DREDGING RESEARCH PROGRAM

CONTRACT REPORT DRP-93-3

GEOTECHNICAL FACTORS IN THE DREDGEABILITY OF SEDIMENTS

Report 1
GEOTECHNICAL DESCRIPTORS
FOR SEDIMENTS TO BE DREDGED

by

S. Joseph Spigolon

SJS Corporation
2220 No. 13th Court
Coos Bay, Oregon 97420-3018

November 1993

Report 1 of a Series

The Dredging Research Program (DRP) is a seven-year program of the U.S. Army Corps of Engineers. DRP research is managed in these five technical areas:

Area 1 - Analysis of Dredged Material Placed in Open Water
Area 2 - Material Properties Related to Navigation and Dredging
Area 3 - Dredge Plant Equipment and Systems Processes
Area 4 - Vessel Positioning, Survey Controls, and Dredge Monitoring Systems
Area 5 - Management of Dredging Projects

Dredging Research Program Report Summary
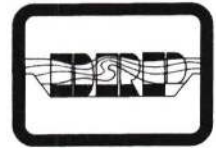
US Army Corps of Engineers
Waterways Experiment Station

Geotechnical Factors in the Dredgeability of Sediments; Report 1: Geotechnical Descriptors for Sediments to be Dredged (CR DRP-93-3)

ISSUE: Existing soil descriptor systems are not universally used or even understood by all groups involved in designing, planning, and executing dredging projects. The disparities increase risk factors and thus the cost of such projects.

RESEARCH: The primary objectives of a Dredging Research Program (DRP) work unit entitled "Descriptors for Bottom Sediments to Be Dredged" are as follows:

- Identify appropriate geotechnical engineering parameters, develop standard dredged material descriptors based on the parameters, and correlate the parameters with dredge equipment performance.

- Identify techniques suitable for measurement of appropriate geotechnical parameters.

A resource review was conducted that included examination of the published literature and interviews with individuals knowledgeable in the area of interest. The results will be used as input to meet both objectives of the work unit.

SUMMARY: The study identified the minimum soil identification test data necessary to establish appropriate descriptors. Suggestions were made for a standard set of descriptive terms and for a new classification system for identifying the dredgeability of in situ sediments.

AVAILABILITY OF REPORT: The report is available through the Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, telephone number 601 634-2355. National Technical Information Service (NTIS) report numbers may be requested from WES Librarians.

To purchase a copy of the report, call NTIS at 703 487-4780.

About the Author: Dr. S. Joseph Spigolon is an engineering consultant, SJS Corporation, Coos Bay, OR.

Point of Contact: Dr. Jack Fowler, Geotechnical Laboratory, WES, Principal Investigator for this work unit.

For further information about the DRP, contact Mr. E. Clark McNair, Jr., Manager, DRP, at 601 634-2070.

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WATERWAYS EXPERIMENT STATION
3909 HALLS FERRY ROAD
VICKSBURG, MISSISSIPPI 39180-6199
PHONE : (601)634-2502

STRUCTURES
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SCALE

500   0   500 m

AREA OF RESERVATION = 2.7 sq km

PREFACE

This report was prepared under Contract No. DACW39-88-P-0769 for the US Army Engineer Waterways Experiment Station (WES) under Dredging Research Program (DRP) Technical Area 2, Work Unit No. 32471, "Descriptors for Bottom Sediments to be Dredged." The DRP is sponsored by Headquarters, US Army Corps of Engineers (HQUSACE). Technical Monitors for Technical Area 2 were Messrs. Barry W. Holliday and David A. Roellig.

