. Army Engineer District, Charleston[55])

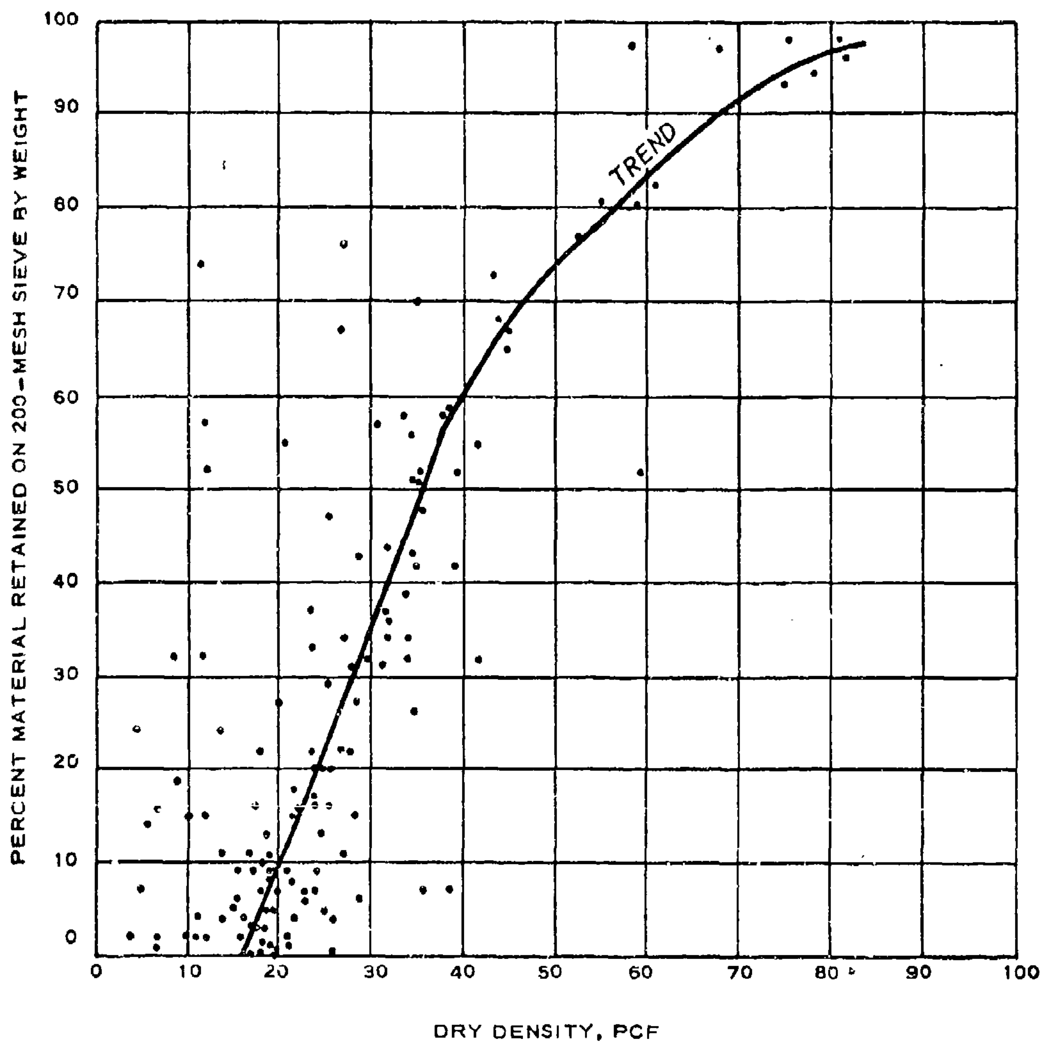


Figure A5. Sand content versus dry density of shoal material in Charleston Harbor, South Carolina (from U. S. Army Engineer District, Charleston[55])

CE studies

8. A study to determine the classification and engineering properties of soils to be dredged is being conducted at the U. S. Army Engineer Waterways Experiment Station (WES).[59] Figures A6 and A7 show the type of material and USCS classification from remolded samples taken from various locations in the United States. Figure A8 summarizes particle size, Atterberg limits, and organic content for remolded samples. Laboratory tests are in progress at WES to determine the specific

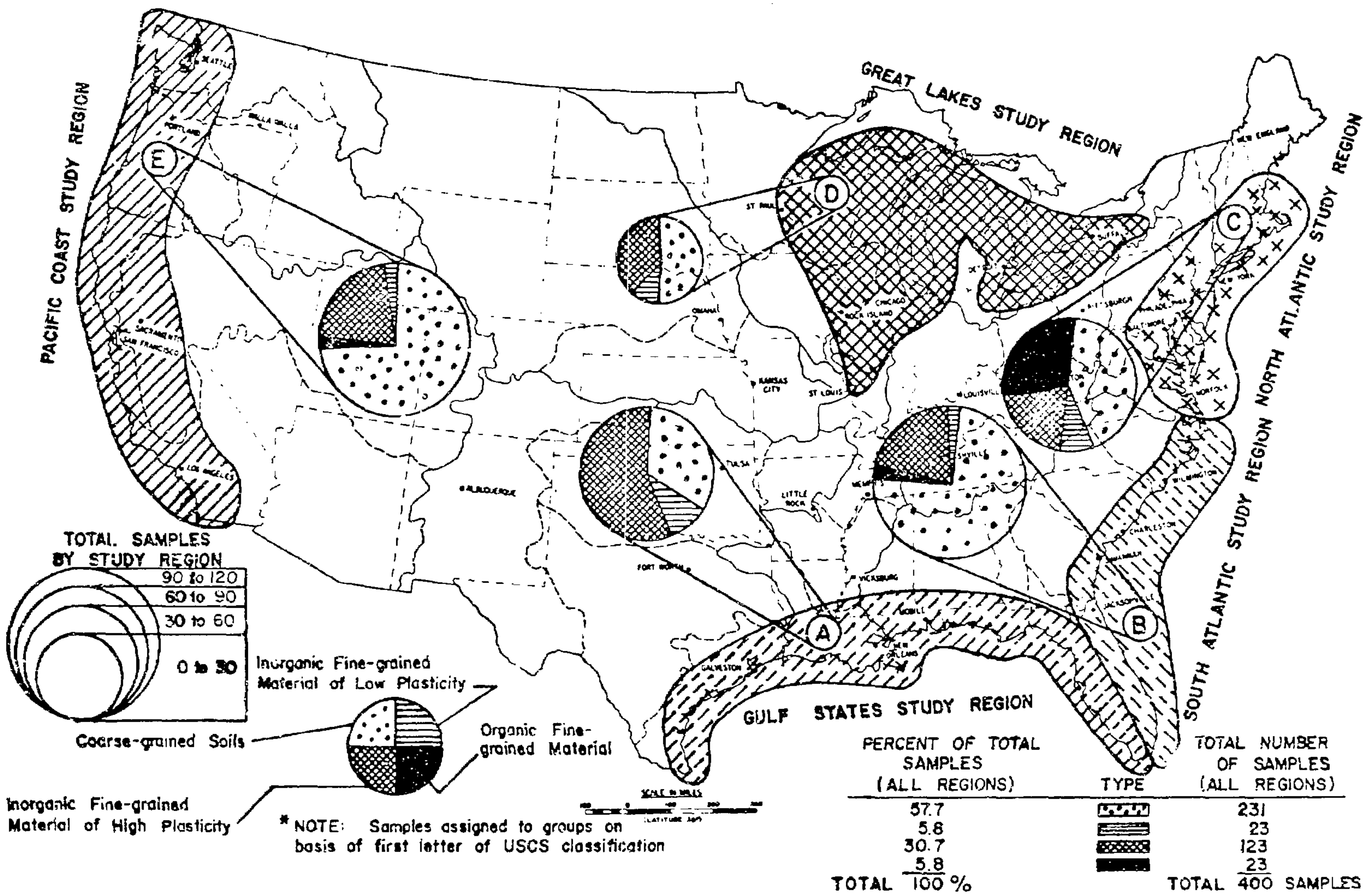


Figure A6. Types of material to be dredged in United States (from Bartos[59])

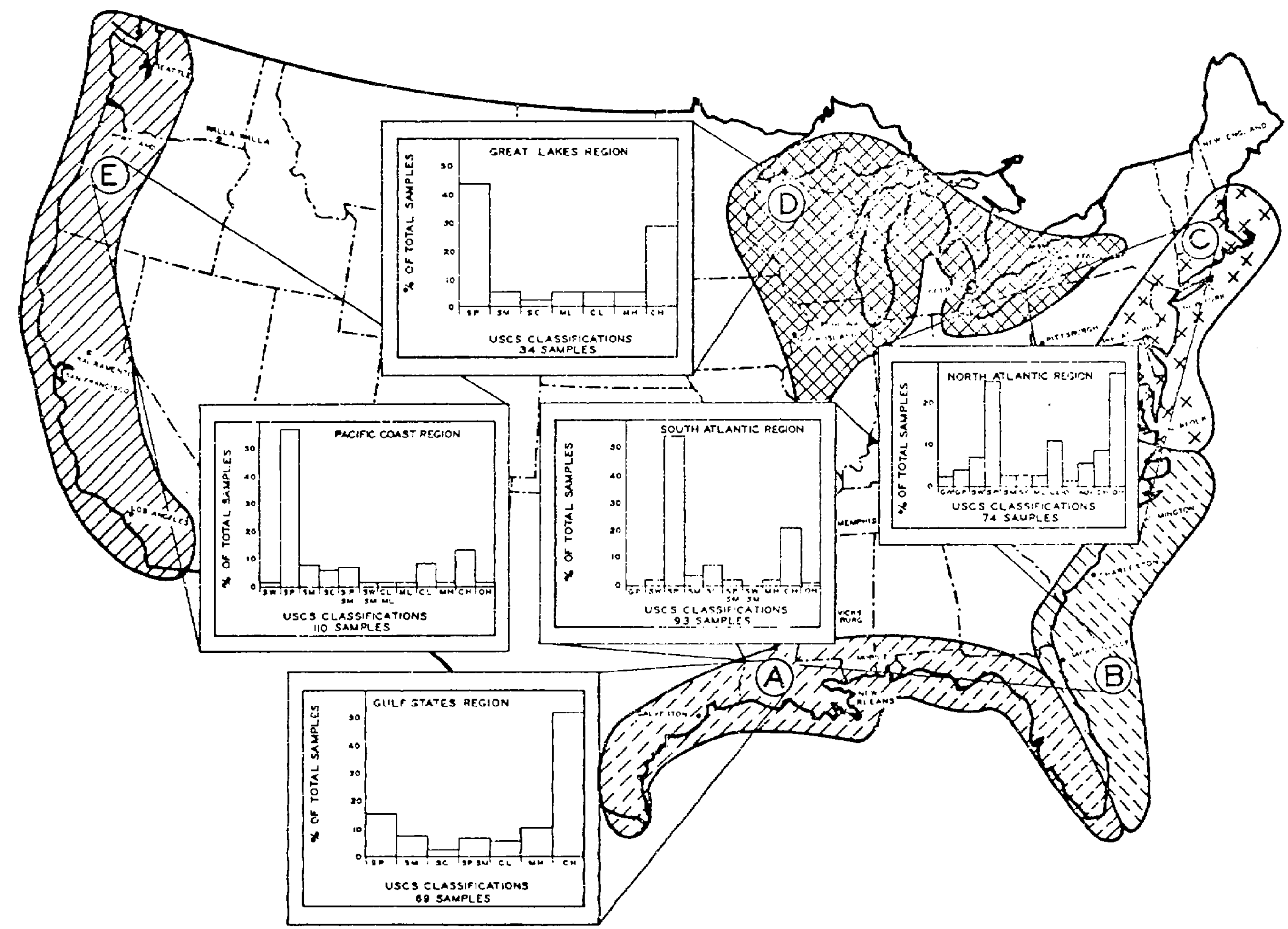


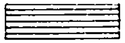
Figure A7. Unified soil classification of material to be dredged in United States (from Bartos[59])

Region	Total No. Samples	Type Material*	Grain Size** D_{10}, mm	D_{60}, mm	D_{90}, mm	Percent Passing No. 200 Sieve	Atterberg Limits LL	PL	PI	Organic Content, %
A	89		81 <0.001-0.24	89 <0.001-0.42	89 0.0065-0.80	89 1-99 63	66 32-202 104	65 17-71 35	65 9-144 69	60 0.17-10.64 3.99
B	93		90 <0.001-0.47	89 <0.001-7.50	90 0.0057-12.00	93 1-100 26	34 21-273 100	33 15-90 35	33 1-183 68	9 0.13-9.61 5.76
C	74		46 <0.001-5.00	74 0.0019-78.00	20 0.008->78.00	74 0.5-99 50	38 29-152 59	38 17-82 41	38 9-98 48	10 0.32-9.74 4.53
D	34		34 <0.001-0.46	34 0.007-1.10	34 0.031-7.00	34 0.5-99 46	18 21-161 72	18 19-69 34	18 2-92 38	34 0.09-13.45 3.67
E	110		109 <0.001-0.45	110 0.0053-2.70	110 0.027-10.30	110 0.0-99 27	33 28-99 55	33 17-43 25	33 5-57 30	10 0.28-6.53 2.77
Nation	400		360 <0.001-5.00	396 <0.001-78.00	397 0.0057->78.00	400 0-100 40	189 21-273 88	187 15-90 35	187 1-183 55	123 0.09-13.45 3.95

Note: For the purpose of this table, silts plot below the A-line and clays plot above the A-line on a plasticity chart.
Conclusions drawn on basis of data shown apply only to samples tested for this study. Data entries for each region are: Number of samples, 73. Range of values, 0.0023-14.91. Average of all samples, 6.53.

* Legend for material types is as follows:

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

 Silt (low plasticity fines).

 Clay (high plasticity fines).

 Organic material.

NOTE: A - Gulf States
B - South Atlantic
C - North Atlantic
D - Great Lakes
E - Pacific Coast

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

Figure A8. Ranges of particle size and Atterberg limits for material to be dredged in the United States (modified from Bartos[59]) gravity compaction characteristics, shear strength, and consolidation characteristics for these soil samples. These soil properties apply to possible use of dredged material as sources of borrow.

Sedimentation of Dredged Material

Effect of type of dredge

9. The dry unit weight of dredged material is dependent upon the type of dredge employed. As shown in Table A7 for dredge types commonly used in maintenance dredging, the density of the slurry following hydraulic dredging is about 1200 g/ℓ.[61,62] As shown in Table A8, a slurry density of 1200 g/ℓ corresponds to a dry unit weight of about 20 pcf. Volume-density-water content relationships for materials having specific gravities of 2.50 and 2.70 are shown in Figure A9.

