DREDGED MATERIAL RESEARCH PROGRAM

TECHNICAL REPORT D-77-18

CLASSIFICATION AND ENGINEERING PROPERTIES OF DREDGED MATERIAL

by

Michael J. Bartos, Jr.

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

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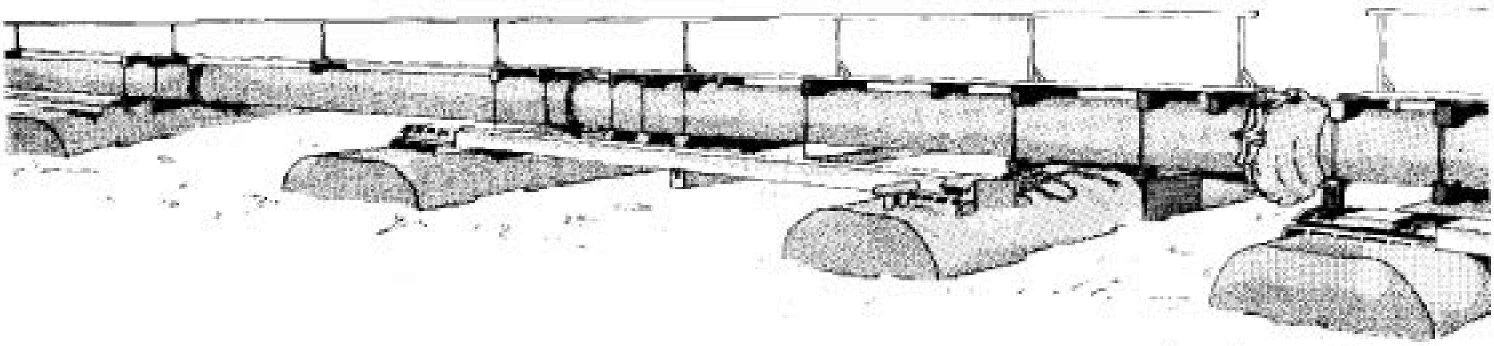
Final Report



Prepared for Office, Chief of Engineers, U. S. Army
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Under DMRP Work Unit 5C02

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

IN REPLY REFER TO: WESYV

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SUBJECT: Transmittal of Technical Report D-77-18

TO: All Report Recipients

1. The report transmitted herewith is the result of a work unit initiated as part of Task 5C (Disposal Area Reuse Research) of the Corps of Engineers' Dredged Material Research Program (DMRP). Task 5C is part of the Disposal Operations Project of the DMRP and, among other considerations, includes developing methods to extend the useful life of confined disposal areas.

2. Confining dredged material on land is a disposal alternative to which little specific design or construction improvement investigations have been addressed. There has been a dramatic increase in the last several years in the amount of land disposal necessitated in part by restrictions on open-water disposal. In order to minimize the amount of land required for the confined disposal areas, a significant proportion of the work in the DMRP has been aimed toward identifying ways of increasing the capacities of containment areas.

3. One concept being considered is that of a reusable disposal site, meaning that a disposal site acts primarily as a rehandling basin from which the material is removed and put to a productive use. One obvious use for dredged material is landfill or construction material; however, very little information has been available on the physical and engineering properties of dredged material. This study (Work Unit 5C02) was initiated to provide a better indication of the properties of dredged material. It was also felt that this study was needed to offset the misconception that dredged material is some exotic material with properties significantly different from upland soils.

4. Data were acquired from Corps of Engineers Districts, from published reports, and a program of sampling and testing of sediments to be dredged. Standard soil properties tests were used to determine the classification and engineering properties of the sediment samples. Samples were classified in accordance with each of four standard soil classification systems: Unified Soil Classification System, the Federal Aviation Agency Classification System, American Association of State Highway Officials Classification System, and the U. S. Department of Agriculture Classification System. The engineering properties of ten samples of

compacted dredged material were determined. In addition, the engineering properties of dredged material in some containment areas were determined to characterize the variation of the properties with depth, time, and distance from the location of the discharge pipe.

5. The study concludes that dredged material is a soil, may be analyzed as a soil, and can be used as a soil. The comparison between soil and dredged material is presented to encourage the productive use of dredged material as a natural resource in urban and other development projects, especially in areas where landfill and construction material needs can be met by available dredged material.

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

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Data pertaining to the classification and engineering properties of dredged material are presented. Data were acquired from Corps of Engineers (CE) Districts, from published reports, and a program of sampling and testing of material to be dredged. Standard soil properties tests were used to determine the classification and engineering properties of dredged material samples. Sampling, test specimen preparation, and test descriptions are presented. Samples were classified in accordance with each of four standard soil classification systems. (Continued)

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20. ABSTRACT (Continued).

The engineering properties of ten samples of compacted dredged material were determined, and the results show that dewatered dredged material has properties comparable to those of similar types of soil. The engineering properties of dredged material in some containment areas are presented, showing the variation of properties with depth, time, and distance from the dredge discharge pipe.

The study concludes that dewatered dredged material is a soil, can be analyzed as a soil, and can be used as a soil. The use of soil mechanics tests and the comparison between soil and dredged material are presented to encourage the productive use of dredged material as a natural resource in urban and other development projects, especially in areas where landfill needs can be met by available dredged material.

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EXECUTIVE SUMMARY

This report presents data pertaining to the classification and engineering properties of dredged material. The impetus for such a study was provided in part by the lack of widespread information on the properties of dredged material. Data were acquired from Corps of Engineers (CE) Districts and from published reports, and a program of sampling and testing of material to be dredged was undertaken. Grab samples of bottom sediment to be dredged were collected from frequently dredged CE navigation projects.

A number of standard soil properties tests were used to determine the physical and engineering properties of dredged material samples. Soil properties tests included classification properties tests, such as grain-size and plasticity analyses and organic content determinations, and engineering properties tests such as compaction, consolidation, and shear strength tests. Dredged material sampling, test specimen preparation, and brief test descriptions are presented. The discussion is very basic and is intended for use by those who deal with dredged material but who may have little or no experience in soils engineering.

Four standard soil classification systems, the Unified Soil Classification System, the American Association of State Highway Officials Classification System, the Federal Aviation Administration System, and the U. S. Department of Agriculture System, are discussed. The samples were classified in accordance with each of the four classification systems. A fifth classification system, the Permanent International Association of Navigation Congresses classification of soils to be dredged, is also discussed. Samples were not classified using this system because the system does not relate to the properties of soils after dredging.

The engineering properties of ten specimens of dredged material, compacted to simulate anticipated field conditions, were determined; the results show that dewatered dredged material has properties comparable to those of similar types of soil. These properties are presented and discussed in a very basic manner to show that dredged material is

not simply the waste product of dredging, but is in fact made up of various types of soil.

The engineering properties of dredged material in containment areas, as reported by others, are reviewed, showing the variation of properties with depth, time, and distance from the dredge discharge pipe. The dredged material in containment areas is generally characterized by a high water content, low dry density, and low shear strength. Properties improve slowly with time and are generally better near the pipe than near the outlet.

The study concludes that dewatered dredged material is a soil, may be analyzed as a soil, and can be used as a soil. The comparison between soils and dredged material is presented to encourage the productive use of dredged material as a natural resource in urban and other development projects, especially in areas where landfill needs can be met by available dredged material.

PREFACE

This report is the result of an investigation concerning the classification and engineering properties of dredged material. The study, Work Unit 5C02, is part of the Dredged Material Research Program (DMRP), conducted for the Office, Chief of Engineers, at the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi. The work unit is part of the DMRP Disposal Operations Project (DOP), Mr. C. C. Calhoun, Jr., Manager.

Initial phases of the study were conducted by Dr. J. W. Spotts, former DOP staff member. The study was completed by personnel of the Environmental Engineering Division (EED) of the Environmental Effects Laboratory (EEL) at WES, under the general supervision of Dr. J. Harrison, Chief, EEL, and Mr. A. J. Green, Chief, EED, and under the direct supervision of Mr. R. L. Montgomery, Chief, Design and Concept Development Branch, EED.

The principal investigator was Mr. M. J. Bartos, Jr. Mr. D. A. Goss assisted in the sample procurement and in the preparation of the figures and tables. Laboratory analysis of dredged material samples obtained during the study was performed by the Soils and Pavements Laboratory (S&PL) at WES under the supervision of Mr. G. P. Hale, Chief, Soil Testing Branch, Soil Mechanics Division. Assistance was provided by many Corps of Engineers (CE) personnel who cooperated in the data and sample procurement. The report was written by Mr. Bartos.

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

CONTENTS

CONTENTS

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
inches	25.4	millimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
square inches	6.4516	square centimetres
square feet	0.09290304	square metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
tons (force) per square foot	95.76052	kilonewtons per square metre
foot-pounds (force) per cubic foot	47.880339	joules per cubic metre
degrees	0.01745329	radians

CLASSIFICATION AND ENGINEERING PROPERTIES OF DREDGED MATERIAL

PART I: INTRODUCTION

Background

1. The Corps of Engineers (CE) is responsible for the maintenance of over 19,000 miles* of navigable waterways and more than 1,000 harbors. Maintenance of these waterways and harbors is currently accomplished by dredging, which involves removing bottom sediments from navigation projects and transporting these sediments elsewhere for disposal. Boyd et al.[1] have conservatively estimated that maintenance dredging results in an annual volume of 300,000,000 cu yd of dredged material. Disposal of this large volume of dredged material is accomplished by one of two general methods: the material is either disposed in open water or confined on land. Concern for the effect of open-water disposal operations on benthic organisms, as well as the effect of contaminants released from the dredged material into the water column, has brought about a decrease in the practice of open-water disposal and a corresponding increase in the use of confined land disposal sites. The resulting shortage of land disposal sites was one factor that led to the creation of the Dredged Material Research Program (DMRP).

2. The objective of the DMRP is to provide more definitive information on the environmental impact of dredging and dredged material disposal operations and to develop new or improved disposal practices. The DMRP will, in effect, result in the development of alternative measures that can be applied singly or in combinations by each CE District to solve its disposal problems. One important improvement is to

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units can be found on page 7.

extend the service life of existing containment areas by removing all or part of the dredged material. The needs for landfill and construction material in terms of dredged material availability have been documented,[2] and dredged material can also be used at the containment area for dike raising. Data concerning the physical and engineering properties of dredged material were required to help evaluate the feasibility of using dredged material for on-site and off-site uses, and this study was conducted to accumulate these data.

Purpose

3. The lack of knowledge of the properties of dredged material has been a major factor contributing to its lack of acceptance as a manageable resource. Past endeavors to describe dredged material according to its physical and engineering properties have produced widely ranging results. In some instances dredged material has been classified according to a recognized system such as the Unified Soil Classification System (USCS), while in other cases dredged material has been described in ambiguous or incorrect terms (such as mud, muck, and sludge) with nonquantified or nonquantifiable properties. The purpose of this study was to accumulate and present information pertaining to the classification and engineering properties of dredged material.

Scope

4. While nationwide in scale, the study focused on those regions of the country where most maintenance dredging occurs. Because of the large area encompassed by this study and because of time and funding limitations, investigations were limited to navigation projects requiring frequent dredging. Investigation of each project studied was necessarily cursory. Properties determined for dredged material samples from study projects included grain-size distribution, plasticity, and organic content. Selected samples were subjected to standard soils engineering tests such as compaction, consolidation, and shear strength tests. The study was not intended to characterize all the dredged

material in the nation, but rather to provide an indication of the ranges and types of properties of material dredged from estuarine, riverine, and lacustrine dredging operations.

Study Projects

5. The large geographical area involved in this study required that only those projects involving the largest volumes of material dredged within a given CE District be investigated. The most up-to-date dredging statistics were furnished in response to a questionnaire[3] sent to each District by the A. D. Little Company of Cambridge, Massachusetts, as part of the National Dredging Study. The questionnaire requested that Districts provide information concerning the dredging performed on each project for the past four maintenance operations, as well as an estimate of dredging for the next 10 years. Raw data from these questionnaires were used in selecting projects to be studied. Figure 1 shows the locations of the projects studied. The study projects are listed individually by District in Table 1, which also shows what percentage of a District's total dredging occurs within a given study project. The information contained in Table 1 is presented graphically in Figure 2, which shows the boundaries of the five study regions.

6. The five study regions used during this study are patterned after those used by Green Associates to report the needs for dredged material.[2] While the Gulf States, South Atlantic, and Pacific Coast study regions are the same as those used by Green Associates, the North Atlantic and Great Lakes study regions were expanded so that more data could be presented. These study regions were used to facilitate the presentation of the data and to show comparisons of the properties of dredged material in different areas of the country. In addition, use of study regions comparable to those of Green Associates permits comparison between regional material needs and regional dredged material characteristics.

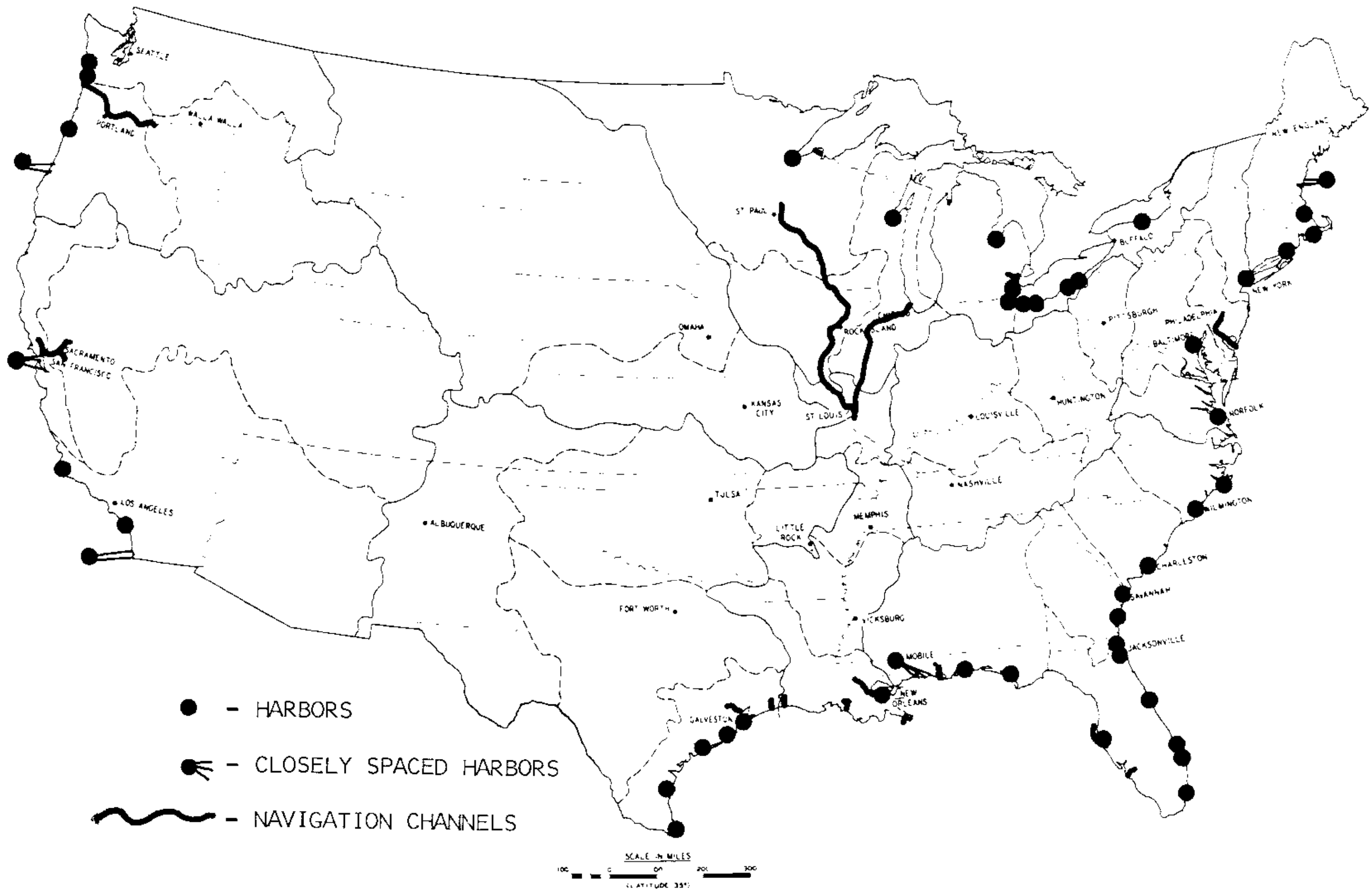


Figure 1. Location of study projects

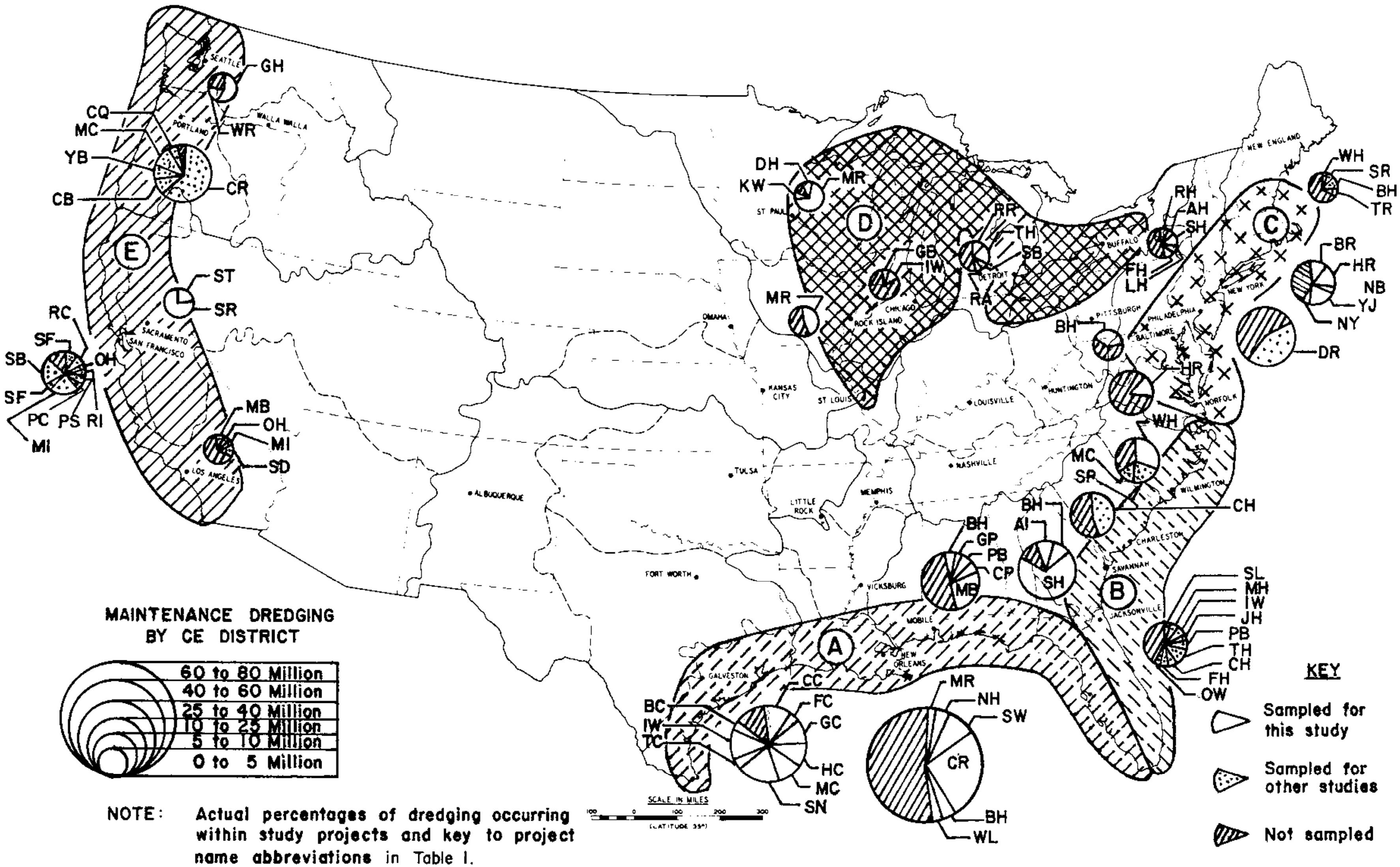


Figure 2. Sampling coverage within CE Districts

PART II: FIELD INVESTIGATIONS

7. An objective of this study was to report the classification and engineering properties of dredged material from as many dredging sites as possible. The accomplishment of this objective required acquisition of data from a variety of sources. Data were made available from the files of CE District offices and were also extracted from published reports. These available data were augmented by a program of bottom sediment sampling and laboratory analysis. The sampling and testing programs provided data for material to be dredged from projects not investigated by previous studies.

8. Detailed information concerning sampling equipment, site selection, and sampling techniques was generally not found in the reports of these previous studies. Sometimes the type equipment used or the reason for sampling was stated, in which case the type of sample may be determined. For example, a District may obtain samples from full hopper bins and record the dredging areas. In such cases the general areas from which the samples were taken and the technique for taking the samples were both known. In other cases, however, only the name of the project was known and details could be determined only through the agency responsible for taking the samples. The sampling program used during this study is the subject of the remainder of this part.

Philosophy of Sampling Program

9. The philosophy of the sampling program, that samples be obtained from as many study projects as possible without duplicating available data, limited the number of samples obtained from any study project. Therefore, care must be used in the interpretation and application of the data obtained. Determination of the properties of an entire shoal requires a much more extensive sampling program than the one undertaken during this study. The properties of one sample may not be representative of the properties of the entire shoal from which the sample was taken. Since there can be considerable variability in the

types of material comprising a shoal, complete characterization of a shoal requires that representative samples of each type of material be obtained and tested. Therefore, the data presented herein are not necessarily representative of all dredged material. Rather, the data may be used to show qualitatively the types of material dredged throughout the nation.

10. The design of the sampling program required determination of the type and location of samples to be taken, and these factors are described in the following sections, with sample type, site selection, sampling equipment, and sampling techniques presented as separate topics.

Sample Type

11. Although some samples were collected from working hopper dredges and a few others from within disposal sites, most samples were collected from shoals of material to be dredged, because this was the most operationally feasible way to obtain a large number of samples in a short period of time. Collecting all samples during the dredging process would have greatly delayed the study by restricting sampling to the dredging schedule. Sampling in disposal sites presents difficulties such as site inaccessibility and material consistency. The soft material is often incapable of supporting the men and equipment necessary to perform the sampling.

12. The dredged material properties reported herein were determined by testing samples of bottom sediment to be dredged. Although the structure and water content of sediment are changed during dredging, reporting sediment properties as those of dredged material is valid, because the test procedures also result in structural disturbance. No tests were intended to determine in situ properties of the shoal and no samples were undisturbed. The classification properties are independent of in situ structure and of natural water content, and engineering properties were determined for samples that had been dewatered and compacted.

Sampling Site Selection

13. Samples of bottom sediment subject to removal by maintenance

dredging were obtained. While the study projects were selected on the basis of maintenance dredging volumes, sampling sites within the study projects were selected on the basis of maintenance dredging locations. Utilizing personal experience, dredging records, and condition surveys, local CE personnel estimated the size and location of the largest repetitive shoals within each study project. With the shoals located and ranked, the largest shoals, equal in number to the number of samples planned for that project, were selected, and a sample was obtained from the vicinity of the center of the shoal. In the case of anchorages, turning basins, and other projects of irregular shape where the shoal was not well defined, the samples were obtained at safe, convenient locations.

Sediment Sampling Equipment

14. Push tube samplers and grab samplers are two general classes of sampling equipment used for obtaining samples of sediment, and several of these samplers are described below. Each of the specific samplers described was used to obtain samples during this study.

Push tube samplers

15. A tube sampler is an open-ended tube that is thrust vertically into the sediment deposit to the depth desired. The sampler is withdrawn from the deposit with the sample retained within the tube. Differences among tube samplers relate to tube size, tube wall thickness, type of penetrating nose, head design including valve, and type of driving force. These terms are illustrated for the types of samplers described below.

16. Phleger tube sampler. The Phleger tube sampler (Figure 3a), often called a harpoon sampler, is widely used for obtaining samples from the upper portion of underwater deposits. Because it obtains its penetrating force from its weight and from pushing by operators in a work boat, it must necessarily be substantially heavy without being awkward to manipulate. The harpoon is available with adjustable weights in the range of 17 to 77 lb and in fixed weights in excess of 90 lb.

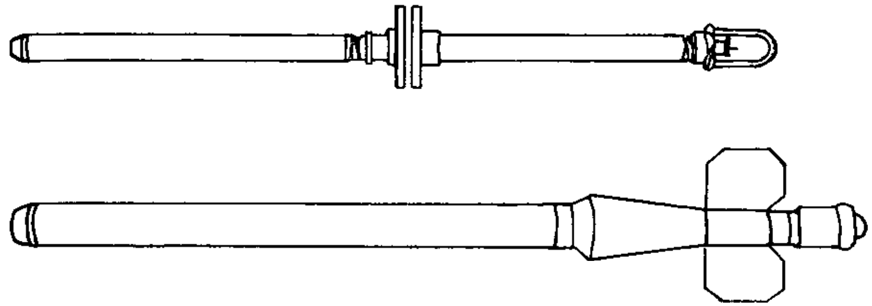
The amount of weight required depends upon the texture of the deposit and the required depth of penetration. Phleger samplers, like most sampling tubes, sample a small area, usually between 2 and 4 sq in.

17. Split barrel sample spoon. This sampler (Figure 3b), often called a split spoon, is a heavy-wall sampler. This term is applied to samplers with a relatively high ratio of tube wall thickness to tube diameter. The split spoon usually has an outside diameter of 2 in. and a wall thickness of 1/4 in. A principal feature of the split spoon is a ball valve in the head, which permits water to pass through the tube during penetration. During retrieval, the valve closes and reduces the possibility of having water wash the sample out of the tube. The sampler is thrust into the deposit by a hammering force exerted on rods connected to the head. The spoon is capable of penetrating very hard sediments provided sufficient force is applied to the rods. During retrieval, the sample is retained within the barrel by a flap. The nose and head are separated from the barrel in order to transfer the sample to a container.

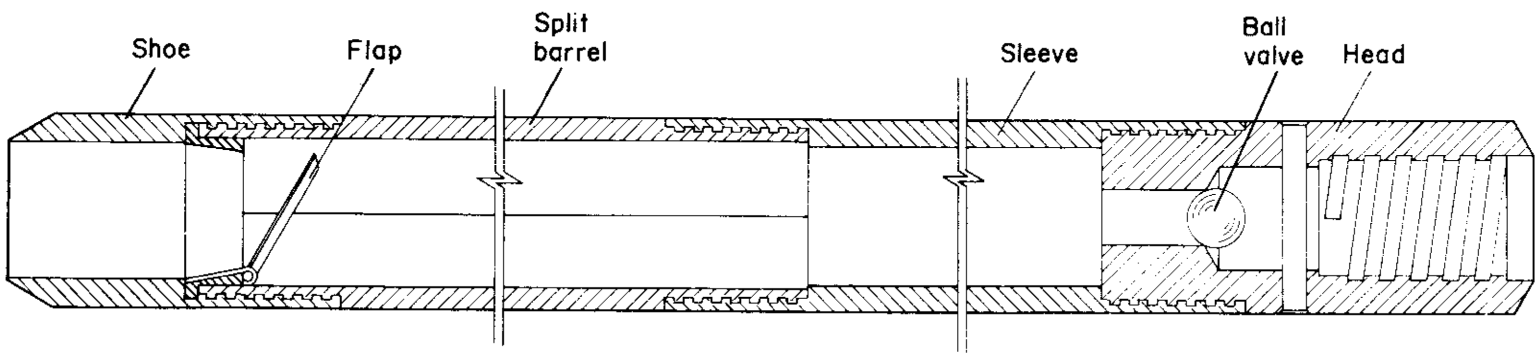
Grab samplers

18. Grab samplers consist of a scoop or bucket container that bites into the sediment deposit and encloses a sample. Grab samplers vary in size and design from the simple Petersen and Ponar samplers to the more sophisticated Shipek. Basic features that may vary include scoop opening and closing mechanism, area of sediment sampled, and depth of penetration.

19. Petersen dredge. The Petersen dredge (Figure 4) was the most extensively used sampler during this study. This sampler has a system of levers to keep the scoop open while the sampler is lowered to the bottom. As the sampler comes to rest on the bottom, the tension in the retrieval line is relaxed, the trip lever drops, and the sampler is ready to obtain the sample. After the trip lever has been released, tension is again applied to the retrieval line. During this time, the jaws slowly shut, enclosing the sample within the scoop. The Petersen is a versatile sampler that will sample a wide range of sediments, from fluffy harbor sediments to dense sand deposits in rivers. The Petersen



a. Phleger tube sampler (from Standard Methods,[4] courtesy American Public Health Assocation)



b. Split barrel sample spoon (courtesy Sprague and Henwood, Inc.)

Figure 3. Tube samplers

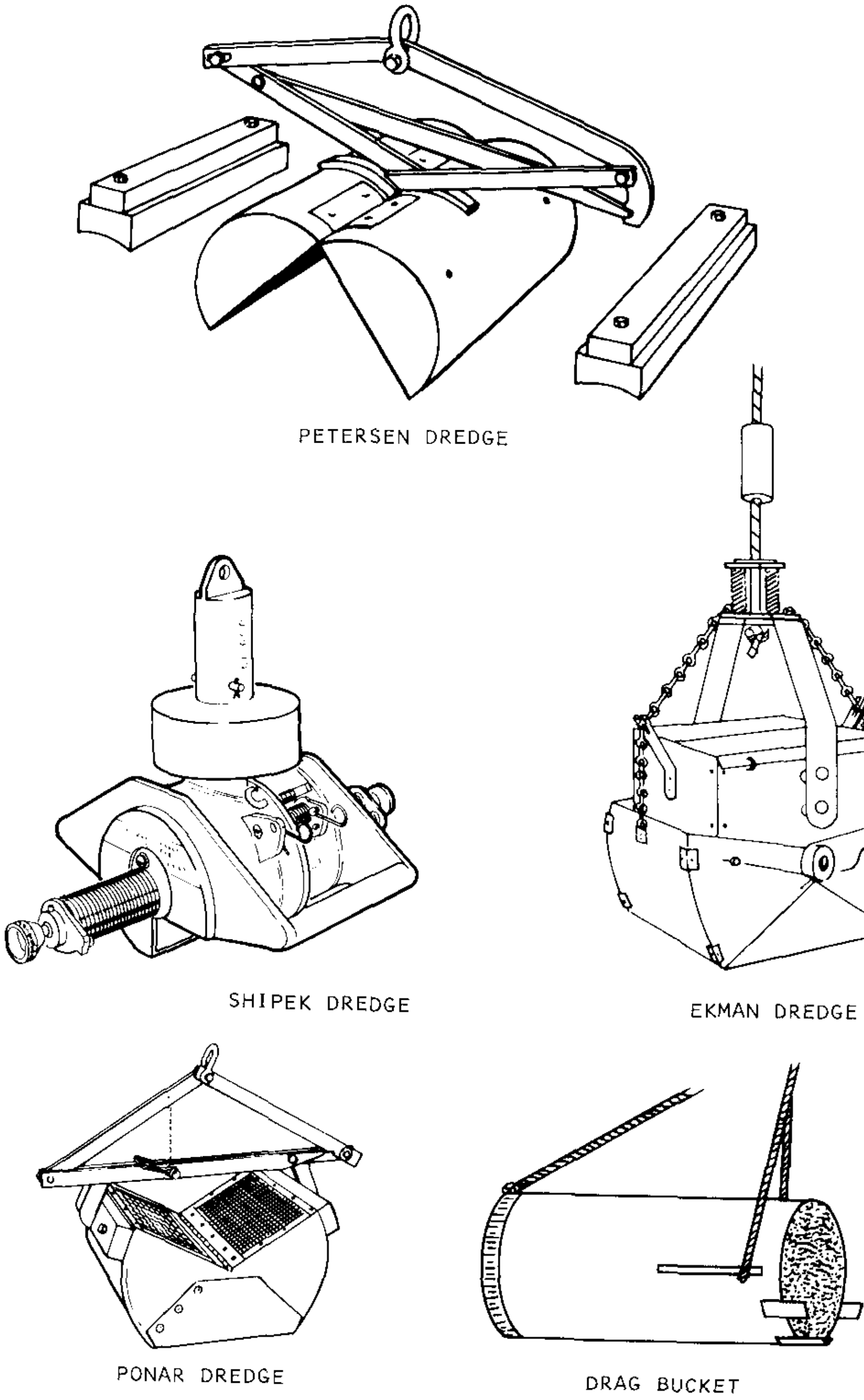
weighs 39 lb empty, with additional weights available to provide a total weight of 93 lb. The sampler samples 144 sq in. to a depth of about 12 in., depending on the consistency of the bottom.

20. Ekman sampler. The Ekman is a widely used piece of equipment (Figure 4). To obtain a sample, the Ekman is lowered to the bottom with its scoop held open by springs. When the sampler is resting on the bottom, the operator releases a weight attached to the retrieval line. The weight slides down the line, striking the tripping mechanism, and the scoop shuts, enclosing the sample. The sampler is raised to the surface, and the sample is transferred to a container. While weights may be added to increase the penetration of the sampler, it is well suited for only very soft sediments. It is excellent for obtaining grab samples of slurries in hopper dredge bins.

21. Ponar sampler. The Ponar (Figure 4) is similar in construction to the Petersen. The Ponar has an empty weight of 45 lb, which may be increased to 60 lb by the addition of two cast iron weights, and samples an area 9 in. by 9 in. to a depth of less than 12 in. in most sediments. The Ponar is ineffective in hard clay. A system of levers keeps the scoop open during descent. Once the sampler is on the bottom, the retrieval line tension is relieved, and the levers are disengaged. After the levers have disengaged and the scoop is free to close, tension is again applied to the retrieval line, closing the scoop. The sampler is then raised to the surface, where the sample is transferred to the sample container.

22. Shipek dredge. The Shipek dredge (Figure 4) utilizes two concentric half-cylinders to form the sample scoop. The sampler is lowered to the bottom, where a weight releases the triggering mechanism. The scoop gathers a sample as it rotates through a half-circular arc under the force of springs. The sampler is then hoisted to the water surface, where the scoop is released; the sample is then transferred to a container. This sampler obtains a sample from an area of approximately 8 in. by 8 in. to a depth of about 4 in. The empty weight of the Shipek is approximately 150 lb.

23. Drag bucket. The drag bucket (Figure 4) differs from the



NOTE: WITH THE EXCEPTION OF THE DRAG BUCKET THE ABOVE FIGURES WERE TAKEN FROM STANDARD METHODS[4] (COURTESY AMERICAN PUBLIC HEALTH ASSOCIATION)

Figure 4. Grab samplers

previously listed equipment, since it does not bite vertically into the sediment. A drag bucket skims an irregular slice off the top of the deposit, and the size and shape of this slice are difficult to ascertain. Drag buckets are available in assorted sizes with round or square biting lips and are suitable for only very soft deposits in quiescent waters.

Sampling Technique

Technique used

24. This section describes generally the manual operation used to obtain samples for this study. Except for the case in which samples were obtained from hopper dredges, the general approach to obtaining a sample was not equipment-dependent. That is, the operation was basically the same whether a grab sampler or push tube was used.

25. Sampling began when the sampling team was on station over the sampling site and the boat had been secured. The sampling device was lowered through the water column to the sediment, and when the sample had been secured within the sampler, it was retrieved. The sediment was emptied into a large tub and additional sediment was obtained until a sufficient amount was accumulated.

26. Samples taken from hopper dredges were obtained from the inflow pipe so that the sample was obtained before the material segregated in the hopper bin. Samples were obtained by using the sample container as a scoop.

Sample type

27. Two different size samples were obtained. Small samples, approximately 0.2 cu ft in volume, were obtained for classification tests. These samples were stored in heavy plastic canisters. Larger samples, approximately 1.0 cu ft in volume, were obtained for engineering properties testing. These larger samples were stored in trash can liners inserted into burlap bags for reinforcement.

28. All samples were disturbed during sampling and during transfer from sampler to container. Since two to four grabs were generally

required for a small sample and more than eight grabs were needed for a large sample, samples were composite and consisted of material from an area of several square feet. No sample preservation measures were undertaken, except that organic samples were kept cool to retard the decomposition of organic matter.

PART III: LABORATORY ANALYSES

29. Dredged material samples were subjected to standard laboratory analyses used for testing soils. The analyses were performed by the Soils and Pavements Laboratory at WES. All tests were conducted in accordance with CE procedures as referenced, and the American Society for Testing and Materials (ASTM) standard procedures[5] are referenced for convenience.

Scope of Testing Program

30. Figure 5 is a flow chart depicting the sequence of events in the laboratory testing program. The chart shows that all samples, including the few selected for engineering properties testing, were subjected to grain-size analysis and organic content (OC)* determination, and that the liquid limit (LL) and plastic limit (PL) were determined for samples containing fine-grained material. Samples selected for engineering tests were grouped into two categories: coarse-grained and fine-grained. Since the engineering properties of sand are well documented, sand samples were not subjected to extensive laboratory testing. Selected silty and clayey samples were subjected to compaction tests, and the data (maximum dry density and optimum moisture content) from the compaction tests were used to establish preparation criteria for test specimens subjected to consolidation and shear strength tests. A brief description of each test is presented in the following sections.

Classification Tests

31. In order to classify a sample of dredged material, certain parameters pertaining to the texture and plasticity of the sample must be evaluated. These parameters, which may vary according to the

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

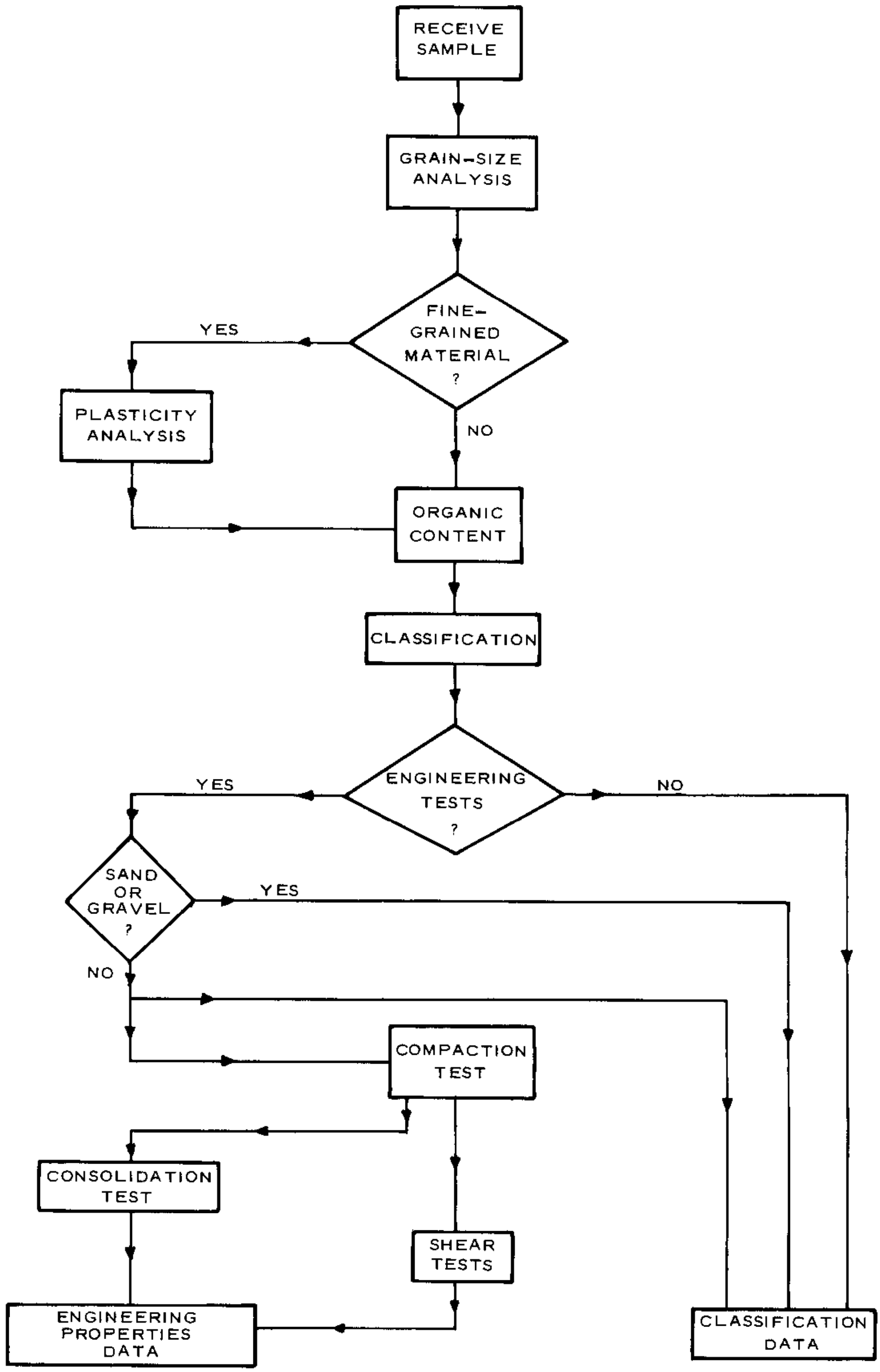

Figure 5. Flow chart for laboratory testing program

classification system used, are obtained from four laboratory tests: grain size, PL, LL, and OC. For classification purposes the OC generally need not be quantified, but rather a knowledge of whether significant organic matter is present is required. For purposes of this study, grain-size analysis, PL, LL, and OC tests have been grouped together as classification tests.

Grain-size analysis

32. The grain-size distribution was determined for every sample of dredged material obtained for this study. Both direct (mechanical analysis) and indirect (hydrometer analysis) methods were used to provide information for a wide range of material with grain sizes from 0.001 to 75 mm. Samples containing both fine and coarse particles were subjected to both the sieve and hydrometer analyses. Predominantly fine-grained samples (all or nearly all particles passing the No. 200 sieve) were analyzed by only the hydrometer method. Sand samples were tested by sieve analysis. Grain-size analysis test procedures may be found in EM 1110-2-1906, Appendix V,[6] and in ASTM D 422-63.[5]

Water content

33. One of the most important factors affecting the properties of dredged material is the presence of water within the soil structure. The relative amount of water is expressed on a dry weight basis, in which the water content is defined as follows:

$$w = \frac{W_w}{W_s} \times 100 \qquad (1)$$

where

w = water content, %

W_w = weight of water in dredged material, g

W_s = weight of solids in dredged material, g

This convention for water content (or moisture content, as the terms are used interchangeably in soils engineering*) is illustrated in Figure 6.

* A glossary of soils engineering terms according to ASTM can be found in Appendix A.

Water content will be referred to in various sections of this report, such as the sections on plasticity analysis, OC, and engineering properties. The test procedure for determining the water content of a soil is found in Appendix I of EM 1110-2-1906,[6] and as ASTM test D 2216-66.[5]

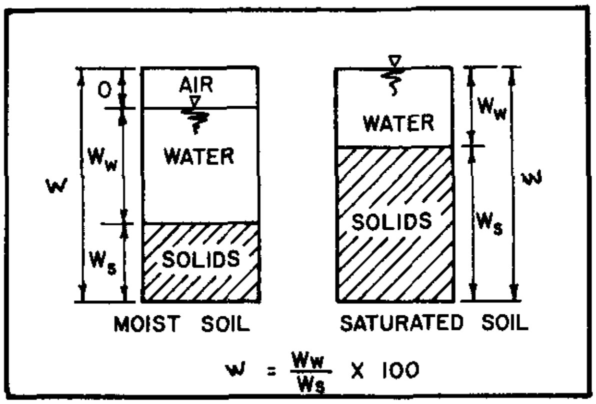

Figure 6. Nomenclature used in determination of water content (from EM 1110-2-1906[6])

Plasticity analysis

34. In order to evaluate the plasticity of fine-grained samples of dredged material, the LL and the PL of these samples were determined. The LL of dredged material is that water content above which the dredged material is said to be in a semiliquid state and below which the dredged material is in a plastic state. Similarly, the water content that is the lower limit of the plastic state and the upper limit of the semisolid state is termed the PL. The plasticity index (PI), defined as the numerical difference between the LL and the PL, is used to express the plasticity of dredged material. A graphical explanation of the relation among LL, PL, and PI is presented in Figure 7. A detailed explanation of the test procedures,

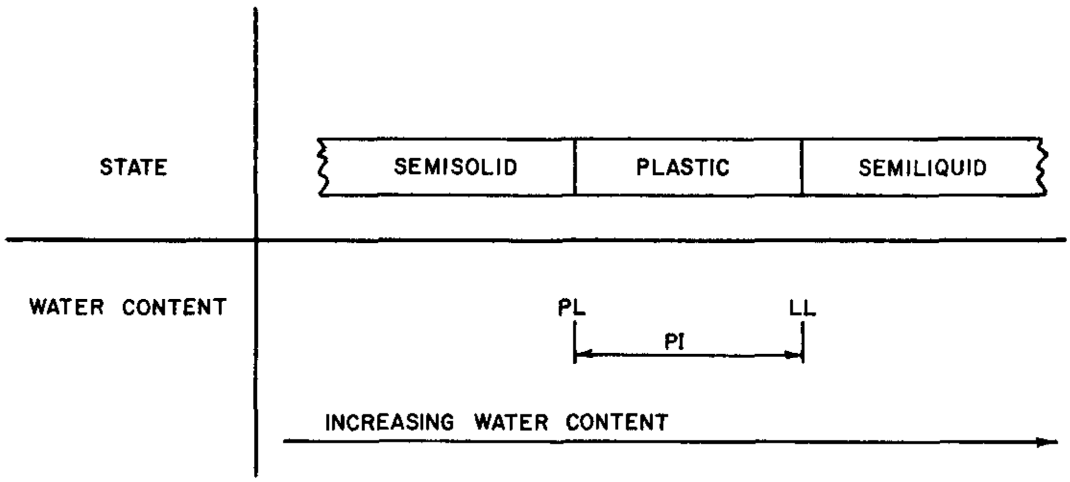

Figure 7. States of consistency (from EM 1110-2-1906[6])

as well as of the apparatus, can be found in Appendix III of EM 1110-2-1906.[6] A procedure for determining the LL can also be found in ASTM D 423-66[5] and one for the PL in ASTM D 424-59.[5]

Organic content

35. The OC, expressed as a percent of sample weight, was determined for the samples obtained during this study. The significance of the OC of dredged material lies in the effect the organic matter may have on the strength and compressibility of the dredged material. Soils containing significant amounts of organic matter generally exhibit lower shear strength and higher compressibility than do inorganic soils.[7] The organic matter also retains moisture in significant amounts without producing a corresponding increase in plasticity.[7] Before any general statements concerning the effect of OC on the properties of dredged material can be made, however, the nature of the constituents of the organic fraction must be known.

36. Organic matter in dredged material may be present in many forms, including sewage, industrial and agricultural waste, plant and animal matter, and petroleum-type substances. Obviously, the wide range of types of material that may comprise the OC of a dredged material complicates any determination of the influence of the OC on its properties. Fibrous matter will certainly have a substantially different impact on plasticity than will a light oil, even though similar OC may be determined from laboratory tests.

37. One of the largest problems in evaluating the impact of the OC on dredged material is the lack of a standard test procedure. There are two general types of tests for determining OC: dry combustion methods and wet combustion methods. Within each of the two categories are many procedures that are basically the same in concept in that they define the OC as the percentage of total sample weight lost as a result of the test procedure. The difference between the two types of methods lies in the procedure for removing the organic matter from the sample. In one case the organics are burned off in a high temperature oven, and in the other case chemicals are used to digest the organic matter.

38. Dry combustion. The dry combustion techniques are simple to

perform, with test procedures differing in the temperatures used and the time required to burn the organic fraction. Suggested procedures range from burning at 375°C for 16 hr[8] to burning at 950°C for 1 hr.[9] The controversy in procedure involves the release of interstitial water from fine-grained soils and in the changes to clay minerals, both of which occur at high temperatures. Differential thermal analyses performed by Arman[9] on montmorillonite samples show that lattice water loss occurs at approximately 450°C, and he suggests that OC tests be conducted at temperatures no higher than 440°C. Krizek[7] suggests that the temperature for testing a particular soil type should be determined by thermogravimetric analysis.

39. Wet combustion. Wet combustion techniques involve the use of chemicals to determine the OC. Differences in procedure involve the types and strengths of the chemical used. The chemicals vary from hydrogen peroxide to sulfuric acid. Complete test procedures are cited in several publications.[10-14] While one procedure may produce accurate results in one soil type, the same procedure may give poor results for another soil type.[7] There is also some question of the actual percentage of OC that is organic carbon; this factor, plus the higher degree of complexity (compared to dry combustion methods), makes the dry combustion techniques more attractive for engineering purposes when simplicity and test time requirements may be important. In evaluating OC and its influence on soil, the test procedure is an important factor.

40. Adopted procedure. In this study the following dry combustion test procedure was used, and the OC was expressed as the percentage of weight lost on ignition.

a. Dry a 40-g sample at 110°C until there is no further weight loss--usually 1 or 2 hr.

b. Weigh sample and place in 440°C oven for 4 hr.

c. Determine OC by dividing the weight lost by the sample while in the 440°C oven by the total weight of the sample at the time it was placed in the 440°C oven.