This report was written by Dr. S. Joseph Spigolon, SJS Corporation, Coos Bay, Oregon, under the supervision of Dr. Jack Fowler, Principal Investigator, Soil Mechanics Branch (SMB), Soil and Rock Mechanics Division (S&RMD), Geotechnical Laboratory (GL), WES. Additional supervision was provided by Mr. G. B. Mitchell, Chief, SMB, GL; Dr. Don C. Banks, Chief, S&RMD, GL; and Dr. W.F. Marcuson III, Director, GL. Dr. Banks and Mr. Hardy J. Smith were the Technical Area Managers for Technical Area 2, "Material Properties Related to Navigation and Dredging," of the DRP. Mr. E. Clark McNair, Jr., and Dr. Lyndell Z. Hales, Coastal Engineering Research Center (CERC), WES, were Manager and Assistant Manager, respectively, of the DRP. Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., were Director and Assistant Director, respectively, of CERC, which oversees the DRP.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

For further information on this report or on the
Dredging Research Program, please contact
Mr. E. Clark McNair, Program Manager, at
(601) 634-2070.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

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

Multiply	By	To Obtain
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
feet per minute	0.005080	metres per second
inches	0.02540	metres
pounds (mass)	0.4535924	kilograms
pounds per inch	0.1785797	kilograms per metre
square inches	0.0006451600	square metres

SUMMARY

    This study consisted of a review of the published literature and personal interviews with Corps of Engineers personnel, dredging contractors, and dredging consultants. The investigation was limited to soil materials; a study of rock descriptors is being conducted separately. The objectives of the study were to (a) identify the physical properties of sediments that directly affect the performance (dredgeability) of the dredging process, (b) identify the geotechnical engineering properties of sediments to be dredged that will directly indicate or readily infer the dredgeability properties of the sediments, and (c) identify the available methods for describing and possibly classifying the geotechnical properties of sediments to be dredged in a standard, internationally understood manner. The desired technical approach to this study was given in the DRP Development Report: " . . . standard dredging-related descriptors for in situ material . . . need to be developed such that engineering properties are either directly given or can be readily inferred for engineering applications such as dredgeability prediction.

    The minimum soil properties test data necessary for the engineering design of dredging projects and for the estimation, planning, and execution of dredging operations include:

    <u>a</u>.   *Properties of the undisturbed soil mass*: the compactness (relative density) of granular soils, the consistency (unconfined compressive strength) and structure of intact cohesive soils, in situ density, and degree of saturation (gas content).

    <u>b</u>.   *Properties of the disturbed soil material*: grain size distribution (including maximum size, median (D_{50}) size, percent fines), the Atterberg limits, the shape and hardness of coarse grains, and the presence of organics, shells, cementation, or debris.

    <u>c</u>.   *Special properties*: the rheologic properties of a slurry, sedimentation rate in salt water, and bulking factors, may be reported separately as the result of special laboratory investigations.

    Soil properties data can be communicated in two basic ways: (1) as raw numerical soil identification test data, and (2) using descriptors. A descriptor is defined as "A word, phrase, or alphanumeric symbol used to identify an item." Descriptors for dredging-related soil properties can be either (a) descriptive terms (words or phrases), (b) an arrangement of soil properties into classification groups, with each group representing an assessment or rating of dredgeability, (c) test results from a specific test device, or suite of devices, or (d) some combination of these.

    Numerical test data can be communicated easily using computer database methods, especially if a standard format is used. The data can be easily manipulated using conventional statistical data reduction methods for such values as average, median, standard deviation, etc. The information can then be interpreted and applied according to the knowledge and experience of the individual contractor or engineer. The format does not easily lend itself to

grouping or categorization on soil profile drawings or in specifications or project records. Furthermore, this method does not indicate or infer dredgeability directly.

Descriptive terms provide word equivalents to the numbers resulting from soil identification tests. When numerical definitions for the words are consistent, word descriptors are practical for communicating information. This method is typified by geotechnical textbook soil descriptions and by the Permanent International Association of Navigation Congresses (PIANC) Soil Classification System. The PIANC system lacks standardized definitions of geotechnical terms used throughout the dredging industry. Geotechnical engineers in the United States use the Unified Soil Classification System (USCS). The two systems define grain size terms and the strength (consistency) of fine grained soils differently.