Sedimentation of hopper loads

10. In 1967, the Philadelphia District investigated sedimentation in the hoppers of a hopper dredge used in maintenance dredging in the Delaware River.[63] Undisturbed samples of dredged material were taken at hourly intervals over a period of 8 to 10 hr from different depths in the hopper bin to determine the density of the dredged material slurry. Significant amounts of free water were released over the 8- to 10-hr test duration. The ratio of average density of dredged material in the hopper bin (1096 g/ℓ) to the average in situ shoal density (1288 g/ℓ) was 0.85.

Percent dry solids entering confined disposal area

11. The percent dry solids entering confined disposal areas is related to the pipeline pumping system. As shown in Figure A10, the percent dry solids is related to the pump speed. Similar relationships could be developed for pump size, diameter and length of discharge line, and transport velocity. Once dredged material enters a confined disposal area, entrance and exit effects generally result in nonuniform deposition of material over the entire area and varying soil properties.[64]

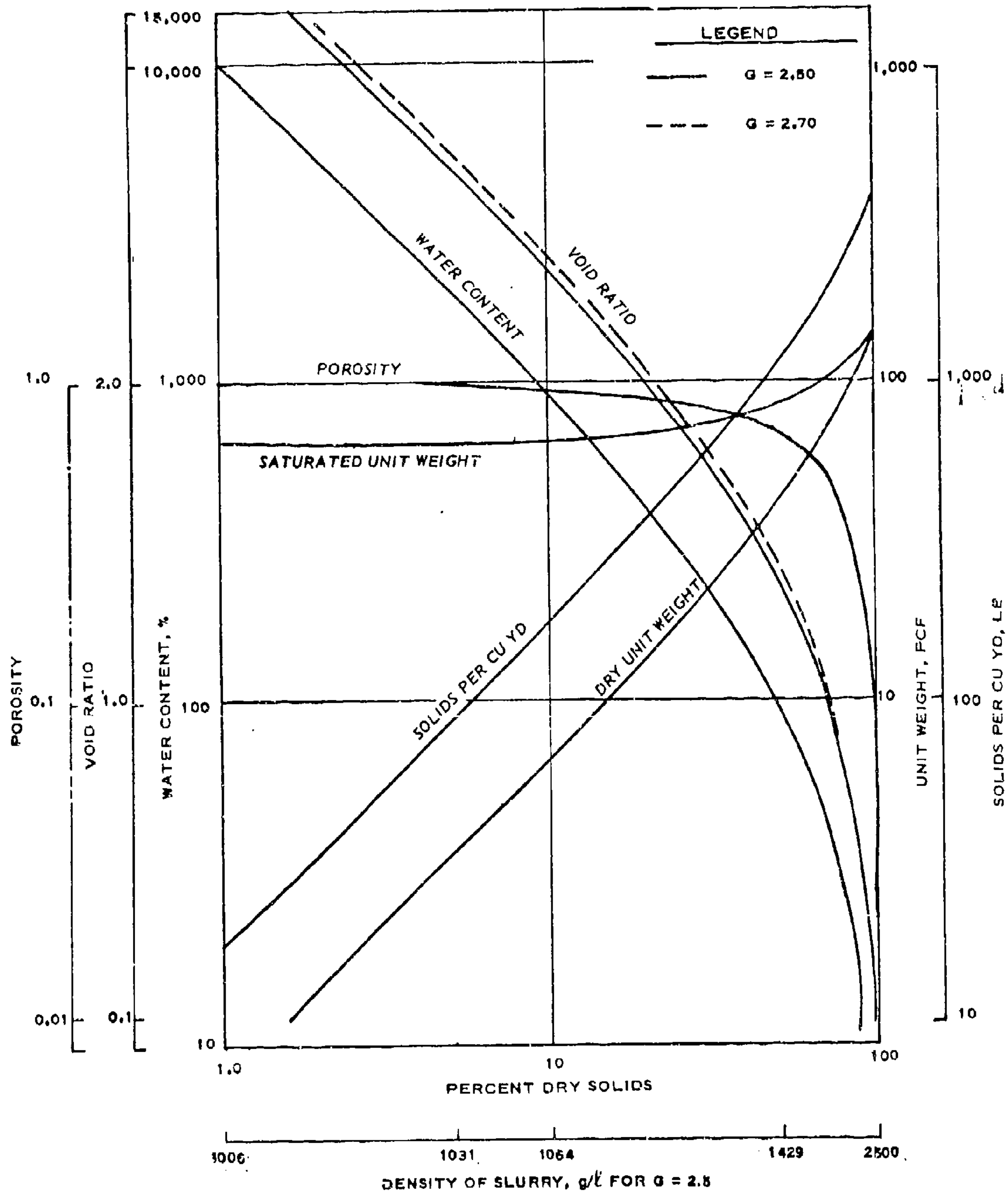


Figure A9. Volume-density-water content relationships

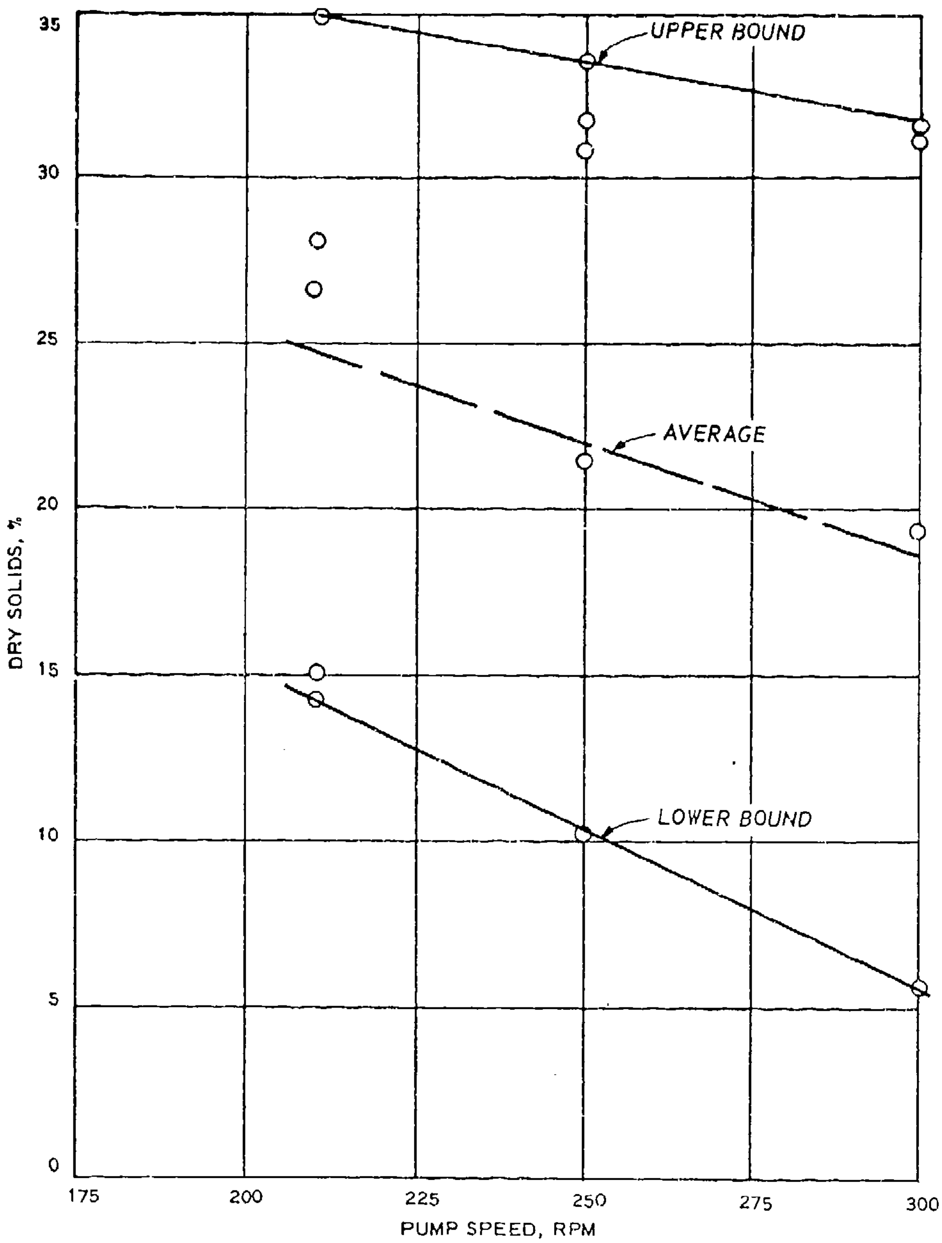


Figure A10. Percent solids versus pump speed for Mississippi River Gulf Outlet dredged material[64]

Sedimentation of clays in nature

12. Skempton[65] has studied sedimentation and consolidation of clays in nature. Table A9 shows rates of deposition for several types of clay deposits.[65,66] Figure A11 shows the relationships between water content and LL for seabed and tidal flat deposits. The large

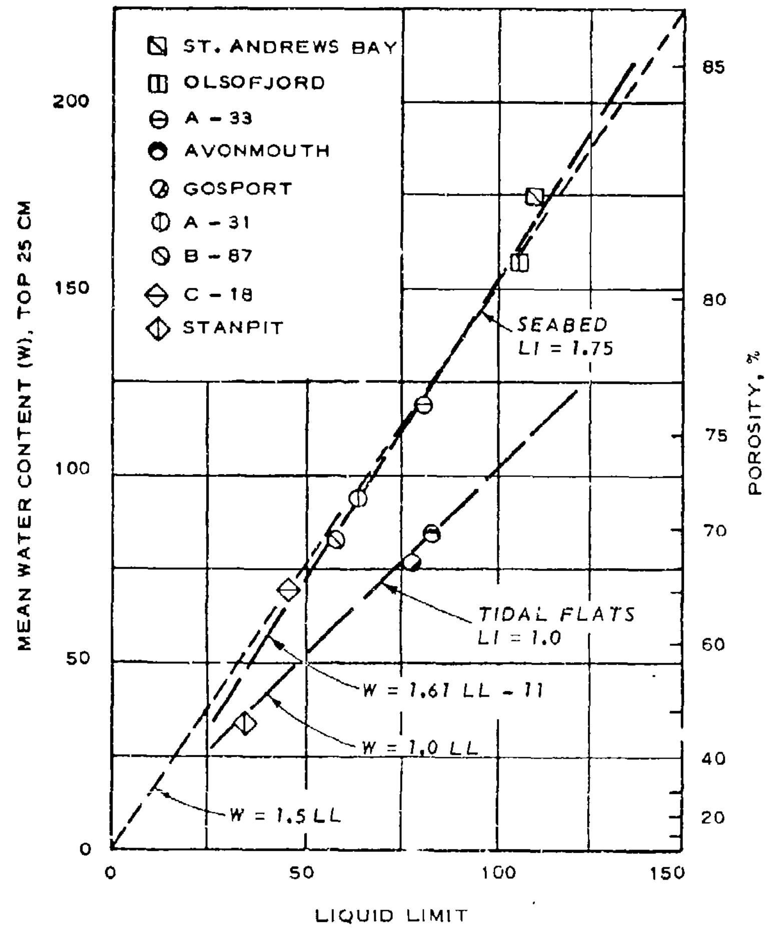


Figure A11. Water content w versus LL for seabed and tidal flat deposits (according to Skempton,[65] courtesy of Geological Society, Burlington House)

difference in water contents between these depositional environments appears significant. The relationship given by Skempton between void ratio (or water content) and depth (or effective overburden pressure) for normally consolidated clays is shown in Figure A12. A similar relationship between LI and depth (or effective overburden pressure) is given in Figure A13 (on which has been added the equation for the dotted line shown). According to these data, water contents of dredged material placed in disposal areas should be expected to be at or above the LL, generally about 1.2 to 1.3 times the LL, decreasing to about the LL at a depth of 10 ft.

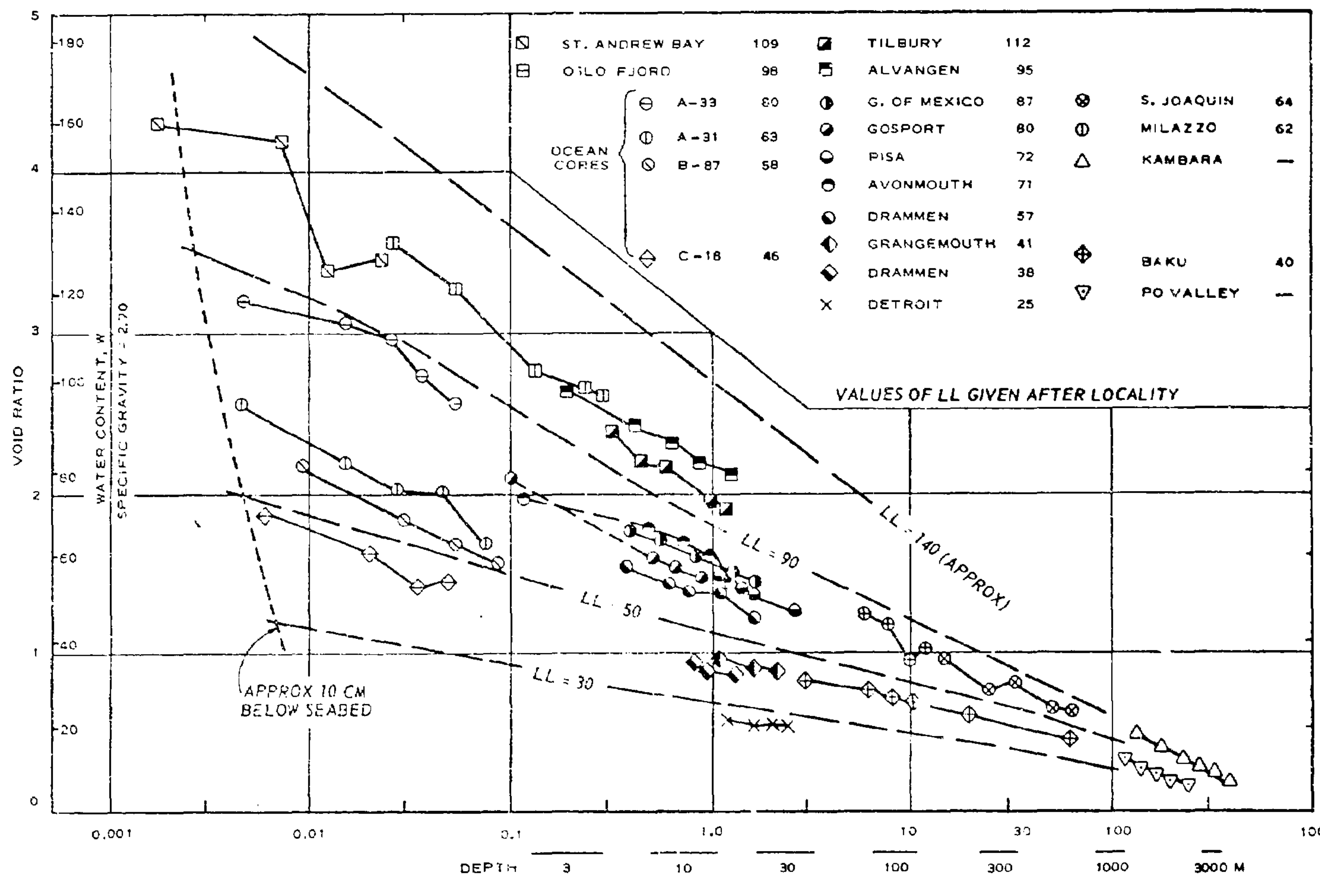


Figure A12. Sedimentation compression curves for normally consolidated clays (according to Skempton,[65] courtesy of Geological Society, Burlington House)