41. It has been seen that the OC determined for a particular sample of soil may be a function of the test procedure used.[7] Additionally, the effect of organic matter on soil properties can be more

dependent upon the nature of the organics than upon the quantity present. Considerable care must be taken in evaluating the effects of the OC on the engineering properties of dredged material.

Engineering Properties Tests

42. To determine the engineering properties of dredged material, ten samples of fine-grained dredged material were subjected to compaction, shear strength, and consolidation tests in the laboratory. A description of test specimen preparation and the test results are reported in Part V, while general test descriptions are presented in the following paragraphs.

Compaction test

43. The objective of performing a compaction test is to establish the relationship between the water content w and dry density γ_d of soil by simulating, in the laboratory, the compactive effort to be employed in the field. During this study the standard Proctor, modified Proctor, and 15-blow tests were used on fine-grained samples of dredged material. The specific apparatus, standards, and procedure are found in EM 1110-2-1906, Appendix VI,[6] as well as in ASTM D 698-70.[5]

Consolidation test

44. As load is applied to laterally confined soil, air and water are squeezed from the void spaces and the soil consolidates, if a bearing failure does not occur. To predict the rate and amount of field consolidation, a laboratory consolidation test is conducted. A carefully prepared specimen of soil is sandwiched between two porous stones and placed in a consolidation ring. A load is applied, and, as water is squeezed out of the soil specimen, the load and deformation are recorded at specific time intervals. During this study the consolidation test described in EM 1110-2-1906 Appendix VIII[6] was performed. The corresponding ASTM test procedure is D 2435-70.[5]

Shear strength tests

45. While normal stresses on a saturated, fine-grained material are initially supported by both the solid particles and the pore water,

shear strength is developed only by the soil particles. During this study unconsolidated-undrained (Q) triaxial shear tests and consolidated-drained (S) direct shear tests were performed using compacted dredged material samples to determine shear strength parameters. The Q-tests were performed in accordance with the procedure in EM 1110-2-1906 Appendix X[6] and in ASTM D 2580-70.[5] The procedure used for the S-test may be found in EM 1110-2-1906 Appendix IX[6] and in ASTM D 3080-72.[5]

PART IV: CLASSIFICATION OF DREDGED MATERIAL

46. In this part the classification properties of dredged material are presented. These properties include not only the results of the laboratory analyses conducted at WES, but also test results obtained from other publications and from CE District office files. Following the presentation and discussion of the classification properties, four soil classification systems are briefly described. Using the classification properties, each sample is classified according to as many of the four classification systems as possible. A system for classifying soils to be dredged is described but not used.

Classification Test Results

47. Data resulting from analyses on samples* obtained from within the five study regions are presented. Classification test data are tabulated in Appendix C. Table 2 presents the ranges of values for the parameters investigated; in cases where meaningful, the average value is presented. The number of samples included within a value range is sometimes less than the total number of samples obtained, generally due to incomplete grain-size distribution curves, or because a test, such as OC, was not conducted. The LL, PL, and PI were determined for the portion of coarse-grained samples that passed the No. 40 sieve, as well as for the fine-grained samples; no differentiation is made in the table.

48. The grain-size distribution was determined for most of the samples, and each test result was presented in the form of a grain-size distribution curve plotting percent finer against particle size. Some curves were generated from only a few points and are, therefore, incomplete. For example, in the New England Division only D_{25}, D_{50}, and D_{75} sizes and the percent passing the No. 200 sieve were known. On the basis of these data, D_{10} and D_{90} were sometimes impossible to determine.

49. Envelopes of grain sizes are presented for fine-grained

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* An explanation of sample numbers is given in Appendix B.

samples and for coarse-grained samples from each region (Figures 8 through 17). Using these envelopes, the range of grain sizes for any percent passing, as well as the range of percent passing any sieve, may be determined. Ranges of values of D_{10}, D_{60}, and D_{90} are shown in Table 2. Use of D_{10} as well as D_{60} is in the computation of the coefficient of uniformity and the coefficient of curvature, which are used in the USCS described in the next section. The percentage of fines, defined by the USCS as the percent passing the No. 200 sieve, was also determined for the samples.

50. In addition to the average and range of values of the LL, PL, and PI presented in Table 2, the samples were plotted on the plasticity chart by region, as shown in Figures 18 through 22. The plasticity parameters were used to classify the samples of fine-grained dredged material. Relationships between the plasticity parameters and the engineering properties of dredged material are discussed in Part V.

51. The OC of each sample obtained specifically for this study was determined. Sixty such determinations were made on samples from the Gulf States study region. All 34 samples from the Great Lakes region and 29 other samples from projects scattered throughout the other three regions were also tested.

Classification Systems

52. The object of a soil classification system is to arrange soils that have similar properties into groups and to give each group a standard name or coded designation. Several systems have been established for classifying soils based on one or more of the following soil characteristics: texture, plasticity, mineralogy, and structure. The following classification systems are described below: the Permanent International Association of Navigation Congresses (PIANC) system for classifying soils to be dredged, the U. S. Department of Agriculture (USDA) classification system, the American Association of State Highway Officials (AASHO) classification system, the Federal Aviation Agency (FAA) classification system, and the USCS.

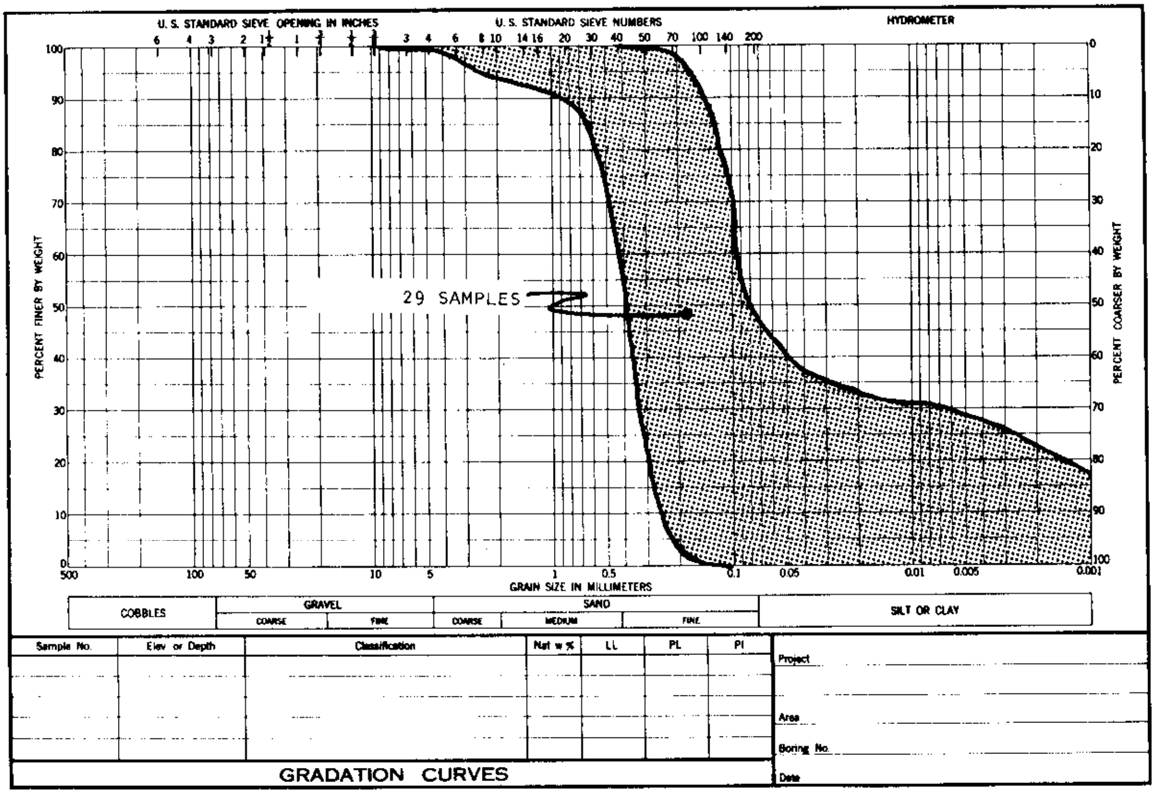


Figure 8. Ranges of grain sizes encountered in coarse-grained samples of dredged material from the Gulf States study region

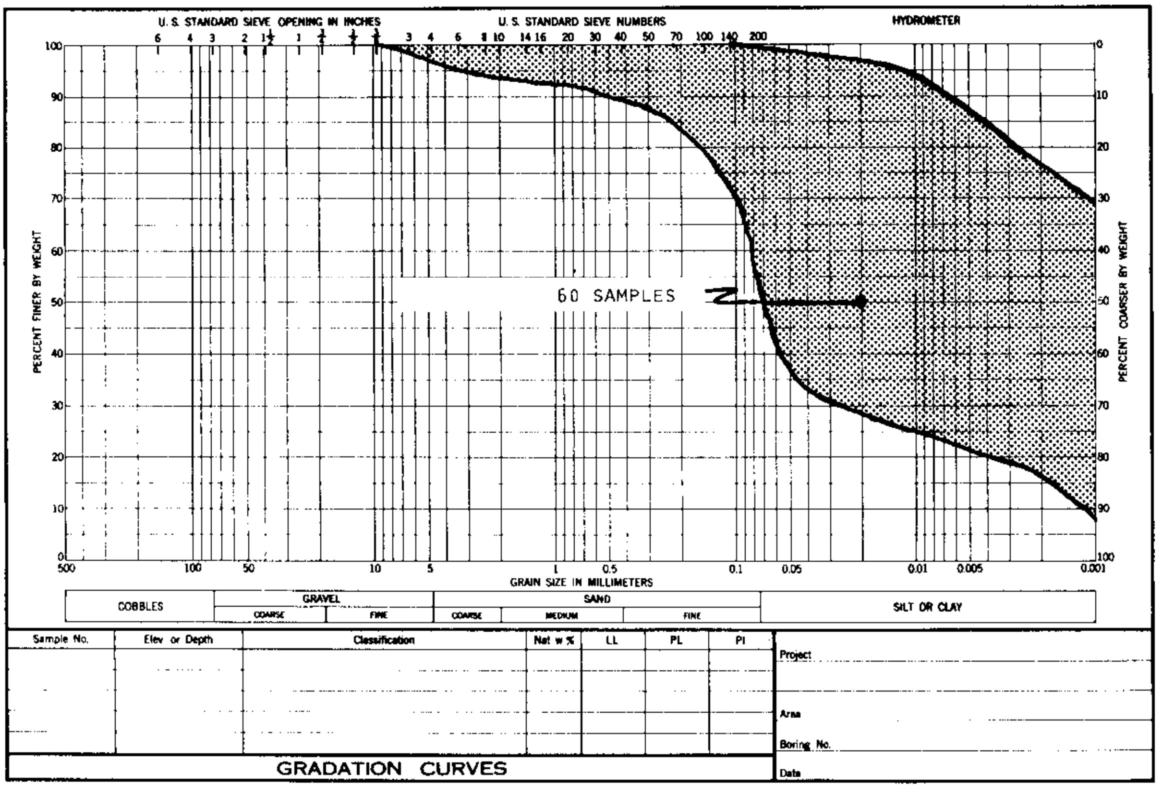


Figure 9. Ranges of grain sizes encountered in fine-grained samples of dredged material from the Gulf States study region

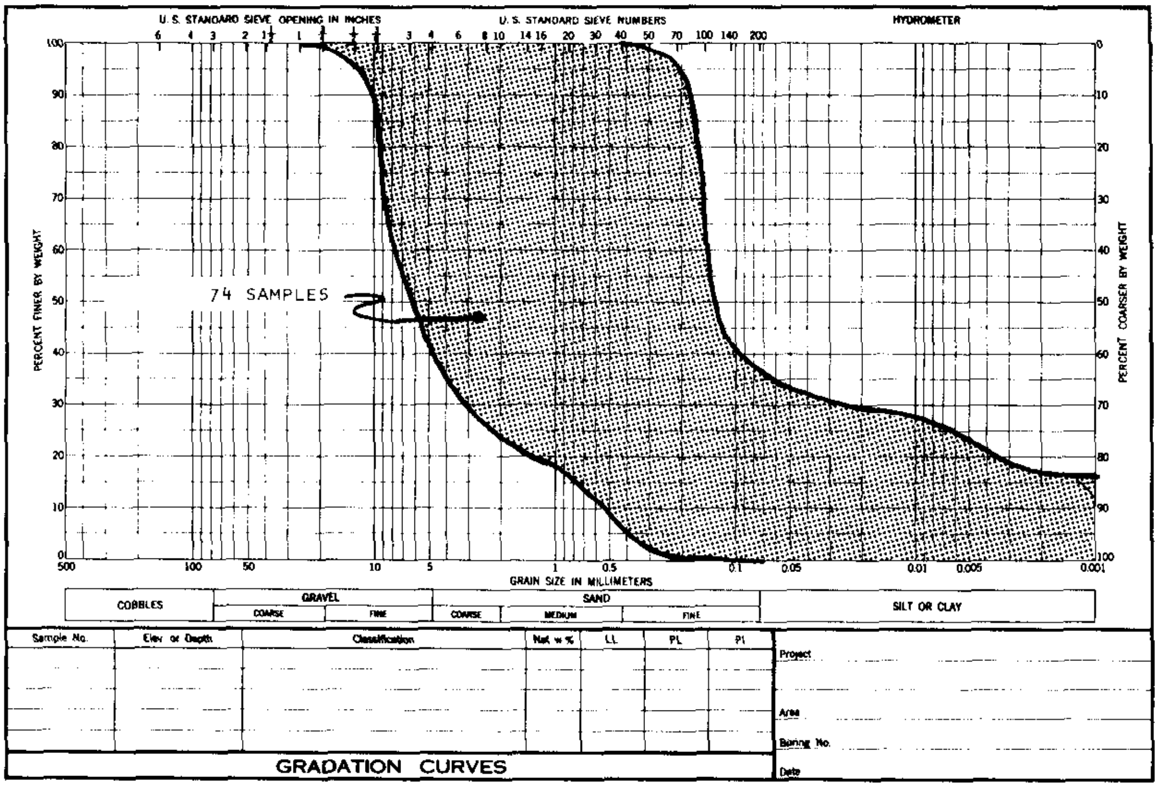


Figure 10. Ranges of grain sizes encountered in coarse-grained samples of dredged material from the South Atlantic study region

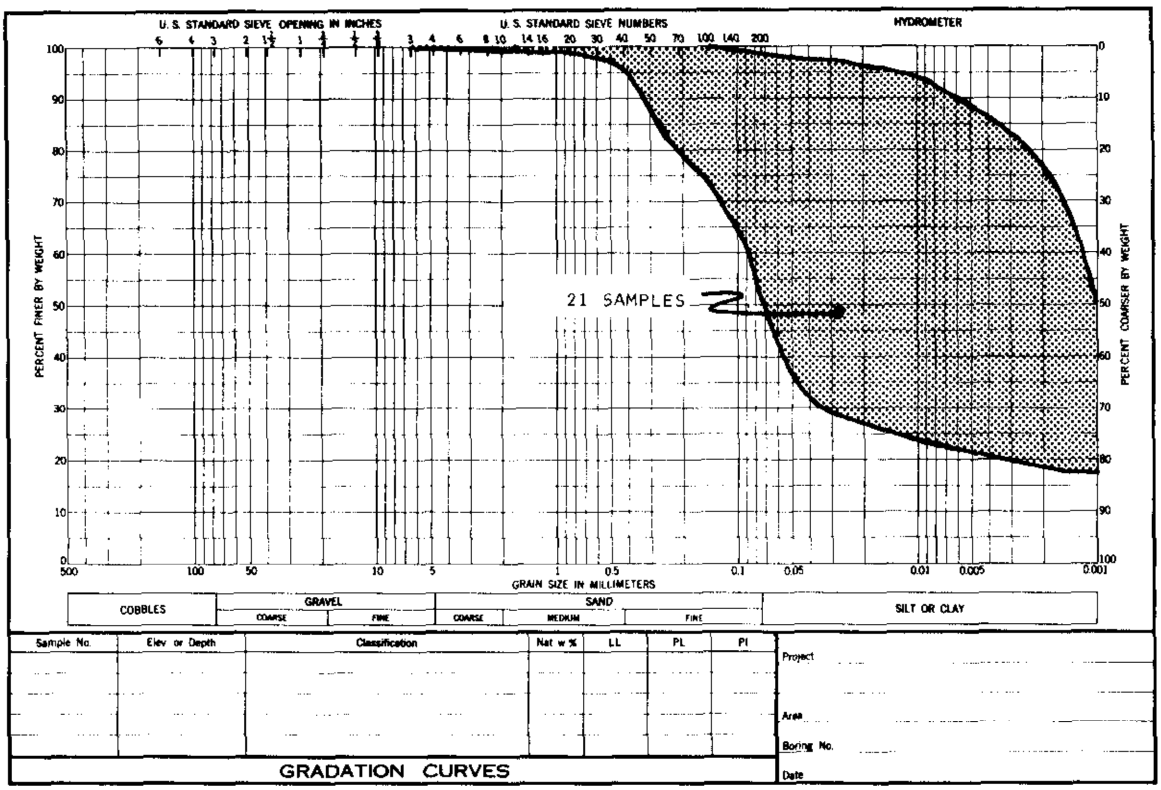


Figure 11. Ranges of grain sizes encountered in fine-grained samples of dredged material from the South Atlantic study region

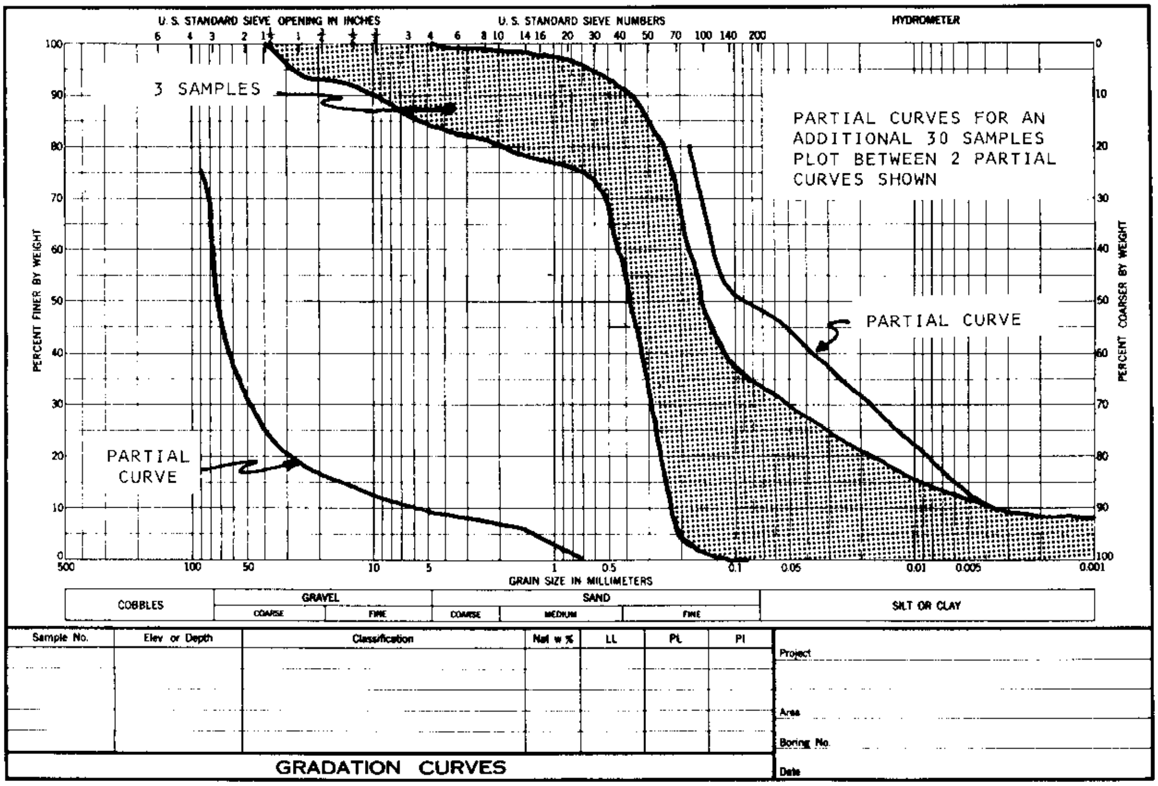


Figure 12. Ranges of grain sizes encountered in coarse-grained samples of dredged material from the North Atlantic study region

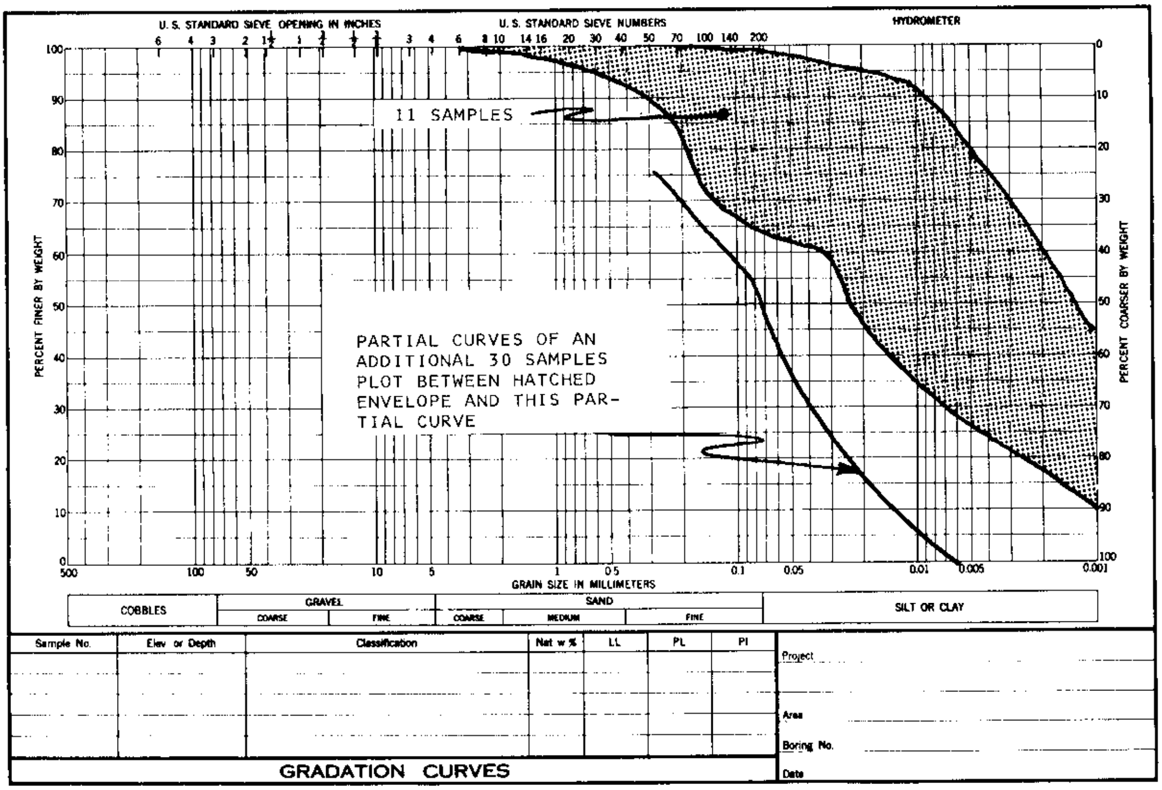


Figure 13. Ranges of grain sizes encountered in fine-grained samples of dredged material from the North Atlantic study region

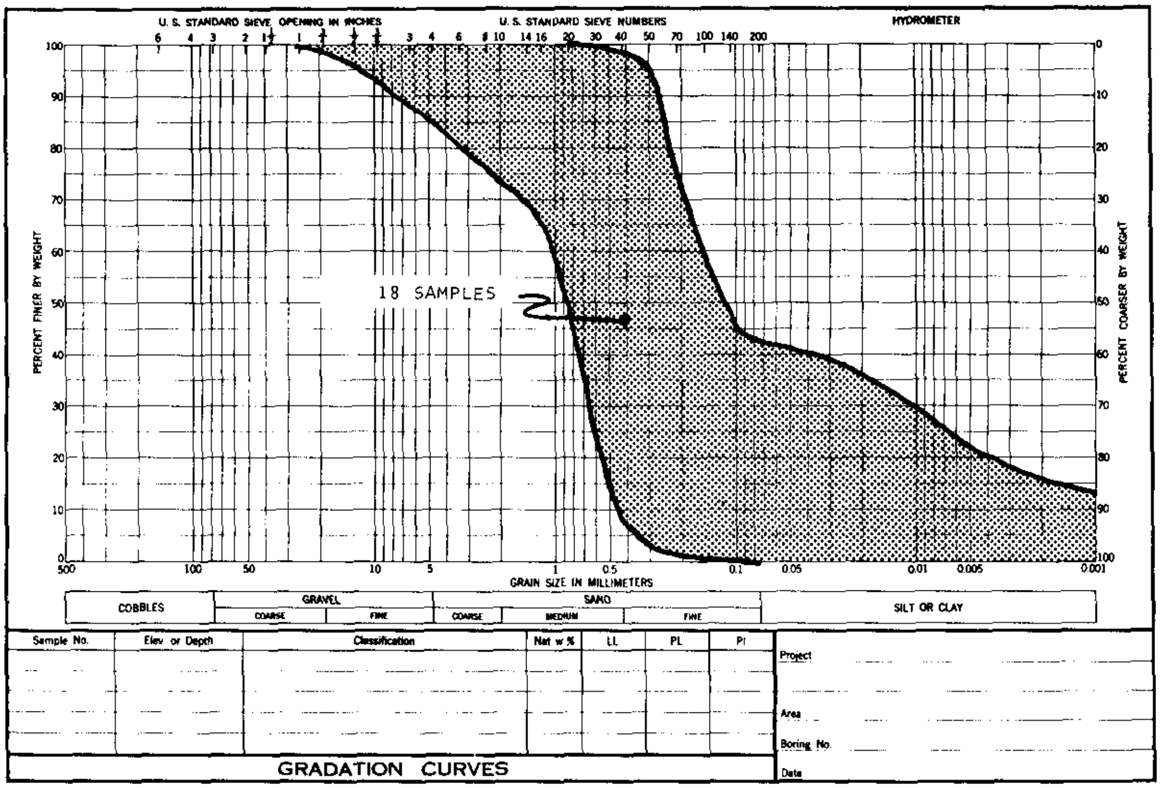


Figure 14. Ranges of grain sizes encountered in coarse-grained samples of dredged material from the Great Lakes study region

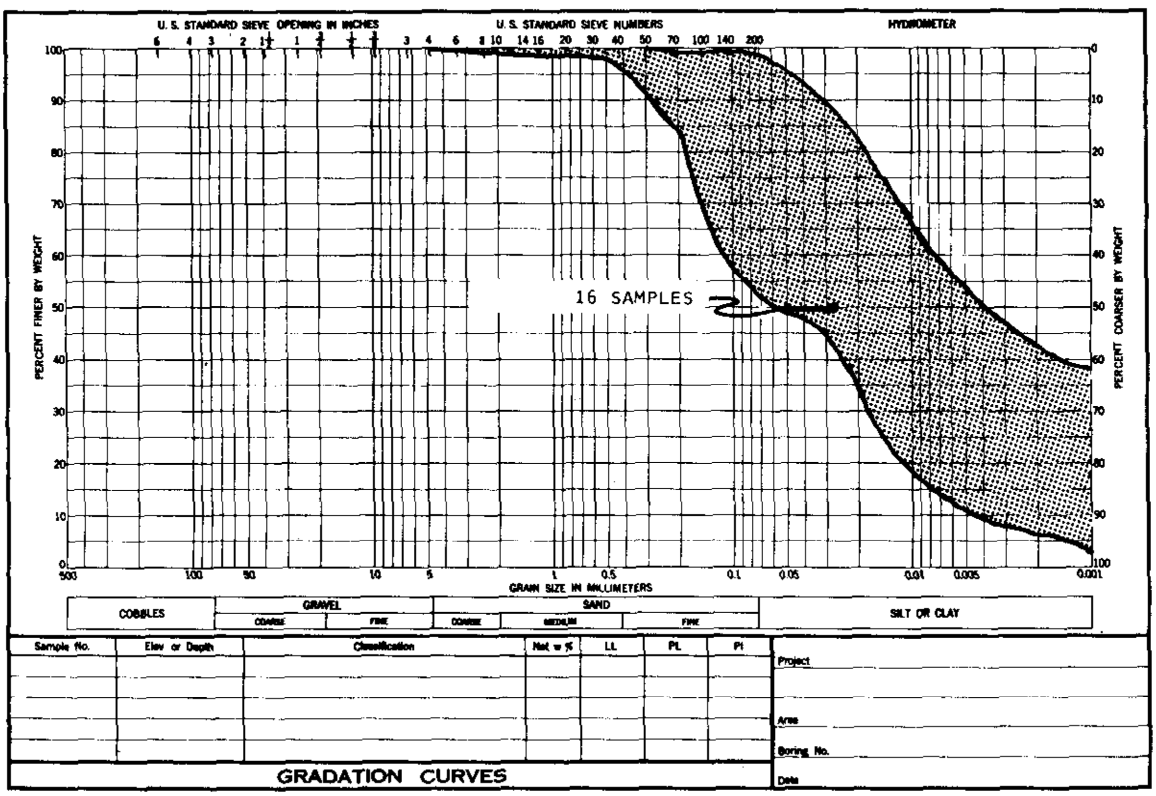


Figure 15. Ranges of grain sizes encountered in fine-grained samples of dredged material from the Great Lakes study region

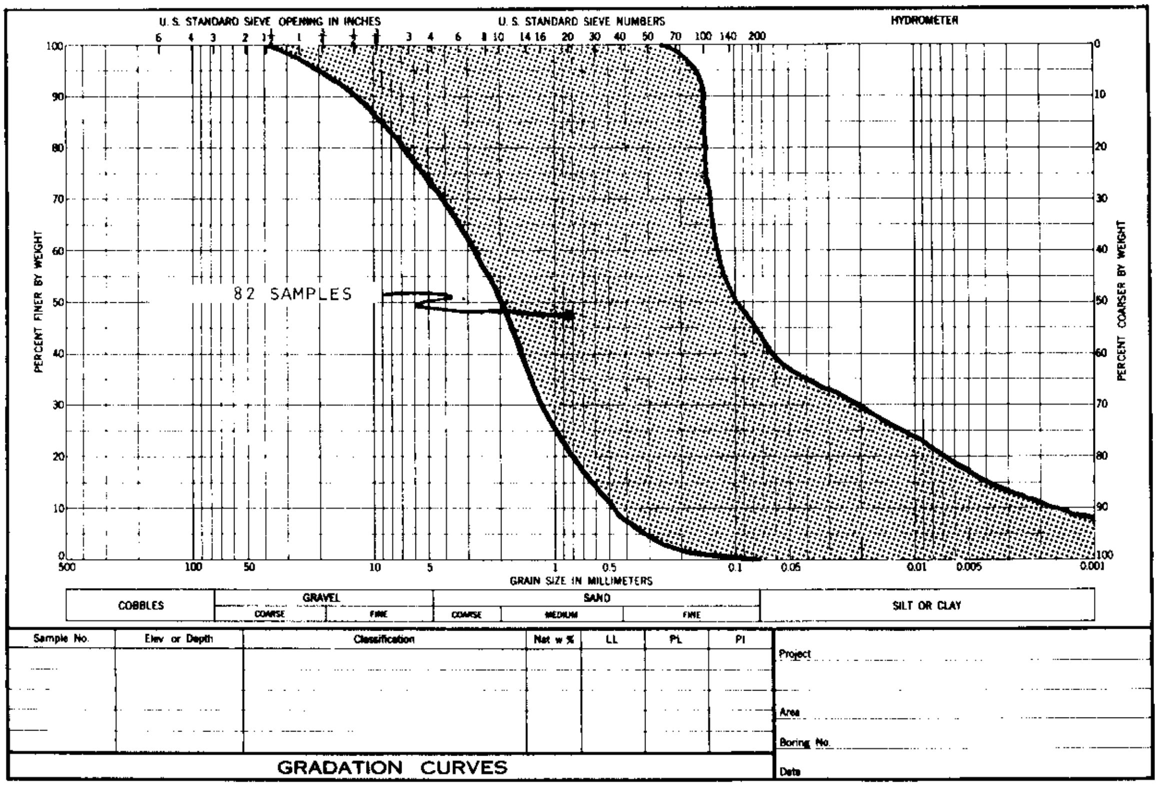


Figure 16. Ranges of grain sizes encountered in coarse-grained samples of dredged material from the Pacific Coast study region

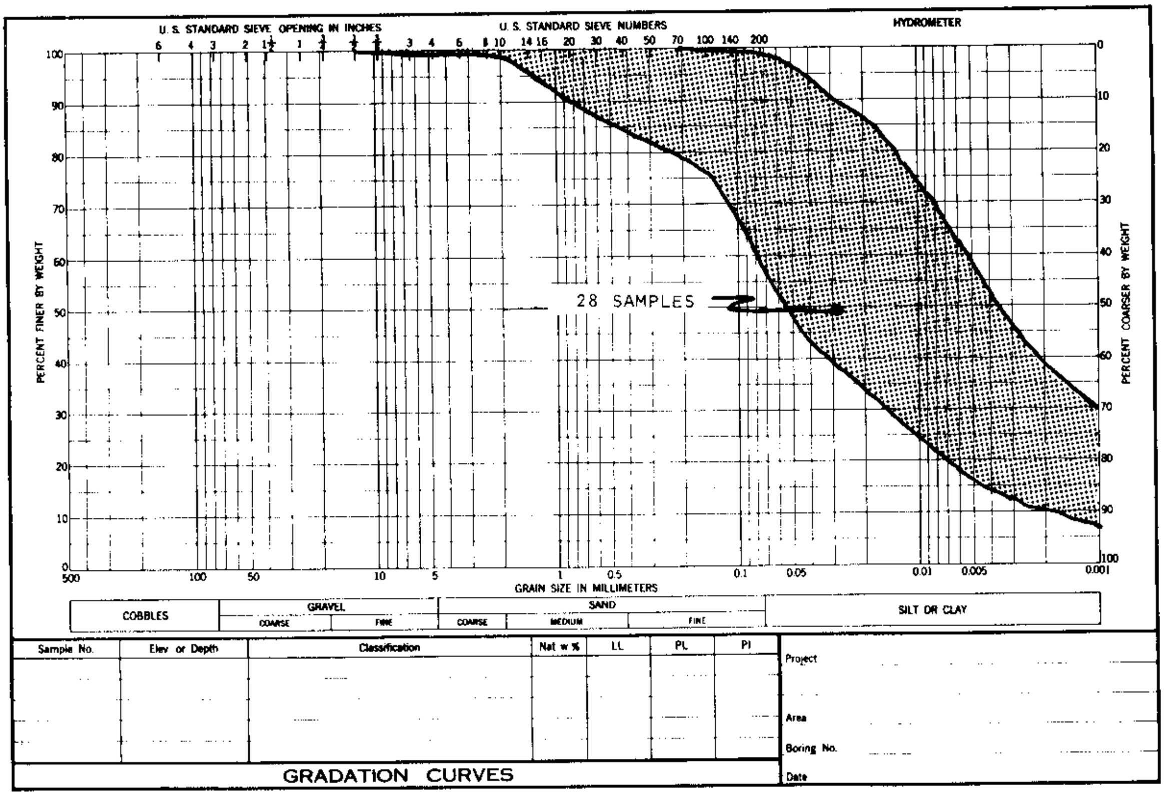


Figure 17. Ranges of grain sizes encountered in fine-grained samples of dredged material from the Pacific Coast study region

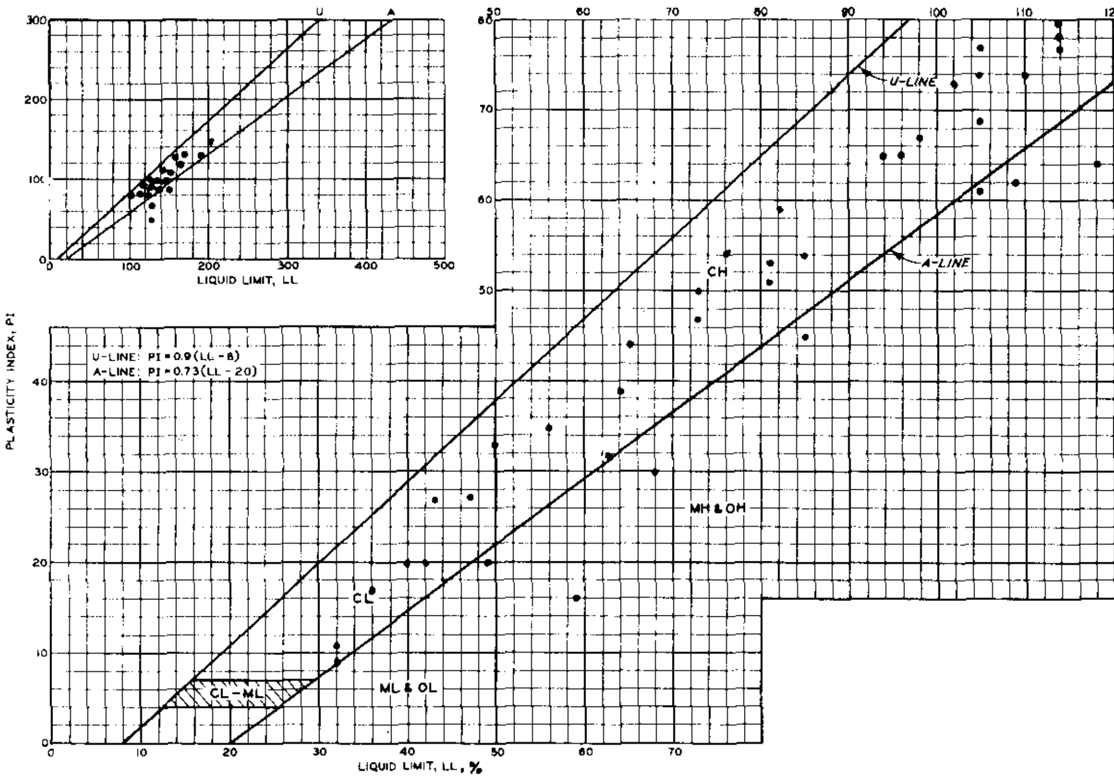


Figure 18. Plasticity chart for fine-grained dredged material from the Gulf States study region

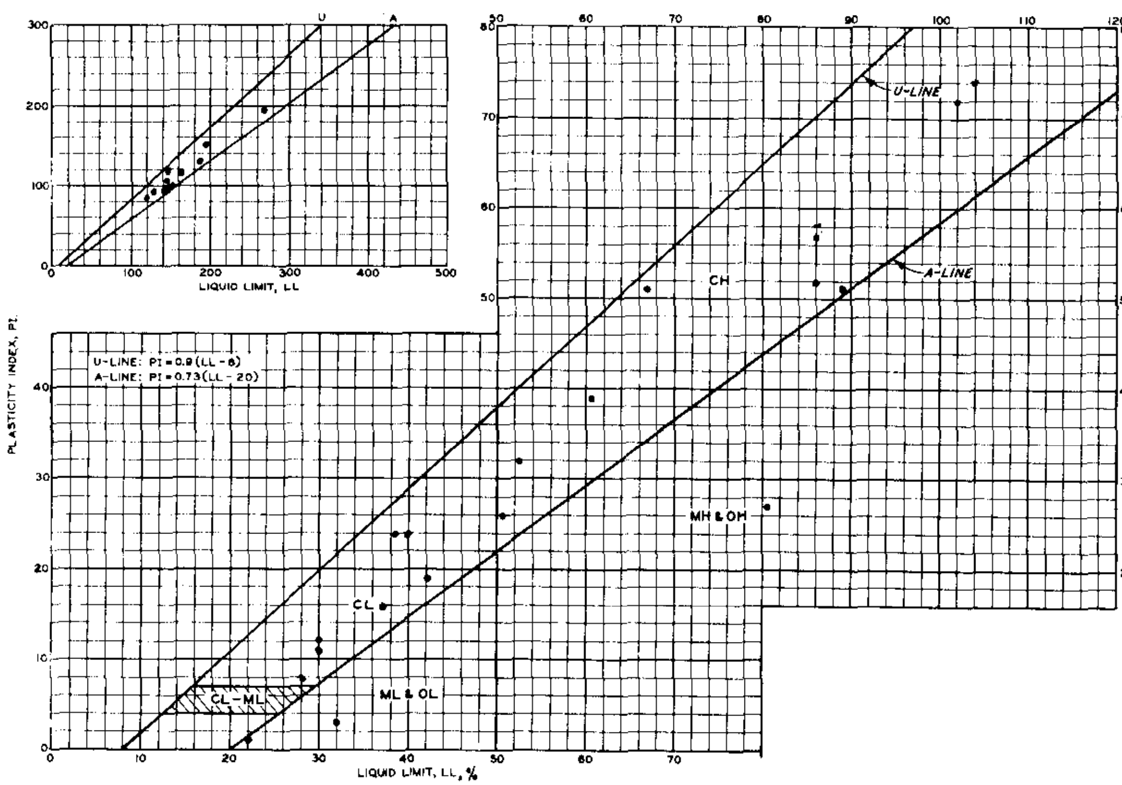


Figure 19. Plasticity chart for fine-grained dredged material from the South Atlantic study region

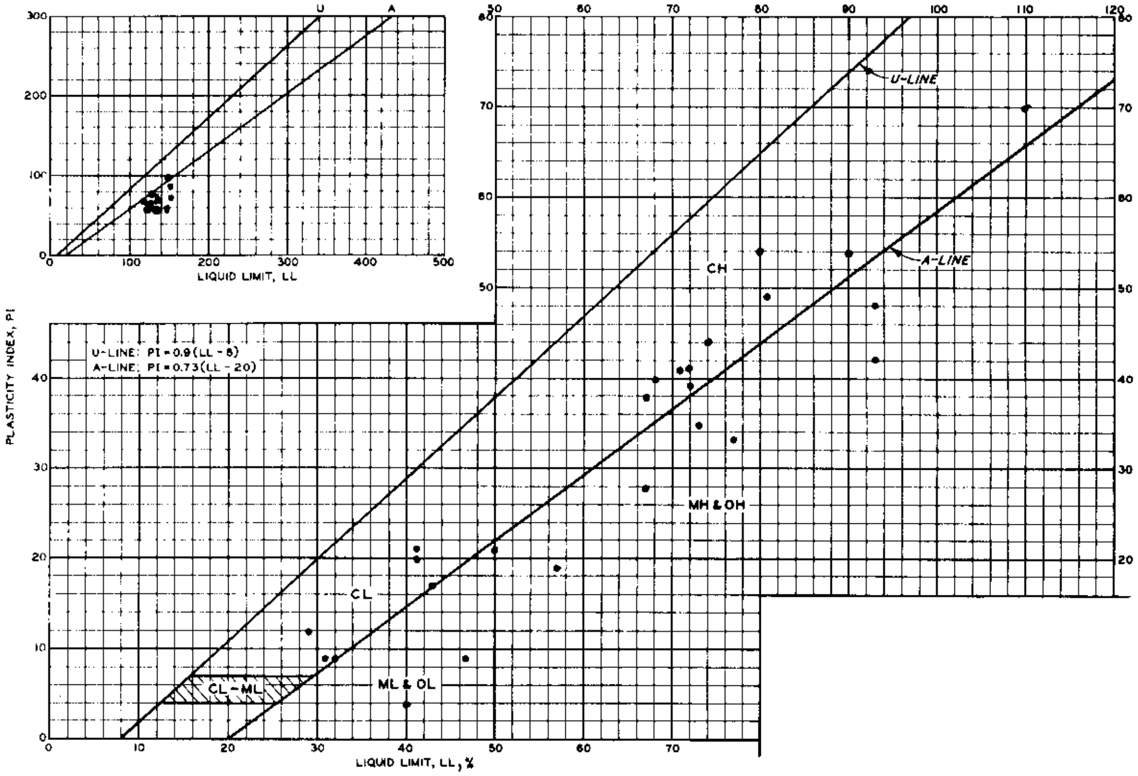


Figure 20. Plasticity chart for fine-grained dredged material from the North Atlantic study region

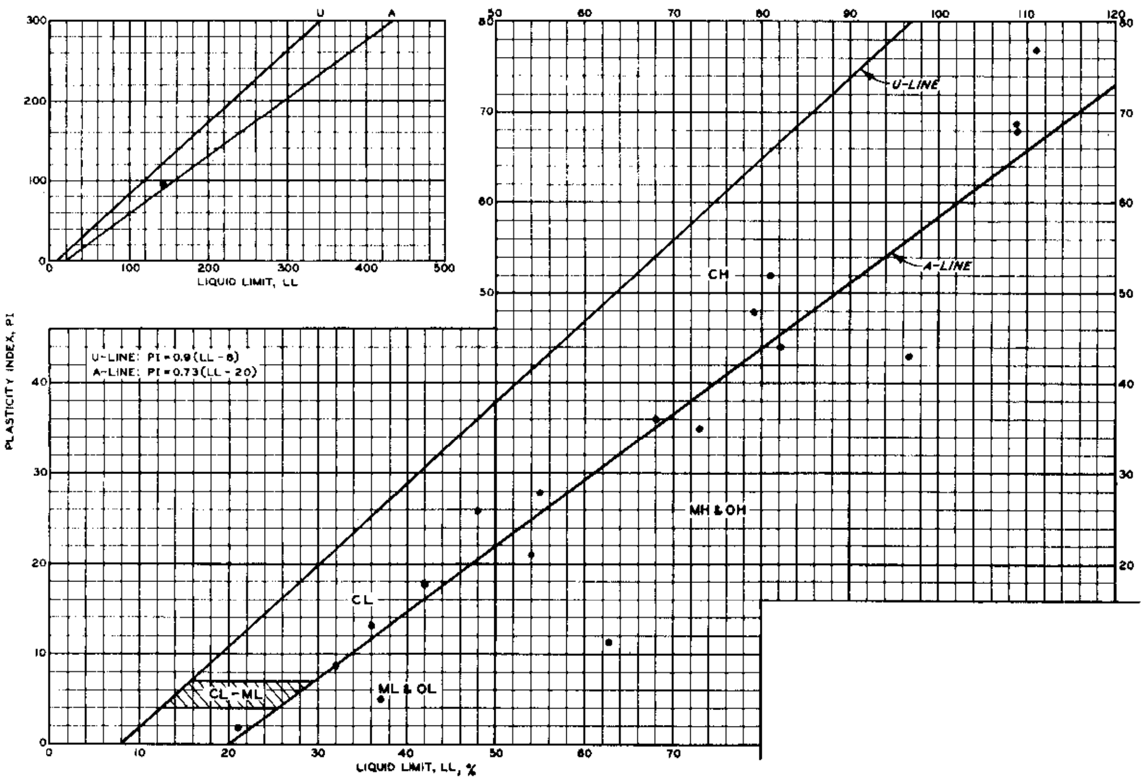


Figure 21. Plasticity chart for fine-grained dredged material from the Great Lakes study region

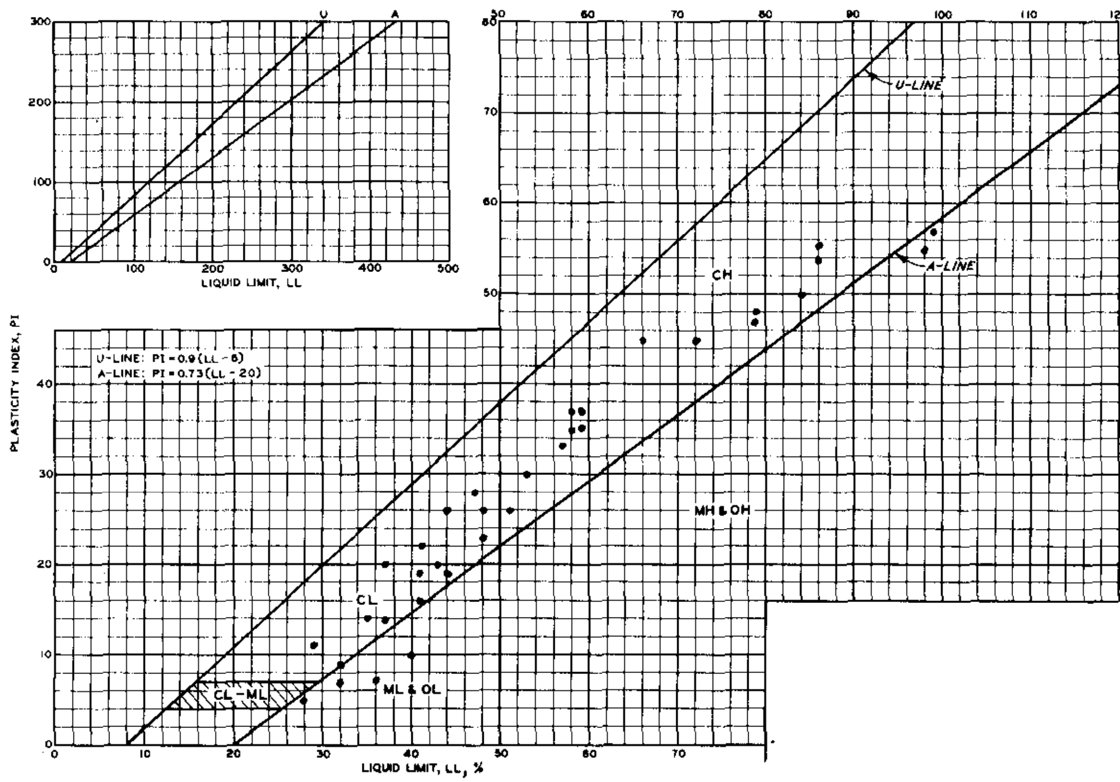


Figure 22. Plasticity chart for fine-grained dredged material from the Pacific Coast study region

53. It is important to emphasize that, while these classification systems group together soils of similar properties, this grouping is not a satisfactory substitute for a program of laboratory testing. The factors that influence the properties of soil are very numerous, and some are not completely understood. It is impractical to evaluate the properties of soil by means of a classification alone. However, since soils within a group do have similar general characteristics, an indication of behavior is possible, which can be of significant value during a preliminary project study for which the expenditure of time and money for a laboratory testing program may not be justified.