Classification indicates a *rating* or *grouping* of soil properties into pre-defined classes according to expected or potential behavior in service. Most existing engineering classification systems are based on the expected behavior of the disturbed soil as a structural medium after compaction and they are all based solely on the texture of the soil, i.e., grain size and plasticity. Unfortunately, the USCS does not, by itself, include all of the applicable descriptor terms needed for a dredging classification system.

A new Dredging Classification System is proposed in the report that considers all of the dredging processes: excavation, removal, transport, and deposition and all types of dredging mechanisms and equipment. Eight sediment categories are defined on a first level:

    <u>a</u>.   Group R -- Rock and Coral
    <u>b</u>.   Group S -- Shale and Cemented Soils
    <u>c</u>.   Group B -- Boulders and Cobbles
    <u>d</u>.   Group G -- Clean Granular Soils
    <u>e</u>.   Group F -- Friable Mixed-Grain Soils
    <u>f</u>.   Group C -- Cohesive Soils
    <u>g</u>.   Group O -- Highly Organic Soils
    <u>h</u>.   Group M -- Fluid Mud

Additional research will be needed to define the geotechnical test criteria for defining the major categories. Each major category will need definitions for necessary sub-categories.

GEOTECHNICAL FACTORS IN THE
DREDGEABILITY OF SEDIMENTS

GEOTECHNICAL DESCRIPTORS FOR
SEDIMENTS TO BE DREDGED

PART I: INTRODUCTION

1.   It is manifest that the lack of precise communication can cause misunderstandings between the owner and the contractor in dredging contracts. A review of dredging claims submitted by contractors to the Corps of Engineers will clearly show the need for a consistent and well-defined set of descriptor terms to characterize the sediments to be dredged.

2.   There is no consistent, standard system for describing and classifying the sediments to be dredged for navigation puposes and for communicating that information to all persoons involved in a dredging project. Virtually all geotechnical engineering soil classification systems were developed for land-based earthwork construction and are not, therefore, directly applicable to the needs of the dredging industry.

3.   In a soil classification report, the Permanent International Association of Navigation Congresses (PIANC 1984) stated:

> It is essential, in the dredging industry, that all those having to communicate information on soils and rocks should employ the same technical language. This calls for a uniform system of classification, particularly at the international level, so as to obviate any misunderstanding.

4.   Geotechnical engineers, geologists, environmental engineers, biologists, estimators, dredging equipment manufacturers, and dredging contractor personnel have methods for describing sediments. These groups do not agree on a common system for characterizing and describing sediment properties. The dredging literature, both published and unpublished (including contract documents), abounds with sediment descriptions that are inconsistent and often convey no specific geotechnical engineering meaning (e.g., What is mud? What are stones?). Testing methods among the various disciplines vary. The grain size limits for defining coarse-grained soils used by geotechnical engineers are different than those used by geologists, sedimentologists, and environmentalists. The water content of a soil is expressed as a percent of dry weight of the soil by geotechnical engineers.

Other scientists and engineers define water content as a percentage of the total mass, soil plus water. Individual dredging contracting firms often have their own internal soil description and dredgeability evaluation methodology (Huston 1970).

5.   The cost to the dredging industry, both the Corps of Engineers and other owners, and the dredging contractors, in claims, litigation, lost time, and the other effects of incomplete understanding of terminology cannot be calculated easily. Most of the dredging-industry-related persons interviewed by this writer, as part of this study, felt that the amount is a continuing, sizeable percentage of the total spent on dredging contracts.

Background

6.   During the past 10 to 15 years, the role of the US Army Corps of Engineers in dredging activities has changed dramatically. A major increase has occurred in the level of contract dredging. Environmental concerns, the consequences of the oil embargo of 1973, dredged material management, and cost consciousness are all major considerations. These factors, and a desire to foster the competitiveness of United States dredging firms in a world market, have motivated the Corps to implement the Dredging Research Program (DRP).