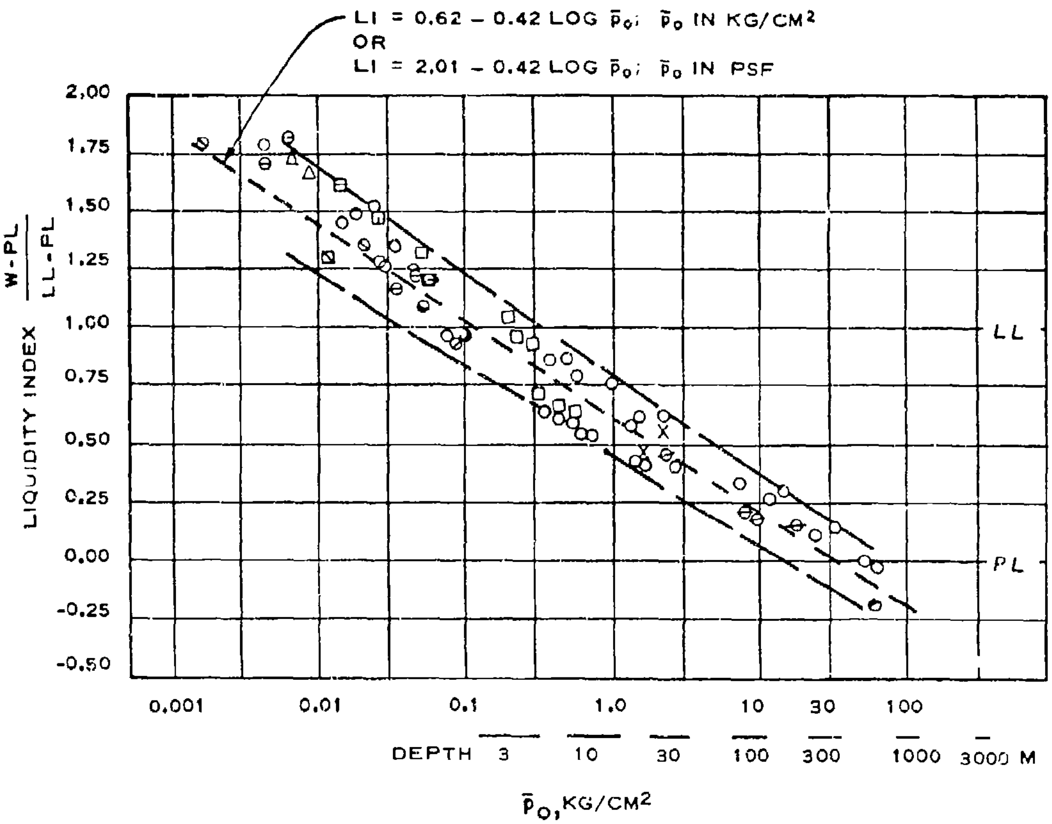


Figure A13. Relationship between LI and effective overburden pressure $\bar{p}_o$ for normally consolidated clay (according to Skempton,[65] courtesy of Geological Society, Burlington House)

Effect of environmental factors on sedimentation

13. The settling velocity of dredged material is influenced by environmental factors such as salinity, temperature, and turbulence.[67-69] The influence of salinity on the settling velocity of clay minerals is given in Table A10.[70] The settling velocity of montmorillonite clay increases with an increase in salinity up to seawater concentration (32.5 ppt). For illite and kaolinite clays, maximum settling velocity is approached at a salinity of about one-fourth that of seawater (7.3 ppt). The temperature of the water in the Delaware River at Philadelphia varies seasonally from 34 to 80°F.[53] The influence of temperature on the settling velocity of clay minerals is shown in Table A10.

A decrease in temperature from 78 to 43°F results in a 40-percent decrease in settling velocity for the three clay minerals tested.

14. Turbulent flow increases the probability of particle contacts and thereby accelerates flocculation.[64,67] However, an increase in turbulence beyond some critical value may disrupt the flocs and result in a decrease in settling velocity. Shoaling occurs in estuaries with maximum current velocities of 3 ft/sec. Between the tidal extremes the flow velocity in the estuary is less than 1 ft/sec and therefore ideal for sedimentation.

Effect of clay mineralogy and concentration on sedimentation

15. The settling velocity of dredged material is influenced by clay mineralogy, as shown in Table A10. Illite settled about 25 percent faster than kaolinite and an order of magnitude or more faster than montmorillonite.

16. The settling velocity of dredged material increased with sediment concentration up to a certain limit and may then decrease with increasing concentration.[68,71] Figure A14 shows the pronounced influence of sediment concentration on the settling velocity of shoal material for Mare Island, San Francisco Bay.[71] The settling velocities of mixtures of clay minerals reveal unique effects at very low salt concentrations or in pure water.[67] Dredged material from Mobile Bay settles rapidly in water with salinity $\leq$ 1 ppt.[72] As the sediment concentration approaches 10 g/ℓ, the settling flocs tend to interfere with one another, there is a decrease in the settling velocity, and a layer of fluid mud results.

Physicochemical aspects of sedimented clays

17. The chemical environment in which clays are deposited can influence physical properties of the clay.[1,2,73] When normally consolidated clays sedimented in salt water are leached by percolation of fresh water, the sensitivity (ratio between the peak undrained strength and the strength when the clay is remolded) will increase. The salinity of the dredged material, rate of leaching by fresh water, and

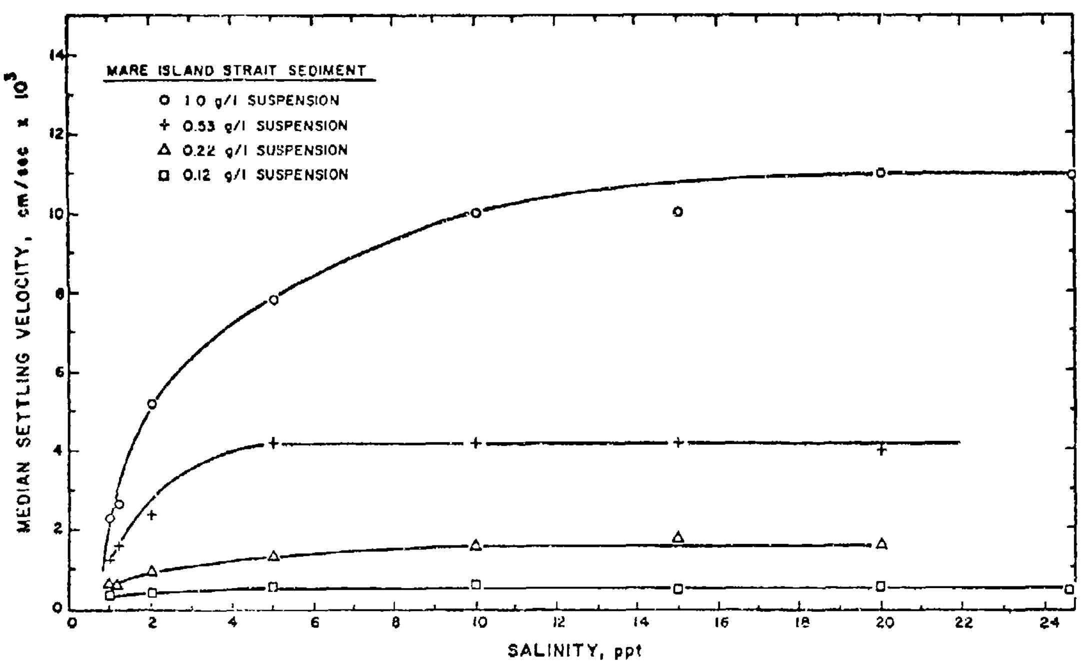


Figure A14. Influence of sediment concentration and salinity of water on median settling velocity (from Krone[71])

possible effect of overconsolidation by desiccation (or other means) determine the variation of sensitivity with time, but an increase in sensitivity might not affect the storage capacity of confined disposal areas. Laboratory tests, shown in Figure A15, indicate that the in situ compressibility of limestone residual clay is essentially the same whether sedimented in distilled water, in salt water, or in salt water that is subsequently leached with fresh water.[73] However, preconsolidation stresses are affected by leaching.

Laboratory sedimentation studies of dredged material

18. Mathematical models to predict the storage capacity of confined disposal areas[10,13,68] require laboratory tests on the dredged material to determine the sedimentation characteristics. The results of laboratory sedimentation tests on shoal material from Charleston Harbor are shown in Figure A16.[55] Suspensions containing 50 percent

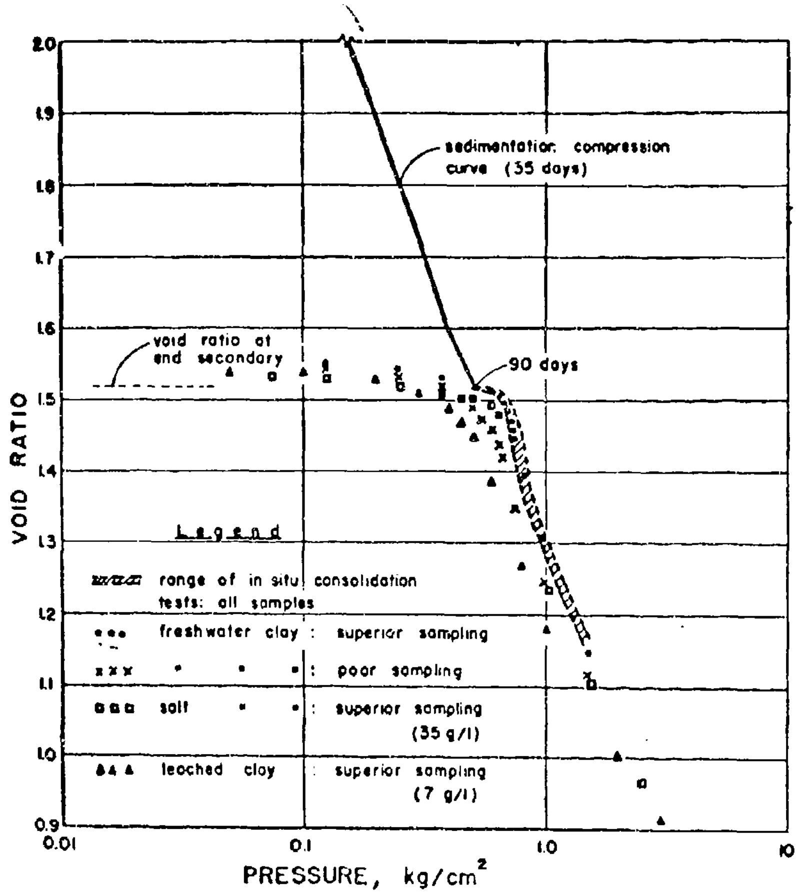
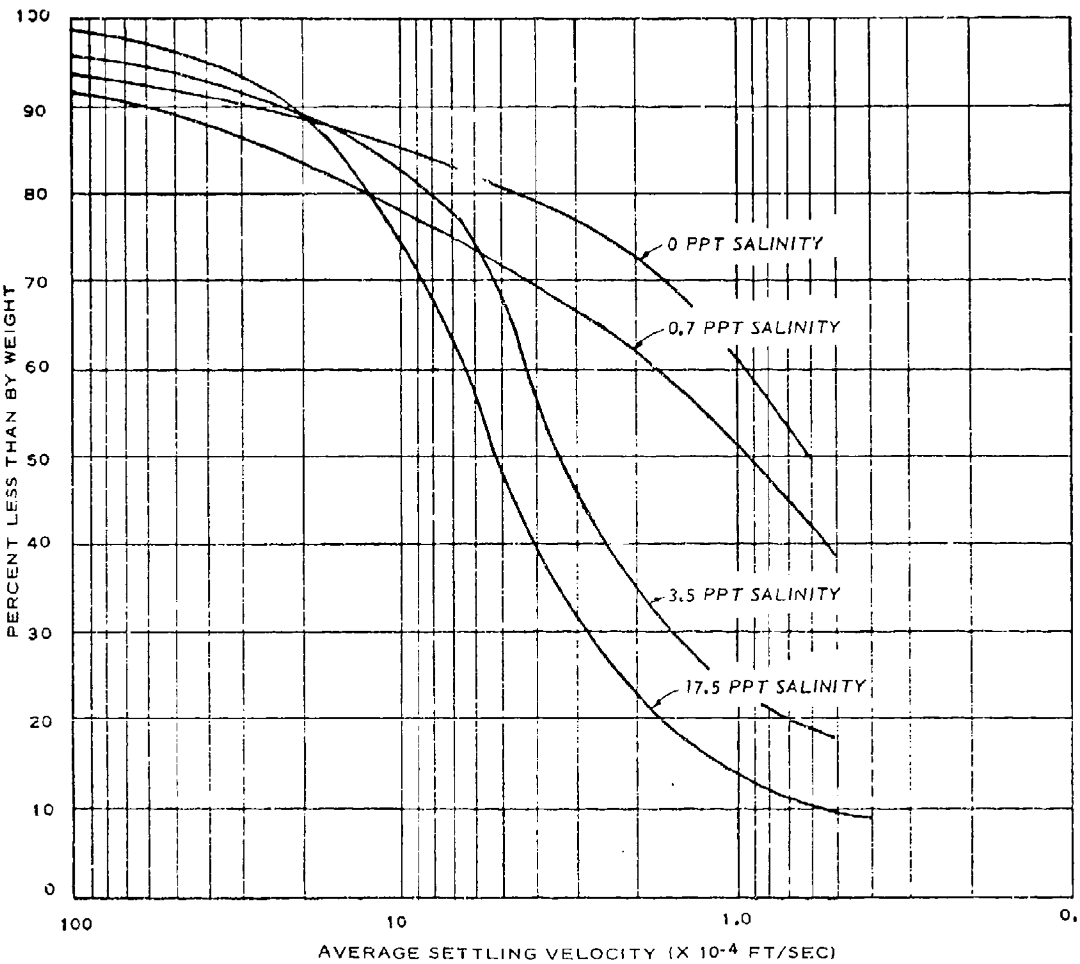


Figure A15. Effect of soil pore water salinity on the in situ compressibility of limestone risidual clay (from Leonards and Altschaeffl[73])

seawater by volume (17.5 ppt salinity) showed 75 percent of the particles had settling velocities of less than 0.001 ft/sec. This is equivalent to 3.6 ft/hr. Samples of suspended sediment collected in so-called fresh water were observed to have flocculated and settled during transport to the testing laboratory. Laboratory sedimentation tests have been conducted in connection with dredging studies for the Military Ocean Terminal at Southport, North Carolina[74] and San Francisco Bay.[57] Figure A17 shows laboratory sedimentation test results on silty clay dredged from Wilmington Harbor.[74].