54. A discussion of each of the classification systems, including the procedure for the use of each in classifying dredged material, is presented below. Major emphasis is placed on the USCS, because this is the system currently used by the Corps as well as the Bureau of Reclamation. Since three of the other systems cited herein are in widespread

use, the samples have also been classified according to these systems. The PIANC classification system is described below, but samples obtained during this study were not classified according to the system. The system is designed for use by dredging companies and does not relate to use and properties of the material after dredging. The USDA system was used so that agencies contemplating the productive use of dredged material for agricultural purposes would have an idea of the soil types involved. Planners and engineers not familiar with the USCS may use either the AASHO or FAA systems, and these systems are included here for the benefit of such parties. Dredged material has been used in highway and airport runway construction, and an identification of dredged material by these latter two systems will facilitate a better understanding of dredged material by the agencies involved.

PIANC system

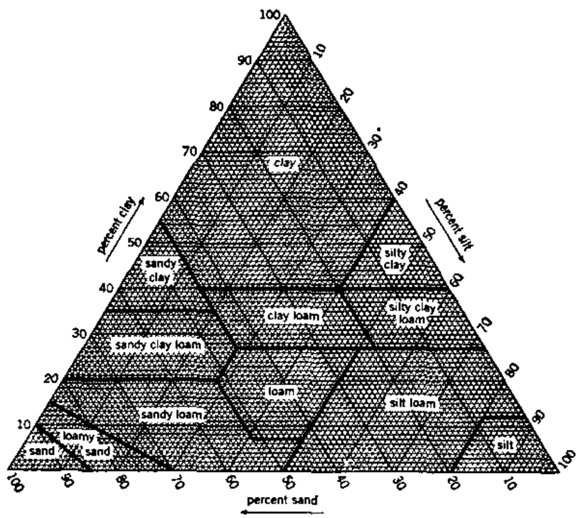
55. This system was developed recently to aid in dredging operations. Visual classification procedures are used to describe the soil in very general terms. Table 3 shows the various classifications and some general characteristics of each classification. While this system is useful in planning dredging projects, other systems such as the USCS are much more suitable for describing dredged material; the dredged material samples were not classified according to the PIANC system.

USDA system

56. This system was developed by Russian agricultural engineers and later adopted by the USDA.[15] Under this system, soils are divided into three categories, called orders: zonal, intrazonal, and azonal. These orders are subsequently divided into suborders, which are divided into great soil groups. Each great soil group is broken into soil series, which are further divided by texture. A complete classification of a soil requires the soil series as well as the textural classification; however, since it is impossible to determine the soil series of a bottom sediment, the samples were classified by texture only.

57. The texture classification is readily obtained by using the charts shown in Figure 23. The percentages present of sand, silt, and clay sizes, whose arbitrary limits are shown in Figure 23, are easily

SAND–2.0 to 0.05 mm DIAMETER
SILT–0.05 to 0.002 mm DIAMETER
CLAY–SMALLER THAN 0.002 mm DIAMETER



U. S. DEPARTMENT OF AGRICULTURE TEXTURAL CLASSIFICATION CHART

PERCENTAGE OF SAND SIZES IN SUBCLASSES OF SAND, LOAMY SAND, AND SANDY LOAM BASIC TEXTURAL CLASSES AS DEFINED BY THE U. S. DEPARTMENT OF AGRICULTURE

Basic soil class	Subclass	Soil separates				
		Very coarse sand, 2.0-1.0 mm	*Coarse* sand, 1.0-0.5 mm	*Medium* sand, 0.5-0.25 mm	*Fine* sand, 0.25-0.1 mm	*Very fine* sand, 0.1-0.05 mm
Sands	*Coarse sand*	25% or more		Less than 50%	Less than 50%	Less than 50%
	Sand	25% or more			Less than 50%	Less than 50%
	Fine sand	Less than 25%		–or–	50% or more	Less than 50%
	Very fine sand					50% or more
Loamy sands	Loamy coarse sand	25% or more		Less than 50%	Less than 50%	Less than 50%
	Loamy sand	25% or more			Less than 50%	Less than 50%
	Loamy fine sand	Less than 25%		–or–	50% or more	Less than 50%
	Loamy very fine sand					50% or more
Sandy loams	Coarse sandy loam	25% or more		Less than 50%	Less than 50%	Less than 50%
	Sandy loam	30% or more		–and–		
		Less than 25%			Less than 30%	Less than 30%
	Fine sandy loam	Between 15 and 30%		–or–	30% or more	Less than 30%
	Very fine sandy loam	Less than 15%		–or–	More than 40%*	30% or more

* Half of fine sand and very fine sand must be very fine sand.

Figure 23. U. S. Department of Agriculture classification system (from Soil Survey Manual[15])

determined from a grain-size distribution curve. In order to determine a textural classification, it is necessary to know the percentages of two of the three basic textural groups (sand, silt, and clay) and enter these into the triangular chart. The area in which the intersection of the two values occurs determines the textural classification.

AASHO system

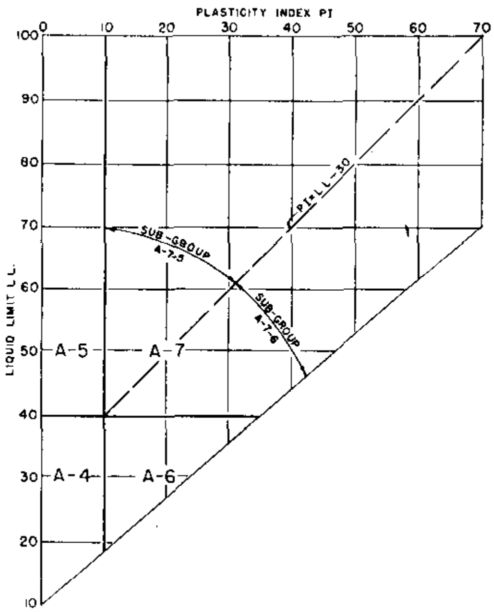
58. The most widely used system for classifying soils for highway subgrade use is the AASHO system, which was established on the basis of field performance of highway subgrades. The system groups together soils of similar load-carrying capacity, although there is a wide range of load-bearing ability within each group, as well as some overlapping between groups. The designations assigned to groups range from A-1 to A-7, where A-1 soils are of the highest quality and A-7 are of the lowest. Some of the groups may be further subdivided on the basis of a group index. The group index is determined by the LL, PI, and grain-size distribution curve, using the classification charts of Figure 24. A more detailed description of the AASHO system, as well as the procedure for employing it, may be found in Reference 16.

FAA system

59. The FAA has established a system for classifying subgrade soils for use as a guide in runway pavement design. Using the grain-size distribution curve, as well as the LL and PI, this system groups soils into 13 designations, E-1 through E-13. In addition to an "E" designation, a soil may also be given a textural classification by use of the biaxial classification chart shown in Figure 25. The use of this chart requires a grain-size analysis of the fraction passing the No. 10 sieve. To select the proper soil group, the results of the sieve analysis and plasticity analysis (LL and PI) are used with Table A of Figure 25.

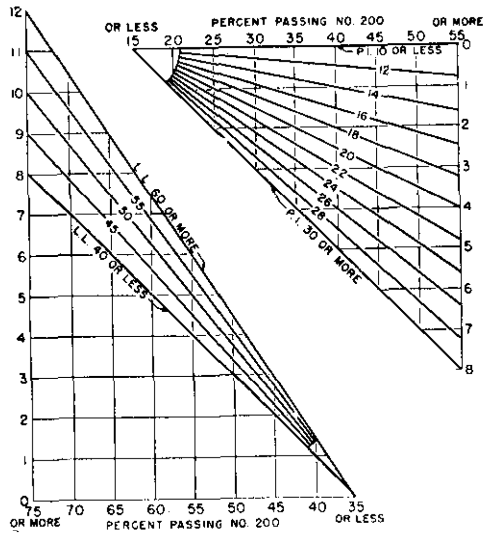
60. Since the classification procedure is based on material passing the No. 10 sieve, percentages taken from a grain-size distribution curve must be evaluated accordingly. The presence of significant amounts of sound, well-graded material retained on the No. 10 sieve, in cases where the presence of such material will effect an increase in stability,

GROUP INDEX CHARTS



LIQUID LIMIT AND PLASTICITY INDEX RANGES FOR A-1, A-5, A-6, AND A-7 SUBGRADE GROUPS

GRAIN SIZE AND PI RELATIONS



GRAIN SIZE AND LL RELATIONS

GROUP INDEX EQUALS SUM OF READINGS ON BOTH VERTICAL SCALES

CLASSIFICATION OF HIGHWAY SUBGRADE MATERIALS
(With Suggested Subgroups)

General Classification	Granular Materials (35% or less passing No. 200)							Silt-Clay Materials (More than 35% passing No. 200)			
	A-1			A-2							A-7
Group Classification	A-1-a	A-1-b	A-3	A-2-4	A-2-5	A-2-6	A-2-7	A-4	A-5	A-6	A-7-5, A-7-6
Sieve Analysis, Percent passing:											
No. 10	50 max.										
No. 40	30 max.	50 max.	51 min.								
No. 200	15 max.	25 max.	10 max.	35 max.	35 max.	35 max.	35 max.	36 min.	36 min.	36 min.	36 min.
Characteristics of fraction passing No. 40:											
Liquid limit				40 max.	41 min.	40 max.	41 min.	40 max.	41 min.	40 max.	41 min.
Plasticity index	6 max.		N.P.	10 max.	10 max.	11 min.	11 min.	10 max.	10 max.	11 min.	11 min.[a]
Group Index[b]	0		0	0		4 max.		8 max.	12 max.	16 max.	20 max.

Classification Procedure: With required test data available, proceed from left to right on above chart and correct group will be found by process of elimination. The first group from the left into which the test data will fit is the correct classification.

[a] Plasticity index of A-7-5 subgroup is equal to or less than LL minus 30. Plasticity index of A-7-6 subgroup is greater than LL minus 30 (see figure 2).

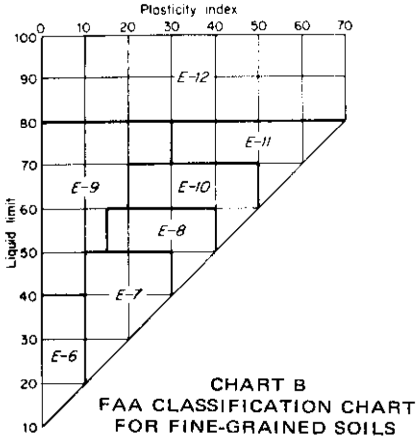
[b] See group index formula and Figure 1 for method of calculation. Group index should be shown in parentheses after group symbol as: A-2-6(3), A-4(5), A-6(12), A-7-5(17), etc.

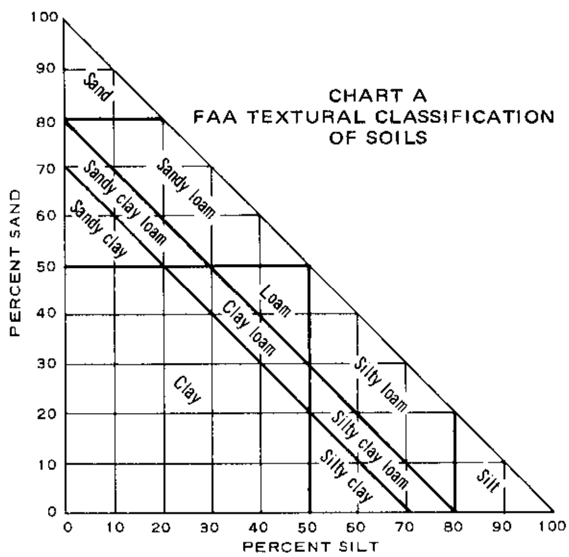
Figure 24. American Association of State Highway Officials classification system (from AASHO[16])

TABLE A
FAA CLASSIFICATION OF SOILS FOR AIRPORT CONSTRUCTION

Soil group	Mechanical analysis				Liquid limit	Plasticity index
	Retained on No. 10 sieve,* percent	Material finer than No. 10 sieve				
		Coarse sands, pass No. 10, ret. No. 60, percent	Fine sand, pass No. 60, ret. No. 270, percent	Combined silt and clay, pass No. 270, percent		
E-1	0–45	40+	60–	15–	25–	6–
E-2	0–45	15+	85–	25–	25–	6–
E-3	0–45	....	....	25–	25–	6–
E-4	0–45	....	....	35–	35–	10–
E-5	0–45	....	....	45–	40–	15–
E-6	0–55	....	....	45+	40–	10–
E-7	0–55	....	....	45+	50–	10–30
E-8	0–55	....	....	45+	60–	15–40
E-9	0–55	....	....	45+	40+	30–
E-10	0–55	....	....	45+	70–	20–50
E-11	0–55	....	....	45+	80–	30+
E-12	0–55	....	....	45+	80+	.....
E-13	Muck and peat—field examination					

* Classification is based on sieve analysis of the portion of the sample passing the No. 10 sieve. When a sample contains material coarser than the No. 10 sieve in amounts equal to or greater than the maximum shown in the table, a raise in classification may be allowed provided the coarse material is reasonably sound and fairly well graded.





Textural class	Percent sand	Percent silt	Percent clay
Sand	80-100	0-20	0-20
Sandy loam	50-80	0-50	0-20
Loam	30-50	30-50	0-20
Silty loam	0-50	50-80	0-20
Silt	0-20	80-100	0-20
Sandy clay loam	50-80	0-30	20-30
Clay loam	20-50	20-50	20-30
Silty clay loam	0-30	50-80	20-30
Sandy clay	50-70	0-20	30-50
Silty clay	0-20	50-70	30-50
Clay	0-50	0-50	30-100

Fraction	Sieve size	Grain size, mm
Coarse sand	#10-#60	2.0 -0.25
Fine sand	#60-#270	0.25-0.05
Silt	<#270	0.05-0.005
Clay	–	<0.005

Figure 25. Federal Aviation Agency classification system (from Hennes and Eske[17])

is justification for raising the classification by one or two groups. For example, an E-3 may be promoted to E-2 or E-1 if warranted by the presence of sound coarse material.

61. In the classification of a fine-grained soil (E-6 to E-12), selection of a single group may be impossible; that is, the soil may meet the requirements of more than one group. In this case, the use of Chart B of Figure 25 is required. In fact, this chart provides a more rapid means of classifying fine-grained (more than 45 percent passing the No. 270 sieve) soils than Table A. More detailed information may be found in Hennes and Eske[17] and Sowers and Sowers.[18]

USCS

62. The USCS is an outgrowth of the Airfield Classification System developed by Dr. Arthur Casagrande of Harvard University for the Corps during World War II. The Airfield Classification System was expanded and revised to apply to foundations and embankments as well as to airfields and roads and has been adopted by the Corps and U. S. Bureau of Reclamation. Like the systems employed by AASHO and FAA, the USCS uses both textural qualities and plasticity characteristics as the basis of classification. The USCS is described in Figures 26 and 27. Instructions for classifying a coarse-grained sample are presented in Figure 26, which is sufficient for classifying coarse-grained material. The classification of fine-grained material is accomplished by use of the plasticity chart shown in Figure 27. Tables 4 through 6 present the characteristics of each of the USCS soil groups. Further information about the USCS, including the procedure for using it and the characteristics of each soil group, is found in WES TM 3-357.[19]

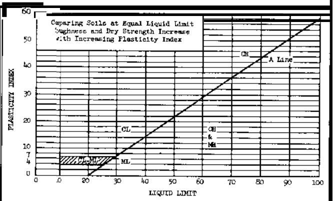
Classification of Dredged Material

63. Samples of dredged material from navigation projects around the continental United States were classified according to the four soil classification systems previously described. The types of material encountered among these samples indicate the variability of the types of soil subject to maintenance dredging. Twelve different USCS types of

Major Divisions (1)			Group Symbols (3)	Typical Names (4)	Field Identification Procedures (5) (Excluding particles larger than 3 in. and basing fractions on estimated weights)			Information Required for Describing Soils (6)	Laboratory Classification Criteria (7)
Coarse-grained Soils. More than half of material is larger than No. 200 sieve size. The No. 200 sieve size is about the smallest particle visible to the naked eye.	Gravels. More than half of coarse fraction is larger than No. 4 sieve size. (For visual classification, the 1/4-in. size may be used as equivalent to the No. 4 sieve size)	Clean Gravels (Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines.	Wide range in grain sizes and substantial amounts of all intermediate particle sizes.			For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions, and drainage characteristics.	$C_u = \frac{D_{60}}{D_{10}}$ Greater than 4; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3
			GP	Poorly graded gravels or gravel-sand mixtures, little or no fines.	Predominantly one size or a range of sizes with some intermediate sizes missing.				Not meeting all gradation requirements for GW
		Gravels with Fines (Appreciable amount of fines)	GM	Silty gravels, gravel-sand-silt mixture.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below).			Give typical name; indicate approximate percentages of sand and gravel, maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbol in parentheses.	Atterberg limits below "A" line or PI less than 4. Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols.
			GC	Clayey gravels, gravel-sand-clay mixtures.	Plastic fines (for identification procedures see CL below).				Atterberg limits above "A" line with PI greater than 7
	Sands. More than half of coarse fraction is smaller than No. 4 sieve size.	Clean Sands (Little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines.	Wide range in grain size and substantial amounts of all intermediate particle sizes.				$C_u = \frac{D_{60}}{D_{10}}$ Greater than 6; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3
			SP	Poorly graded sands or gravelly sands, little or no fines.	Predominantly one size or a range of sizes with some intermediate sizes missing.			Example: Silty sand, gravelly; about 20% hard, angular gravel particles 1/2-in. maximum size; rounded and subangular sand grains, coarse to fine; about 15% nonplastic fines with low dry strength; well compacted and moist in place; alluvial sand; (SM).	Not meeting all gradation requirements for SW
		Sands with Fines (Appreciable amount of fines)	SM	Silty sands, sand-silt mixtures.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below).				Atterberg limits below "A" line or PI less than 4. Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols.
			SC	Clayey sands, sand-clay mixtures.	Plastic fines (for identification procedures see CL below).				Atterberg limits above "A" line with PI greater than 7
					Identification Procedures on Fraction Smaller than No. 40 Sieve Size				
					Dry Strength (Crushing characteristics)	Dilatancy (Reaction to shaking)	Toughness (Consistency near PL)		
Fine-grained Soils. More than half of material is smaller than No. 200 sieve size. The No. 200 sieve size is about the smallest particle visible to the naked eye.	Silts and Clays. Liquid limit is less than 50		ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity.	None to slight	Quick to slow	None	For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions.	
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.	Medium to high	None to very slow	Medium		
			OL	Organic silts and organic silty clays of low plasticity.	Slight to medium	Slow	Slight	Give typical name; indicate degree and character of plasticity; amount and maximum size of coarse grains; color in wet condition; odor, if any; local or geologic name and other pertinent descriptive information; and symbol in parentheses.	
	Silts and Clays. Liquid limit is greater than 50		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.	Slight to medium	Slow to none	Slight to medium		
			CH	Inorganic clays of high plasticity, fat clays.	High to very high	None	High		
			OH	Organic clays of medium to high plasticity, organic silts.	Medium to high	None to very slow	Slight to medium	Example: Clayey silt, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (ML).	
Highly Organic Soils			Pt	Peat and other highly organic soils.	Readily identified by color, odor, spongy feel and frequently by fibrous texture.				

Use grain-size curve in identifying the fractions as given under field identification.

Determine percentages of gravel and sand from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse-grained soils are classified as follows: Less than 5% = GW, GP, SW, SP. More than 12% = GM, GC, SM, SC. 5% to 12% = Borderline cases requiring use of dual symbols.



PLASTICITY CHART

For laboratory classification of fine-grained soils

(1) Boundary classifications: Soils possessing characteristics of two groups are designated by combinations of group symbols. For example GW-GC, well-graded gravel-sand mixture with clay binder. (2) All sieve sizes on this chart are U. S. standard.

FIELD IDENTIFICATION PROCEDURES FOR FINE-GRAINED SOILS OR FRACTIONS

These procedures are to be performed on the minus No. 40 sieve size particles, approximately 1/64 in. For field classification purposes, screening is not intended, simply remove by hand the coarse particles that interfere with the tests.

Dilatancy (reaction to shaking)

After removing particles larger than No. 40 sieve size, prepare a pat of moist soil with a volume of about one-half cubic inch. Add enough water if necessary to make the soil soft but not sticky.

Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens, and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil.

Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

Dry Strength (crushing characteristics)

After removing particles larger than No. 40 sieve size, mold a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely by oven, sun, or air-drying, and then test its strength by breaking and crumbling between the fingers. This strength is a measure of the character and quantity of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity.

High dry strength is characteristic for clays of the CH group. A typical inorganic silt possesses only very slight dry strength. Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when powdering the dried specimen. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

Toughness (consistency near plastic limit)

After particles large than the No. 40 sieve size are removed, a specimen of soil about one-half inch cube in size, is molded to the consistency of putty. If too dry, water must be added and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about one-eighth inch in diameter. The thread is then folded and rerolled repeatedly. During this manipulation the moisture content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached.

After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles.

The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the A-line.

Highly organic clays have a very weak and spongy feel at the plastic limit.

Adopted by Corps of Engineers and Bureau of Reclamation, January 1952.

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Figure 26. USCS classification chart

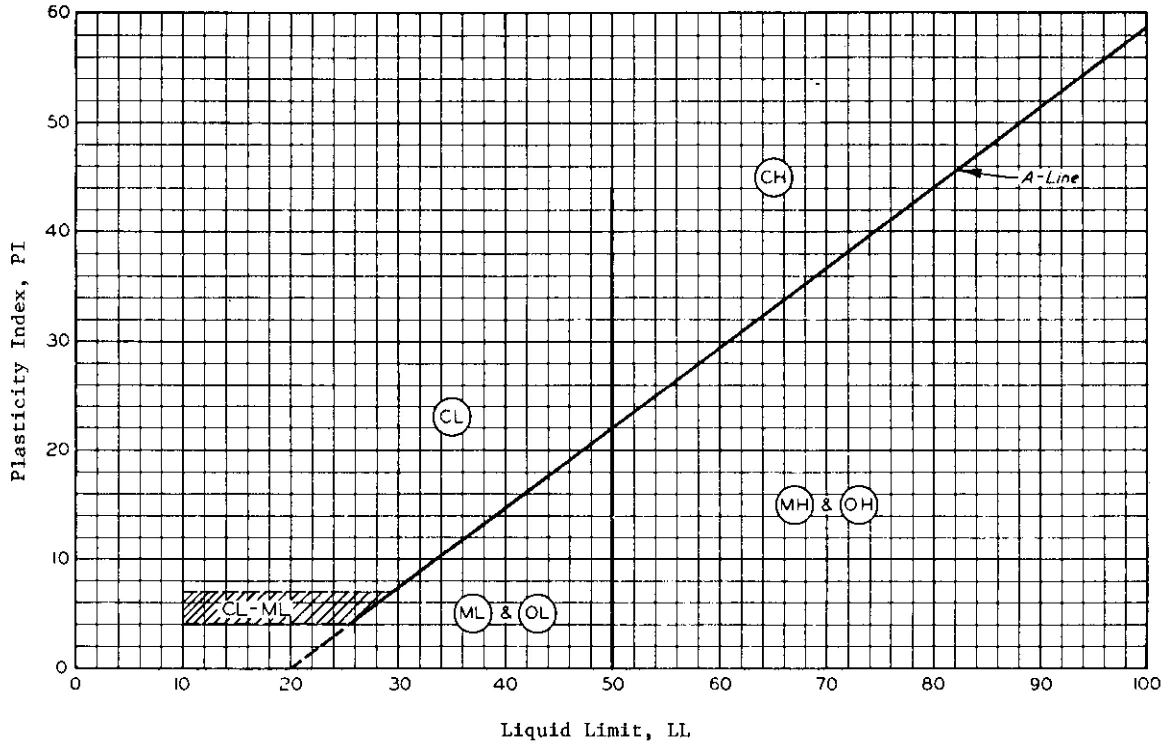


Figure 27. Plasticity chart

dredged material were encountered, ranging from well-graded gravel to organic clay. In the following paragraphs observations regarding the types of material encountered within each study region are made. It should be kept in mind that the absence of one or more types of dredged material from the samples taken within a given study region does not mean that the absent type is not present within the maintenance dredgings of that region. It means only that those were not sampled. The classification of dredged material within each study region is presented in terms of USCS classifications, while classification of the samples using the USDA, FAA, and AASHO systems is presented on a nationwide basis following the regional presentations.

Classification of dredged material using USCS

64. The classification properties previously reported were used to classify the samples in accordance with the USCS. Figure 28 shows the USCS classifications applicable to the samples taken from within each study region and displays graphically the predominant types of material

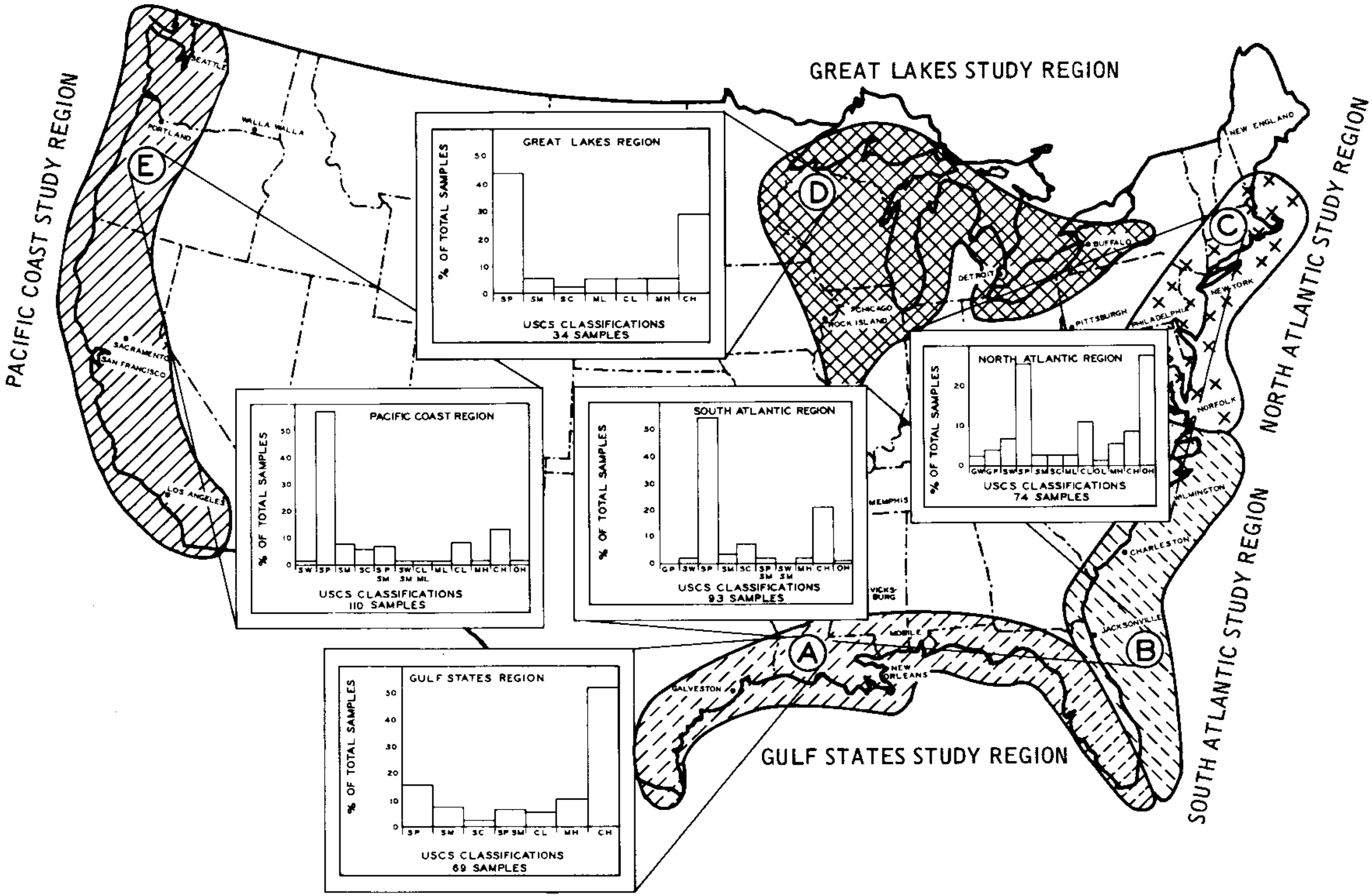


Figure 28. Regional distribution of dredged material types according to USCS classifications

sampled in each region. In Figure 29 the samples are divided into four categories. These categories, assigned on the basis of the first letter of the USCS classification, are intended only to show the fractions of the samples that were coarse, plastic, nonplastic, or organic. It must be emphasized that the information presented in these figures applies only to the samples analyzed for this study and does not constitute a quantitative representation of all the dredged material in the study regions. However, the information presented should be indicative of the types of dredged material found in each of the study regions.

65. Study region A - the Gulf States region. The samples of dredged material taken from within the Gulf States study region fell into seven of the USCS classification groups. The seven soils groups ranged in texture from poorly graded sand (SP) to inorganic fines of high plasticity (CH). Figure 28 shows that slightly less than one-third (33 percent) of the samples were classified as sandy material. Most of the samples of sandy dredged material in this region were taken from the coast of Florida. The remaining two-thirds (67 percent) of the samples were classified in one of the fine-grained designations, mostly CH. There were no samples of organic dredged material, although it is thought that organic dredged material is common in the region.

66. Study region B - the South Atlantic region. Ten types of dredged material were encountered among the 98 samples, ranging from poorly graded gravels (GP) to plastic and organic clays (CH and OH). Three-fourths of all samples were classified as sands and gravels. Only 24.5 percent of the samples were fine grained. Most (89 percent) of the data pertaining to the South Atlantic study region related to either the Wilmington (37 percent) or the Jacksonville (52 percent) Districts. More than one-half of the samples were classified as poorly graded sand (SP). All but one of these samples of SP material were taken in either the Wilmington or Jacksonville Districts. In fact, 58 percent of the Wilmington samples and 67 percent of the Jacksonville samples were classified SP.

67. Study region C - the North Atlantic region. Slightly fewer data points were accumulated within this region than from either the

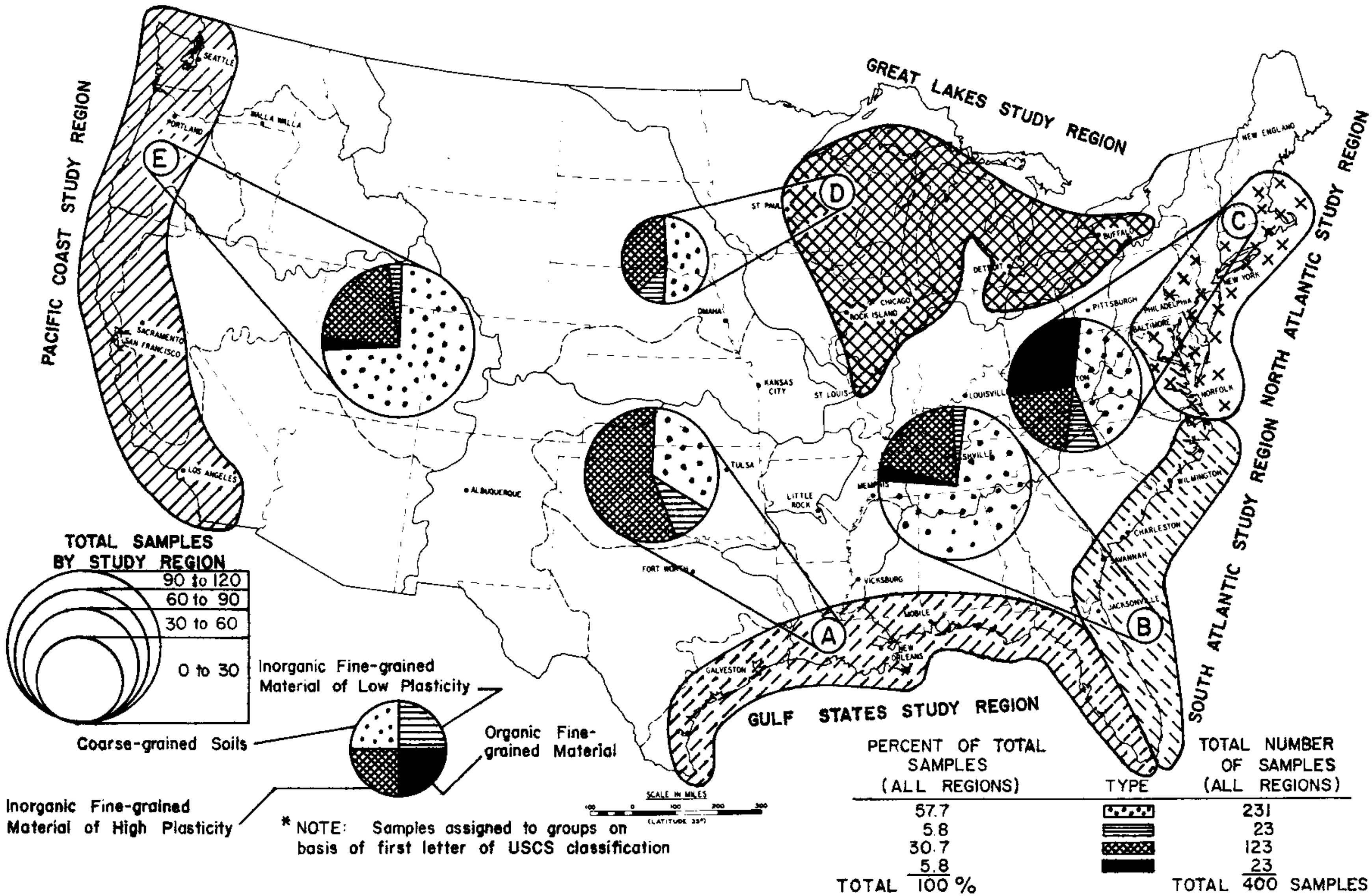


Figure 29. Types* of dredged material samples, by region

Gulf States or South Atlantic regions. The samples divided into 12 of the 15 USCS classifications. The most frequently encountered classifications were poorly graded sand (SP) and organic clay with high LL (OH). Among the samples, 27 percent were OH and 26 percent were SP; the remainder of the samples were fairly evenly distributed among ten classifications. Forty-seven percent of the samples were coarse grained, mostly sand. The remaining 53 percent were fine material, mostly CL and OH. About one-half (51.2 percent) of the fine-grained samples were organic (OL or OH).

68. Study region D - the Great Lakes region. Thirty-four samples of dredged material were obtained from navigation projects within the Great Lakes study region. A total of seven USCS dredged material types were sampled within this study region, with the predominant types being SP and CH. Slightly more than half of the samples, 52.9 percent, were coarse-grained material, and the remaining 47.1 percent were fine grained. Among the 18 coarse-grained samples, all but three were poorly graded sand (SP). The majority of the fine-grained material was highly plastic, CH, with two samples each of ML, CL, and MH comprising the rest. There were no samples of organic dredged material, although organic dredged material is thought to occur in this region.

69. Study region E - the Pacific Coast region. More data were accumulated from within the Pacific Coast study region than from any other region during this study. Eight different types of dredged material were sampled. In addition, there were three borderline classifications. The material ranged from well-graded sand (SW) to organic fines (OH). The predominant type of dredged material was poorly graded sand (SP). Over half of the samples (53.6 percent) were classified SP. The remaining samples were fairly evenly divided among SM, SP-SM, CL, and CH. There were also single samples of SW-SM, CL-ML, ML, SW, MH, and OH. Approximately three-fourths (75.5 percent) of the samples were coarse grained. Only one sample proved to be organic dredged material.

AASHO system

70. The AASHO classification system was used to classify as many of the samples as possible, and the distribution of the classified

samples is shown on a national basis in Figure 30 and broken into study regions in Figure 31. Figure 30 shows that the bars for A-1, A-2, and A-7 soils are divided, just as these classifications are divided in the system. The hatched segments of each divided bar represent the portions of the total samples that comprise the single classification. For example, the A-7 group is divided into two parts, A-7-5 and A-7-6. Since 26.8 percent of the samples were classified A-7-5, and 12.4 percent were classified A-7-6, 39.2 percent were classified A-7 soils, which is represented by the top of the A-7 bar. The A-1 and A-2 bars are treated similarly.

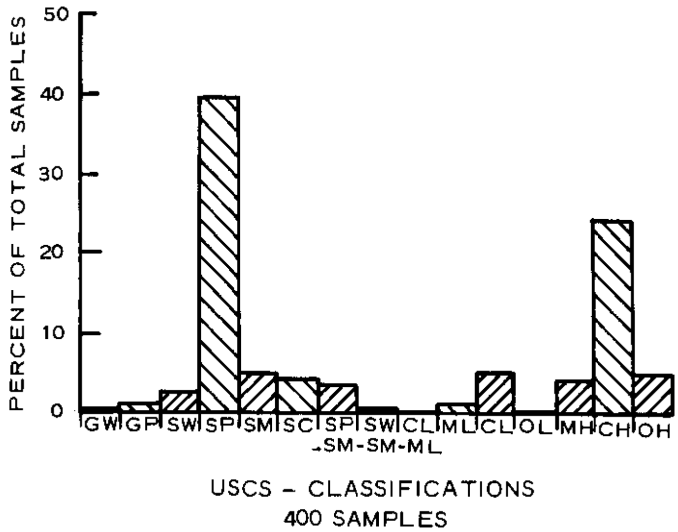
71. Figure 30 shows that six of the seven types of dredged material were sampled. No samples of A-5 material, elastic fine-grained dredged material, were obtained. Slightly more than half the samples were coarse grained, according to this classification system. The most frequently encountered group was A-3, fine sand. Most of the fines (more than 35 percent passing the No. 200 Sieve) were classified A-7, with a few A-4's and A-6's.

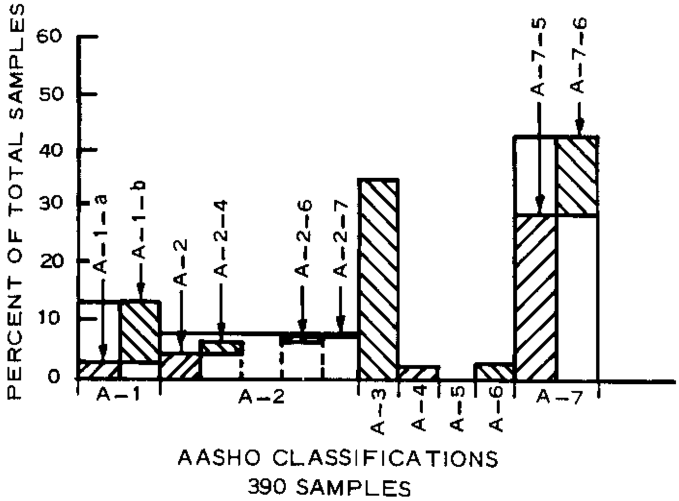
FAA system

72. Sufficient data were available to classify most of the samples using the FAA classification system. Figures 30 and 32 are graphical representations of the types of material sampled. All but two of the FAA types of dredged material were sampled. The two types not sampled were E-9, elastic silts and clays, and E-13, organic swamp soils. Slightly more than half (56 percent) of the samples were classified granular, mostly E-1 (30 percent), E-2 (11 percent), and E-3 (13 percent). The remaining 44 percent of the samples were fine grained, mostly E-12, highly plastic clay.

Comparison of systems

73. Table 7 shows the large number of USCS designations that may apply to specific samples of any of the AASHO or FAA soil types. Since each of these systems has its own definition of fines, some samples of dredged material were classified as fine grained using the FAA and AASHO systems, and as coarse grained using the USCS. The only emerging patterns seem to be the classification of SP samples as A-3 and the





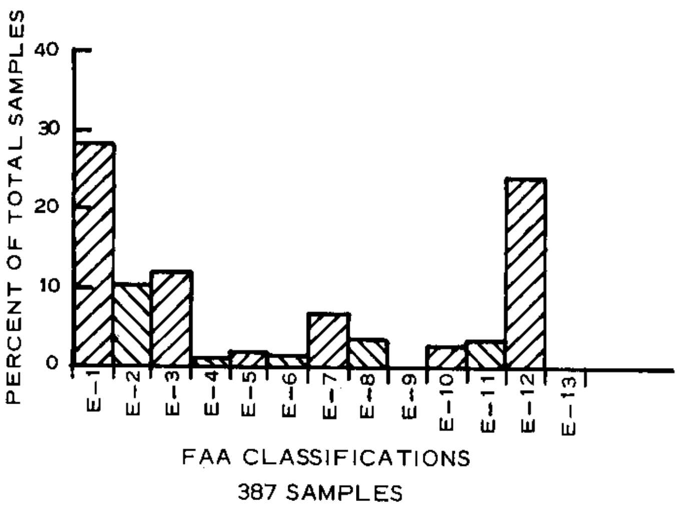


Figure 30. Dredged material classification distribution graph for the nation

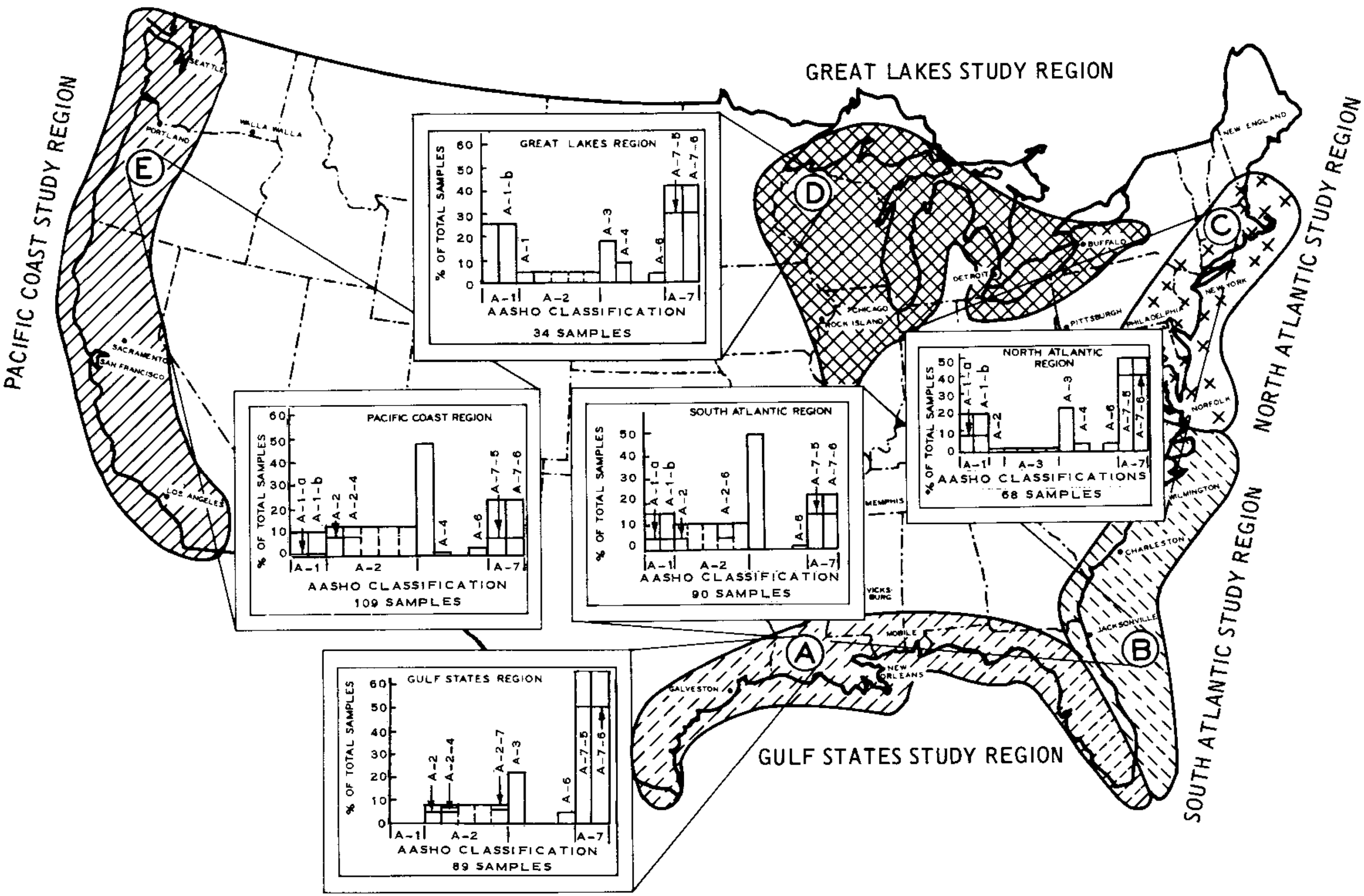


Figure 31. Regional distribution of dredged material types according to AASHO classifications

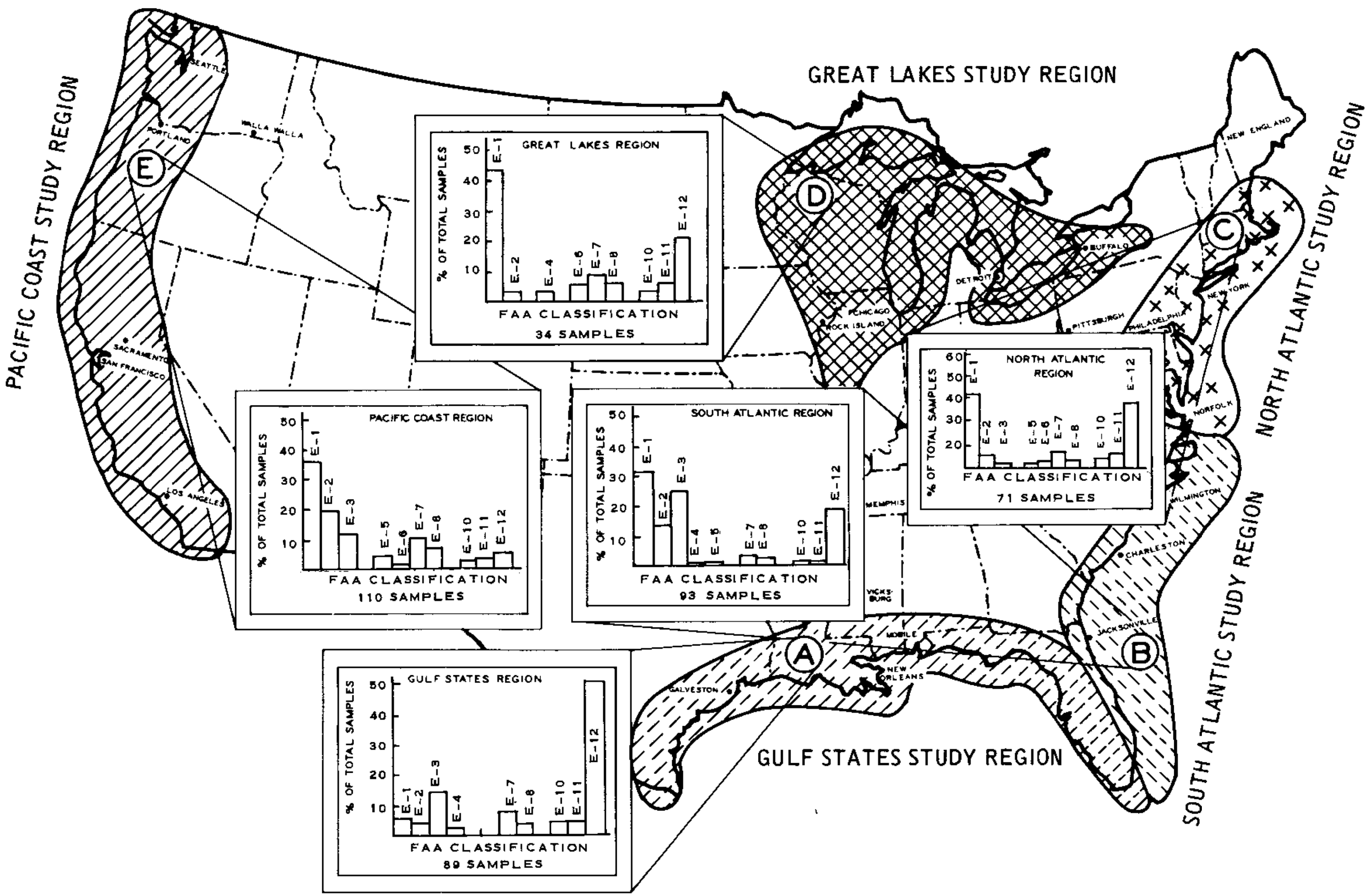


Figure 32. Distribution of FAA classifications by region

classification of CH samples as E-12 and A-7. An indication of the interrelation of individual classifications of the FAA, USCS, and AASHO systems is shown in Figure 33. This figure shows, by overlaying LL versus PI plots, that one USCS classification may be applicable to several classifications in the other systems and vice versa.