Objective of the Study

7.   This report is the first phase of the topic area: "Standard Dredging-Related Descriptors for In Situ Material," a part of the Material functional area of the DRP. The desired technical approach to this topic area was given by Calhoun et al. (1986):

> "The development of standard dredging-related descriptors for in situ material is critically needed. The methods of observation and the descriptors now used represent a mixture adopted (sometimes not adapted) from diverse fields such as environmental engineering, geology, soil mechanics and foundation engineering. Descriptors need to be developed such that engineering properties are either directly given or can be readily inferred for engineering applications such as dredgeability prediction. The term 'dredgeability' is given to mean the ability to excavate underwater with respect to known or assumed equipment, methods, and in situ material characteristics."

For purposes of this report, the definition of *dredgeability* quoted above has been modified to encompass the effect of sediment properties on the entire

dredging process--"The term 'dredgeability' is given to mean the ability to excavate underwater, remove to the surface, transport, and deposit sediments with respect to known or assumed equipment, methods, and in-situ material characteristics."

8. The topic area has been further divided into (a) soil and (b) rock materials. This report considers only in-situ *soil* sediments to be dredged; rock descriptors are being studied separately. Both maintenance dredging and new work dredging of soils, offshore and/or onshore, are considered. The objectives of this study were to:

a. Identify the physical properties of sediments that directly affect the performance (dredgeability) of the dredging process;

b. To identify the geotechnical engineering properties of sediments to be dredged that will directly indicate or readily infer the dredgeability properties of the sediments; and

c. To identify the available methods for describing and possibly classifying the geotechnical properties of sediments to be dredged in a standard, internationally understood manner.

9. The geotechnical properties of in-situ soil can be described in two basic ways: (1) as raw identification test data, using numbers or identifying words, and (2) by means of descriptors. Webster's Dictionary defines a descriptor as:

"A word or phrase (as an index term) used to identify an item . . . especially in an information retrieval system; also: an alphanumeric symbol used similarly."

Descriptors for dredging-related soil properties can be either (a) descriptive terms that use words to represent and summarize the raw identification test data, (b) an arrangement of soil properties into classification groups, represented by letter-number symbols, with each group suggesting a rating of dredgeability, (c) test results from a specific test device, or suite of devices, which will directly give, or infer, the dredgeability, or (d) some combination of these.

Scope of the Report

10. The first phase of the projected six year study of this topic area consisted of a survey of available resources, including the published literature and interviews with knowledgeable persons in the dredging industry. This

report contains the results of the survey as it applies to the objectives stated above.

11. The published literature in the fields of geotechnical engineering, dredging operations, and related areas was examined. The published literature of geotechnical engineering related to soil identification and soil description has been growing steadily for over 60 years and is voluminous; therefore, only a few of the pertinent references are given in this report. Where possible and appropriate, the original reference on a subject has been included. Where a substantial literature review is contained in a newer, authoritative paper, that document is often referenced instead. The literature of dredging-related soils descriptions, mostly contained in conference proceedings, has developed only in the past 10 to 15 years. And, only in the past few years has it shown a growing geotechnical engineering influence.

12. Another important resource to this study was the knowledge, experience, and perspectives of dredging industry experts. This phase of the resource survey was accomplished by interviews, conducted in person, or occasionally by telephone. The persons interviewed came from three major groups: US Army Corps of Engineers personnel in geotechnical groups and in dredging operations groups, dredging contractors, and dredging-related private consultants. The persons interviewed, and their affiliations, are listed in Appendix A. Although not directly quoted, the opinions expressed by the persons interviewed are reiterated throughout the text.

Organization of the Report

13. Part II of the report examines the behavior of various soil types during the dredging operations of dislodging, removing, transporting, and disposing of the sediments. The study of the relationship of the *dredgeability* properties of sediments and their *geotechnical engineering* properties starts with a summary review of the physical mechanisms of the dredging processes. Dredging equipment is described in terms of the dredging mechanisms employed. The dredgeability properties of soil sediments are defined. The geotechnical properties that are important for directly indicating or implying the behavior of soils in dredging operations are identified.