NOTE: MATERIAL FINER THAN 200-MESH SIEVE
CONCENTRATION OF SOLIDS OF THE
ORDER OF 300 PPM

Figure A16. Laboratory sedimentation test results for shoal material from Charleston Harbor, South Carolina (from U. S. Army Engineer District, Charleston[55])

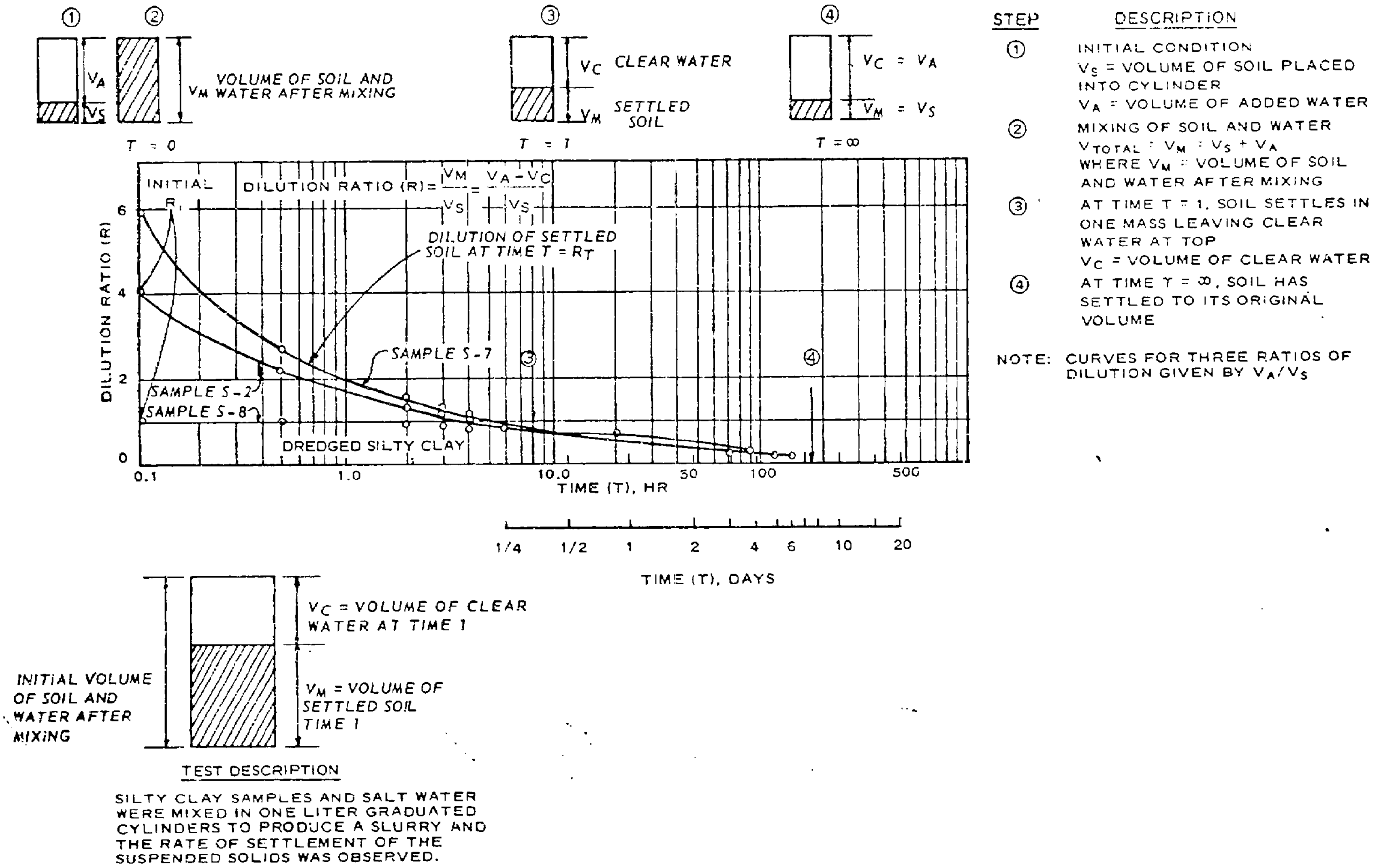


Figure A17. Laboratory sedimentation test on silty clay dredged from Wilmington Harbor, North Carolina (from U. S. Army Engineer District, Wilmington[74])

Table A1

Estimated Salinity of Maintenance Dredgings in United States (after Boyd et al.)

Region	Total*	Saline	Fresh
Coastal	222.4	208.4	14.0**
Great Lakes	13.5	--	13.5
Subtotal	235.9	208.4 (88%)	27.5 (12%)
Interior riverine	62.5	--	62.5
National total	298.4	208.4	90.0

* Million cubic yards of dredged material.

** Assumes half of river channel dredging in coastal districts is in fresh water.

Table A2

Permanent International Association of Navigation Congresses Classification of Soils to be Dredged

(Courtesy of International Association of Dredging Companies[54])

Main Soil* Type	Particle Size Identification: Range of Size	Particle Size Identification: B. S. Sieve**	Identification	Strength and Structural Characteristics
Granular (Noncohesive)				
Boulders Cobbles	Larger than 200 mm Between 200-60 mm	†	Visual examination and measurement	Not applicable
Gravels	Coarse 60-20 mm Medium 20-6 mm Fine 6-2 mm	3 in.-3/4 in. 3/4 in.-1/4 in. 1/4 in.-No. 7	Easily identifiable by visual examination	Possible to find cemented beds of gravel which resemble weak conglomerate rock. Hard-packed gravels may exist intermixed with sand
Sands††	Coarse 2-0.6 mm Medium 0.6-0.2 mm Fine 0.2-0.06 mm	7-25 25-72 72-200	All particles visible to the naked eye. Very little cohesion when dry	Deposits will vary in strength (packing between loose, compact, and cemented. Structure may be homogeneous or stratified. Intermixture with silt or clay may produce hard packed sands
Cohesive				
Silts††	Coarse 0.06-0.02 mm Medium 0.02-0.006 mm Fine 0.006-0.002 mm	Passing No. 200	Generally particles are invisible and only grains of a coarse silt may just be seen with naked eye. Best determination is to test for dilatency.‡ Material may have some plasticity, but silt can easily be dusted off fingers after drying and dry lumps powdered by finger pressure	Essentially nonplastic but characteristics may be similar to sands if predominantly coarse or sandy in nature. Finer will approximate to clay with plastic character. Very often intermixed or interleaved with fine sands or clays. May be homogeneous or stratified. The consistence may vary from fluid silt through stiff silt onto "siltstone"
Clays	Below 0.002 mm Distinction between silt and clay should not be based on particle size alone since the more important physical properties of silt and clay are only related indirectly to particle size	Not applicable	Clay exhibits strong cohesion and plasticity, without dilatency. Moist sample sticks to fingers, and has a smooth, greasy touch. Dry lumps do not powder, shrinking and cracking during drying process with high dry strength	Strength / Shear strength‡‡: Very soft — May be squeezed easily between fingers — Less 0.17 kg/cm² Soft — Easily moulded by fingers — 0.17-0.45 kg/cm² Firm — Requires strong pressure to mould by fingers — 0.45-0.90 kg/cm² Stiff — Cannot be moulded by fingers, indented by thumb — 0.90-1.34 kg/cm² Hard — Tough, indented with difficulty by thumb nail — Above 1.34 kg/cm² Structure may be fissured, intact, homogeneous, stratified, or weathered
Organic				
Peats and organic soils	Not applicable	Not applicable	Generally identified by black or brown color, often with strong organic smell, presence of fibrous or woody material	May be firm or spongy in nature. Strength may vary considerably in horizontal and vertical directions

* Soil may be defined in the engineering sense as any naturally occurring loose or soft deposit forming part of the earth's crust. The term should not be confused with "pedological soil" which includes only the topsoil capable of supporting plant growth, as considered in agriculture.

** Or National equivalent sieve size/numbers.

† Though only visual examination and measurement are possible, an indication should be given with respect to the size of the "grain" as well as to the percentages of different sizes.

†† There may be some justification for including a range of "extra fine" sand and "extra coarse" silt over the particle size ranges (0.1-0.06 mm) and (0.06-0.04 mm), respectively. It is recommended that whenever possible in borehole description or verbal discussion such further identification of these soils be used. However, to avoid confusion, if the classification "fine" sand or "coarse" silt is used without further qualification, it will be taken that the particle size ranges fall within those given in Table 1 of Reference 54.

‡ Dilatency is the property exhibited by silt as a reaction to shaking due to the higher permeability of silt. If a moistened sample is placed in the open hand and shaken, water will appear on the surface of the sample giving a glossy appearance. A plastic clay gives no reaction.

‡‡ Defined as the undrained (or immediate) shear strength ascertained by the applicable in situ or laboratory test procedure.

Table A3

Engineering Properties of Shoal Material in Charleston Harbor, South Carolina

(from U. S. Army District, Charleston[55])

Shoal No.	Wet Unit Weight pcf	Water Content %	Dry Unit Weight pcf	Specific Gravity of Solids	Liquid Limit %	Plastic Limit %	Plasticity Index %	Organic Matter* %	Void Ratio	Degree of Saturation %	Liquidity Index**	Water Content: Liquid Limit
1 & 2	75.9	166	28.5	2.35	143	59	84	10.7	4.15	94.0	1.27	1.16
3	74.9	197	25.2	--	128	51	77	--	--	--	1.90	1.54
4	97.0	63	59.5	2.40	131	52	79	10.5	1.52	99.5	0.14	0.48
5	81.4	170	30.1	2.39	157	55	102	8.2	3.95	102.9	1.13	1.08
5A	70.6	347	15.8	2.44	166	55	111	9.5	8.64	98.0	2.63	2.09
6	70.6	278	18.7	2.49	146	55	91	11.7	7.44	93.0	2.45	1.90
6A	70.7	328	16.5	--	--	--	--	10.8	--	--	--	--
6B	78.6	169	29.2	2.36	111	49	62	10.3	4.04	98.7	1.94	1.52
6C	72.6	227	22.2	--	--	--	--	--	--	--	--	--
7	69.6	282	18.2	--	140	55	85	7.1	--	--	2.67	2.01
Average	76.2	228	26.4	2.41	140	54	86	9.9	4.96	97.2	1.77	1.47

* Based on dry weight.

** Liquidity Index = (Water Content - Plastic Limit)/(Liquid Limit - Plastic Limit).

Table A4

Engineering Properties of Marcus Hook Shoal Material in Delaware River

(from U. S. Army District, Philadelphia[56])

Boring and Sample No.	Depth ft	Wet Unit Weight pcf	Water Content %	Dry Unit Weight pcf	Specific Gravity of Solids	Liquid Limit %	Plastic Limit %	Plasticity Index %	Void Ratio	Degree of Saturation %	Liquidity Index*	Water Content: Liquid Limit
RB14-S1	38.7-40.7	83.4	110.2	39.7	2.51	87	39	48	2.95	93.8	1.48	1.27
-S2	41.7-43.7	79.0	133.4	33.9	2.50	101	40	61	3.60	92.6	1.53	1.32
-S3	45.7-47.7	78.3	135.4	33.3	2.53	73	34	39	3.74	91.6	2.60	1.85
RB15-S1	18.2-20.2	88.2	104.3	43.1	2.55	89	36	53	2.69	98.9	1.29	1.17
-S2	20.5-22.5	85.6	139.2	35.8	2.54	111	41	70	3.43	103.1	1.40	1.25
-S3	23.0-25.0	79.7	143.7	32.7	2.49	113	39	74	3.75	95.4	1.41	1.27
-S4	26.4-28.4	82.5	119.1	37.6	2.47	97	39	58	3.10	94.9	1.38	1.23
-S5	32.0-34.0	83.4	116.2	38.6	2.56	101	34	67	3.14	94.7	1.23	1.15
-S6	35.7-37.7	78.2	136.5	33.1	2.53	105	40	65	3.77	91.6	1.48	1.30
-S7	41.0-43.0	83.6	110.7	39.7	2.58	122	46	76	3.06	93.3	0.85	0.91
RB16-S1	20.5-22.5	76.4	151.1	30.4	2.54	118	41	77	4.21	91.2	1.43	1.28
-S2	23.5-25.5	78.8	150.2	31.5	2.59	117	41	76	4.13	94.2	1.44	1.28
-S3	26.5-28.5	80.5	128.3	35.2	2.53	101	40	61	3.49	93.0	1.45	1.27
-S4	33.5-35.5	83.8	123.4	37.5	2.49	101	41	60	3.14	97.9	1.37	1.22
-S5	38.0-40.0	82.1	117.7	37.7	2.58	111	40	71	3.27	92.9	1.09	1.06

* Liquidity Index = (Water Content - Plastic Limit)/(Liquid Limit - Plastic Limit).

Table A5

Engineering Properties of Material from San Francisco Bay

(from U. S. Army District, San Francisco[57])

Location	Wet Unit Weight pcf	Water Content %	Dry Unit Weight pcf	Liquid Limit %	Plastic Limit %	Plasticity Index %	Classification*	Liquidity Index**	Water Content: Liquid Limit
San Francisco	--	--	--	59	24	35	CH	--	--
Redwood City	--	--	--	79	32	47	CH	--	--
Oakland	--	--	--	78	31	47	CH	--	--
Richmond	93.2	82.7	51.0	57	24	33	CH	1.78	1.45
San Rafael	--	--	--	72	27	45	CH	--	--
Pinole Shoal	--	--	--	48	22	26	CH	--	--
Mare Island	87.1	112.4	41.0	84	34	50	CH	1.57	1.34
Suisun Bay	106.4	66.2	64.0	43	23	20	SC	2.16	1.54
Napa River	--	--	--	44	25	19	CL	--	--
Petaluma River	--	--	--	86	31	55	CH	--	--

* Unified Soil Classification System.