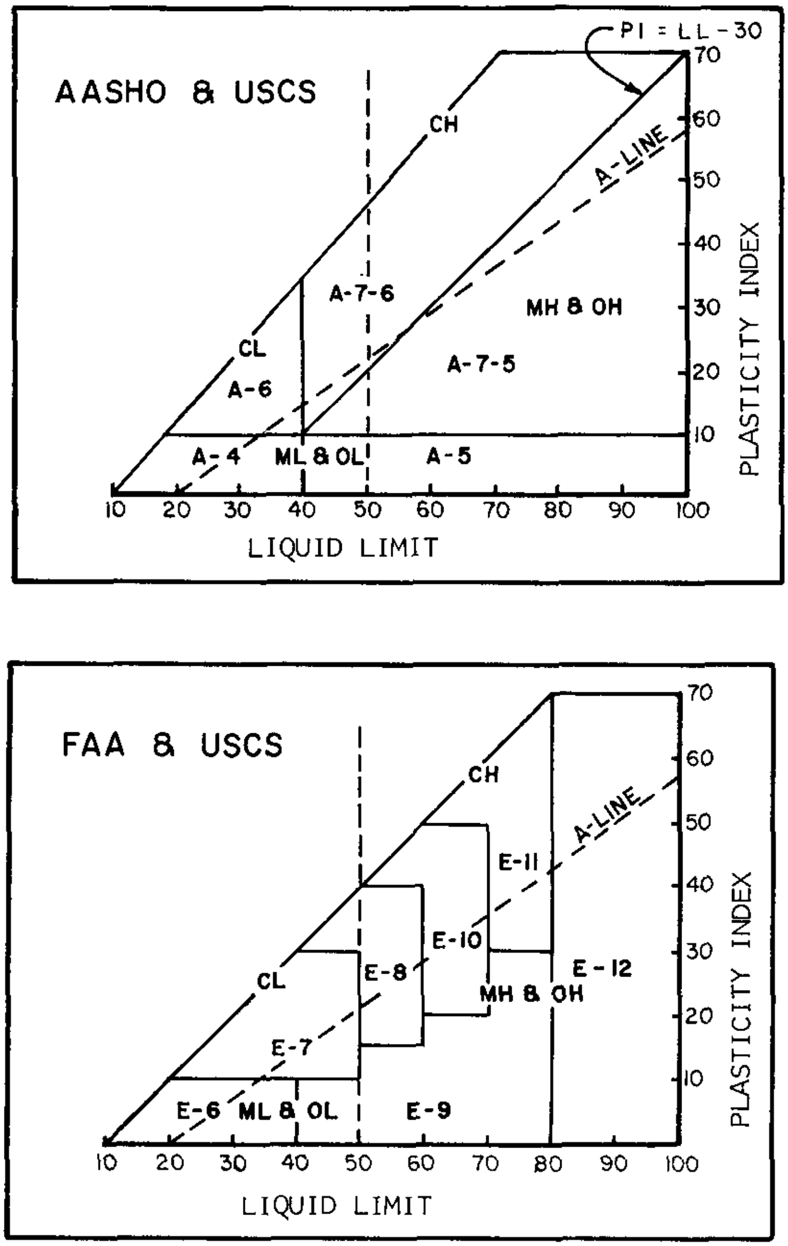


Figure 33. Interrelationship of fine-grained classifications by FAA, AASHO, and USCS

PART V: ENGINEERING PROPERTIES OF DREDGED MATERIAL

74. Before the design or analysis of earth structures and foundations may be undertaken, a thorough understanding of the properties of the soils involved is necessary. Similarly, the engineering properties of dredged material must be investigated in order to evaluate its suitability for use in conventional soils-related applications. The engineering properties of compacted (dewatered and densified) samples of dredged material were determined to show what properties are exhibited by dredged material that is similar to other soils being used in earthwork construction. These properties are useful in estimating the potential for the productive use of dredged material in earthwork construction projects.

75. In this part the engineering properties of compacted samples of dredged material are presented in several sections, each of which presents the results of one type of test (e.g., consolidation test). The engineering properties of fine-grained dredged material were determined by laboratory compaction and testing of dredged material specimens. Properties reported include the results of classification, compaction, shear strength, and consolidation tests.

76. Since the engineering properties of clean sands are well documented and fall into rather predictable and narrow ranges, only the classification properties of the samples of clean sandy dredged material were determined. A limited amount of data concerning the properties of dredged material deposits within containment areas is also presented.

Classification Properties

77. The grain-size distribution, LL, PL, OC, and USCS classification were determined for the samples; all values but the OC were available for four samples from the San Francisco District. The grain-size distribution for each of the samples is presented in Figure 34, and the other classification properties, as well as the USCS classifications, are presented in Table 8.

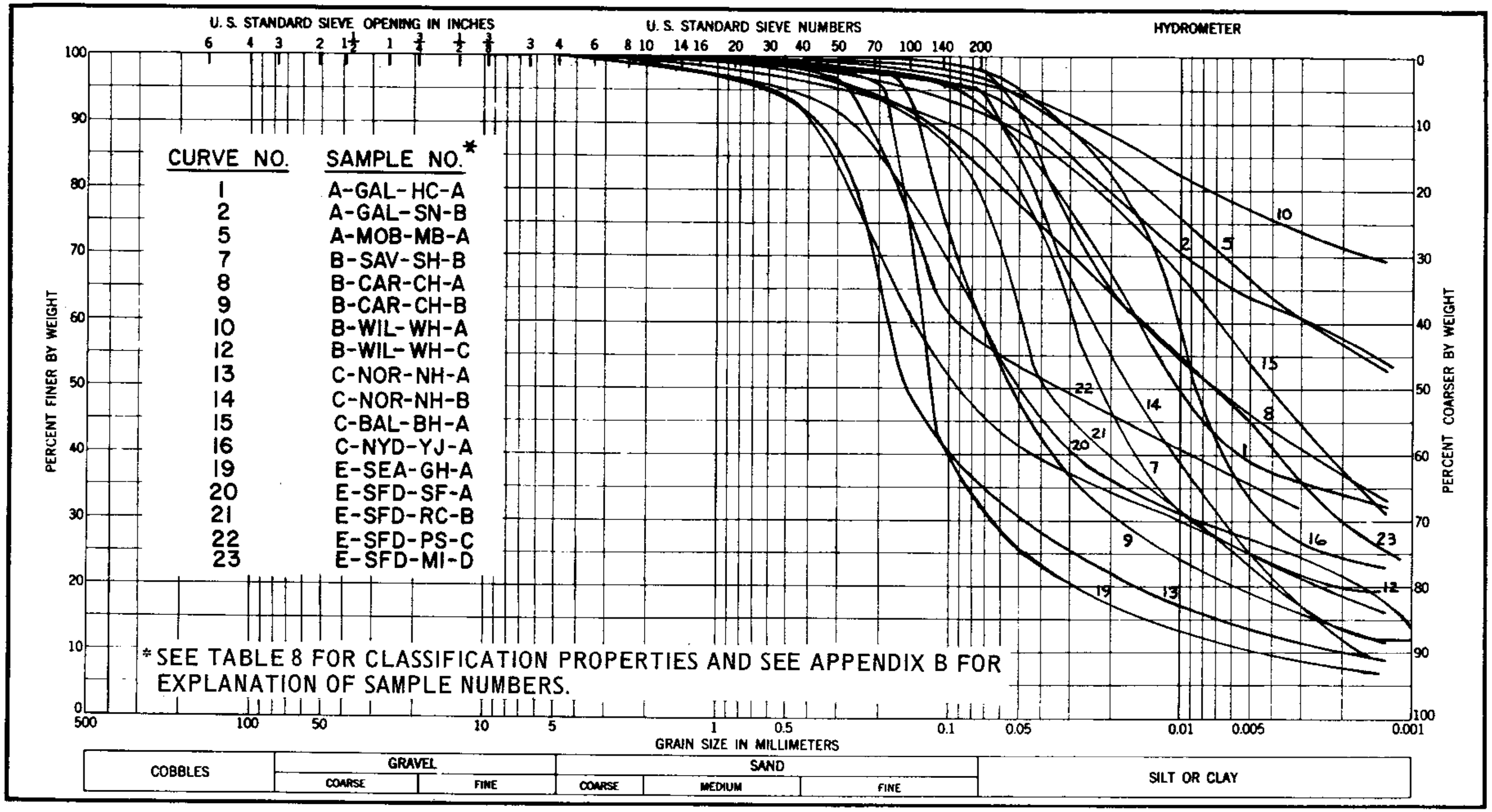


Figure 34. Grain-size distribution curves of dredged material samples subjected to engineering properties testing

78. The classification properties of the samples of dredged material whose engineering properties were determined in the laboratory are presented in this part for correlation with engineering properties. The classification properties of some 400 samples of dredged material appear in Part IV and are more indicative of dredged material as a whole than are the samples analyzed in this section.

Grain-size distribution

79. Figure 34 shows that a wide range of material is represented among the 17 samples. The percent fines (percent passing No. 200 sieve) varies between 35 and 98 percent. The presence of a large percent of fines usually indicates low permeability and high compressibility.[21] Since the permeability and compressibility of fine-grained soils are affected by other factors in addition to grain size, no correlation between percent fines and these parameters would be meaningful. The permeability and compressibility of fine-grained dredged material are discussed later in this part, as they are best evaluated by direct testing.

Plasticity

80. The LL, PL, and PI were determined for each fine-grained dredged material sample and for the fine fraction of coarse-grained samples with significant fines. The values obtained for these parameters are tabulated for each sample in Table 8. Correlations between plasticity parameters and engineering properties parameters are discussed in later sections of this part.

81. Care must be exercised in using some of the data presented in Table 8. The LL and PL of five samples (noted in Table 8) were inadvertently determined using dried specimens. Drying may alter dredged material by driving off water adsorbed on the particles. This adsorbed water may not be entirely regained upon rewetting. Drying may also cause chemical changes in any organic material present. Either of these effects can result in erroneous values of the Atterberg limits.[22,23] Unfortunately, neither the magnitude nor the direction of error can be predicted. For example, Casagrande[23] reported that air drying of a clay sample caused the LL to be 20 percent greater than the correct

value determined on the soil prior to air drying. However, the LL of an oven-dried sample of the same soil was 24 percent less than the correct value. The Atterberg limits of the dried samples are not included in any correlation between plasticity and engineering properties, except as specifically noted.

Organic content

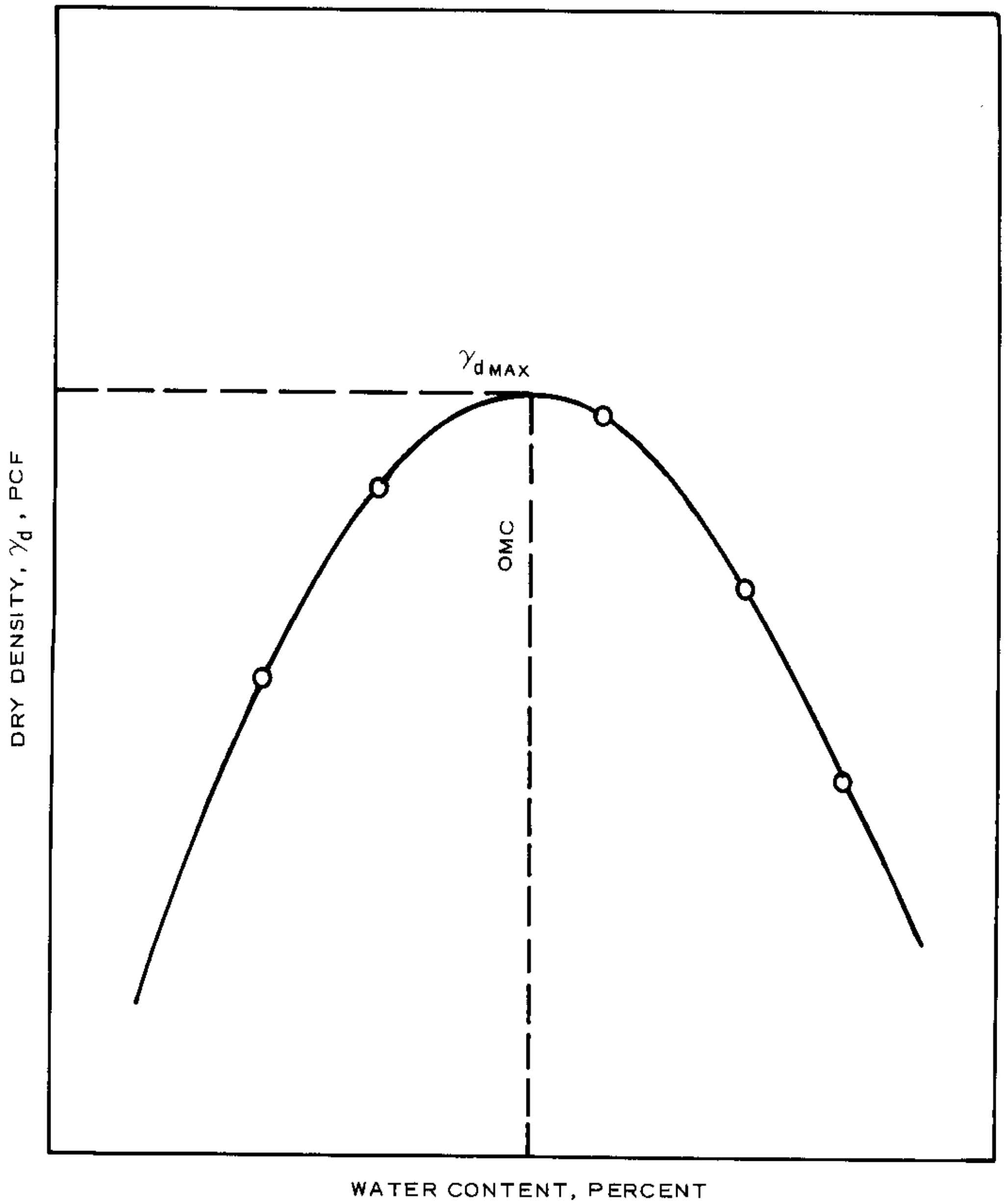
82. The OC was determined for each sample, and values are tabulated in Table 8. Since the properties of dredged material are affected by many factors, the effect of OC on the properties of dredged material must be determined using samples of material that differ only in OC. As none of the samples contained sufficient organic material to have a significant effect on the properties of the samples (Millar and Turk[24] estimate that at least 20 percent OC is required to affect properties), and in view of the different materials involved, no further investigations concerning OC were pursued. This subject is recommended for further research.

Compaction of Dredged Material

Laboratory tests

83. To simulate in the laboratory the compaction that may be achieved during field construction operations involving dredged material, samples of dredged material were subjected to one of three compaction tests: the Standard Proctor, 15-blow, and Modified Proctor. The maximum dry density γ_d and the optimum moisture content OMC were used as criteria for the preparation of test specimens to be used for shear strength and consolidation tests. Figure 35 shows the compaction criteria to which the specimens were prepared.

84. Most specimens were dewatered to water contents wet of optimum since it was believed that such specimens would be more representative of conditions that will prevail in field projects involving the use of dredged material as a construction material. For example, in construction of an embankment, dewatering and compaction of dredged material will be required. Since the effort required to dewater fine-grained



TEST	W, PERCENT	γ_d, PCF
CONSOLIDATION	OMC + 5	0.9 γ_d MAX
DIRECT SHEAR	OMC + 5	0.9 γ_d MAX
TRIAXIAL SHEAR	OMC + 5 & OMC − 5	0.9 γ_d MAX

Figure 35. Sample preparation criteria

dredged material is likely to be quite high, it is reasonable that the amount of dewatering be limited to the minimum that will result in satisfactory properties. It is anticipated that this minimum dewatering will result in dredged material considerably wetter than the OMC in most, if not all, cases.

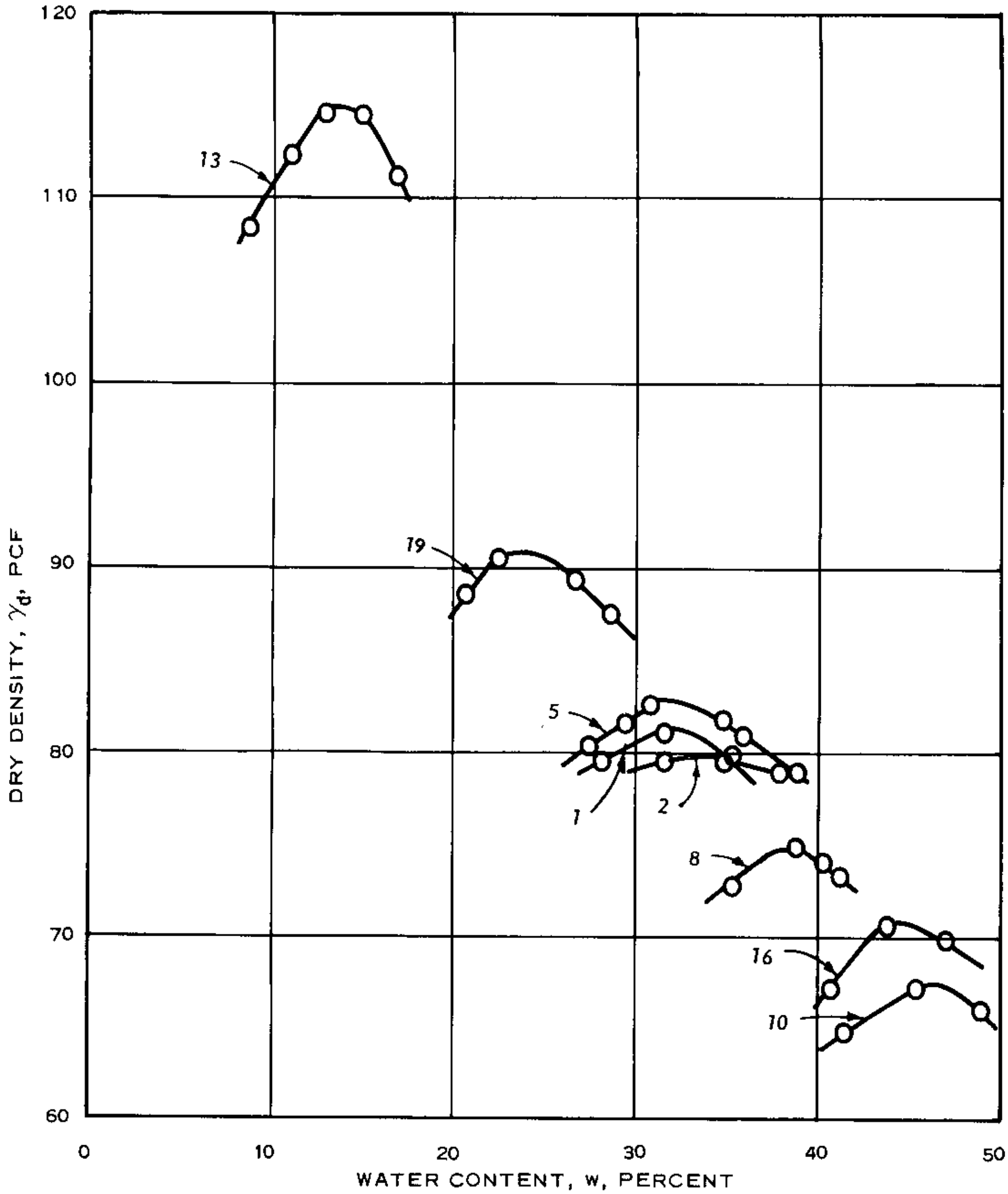
Results of compaction tests

85. The results of the Standard Proctor, 15-blow, and Modified Proctor compaction tests are presented in Figures 36, 37, and 38, respectively. Figure 39 presents the range and average values of γ_d and OMC for each test type. As expected, the greater compactive effort of the Modified Proctor test resulted in higher values of γ_d at lower OMC values than the other tests. The results of the Standard Proctor test showed an average γ_d slightly higher than that of the 15-blow test, at virtually the same OMC. These trends, although expected because of the difference in compactive effort, reveal very little about the properties of the samples. Due to the dissimilarity of the samples and to the limited number of tests conducted, the averages and ranges shown in Figure 39 are meaningful only as a summarization of the results of the compaction tests involved.

86. Woods[25] states that the OMC for fine-grained soils is usually a few percent less than the PL. Figure 40 shows that for the tests performed during this study the OMC for fine-grained dredged material is generally less than the PL, showing agreement with Woods.[25]

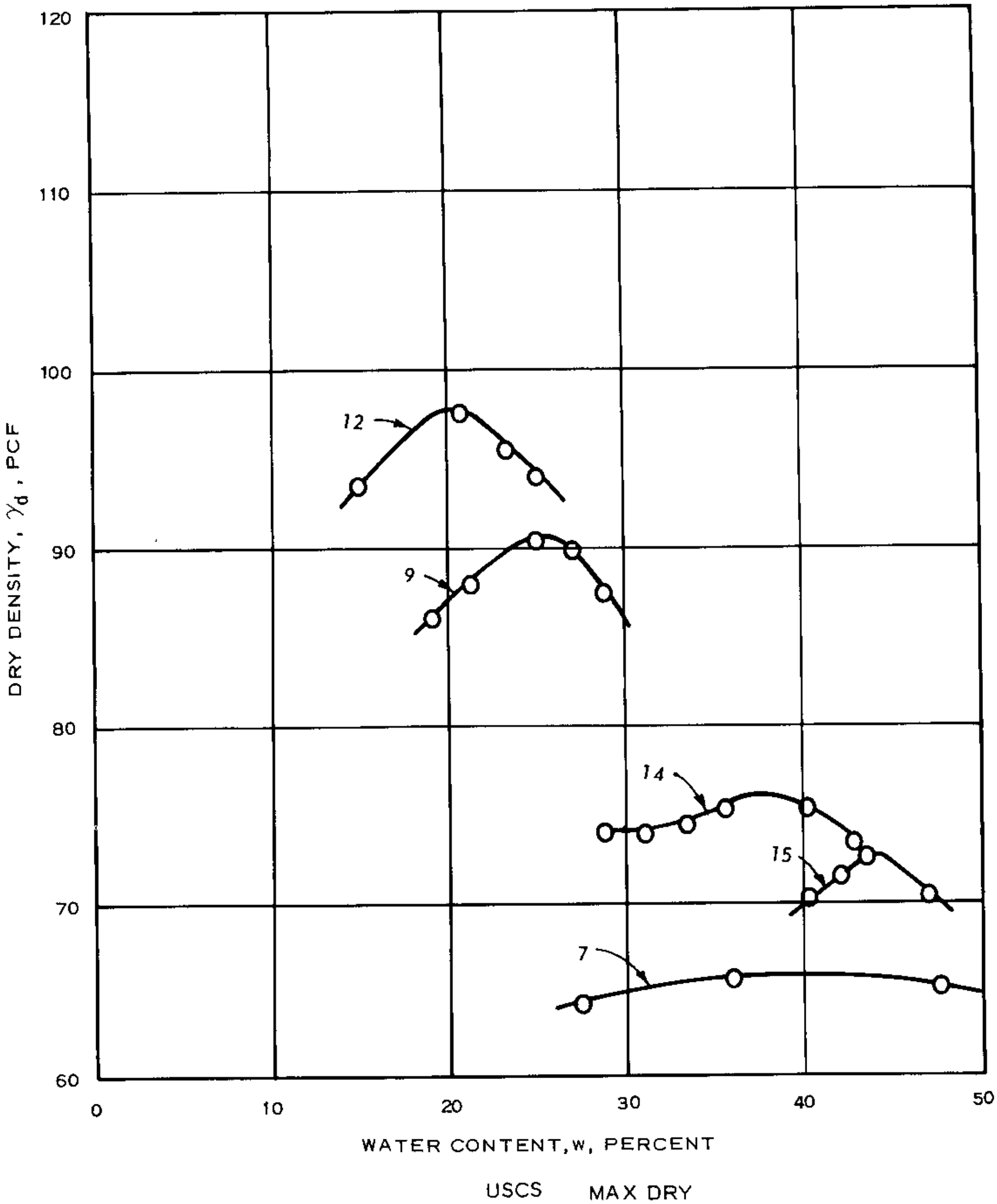
Shear Strength of Dredged Material

87. Shear strength is often the most important property under consideration during an analysis of the behavior of soil under load. The ultimate bearing capacity of a soil is dependent on shear strength; the stability of earth slopes is directly related to the shear strength; and earth pressures against structures such as retaining walls and bulkheads are known to vary with shear strength. In view of the importance of shear strength, any study investigating the potential for construction-oriented productive uses of dredged material must take



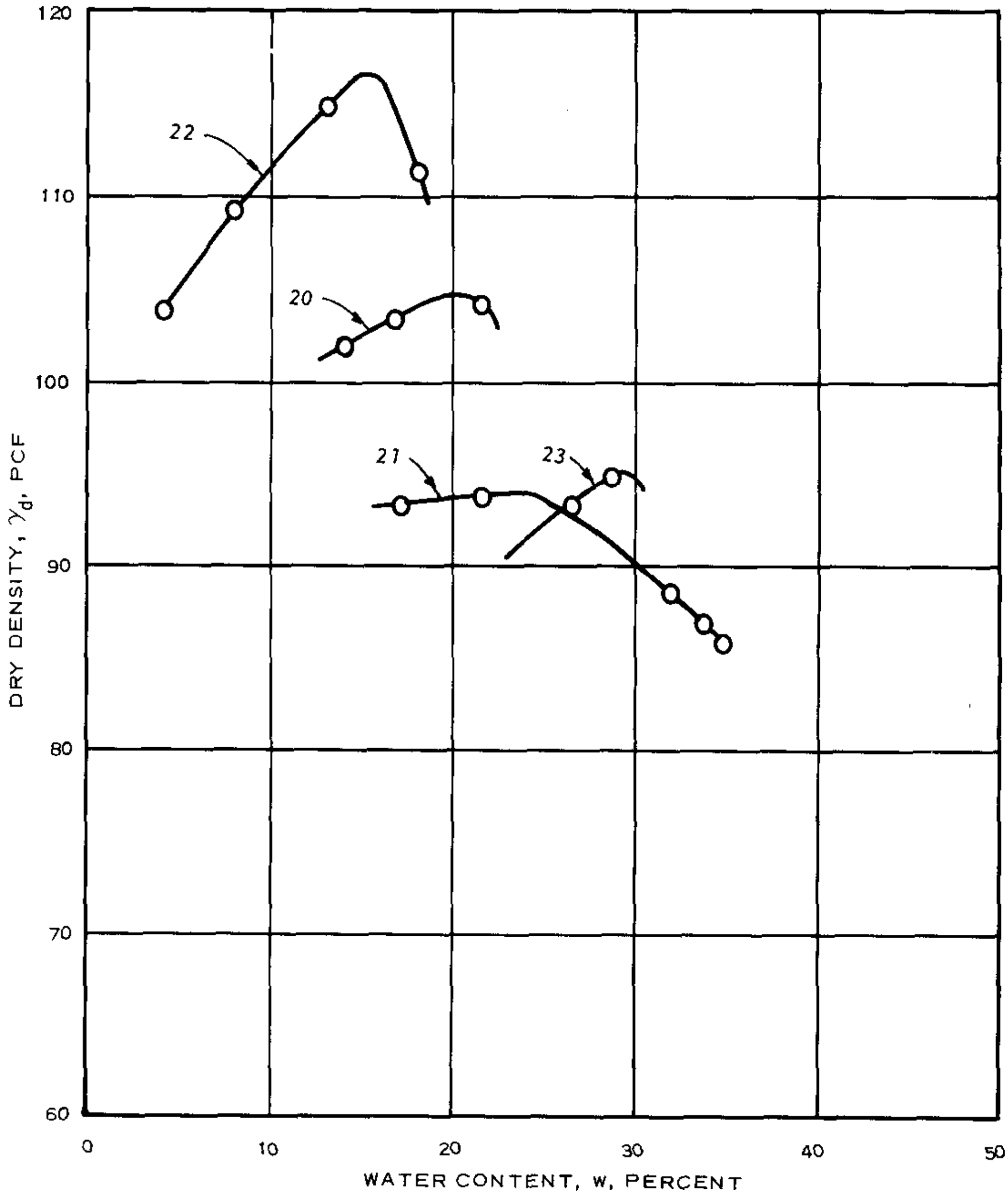
CURVE NO.	SAMPLE NO.	USCS CLASSI-FICATION	MAX DRY DENSITY PCF	OMC, PERCENT
1	A-GAL-HC-A	CH	81.2	32.2
2	A-GAL-SN-B	CH	79.8	33.9
5	A-MOB-MB-A	CH	82.9	32.1
8	B-CAR-CH-A	CH	74.8	38.6
10	B-WIL-WH-A	OH	67.4	46.8
13	C-NOR-NH-A	SC	115.0	13.7
16	C-NYD-YJ-A	CH	70.9	44.6
19	E-SEA-GH-A	SM	90.9	24.0

Figure 36. Moisture-density relationships for samples of dredged material subjected to the Standard Proctor compaction test



CURVE NO.	SAMPLE NO.	USCS CLASSI-FICATION	MAX DRY DENSITY PCF	OMC, PERCENT
7	B-SAV-SH-B	MH	65.9	40.0
9	B-CAR-CH-B	CH	90.6	25.4
12	B-WIL-WH-C	SC	97.9	20.0
14	C-NOR-NH-B	CH	76.1	38.1
15	C-BAL-BH-A	MH	72.5	44.1

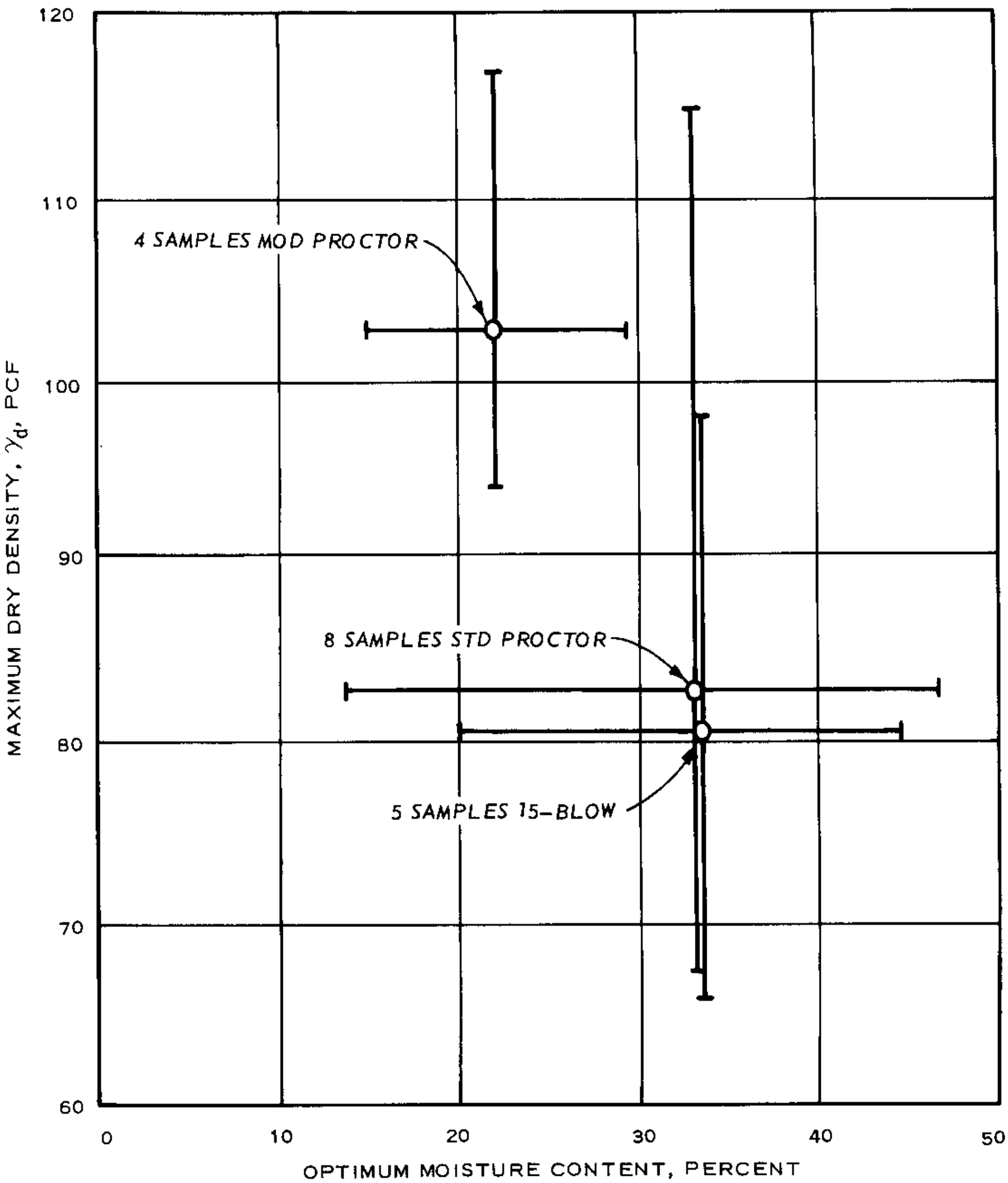
Figure 37. Moisture-density relationships for samples of dredged material subjected to the 15-blow compaction test



CURVE NO.	SAMPLE NO.	USCS CLASSI-FICATION	MAX DRY DENSITY PCF	OMC, PERCENT
20	E-SFD-SF-A	CH	105.0	20.5
21	E-SFD-RC-B	CH	94.0	24.0
22	E-SFD-PS-C	CL	117.0	15.0
23	E-SFD-MI-D	CH	95.0**	29.5**

**APPROXIMATE VALUES

Figure 38. Moisture-density relationships for samples of dredged material subjected to the Modified Proctor compaction test



TYPE TEST	COMPACTIVE EFFORT FT-LB/CF	NO. OF SAMPLES	MAX DRY DENSITY, PCF	OMC, PERCENT
15-BLOW	7, 400	5	65.9-97.9 (80.6)*	20.0-44.1 (33.5)
STANDARD PROCTOR	12, 200	8	67.4-115.0 (82.9)	13.7-46.8 (33.2)
MODIFIED PROCTOR	56, 000	4	94.0-117.0 (102.8)	15.0-29.5 (22.3)

*AVERAGE VALUES SHOWN IN PARENTHESES

Figure 39. Average maximum dry density versus average optimum moisture content of dredged material samples

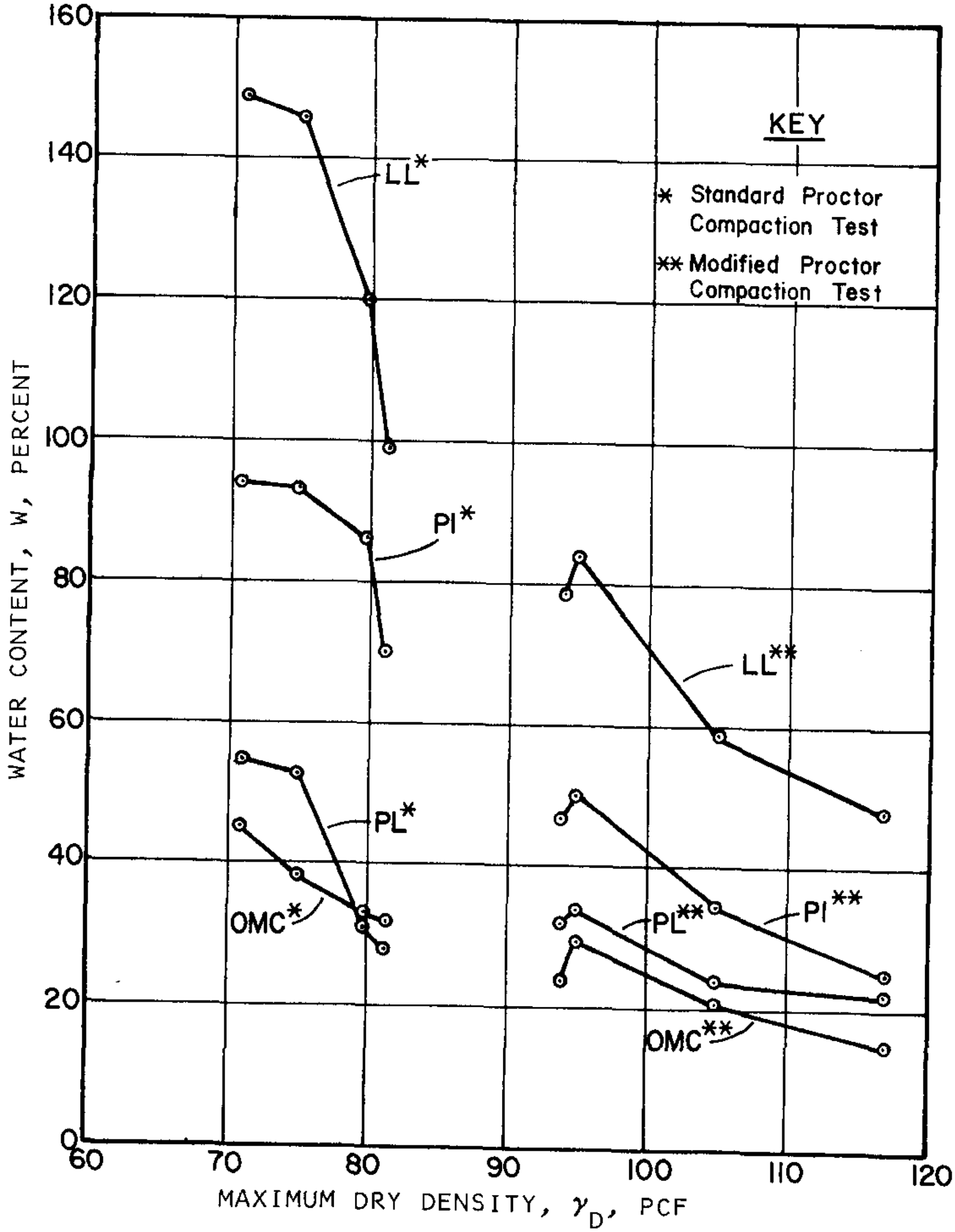


Figure 40. Relation between compaction and plasticity characteristics for dredged material samples

into consideration the shear strength of the dredged material. Similarly, a study to determine the engineering properties of dredged material must include an investigation of shear strength. In the following pages, the results of shear strength tests conducted on compacted samples of dredged material are presented and discussed.

Test types

88. Two types of shear strength tests were used. Consolidated-drained direct shear tests (S-tests) were conducted using dredged material compacted to 90 percent of the maximum γ_d at a moisture content equal to the OMC plus 5 percent. Unconsolidated-undrained triaxial shear tests (Q-tests) were also conducted using specimens of dredged material compacted to 90 percent of the maximum γ_d at the OMC plus 5 percent -- the same sample preparation used during the S-tests. A second series of Q-tests were performed using dredged material specimens compacted to 90 percent of the maximum γ_d at the OMC minus 5 percent.

Shear strength

89. Coulomb's Law[21,26] relating shear strength to effective normal stress and unit cohesion is expressed mathematically as follows:

$$\tau = \sigma \tan \phi + c \qquad (2)$$

where

τ = shear strength, tsf

σ = effective normal stress, tsf

ϕ = angle of internal friction, deg

c = unit cohesion, tsf

90. While this equation greatly oversimplifies the situation, the explanation of shear strength test results is facilitated by reference to Coulomb's Law. The strength envelope for a noncohesive soil, or a clay loaded very slowly under fully drained conditions, is a straight line whose slope is $\tan \phi$ and which passes through the origin. In this case, Coulomb's Law may be expressed as

$$\tau = \sigma \tan \phi \qquad (3)$$

The strength envelope for a saturated clay under undrained conditions is a horizontal line whose equation is

$$\tau = c \tag{4}$$

which is the case for $\phi = 0$.

91. Noncohesive silts, silts with little or no dry strength, tend to exhibit behavior similar to that of sand. In the fully drained condition, noncohesive silts will have internal friction angles somewhat lower than those of sand. Due to the low permeability of silt, the undrained condition is more likely to govern, however, and analysis should be in terms of the apparent angle of internal friction ϕ_a , which results from test conditions in which pore pressures are developed. The shear strength of silts with appreciable cohesion may be analyzed in the same way as for clays.

Results of S-tests

92. The results of the S-tests conducted during this study are presented as plots of τ (on the ordinate) against σ (on the abscissa). All S-test envelopes, referred to as S-lines, were straight lines whose slopes were $\tan \phi$ and whose τ-intercepts were c ($c = 0$ for true drained test). In three tests, the line passed through the origin, while the other seven tests showed values of c ranging from 0.09 to 0.19 tsf. The value ranged from 21 to 34 deg. The range of τ versus σ for the 10 S-tests is shown in Figure 41a. All 10 S-lines fell within the shaded area of Figure 41a. The values of c and ϕ for each sample are tabulated in Table 9.

Results of Q-tests

93. The strength envelope for a Q-test is more difficult to explain in terms of Coulomb's Law. Q-lines assume different shapes depending on factors such as the type of sample (undisturbed, remolded, compacted, etc.) and the degree of saturation. Referring to Figure 42a, which is a sample Q-line for a compacted cohesive soil, the relation between τ and σ is nonlinear and approaches a horizontal asymptote with increasing σ . More detailed explanation of factors influencing Q-tests

results and of shear strength may be obtained from Means[21] and Hough.[26]

94. The Q-lines for both series of Q-tests were generally of the characteristic shape shown in Figure 42a. The envelopes of the tests on samples remolded at the OMC plus 5 percent were much flatter and reflected lower τ than the samples remolded at the OMC minus 5 percent. The explanation for this is uncertain; the higher shear strength might be attributed either to incomplete sample saturation or to negative pore pressures.

95. The range of τ versus σ is shown in Figure 41b and 41c for the two sets of Q-tests, and the values of c and ϕ are shown in Table 9. These shear strength parameters were determined for the low range of σ using the method set forth in EM 1110-2-1902.[27] This method, which involves the construction of a linear approximation to the strength envelope in the stress range desired, is illustrated in Figure 42c.

Compressibility of Compacted Dredged Material

96. Compressibility, the susceptibility of a material to volume reduction under load, is an important consideration in the evaluation of the engineering properties of dredged material. Compressibility determines the nature and rate of consolidation and settlement, which must be studied carefully before load is applied. The compressibility of dredged material can be estimated from other physical properties, but is best evaluated by means of the consolidation tests.

97. Consolidation is the process of volume reduction under compressive pressure. The consolidation of a sample of saturated soil involves the expulsion of pore water and a corresponding void reduction. In the case of partially saturated soil, the air occupying the void spaces is dissolved in the pore water or squeezed out of the soil mass, and then the pore water is expelled. The consolidation process is divided into two processes: primary consolidation and secondary consolidation. A load applied to a saturated soil specimen is initially borne by the pore water, which is incompressible compared to the soil

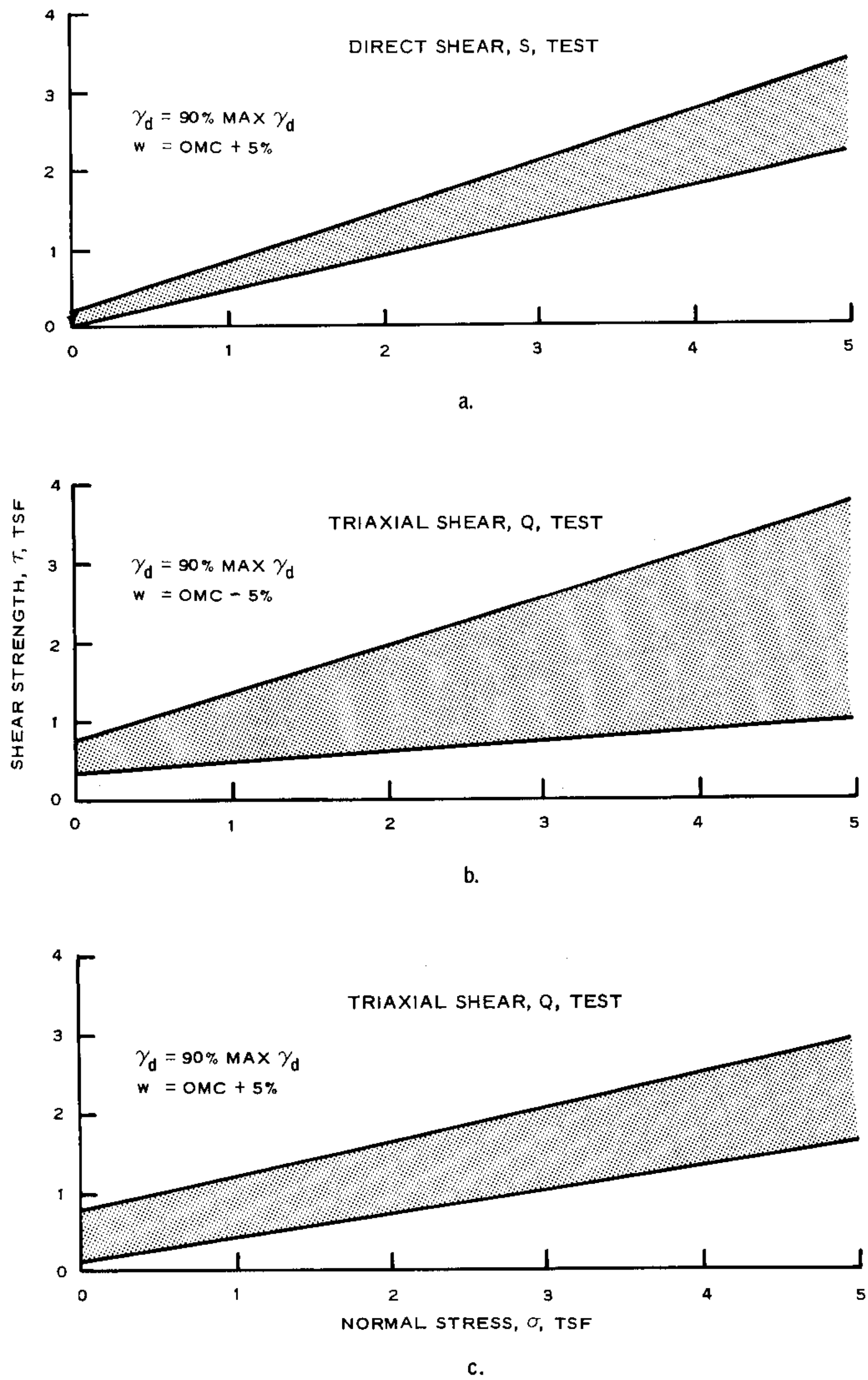


Figure 41. Range of shear strength versus normal stress for 10 compacted samples of dredged material

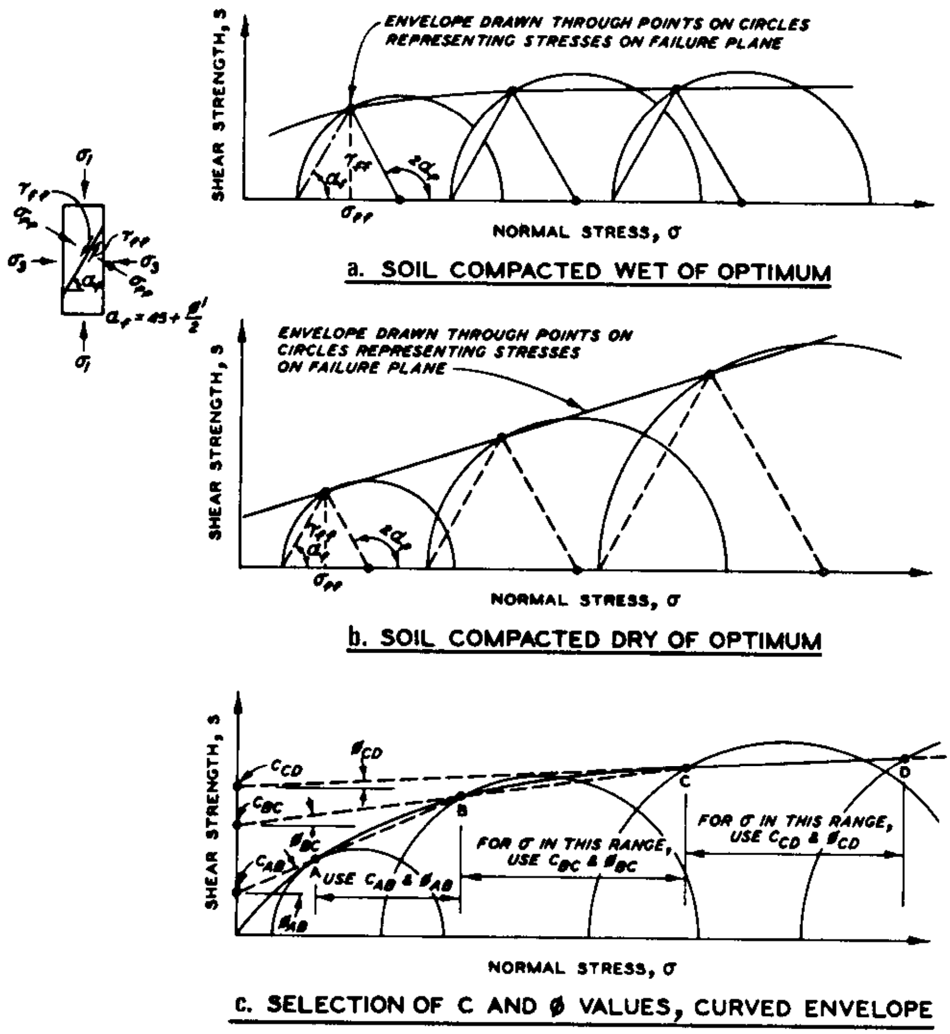


Figure 42. Construction of failure envelopes[27]

structure. As the water is squeezed from the pore spaces, the load is shifted to the soil structure. This expulsion of pore water with corresponding void reduction constitutes primary consolidation. The transfer of load to the soil structure causes further reduction in void spaces by plastic flow and rearrangement of particles. This latter void reduction is called secondary consolidation.