14. Part III reviews the methods for geotechnical description of soil properties--as numerical identification test data and as *descriptors*. The value and limitations of identification test data communication are explored. Three types of descriptor methods are defined--descriptive terms, classification symbols, and special devices. The advantages and limitations of each of the descriptor methods are discussed.

15. Part IV presents the various descriptive term systems that are in common use for describing soils for engineering purposes. Recommendations are made for standardized descriptive word terms for use in a dredging-related soil description system.

16. In Part V, existing soil classification systems are considered for possible use, in whole or in part, in a potential dredging classification system. A new Dredging Classification System is proposed and discussed.

17. Part VI presents conclusions from this literature survey report. Recommendations are made for further work to define a useable, standard system for communicating soils properties data in a form that will directly indicate, or infer, dredgeability.

PART II: DREDGEABILITY PROPERTIES OF SEDIMENTS

18. Several factors affect the estimating, planning, selection of dredging equipment, scheduling, and operating procedures of the dredging process for a specific project. The independent variables that affect overall dredging performance on a specific project are (Bray 1975, 1979):

  a. Equipment type and rated capacity;

  b. Characteristics of the sediment to be dredged--locations, depths, volumes, and the physical properties of the soil or rock;

  c. Geometry of the site--depth of water, length and width of dredging area, thickness of material to be dredged, location of disposal area;

  d. Physical conditions at the dredging site--wind, rain, fog, temperature, waves and swell, currents, tides, and local traffic;

  e. Operational concerns--contractor's management and crew efficiency, equipment breakdowns, fiscal capability, availability of equipment and personnel;

  f. Contractual constraints--contract period and timing, environmental concerns.

Of these variables, *only the effect of soil properties on equipment performance* will be discussed in this report. The influence of the other factors on the effectiveness of the total dredging project is beyond the scope of this study.

Dredging Processes and Equipment

19. The term *dredgeability*, as used here, refers only to that part of the total production rate and/or required fuel energy for a specific type and configuration of dredging equipment that is directly influenced by the properties of the soil/rock to be dredged. The dredging process involves (Verbeek 1984):

  a. *Excavation* of the in-situ material, which involves a loosening or dislodgement of individual material grains or of a cohesive group of particles;

  b. *Removal* of the material from the bottom to a hydraulic pump or to a mechanical transport system;

  c. *Transportation* of the material to a disposal site by means of a slurry pipeline or mechanical conveyances; and

  d. *Disposal* of the material on land or into a water disposal area.

20. The mechanisms used in the four stages of a dredging operation are shown in Table 1. Each of the dredging stages is accomplished using one or a combination of two basic methods:

    a. *Hydraulic or pneumatic*--using fluid flow in the form of high-velocity, high-volume water or air streams for in situ erosion and/or for removal and for the transport of the soil in a slurry;

    b. *Mechanical*--involving the use of buckets, grabs, scoops, shovels, knife blades or teeth in the dislodgement and removal of the soil, and of vessels or other conveyances to transport the soil.

The final disposal action by the contractor may also include manipulation of the soil in the disposal area, such as shaping, or even drying and compacting the soil.

21. Dredging equipment is usually classified according to the specific methods (hydraulic or mechanical) used for dislodging, removing, and transporting the soil. Several published references discuss dredging equipment in general. Among these are Bray (1975, 1979), Murden (1984), Reid (1986), International Association of Ports and Harbors (IAPH 1987), and Verhoeven, de Jong, and Lubking (1988). The common types of dredging equipment for performing the various stages of the dredging process are shown in Table 2. The dredge type designations of Table 2 are those used in World Dredging, Mining & Construction (WDMC 1991).