** Liquidity Index = (Water Content - Plastic Limit)/(Liquid Limit - Plastic Limit).

Table A6

Engineering Properties of Material from York River, Va. (courtesy of American Elsevier Publishing Company[58])

Depth in.	Wet Unit Weight pcf	Water Content %	Dry Unit Weight pcf	Liquid Limit %	Plastic Limit %	Plasticity Index %	Void Ratio	Liquidity Index*	Water Content: Liquid Limit	Salinity ppt
3-4	84.2	220	26.3	157	43	114	5.7	1.55	1.40	24
5-6	83.0	220	25.9	158	43	115	5.7	1.54	1.39	28
12-13	86.1	219	27.0	150	43	107	5.7	1.64	1.46	29
16-18	81.1	167	30.4	160	38	122	4.4	1.06	1.04	32

* Liquidity Index = (Water Content - Plastic Limit)/(Liquid Limit - Plastic Limit).

Table A7

Dredged Material Density for Various Dredge Types

(From Mohr[60])

Dredge Type	Dredged Material Density
Dragline on barge	Approaches in-place density in mud and silt. Approaches dry density in coarser material.
Dipper dredge	
Clam shell or orange peel bucket dredge	
Endless chain bucket dredge	
Cutterhead dredge	Diluted to an average of 1200 g/ℓ.
Dustpan dredge	
Hopper dredge	
Sidecasting dredge	

Table A9

Fundamental Relationships for Saturated Dredged Material

		Specific Gravity = 2.40				Specific Gravity = 2.60				Specific Gravity = 2.80			
Dry Solids %	Water* Content %	Density** of Slurry g/ℓ	Void Ratio	Dry Unit Weight pcf	Wet Unit Weight pcf	Density of Slurry g/ℓ	Void Ratio	Dry Unit Weight pcf	Wet Unit Weight pcf	Density of Slurry g/ℓ	Void Ratio	Dry Unit Weight pcf	Wet Unit Weight pcf
1	9900	1006	237.60	0.6	62.8	1006	247.40	0.6	62.8	1007	277.20	0.6	62.8
5	1900	1030	45.60	3.2	64.0	1032	49.40	3.2	64.0	1033	53.20	3.2	64.5
10	900	1062	21.60	6.6	66.0	1066	23.40	6.6	66.0	1069	25.20	6.7	66.7
15	567	1096	13.61	10.3	68.7	1102	14.74	10.3	68.7	1107	15.88	10.4	69.0
20	400	1132	9.60	14.1	70.5	1140	10.40	14.2	71.0	1149	11.20	14.3	71.6
25	300	1171	7.20	18.3	73.2	1182	7.80	18.4	73.6	1192	8.40	18.6	74.3
30	233	1212	5.59	22.7	75.6	1226	6.06	22.9	76.3	1239	6.52	23.2	77.4
35	186	1257	4.46	26.9	76.9	1275	4.84	27.8	79.5	1290	5.21	28.1	80.5
40	150	1304	3.60	32.6	81.5	1327	3.90	33.1	82.8	1346	4.20	33.6	84.0
45	122	1356	2.93	38.1	84.6	1383	3.17	38.9	86.4	1407	3.42	39.5	87.8
50	100	1412	2.40	44.1	88.2	1444	2.60	45.1	90.2	1474	2.80	46.0	92.0
55	82	1472	1.97	50.4	91.7	1512	2.13	51.8	94.3	1547	2.30	52.9	96.4
60	67	1539	1.61	57.4	95.9	1585	1.74	59.2	98.9	1628	1.88	60.7	101.3
65	54	1611	1.30	65.1	100.3	1667	1.40	67.6	104.1	1718	1.51	69.6	107.2
70	43	1690	1.03	73.8	105.5	1757	1.12	76.5	109.4	1818	1.20	79.4	113.6
75	33	1778	0.79	83.7	111.3	1857	0.56	87.2	116.0	1931	0.92	91.0	121.0
80	25	1875	0.60	93.6	117.0	1970	0.65	95.3	122.9	2069	0.70	102.8	128.5
85	18	1984	0.43	104.7	123.6	2097	0.47	110.4	130.3	2205	0.50	116.5	137.5
90	11	2105	0.26	118.9	132.0	2241	0.29	125.8	139.6	2373	0.31	133.4	148.0
95	5	2243	0.12	133.7	140.4	2407	0.13	143.6	150.8	2569	0.14	153.3	160.9
100	0	2400	0.00	149.8	149.8	2600	0.00	162.2	162.2	2800	0.00	174.7	174.7

* Water Content = $100 \left(\frac{100}{\text{Dry Solids}} - 1 \right)$

** Density of Slurry = $\dfrac{1000}{\dfrac{\text{Dry Solids}}{100\ (\text{Specific Gravity})} + 1 - \dfrac{\text{Dry Solids}}{100}}$

Table A9

Thickness and Rate of Deposition of Clay Deposits (after Skempton,[65] courtesy of Geological Society, Burlington House

Type of Deposit	Thickness of Deposit m	Rate of Deposition m/1000 yr
Deltaic		
Mississippi	55	120
Rhone	65	17
Orinoco	40	8
Estuarine		
Avonmouth	13	2.5
Tilbury	16	2.0
Pisa	10	2.5
Shallow Marine		
Oslofjord	--	0.8
Po Valley	3000	1.0
Kambara	2600	0.9
Deep Marine		
Caribbean	--	0.03

Table A10

Characteristic Settling Velocities of Clay Minerals in Saline Waters

(after Whitehouse,[70] courtesy of Pergamon Press)

Temperature °F	Clay Mineral	Salinity, ppt 0.9	1.8	3.6	7.3	10.9	14.5	21.7	28.9	32.5
78	Kaolinite	11.5	11.7	11.8	11.8	11.8	11.8	11.8	11.8	11.8
	Illite	12.9	14.3	15.1	15.8	15.8	15.8	15.8	15.8	15.8
	Montmorillonite	0.03	0.05	0.11	0.36	0.58	0.86	1.1	1.2	1.3
72	Kaolinite	10.7	10.9	11.0	11.0	11.0	11.0	11.0	11.0	11.0
	Illite	12.0	13.3	14.0	14.7	14.7	14.7	14.7	14.7	14.7
	Montmorillonite	0.03	0.05	0.10	0.33	0.54	0.81	1.03	1.1	1.2
64	Kaolinite	10.0	10.1	10.2	10.2	10.2	10.2	10.2	10.2	10.2
	Illite	11.1	12.2	12.9	12.9	12.9	12.9	12.9	12.9	12.9
	Montmorillonite	0.03	0.04	0.09	0.31	0.50	0.75	0.96	1.05	1.1
57	Kaolinite	9.2	9.2	9.3	9.3	9.3	9.3	9.3	9.3	9.3
	Illite	10.2	11.2	11.8	11.8	11.8	11.8	11.8	11.8	11.8
	Montmorillonite	0.02	0.03	0.08	0.29	0.45	0.69	0.87	0.95	1.0
50	Kaolinite	7.6	7.6	7.8	7.8	7.8	7.8	7.8	7.8	7.8
	Illite	8.5	9.6	10.3	10.3	10.3	10.3	10.3	10.3	10.3
	Montmorillonite	0.02	0.03	0.07	0.24	0.38	0.59	0.71	0.79	0.85
46	Kaolinite	7.3	7.4	7.5	7.5	7.5	7.5	7.5	7.5	7.5
	Illite	8.2	9.1	9.6	10.0	10.0	10.0	10.0	10.0	10.0
	Montmorillonite	0.02	0.03	0.07	0.23	0.37	0.55	0.70	0.76	0.83
43	Kaolinite	6.8	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
	Illite	7.6	8.4	8.9	9.2	9.2	9.2	9.2	9.2	9.2
	Montmorillonite	0.02	0.03	0.06	0.21	0.34	0.51	0.65	0.71	0.76

Note: $7.5 \le pH \le 8.5$, freshwater size $\le 2\mu$, concentration 0.01-3.6 g/ℓ, velocity in metres/day.

APPENDIX B: SUMMARY OF CONVENTIONAL DEWATERING AND DENSIFICATION METHODS

Dewatering

1. The most common and generally useful methods for soil improvement are dewatering and densification, which are interconnected. Dewatering, or the removal of water from the soil, is a method for soil improvement which densifies the dewatered soil. In fine-grained soils, which are the main concern of this report, dewatering results in the removal of part of the pore water and in reduction of pore pressure. It speeds up consolidation which is accompanied by an increase in strength and reduction in compressibility.

2. There are several dewatering methods currently in practice. In order to decide on the appropriate method to be used it is necessary to know:

   a. Depth and extent of the formation to be dewatered.

   b. Succession and grain-size distribution of each stratum.

   c. Average permeability of the soil strata.

   d. Groundwater conditions.

3. These data are useful in estimating the time necessary for dewatering and the amount of water to be removed, which are major factors influencing the kind and size of equipment needed.

4. Soils with high or medium permeability are drained by gravity drainage methods. In these methods the force which produces drainage is the weight of water. The gravity drainage methods are: pumping from open sumps, wellpoints, and deep or shallow bored walls and drainage with horizontal subdrains.

5. In saturated fine-grained soils, the low permeability restricts the flow. Therefore, soils with average effective grain size less than about 0.05 mm, or soils with low permeability, are more rapidly drained by vacuum methods. A vacuum is applied to the filters surrounding wellpoints or wells. The vacuum increases the force which produces drainage.

6. Soils with very low coefficients of permeability may be stabilized by electro-osmosis. Dewatering of soft, fine-grained soils with low permeability can also be achieved by consolidation produced by a load on the soil mass. Vertical sand drains, cardboard wicks, or plastic drainage wicks are sometimes used to accelerate consolidation.

7. At this time, there is no practical and economical dewatering technique which can be used in the rapid dewatering of clay-size materials. Several techniques have been proposed and some are investigated. Centrifuge densification, vacuum filtration, use of wetting agents, pressure injection of sand slurry, mechanical aerating, chemical flocculation, ultrasonic vibration, and evapotranspiration are under consideration.

Wellpoint systems

8. Conventional wellpoint systems. The wellpoint dewatering method is the most common dewatering technique used for construction purposes. A wellpoint system consists of several wellpoints connected to 2- to 3-in.-diam riser pipes and inserted into the ground at a spacing of 3 to 6 ft, by driving, jetting, or placing in drilled holes. The upper ends of the riser pipes are attached to a horizontal header pipe which leads to a combined vacuum-centrifugal pump. The groundwater is drawn by the pump from the surrounding soil into the wellpoints and through the system to the pump, which discharges the water into a discharge line.

9. The wellpoint itself is a 2- to 5-ft-long, 2- to 4-in.-diam perforated pipe covered with a screen. It is constructed with either closed ends or self-jetting tips. Recently, nonmetal wellpoints have been used, consisting of polyvinyl plastic pipes with machined slots which resist corrosion and require relatively little maintenance. They are more economical than metal wellpoints.

10. In soils finer than clean sands and sandy gravels, a sand filter is necessary around the wellpoint to prevent clogging. The maximum depth of lowering the water table with one stage of wellpoints is about 18 ft. The main advantage of the method is that several wellpoints can be operated by a single pump.

11. Vacuum wellpoint system. A vacuum wellpoint system is similar to a conventional wellpoint system; the difference is that the wellpoint and riser pipe are surrounded with a sand filter sealed at the top by a plug of bentonite, cement, or clay. In additional to conventional pumping equipment, a vacuum pump is attached to the header pipe creating a vacuum in the sand filter and helping draw water out of the surrounding soil.

12. The vacuum system can lower the water table to a depth of 18-25 ft in a single lift, but for these depths, the vacuum induced is small. The method can be used for dewatering silty fine sands and sandy silts with a low coefficient of permeability.

13. Eductor wellpoint system. The jet-eductor wellpoint system consists of a wellpoint above which, in a 4-in.-diam casing, a jet-eductor pump is located and attached to two riser pipes. The riser pipes are connected to separate headers, one to supply water under pressure to the eductor pumps and the other for the discharge from the wellpoints. The jet-eductor pumps make dewatering possible in a single stage to a depth of 50-100 ft. The method can be used for dewatering sands or silty sands and, with proper control, sandy silts. It is useful for large drawdowns where pumping volumes are small.

14. Horizontal wellpointing. A new dewatering method is currently being used in England. A machine excavates an 0.75-ft-wide and 6- to 20-ft-deep trench, into which a long, 3- to 4-in.-diam perforated plastic pipe is laid horizontally. At random intervals the plastic pipe is cut and connected to an unperforated pipe, which is brought up to the ground surface and connected to a wellpoint pump. The trench is then backfilled with the excavated material or with a granular fill. The system can be installed economically in a very short time.

Deep well systems

15. Deep wells for dewatering are similar to commercial water wells. A 6- to 36-in.-diam casing with a length up to 100 ft or more is installed in a bored hole. The casing is perforated some or all of its length and provided with a screen. Recently, the traditionally steel

well screen has been made of glass fiber, which has a strength similar to steel but is inert to corrosion.

16. If the soil is too fine-grained to be filtered by the screen alone, a gravel-sand filter is placed around the screen. A deep well pump is installed near the bottom of each well and attached to a riser pipe. The riser pipe is connected to a suitable header system through which the water is discharged.

17. Both the wellpoint and the deep well system may be used in conjunction with a vacuum system to dewater fine-grained sands and sandy silts. Deep wells are highly effective for removing large volumes of water from all types of permeable soils but installation and operational costs are high.

Subsurface drainage systems

18. Subsurface drains are conduits embedded in a backfill of filter material laid on the bottom of a trench which collect and dispose of water that occurs below the ground surface.

19. A subsurface drainage system consists of three components: the filter, the conduit, and the disposal system. Filter materials are well-graded sand-gravel mixtures with two requirements: they must be fine enough to prevent infiltration of the soil grains into the drain and coarse and pervious enough to permit the flow of water into the drain.

20. The conduit collects water from the filter and carries it to the disposal system. Conduits can be pipes of metal, clay, plastic, or fibrous material, or open-jointed tiles. The disposal system removes the water from the area by gravity or by pumping.