Sample preparation

98. Since simulation of anticipated field conditions was desired, specimens of dredged material were compacted to 90 percent of the maximum γ_d at a water content 5 percent higher than the OMC. The samples were from 67 to 98 percent saturated prior to testing.

Test results

99. Ten samples obtained during this study were subjected to the consolidation tests. In addition, the void ratio-pressure plots of four consolidation tests conducted for the San Francisco District were used to augment the data.

100. Void ratio-pressure plots. Each consolidation test report includes a semi-log plot of void ratio e against consolidation pressure p. Figure 43 shows the 14 $e\text{-}\log_{10}p$ plots for compacted samples of dredged material. The figure shows a large range of e for any increment of p. This large range of e is an indication of the diversity of test specimens.

101. Compression index. The main objective of a consolidation test is to determine the value of the compression index. This parameter is determined by use of the following equation:

$$Cc = \frac{\Delta e}{\Delta \log_{10} p} \qquad (5)$$

where

Cc = compression index for compacted sample

Δe = the change in void ratio over the pressure increment from p_1 to p_2

$\Delta \log_{10} p = \log_{10} p_2 - \log_{10} p_1$

p_1, p_2 = arbitrary values of consolidation pressures taken along the straight portion of the $e\text{-}\log_{10}p$ plot

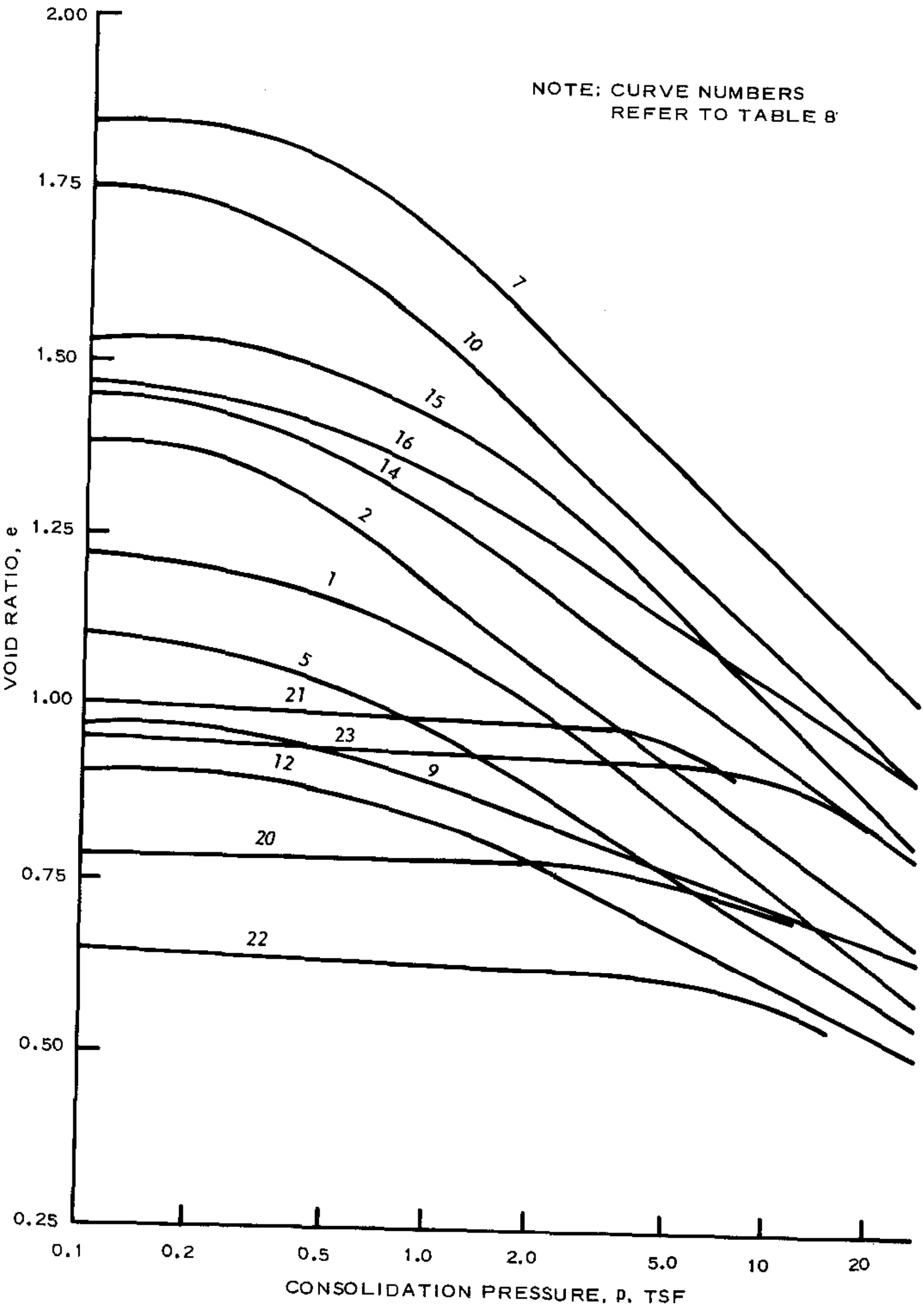


Figure 43. Void ratio versus consolidation pressure for 14 compacted samples of dredged material

The Cc gives an indication of the compressibility of the soil, with increasing values indicative of increasing compressibility. The values of Cc ranged from 0.16 to 0.58 and are listed in Table 10.

102. Skempton[28] determined a correlation between the LL and the compression index of remolded inorganic clay specimens. He stated this relationship mathematically as:

$$Cc' = 0.007(LL - 10) \tag{6}$$

where Cc' = compression index for remolded specimens. Figure 44, on which Skempton's equation is plotted for reference, presents the relationship between the Cc and the LL of the compacted dredged material samples. Two sets of data are plotted on this figure: one set for those samples whose LL was determined in the standard manner and one set for those whose LL was inadvertently determined using dried material. While the dried LL values are considered incorrect, the excellent agreement between these data and those of Skempton is noteworthy. The least-squares line that empirically describes the relation between LL and Cc for the dried material is:

$$Cc = 0.007(LL - 4.8) \tag{7}$$

103. The third line shown in Figure 44 expresses the relationship between the LL and Cc of nine samples whose LL's were determined in the standard manner. This relation is stated mathematically as:

$$Cc = 0.002(LL + 103.4) \tag{8}$$

This line is seen to be considerably flatter than that of Skempton,[28] indicating a slower increase in compressibility with increasing LL. The reason for the lack of agreement between the two empirical relationships is probably the difference in sample preparation, since Cc is known to be influenced by initial e. Skempton remolded his samples at the LL, while the dredged material samples were dewatered to water contents well

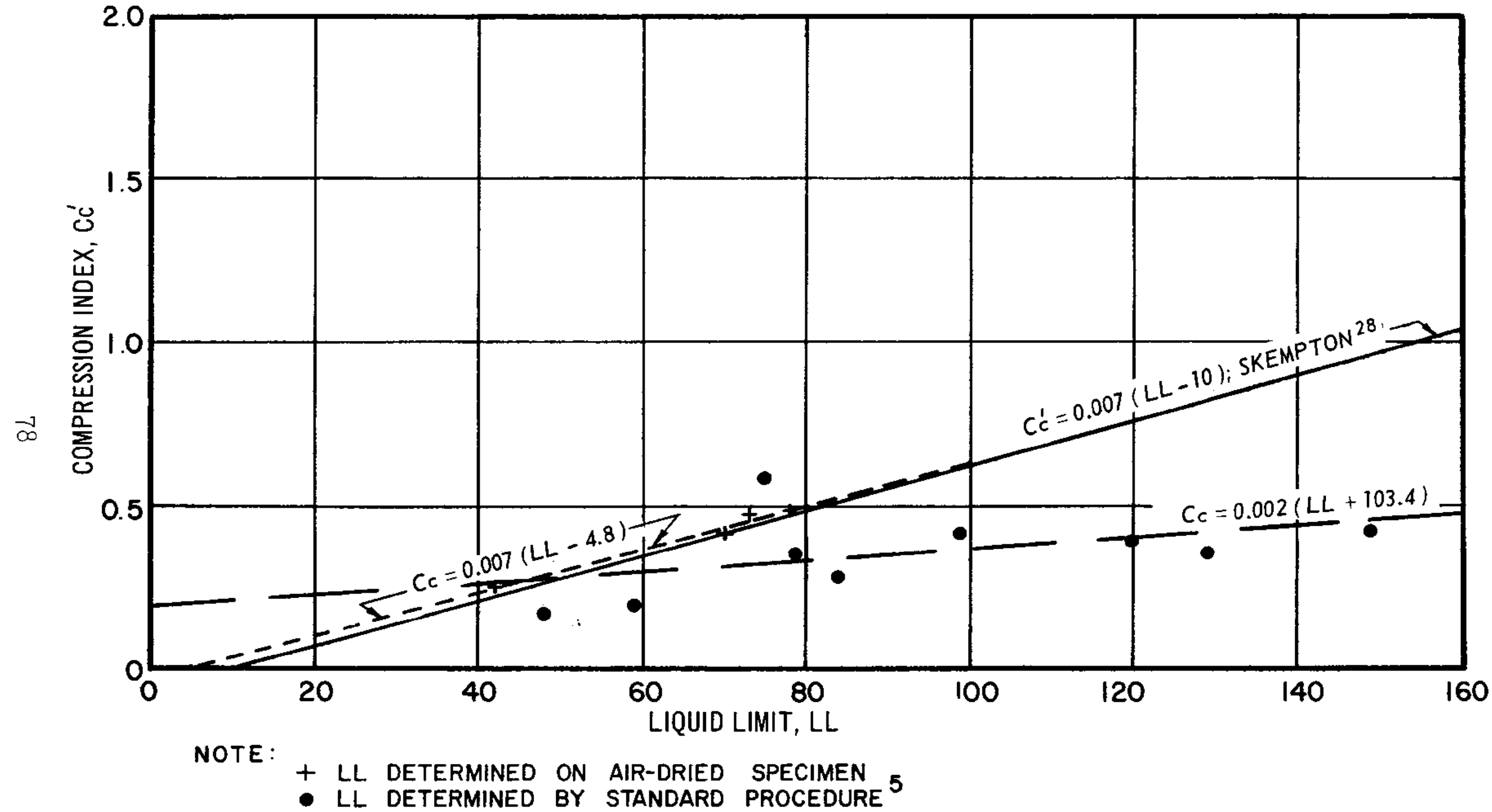


Figure 44. Variation of compression index with liquid limit of compacted samples of fine-grained dredged material

below the LL. Additionally, all samples used by Skempton were clay soils, while samples of dredged material included silty as well as clayey material. Also, nine samples are probably not enough to define the LL-Cc relationship accurately.

104. Coefficient of compressibility. Another parameter whose value was determined from the results of each consolidation test is the coefficient of compressibility a_v defined as the slope of the curve expressing the e-p relationship. Since the e-p relationship was plotted as $\log_{10}p$ versus e, rather than p versus e, a_v values for pressure increments in the straight portion of the e-log p curve were found from Cc by:

$$a_v = \frac{0.435Cc}{p} \qquad (9)$$

where $p = \frac{p_1 + p_2}{2}$, tsf.

105. For pressure increments in which the e-$\log_{10}p$ curve was nonlinear, a_v was determined by the following equation:

$$a_v = -\frac{\Delta e}{\Delta p} \qquad (10)$$

where

$\Delta e = e_2 - e_1$

$\Delta p = p_2 - p_1$, increment of p corresponding to Δe

The range and average values for a_v for each sample are shown in Table 10.

106. Coefficient of consolidation. The coefficient of consolidation c_v, which is a measure of the time rate of settlement and is used to compute the coefficient of permeability, was determined for each increment of pressure of every consolidation test from the following equation:

$$c_v = \frac{0.2H^2}{t_{50}} \qquad (11)$$

where

H = length of drainage path, one-half specimen thickness, ft

t_{50} = time for 50 percent primary consolidation, min

Terzaghi's theory of consolidation assumes that c_v is constant for a given material, but this was not true for samples of dredged material. Table 10 shows the range and average value for c_v for each sample and Figure 45 shows the relationship between c_v and p.

107. Permeability. Darcy's coefficient of permeability k, defined as the discharge velocity through unit area under unit hydraulic gradient, was determined from the results of the consolidation tests by using the following equation:

$$k = \frac{c_v \, a_v \, \gamma_w}{1 + e} \tag{12}$$

where γ_w is the unit weight of water (taken as 62.4 pcf).

108. During this study k was determined for each pressure increment for each sample, at 50 percent of primary consolidation, using Equation 12. The values of k ranged from 0.085×10^{-8} to 41.0×10^{-8} cm/sec. The range and average values of k for each sample are presented in Table 10. In Figure 46, k is plotted against e. As expected, increasing e is generally indicative of increasing k, although there is considerable scatter in the data points for some of the samples.

109. The very low values of k show that the samples of dredged material were impervious for all practical purposes. The values of k reported herein are meaningful only for dredged material that has been dewatered and compacted at water contents near optimum.

Properties of Dredged Material in Confined Disposal Areas

110. During a disposal operation in which hydraulically transported dredged slurry is confined within a disposal area, segregation of particle sizes occurs. Large particles, such as rocks, gravel, and clay chunks, are deposited in a mound near the discharge pipe. Sand is carried slightly farther; fine-grained material remains in suspension for a longer period of time and is deposited nearest the outlet structure.

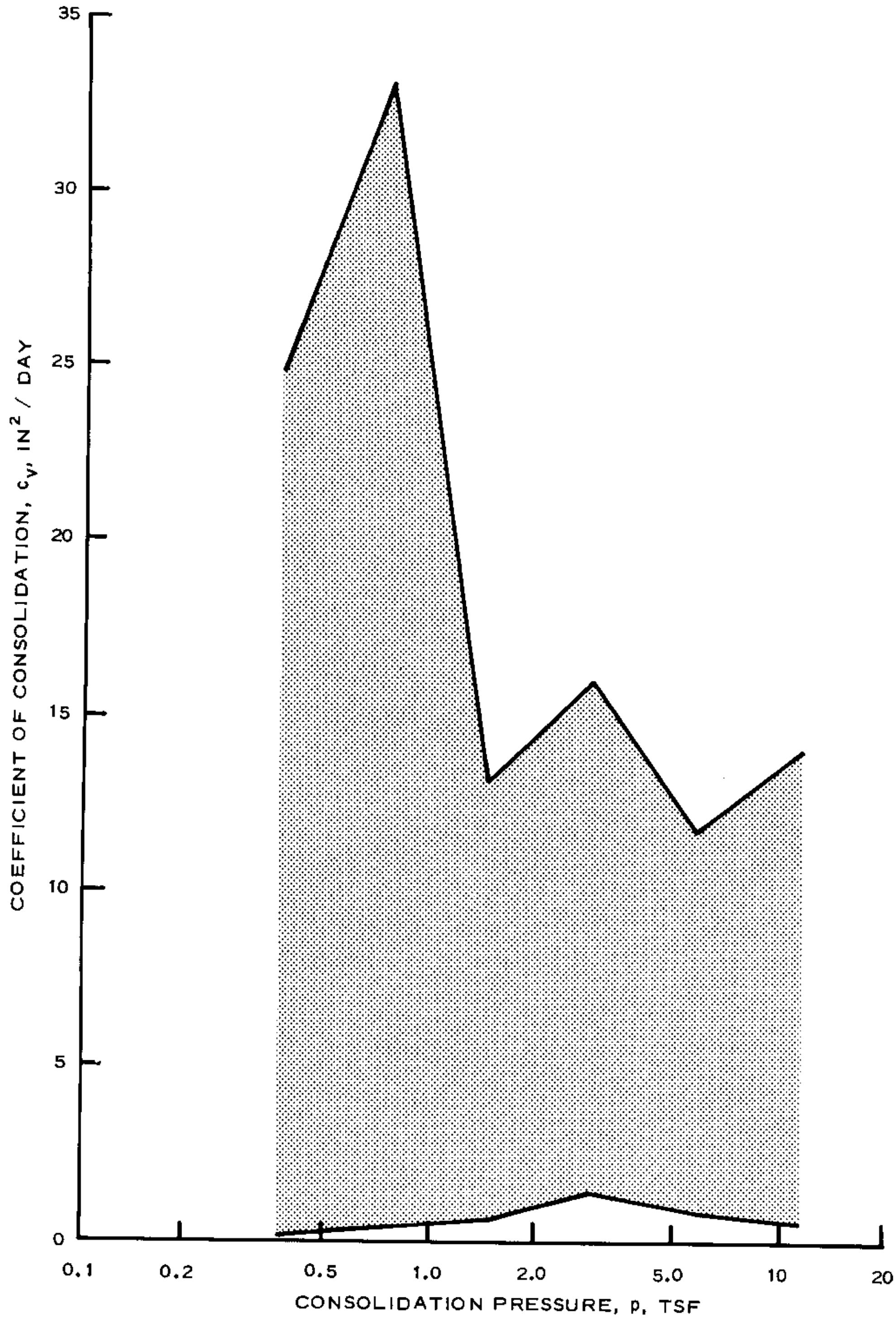


Figure 45. Range of coefficient of consolidation for 10 compacted samples of dredged material

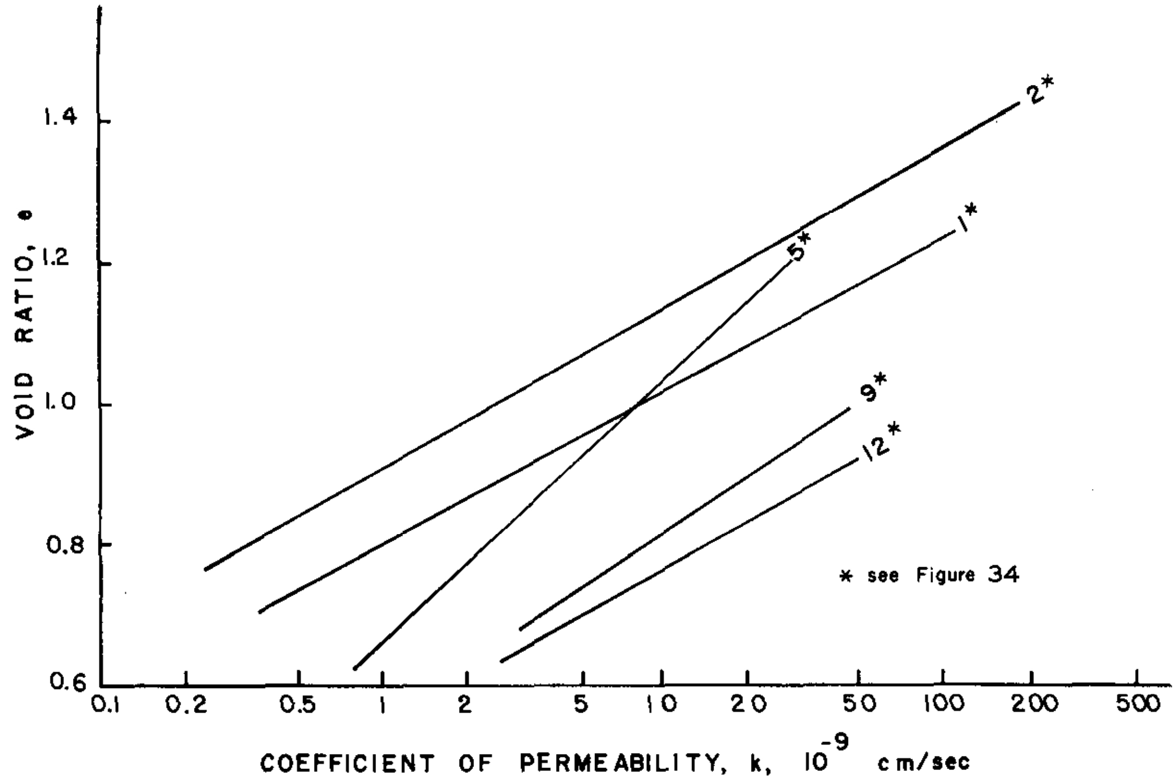


Figure 46. Void ratio versus permeability for five samples of compacted dredged material

111. The coarse and sandy materials deposited near the discharge pipe are generally free draining and exist at relatively low water contents. Suspended silts and clays, however, settle from suspension very slowly to form a deposit of low γ_d and high water content, and remain so for long periods of time, depending on drainage conditions, deposit thickness, vegetation, climate, etc.

112. After ponded surface water has been decanted, desiccation of the surface of the dredged material begins through evaporation, and a crust begins to form. As desiccation progresses, the thickness of the crust increases, and desiccation cracks extending down to the water table appear. These desiccation cracks expose additional area to evaporation as they extend into the deposit and stop near the water table. The water table generally remains at a level just below the surface and is intermittently recharged by rainfall. The underlying dredged material may remain at water contents approaching or exceeding the LL of the

material for years after disposal operations if nothing is done to lower the water table and dewater the dredged material. The location of the water table is now thought to be the important factor in crust management.

113. In the following paragraphs, the properties of dredged material placed in the containment areas, as reported by other investigators, are reviewed. The classification properties for dredged material in 26 different disposal areas are presented, and the engineering properties of the deposits in 12 of these areas are reported. Limited data are presented to show the variation of properties with depth, time, and distance from the discharge pipe.

Classification and engineering properties

114. Table 11 presents a tabulation of the classification and engineering properties of dredged material in confined disposal areas. This table consolidates data published in previous reports, as noted, and presents ranges and average values of a number of dredged material properties. These ranges are presented by disposal area without regard to sample location or depth. Figures 47, 48, and 49 are the plasticity charts for dredged material in 12 containment areas in the Philadelphia (Figure 47), Detroit (Figure 48), and Mobile and Buffalo (Figure 49) Districts.

Variation of properties with depth

115. The change in dredged material properties with depth in a disposal area is important when investigating the area for purpose of utilizing the area productively. The variation of selected properties with depth in each of 12 disposal areas located in the Philadelphia, Detroit, Mobile, and Buffalo Districts is presented below.

116. Philadelphia District. Figures 50-54, showing the variation of properties with depth for five containment areas within the Philadelphia District, were prepared by plotting a number of boring logs on the same figure. The resulting figures show the properties at several different locations throughout each area and how the properties vary with depth. The individual boring logs were originally published by the

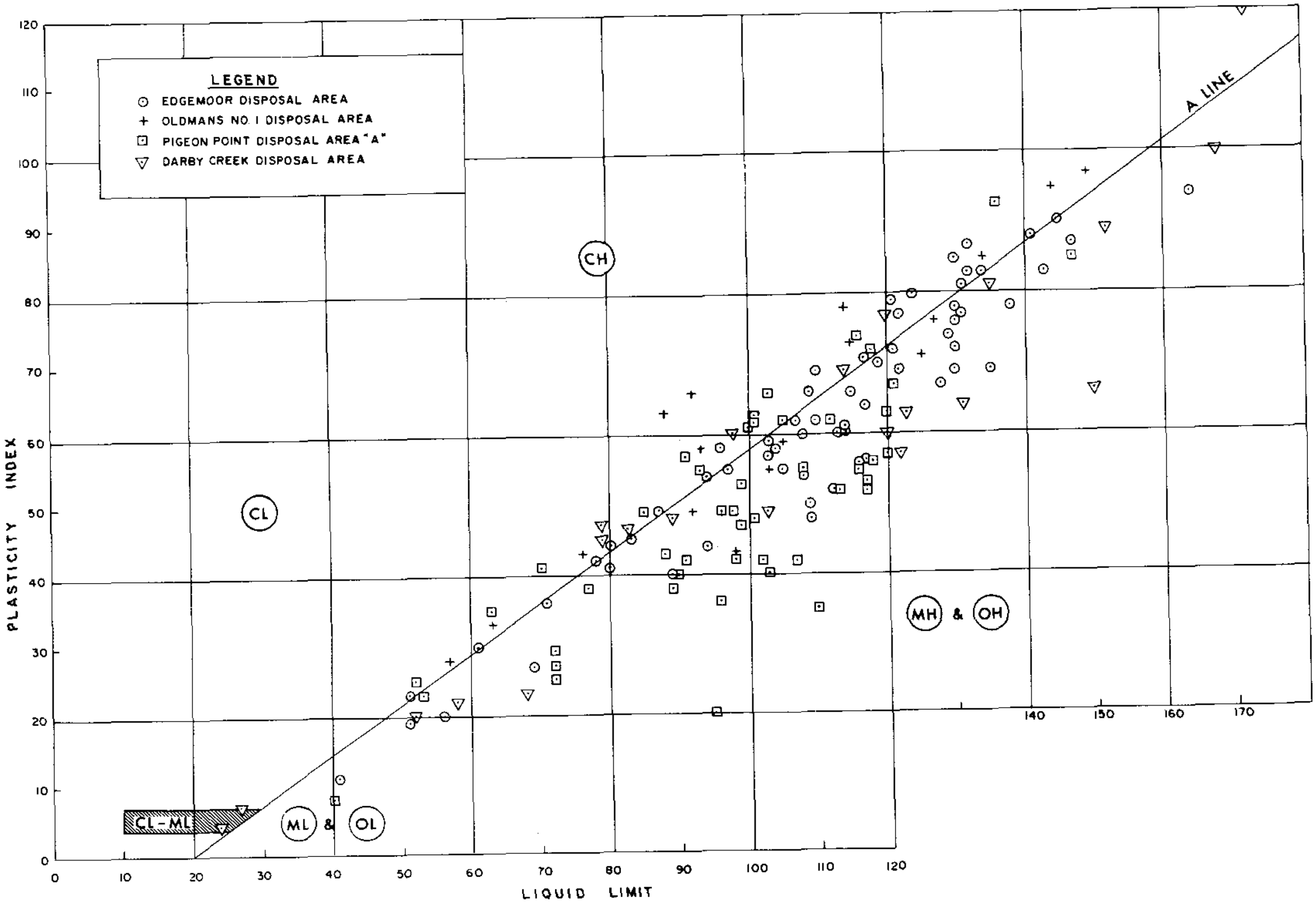


Figure 47. Plasticity chart for dredged material in four containment areas in the Philadelphia District[29]

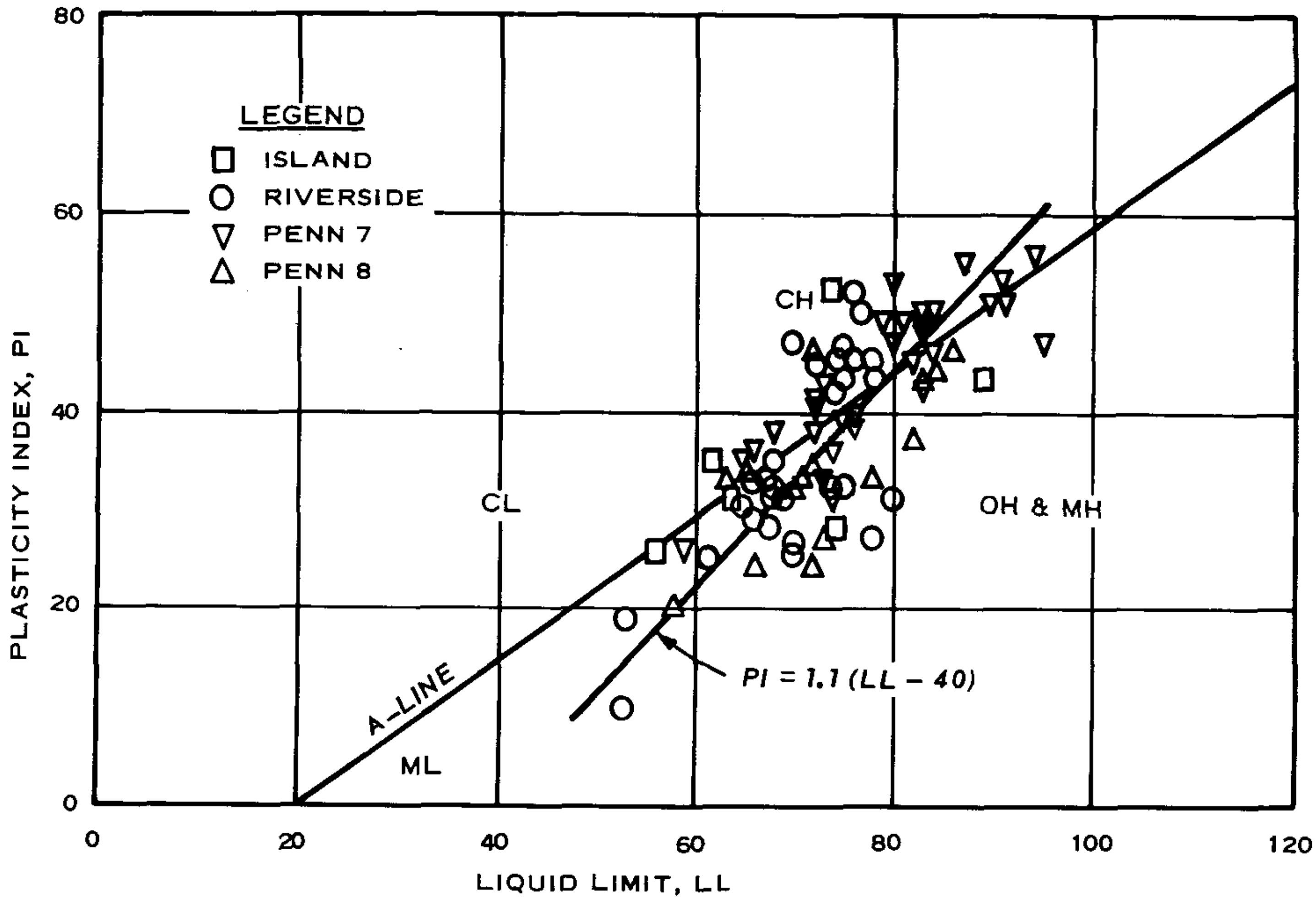


Figure 48. Plasticity chart for dredged material in four containment areas in the Detroit District (from reference 30)

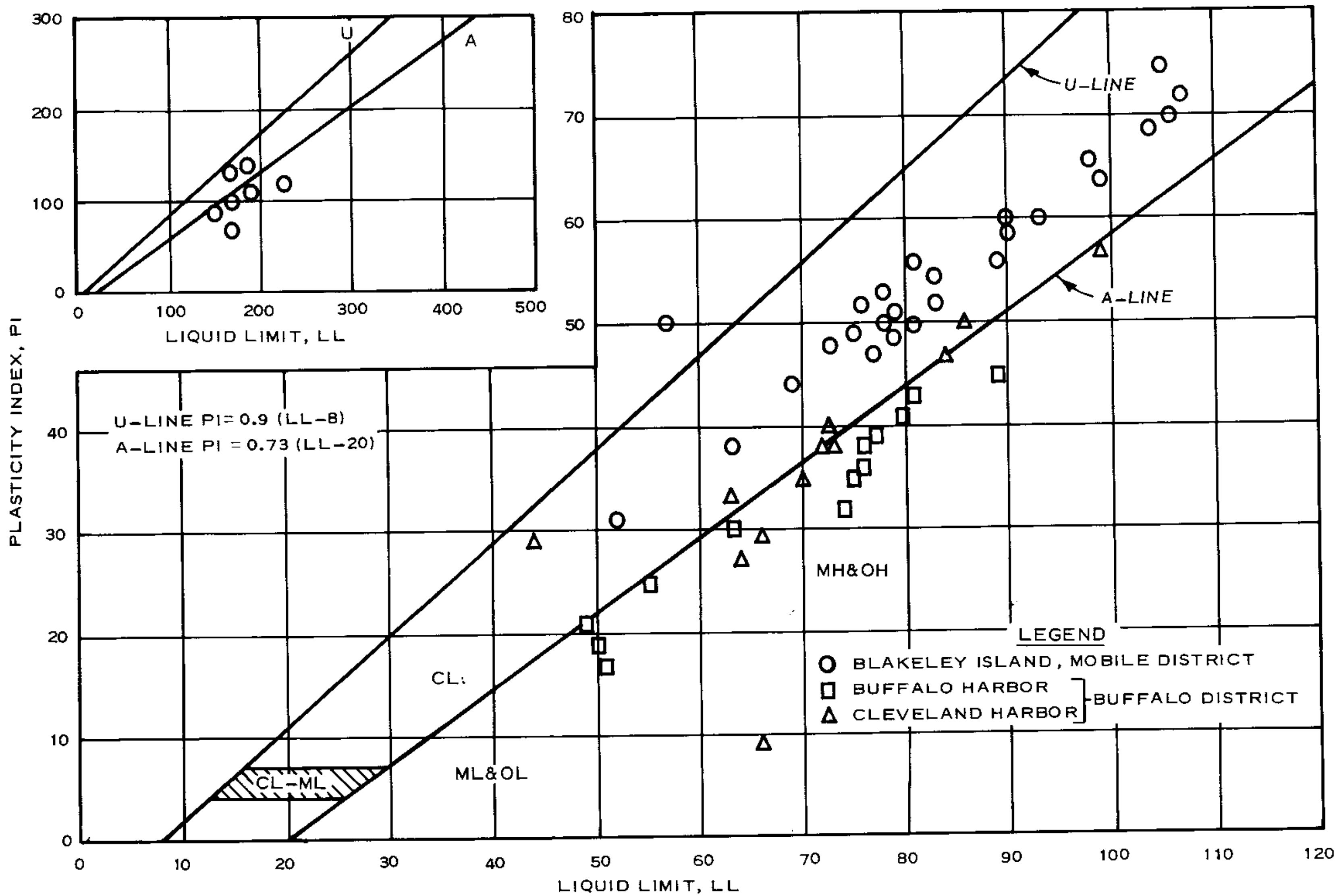


Figure 49. Plasticity chart for dredged material in containment areas in the Mobile and Buffalo Districts

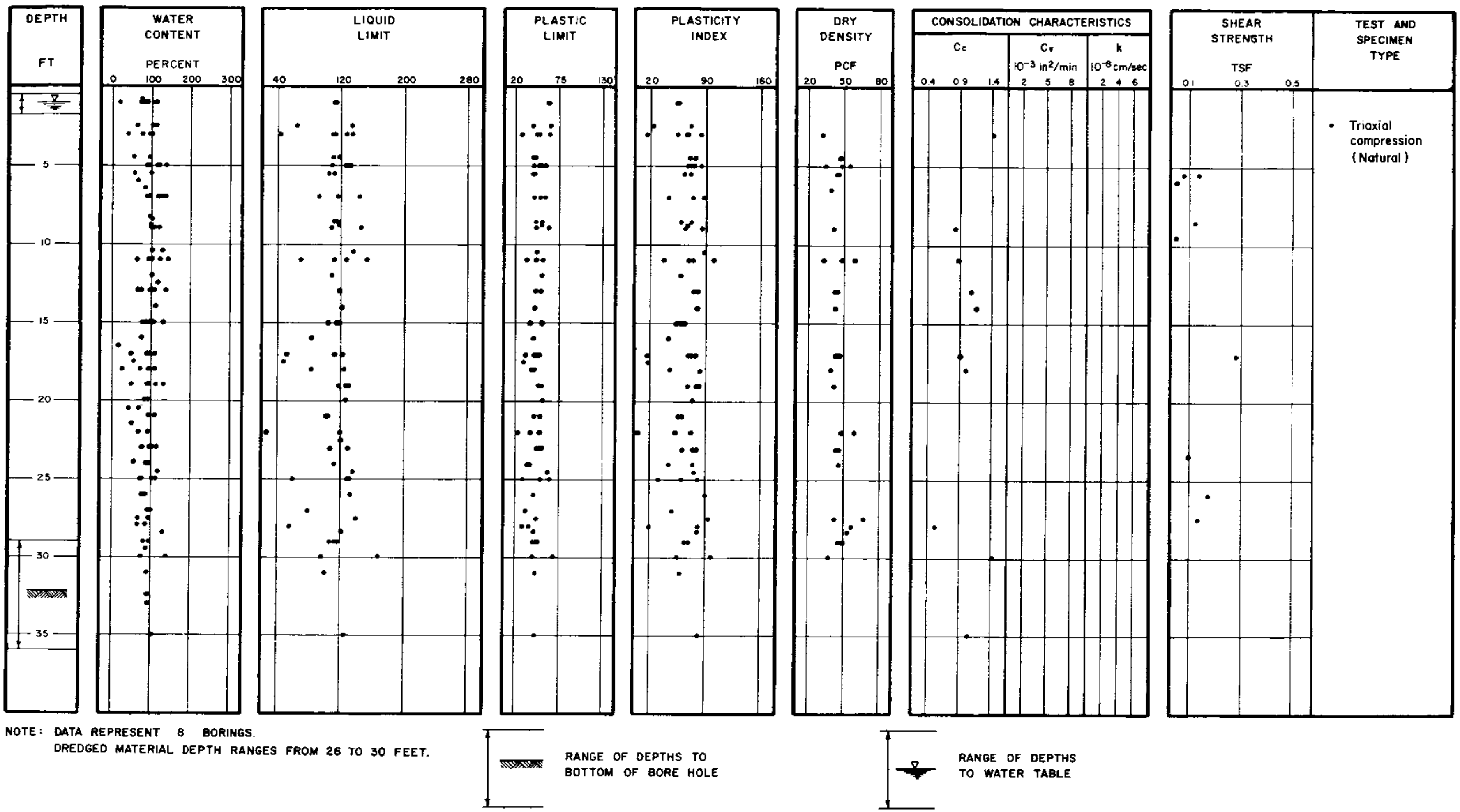


Figure 50. Variation of properties with depth at Edgemoor A disposal area, Philadelphia District

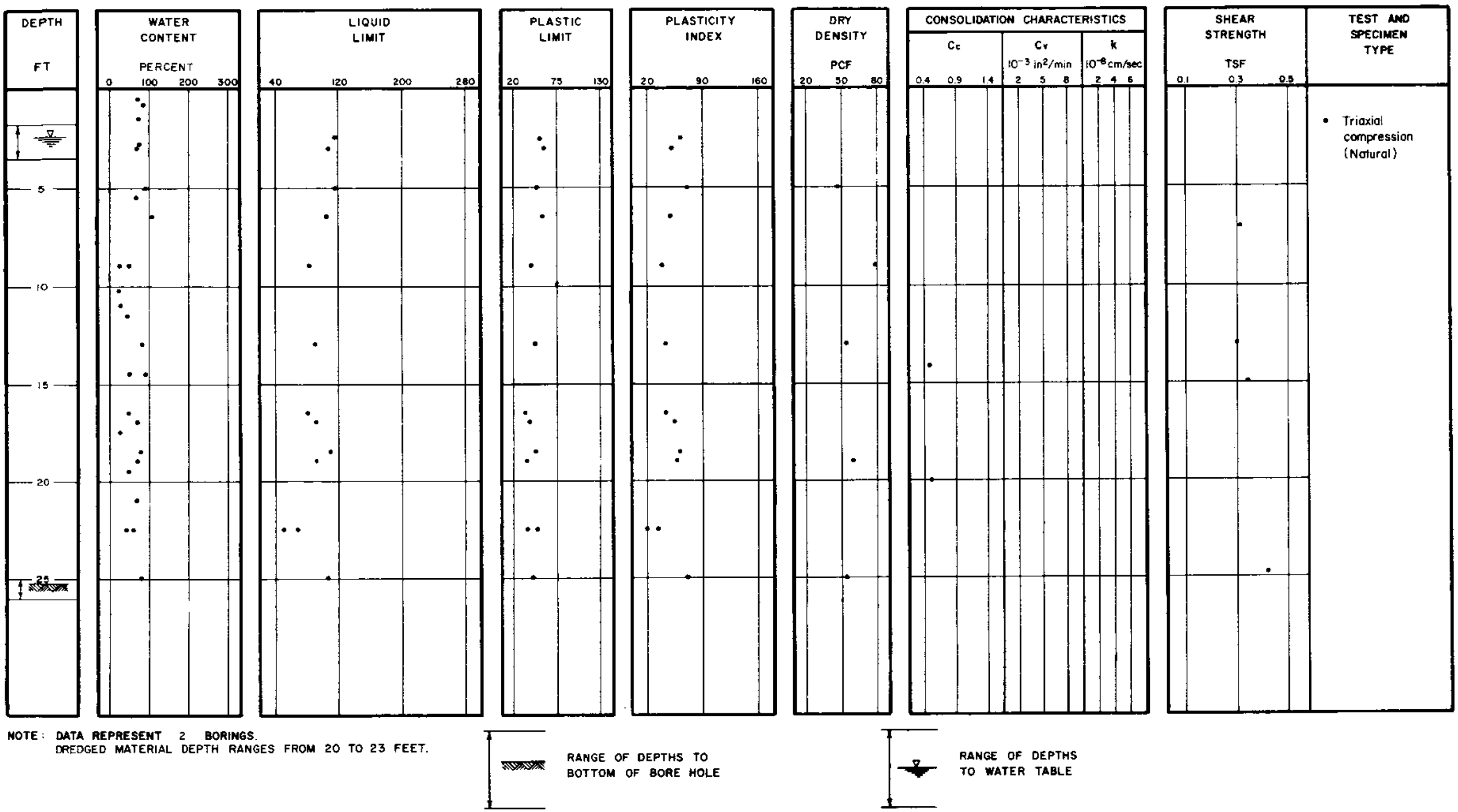


Figure 51. Variation of properties with depth at Edgemoor B disposal area, Philadelphia District

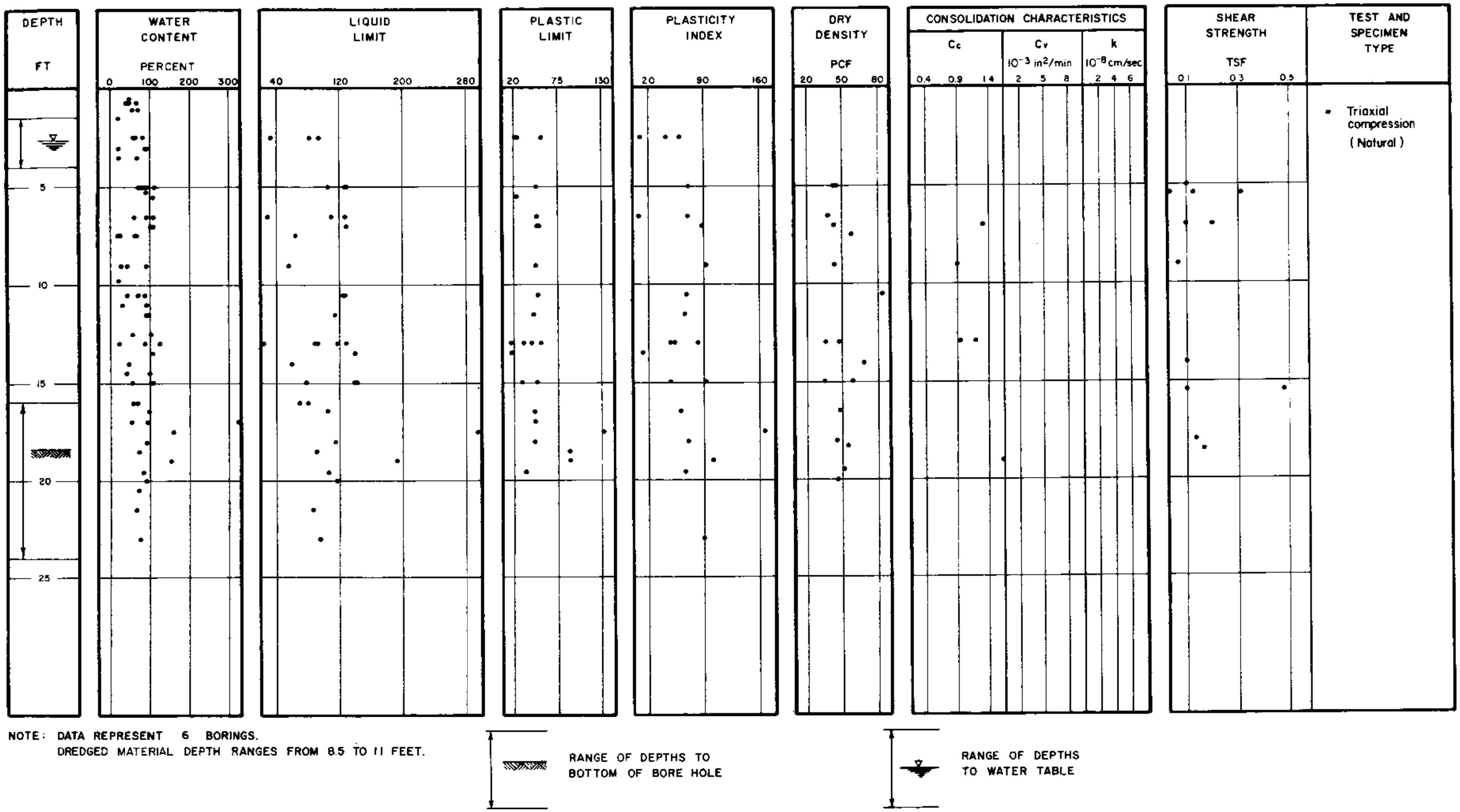


Figure 52. Variation of properties with depth at Oldman's No. 1 disposal area, Philadelphia District

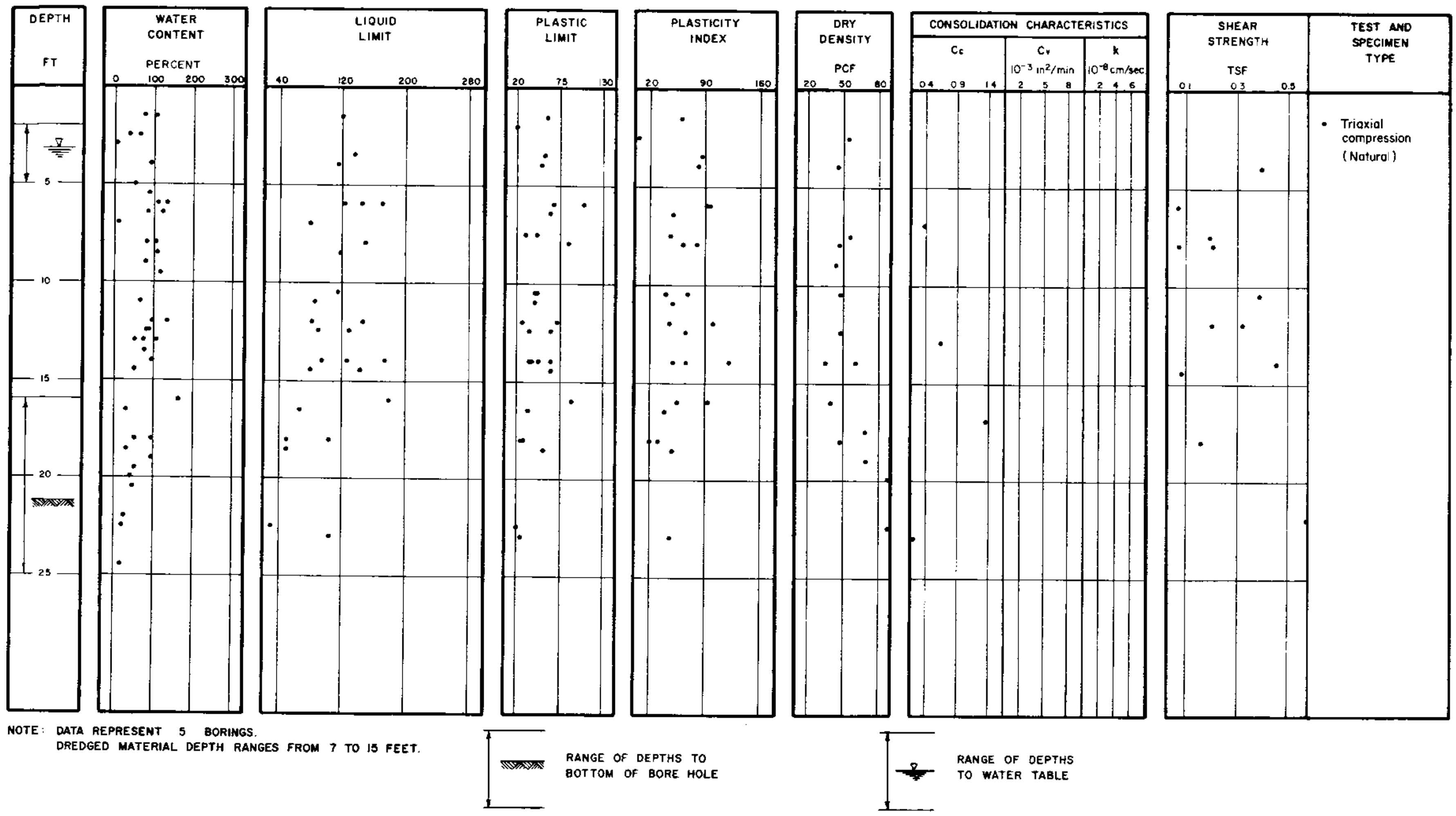


Figure 53. Variation of properties with depth at Darby Creek disposal area, Philadelphia District

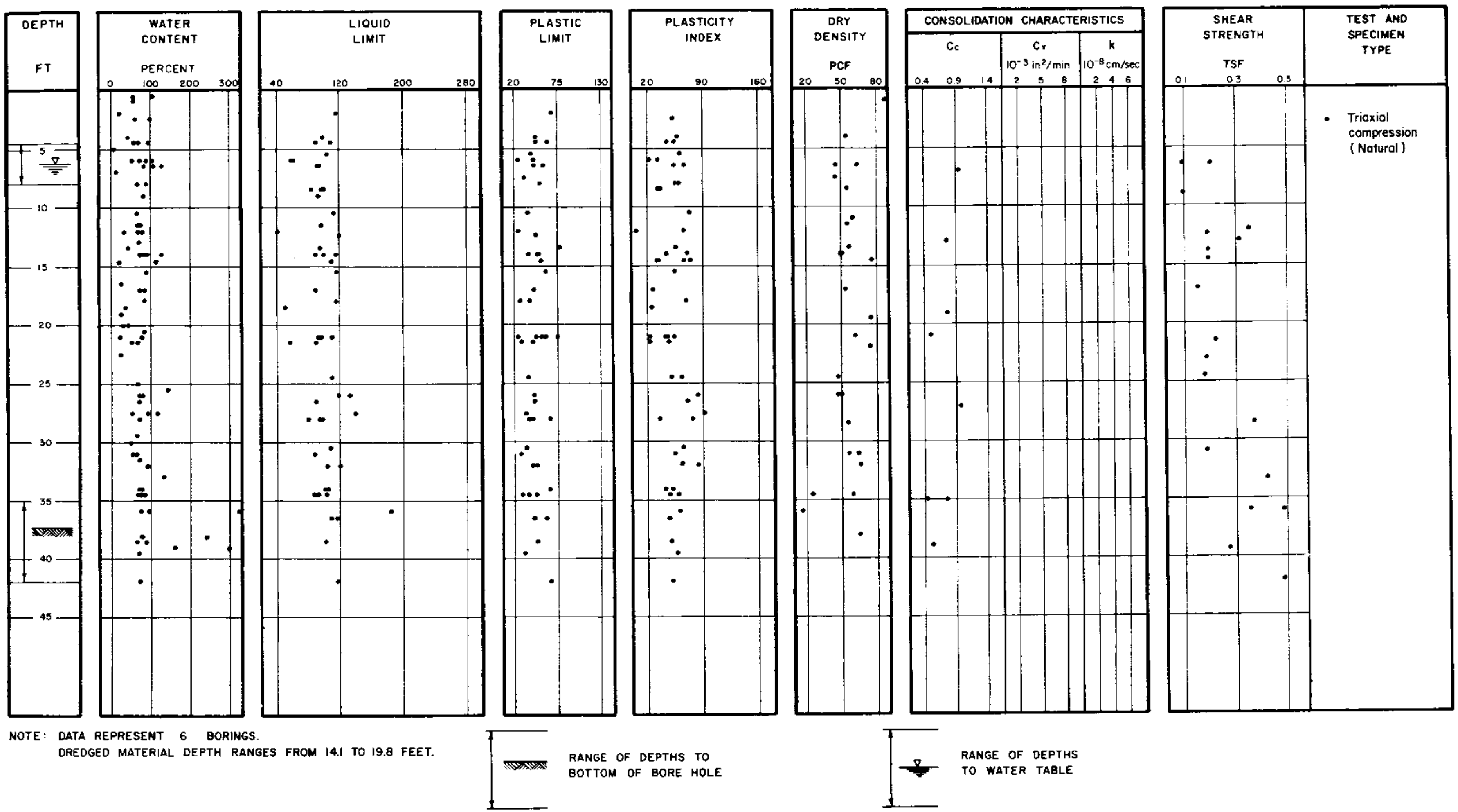


Figure 54. Variation of properties with depth at Pigeon Point disposal area, Philadelphia District

Philadelphia District. A description and history of each of the areas is also presented in Reference 29.