Dredgeability Properties of Soil Sediments

22. The dredgeability of a soil deposit is directly dependent on the type of dredging equipment used. Considering the dredging mechanisms described in Table 1, the dredgeability properties of soil sediments during the four stages of dredging operations are:

    a. *Excavation* properties:

        (1) Suctionability,
        (2) Erodability (scourability),
        (3) Cuttability (affected by friability),
        (4) Scoopability, and
        (5) Flowability (underwater slope instability).

    b. *Removal and transport* properties:

        (1) Pumpability (affected by rheologic properties of slurry),
        (2) Abradability (abrasiveness in a pipeline),
        (3) Clay balling (affected by stickiness),
        (4) Sedimentation rate in a hopper, and
        (5) Amount of bulking.

Table 1	
Dredging Mechanisms	
Excavation Mechanisms	
Direct Suction	Suction is applied to a pipe inserted into extremely soft soil. External pressure causes the soil to enter the pipe as a soft mass at nearly 100% of in-situ volume, i.e., with no excess water.
Direct Hydraulic Erosion (Scour)	The flow of a high velocity, high volume water stream across the surface of a clean granular material causes scour, which pushes and lifts the grains into the water stream. Due to the high volume of water required, the resulting slurry contains much less than 100% of in situ volume, i.e., low solids content.
Mechanical Dislodgement -- Cutting	If soil/rock is dense granular, friable (easily crumbled or pulverized), or cohesive, cutting it with a rotating or fixed blade or ripping it with plows or knives moves the soil/rock particles into a water stream to form a low solids content slurry.
Mechanical Dislodgement -- Scooping	In space restricted areas or locations where hydraulic processing is not feasible, scooping of the soil/rock may be done with a bucket, shovel, or clamshell.
Removal Mechanisms	
Hydraulic Pipeline	A suction pipeline is used to move the soft mass or the hydraulic slurry from the excavation area at the bottom to the pumping system.
Mechanical Containers	A bucket, scoop, shovel, clamshell, bucket ladder, bucketwheel, or other container is used to move the material from the bottom to the surface; often this is the same device used for excavation.
Transport Mechanisms	
Hydraulic Pipeline	The particles, clumps of material, or clay balls, are pumped in a pipeline as a soil-water slurry.
Mechanical Containers	The material is moved in the hold of a hopper ship, a barge (self propelled or towed), or a land based device such as a truck or conveyor belt.
Disposal Mechanisms	
Hydraulic Pipeline	The pipeline slurry is directly discharged into a land or water disposal area.
Mechanical Devices	Materials are discharged from mechanical containers by: bottom discharge from hopper ship or barge; direct dumping from the transport unit; mechanical removal using a scraper, bucket, clamshell, or high pressure water stream.

		Table 2		
		Characteristics of Dredging Equipment		
Dredge Type	Excavation Method	Removal Method	Transport Method	Disposal Method
		Hopper Dredges		
Cutting Draghead Hopper	Mechanical dislodgement using knives or blades; hydraulic erosion.	Hydraulic pipeline suction using pump.	Soil settles in vessel hopper; vessel moves to disposal site.	Bottom dump from hopper ship or barge; side casting from hopper ship.
Direct Suction Draghead Hopper	Hydraulic erosion; direct suction.			
Bucket Hopper	Mechanical dislodgement, scooping by mechanical bucket system.	Mechanical bucket.		
		Pipeline Dredges		
Cutter Suction	Mechanical dislodgement using rotary cutter.	Hydraulic pipeline suction using pump.	Pipeline as a soil-water slurry.	Direct discharge on land or water disposal site as a soil-water slurry.
Direct Suction	Hydraulic erosion; direct suction.			
Suction Dustpan	Direct suction; scour using water jets			
Bucket Wheel Suction	Mechanical dislodgement, scooping with buckets.			
		Mechanical Dredges		
Bucket Ladder	Mechanical dislodgement, scooping with buckets.	Series of buckets.	Barge; land-based conveyor belt; trucks.	Bottom dump or scraper to unload barges; direct discharge from belt or trucks.
Clamshell	Mechanical dislodgement, scooping with clamshell.	Clamshell bucket.		
Dipper	Mechanical dislodgement, scooping with bucket.	Dipper bucket.		
Dragline	Mechanical dislodgement, scooping with dragline bucket.	Dragline bucket.		
Backhoe	Mechanical dislodgement, scooping with backhoe.	Backhoe bucket.		