21. Subsurface drainage systems are effective in all types of permeable soils.

Vertical sand drains

22. Vertical sand drains are used mainly in thick, highly compressible deposits of organic soil, silt, or clay. Their purpose is to accelerate the consolidation of compressible layers of fine-grained soils. They provide vertical drainage outlets for water squeezed from the surrounding soil by the weight of a surcharge load, thereby

increasing the shear strength of the soft soil and decreasing post-construction settlements to tolerable values.

23. Vertical sand drains consist of a series of 6- to 18-in.-diam vertical cylindrical columns of free-draining sand, installed at 6- to 15-ft spacings. The upper ends of the sand drains are connected at the ground surface by a drainage blanket on which a surcharge fill is placed. The weight of the surcharge fill squeezes water out of the underlying soft soil and causes flow toward the sand drains. The water rises in the sand drains to the drainage blanket, where it drains away to the sides of the area occupied by the drains. If the area extent of the fill is large, collector pipes or ground drains are provided in the drainage blanket. After the compressible soil formation has been consolidated, the surcharge is removed. If the fine-grained compressible soil formation overlies a pervious stratum, the drainage can be performed downward into the more permeable stratum, which can be dewatered with wells or wellpoints.

24. Sand drains are installed by various methods. The displacement method uses a hollow mandrel with a closed bottom plate which is driven into the soil. The mandrel is filled with sand and then withdrawn while the bottom plate opens. The sand is forced out by air pressure to form a continuous sand column in the ground. The displacement method of sand drain installation causes disturbance and "smear" in the fine-grained soil in a zone next to the drain. While disturbance reduces the permeability of the disturbed zone, secondary compression settlements are reduced for small loading increments. Nondisplacement methods, such as augered holes or jetted holes, are sometimes used to minimize disturbance but may still cause some smear of the walls of the holes. Dredged material is fully remolded and any installation method could be used.

25. The surcharge load has to be applied in stages when the soft soil is too weak to support the entire load. By overloading the ground, shear failures may occur in the subsoil and the sand drains are likely to become discontinuous and ineffective. In a new type of vertical sand drain, sand is placed in jute textile bags which resist shear

failure of the drain caused by displacements. Stockings, made of woven polypropylene, can also be filled with sand and used for vertical sand drains.

26. The design of vertical sand drain systems has developed from an empirical to a more rational procedure based on theoretical consolidations. The theoretical principles needed in the design are based on the consolidation theory as applied to radial flow. The following design data can be estimated: diameter and spacing of sand drains; thickness of drainage blanket; safe rates of load application; height of surcharge fill necessary to produce a required degree of consolidation; needed time for the completion of the project; and the amount of settlement to be anticipated.

27. One of the major problems with sand drain projects is shear failure in the unstable subsoil during construction. To ensure against these failures, stability analyses should be made at various times during the construction.

28. Since there are some uncertainties involved in the determination of calculated design data, field control observations are required during and after construction. By measuring pore pressures and horizontal and vertical displacements, the rate of loading can be controlled for various heights of fill placement.

29. The improved drainage afforded by vertical sand drains accelerates primary consolidation (which is due to pore water extrusion) but does not affect secondary compression. Settlements due to secondary compression can be reduced by temporary surcharge loading.

30. Sand drains should not be expected to be of value in highly organic deposits or peat subsoils, since such materials normally have high coefficients of consolidation. The drains are useful beneath large loaded areas supported by formations consisting of alternate strata of sand and clay, but are not required if the loaded areas are small. Sand drains are particularly effective in thick, homogeneous clay deposits, where, because of their low permeability and large drainage paths, consolidation without sand drains would be very slow.

31. The installation of vertical sand drains is rather expensive;

therefore, the designer should first determine if it is necessary to accelerate consolidation before recommending sand drains. Generally, 6 months to 2 yr is required for consolidation of a soft soil deposit with sand drains.

32. Cardboard wicks. In Sweden, corrugated, band-shaped cardboard wicks were tried instead of sand drains with a good result. These have no capillary action and the use of the term "wicks" to describe them is probably incorrect. They are driven into the ground by a machine designed for this purpose. The maximum driving depth is 65 ft. Cardboard wicks were used on a large-scale basis in the building of Halmson Airport near Stockholm in a 23-ft-deep layer of very soft alluvial silt, underlain by shell sand. Wicks have also been used in the port of Antwerp, Belgium, and they are also extensively used in Japan.

33. Electro-osmatic dewatering. Electro-osmatic or the electrical drainage method can be highly effective in dewatering fine-grained soils, such as silts, clayey silts, and fine clayey silty sands. This method is quite costly because the power requirements are usually high, especially in saltwater areas. It is mainly used in those countries where electricity is relatively inexpensive, such as Canada, Norway, and Switzerland. It has been used only on a few occasions in the United States.

Dewatering dredged material

34. One purpose in dewatering dredged material is to increase the storage capacity of disposal areas by reducing the volume of water in the slurry. Another purpose is to develop land suitable for cultivation or building sites.

35. In Holland, a deposit area is prepared and divided into smaller areas of lagoons. Around the lagoons small dikes and drainage ditches are built. The slurry is pumped into the lagoons in 5-ft layers. Each layer is left to drain for approximately 12 months through outlets cut into the dike. The lagoons are filled and drained in rotation. By this method a 15-ft-thick layer of dredged material can be drained and densified.

36. A chemical dewatering technique, the "Panfloc Method," used in Japan, is based on the transformation of dredged slurry from a

single-grained to an aggregated structure. A coagulant, carboxymethyl cellulose grafted with acrylic acids (Panfloc X) is added to the dredged material in the delivery pipe, causing clay and silt particles to coagulate with sand grains. The coagulated particles then settle with an increased sedimentation velocity.

37. A method used at the Rotterdam (Holland) Harbor for preparing drainage ditches in dredged material depots uses a vehicle supported lengthwise by two cylinders which enable it to move on the mud surface. Rotating spiral cutting edges are mounted along the length of both cylinders propelling the vehicle through the mud. The dredged material is deposited into diked areas in layers about 1 m thick and consolidated for 2 months. During this time the emerging water is drained into a canal outside the depot dike. A surface drainage system is then established in three stages. During the first stage the vehicle enters the depot and moves across the mud surface producing ditches in the mud about 10 cm deep. Two months later, during the second stage, the ditches are deepened by a set of small disk wheels pulled by the vehicle. The mud is then left to consolidate for another 2 months. In the third stage the big disk wheel is pulled by a tractor making ditches about 0.5 to 0.6 m deep and 10 m apart. When the first layer of mud has been sufficiently drained and consolidated, a new layer is spread out and the treatment is repeated. With this procedure seven layers can be deposited, which after drainage and shrinking decrease to a 4-m final thickness. About a 10-yr period is necessary to consolidate a seven-layer depot and to change the dredged material from mud to earth.

38. Besides the above-mentioned dewatering methods, several other methods are under investigation.

Dewatering industrial wastes

39. Dewatering of ore tailings, sewage sludges, and industrial wastes brings up similar problems which occur in connection with dewatering dredged material. The study of methods used in dewatering these materials can help obtain a solution for dewatering dredged material and vice versa. There are several dewatering techniques used by industry, but unfortunately published information on the subject is surprisingly scarce.

Densification

Vibroflotation

40. Vibroflotation techniques have been used extensively in densifying loose granular materials with good results. Unfortunately, the method becomes ineffective if the sand contains fines in excess of about 20 percent, with clays not responding to vibration at all.

41. For strengthening cohesive soils, the "stone column" or the "vibro-replacement" technique is adapted. The technique may be applied to any soft or firm cohesive soil. It can be used successfully even in the treatment of soft organic clays.

42. In the process, vertical holes are formed in the ground by vibroflotation. The holes are then backfilled with coarse gravel or crushed stone, and compacted in stages by the vibration and weight of the vibrofloat. The compacted granular columns interact with the treated soil increasing the average shear strength and reducing the compressibility of cohesive soils. They also act as drains and speed up consolidation.

Precompression of soils

43. Precompression, also called preloading or surcharging, is an effective and economical procedure for improving the bearing capacity of weak, compressible subsoils prior to construction.

44. The method is especially effective on compressible soils in which consolidation takes place rather rapidly such as soft, fine-grained silts and clays, organic deposits, and sanitary landfills. Even in such soils the available time limits the thickness of the soil layer to be precompressed to approximately 15 ft. Thinner layers of soils that consolidate slowly can also be treated, but slowly consolidating clays of great thickness are not suitable for preloading since the required loading period to obtain the necessary settlement is long. Vertical drains can be installed to accelerate consolidation, if necessary.

45. Precompression involves placement of a temporary surface load over the area to be loaded by the structure with load generally exceeding the ultimate structural load. This procedure squeezes water out of

the soil voids, and when the desired percentage of consolidation is reached, the load is removed. Due to the effect of precompression, the consolidation is accelerated, the shear strength of the subsoil increased, and the magnitude of postconstruction settlements reduced.

46. Precompression is most frequently accomplished by placing dead load in the form of earthfills or water in tanks or ponds over the area of the future construction. The Elizabeth-Port Authority Marine Terminal on Newark Bay was stabilized by using seawater. The preload was provided by two reservoirs lined with plastic membranes and filled with water. One of the advantages of the water surcharge technique is that water can be placed and removed faster than earthfills.

47. Planning of a precompression project needs detailed subsoil investigations, laboratory tests, and design analyses. During the placement of the load and during the consolidation period, field observations of settlement and pore pressure are required so that modifications can eventually be made to assure the required result.

48. The precompression method was introduced with the construction of highway embankments. The method has been extensively used for light to medium buildings, oil storage tanks, and highway bridges. However, its use is not advisable where local highly concentrated loadings exist.

Compaction with mechanical equipment

49. Compaction, or densification with mechanical equipment, is a standard method for improving the bearing capacity of natural soil deposits or man-made fills. Compaction is effective only in partially saturated soils; hence, the method is not applicable for densifying dredged material and will not be reviewed.

Thermal and Chemical Soil Treatment

Thermal soil treatment

50. One method of improving the physical properties of soils is to heat them to sufficiently high temperatures. By thermal treatment, the water content and compressibility of the soil are reduced and its shear strength and permeability increased. The thermal energy required

to develop adequate soil strength depends on the water content and the mineralogical and chemical composition of the soil. The required energy varies widely from soil to soil. Thermal treatment is used as a procedure for stopping slides and plastic flow in clays, for reducing uneven settlements in soaked loess, and for improving the trafficability of soils.

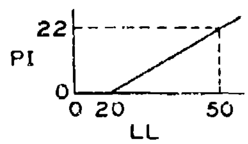
51. Thermal treatment of soils by burning fluid or gas fuel in borings was experimented and applied in the U. S. S. R., Rumania, and Japan. Since the thermal diffusivity of soil is small, a considerable duration of combustion is necessary to increase the range of soil solidification. The effective range of soil strengthening around a boring at the burning temperature of 460°C, and for burning duration of 10 days, has a diameter of about 20 cm. The resulting final strength of soil is about 10 or 20 times the initial strength. Surface treatment has been observed to a depth of about 6 in.

Chemical soil treatment

52. Experience gained in the field of chemical soil treatment may provide a method of changing the properties of dredged material to allow better drainage possibilities. In the operation of water supplies, sewage systems, and in the treatment of papermill wastewater and other industrial wastes, flocculants are added to suspensions which, by increasing the electrical attraction between fine-grained particles, tend to flocculate the particles, making larger particles of smaller ones. The flocculation of the particles causes a rapid settling rate and a higher permeability for the settled dredged material.

Settlement Under Temporary Surcharge Fill

1. Assume that soils plot on A-line and that initial water content = liquid limit; i.e., $w_o = LL$.



$$PI = \frac{22}{30}\left(LL - 20\right) \text{ or } \begin{cases} PI = 0.733\ LL - 14.67 \\ LL = \dfrac{PI + 14.67}{0.733} \end{cases}$$

Soils Plotting on A-Line			For w_o = LL , e_o is	
LL	PL	PI	G = 2.5	G = 2.7
50	28	22	1.25	1.35
100	41	59	2.50	2.70
150	55	95	3.75	4.05
200	68	132	5.00	5.40
300	95	205	7.50	8.10
500	148	352	12.50	13.50

$$e_o = w_o G \quad \text{or} \quad w_o = \frac{e_o}{G}$$

$$\Delta H = \frac{C_c H_o}{1 + e_o} \log \frac{\overline{p}_o + \Delta\overline{p}}{\overline{p}_o}$$

a. C_c from Nishida's relationship: $C_c = 0.54\ (e_o - 0.35)$

LL	C_c for G = 2.5	$C_c/1 + e_o$ for G = 2.5	C_c for G = 2.7	$C_c/1 + e_o$ for G = 2.7
50	0.486	0.216	0.540	0.230
100	1.161	0.332	1.269	0.343
150	1.836	0.387	1.998	0.396
200	2.511	0.418	2.727	0.426
300	3.861	0.454	4.185	0.460
500	6.561	0.486	7.101	0.490

b. From NAVFAC DM-7[75]* for soils at the LL:

LL	C_c for e_o	$C_c/1 + e_o$
50	0.46	0.196
100	1.12	0.307
150	1.76	0.371

c. From Bishop and Vaughan (Figure 6 in Reference 2):

LL	C_c	$C_c/1 + e_o$ (Assume G = 2.5)
30	0.18	0.103
50	0.36	0.160
80	0.63	0.210
140	1.17	0.260

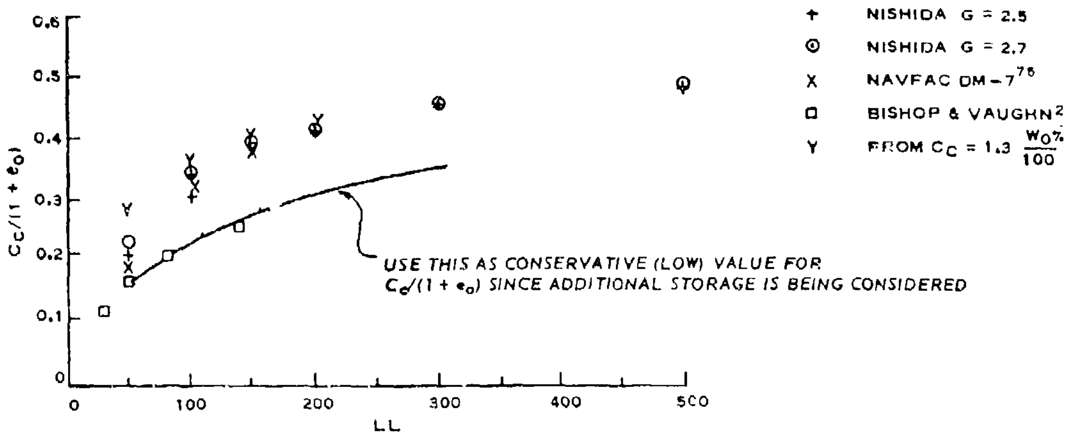
d. From $C_c = 0.01\ (LL - 13)$:

LL	C_c	$C_c/1 + e_o$ (Assume G = 2.5)
50	0.37	0.164
100	0.87	0.249
150	1.37	0.288
200	1.87	0.312
300	2.87	0.338
500	4.87	0.361
75	0.62	0.216

e. From $C_c = 1.3 \times \frac{w_o\%}{100}$:

LL	C_c	$C_c/1 + e_o$ for G = 2.5
50	0.65	0.289
100	1.30	0.371
150	1.95	0.411
200	2.60	0.433

* Raised numbers refer to similarly numbered items in the References at the end of the main text.