117. At Edgemoor A, last used in 1965, the water table is very close to the surface. Figure 50 shows that eight borings were taken at this area and that the water table at every location was within 2 ft of the surface. Properties are variable throughout the area and show no dependence on depth. A comparison of water content with LL shows that the dredged material in Edgemoor A disposal area existed at approximately the LL at the time the borings were tested (1967).

118. Edgemoor B, last used in 1958, also has a high water table, though somewhat lower than that of Edgemoor A. Only two borings were taken at this area, insufficient for a reasonable picture of the material contained therein. No clear-cut dependence of properties on depth is seen in Figure 51. The water content of the dredged material is somewhat lower than the LL. The material appears to exist at a water content somewhere in the plastic range between the PL and LL.

119. Six borings taken at Oldman's No. 1 disposal area, last used in 1962, have been plotted in Figure 52. As in the case of Edgemoor A and Edgemoor B, a high water table exists at this area and no variation of properties with depth is obvious.

120. Figure 53 shows the logs of five boreholes made at Darby Creek disposal area, which was last used in 1966. The water table is seen to be within 5 ft of the surface. The water content of the foundation strata is somewhat lower than that of the overlying dredged material. Corresponding to lower water content at greater depth, γ_d is greater in the foundation strata. No further dependence on depth is noticeable.

121. At Pigeon Point, last used in 1966, the water table is lower than in the other areas, between 5 and 8 ft from the surface for the six borings shown in Figure 54. No variation of properties is seen to be dependent on depth.

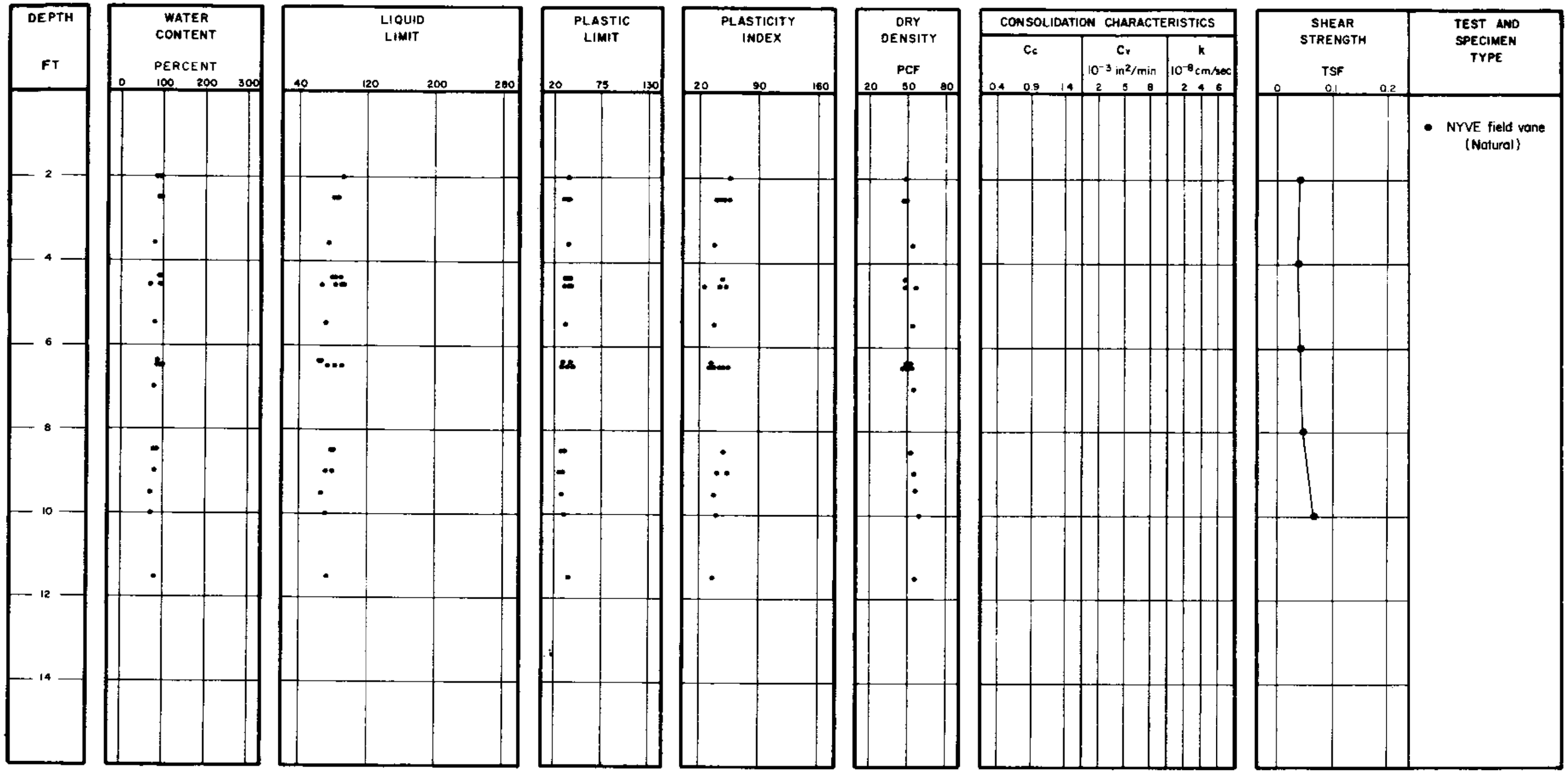
122. Detroit District. Krizek[7,30] has done considerable sampling and testing of dredged material. Four disposal sites located in Toledo Harbor have been investigated, and the resulting data are presented

herein. Individual boring logs, showing properties versus depth, have been grouped together by disposal area in Figures 55 through 58. The individual logs originally appeared in work by Krizek.[7,30] Krizek used several combinations of specimen and test types for determining the strength of dredged material. Only a few profiles, one boring per area, are presented here because the large number of data points would be confusing if plotted simultaneously. Material was deposited in each of these four containment areas in 1974, the same year as samples were taken.

123. Figure 55 shows the variation of dredged material properties with depth at the Penn 7 disposal area. Water content, LL, and PL seem fairly constant with depth, with water content decreasing very slightly. The water content of the dredged material is generally within the plastic range indicated for the material. Dry density shows a slight increase with depth. Vane shear strength of in situ material also increases with depth, though all determinations show very weak material.

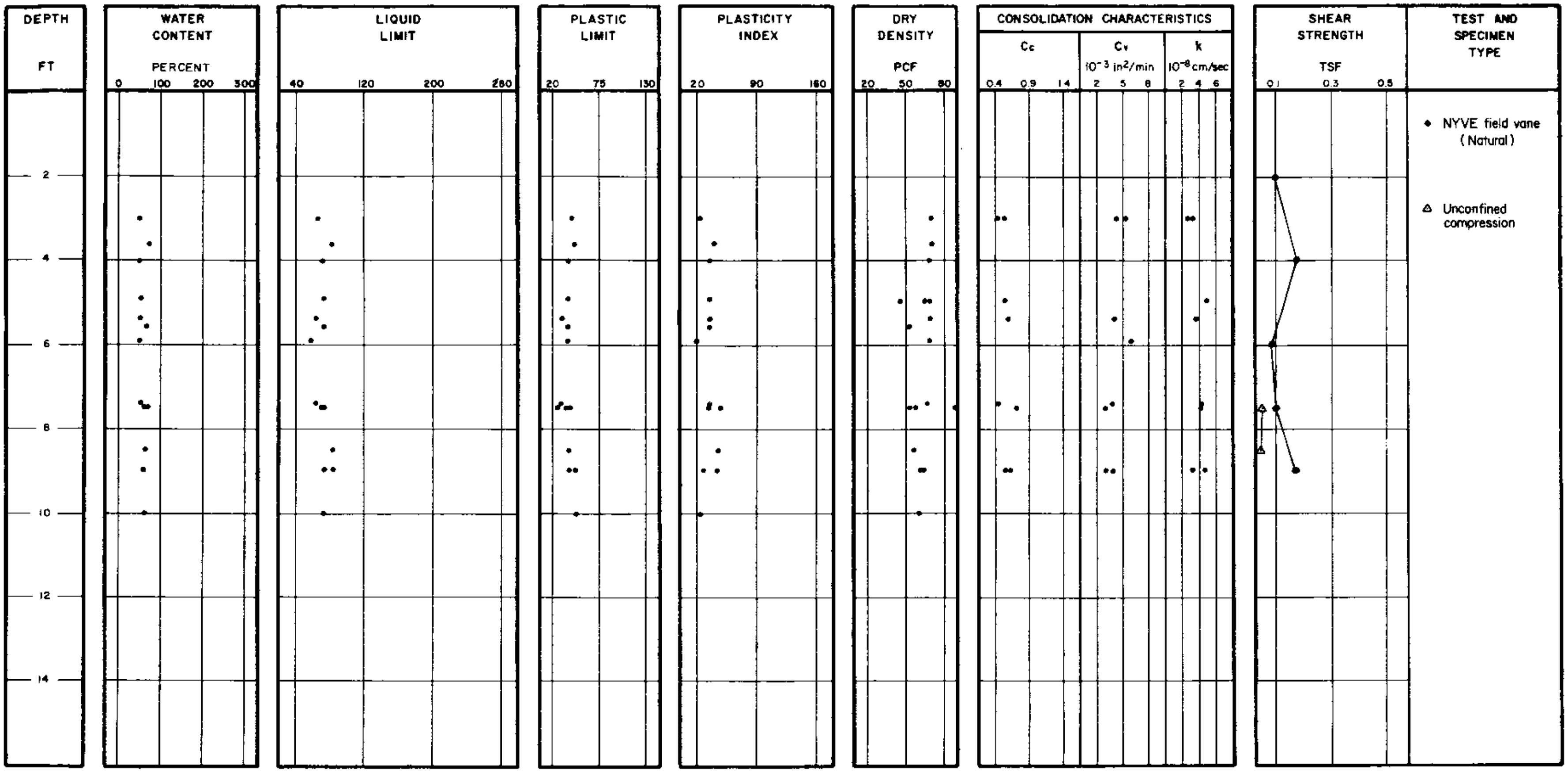
124. Data from four borings taken at Penn 8 disposal area are shown in Figure 56. Water content, LL, and PL are fairly constant throughout. There is considerable scatter in γ_d , but values are independent of depth. Shear strengths, as determined by field vane, exhibit a variation with depth. Strength near the surface is low and increases until a depth of 4 ft. Below 4 ft strength decreases, then increases toward the bottom of the boring. This characteristic strength profile shape also resulted when some of the other types of strength tests were performed, as seen in the profiles presented in Krizek.[30] The individual profiles also show a large variation in strength, dependent upon the type test and type specimen.

125. Figure 57 shows the data from two borings at the Island site in Toledo Harbor. Based on these data, a gradual increase in γ_d and corresponding decrease in water content with depth are seen. The NYVE field vane strength profile exhibits the same characteristic strength profile as that of Penn 8 (Figure 57). Other test and specimen types show other profile shapes, however, and there is variation in properties according to test and specimen type.



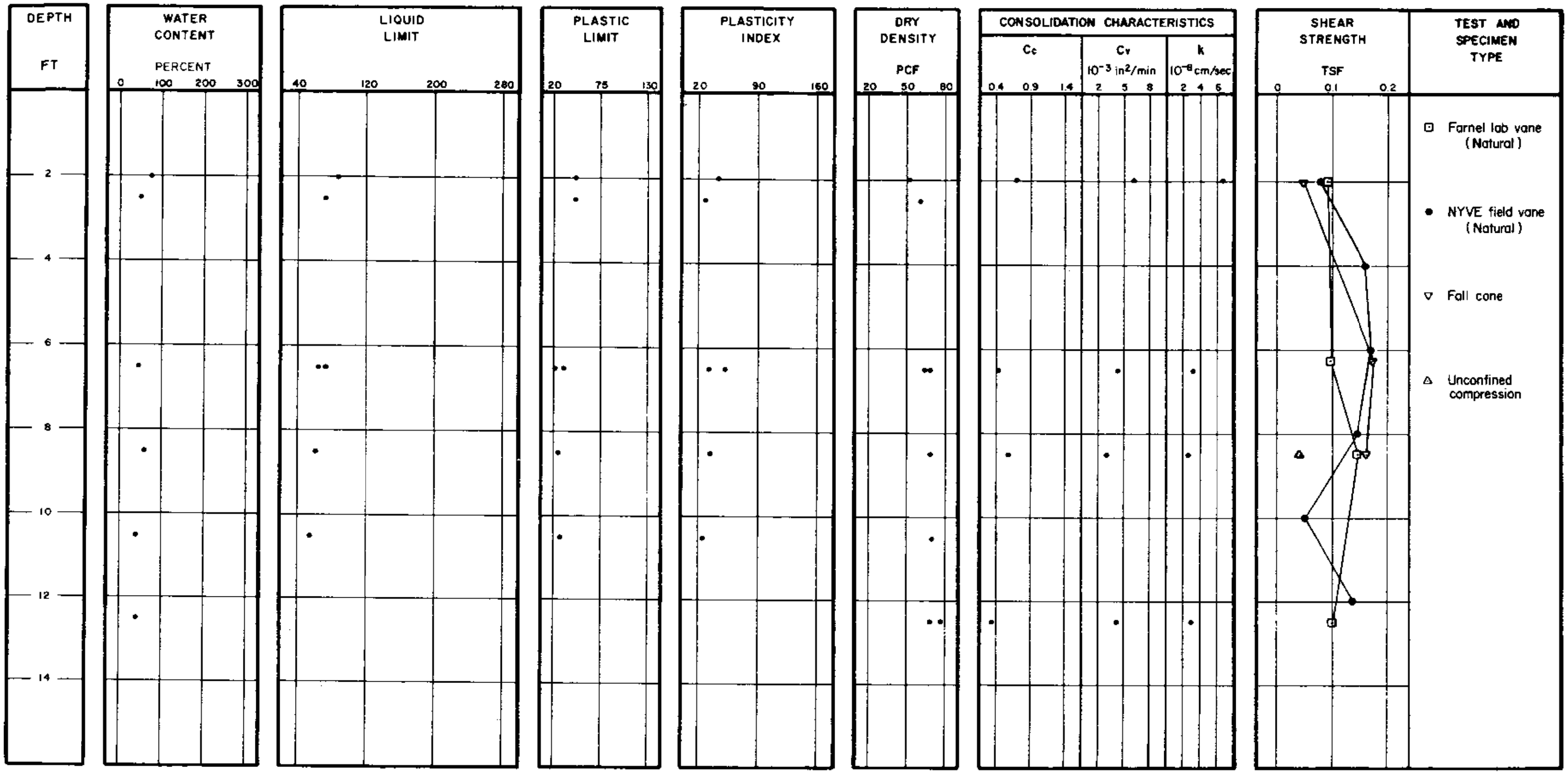
NOTE: DATA REPRESENT 9 BORINGS.

Figure 55. Variation of properties with depth at Penn 7 disposal area, Toledo Harbor, Detroit District



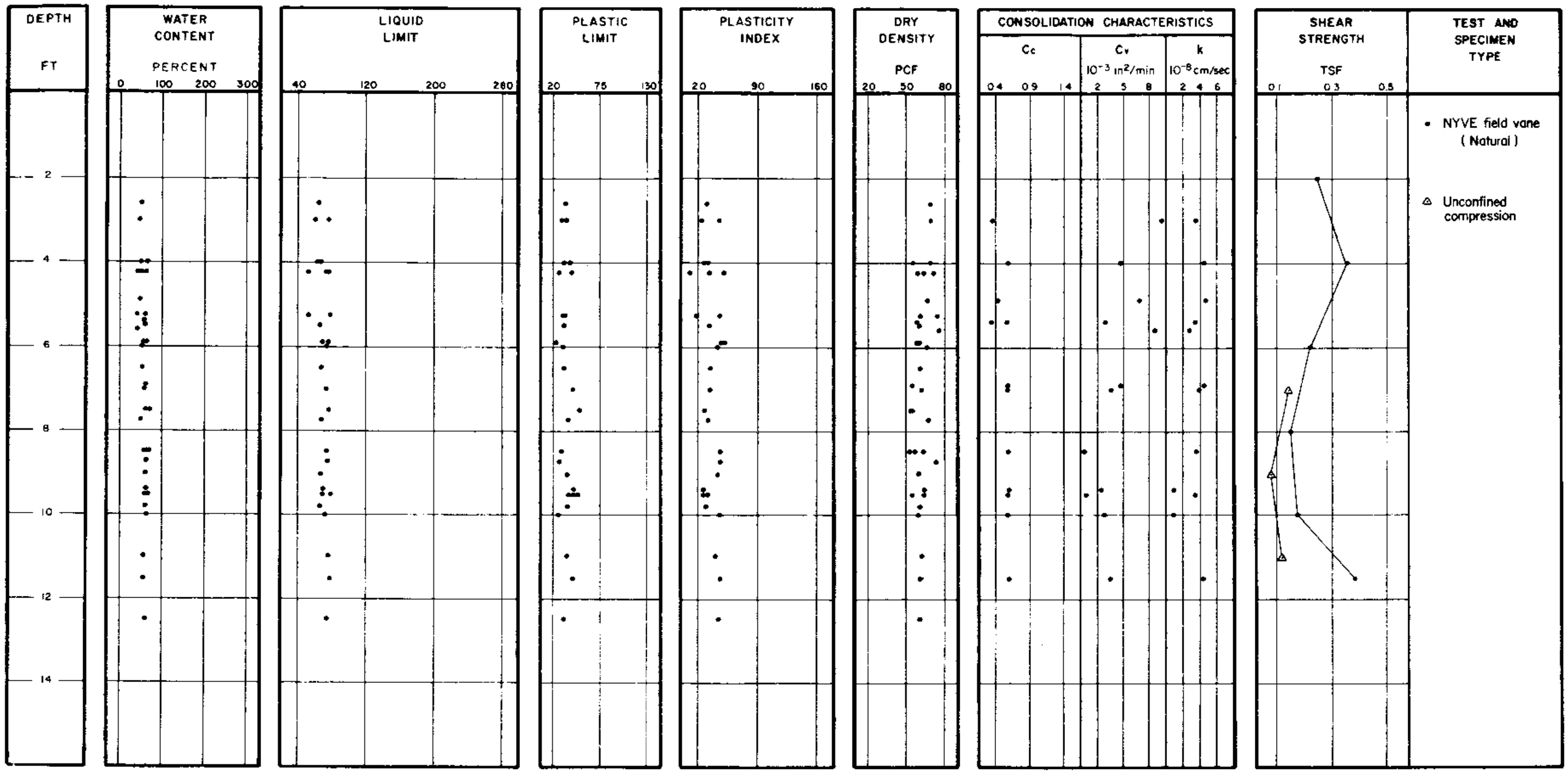
NOTE: DATA REPRESENT 4 BORINGS.

Figure 56. Variation of properties with depth at Penn 8 disposal area, Toledo Harbor, Detroit District



NOTE: DATA REPRESENT 2 BORINGS.

Figure 57. Variation of properties with depth at Island disposal area, Toledo Harbor, Detroit District



NOTE: DATA REPRESENT 13 BORINGS.

Figure 58. Variation of properties with depth at Riverside disposal area, Toledo Harbor, Detroit District

126. There was excellent coverage of the Riverside site, with the logs of 13 borings included in Figure 58. Water content, LL, and PL are fairly constant with depth. Dry density, ranging between 50 and 80 pcf, is also fairly independent of depth, although upper strata appear to be of higher γ_d than lower strata. The field vane strength profile has the same characteristic shape as those of Island and Penn 8. The unconfined compression tests yielded a similar shape but at a lower strength level.

127. Mobile District. An extensive laboratory testing program was conducted as part of another DMRP study to evaluate the dredged material in the upper disposal area on Blakeley Island. This testing program was conducted as part of an investigation of field trenching as a technique for dewatering and densifying fine-grained dredged material. Twenty-five borings were taken, with samples at 2.5-ft intervals tested. In general, water content, LL, and PL decreased with depth until approximately 8 ft, increasing with increasing depth thereafter (Figure 59). At the 8-ft depth water contents are generally higher than the LL, indicating a very weak consistency. The reversal in trend in attributed to the very weak foundation material, which is highly organic and has a high water content. Dry density increased in the dredged material and decreased in the foundation. The foundation is also more compressible than the dredged material. Shear strength seems to increase with depth, even through the foundation, which is of lower γ_d .

128. Buffalo District. Data from subsurface investigations at disposal areas in Buffalo Harbor and Cleveland Harbor were provided by the Buffalo District. These data have been plotted as properties versus depth in Figure 60 (Buffalo Harbor Area No. 1) and in Figure 61 (Cleveland Harbor Area No. 1). In Buffalo Harbor Area No. 1 water content, LL, PL, and γ_d all seem to be variable, but there are no clear indications of dependence on depth. There seems to be a tendency toward lower water content and higher γ_d with increasing depth, but the trend is not well pronounced. No trends of dependence of properties with depth are evident from the data presented in Figure 61, Cleveland Harbor Area No. 1.

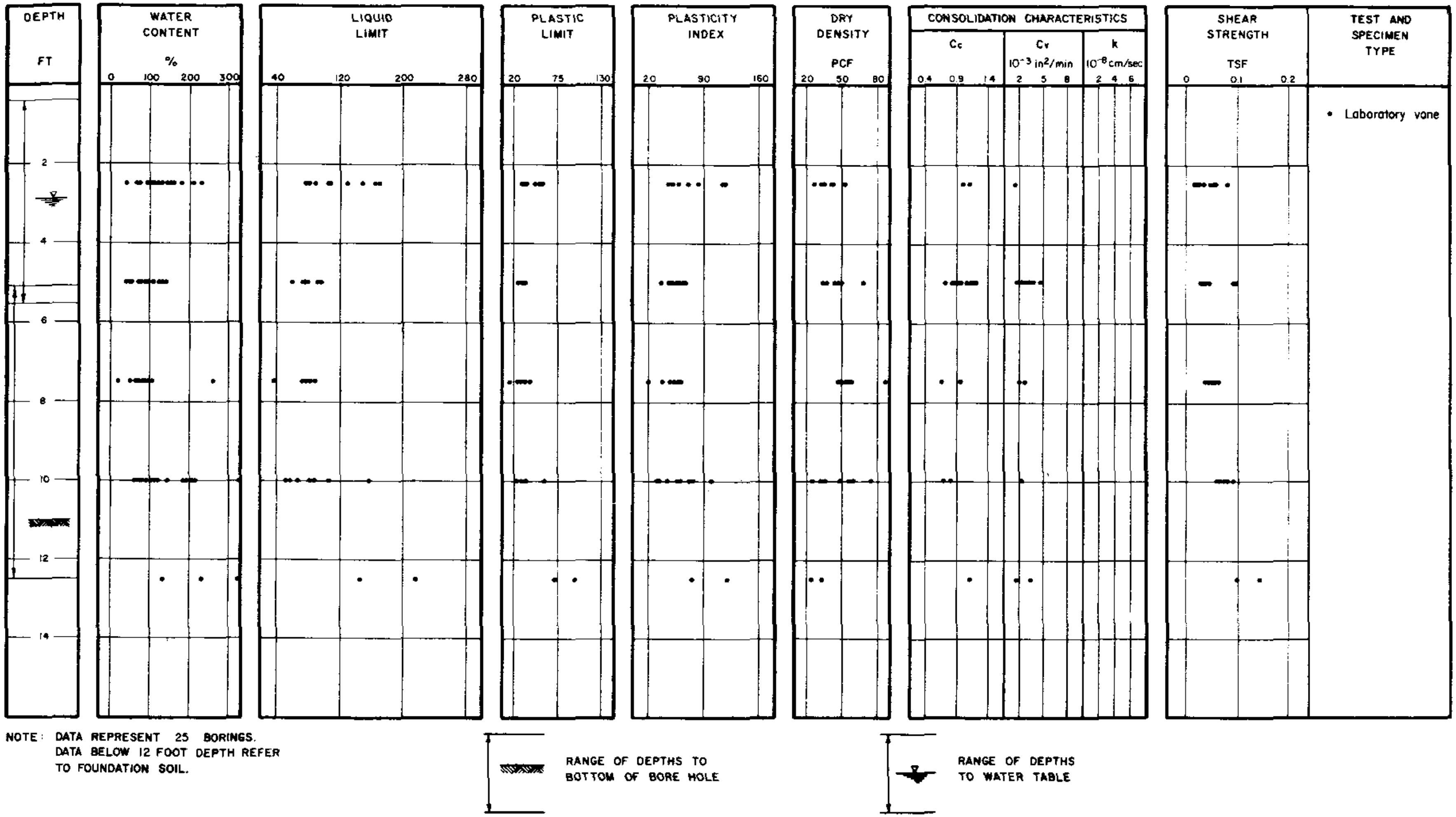
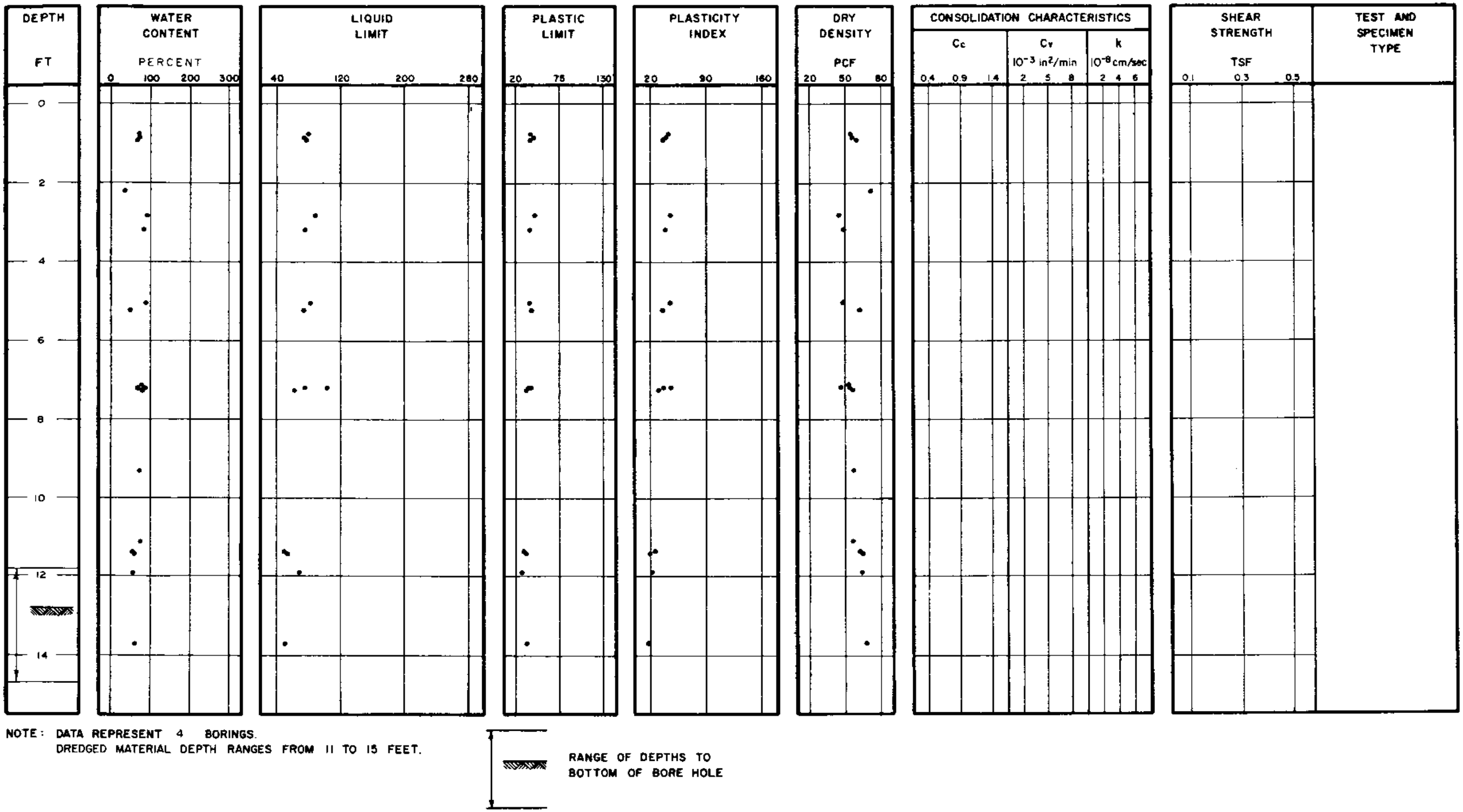


Figure 59. Variation of properties with depth at Blakeley Island upper disposal site, Mobile District



NOTE: DATA REPRESENT 4 BORINGS.
DREDGED MATERIAL DEPTH RANGES FROM 11 TO 15 FEET.

RANGE OF DEPTHS TO BOTTOM OF BORE HOLE

Figure 60. Variation of properties with depth at Disposal Area No. 1, Buffalo Harbor, Buffalo District

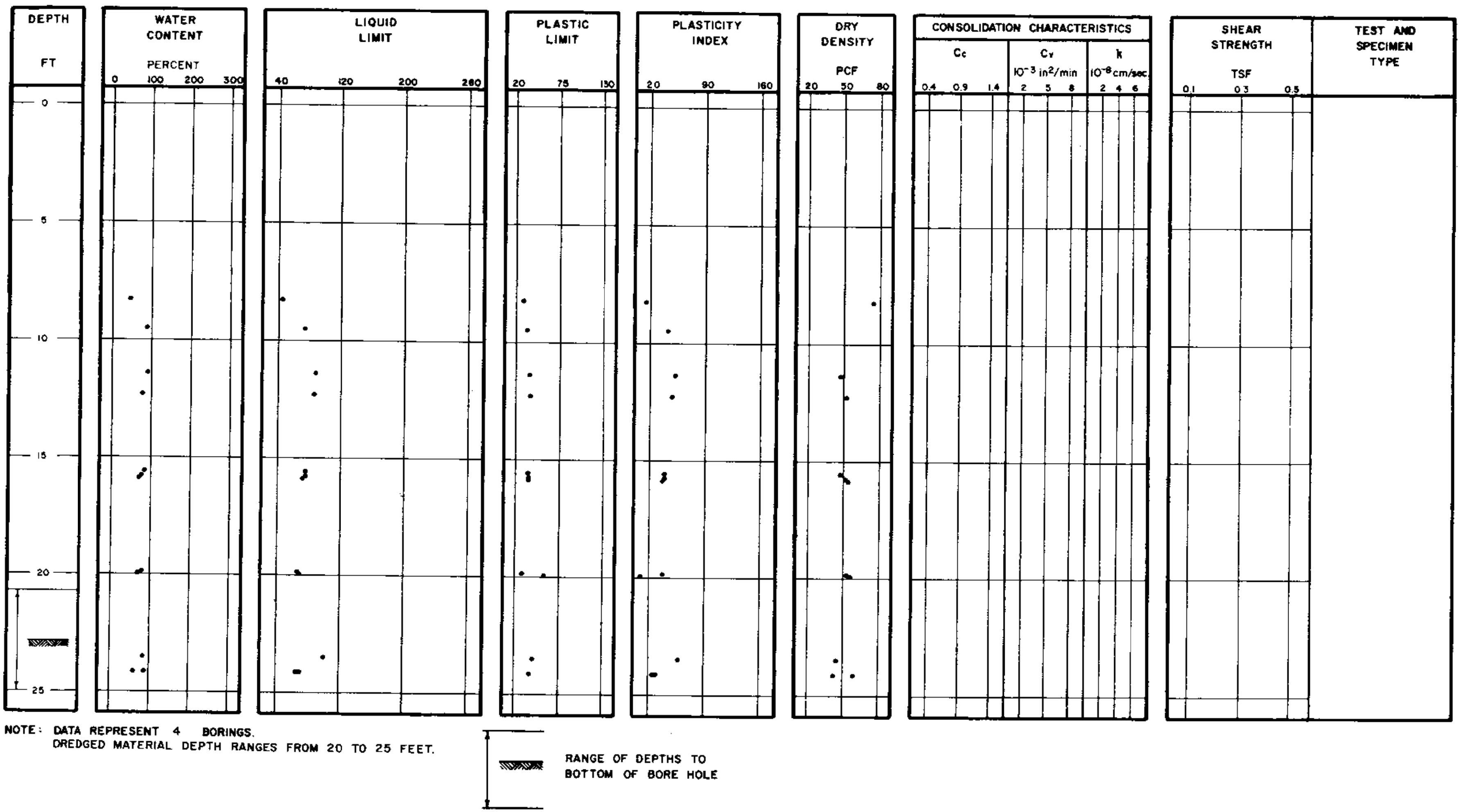


Figure 61. Variation of properties with depth at Disposal Area No. 1, Cleveland Harbor, Buffalo District

Variation of properties with time

129. After surface water has been decanted from a disposal area, the dredged material exists therein with a high water content and generally a low γ_d . As time passes, the deposit slowly densifies. If surface drainage is provided and the groundwater table is lowered, the dredged material improves rapidly. Krizek[30] analyzed the time rate of increase in γ_d of the dredged material in four disposal areas at Toledo Harbor. He found that for a time period between 1 and 8 years the data could be approximated by a straight line, as shown in Figure 62. This figure shows that γ_d increased at approximately 2 pcf per year. This indicates that, assuming the dredged material to be completely

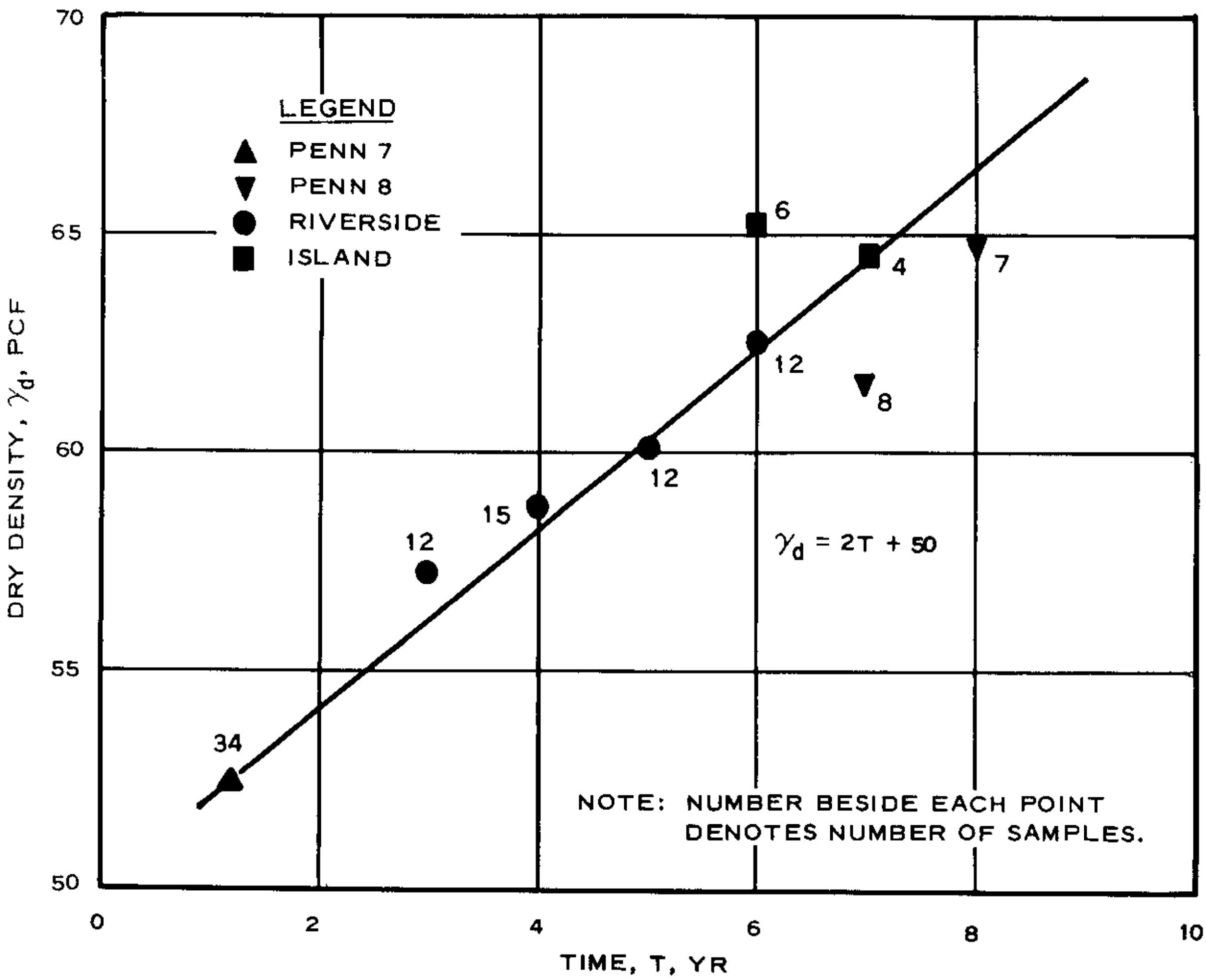


Figure 62. Increase in dry density with time (from Krizek[30])

saturated at all times, the storage capacity is annually increased by approximately 4 percent of the original volume of dredged material. Long-term data are needed to define this relationship further. It is not likely that this relationship will remain linear indefinitely.

130. Figure 63 shows that, for various locations between the dredge discharge pipe and the outlet structure, the average field vane shear strength increased with time.

Variation of properties with
distance from dredged discharge pipe

131. Figure 63 shows that the rate of increase in τ with time is dependent on the distance from the discharge pipe. In Figures 63-65 the ratio x/ℓ indicates the relative distance from the discharge pipe, with high values corresponding to locations far from the pipe. Figure 64 also shows that the rate of change of τ with time increases with distance from the outlet structure. Figure 65 shows the change in τ with distance and that τ generally decreases from the inlet toward the outlet. Figure 65 does not include the time factor but presents plots for different years.

132. The reader is encouraged to refer to the referenced reports for more complete data concerning the properties of dredged material in confined disposal areas. In addition, more complete analysis of the data is available therein.

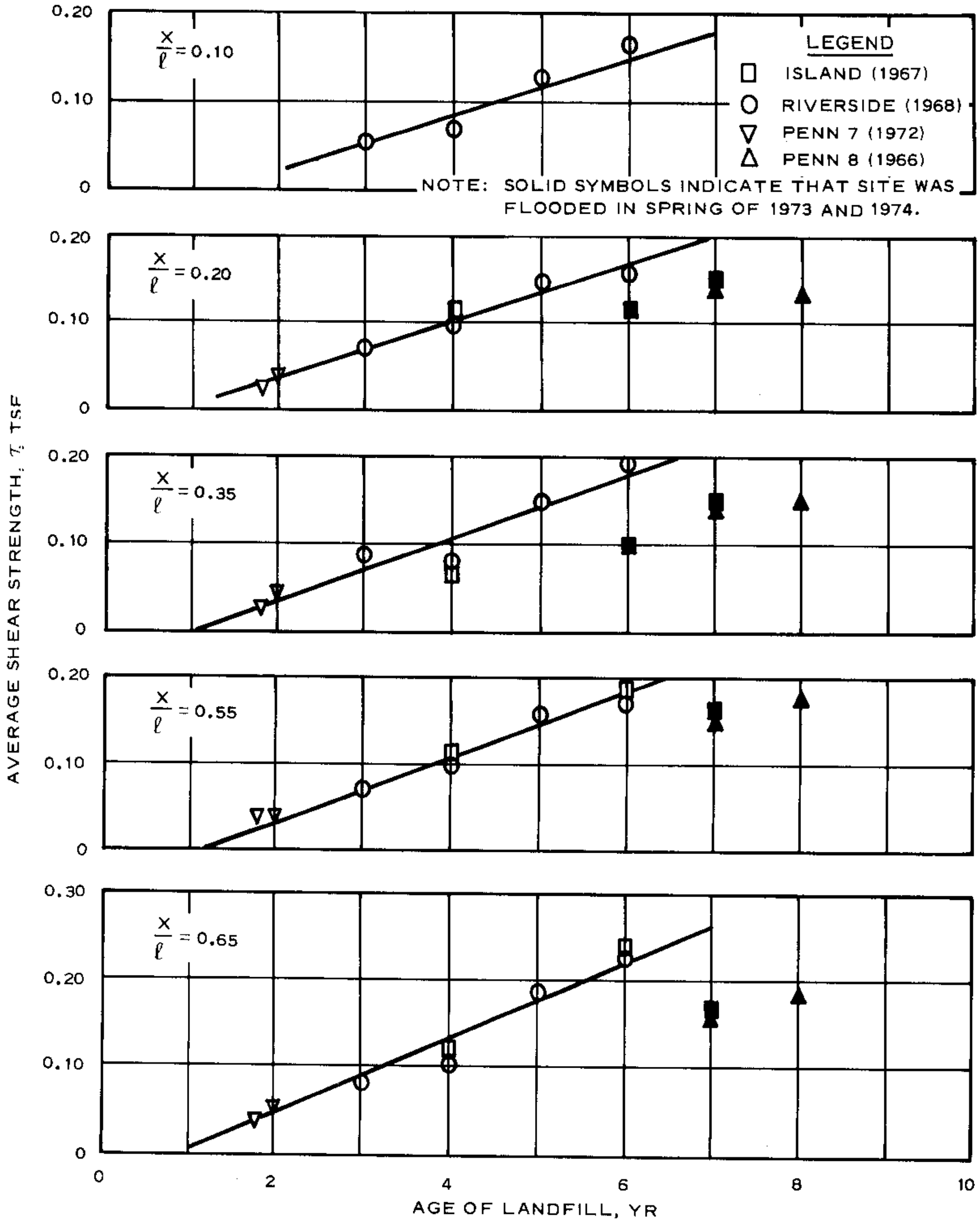


Figure 63. Average field vane strength versus time (from reference 30)

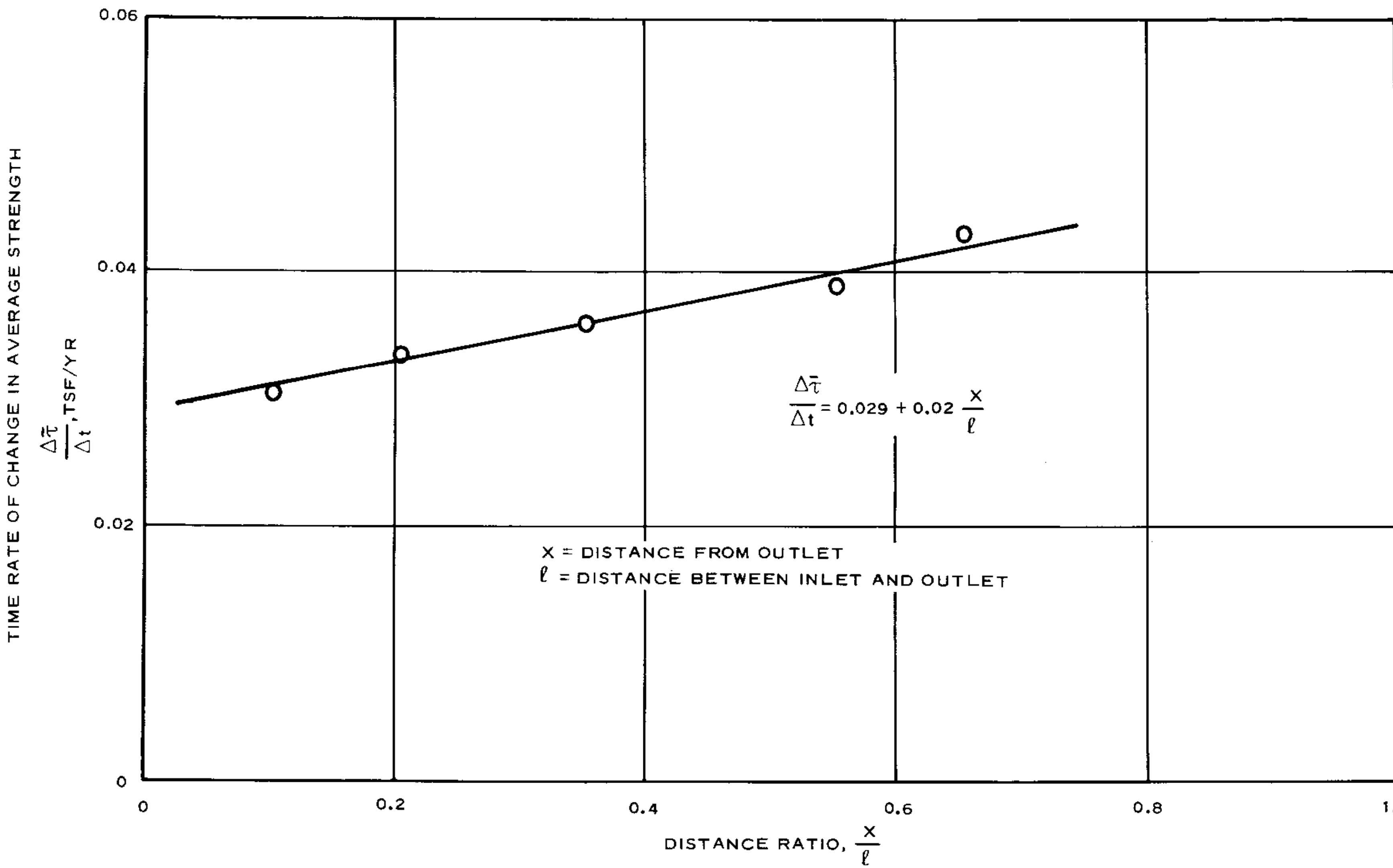


Figure 64. Rate of change of average strength versus distance from discharge pipe (from Reference 30)

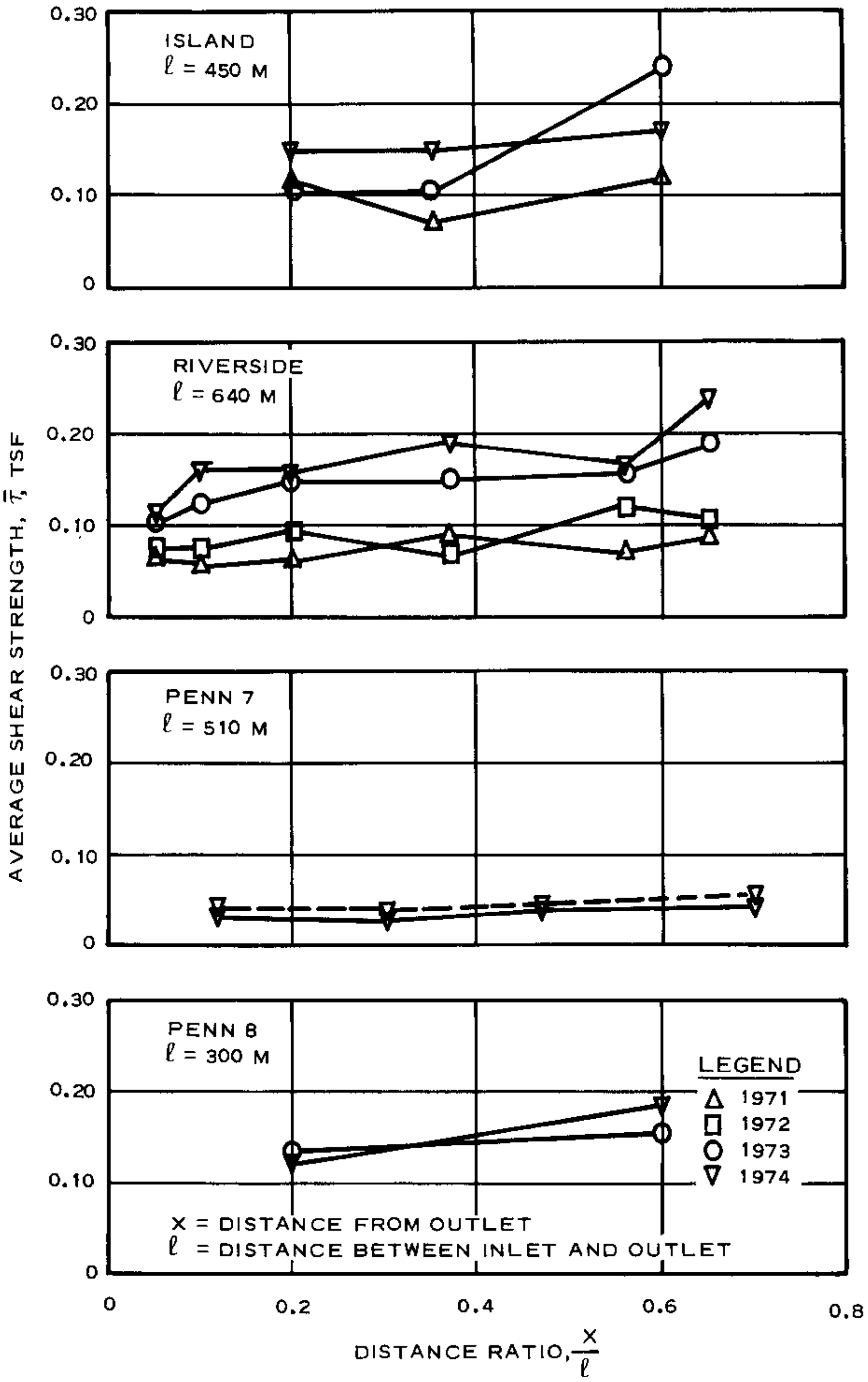


Figure 65. Average field vane strength versus horizontal distance (from reference 30)

PART VI: PRODUCTIVE USE OF DREDGED MATERIAL

133. If the reuse of dredged material disposal areas is to be achieved, then off-site, productive utilization of dredged material must be accomplished. The purpose of this part is to review the concept of using dredged material gainfully. Green Associates have conducted a study[2] to determine the needs for landfill and construction material in those geographic regions where most dredging is required. In addition, there are several other studies being designed and managed under the DMRP, and the studies will investigate a wide range of potential uses for dredged material. This part discusses the potential of the productive use of dredged material in terms of the dredged material properties determined during this study.