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<u>c</u>.   *Disposal* properties:

   (1)   Dumpability (affected by friability and stickiness),
   (2)   Sedimentation rate in a disposal area,
   (3)   Amount of bulking, and
   (4)   Compactability.

23.   Each of the dredgeability properties given above can be determined by a full scale test using a particular sediment and equipment combination. This, in effect, constitutes test dredging. This will invariably prove impractical because of the high cost, unless the site is completely uniform (highly unlikely) and the test dredging can actually be done economically. The usual practice is to determine the geotechnical properties of the sediment with a site investigation, i.e., making in-situ strength tests, obtaining samples, and making laboratory tests of the samples.

24.   There are very few, if any, valid theoretical treatments of the physical behavior of sediments for each of the dredging mechanisms described, and those that exist are still in the developmental stage. Therefore, none of the dredgeability properties given above can be directly indicated by any of the geotechnical properties of a soil sediment. However, there do exist a number of empirical relationships between the dredgeability properties and the geotechnical properties of soil sediments. A description of the physical mechanisms, and the geotechnical properties needed for readily inferring them, i.e., for arriving at a reasonable estimate of dredgeability, are given in the following sections.

<u>Suctionability during excavation</u>

25.   Direct suction during dredging excavation occurs when the sediment enters the hydraulic suction pipe at, or very near, its in-situ density, i.e. with little or no diluting water. For direct suction to develop, the shear strength of the soil must be so low that it will flow into the suction pipe like a viscous liquid. Erosion or mechanical cutting are not needed. If a soil is extremely soft or loose, the differential pressure caused by direct suction on a pipe imbedded in the soil mass will cause a shear failure in the soil and a flow of the soil mass into the pipe. This can occur with an extremely soft cohesive soil or a fluid mud, typically composed of silts and clays, having a water content well above its liquid limit, and with a high void ratio. Granular soils, in which self weight causes a vertical effective stress, derive shear strength from grain to grain contact and do not easily flow in a constricted pipe except as a high water content slurry.

26. Therefore good direct suctionability is typified by an extremely low in-situ shear strength, very high silt and clay content, liquid and plastic limits consistent with high fines content, very low in-situ density, and a high liquidity index (greater than 1.0).

Erodability during excavation

27. Erodability is the relative amount of energy required to excavate particles, or aggregations of particles, by scour with a flowing fluid. If a granular soil is free of cohesive fines and is relatively loose, the grains can be easily eroded, or scoured, hydraulically or pneumatically. They can then be entrained in a high velocity, high volume water stream as a slurry. Therefore, the soil must be loose, coarse grained, have a low fines content, and a low plasticity.

28. The forces on a soil particle in hydraulic dislodgement involve its own body weight, the friction force between soil particles, the energy required to lift a particle over its neighbors, the pushing force of current flow, and the suction force of the current due to shear forces (Salzmann 1977; Christensen 1983; and others). Additionally, there are physico-chemical forces of attraction and repulsion between the particles. The critical shear force, the fluid shear needed to erode a soil, is a function of the grain sizes of the soil mixture and of its shear strength, which in turn is a function of compactness or consistency.

29. As shown by Hjulstr"m (1939), hydraulic erosion, or scour, works best with sand-sized particles without cohesive fines. The minimum water velocity for traction and suspension occurs in fine sand sizes, about 0.2 to 0.4 mm. If the grains are coarser, the energy needed to erode the soil and suspend the grains in a slurry increases because of the body weight of the particles. In finer soils, the required shear force (erosion energy) is higher because of the cohesion forces between the clay particles. Shells, because of their flat shape, require a much higher tractive force than spherical grains.

30. For large particles, such as nonplastic silt, sand, gravel, and boulders (i.e., relatively free of plastic clay), the inter-particle physico-chemical forces are much smaller than the particle weight and are, therefore, of little consequence. Such soils can be dislodged by a sufficiently powerful hydraulic current.