Settlement: $\Delta H = H_o \frac{C_c}{1 + e_o} \log \frac{\bar{p}_o + \Delta\bar{p}}{\bar{p}_o}$

2. Assume that groundwater level at a 2-ft depth and γ_{sub} = 28 pcf. Then assume $\bar{p}_o$ = 266 psf.

$\Delta\bar{p}$, psf	LL	$C_c/1 + e_o$	ΔH for H_o = 10 ft	Cost/Cu Yd of Added Storage	Cost/Acre of Disposal Area
100	50	0.16	0.22	$4.55	$ 1,600
	100	0.25	0.35	2.86	
	150	0.29	0.40	2.50	
	200	0.31	0.43	2.38	
500	50	0.16	0.73	6.85	8,100
	100	0.25	1.15	4.35	
	150	0.29	1.33	3.76	
	200	0.31	1.42	3.52	
1000	50	0.16	1.08	9.26	16,100
	100	0.25	1.69	5.92	
	150	0.29	1.96	5.10	
	200	0.31	2.10	4.76	

3. Assume that temporary surcharge fill weighs 100 pcf and does not settle below groundwater level. For convenience, assume fill cost = $1/cu yd.

Then: Added storage obtained = $(\Delta H \times \text{area})/27$, sq ft

Fill cost = \$1/cu yd or for height of H_F

$$\text{Fill cost} = \frac{\$1}{9} \times \frac{H_F}{3} \times \text{area, sq ft}$$

Cost of added storage obtained per cubic yard

$$= \frac{\text{fill cost}}{\text{added vol}} = \frac{\$1 \times H_F \times A}{27} \times \frac{27}{\Delta H \times A} = \frac{\$1 \times H_F \text{ in feet}}{\Delta H \text{ in feet}}$$

Temporary Surcharge Fill with Vertical Drains

4. Assume thickness of dredged material to be densified = 20 ft. Assume that 5 years time is available to secure 90-percent average densification and that $c_v = 0.02$ sq ft/day.

5. Place sand blanket on surface with collector pipes and assume one-way vertical drainage, i.e., no underdrainage.

Vertical drainage component:

$$\text{Assume} \quad t = \frac{T_v H^2}{c_v} \text{ or } T_v = \frac{tc_v}{H^2} \text{ ; at 5 years } T_v = \frac{5 \times 365 \times 0.02}{20^2}$$

$$\text{or} \quad T_v = 0.091 \quad \text{for which} \quad \overline{U}_v = 34 \text{ percent and } \frac{\overline{u}_r}{u_o} = 0.66$$

Combined radial and vertical drainage:

$$\text{For} \quad \overline{U}_{ave} = 90 \text{ percent , then } \left(\frac{\overline{u}}{u_o}\right)_{ave} = 0.10 = \left(\frac{\overline{u}}{u_o}\right)_v \times \left(\frac{\overline{u}}{u_o}\right)_r$$

$$\text{or} \quad \left(\frac{\overline{u}}{u_o}\right)_{radial} = \frac{0.10}{0.66} = 0.15 \quad \text{and } (U)_r = 85 \text{ percent.}$$

$$\text{Also,} \quad T_r = \frac{tc_r}{d_e^2}$$

For 12-in.-diam drains; from nomograph[30] $d_e = 9.2$ ft for triangular array or $9.2/1.072 = 8.5$-ft outer circumference for square array.

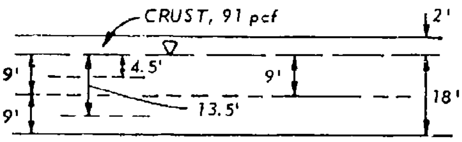
For 20-ft-long drains costing \$1/lin ft, the cost of drains = \$1 × 20/ 8.5^2 = \$0.2768/sq ft treated area or \$12,100/acre treated area.

Sand blankets:

For 1-ft-thick blanket the cost at \$1/cu yd = \$1 × 1/27 \$0.03704/sq ft = \$1600/acre treated area. For collector pipes at \$1200/acre the total cost is:

Vertical drains	\$12,100/acre
Sand blanket	1,600/acre
Collectors	1,200/acre
Total	\$14,900/acre, plus fill

Settlement of 20-ft-thick layer of dredged material:



$$\Delta H = \frac{H \times C_c}{1 + e_o} \log \frac{\overline{p}_o + \Delta p}{\overline{p}_o}$$

Upper layer: $\overline{p}_o = 28 \times 4.5 + 182 = 308$ psf

Lower layer: $\overline{p}_o = 28 \times 13.5 + 182 = 560$ psf

$$\Delta H = 9 \times \frac{C_c}{1 + e_o} \log \frac{\overline{p}_o + \Delta\overline{p}}{\overline{p}_o}$$

Calculations in Increased Storage Volume

$\Delta\overline{p}$ psf	LL	$\frac{C_c}{1 + e_o}$	ΔH_U ft	ΔH_L ft	ΔH_{total} ft	Volume cu yd/acre
100	50	0.16	0.18	0.10	0.28	452
	75	0.22	0.24	0.14	0.38	613
	100	0.25	0.27	0.16	0.43	694
	150	0.29	0.32	0.19	0.51	823
	200	0.31	0.34	0.20	0.54	871
500	50	0.16	0.60	0.40	1.00	1613
	75	0.22	0.83	0.55	1.38	2226
	100	0.25	0.94	0.62	1.56	2517
	150	0.29	1.09	0.72	1.81	2920
	200	0.31	1.17	0.77	1.94	3130
1000	50	0.16	0.90	0.64	1.54	2485
	75	0.22	1.24	0.88	2.12	3420
	100	0.25	1.41	1.00	2.41	3888
	150	0.29	1.64	1.16	2.80	4517
	200	0.31	1.75	1.24	2.99	4824

For:

$\Delta\overline{p}$ = 100 psf	Fill cost	=	$ 1,600/acre	(1-ft fill)
	Vertical drains	=	$12,100/acre	
	Collectors	=	1,200/acre	
	Total		$14,900/acre	
$\Delta\overline{p}$ = 500 psf	Fill (sand)	=	$ 8,100/acre	(5-ft fill)
	Vertical drains	=	12,100/acre	
	Collectors	=	1,200/acre	
	Total		$21,400/acre	
$\Delta\overline{p}$ = 1000 psf	Fill	=	$16,100/acre	(10-ft fill)
	Vertical drains	=	12,100/acre	
	Collectors	=	1,200/acre	
	Total		$29,400/acre	

$\Delta\overline{p}$ psf	LL	Cost of Added Storage $/cu yd
100	50	33.00
	75	24.30
	100	21.50
	150	18.10
	200	17.10
500	50	13.30
	75	9.60
	100	8.50
	150	7.30
	200	6.80
1000	50	11.80
	75	8.60
	100	7.60
	150	6.50
	200	6.10

Water Surcharge Load with Underdrainage, Surface Membrane, and Collectors

6. New York Port Authority[56] (NYPA) work cost for 63 acres is:

	Total	Cost/Acre	Cost/ Sq Ft
PVC lining and reservoir filling to 21 ft	$625,500	$ 9,929	$0.23
Underdrains	63,900	1,014	0.02
Instrumentation	16,500	261	0.01
Total	$705,900	$11,204	$0.26

For NYPA work, PVC lining and filling cost $0.26/sq ft. Per discussion with Dr. Charles E. Staff of Staff Industries, Inc:*

Liner, 10-mil thick	$0.06/sq ft delivered
Liner, 20-mil thick	$0.11/sq ft delivered
Labor to install	$0.025/sq ft delivered

Per Mr. Staff, liner cost would be about $0.14/sq ft for 20-mil liner or about $6100/acre.

Above liners are unreinforced PVC intended for single use.

7. For PVC reinforced with nylon scrim fabric with 100-lb tear strength, as used in the permanent pond at U. S. Army Engineer Waterways Experiment Station (WES), the probable cost would be:

Liner	$0.30/sq ft
Labor	0.25/sq ft
Equipment	0.15/sq ft
Total	$0.70/sq ft (or $30,500/acre, plus drainage)

Using unreinforced PVC liner:

PVC liner with filling	$ 9,900/acre
Underdrainage layer	1,600/acre
Collectors	1,200/acre
Total	$12,700/acre

* Personal communication, 10 October 1975, Dr. Charles E. Staff, Staff Industries, Inc.

Effect of water ponding:

1 ft of water loading = 0.63 ft of soil load

10 ft of water loading = 6.3 ft of soil load

20 ft of water loading = 12.6 ft of soil load

or

1 ft of soil load = 1.59 ft of water load

5 ft of soil load = 7.94 ft of water load

10 ft of soil load = 15.87 ft of water load

(Total cost = $12,700/acre)

Depth Water Load	Added Storage in Cu Yd/Acre					Dollars/Cu Yd of Added Storage				
	LL					LL				
ft	50	75	100	150	200	50	75	100	150	200
1.6	350	480	560	650	680	36.30	26.50	22.70	19.50	18.70
7.9	1180	1620	1860	2150	2290	10.80	7.80	6.80	5.90	5.50
15.9	1740	2400	2730	3160	3390	7.30	5.30	4.60	4.00	3.70

Surface Vacuum Mat with Drainage Layer and Collectors

8. For a vacuum induced in a sand blanket:

Induced Vacuum		
Inches of Hg	psi	psf
10	4.9	707
15	7.4	1061
17	8.4	1203
20	9.8	1415

1 in. of Hg = 1.133 ft of water

= 0.03342 atm

= 0.4913 psi

= 70.743 psf

A vacuum of 15 to 20 in. of Hg can be attained. This can be regarded as equivalent to 1000-1400 psf, approximately. For a 10-ft layer:

$$\Delta H = H \frac{C_c}{1 + e_o} \log \frac{\bar{p}_o + \Delta\bar{p}}{\bar{p}_o} \; ; \; \bar{p}_o = 266 \text{ psf}$$

LL	$\frac{C_c}{1 + e_o}$	$\Delta\bar{p}$ = 1000 psf ΔH ft	ΔV cu yd/acre	$\Delta\bar{p}$ = 1400 psf ΔH ft	ΔV cu yd/acre
50	0.16	0.87	1404	1.02	1646
75	0.22	1.19	1920	1.40	2259
100	0.25	1.36	2194	1.59	2565
150	0.29	1.57	2533	1.85	2985
200	0.31	1.68	2710	1.98	3194

Assume cost as: 20-mil PVC membrane at \$0.14/sq ft = \$6100/acre

1-ft sand blanket = 1613/acre

Collectors = 1200/acre

Construction cost = \$8913/acre

Assuming that power and equipment costs are \$50/day and that one shift of labor cost = 12 × 8 × 5 = \$500/week = \$2000/month, say \$30,000/year + 300 × 50; total = \$45,000/year.

9. For a 10-ft thickness with one-way drainage (see Figure 30 of main text), assume that pumping is required for 5 years to get 50-percent consolidation. For 5 years, operating cost is \$225,000. Assuming a 1,000- by 3,000-ft disposal area, or 68.87 acres, operating cost is \$3,267/acre.

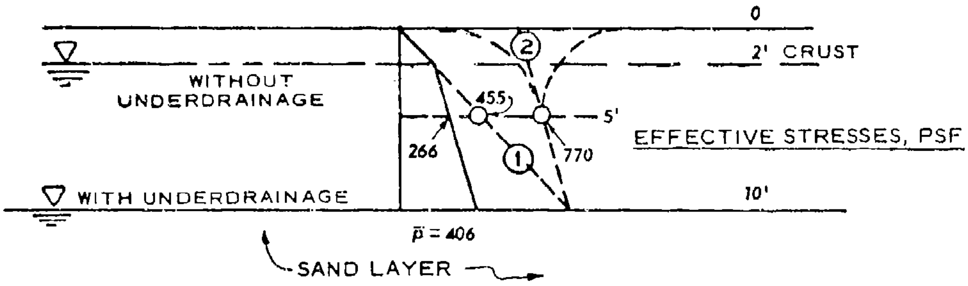
Membrane and collectors = \$ 8,913/acre

Pumping = 3,267/acre

Total = \$12,180/acre

LL	$\Delta\bar{p}$ = 1000 psf ΔV, cu yd/acre	Cost/Cu Yd	$\Delta\bar{p}$ = 1400 psf ΔV, cu yd/acre	Cost/Cu Yd
50	1404	\$8.60	1646	\$7.34
75	1920	6.29	2259	5.35
100	2194	5.51	2565	4.71
150	2533	4.77	2985	4.05
200	2710	4.46	3194	3.78

Underdrainage Densification



Case 1: Groundwater level at base of dredged material. No suction in pore water in dredged material.

Case 2: Same, with suction.

10. Compute settlements and costs corresponding to the incremental benefits of suddenly turning on the underdrainage system after a crust had formed.

Case 1: $\bar{p}_o = 266$ psf $\quad \bar{p}_o + \Delta\bar{p} = 455$ psf, neglect crust settlement

Case 2: $\bar{p}_o = 266$ psf $\quad \bar{p}_o + \Delta\bar{p} = 770$ psf

LL	$\frac{C_c}{1 + e_o}$	Case 1 ΔH, ft	Case 1 Cu yd/acre	Case 2 ΔH, ft	Case 2 Cu yd/acre
50	0.16	0.37	597	0.74	1192
75	0.22	0.51	823	1.02	1638
100	0.25	0.58	936	1.15	1861
150	0.29	0.68	1097	1.34	2160
200	0.31	0.72	1162	1.43	2308

11. Cost of obtaining underdrainage varies with conditions, but a collector pipe system on top of the foundation is probably the minimum possible that will be required to avoid building up high pore pressures in a natural sand foundation. In this case, assume collector cost as \$1200/acre.