134. In the following discussion, it must be understood that the use of dredged material for productive uses must not result in adverse impacts on the environment in which it is used. The discussion herein is based on the physical and engineering properties of dredged material and does not consider the pollution status of the dredged material. The pollution aspects of dredged material are covered under other DMRP research studies (DMRP tasks 1C, 1D, 1E, 2D, 6B).

135. One of the most attractive uses for dredged material is the construction of landfills. The Philadelphia District has successfully sold dredged material for use as landfill material to local construction contractors. The details of these dredged material sales appear in Table 12. The Green study, in keeping with the use of dredged material as landfill, "was designed to investigate present and potential landfill needs...within 100 miles of major dredging activities."[2] The report[2] presented these landfill needs subdivided two ways: by project status and by land-use classification. Projects involving landfill were labelled existing, proposed, or potential. Existing projects were those completed on landfills of dredged material. Proposed projects were those planned for construction on dredged material landfills. Potential projects were those reported to have possibilities for construction on dredged material landfills. All projects were also grouped according to

land-use classification: urban, environmental, economic, and resource. Tables 13 through 15 show activities that may involve fill material. These activities are grouped according to land-use classifications.

136. The discussion herein is presented in terms of some of the existing, proposed, and potential uses reported by Green Associates.[2] In addition to landfill-related uses, the use of dredged material as a construction material will be discussed. Case histories of the successful productive use of dredged material will be cited as appropriate to reinforce the discussion. This part will conclude with a review of pertinent research related to the use of dredged material, including projects conceived under other areas of the DMRP.

Land-Use Categories

137. The use categories shown in Tables 13 through 15 indicate the types of projects that have proven or may prove successful using dredged material. The uses are divided into urban-, environmental-, economic-, and resource-related groupings, which are defined below. The types of land uses found under each grouping are briefly described.

Urban

138. Urban projects are those associated with the development of concentrated communities, but do not include heavy industry, park areas, and other projects that fit better into one of the other groupings. Most of the urban types of uses were associated with waterfront activities, such as the construction of flood-control structures (dikes and levees) and the creation of waterfront land by filling. Other uses involve the filling of low-lying land areas for housing construction. Still others involve dredged material used in conjunction with solid waste, as in using dredged material combined with solid waste to construct levees, or in using dredged material for sanitary landfill cover material.

Environmental

139. Landfill-based projects established for the creation, enhancement, or preservation of open spaces for public use or designed to

protect the natural environment through pollution abatement or habitat development were classified as environmental projects. Examples include the reclamation and filling of man-made pits or depressions, such as strip mines, quarries, and borrow areas. Other environmental projects involve the creation of artificial landforms such as islands. These landforms may be for the benefit of man, as in the case of recreation islands or beaches, or may be used to create fish and wildlife habitats, as in the creation of a salt marsh. Still other environmental projects are intended for protection against the elements of nature, like floods and hurricanes.

Economic

140. Economic projects pertain to heavy industry, transportation, communication, utilities, etc. Examples include land expansion for heavy industrial use, highway and airport embankments, and the creation of islands for power plants and oceanic transshipment terminals.

Resource

141. Resource projects involve the use of dredged material for mineral extraction, landfills for food production, and creation of land. Example resource projects include the extraction of sand and gravel for use as concrete aggregate and replacement of low-quality soils. Dredged material may also be used for agricultural purposes as fertilizer or topsoil, with or without other materials.

Dredged Material Landfills

142. Many of the uses of dredged material described in the Green Associates' report[2] and summarized in Tables 13 through 15 involve the construction of a landfill using dredged material. Landfills may be constructed to raise low-lying land or to extend waterfront land by filling in water behind bulkheads, or may result from the unconfined placement of material in open water. Landfills may be constructed using slurry directly from the dredge pipe outlet with or without subsequent dewatering. Also, dredged material may be temporarily placed in one area for dewatering and densification and subsequently moved to

the landfill site for placement and compaction. The construction technique will depend upon many factors, such as ultimate site usage, economics, environmental impact, availability of temporary disposal/rehandling sites, and the properties of the dredged material.

Landfills constructed of slurry

143. The placement of dredged material is generally most economical when accomplished while the material is a slurry. The drawbacks to this method of placement of material are related to the extremely high water content of slurries. The water in the slurry may be difficult to remove from fine-grained material, and landfills constructed from such materials may remain soft for many years in the absence of some effective dewatering scheme. Such soft landfills may be used successfully, however, as wildlife refuges. After some consolidation, soft fills may find use for recreation purposes, but construction activities are extremely hampered by difficulties in supporting equipment on the fill and by the need of foundations that must penetrate the entire thickness of the fill to develop sufficient bearing capacity.

144. Slurry landfills may be greatly improved by consolidation of the fill. To state quantitatively the amount of effort required to result in a suitable landfill is very difficult at best. Each landfill must be studied individually in light of its intended function in order to evaluate required site improvements. Krizek[7] has offered some general quidelines relating the degree of consolidation to the types of activity that may be expected to succeed. He suggests that "with moderate effort, most spoil fills can be made into park and recreational areas." He also suggests that "...housing developments and light industrial buildings...would usually dictate the use of some dewatering scheme together with either compaction or preloading...". The loads associated with heavy industrial buildings would require a deep-type foundation to transfer the load to deeper substrata.

Landfills of rehandled material

145. To construct a landfill of fine-grained dredged material at moisture/density conditions comparable to the conditions of the laboratory test specimens (see Part V), rehandling of the material may be

necessary. Research into the dewatering of dredged material is currently in progress, and the techniques being investigated are listed later in this part. Assuming that the dredged material can be dewatered, the success of the landfill will depend heavily upon the degree of compaction achieved during placement. This compaction will normally require that the dewatering have been accomplished prior to placement.

146. Assuming that a landfill can be placed at the same conditions as the compacted test specimens, lightweight structures could be successfully founded, although substantial settlement occurring over a considerable period of time may be anticipated. Some types of material would be more suitable than others, of course, but this is true of all soils, including dredged material.

147. An indication of which types of dredged material would be most susceptible to settlement is provided by C_c. Increasing values of C_c predict increasing amounts of settlement. Any analysis on the basis of these test results is purely academic, however, due to the lack of correlation between field and laboratory conditions in terms of fill uniformity. However, the test results do show that dewatered and densified dredged material will perform as well in landfill applications as the same types of soil at similar moisture and density conditions.

148. Dredged material may be combined with other materials, such as solid waste, for their mutual benefaction. This type of operation may involve the intimate mixture of the different materials and subsequent landfill construction, or may involve a layering operation. An example of a layering operation involves the use of layers of dredged material to cover compacted layers of solid waste in a sanitary landfill.

Dredged Material for Construction

149. There is great potential for the use of dredged material as a construction material. As supplies of naturally occurring construction material dwindle, new sources and substitutions for these materials must be developed. Demonstration of the suitability of dredged material for

use as construction material will diminish the effects of material shortages and will increase the capacity of dredged material disposal areas.

150. Dredged material, dewatered and densified as necessary, may be used as a construction material in several ways. It may be used as a conventional soil, or a fraction, such as sand and gravel, may be extracted for use. All or part of the dredged material may be used alone or in combination with other materials. For example, the sand fraction may be used with aggregate and cement for making concrete, or dredged material may be combined with solid waste and used for construction. In addition, fractions of dredged material having different grain sizes can be mixed to provide a construction material with desirable physical and engineering properties. Based on this study, it is reasonable to believe that almost any desired soil properties can be obtained by dewatering, mixing, and compacting dredged material. The use of dredged material, alone or in combination with other materials, as a construction material is the subject of the discussion below.

Dredged material used alone

151. Dredged material, dewatered and densified as necessary, may be used as a construction material in much the same way as any conventional soil. Examples of productive uses of dredged material for construction cited by Green Associates[2] include the construction of flood-control dikes and levees, use as a preload material, and the construction of highway and runway embankments.

152. The fine-grained dredged material tested during this study would be suitable for use in the construction of flood-control dikes and levees. The dewatered dredged material, which is of extremely low permeability, would be especially suited for use as impermeable cores for these structures. Fine-grained dredged material would also be suitable for use as a preload fill, whose main requirement is weight. The construction of highway and runway fills of dredged material would require that granular material be used. In addition, careful control of moisture conditions and compaction techniques would be required for material with fines. This control would not be in excess of that normally exercised during embankment construction.

153. The viability of using dredged material for highway embankments has been demonstrated by the California Department of Transportation. Since 1959, approximately 9,220,000 cu yd of dredged material have been removed from disposal areas and used in the construction of highways.

154. Green Associates' report[2] also documents a growing shortage of sand and gravel for use as concrete aggregate. This shortage may be alleviated by the use of dredged material. In some areas of the country, notably the Pacific coast and Florida areas, considerable amounts of sand that could be used are dredged. In other areas the sand fraction may be separated from the slurry.

Dredged material combined with other materials

155. In cases where the quality of the available dredged material is not adequate for a specific purpose, the addition of another material may solve the problem. For example, in New York sandy dredged material has been blended with sewage sludge to form a suitable sanitary landfill cover material.

156. In other cases dredged material may be used to improve the quality of another material. In California dredged material was combined with solid waste, and the resulting combination was used to rebuild dikes.

Current Research

157. The feasibility of the productive use of dredged material is predicated upon two main constraints: the identification of uses for which dredged material is or may be made to be suitable, and the processes required to make the dredged material suitable (dewatering).

Productive uses research

158. Four general task areas are being investigated under the DMRP Productive Uses Project (PUP). These areas, upland disposal, land improvement, products, and disposal land use, are each made up of individual work units. One study being conducted under the upland disposal task is investigating all aspects of transporting dredged material from

the disposal area to the site of ultimate use. Another study under this task is concerned with the use of dredged material for the reclamation of strip mines. Studies to determine the feasibility of using dredged material for agricultural purposes and in conjunction with solid waste management are being conducted under the land improvement task area. Products that may be made using dredged material are being studied. These products include lawn sod and shrimp mariculture. Other product-type uses that are being monitored include beach nourishment and aggregate production. The productive use of filled disposal areas as recreation areas is being studied, along with land-use policy and case studies of the use of disposal areas. The work units of PUP will, ultimately, be synthesized into a set of guidelines for the productive use of dredged material.

Dewatering

159. Since most uses for dredged material will require that the material be in a form suitable for use, intensive research is ongoing within the DMRP to develop methods for dewatering dredged material. The methods being investigated include:

- a. Mechanical slurry agitation
- b. Electro-osmosis
- c. Aeration*
- d. Crust management*
- e. Frost action*
- f. Field trenching
- g. Vacuum well points
- h. Wicking*
- i. Sand injection*
- j. Containment area management*

The dewatering of dredged material will be a major step toward the productive use of dredged material.

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* Indicates innovative dewatering methods being investigated especially for dredged material. All reports were in preparation at the time of this study.

PART VII: CONCLUSIONS AND RECOMMENDATIONS

160. Based on the results of this study of the classification and engineering properties of dredged material and based on the experience gained while conducting the investigation, the following conclusions are advanced; recommendations are made as warranted to improve the state of knowledge of dredged material.

Conclusions

161. The results of testing compacted samples of dredged material show that dewatered dredged material is a soil and exhibits engineering properties similar to those of similar types of soil.

162. Since dewatered dredged material behaves as a soil, it is reasonable to expect that dewatered dredged material can satisfy the landfill and construction material needs cited by Green Associates.[2]

163. The USCS, AASHO, and FAA classification systems are applicable to the classification of dredged material, depending on the intended use of the dredged material. The USDA classification system is of limited value since a complete classification cannot be assigned, and the PIANC system is useful only prior to dredging.

164. The results of testing more than 100 samples of dredged material indicate that the organic content of dredged material is seldom greater than 10 percent.

165. Standard soil properties tests are applicable and meaningful for use on dredged material. Due to the high water content often characteristic of dredged material, longer periods of time are required to complete test procedures that require drying or consolidation.

Recommendations

166. All data resulting from routine testing of dredged material should be preserved by the test sponsor and made available to parties investigating the possibility of using dredged material productively.

167. CE Districts should consider implementation of a program of tube sampling prior to dredging. During the condition survey, the crew could obtain tube samples from each shoal to be dredged, visually classifying and measuring the thickness of each type of material present. This information combined with the volume of the shoal would enable the District to quantify the approximate amounts of each type of material to be dredged. Using these data, disposal areas could be managed for more efficient operation, and material could be selectively mined for productive use.

168. Further research into the determination and evaluation of organic content is recommended. A standard rationale for determining organic content should be developed; evaluation of the effect of organic matter on dredged material properties should be investigated, with attention paid to the nature of the organic matter.

169. It is recommended that the USCS be used in describing dredged material. Such practice would be a positive step toward treating dredged material as a soil and would standardize terminology in dredged material description.

170. It is also recommended that Districts keep careful records of the types, amounts, and locations of dredged material placed in disposal areas to facilitate investigations of using dredged material productively, as well as to provide a record of subsurface characteristics for studies of ultimate disposal site usage.

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Table 1

Occurrence Distribution of Maintenance Dredging (by Volume) Among Navigation Projects Within Continental United States by District

Project	Dredging Distribution Volume Basis, Percent
A. Gulf States Region	
Galveston District	
CC--Corpus Christi Ship Harbor and Ship Channel	12.6
FC--Freeport Harbor	3.2
GC--Galveston Harbor and Channel	10.1
HC--Houston Ship Channel	9.9
MC--Matagorda Ship Channel	12.3
SN--Sabine Neches Waterway	19.4
TC--Texas City Channel	4.7
IW--GIWW Main Channel	13.0
BC--Brazos Island Harbor	4.0
Projects not studied	10.8
Total	100.0
New Orleans District	
MR--Mississippi River Channel Crossings	2.1
NH--Mississippi River - New Orleans Harbor	2.8
SW--Mississippi River Southwest Pass	9.2
CR--Calcasieu River and Pass	10.3
Calcasieu River and Pass Bar Channel	16.9
BH--Atchafalaya Basin Berwick Harbor	0.6
WL--GIWW - Wax Lake	3.0
Projects not studied	55.1
Total	100.0
Mobile District	
BH--Biloxi Harbor	1.5
GP--Gulfport Harbor	0.9
PB--Pensacola Harbor	3.2
CP--Panama City Harbor	1.8
MB--Mobile Bay Channel and River Channel	28.2
Projects not studied	64.4
Total	100.0
Jacksonville District	
IW--IWW - Jacksonville to Miami	2.9
OW--Okeechobee Waterway	0.4
TH--Tampa Harbor	9.9
Total	13.2
B. South Atlantic Region	
Jacksonville District	
SL--St. Lucie Inlet	0.3
MH--Miami Harbor	0.6
PB--Palm Beach Harbor	0.9
JH--Jacksonville Harbor	5.5
CH--Canaveral Harbor	10.6
FH--Fernandina Harbor	2.0
Projects not studied	66.9
Total	86.8

Project	Dredging Distribution Volume Basis, Percent
South Atlantic Region (Continued)	
Savannah District	
AI--Atlantic Intracoastal Waterway	8.7
BH--Brunswick Harbor	10.0
SH--Savannah Harbor	69.3
Projects not studied	12.0
Total	100.0
Charleston District	
CH--Charleston Harbor	46.1
Projects not studied	53.9
Total	100.0
Wilmington District	
WH--Wilmington Harbor	29.0
SP--Military Ocean Terminal - Sunny Point	22.8
MC--Morehead City Harbor	10.0
Projects not studied	38.1
Total	100.0
C. North Atlantic Region	
Norfolk District	
HR--Norfolk Harbor, Hampton Roads Channel	16.0
Projects not studied	84.0
Total	100.0
Baltimore District	
BH--Baltimore Harbor	38.2
Projects not studied	61.8
Total	100.0
Philadelphia District	
DR--Delaware River, Philadelphia to sea	42.7
Projects not studied	57.3
Total	100.0
New York District	
BR--Bay Ridge and Red Hook Channels	8.8
HR--Hudson River Channel	19.5
NB--Newark Bay - Hackensack and Passaic Rivers	2.4
YJ--New York and New Jersey Channels	21.2
NY--New York Harbor, Ambrose and Anchorage Channels	2.8
Projects not studied	45.3
Total	100.0

(Continued)

Note: Percentages based upon volumes of dredging as reported in Reference 3.

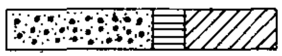
Table 1 (Concluded)

Project	Dredging Distribution Volume Basis, Percent
North Atlantic Region (Continued)	
New England Division	
VH--Wells Harbor	1.5
SR--Scarboro River	0.9
BH--Boston Harbor	15.3
TR--Thames River	7.8
Projects not studied	74.5
Total	100.0
D. Great Lakes Region	
Buffalo District	
RH--Rochester Harbor	9.2
AH--Ashtabula Harbor	5.2
SH--Sandusky Harbor	11.9
LH--Lorain Harbor	5.2
FH--Fairport Harbor	10.2
Projects not studied	58.3
Total	100.0
Detroit District	
RA--Raisin River	5.5
RR--Rouge River	8.7
TH--Toledo Harbor	24.5
SB--Saginaw Bay and SR--Saginaw River	1.2
Projects not studied	60.1
Total	100.0
St. Paul District	
DH--Duluth - Superior Harbor	6.3
MR--Upper Mississippi River	77.1
KW--Keewenaw Waterway	3.6
Projects not studied	13.0
Total	100.0
Chicago District	
GB--Green Bay Harbor	2.4
IR--Illinois Waterway	11.6
Projects not studied	86.0
Total	100.0
Rock Island District	
MR--Upper Mississippi River	46.5
Projects not studied	53.5
Total	100.0
E. Pacific Coast Region	
Seattle District	
GH--Gray Harbor and Chehalis River	56.0
WR--Willapa River and Harbor and Naselle River	20.8
Projects not studied	23.1
Total	100.0

Project	Dredging Distribution Volume Basis, Percent
Pacific Coast Region (Continued)	
Portland District	
CR--Columbia and Lower Willamette Rivers Below Vancouver	48.5
Columbia River - Vancouver to the Dalles	17.3
CB--Coos Bay	9.6
YB--Yaquina Bay and Harbor	4.8
MC--Columbia River at Mouth	14.0
CQ--Coquille River	0.3
Projects not studied	5.5
Total	100.0
Sacramento District	
ST--Stockton Deepwater Ship Channel	20.7
SR--Sacramento River Deepwater Channel and Shallow Draft Channel	79.3
Total	100.0
San Francisco District	
SB--Suisan Bay Channel	22.1
SF--San Francisco Harbor	9.0
RC--Redwood City Harbor	7.3
OK--Oakland Harbor	3.8
RI--Richmond Harbor	4.3
PS--Pinole Shoal	7.8
PC--Petaluma River	1.5
MI--San Pablo Bay and Mare Island Strait	25.4
SR--San Rafael Creek	3.4
Projects not studied	15.4
Total	100.0
Los Angeles District	
MB--Morro Bay	3.4
OH--Oceanside Harbor	5.9
MI--Mission Bay Harbor	6.6
SD--San Diego Harbor	11.7
Projects not studied	72.4
Total	100.0

Table 2

Ranges of Classification Test Data Determined for Dredged Material*

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

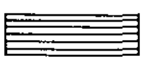
Note: For the purpose of this table, silts plot below the A-line and clays plot above the A-line on a plasticity chart.

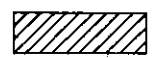
* Conclusions drawn on basis of data shown apply only to samples tested for this study. Data entries for each region are shown in the following format:

xx	Number of samples
xx-xx	Range of values
xx	Average value, if meaningful

** Legend for material types is as follows:

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

 Silt (low plasticity fines).

 Clay (high plasticity fines).

 Organic material (soil with organic matter present)

† D_{10} = Grain size at 10% passing.

D_{60} = Grain size at 60% passing.

D_{90} = Grain size at 90% passing.

Table 3

General Basis for Identification and Classification of Soils* for Dredging Purposes (Proposed by PIANC)

Main Soil Type	Particle Size Identification: Range of Size, mm	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 Medium, 20-6 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 that resemble weak conglomerate rock. Hard-packed gravels may exist intermixed with sand
Sands††	Coarse, 2-0.6 Medium, 0.6-0.2 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 Medium, 0.02-0.006 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 the 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. If finer, will approximate to clay with plastic character. Very often intermixed or interleaved with fine sands or clays. May be homogeneous or stratified. The consistency may vary from fluid silt through stiff silt on to "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, cracking, and increasing strength when drying	Strength — Characteristics — Shear Strength‡‡ Very soft — May be squeezed easily between fingers — Less 0.17 kg/cm² Soft — Easily molded by fingers — 0.17-0.45 kg/cm² Firm — Requires strong pressure to mold by fingers — 0.45-0.90 kg/cm² Stiff — Cannot be molded 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.

** National equivalent sieve size/no.

† 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 should be used. However, to avoid the chance of confusion, 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 the table above.

†† 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.

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

Table 4

Characteristics and Ratings of USCS Soil Types

Class	Maximum Dry Density Standard Proctor[19] pcf	Value as a Foundation Material[19]	Compressibility and Expansion[19]	Value as an Embankment Material[18]**	Value as Base Course[18]**
GW	125-135	Good bearing value	Almost none	Very stable	Good
GP	115-125	Good bearing value	Almost none	Reasonably stable	Poor to fair
GM	120-135	Good bearing value	Slight	Reasonably stable	Fair to poor
GC	115-130	Good bearing value	Slight	Reasonably stable	Good to fair*
SW	110-130	Good bearing value	Almost none	Very stable	Fair to poor
SP	100-120	Good to poor bearing value depending on density	Almost none	Reasonably stable when dense	Poor
SM	110-125	Good to poor bearing depending on density	Slight	Reasonably stable when dense	Poor
SC	105-125	Good to poor bearing value	Slight to medium	Reasonably stable	Fair to poor*
ML	95-120	Very poor, subject to liquefaction	Slight to medium	Poor stability, high density required	Not suitable
CL	95-120	Good to poor bearing value	Medium	Good stability	Not suitable
OL	80-100	Fair to poor bearing, may have excessive settlements	Medium to high	Unstable, should not be used	Not suitable
MH	70-95	Poor bearing value	High	Poor stability, should not be used	Not suitable
CH	80-105	Poor to fair bearing value	Very high	Fair stability, may soften on expansion	Not suitable
OH	65-100	Very poor bearing value	High	Unstable, should not be used	Not suitable
Pt		Remove from foundations	Very high	Should not be used	Not suitable

* Not suitable if subject to frost.

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Table 5

Relative Suitability of USCS Soil Types as Roadways

Class	Value for Permanent Roadways*[20] Embankment	Base Course	Wearing Course	Value for Temporary Roadways[18] With Dust Abatement	With Bituminous Treatment
GW	1	1	3	Fair to poor	Excellent
GP	3	5	No	Poor	Fair
GM	7	6	5	Poor	Poor to fair
GC	4 or 6**	2 or 9** Very poor	1 or 4**	Excellent	Excellent
SW	2	3	6 Poor	Fair to poor	Good
SP	8	8 Poor	No	Poor	Poor to fair
SM	9	7	No	Poor	Poor to fair
SC	5 or 10** No	4 or 10** No	2 or 7** Poor	Excellent	Excellent
ML	12 Poor	12 No	No	Poor	Poor
CL	11 No	11 No	8 Very poor	Poor	Poor
OL	13 Poor	13 No	No	Not suitable	Not suitable
MH	16 Very poor	16 No	No	Very poor	Very poor
CH	14 Poor	14 No	No	Very poor	Not suitable
OH	15 Very poor	15 No	No	Not suitable	Not suitable
Pt	← Entirely unsuitable →				

* Numbers in columns indicate relative suitabilities of soil types. Numbers increase as suitability decreases.

** The first number shows relative suitability with clay binder; second number shows suitability for material with excess clay.

Table 6

Relative Suitability of USCS Soil Types for Permeability - Dependent Applications

Class	Permeability Classification[20]	Value for Earth Dams*[20] Homogeneous Embankment	Zone 1 Impervious	Zone 2 Semipervious	Zone 3 Free-Draining	Value for Compacted Canal Linings[20]
GW	Pervious			1	1	No
GP	Very pervious				2	No
GM	Semipervious to impervious	2	2	2		4
GC	Impervious	1 or 3**	1 or 3**			2 or 3**
SW	Pervious		3	3 If gravelly		No
SP	Pervious		4	4 If gravelly		No
SM	Semipervious to impervious	6	7	5		No
SC	Impervious	4 or 5**	4 or 5**			1 or 5**
ML	Semipervious to impervious	8	8	6		No
CL	Impervious	7	6			6
OL	Semipervious to impervious	9	9			No
MH	Semipervious to impervious	11	11			No
CH	Impervious	10	10			7 Questionable
OH	Impervious	12	12			No
Pt	← Entirely unsuitable →					

* Numbers in columns indicate relative suitabilities of soil types. Numbers increase as suitability decreases.

** The first number shows relative suitability with clay binder; second number shows suitability for material with excess clay.

Table 7

Comparison Between Classification Groups of USCS and Those of FAA and AASHO Systems

			USCS Classifications														
			Coarse-Grained								Fine-Grained						
			GW	GP	SW	SP	SM	SC	SP-SM	SW-SM	CL-ML	ML	CL	OL	MH	CH	OH
FAA Classifications	Coarse	E-1	1	4	8	92	2	2	3	2							
		E-2				34	3	1	5								
		E-3				33	7		7								
		E-4					3	1									
		E-5					1	5									
	Fine	E-6						1			1	2	1				
		E-7					2	7				2	17	1			
		E-8					1								1	12	2
		E-9															
		E-10											1			8	2
		E-11														9	4
		E-12													16	68	12
AASHO Classifications	Coarse	A-1-a	2	4	1	2											
		A-1-b			7	28	1			1							
		A-2				1	11	1	3	1							
		A-2-4					5	2	2								
		A-2-6						4									
		A-2-7						1									
		A-3				129			10								
	Fine	A-4					1	2			1	3	1				
		A-6					1	4					6				
		A-7-5					2						1	1	17	67	18
		A-7-6					1	4				1	11			30	2

Note: Two samples were classified GW by FAA: E-1 and E-3. AASHO classified both as A-1-a.

Table 8

Classification Properties of Samples of Dredged Material Subjected to Engineering Properties Testing

Sample Number*	Curve Number (Figure 34)	USCS Classification	Liquid Limit	Plastic Limit	Plasticity Index	Organic Content percent
A-GAL-HC-A	1	CH	99	28	71	9.17
A-GAL-SN-B	2	CH	120	31	89	4.09
A-MOB-MB-A	5	CH	129	32	97	10.64
B-SAV-SH-B	7	MH	78**	51**	27**	8.68
B-CAR-CH-A	8	CH	146	53	93	7.41
B-CAR-CH-B	9	CL	42**	20**	22**	4.30
B-WIL-WH-A	10	OH	75	46	29	8.78
B-WIL-WH-C	12	SC	42**	23**	19**	3.37
C-NOR-NH-A	13	SC	29	17	12	1.80
C-NOR-NH-B	14	CH	70**	37**	47**	6.55
C-BAL-BH-A	15	MH	73**	38**	35**	7.54
C-NYD-YJ-A	16	CH	149	55	94	9.74
E-SEA-GH-A	19	SM	NP†	NP†	NP†	3.44
E-SFD-SF-A	20	CH	59	24	35	
E-SFD-RC-B	21	CH	79	32	47	
E-SFD-PS-C	22	CL	48	22	26	
E-SFD-MI-D	23	CH	84	34	50	

* See Appendix B for explanation of sample numbers.
** LL, PL, and PI were determined using dried specimens.
† NP means nonplastic.

Table 9

Shear Strength of Dredged Material Samples

		Direct Shear (S) Tests OMC + 5%				Triaxial Shear (Q) Tests							
						OMC + 5%				OMC - 5%			
		Initial Conditions		Strength Parameters		Initial Conditions		Strength Parameters		Initial Conditions		Strength Parameters	
Sample	USCS Classification	γ_d , pcf	w , %	ϕ , deg	c , tsf	γ_d , pcf	w , %	ϕ , deg	c , tsf	γ_d , pcf	w , %	ϕ , deg	c , tsf
A-GAL-HC-A*	CH	73.8	37.4	25	0.09	74.2	36.5	4.6	0.36	73.6	27.1	13.5	0.56
A-GAL-SN-B	CH	72.3	38.1	24.5	0	73.2	38.1	10.2	0.25	72.4	29.0	19.8	0.36
A-MOB-MB-A	CH	72.3	45.2	21	0.19	74.6	36.5	9.1	0.30	74.8	27.1	22.3	0.38
B-SAV-SH-B	MH	59.7	44.3	34	0	59.5	45.1	17.7	0.27	60.4	34.9	25.6	0.32
B-CAR-CH-B	CL	81.8	30.0	33	0.12	82.1	30.0	7.8	0.27	80.6	20.8	31.8	0.18
B-WIL-WH-A	OH	60.9	51.9	33	0.10	61.4	50.4	9.1	0.38	59.9	41.7	24.3	0.29
B-WIL-WH-C	SC	88.5	24.7	32	0.14	88.1	25.2	10.7	0.27	86.9	16.2	26.6	0.30
C-NOR-NH-B	CH	68.9	42.3	27	0.15	68.5	43.0	7.5	0.24	68.6	32.7	29.2	0.22
C-BAL-BH-A	MH	69.3	48.1	30	0.12	66.3	48.2	6.3	0.25	66.7	38.4	16.7	0.50
C-NYD-YJ-A	CH	64.7	48.9	34	0	64.2	48.8	2.5	0.26	63.7	39.9	15.4	0.75

* See Appendix B for explanation of sample numbers.

Table 10

Summary of Results of Consolidation Tests Conducted on Dredged Material Samples

Sample No.	USCS Classification	Initial Conditions: Dry Density γ_d, pcf	Initial Conditions: Moisture Content w, %	Compression Index, Cc	Coefficient of Consolidation, c_v sq in./day	Coefficient of Compressibility, a_v 10^{-5} sq ft/lb	Coefficient of Permeability, k 10^{-8} cm/sec
A-GAL-HC-A	CH	73.3	37.5	0.41	0.6-14.7 (4.6)*	0.75-6.12 (3.83)	0.085-1.0 (0.4)
A-GAL-SN-B	CH	72.7	38.7	0.39	0.8-24.9 (6.4)	0.75-12.2 (4.62)	0.11-41.0 (8.3)
A-MOB-MB-A	CH	76.8	37.5	0.35	1.8-2.5 (2.1)	0.69-9.0 (4.16)	0.26-2.3 (1.3)
B-SAV-SH-B	MH	58.9	46.8	0.49	5.0-11.8 (7.3)	0.88-10.0 (5.31)	0.43-7.4 (3.5)
B-CAR-CH-B	CL	83.5	30.1	0.25	4.1-14.7 (8.8)	0.47-5.4 (2.35)	0.71-4.4 (2.7)
B-WIL-WH-A	OH	59.7	52.5	0.58	0.1-11.2 (5.5)	1.06-12.0 (5.55)	0.1-5.6 (2.1)
B-WIL-WH-C	SC	87.4	25.4	0.23	4.8-16.2 (10.0)	0.44-3.2 (1.87)	0.96-5.0 (2.9)
C-NOR-NH-B	CH	68.2	42.0	0.41	5.2-33.2 (14.5)	0.75-9.0 (4.54)	1.3-35.0 (10.0)
C-BAL-BH-A	MH	65.9	49.0	0.47	0.5-14.1 (7.9)	0.42-6.0 (3.74)	0.34-5.3 (2.6)
C-NYD-YJ-A	CH	64.3	50.1	0.42	0.4-10.6 (4.4)	0.75-6.0 (2.99)	0.2-2.2 (0.99)
E-SFD-SF-A	CH	94.0	26.7	0.19		0.43-1.1 (0.78)	
E-SFD-RC-B	CH	79.0	40.1	0.35		0.38-1.1 (0.72)	
E-SFD-PS-C	CL	100.0	23.4	0.16		0.36-2.0 (1.00)	
E-SFD-MI-D	CH	83.0	35.7	0.28		0.56-4.0 (1.4)	

* Average values shown in parentheses.

Table 11

Properties of Dredged Material in Confined Disposal Areas

Area and District	Material Depth ft	Water Content w, %	Liquid Limit LL	Plastic Limit PL	Plasticity Index PI	Organic Content OC, %	Effective Size D_{10}, mm	Percent Fines <#200, %	Dry Density γ_d, pcf	Shear Strength τ, tsf	Compression Index Cc	Coefficient of Consolidation, c_v 10^{-3} in.^{2}/min	Coefficient of Permeability, k 10^{-8} cm/sec
Edgemoor-A, Philadelphia	26-30	82.4-102.3 (93)*	25-147 (110)	23-66 (50)	2-90 (60)		<0.001-0.04		42.0-55.7 (49)	0.05-0.28 (0.19)	0.05-0.28 (0.098)	0.67-1.50 (1.02)	
Edgemoor-B, Philadelphia	20-23	61.8-79.8 (70)	51-114 (92)	28-61 (45)	23-62 (47)		<0.001		53.3-63.3 (58)	0.30-0.41 (0.33)	0.48-0.50 (0.49)	4.63-4.63 (4.63)	
Oldman's No. 1, Philadelphia	8.5-11	76.0-95.8 (84)	24-297 (100)	18-132 (43)	6-165 (57)		<0.001-0.06		47.0-53.7 (52)	0.07-0.48 (0.20)	0.90-1.28 (1.09)	0.65-1.00 (0.83)	
Darby Creek, Philadelphia	7-15	61.3-98.4 (84)	27-172 (110)	20-84 (53)	7-120 (56)		<0.001		48.0-60.6 (52)	0.05-0.42	0.39	1.20	
Pigeon Point, Philadelphia	14.1-12.8	65.0-87.9 (76)	53-193 (104)	30-75 (54)	20-150 (50)		<0.001		46.4-60.3 (54)	0.09-0.55 (0.25)	0.75-0.96 (0.83)	0.60-1.00 (0.84)	
Penn 7 Detroit		64-98 (85)	59-95 (79)	27-48 (35)	26-56 (44)		0.0020	83	46-61 (51)	0.004-0.09 (0.03)			
Penn 8 Detroit		51-74 (61)	58-86 (73)	26-48 (39)	20-46 (34)		0.0022	85	51-69 (61)	0.02-0.46 (0.16)	0.43-0.67 (0.52)	2.98-5.95 (4.10)	2.7-4.7 (3.75)
Island, Detroit		43-78 (57)	56-89 (70)	21-46 (34)	26-52 (36)	3.84-7.43 (5.91)	0.0026	81	52-77 (66)	0.02-0.17 (0.07)	0.33-0.69 (0.50)	2.98-6.05 (4.35)	2.6-6.6 (3.8)
Riverside, Detroit		42-73 (60)	53-80 (71)	23-51 (36)	10-52 (35)	6.0-7.6 (6.44)	0.0019	86	53-77 (63)	0.02-0.45 (0.12)	0.35-0.56 (0.51)	2.33-9.58 (4.44)	2.7-4.6 (3.6)
Blakeley Island, Mobile		22.3-347.5 (109)	37-217 (101)	17-97 (35)	20-120 (67)	6-15		26-65	23.8-73.8 (55)	0.02-0.14 (0.05)			
Ashley River, Charleston			NP-82	5-24		3-18		17-81					
Calumet Harbor, Chicago			NP-56	NP-20		1-9		11-76					
Corpus Christi Bay, Galveston			NP-35	NP-18		1-3		10-34					
Buffalo Harbor No. 1, Buffalo	11-15	37.8-89.7 (68)	24-89 (67)	24-44 (36)	0-45 (31)				46.5-71.1 (57)				
Cleveland Harbor No. 1, Buffalo	20-25	48.2-90.7 (77)	44-99 (72)	29-57 (37)	9-57 (35)				41.6-73.0 (52)				
Jupiter Point, Jacksonville			NP	NP		0-2		3-8					
Sweetwater Marsh, Los Angeles			NP-48	NP-12		0-8		1-57					
Alcoa, Mobile			NP	NP		6		38					
Green Harbor, New England			NP	NP-19		0-2		1-9					
Mississippi River Gulf Outlet Canal New Orleans			NP-79	NP-22		1-8		13-69					

(Continued)

Note: Philadelphia District data from Reference 29; Blakely Island data from M. Palermo, WES; Buffalo and Cleveland data from Buffalo District; Detroit District data from References 7 and 30, remainder of data from Reference 31.

* Average values shown in parentheses.

Table 11 (Concluded)

Area and District	Material Depth ft	Water Content w, %	Liquid Limit LL	Plastic Limit PL	Plasticity Index PI	Organic Content OC, %	Effective Size D_{10}, mm	Percent Fines <#200, %	Dry Density γ_d, pcf	Shear Strength τ, tsf	Compression Index Cc	Coefficient of Consolidation, c_v 10^{-3} in.^{2}/min	Coefficient of Permeability, k 10^{-8} cm/sec
Craney Island, Norfolk			NP-80	NP-28		1-26		8-66					
Pearce Creek, Philadelphia			NP-70	NP-28		0-11		1-86					
Everett Harbor, Seattle			NP	NP		1-7		3-21					
Gray's Harbor, Seattle			NP	NP		2		7-12					
Willapa Bay, Seattle			NP-83	NP-25		2-13		10-76					
Verdigris River, Tulsa			NP-50	NP-19	1-6		9-69						

Table 12

Sale of Fill Material from Disposal Areas in Philadelphia District

Disposal Area	Bid/Cu Yd	Cubic Yards	Date Awarded
Pedricktown	$0.11	300,000	Oct 72
National Park	0.11	10,000	Jul 73
National Park	0.12	300,000	Jul 73
Fort Mifflen	0.25	150,000	Jan 73
Fort Mifflen	0.82	100,000	Jan 73
Penns Grove	0.40	30,000	Oct 73
Penns Grove	0.35	300,000	Aug 73
National Park	0.12	60,000	Sep 73
National Park	0.10	17,000	Dec 73
Penns Neck	0.15	25,000	Jan 74
Penns Grove	0.08	4,500,000	May 74
Pedricktown	0.40	5,000	May 74
National Park	0.10	15,000	Jun 74

Table 13

Existing Uses of Dredged Material

Urban	Environmental
1. Landfill for housing construction	1. Beach construction and nourishment
2. Resort expansion	2. Fish and wildlife habitat creation
3. Pier extension	3. Flood control
4. Commercial development	4. Erosion protection
5. Waterfront real estate creation	5. Hurricane protection
6. Fill for low land areas	6. Sanitary landfill cover and liner material

Economic	Resource
1. Highway and runway construction/stabilization	1. Creation/enhancement of cattle range area
2. Breakwater and groin construction	2. Extraction of sand and gravel
	3. Creation of artificial landforms (islands)
	4. Land reclamation

Table 14

Proposed Uses of Dredged Material

Urban	Environmental
1. Residential/commercial/industrial expansion	1. Beach nourishment
2. Resort development	2. Sanitary landfill cover material
3. Use as fill to combat landfill fires	3. Flood control
4. Fill for eroded sand pits	4. Fish and wildlife habitat creation
5. Fill for landscaping	5. Creation of artificial landforms (islands and marshes)
6. Flood-control dikes	6. Borrow pit/strip mine reclamation
	7. Erosion protection
	8. Use to decrease water depth - ultimate use: ice skating

Economic	Resource
1. Industrial land development and expansion	1. Agricultural uses (forestry, topsoil, fertilizer, agricultural land creation)
2. Highway/runway/helipad construction	2. Creation/enhancement of marshes and swamps
3. Creation of artificial landforms (island for use as transshipment terminal)	3. Hurricane protection levees
4. Construction/expansion of marina	4. Research on use as building materials
5. Creation of wildlife habitat	5. Extraction of sand and gravel
	6. Flood-control dikes

Table 15

Potential Uses of Dredged Material

Urban	Environmental
1. Fill low-lying areas for urban housing	1. Construction of flood-control structures
2. Construction of parking lots	2. Sanitary landfill cover material
3. Resort development	3. Borrow pit/strip mine/quarry/gold mine reclamation
4. Land reclamation of industrial development	4. Fish and wildlife habitat creation/enhancement
5. Replacement of poor quality soils for use with septic tanks and drainage fields	5. Creation of artificial landforms (islands, marshes, oyster reefs)
6. Combine with solid waste to rebuild levees	6. Beach creation/nourishment
	7. Remove contaminated lake bottoms - replace with dredged material
	8. Erosion control
	9. Park landscaping - hills for sledding

Economic	Resource
1. Highway construction - fill, embankments	1. Fill in areas to curtail subsidence
2. Fill for jetport	2. Use as preload fill
3. Creation of new land for industrial expansion	3. Extraction of sand and gravel
	4. Creation of artificial landforms (islands, mountains)
	5. Reclaim low land areas
	6. Erosion
	7. Agricultural uses (soil creation/nourishment, mulch for cranberry crops)
	8. Possible use in glass production
	9. Hurricane protection

APPENDIX A: GLOSSARY OF TERMS

1. A great deal of confusion caused by nonstandard use of terms related to soil mechanics has plagued communication concerning description of dredged material. To reduce the use of ambiguous terminology in reference to dredged material, a listing of some pertinent terms, together with a brief definition, is presented here. The terms and definitions are those of the American Society for Testing and Materials.

absorbed water -- Water held mechanically in a soil mass and having physical properties not substantially different from ordinary water at the same temperature and pressure.

adsorbed water -- Water in a soil mass, held by physiochemical forces, having physical properties substantially different from absorbed water or chemically combined water, at the same temperature and pressure.

alluvium -- Soil, the constituents of which have been transported in suspension by flowing water and subsequently deposited by sedimentation.

angle of internal friction, ϕ (degrees) -- Angle between the abscissa and the tangent of the curve representing the relationship of shearing resistance to normal stress acting within a soil.

angle of repose, α (degrees) -- Angle between the horizontal and the maximum slope that a soil assumes through natural processes. For dry granular soils the effect of the height of slope is negligible; for cohesive soils the effect of height of slope is so great that the angle of repose is meaningless.

area ratio of a sampling spoon, sampler, or sampling tube, A_r (D) -- The area ratio is an indication of the volume of soil displaced by the sampling spoon (tube), calculated as follows:

$$A_r = \left[(D_e^2 - D_i^2)/D_i^2\right] \times 100$$

where

D_e = maximum external diameter of the sampling spoon, and

D_i = minimum internal diameter of the sampling spoon at the cutting edge.

base course (base) -- A layer of specified or selected material of planned thickness constructed on the subgrade or subbase for the purpose of serving one or more functions such as distributing load, providing drainage, minimizing frost action, etc.

bentonitic clay -- A clay with a high content of the mineral montmorillonite, usually characterized by high swelling on wetting.

binder (soil binder) -- Portion of soil passing No. 40 (425-μm) U. S. standard sieve.

boulders -- A rock fragment, usually rounded by weathering abrasion, with an average dimension of 12 in. or more.

capillary action (capillarity) -- The rise or movement of water in the interstices of a soil due to capillary forces.

clay (clay soil) -- Fine-grained soil or the fine-grained portion of soil that can be made to exhibit plasticity (putty-like properties) within a range of water contents, and that exhibits considerable strength when air-dry. The term has been used to designate the percentage finer than 0.002 mm (0.005 mm in some cases), but it is strongly recommended that this usage be discontinued, since there is ample evidence from an engineering standpoint that the properties described in the above definition are many times more important.

clay size -- That portion of the soil finer than 0.002 mm (0.005 mm in some cases) (see clay).

cobble (cobblestone) -- A rock fragment, usually rounded or semirounded, with an average dimension between 3 and 12 in.

coefficient of compressibility (coefficient of compression), a_v (L^2F^{-1}) -- The secant slope, for a given pressure increment of the pressure-void ratio curve. Where a stress-strain curve is used, the slope of this curve is equal to $a_v/(1 + e)$.

coefficient of consolidation, c_v (L^2T^{-1}) -- A coefficient utilized in the theory of consolidation, containing the physical constants of a soil affecting its rate of volume change.

$$c_v = k(1 + e)/a_v\gamma_w$$

where

k = coefficient of permeability, LT^{-1} ,

e = void ratio, D ,

a_v = coefficient of compressibility, L^2F^{-1} , and,

γ_w = unit weight of water, FL^{-3} .

NOTE -- In the literature published prior to 1935, the coefficient of consolidation, usually designated c , was defined by the equation:

$$c = k/a_v\gamma_w(1 + e)$$

This original definition of the coefficient of consolidation may be found in some more recent papers and care should be taken to avoid confusion.

coefficient of internal friction -- The tangent of the angle of internal friction (see internal friction).

coefficient of permeability (permeability), $k(LT^{-1})$ -- The rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions (usually 20°C).

coefficient of uniformity, C_u (D) -- The ratio D_{60}/D_{10}, where D_{60} is the particle diameter corresponding to 60 percent finer on the grain-size curve, and D_{10} is the particle diameter corresponding to 10 percent finer on the grain-size curve.

coefficient of volume compressibility (modulus of volume change), $m_v(L^2F^{-1})$ -- The compression of a soil layer per unit of original thickness due to a given unit increase in pressure. It is numerically equal to the coefficient of compressibility divided by one plus the original void ratio, or $a_v/(1 + e)$.

cohesion, c (FL^{-2}) -- The portion of the shear strength of a soil indicated by the term c , in Coulomb's equation, $s = c + p \tan \phi$.

apparent cohesion -- Cohesion in granular soil due to capillary forces.

cohesionless soil -- A soil that when unconfined has little or no strength when air-dried and that has little or no cohesion when submerged.

cohesive soil -- A soil that when unconfined has considerable strength when air dried and that has significant cohesion when submerged.

colloidal particles -- Soil particles that are so small that the surface activity has an appreciable influence on the properties of the aggregate.

compaction -- The densification of a soil by means of mechanical manipulation.

compaction curve (Proctor curve) (moisture-density curve) -- The curve showing the relationship between the dry unit weight (density) and the water content of a soil for a given compactive effort.

compaction test (moisture-density test) -- A laboratory compacting procedure whereby a soil at a known water content is placed in a specified manner into a mold of given dimensions, subjected to a compactive effort of controlled magnitude, and the resulting unit weight determined. The procedure is repeated for various water contents sufficient to establish a relation between water content and unit weight.

compressibility -- Property of a soil pertaining to its susceptibility to decrease in volume when subjected to load.

compression curve -- See pressure-void ratio curve.

compression index, C_c(D) -- The slope of the linear portion of the pressure-void ratio curve on a semi-log plot.

compressive strength (unconfined compressive strength), P_c , $q_u(FL^{-2})$ -- The load per unit area at which an unconfined prismatic or cylindrical specimen of soil will fail in a simple compression test.

consistency -- The relative ease with which a soil can be deformed.

consolidated-drained test (slow test) -- A soil test in which essentially complete consolidation under the confining pressure is followed by additional axial (or shearing) stress applied in such a manner that even a fully saturated soil of low permeability can adapt itself completely (fully consolidate) to the changes in stress due to the additional axial (or shearing) stress.

consolidated-undrained test (consolidated quick test) -- A soil test in which essentially complete consolidation under the vertical load (in a direct shear test) or under the confining pressure (in a triaxial test) is followed by a shear at constant water content.

consolidation -- The gradual reduction in volume of a soil mass resulting from an increase in compressive stress.

initial consolidation (initial compression) -- A comparatively sudden reduction in volume of a soil mass under an applied load due principally to expulsion and compression of gas in the soil voids preceding primary consolidation.

primary consolidation (primary compression) (primary time effect) -- The reduction in volume of a soil mass caused by the application of a sustained load to the mass and due principally to a squeezing out of water from the void spaces of the mass and accompanied by a transfer of the load from the soil water to the soil solids.

secondary consolidation (secondary compression) (secondary time effect) -- The reduction in volume of a soil mass caused by the application of a sustained load to the mass and due principally to the adjustment of the internal structure of the soil mass after most of the load has been transferred from the soil water to the soil solids.

consolidation ratio, U_s(D) -- The ratio of: (1) the amount of consolidation at a given distance from a drainage surface and at a given time, to (2) the total amount of consolidation obtainable at that point under a given stress increment.

consolidation test -- A test in which the specimen is laterally confined in a ring and is compressed between porous plates.

consolidation-time curve (time curve) (consolidation curve) (theoretical time curve) -- A curve that shows the relation between: (1) the degree of consolidation, and (2) the elapsed time after the application of a given increment of load.

deflocculating agent (deflocculant) (dispersing agent) -- An agent that prevents fine soil particles in suspension from coalescing to form flocs.

degree of consolidation (percent consolidation), U(D) -- The ratio, expressed as a percentage, of: (1) the amount of consolidation at a given time within a soil mass, to (2) the total amount of consolidation obtainable under a given stress condition.

deviator stress, Δ, σ (FL^{-2}) -- The difference between the major and minor principal stresses in a triaxial test.

dilatancy -- The expansion of cohesionless soils when subject to shearing deformation.

direct shear test -- A shear test in which soil under an applied normal load is stressed to failure by moving one section of the soil container (shear box) relative to the other section.

effective diameter (effective size), D_{10}, D_e(L) -- Particle diameter corresponding to 10 percent finer on the grain-size curve.

effective porosity (effective drainage porosity), n_e(D) -- The ratio of: (1) the volume of the voids of a soil mass that can be drained by gravity, to (2) the total volume of the mass.

equivalent diameter (equivalent size), D(L) -- The diameter of a hypothetical sphere composed of material having the same specific gravity as that of the actual soil particle and of such size that it will settle in a given liquid at the same terminal velocity as the actual soil particle.

filter (protective filter) -- A layer or combination of layers of pervious materials designed and installed in such a manner as to provide drainage, yet prevent the movement of soil particles due to flowing water.

fines -- Portion of a soil finer than a No. 200 (75-μm) U. S. standard sieve.

floc -- Loose, open-structured mass formed in a suspension by the aggregation of minute particles.

flocculation -- The process of forming flocs.

foundation -- Lower part of a structure that transmits the load to the soil.

foundation soil -- Upper part of the earth mass carrying the load of the structure.

free water (gravitational water) (ground water) (phreatic water) -- Water that is free to move through a soil mass under the influence of gravity.

free water elevation (water table) (ground water surface) (free water surface) (ground water elevation) -- Elevations at which the pressure in the water is zero with respect to the atmospheric pressure.

gradation (grain-size distribution) (soil texture) -- Proportion of material of each grain size present in a given soil.

grain-size analysis (mechanical analysis) -- The process of determining gradation.

gravel -- Rounded or semirounded particles of rock that will pass a 3-in. (76.2-mm) and be retained on a No. 4 (4.75-mm) U. S. standard sieve.

horizon (soil horizon) -- One of the layers of the soil profile, distinguished principally by its texture, color, structure, and chemical content.

"A" horizon -- The uppermost layer of soil profile from which inorganic colloids and other soluble materials have been leached. Usually contains remnants of organic life.

"B" horizon -- The layer of a soil profile in which material leached from the overlying "A" horizon is accumulated.

"C" horizon -- Undisturbed parent material from which the overlying soil profile has been developed.

humus -- A brown or black material formed by the partial decomposition of vegetable or animal matter; the organic portion of soil.

internal friction (FL^{-2}) -- The portion of the shearing strength of a soil indicated by the terms $p \tan \phi$ in Coulomb's equation $s = c + p \tan \phi$. It is usually considered to be due to the interlocking of the soil grains and the resistance to sliding between the grains.

landslide (slide) -- The failure of a sloped bank of soil in which the movement of the soil mass takes place along a surface of sliding.

leaching -- The removal of soluble soil material and colloids by percolating water.

linear expansion, L_E(D) -- The increase in one dimension of a soil mass, expressed as a percentage of that dimension at the shrinkage limit, when the water content is increased from the shrinkage limit to any given water content.

linear shrinkage, L_s(D) -- The decrease in one dimension of a soil mass, expressed as a percentage of the original dimension, when the water content is reduced from a given value to the shrinkage limit.

liquefaction (spontaneous liquefaction) -- The sudden large decrease of the shearing resistance of a cohesionless soil. It is caused by a collapse of the structure by shock or other type of strain and is associated with a sudden but temporary increase of the prefluid pressure. It involves a temporary transformation of the material into a fluid mass.

liquid limit, LL, L_ω, W_L (D) -- (a) The water content corresponding to the arbitrary limit between the liquid and plastic states of consistency of a soil. (b) The water content at which a pat of soil, cut by a groove of standard dimensions, will flow together for a distance of

1/2 in. (12.7 mm) under the impact of 25 blows in a standard liquid limit apparatus.

liquidity index (water-plasticity ratio) (relative water content), B, R_ω, I_L (D) -- The ratio, expressed as a percentage, of: (1) the natural water content of a soil minus its plastic limit, to (2) its plasticity index.

loam -- A mixture of sand, silt, or clay, or a combination of any of these, with organic matter (see humus). It is sometimes called topsoil in contrast to the subsoils that contain little or no organic matter.

Mohr circle -- A graphical representation of the stresses acting on the various planes at a given point.

Mohr envelope (rupture envelope) (rupture line) -- The envelope of a series of Mohr circles representing stress conditions at failure for a given material. According to Mohr's rupture hypothesis, a rupture envelope is the locus of points the co-ordinates of which represent the combinations of normal and shearing stresses that will cause a given material to fail.

moisture content (water content), W (D) -- The ratio, expressed as a percentage, of: (1) the weight of water in a given soil mass, to (2) the weight of solid particles.

muck -- An organic soil of very soft consistency.

mud -- A mixture of soil and water in a fluid or weakly solid state.

normally consolidated soil deposit -- A soil deposit that has never been subjected to an effective pressure greater than the existing overburden pressure.

optimum moisture content (optimum water content), OMC, W_o (D) -- The water content at which a soil can be compacted to a maximum dry unit weight by a given compactive effort.

organic clay -- A clay with a high organic content.

organic silt -- A silt with a high organic content.

organic soil -- Soil with a high organic content. In general, organic soils are very compressible and have poor load-sustaining properties.

peat -- A fibrous mass of organic matter in various stages of decomposition, generally dark brown to black in color and of spongy consistency.

percent compaction -- The ratio, expressed as a percentage, of: (1) dry unit weight of a soil, to (2) maximum unit weight obtained in a laboratory compaction test.

percolation -- The movement of gravitational water through soil (see seepage).

plasticity -- The property of a soil which allows it to be deformed beyond the point of recovery without cracking or appreciable volume change.

plasticity index, I_p, PI, I_ω (D) -- Numerical difference between the liquid limit and the plastic limit.

plastic limit, w_p, PL, P_ω (D) -- (a) The water content corresponding to an arbitrary limit between the plastic and the semisolid states of consistency of a soil. (b) Water content at which a soil will just begin to crumble when rolled into a thread approximately 1/8 in. (3.2 mm) in diameter.

plastic soil -- A soil that exhibits plasticity.

plastic state (plastic range) -- The range of consistency within which a soil exhibits plastic properties.

porosity, n (D) -- The ratio, usually expressed as a percentage, of: (1) the volume of voids of a given soil mass, to (2) the total volume of the soil mass.

preconsolidation pressure (prestress), P_e (FL^{-2}) -- The greatest effective pressure to which a soil has been subjected.

pressure-void ratio curve (compression curve) -- A curve representing the relationship between effective pressure and void ratio of a soil as obtained from a consolidation test. The curve has a characteristic shape when plotted on semilog paper with pressure on the log scale. The various parts of the curve and extensions to the parts of the curve and extensions to the parts have been designated as recompression, compression, virgin compression, expansion, rebound, and other descriptive names by various authorities.

quick condition (quicksand) -- Condition in which water is flowing upwards with sufficient velocity to reduce significantly the bearing capacity of the soil through a decrease in intergranular pressure.

remolded soil -- Soil that has had its natural structure modified by manipulation.

rock -- Natural solid mineral matter occurring in large masses or fragments.

sand -- Particles of rock that will pass the No. 4 (4.75-mm) sieve and be retained on the No. 200 (75-µm) U. S. standard sieve.

seepage (percolation) -- The slow movement of gravitational water through the soil.

seepage force, J (F) -- The force transmitted to the soil grains by seepage.

sensitivity -- The effect of remolding on the consistency of a cohesive soil.

shaking test -- A test used to indicate the presence of significant amounts of rock flour, silt, or very fine sand in a fine-grained soil. It consists of shaking a pat of wet soil, having a consistency of thick paste, in the palm of the hand; observing the surface for a glossy or livery appearance; then squeezing the pat and observing if a rapid apparent drying and subsequent cracking of the soil occurs.

shear strength, s, τ_f (FL^{-2}) -- The maximum resistance of a soil to shearing stresses.

shrinkage index, SI(D) -- The numerical difference between the plastic and shrinkage limits.

shrinkage limit, SL, w_s (D) -- The maximum water content at which a reduction in water content will not cause a decrease in volume of the soil mass.

silt (inorganic silt) (rock flour) -- Material passing the No. 200 (75-μm) U. S. standard sieve that is nonplastic or very slightly plastic and that exhibits little or no strength when air-dried.

silt size -- That portion of the soil finer than 0.02 mm and coarser than 0.002 mm (0.05 mm and 0.005 mm in some cases).

soil (earth) -- Sediments or other unconsolidated accumulations of solid particles produced by the physical and chemical disintegration of rocks, and which may or may not contain organic matter.

soil structure -- The arrangement and state of aggregation of soil particles in a soil mass.

flocculent structure -- An arrangement composed of flocs of soil particles instead of individual soil particles.

honeycomb structure -- An arrangement of soil particles having a comparatively loose, stable structure resembling a honeycomb.

single-grained structure -- An arrangement composed of individual soil particles; characteristic structure of coarse-grained soils.

soil suspension -- Highly diffused mixture of soil and water.

specific gravity of solids, G, G_s, S_s (D) -- Ratio of: (1) the weight in air of a given volume of soil solids at a stated temperature to (2) the weight in air of an equal volume of distilled water at a stated temperature.

apparent specific gravity, G_a, S_a (D) -- Ratio of: (1) the weight in air of a given volume of the impermeable portion of a permeable material (that is, the solid matter including its impermeable pores or voids) at a stated temperature to (2) the weight in air of an equal volume of distilled water at a stated temperature.

bulk specific gravity (specific mass gravity), G_m, S_m (D) -- Ratio of: (1) the weight in air of a given volume of a permeable material (including both permeable and impermeable voids normal to the material) at a stated temperature to (2) the weight in air of an equal volume of distilled water at a stated temperature.

stone -- Crushed or naturally angular particles of rock that will pass a 3-in. (75-mm) sieve and be retained on a No. 4 (4.75-mm) U. S. standard sieve.

strain, ε (D) -- The change in length per unit of length in a given direction.

subbase -- A layer used in a pavement system between the subgrade and base course, or between the subgrade and portland cement concrete pavement.

subgrade -- The soil prepared and compacted to support a structure or a pavement system.

subgrade surface -- The surface of the earth or rock prepared to support a structure or a pavement system.

subsoil -- (a) Soil below a subgrade or fill. (b) That part of a soil profile occurring below the "A" horizon.

thixotropy -- The property of a material that enables it to stiffen in a relatively short time on standing, but upon agitation or manipulation to change to a very soft consistency or to a fluid of high viscosity, the process being completely reversible.

topsoil -- Surface soil, usually containing organic matter.

torsional shear test -- A shear test in which a relatively thin test specimen of solid circular or annular cross section, usually confined between rings, is subjected to an axial load and to shear in torsion. In-place torsion shear tests may be performed by pressing a dentated solid circular or annular plate against the soil and measuring its resistance to rotation under a given axial load.

transported soil -- Soil transported from the place of its origin by wind, water, or ice.

triaxial shear test (triaxial compression test) -- A test in which a cylindrical specimen of soil encased in an impervious membrane is subjected to a confining pressure and then loaded axially to failure.

unconsolidated-undrained test (quick test) -- A soil test in which the water content of the test specimen remains practically unchanged during the application of the confining pressure and the additional axial (or shearing) force.

underconsolidated soil deposit -- A deposit that is not fully consolidated under the existing overburden pressure.

undisturbed sample -- A soil sample that has been obtained by methods in which every precaution has been taken to minimize disturbance to the sample.

unit weight, $\gamma (FL^{-3})$ -- Weight per unit volume.

- dry unit weight (unit dry weight), γ_d, $\gamma_o (FL^{-3})$ -- The weight of soil solids per unit of total volume of soil mass.
- effective unit weight, $\gamma_e (FL^{-3})$ -- That unit weight of a soil which, when multiplied by the height of the overlying column of soil, yields the effective pressure due to the weight of the overburden.
- maximum unit weight, $\gamma_{max} (FL^{-3})$ -- The dry unit weight defined by the peak of a compaction curve.

saturated unit weight, γ_G, γ_{sat} (FL^{-3}) -- The wet unit weight of a soil mass when saturated.

submerged unit weight (buoyant unit weight), γ_m, γ', γ_{sub} (FL^{-3}) -- The weight of the solids in air minus the weight of water displaced by the solids per unit of volume of soil mass; the saturated unit weight minus the unit weight of water.

unit weight of water, γ_ω (FL^{-3}) -- The weight per unit volume of water; nominally equal to 62.4 lb/ft^3 or 1 g/cm^3.

wet unit weight (mass unit weight), γ_m, γ_{wet} (FL^{-3}) -- The weight (solids plus water) per unit of total volume of soil mass, irrespective of the degree of saturation.

zero air voids unit weight, γ_z, γ_s (FL^{-3}) -- The weight of solids per unit volume of a saturated soil mass.

uplift -- The upward water pressure on a structure.

	Symbol	Unit
Unit symbol	u	FL^{-2}
Total symbol	U	F or FL^{-1}

vane shear test -- An in-place shear test in which a rod with thin radial vanes at the end is forced into the soil and the resistance to rotation of the rod is determined.

void -- Space in a soil mass not occupied by solid mineral matter. This space may be occupied by air, water, or other gaseous or liquid material.

void ratio, e (D) -- The ratio of: (1) the volume of void space, to (2) the volume of solid particles in a given soil mass.

critical void ratio, e_c (D) -- The void ratio corresponding to the critical density.

volumetric shrinkage (volumetric change), V_s (D) -- The decrease in volume, expressed as a percentage of the soil mass when dried, of a soil mass when the water content is reduced from a given percentage to the shrinkage limit.

zero air voids curve (saturation curve) -- The curve showing the zero air voids unit weight as a function of water content.

APPENDIX B: EXPLANATION OF SAMPLE NUMBERS

1. The following key explains the number assigned to each sample whose properties are reported herein:

x	-	xxx	-	xx	-	x
Study region (see Table B1)		District within study region (see Table B2)		Study project within District (see Table 1)		Sample No. within District

Table B1

Key to Study Region Abbreviations

Abbreviation	Study Region
A	Gulf States
B	South Atlantic
C	North Atlantic
D	Great Lakes
E	Pacific Coast

Table B2

Key to District Abbreviations

Abbreviations	District
BAL	Baltimore
BUF	Buffalo
CHD	Charleston
CHI	Chicago
DET	Detroit
GAL	Galveston
JAX	Jacksonville
LAD	Los Angeles
MOB	Mobile
NED	New England Division
NOD	New Orleans
NOR	Norfolk
NYD	New York
PHD	Philadelphia
POR	Portland
RID	Rock Island
SAC	Sacramento
SAV	Savannah
SEA	Seattle
SFD	San Francisco
SPD	St. Paul
WIL	Wilmington

APPENDIX C: CLASSIFICATION TEST DATA

1. The classification test data accumulated during this study are presented below in Tables C1 through C22; an explanation of the sample numbers appears in Appendix B.

Table C1

Classification Test Data - Galveston District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
A-GAL-HC-A	CH		0.016	94	99	28	71	9.17
A-GAL-SN-B	CH		0.0027	96	120	31	89	4.09
A-GAL-CC-1	CH			98	117	36	81	5.69
A-GAL-FC-2	CH		0.014	89	56	21	35	2.13
A-GAL-TC-3	CH			99	160	35	125	4.29
A-GAL-TC-4	CH		0.0015	94	102	29	73	3.45
A-GAL-BC-5	CL		0.086	53	32	21	11	1.12
A-GAL-IW-6	CH		0.007	98	85	31	54	4.73
A-GAL-CC-7	CH		0.008	87	73	23	50	3.12
A-GAL-CC-8	CH		0.0023	89	109	27	82	5.24
A-GAL-CC-9	CH		0.024	76	105	28	77	3.14
A-GAL-SN-10	CH			99	127	34	93	4.95
A-GAL-HC-11	CH			99	124	35	89	5.52
A-GAL-HC-12	CH		0.018	88	82	23	59	6.63
A-GAL-HC-13	CH		0.014	89	105	31	74	7.19
A-GAL-HC-14	CH		0.008	88	76	22	54	2.98
A-GAL-MB-15	SM		0.11	27				6.69
A-GAL-MB-16	CH		0.067	68	50	17	33	2.08
A-GAL-MC-17	CH			99	114	34	80	4.19
A-GAL-MC-18	CH			99	113	32	81	3.78

Table C2

Classification Test Data - New Orleans District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
A-NOD-MR-A	SP-SM	0.086	0.13	6				0.49
A-NOD-BC-B	SP-SM	0.081	0.14	7				0.32
A-NOD-MR-1	CH			99	133	41	92	0.24
A-NOD-MR-2	SP	0.11	0.15	3				0.21
A-NOD-MR-3	CL		0.033	74	40	20	20	2.26
A-NOD-NH-4	CH		0.0017	98	110	36	74	3.94
A-NOD-NH-5	CH		0.012	96	64	25	39	2.43
A-NOD-NH-6	SP-SM	0.082	0.18	8				0.51
A-NOD-SW-7	SP-SM	0.079	0.14	9				0.23
A-NOD-SW-8	CH		0.0036	94	81	30	51	3.95
A-NOD-SW-9	CH		0.013	94	63	24	39	3.58
A-NOD-SW-10	CH		0.0074	97	73	26	47	3.77
A-NOD-SW-11	CL		0.027	85	47	22	25	
A-NOD-CR-12	CH		0.026	81	65	21	44	0.95
A-NOD-CR-13	CH		0.0039	97	96	31	65	3.85
A-NOD-CR-14	CL		0.017	71	43	18	25	2.50
A-NOD-BH-15	CL		0.043	82	36	19	17	1.96
A-NOD-WL-16	SM	0.054	0.14	16				0.78

Table C3

Classification Test Data - Mobile District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
A-MOD-MB-A	CH		0.0027	98	129	32	97	10.64
A-MOD-BH-1	CH		0.004	97	147	43	104	5.92
A-MOD-BH-2	CH		0.01	90	130	43	87	3.89
A-MOD-BH-3	CH		0.01	82	126	38	88	5.72
A-MOD-PS-4	SP	0.17	0.30	2				4.37
A-MOD-PS-5	CH		0.0024	99	142	49	93	7.85
A-MOD-PS-6	CH		0.062	68	81	28	53	0.58
A-MOD-PS-7	CH		0.0045	84	105	36	69	5.17
A-MOD-GP-8	CH		0.0025	99	169	48	121	6.30
A-MOD-PB-9	SP	0.21	0.36	1				0.17
A-MOD-PB-10	SP	0.19	0.33	1				0.18
A-MOD-PB-11	SM		0.11	36	49	29	20	3.15
A-MOD-PB-12	CH		0.024	82	133	34	99	5.88
A-MOD-PB-13	CH		0.014	94	202	58	144	6.19
A-MOD-CP-14	SP	0.24	0.42	1				0.22
A-MOD-CP-15	SP	0.18	0.27	1				0.22
A-MOD-CP-16	CH		0.065	63	68	32	36	8.37
A-MOD-MB-17	CH			99	140	45	95	8.24
A-MOD-MB-18	CH		0.0032	97	138	42	96	5.83
A-MOD-MB-19	CH		0.0059	96	114	36	78	5.57
A-MOD-MB-20	SP	0.13	0.16	4				5.85
A-MOD-MB-21	CH			99	140	42	98	7.05
A-MOD-MB-22	CH		0.0034	97	114	37	77	7.92

Table C4

Classification Test Data - Jacksonville District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
A-JAD-IW-12	SP	0.10	0.17	2				
A-JAD-IW-13	SP	0.11	0.16	4				
A-JAD-IW-14	SP	0.14	0.21	2				
A-JAD-OW-44	SP	0.10	0.14	3				
A-JAD-OW-45	SP	0.10	0.19	3				
A-JAD-OW-46	SP	0.092	0.14	4				
A-JAD-OW-47	SP	0.12	0.14	4				
A-JAD-TH-57	SM	0.0013	0.086	35	34			
A-JAD-TH-58	SP-SM	0.072	0.095	11				
A-JAD-TH-59	SM	0.05	0.12	17				
A-JAD-TH-60	MH		0.022	82	109	47	62	
A-JAD-TH-61	SP-SM	0.075	0.16	10				
A-JAD-TH-62	MH		0.044	73	105	44	61	
A-JAD-TH-63	MH		0.028	74	135	59	76	
A-JAD-TH-64	MH		0.0066	87	118	54	64	
A-JAD-TH-65	MH		0.0068	87	156	60	96	
A-JAD-TH-66	MH	0.0014	0.0063	95	194	69	125	
A-JAD-TH-67	MH		0.0057	95	171	71	100	
A-JAD-TH-68	SC	0.0013	0.13	24	32	23	9	
A-JAD-TH-69	SC	0.0014	0.092	33	42	22	20	
A-JAD-TH-70	CH		0.048	78	154	40	114	
A-JAD-TH-71	CH		0.079	51	94	29	65	
A-JAD-TH-72	CH		0.052	88	168	42	126	
A-JAD-TH-73	CH		0.08	51	98	31	67	
A-JAD-TH-74	SM		0.089	49	59	43	16	
A-JAD-TH-75	MH		0.0098	88	137	54	83	
A-JAD-TH-76	MH		0.014	72	131	53	78	
A-JAD-TH-77	SM		0.13	50	85	40	45	
B-JAD-SL-1	SP	0.13	0.34	2				
B-JAD-SL-2	SP	0.18	0.68	1				

(Continued)

Table C4 (Continued)

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
B-JAD-MH-3	GP	0.32	7.50	3				
B-JAD-MH-4	SP	0.11	0.25	4				
B-JAD-MH-5	SW	0.45	4.10	2				
B-JAD-MH-6	SW	0.26	2.20	4				
B-JAD-MH-8	SP	0.16	0.28	3				
B-JAD-MH-9	SP	0.16	0.51	3				
B-JAD-PB-15	SP	0.32	0.58	2				
B-JAD-PB-16	SP	0.25	0.49	2				
B-JAD-JH-17	SP	0.17	0.18	2				
B-JAD-JH-18	SP	0.13	0.16	2				
B-JAD-JH-19	SP	0.12	0.16	4				
B-JAD-JH-20	SP	0.16	0.26	3				
B-JAD-JH-21	SP	0.12	0.30	4				
B-JAD-JH-22	SP	0.14	0.25	2				
B-JAD-JH-23	SP	0.09	0.15	3				
B-JAD-JH-24	SP	0.15	0.23	2				
B-JAD-JH-25	SP	0.13	0.17	2				
B-JAD-JH-26	SP	0.09	0.15	3				
B-JAD-JH-27	SP	0.13	0.16	2				
B-JAD-JH-28	SP	0.11	0.16	3				
B-JAD-JH-29	SP	0.15	0.22	3				
B-JAD-JH-30	SP	0.11	0.23	1				
B-JAD-JH-31	SP	0.12	0.17	3				
B-JAD-JH-32	SM	0.0074	0.16	16				
B-JAD-JH-33	SP-SM	0.079	0.15	8				
B-JAD-JH-34	SW-SM	0.04	0.34	12				
B-JAD-JH-36	SP	0.17	0.26	3				
B-JAD-JH-37	SP	0.15	0.25	2				
B-JAD-JH-38	SP	0.12	0.30	4				
B-JAD-JH-40	SM	0.093	0.16	7				

(Continued)

Table C4 (Concluded)

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
B-JAD-JH-43	SP	0.12	0.45	4				
B-JAD-FH-48	SP	0.26	0.53	1				
B-JAD-FH-49	SP	0.14	0.30	2				
B-JAD-FH-50	SP	0.16	0.30	2				
B-JAD-FH-51	SP	0.33	1.30	1				
B-JAD-FH-53	CH		0.057	92	199	49	150	
B-JAD-FH-54	CH		0.05	76	142	36	106	
B-JAD-FH-55	CH		0.05	75	147	38	109	
B-JAD-FH-56	CH		0.071	61	104	30	74	
B-JAD-CH-78	CH		0.072	63	51	25	26	
B-JAD-CH-79	CH		0.07	67	53	21	32	
B-JAD-CH-80	CH		0.013	92	119	33	86	
B-JAD-CH-81	CH		0.0031	93	118	29	89	
B-JAD-CH-82	CH		0.088	51	61	22	39	

Table C5

Classification Test Data - Savannah District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
B-SAV-SH-B	MH		0.031	87	78	51	27	8.68
B-SAV-SH-A	SP	0.47	0.91	1				0.13
B-SAV-AI-1	CH		0.0075	95	194	59	135	9.02
B-SAV-AI-2	CH		0.0034	91	181	49	132	9.61
B-SAV-BH-3	CH		0.0036	98	273	90	183	6.77
B-SAV-BH-4	SC	0.042	0.47	12	30	19	11	1.30
B-SAV-SH-5	CH		0.025	93	89	38	51	5.56
B-SAV-SH-6	CH		0.0068	91	86	34	52	9.20

Table C6

Classification Test Data - Charleston District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
B-CAR-CH-A	CH		0.016	83	146	53	93	7.41
B-CAR-CH-B	CL		0.076	59	42	20	22	4.30
B-CAR-CH-1	OH			100	105	29	76	
B-CAR-CH-2	MH			91	114	52	62	
B-CAR-CH-3	CH			87	140	42	98	

Table C7

Classification Test Data - Wilmington District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
B-WIL-WH-C	SC		0.15	46	42	23	19	3.37
B-WIL-WH-A	SP	0.23	0.54	1				
B-WIL-WH-B	SM	0.0066	0.16	26	32	29	3	2.80
B-WIL-MC-1	SP	0.19	0.75	1				
B-WIL-MC-2	SC	0.004	0.43	24	40	16	24	
B-WIL-MC-3	SP	0.13	0.53	4				
B-WIL-MC-4	SP	0.26	0.65	1				
B-WIL-MC-5	SP	0.14	0.35	2				
B-WIL-MC-6	SP	0.13	0.16	2				
B-WIL-MC-7	SP	0.22	0.43	2				
B-WIL-MC-8	SP	0.15	0.20	2				
B-WIL-MC-9	SP	0.15	0.39	1				
B-WIL-MC-10	SP	0.14	0.16	1				
B-WIL-MC-11	SP	0.17	0.33	1				
B-WIL-MC-12	SC	0.004	0.14	30	30	18	12	
B-WIL-MC-13	SP	0.13	0.16	2				
B-WIL-MC-14	SP	0.10	0.16	3				
B-WIL-MC-15	SP-SM	0.072	0.15	11	22	21	1	
B-WIL-MC-16	SP	0.13	0.16	3				
B-WIL-MC-17	SP	0.10	0.15	3				
B-WIL-MC-18	SP	0.12	0.16	2				
B-WIL-MC-19	SP	0.095	0.16	4				
B-WIL-MC-20	SP	0.13	0.17	2				
B-WIL-MC-21	CH		0.0025	98	102	30	72	
B-WIL-MC-22	SP	0.25	0.73	1				
B-WIL-SP-23	SC	0.0014	0.18	37	39	15	24	
B-WIL-SP-24	SP	0.16	0.44	3				
B-WIL-SP-25	SP	0.16	0.43	5				
B-WIL-SP-26	CH		0.071	65	86	29	57	
B-WIL-SP-27	CH			97	140	48	92	
B-WIL-SP-28	SC		0.17	38	67	16	51	
B-WIL-SP-29	SM	0.07	0.17	12	21			
B-WIL-SP-30	SC	0.005	0.25	14	28	20	8	
B-WIL-SP-31	SC	0.06	0.41	16	37	21	16	
B-WIL-SP-32	MH		0.0041	94	153	68	85	
B-WIL-WH-33	CH		0.011	90	125	39	86	
B-WIL-WH-34	CH		0.0082	93	153	47	106	

Table C8

Classification Test Data - Norfolk District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
C-NOR-NH-A	SC	0.0021	0.18	36	29	17	12	1.80
C-NOR-NH-I	CL		0.028	78	41	20	21	1.31
C-NOR-NH-B	CH	0.0018	0.026	95	70	37	33	6.55

Table C9

Classification Test Data - Baltimore District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
C-BAL-BH-B	MH		0.0068	93	73	38	35	7.54
C-BAL-BH-1	MH		0.0019	99	123	48	75	
C-BAL-BH-2	MH		0.0024	99	123	48	75	
C-BAL-BH-3	MH		0.0032	99	123	48	75	
C-BAL-BH-4	MH		0.0026	99	123	48	75	

Table C10

Classification Test Data - Philadelphia District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
C-PHD-DR-1	SW	0.09	0.56	8				
C-PHD-DR-2	SP	0.084	0.22	7				
C-PHD-DR-3	SP	0.084	0.36	3				
C-PHD-DR-4	SM		0.96	13				
C-PHD-DR-5	CL		0.0046	91				
C-PHD-DR-6	CL		0.0095	87				
C-PHD-DR-7	ML		0.032	77.4				
C-PHD-DR-8	CL		0.0064	97.5				
C-PHD-DR-9	CL		0.022	88				
C-PHD-DR-10	CL		0.005	82.5				
C-PHD-DR-12	SP	0.08	0.23	7				

Table C11

Classification Test Data - New York District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
C-NYD-YJ-A	CH		0.011	98	149	55	94	9.74
C-NYD-NB-1	CH		0.03	64	68	28	40	3.75
C-NYD-NY-2	SP	0.14	0.26	1				0.64
C-NYD-NY-3	SP	0.23	0.44	1				0.32
C-NYD-BR-4	CH		0.016	97	110	40	70	6.41
			0.019					
C-NYD-HR-5	CH		0.013	97	90	36	54	5.94
C-NYD-YJ-6	CH		0.014	97	125	47	78	6.38
C-NYD-NB-7	CH			97	149	51	98	8.98

Table C12

Classification Test Data - New England Division

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
C-NED-BB-PE-1	OH		0.13	53	67	39	28	
C-NED-BB-GE-2	GW	0.30	9.70	1				
C-NED-BB-GE-3	SP	0.14	0.38	1				
C-NED-BB-GE-4	SP	0.14	0.36	1				
C-NED-BB-GE-5	SW	0.18	0.72	0.5				
C-NED-BB-GE-6	SW	0.25	1.50	0.5				
C-NED-BB-GE-7	GW	2.0	10.40	1				
C-NED-BB-GE-8	SP	0.15	6.30	1				
C-NED-BB-GE-9	SW	0.23	1.50	1				
C-NED-BH-GE-1	GP	5.00	78.00	1				
C-NED-BH-GE-7	GP	0.30	14.00	8				
C-NED-BH-GE-8	GP	0.49	8.80	3				
C-NED-BH-KE-6	SC		0.14	48	32	23	9	
C-NED-BH-KE-9	OL		0.055	74	47	33	14	
C-NED-BH-KE-10	OH		0.034	92	72	33	39	
C-NED-BH-KE-11	OH		0.0068	96	74	30	44	
C-NED-BH-KE-12	OH		0.016	86	67	29	38	
C-NED-BH-KE-13	OH		0.0085	96	80	32	48	
C-NED-BH-KE-14	OH		0.013	97	80	32	48	
C-NED-BH-KE-15	OH		0.054	68	50	29	21	
C-NED-BH-KE-16	OH		0.016	92	81	33	48	
C-NED-BH-KE-17			0.083	50	40	26	14	
C-NED-BH-KE-18	OH		0.049	71	72	31	41	
C-NED-BH-KE-19	ML		0.075	59	43	26	17	
C-NED-BH-KE-20	OH		0.03	83	71	30	41	
C-NED-BH-KE-21	CL		0.068	63	31	22	9	
C-NED-BH-KE-22	CL		0.011	87	41	21	20	
C-NED-BH-KE-23	OH		0.012	93	121	52	69	
C-NED-SR-GE-1	SP	0.11	0.27	0.5				
C-NED-SR-GE-2	SP	0.12	0.32	1				
C-NED-SR-GE-3	SP	0.25	1.40	1				
C-NED-SR-GE-4	SP	0.16	0.54	1				
C-NED-SR-GE-5	SP	0.17	0.35	0.5				
C-NED-SR-GE-6	SP	0.14	0.28	1				
C-NED-TR-GE-2	OH		0.031	81	142	82	60	

(Continued)

Table C12 (Concluded)

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
C-NED-TR-GE-3	OH		0.045	68	152	74	78	
C-NED-TR-GE-4	SP	0.083	0.32	9				
C-NED-TR-GE-5	SP		0.16	13				
C-NED-TR-GE-6	OH		0.029	91	122	62	60	
C-NED-TR-GE-7	OH		0.037	81	93	51	42	
C-NED-TR-GE-9	OH		0.09	50	57	38	19	
C-NED-TR-GE-10	OH		0.025	94	130	65	65	
C-NED-TR-GE-11	OH		0.017	93	95	47	48	
C-NED-TR-GE-12	OH		0.021	92	122	62	60	
C-NED-TR-GE-13	OH		0.016	98	133	58	75	
C-NED-WH-GE-1	SP	0.12	0.34	1				
C-NED-WH-GE-2	SW	0.19	1.30	1				
C-NED-WH-GE-4	SP	0.16	0.41	1				
C-NED-WH-GE-5	SP	0.17	0.33	1				

Table C13

Classification Test Data - Detroit District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
D-DET-SR-A	SP	0.16	0.29	3				1.98
D-DET-RR-1	CH		0.014	94	82	38	44	13.45
D-DET-RR-2	CH		0.016	91	75	40	35	7.99
D-DET-RA-3	CH		0.011	97	109	40	69	8.76
D-DET-RA-4	CH		0.03	78	97	54	43	8.26
D-DET-TH-5	CH		0.007	96	79	31	48	5.41
D-DET-SR-6	SC		0.17	44	48	22	26	3.11
D-DET-SR-7	CH		0.038	73	68	32	36	6.19
D-DET-SB-8	CH		0.0086	97	111	34	77	8.56
D-DET-SB-9	CH		0.008	99	109	41	68	8.09

Table C14

Classification Test Data - Rock Island District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
D-RID-MR-A	SP	0.25	0.71	3				0.39
D-RID-MR-1	SP	0.36	0.68	1				0.35
D-RID-MR-2	SP	0.27	0.40	1				0.17
D-RID-MR-3	SP	0.24	0.50	0.5				0.67
D-RID-MR-4	SP	0.36	0.74	0.5				0.12
D-RID-MR-5	SP	0.28	0.55	1				0.09
D-RID-MR-6	SP	0.46	1.10	0.5				0.28

Table C15

Classification Test Data - Buffalo District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
D-BUF-RH-1	CL	0.0033	0.055	74	36	23	13	1.97
D-BUF-AH-2	ML	0.0042	0.038	92	32	23	9	1.80
D-BUF-SH-3	CH		0.017	88	81	29	52	4.38
D-BUF-LH-4	MH		0.02	89	54	33	21	4.59
D-BUF-FH-5	CL		0.016	94	42	24	18	2.94

Table C16

Classification Test Data - St. Paul District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
D-SPD-MR-1	SP	0.20	0.31	3				0.28
D-SPD-MR-2	SP	0.24	0.55	1				0.37
D-SPD-MR-3	SP	0.25	0.44	1				0.27
D-SPD-DH-4	SM	0.0014	0.16	38	21	19	2	2.57
D-SPD-DH-5	CH		0.12	53	55	27	28	5.08
D-SPD-DH-6	SM	0.034	0.19	23				0.49
D-SPD-DH-7	ML	0.0017	0.03	89	37	32	5	4.51

Table C17

Classification Test Data - Chicago District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
D-CHI-IR-1	SP	0.22	0.70	2				1.73
D-CHI-IR-2	SP	0.17	0.56	1				0.24
D-CHI-IR-3	SP	0.16	0.30	2				9.17
D-CHI-IR-4	SP	0.26	0.41	1				0.37
D-CHI-GB-5	MH		0.009	95	161	69	92	10.28

Table C18

Classification Test Data - Portland District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
E-POD-CQ-1	SP	0.17	0.24	0.5				
E-POD-CQ-2	SP	0.17	0.24	1				
E-POD-CQ-3	SP	0.17	0.24	1				
E-POD-CQ-4	SP	0.23	0.42	0				
E-POD-CQ-5	SW	0.24	1.60	1				
E-POD-CQ-6	SP	0.45	2.70	1				
E-POD-CR-7	SP	0.26	0.70	1				
E-POD-CR-8	SP	0.17	0.37	0.5				
E-POD-CR-9	SP	0.26	0.85	1				
E-POD-CR-10	SP	0.27	1.00	1				
E-POD-CR-11	SP	0.32	0.92	0.5				
E-POD-CR-12	SP	0.28	0.62	1				
E-POD-CR-13	SP	0.23	0.53	1				
E-POD-MC-14	SP	0.16	0.24	0.5				
E-POD-MC-15	SP	0.16	0.25	0.5				
E-POD-MC-16	SP	0.15	0.24	0				
E-POD-MC-17	SP	0.14	0.19	1				
E-POD-MC-18	SP	0.21	0.27	0.5				
E-POD-YB-19	SP	0.16	0.26	0				
E-POD-YB-20	SP	0.16	0.26	0				
E-POD-YB-21	SP	0.16	0.26	1				
E-POD-YB-22	SP	0.16	0.26	1				
E-POD-YB-23	SP	0.16	0.23	1				
E-POD-YB-24	SP	0.16	0.24	1				
E-POD-YB-25	SP	0.16	0.25	0				
E-POD-YB-26	SP	0.16	0.25	1				
E-POD-CB-27	SP	0.16	0.25	1				
E-POD-CB-28	SP	0.17	0.36	1				
E-POD-CB-29	SP	0.16	0.26	1				
E-POD-CB-30	SP	0.19	0.40	1				
E-POD-CB-31	SP	0.16	0.25	3				
E-POD-CB-32	SP	0.16	0.27	2				
E-POD-CB-33	SP	0.18	0.37	1				
E-POD-CB-34	SP	0.17	0.36	1				
E-POD-CB-35	SP	0.18	0.30	1				
E-POD-CB-36	SP	0.17	0.32	1				
E-POD-CB-37	SP	0.18	0.37	1				

Table C19

Classification Test Data - Seattle District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
E-SEA-GH-1	ML	0.0015	0.055	70	40	30	10	6.53
E-SEA-GH-2	SM	0.0067	0.14	33				3.44
E-SEA-GH-3	SP	0.12	0.23	1				0.66
E-SEA-WR-4	SP	0.14	0.19	1				0.38
E-SEA-WR-5	CH		0.04	90	86	32	54	5.76
E-SEA-WR-6	SM	0.0048	0.32	29	36	29	7	4.77

Table C20

Classification Test Data - Sacramento District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
E-SAC-SR-1	SP	0.23	0.46	1				0.28
E-SAC-SR-2	SP	0.27	0.39	1				0.42
E-SAC-SR-3	CL		0.036	89	37	23	14	2.28
E-SAC-SR-4	CH		0.011	90	58	21	37	3.13
E-SAC-ST-5	SC	0.0014	0.23	40	29	18	11	
E-SAC-ST-6	CL		0.015	87	47	19	28	
E-SAC-ST-7	SC	0.004	0.18	39	35	21	14	
E-SAC-ST-8	CH		0.0085	99	51	25	26	
E-SAC-ST-9	CH		0.018	83	58	23	35	
E-SAC-ST-10	SP-SM	0.065	0.36	11				
E-SAC-ST-11	SP-SM	0.082	0.25	7				
E-SAC-ST-12	SM	0.04	0.16	16				
E-SAC-ST-13	MH	0.0014	0.042	91	99	42	57	
E-SAC-ST-20	SP-SM	0.064	0.37	16				
E-SAC-ST-21	CH		0.031	75	66	21	45	
E-SAC-ST-22	CH		0.0053	94	98	43	55	
E-SAC-ST-23	CL	0.0014	0.07	61	41	19	22	
E-SAC-ST-24	CL-ML	0.0043	0.069	63	28	23	5	
E-SAC-ST-25	SC	0.0059	0.14	45	41	25	16	
E-SAC-ST-26	CH		0.038	68	59	22	37	
E-SAC-ST-27	CH		0.011	93	53	22	30	
E-SAC-ST-28	SP-SM	0.06	0.23	12				
E-SAC-ST-29	OH		0.012	99				
E-SAC-ST-30	CL		0.048	67	37	17	20	
E-SAC-ST-31	CL		0.035	87	41	22	19	
E-SAC-ST-32	CL		0.016	76	44	18	26	

Table C21

Classification Test Data - Los Angeles District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
E-LAD-MB-1	SP	0.13	0.15	2				
E-LAD-MB-2	SP	0.14	0.16	1				
E-LAD-MB-3	SP	0.12	0.15	1				
E-LAD-MB-4	SP	0.14	0.16	1				
E-LAD-MB-5	SP	0.11	0.16	2				
E-LAD-MB-6	SP	0.16	0.22	1				
E-LAD-MB-7	SP	0.12	0.16	2				
E-LAD-MB-8	SP	0.11	0.16	5				
E-LAD-MB-9	SP	0.12	0.16	3				
E-LAD-OH-10	SP-SM	0.085	0.14	5				
E-LAD-OH-11	SM	0.07	0.099	8				
E-LAD-OH-12	SM	0.035	0.14	26				
E-LAD-OH-13	SP-SM	0.13	0.42	5				
E-LAD-OH-14	SP	0.095	0.17	4				
E-LAD-OH-15	SM	0.035	0.099	24				
E-LAD-MI-16	SP	0.16	0.28	1				
E-LAD-MI-17	SP	0.16	0.22	2				
E-LAD-MI-18	SP	0.18	0.60	2				
E-LAD-MI-19	SC	0.03	0.28	14				
E-LAD-MI-20	SW-SM	0.10	0.66	7				
E-LAD-MI-21	SP	0.17	1.20	3				
E-LAD-SD-22	SP	0.08	0.16	3				
E-LAD-SD-23	SP-SM	0.071	0.17	11				
E-LAD-SD-24	SP	0.14	0.38	3				
E-LAD-SD-25	SP	0.12	0.47	3				

Table C22

Classification Test Data - San Francisco District

Sample	USCS	D_{10} mm	D_{60} mm	Percent Passing No. 200 Sieve	LL	PL	PI	OC %
E-SFD-SF-1	CH		0.078	58	59	24	35	
E-SFD-RC-2	CH		0.056	81	79	32	47	
E-SFD-OK-3	CH		0.0061	99	78	31	47	
E-SFD-RI-4	CH		0.018	87	57	24	33	
E-SFD-SR-5	CH		0.02	96	72	27	45	
E-SFD-PS-6	CL		0.10	55	48	22	26	
E-SFD-MI-7	CH		0.016	99	84	34	50	
E-SFD-SB-8	SC		0.16	48	43	23	20	
E-SFD-NR-9	CL		0.055	64	44	25	19	
E-SFD-PC-10	CH		0.0076	99	86	31	55	
E-SFD-SB-11	SM	0.009	0.26	15				
E-SFD-SB-12	SP	0.12	0.30	5				
E-SFD-SB-13	SM	0.014	0.17	15				
E-SFD-SB-14	CL		0.027	80	48	25	23	
E-SFD-SB-15	SC	0.004	0.14	43	32	25	7	
E-SFD-SB-16	SP	0.12	0.23	3				

APPENDIX D: NOTATION

a_v	Coefficient of compressibility, sq ft/lb
c	Unit cohesion, tsf
Cc	Compression index
Cc'	Compression index for remolded specimens
c_v	Coefficient of consolidation, sq in./day
D_{10}	Effective size, mm
e	Void ratio
H	One-half specimen thickness, ft
k	Coefficient of permeability, cm/sec
LL	Liquid limit
ℓ	Distance between inlet and outlet in dredged material containment area, ft
OC	Organic content, percent
OMC	Optimum moisture content, percent
p, p_1, p_2	Consolidation pressure, tsf
PI	Plasticity index
PL	Plastic limit
T	Time, year
t_{50}	Time for 50 percent primary consolidation, min
w	Water content, percent
W_s	Weight of solids, g
W_w	Weight of water, g
x	Distance from outlet, ft

γ_d Dry density, pcf

γ_w Unit weight of water, pcf

σ Effective normal stress, tsf

τ Shear strength, tsf

ϕ Angle of internal friction, deg

ϕ_a Apparent angle of internal friction, deg

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Bartos, Michael J
Classification and engineering properties of dredged material / by Michael J. Bartos, Jr. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1977.
119, [51] p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; D-77-18)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under DMRP Work Unit 5C02.
References: p. 117-119.

1. Dredged material. 2. Soil classification. 3. Soil properties. 4. Soil sampling. I. United States. Army. Corps of Engineers. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; D-77-18.
TA7.W34 no.D-77-18