12. If a sand blanket must be provided, assume sand is available

at $1/cu yd by dredging deeper, and use collector pipe system

Sand = $1613/acre

Collectors = 1200/acre

Total = $2813/acre

Cost/Cu Yd of Added Storage

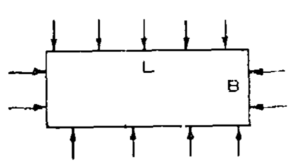
LL	Case 1: Collectors Only	Case 1: Sand Blanket and Collectors	Case 2: Collectors Only	Case 2: Sand Blanket and Collectors
50	$2.01	$4.71	$1.01	$2.36
75	1.46	3.42	0.73	1.72
100	1.28	3.01	0.64	1.51
150	1.09	2.56	0.56	1.30
200	1.03	2.42	0.52	1.22

Underlying Drainage Layer with Vacuum Pumps

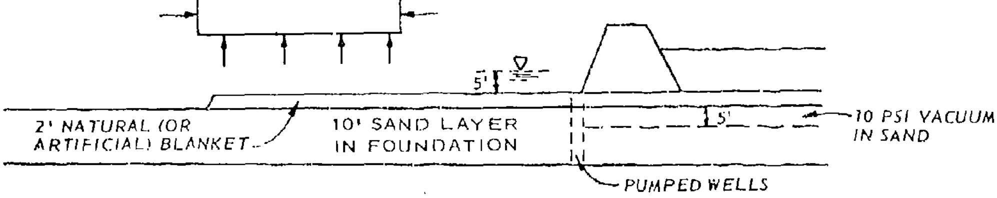
13. See Figure 36 of main text for conditions assumed--compute benefits assuming that crust has formed to 2 ft, $\overline{p}_o$ = 266 psf, $\overline{p}_o + \Delta\overline{p}$ = 2210 psf, and H_o = 10 ft.

LL	$\frac{C_c}{1 + e_o}$	ΔH ft	ΔV cu yd/acre
50	0.16	1.47	2374
75	0.22	2.02	3264
100	0.25	2.30	3709
150	0.29	2.67	4302
200	0.31	2.85	4599

Pumping required:



It is difficult to describe what is "average." As an extreme case, assume seepage entrance face at perimeter of disposal area with sand at surface.



14. Effective length of blanket is $1/a \tanh(aL)$, where

$$a = \sqrt{\frac{k_b}{k_f Z_f Z_b}}$$

L = length of blanket, approximately ͘00 ft.

Take $k_b/k_f = 1/10$, $\therefore a = \sqrt{1/10 \times 10 \times 2} = 0.0707107$.

$\tanh(aL) = \tanh 21.213 = 1.00$

$\therefore$ effective length = 14.14 ft

$q = k_f iA = k_f(10/14.1)$ 10 per foot of perimeter

For $k_f = 0.01$ fpm, q = 0. × 100/14.1 = 0.07092 cfm/ft

or q = 0.53 gpm/ft

For a disposal area 1000 ft × 3000 ft, Q = 4240 gpm. In addition, flow would be increased by water draining from dredged material as it consolidates. Assume

ΔH = 2 ft in 1 year

$$\Delta Q = \frac{2 \text{ ft} \times 1000 \text{ ft} \times 3000 \text{ ft}}{365 \times 1440} = 11.42 \text{ cfm} = 85 \text{ gpm}$$

and

Q = 4325 gpm total flow.

15. Assume three 100-hp pumps would be used. For electric pumps, approximately 63 kw at \$0.02/kwhr = \$1.26/hr:

3 pumps = 3 × 1.26 × 24 = \$90.72/day power cost

Assume automatic pumps with one man on day shift only:

Labor at \$15/hr including overhead and profit = \$120/day.

Equipment - \$30,000/year.

For a 1-year period:

Power: 365 days at \$90.72	=	\$ 33,100/year
Labor: 120 × 5 × 52	=	31,200/year
Equipment rental	=	30,000/year
Total	=	\$100,000/year

$$\text{or cost/acre} = \frac{\$100{,}000 \times 43{,}560}{1{,}000 \times 3{,}000} = \$1{,}452/\text{year.}$$

16. For a 10-ft-thick layer and c_v = 0.01 sq ft/day,

$\overline{U}$ = 50 percent in 5 years (see Figure 30 of main text).

a. For no underdrainage sand layer, cost = $1450/acre/year.

b. With 1-ft-thick underdrainage sand layer and collector pipes, cost is:

Sand at $1/cu yd	=	$ 1,613/acre
Collectors	=	1,200/acre
Pumping (5 × 1,450)	=	7,250/acre
Total	=	$10,063/acre

LL	ΔV cu yd/acre	50% × ΔV cu yd/acre	Cost/Cu Yd for 5-year Pumping: Pumping Only	Cost/Cu Yd for 5-year Pumping: Pumping with Sand and Collectors
50	2374	1187	$6.11	$8.48
75	3264	1632	4.40	6.17
100	3709	1854	3.91	5.43
150	4302	2151	3.37	4.68
200	4599	2299	3.15	4.38

If consolidation proceeded more rapidly, volume of storage would be increased and cost per cubic yard might be decreased--possibly by 100 and 50 percent, respectively.

Water Surcharge Load with Underdrainage--No Membrane

17. Settlement induced by seepage above that induced by initial desiccation and consolidation

$$\Delta H = H \frac{C_c}{1 + e_o} \log \frac{\overline{p}_o + \Delta\overline{p}}{\overline{p}_o}$$

where H = 8 ft; 2-ft crust incompressible

LL	$\frac{C_c}{1 + e_o}$	ΔH ft	ΔV cu yd/acre	50% × ΔV in 5 Years cu yd	Cost/Cu Yd Initial Fill at $100/Acre
50	0.16	0.756	1219	610	$0.16
75	0.22	1.039	1676	838	0.12
100	0.25	1.181	1905	952	0.10
150	0.29	1.370	2210	1105	0.09
200	0.31	1.464	2362	1181	0.08

$\underline{a}$. Pumping required: For 1-ft settlement per year and 1000-ft by 3000-ft area

$$\Delta q = \frac{1 \text{ ft} \times 1000 \text{ ft} \times 3000 \text{ ft}}{365 \times 1440} = 5.71 \text{ cfm}$$

or $\Delta q = 42.7$ gpm, but this would not be required to maintain H_w at 10 ft.

$\underline{b}$. Seepage: $Q = kiA = 1 \times 10^{-7} \times 2 \times 1{,}000 \times 3{,}000 = 0.60$ cfm or $Q = 4.5$ gpm or 6,463 g/day or 194,000 g/month.

$\underline{c}$. Evaporation: Evaporation will equal yearly rainfall in areas where dredging is done.

$\underline{d}$. Initial filling: Assume filling in 1 month,

$$Q = \frac{10 \text{ ft} \times 3000 \text{ ft} \times 1000 \text{ ft}}{30 \text{ days} \times 1440} = 2272 \text{ cfm} = 17{,}000 \text{ gpm}$$

To lift water a total of 20 ft:

$$(\text{Work done} = \underbrace{\underbrace{10 \text{ ft} \times 3000 \text{ ft} \times 1000 \text{ ft}}_{\text{quantity}} \times 20 \text{ ft} \times 63 \text{ pcf})}_{\text{ft-lb}}$$

$$\times 3.77 \times 10^{-7} = 1002 \text{ kwhr}$$

Labor = 8 hr at \$15 = \$120/day; 1000 ft × 3000 ft = 68.87 acres. Approximately \$3000 total cost to fill.

$$\text{Cost/acre} = \frac{\$3000}{68.87} = \$43.56/\text{acre}$$

Assume \$100/acre to fill with water (see tabulation above for cost/cu yd of storage obtained). Note that the presence of intermediate drying crusts would decrease consolidation of material above crust and increase that of material below crust. Also note that underdrainage is assumed.

18. If natural effective underdrainage does not exist, cost would be increased by:

1-ft sand blanket at \$1/cu yd	=	\$1633/acre
Collectors	=	1200/acre
Total		\$2833/acre

For this case, costs are:

100% ΔV	LL	Cost/Cu Yd of Added Storage w/100% ΔV
1220	50	$2.32
1680	75	1.69
1900	100	1.49
2210	150	1.28
2360	200	1.20

Desiccation

19. Volume decrease that occurs from desiccation can be related to effective stresses induced. From data given by Bishop and Vaughan,[2] it appears that drying depths from field observations are:

Depth ft	Time Year
0.1	0.07
0.5	0.5
1.2	3.0
2.4	7.0

20. For surface suction of one atmosphere, depth d_{50} to which suction has increased to 0.50 atm in time t is:

$$d_{50} = 0.99\sqrt{c_v t}$$

or

$$t = \frac{1.02\ d_{50}^2}{c_v}$$

for $c_v = 0.02$ sq ft/day

d_{50} ft	t* Year
0.5	0.03
1.0	0.14
1.5	0.31
2.0	0.56
2.5	0.87
3.0	1.26

* 1-3 ft/year might be practicable.

21. From Figure 29 of the main text, potential volume increases

for the initial volume corresponding to percent $w = 2 \times LL$.

$\frac{\Delta V}{V_o}$ from w% = 2 × LL to	LL, %			
	50	100	150	200
LL	36	42	44	46
PL	52	66	72	76
LL to PL	16	24	28	30

22. For 10 ft of dredged material, added storage volume for drying from LL to Pl will be:

	LL			
	50	100	150	200
Added storage cu yd/acre	2580	3870	4520	4840

Assuming that this will require three men for 1 month/year for 10 years, labor cost would be $15/hr including overhead.

$$3 \times 22 \times 8 \times 15 = \$7{,}920/\text{year} \times 10 = \$79{,}200$$

For a disposal area of 1000 ft × 3000 ft or 68.9 acres,

$$\text{total cost} = \$1150/\text{acre}$$

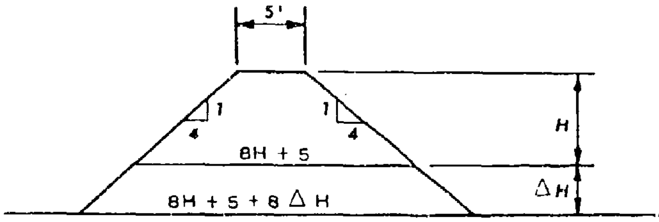
then:

	LL			
	50	100	150	200
Cost/cu yd for additional storage	$0.45	$0.30	$0.25	$0.24

Note that these costs do not include equipment costs. Increase by $30,000/$79,200 or 37.9 percent for equipment. Then total cost is $1,610/acre and

	LL			
	50	100	150	200
Cost/cu yd for additional storage	$0.62	$0.42	$0.36	$0.33

23. For raising dikes:



$$V_o = \left(\frac{8H}{2} + 5\right) \times \frac{H}{27} = \frac{8H^2}{54} + \frac{10H}{54}$$

$$\Delta V = \frac{16H + 8\Delta H + 10}{2} \times \frac{\Delta H}{27} = \frac{16H(\Delta H) + 8\overline{\Delta H}^2 + 10\ \Delta H}{54}$$

$$\frac{\Delta V}{V_o} = \frac{16H(\Delta H) + 8\overline{\Delta H}^2 + 10(\Delta H)}{8H + 10H}$$

ΔV per foot for:

H_o, ft	ΔH, ft	ΔV/ft cu yd/ft
10	0.5	1.61
	1.0	3.30
	1.5	5.06
	2.0	6.89
	2.5	8.80
	3.0	10.78

24. For a 1000- to 3000-ft disposal area:

$$\Delta V = 8000 \times \Delta V/\text{ft}$$

$$\frac{\Delta V}{\text{area}} = \frac{8000 \times \Delta V/\text{ft}}{68.87 \text{ acres}}$$

ΔH, ft	ΔV of Dikes cu yd/acre Disposal Area
0.5	187
1.0	383
1.5	588
2.0	800
2.5	1022
3.0	1252

Added storage volume obtained by raising dikes

ΔH, ft	ΔV of Dredged Material cu yd/acre
0.5	806
1.0	1613
1.5	2420
2.0	3226
2.5	4033
3.0	4839

Cost of added storage assuming dike cost of $1.00 per cu yd:

ΔH, ft	Cost of Added Storage per acre	per cu yd
0.5	$ 187	$0.23
1.0	383	0.24
1.5	588	0.24
2.0	800	0.25
2.5	1022	0.25
3.0	1252	0.26

APPENDIX D: NOTATION

A	Area of disposal area
B	Base width of disposal area
c_v	Coefficient of consolidation
C_c	Compression index
C_u	Uniformity coefficient
d	Depth
d_e	Effective diameter of area tributary to sand drain
D_{10}	Effective particle size
e	Void ratio
e_o	Initial void ratio
G	Specific gravity
H	Thickness of dredged material; length of one-way drainage path; initial height of levee
H_F	Height of temporary fill
H_o	Initial thickness
H_w	Height of water
i	Hydraulic gradient
k	Coefficient of permeability
k_b	Coefficient of permeability of blanket
k_f	Coefficient of permeability of sand layer
L	Length of disposal area
LI	Liquidity index
LL	Liquid limit
$\bar{p}$	Effective stress
$\bar{p}_o$	Initial effective stress
PI	Plasticity index
PL	Plastic limit
q	Discharge per unit time per unit length of perimeter
Q	Discharge per unit time
t	Time
T_r	Time factor for radial drainage
T_v	Time factor

$\bar{u}$	Average excess pore water pressure
$\bar{u}_o$	Initial excess pore water pressure
$\bar{u}_v$	Average excess pore water pressure in vertical drainage only
$\bar{U}$	Percent consolidation
$\bar{U}_v$	Average percent consolidation for vertical drainage only
V_o	Original volume
$\bar{V}_v$	Average percent consolidation in vertical drainage and vertical consolidation
w	Water content
w_o	Initial water content
Z_b	Thickness of blanket
Z_f	Thickness of sand layer
γ_{sub}	Submerged unit weight
Δe	Change in void ratio
$\Delta\bar{p}$	Increase in effective stress
Δw	Decrease in water content
ΔH	Decrease in dredged material thickness
ΔH_L	Lower layer change in thickness
ΔH_U	Upper layer change in thickness
ΔV	Decrease in volume

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Johnson, Stanley J

State-of-the-art applicability of conventional densification techniques to increase disposal area storage capacity, by Stanley J. Johnson, Robert W. Cunny, Edward B. Perry, [and] Leslie Devay. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1977.

1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Technical report D-77-4)

Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C.; monitored by Environmental Effects Laboratory, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., under DMRP Work Unit No. 5A03.

App. A, B, and C on microfiche at end of text.

Includes bibliography.

1. Densification. 2. Dewatering. 3. Dredged material disposal. 4. Soil stabilization. 5. Waste disposal sites. I. Cunny, Robert W., joint author. II. Devay, Leslie, joint author. III. Perry, Edward Belk, joint author. IV. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report D-77-4)

TA7.W34 no.D-77-4