31. In soils with a high clay content, the physico-chemical forces are dominant and the body weight of individual particles becomes insignificant.

Partheniades (1972), in his paper on the erosion and deposition of cohesive sediments, discusses this question:

> The substantial difference between these two groups of sediment (granular and cohesive) lies not so much in their mechanical gradation but in the relative importance of the interparticle physico-chemical attractive and repulsive forces. Under proper environmental conditions, such as the presence of slight salinity, the net effect of these forces is attractive. Colliding suspended fine particles then tend to cling to each other forming agglomerations known as flocs, of sizes and settling velocities much higher than those of the individual particles. This phenomenon, known as flocculation, is the main cause of deposition of fine sediments. The same net attractive forces provide the main resistance to erosion of cohesive sediment beds. In the absence of these forces, a fine-sediment bed would have practically no resistance to erosion, whereas the slightest degree of agitation would prevent most of a fine sediment from settling.

Because of these forces, simple suction of grains or flocs is not practically possible in sedimented (consolidated) cohesive soil masses and cutting becomes necessary. Then, the undrained shear strength of the soil becomes the dominant factor. However, some dispersed (unflocculated) cohesive soils exist in a low density slurry in harbor bottoms. Such soils, referred to as "fluid muds," can be easily excavated hydraulically.

32. Erodibility properties of shells have been investigated by Mehta and Christensen (1977). They noted that the size and shape of a shell determines its airfoil characteristics. Critical bed shear stress is dependent on near-bed turbulence, the shape and size of a shell, and shell bed geometry.

33. Leussen and Nieuwenhuis (1984) concluded that the major parameters for erodability of a sand are angle of internal friction of the sand, angle of friction between soil and cutting blade, porosity and permeability of the sand, and the dilatency tendency of the sand. Vanoni (ASCE 1975) stated that the critical shear stress of a cohesive soil increases with: (a) unconfined compressive strength, (b) plasticity index, (c) percent clay, and (d) decreasing median size. These factors are, however, all interrelated.

Friability during excavation

34. Friability is the facility with which a soil will crumble or pulverize upon cutting or crushing. Soils to be dredged often contain a large range of grain sizes, even in the well-sorted (uniform) deposits encountered in maintenance dredging. The distinction between granular and cohesive soils is not straightforward. Friability appears to be a distinguishing factor. A friable soil such as a clean or silty sand can be loosened, removed, and transported

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hydraulically. Other soils, with some cohesiveness, will require cutting or scraping for pulverization, i.e., to loosen the particles. As the cohesiveness of the clay becomes dominant, the soil may no longer pulverize, but will cut into large clumps or clods.

35. Friable soils have a very low, or zero, plasticity index. According to Wintermeyer (1926):

> "Soils may be divided into two classes designated as plastic and friable, and the degree of plasticity or friability is indicated by the plastic range [plasticity index], the greater ranges indicating the more plastic soils. "(As water is added) . . . in increasing quantities to a plastic soil it passes from the solid or semisolid state into a plastic state and then into the liquid state. The friable soils, on the other hand, pass directly from the solid to the liquid state." Furthermore, "The silty friable soils differ from the sandy friable soils in that they require a greater percentage of moisture before they reach the point of transition to the liquid state."

36. The Atterberg limits tests are made only on that portion of a sample which is finer than 0.42 mm (no. 40 screen). Terzaghi (1926) quoted Atterberg's classification of plasticity:

a. *Friable* soils have a plasticity index less than 1;

b. *Feebly plastic* soils have a plasticity index between 1 and 7;

c. *Medium plastic* soils have a plasticity index between 7 and 15;

d. *Highly plastic* soils have a plasticity index greater than 15.

37. Friable soils include gravel, sand, some silts, mica, diatoms, and peat. In mixed grain soils, such as: sandy clayey gravel, clayey sand, etc., the "stickiness" of the clay fraction determines friability. If the liquidity index is high (water content near or above the liquid limit), the clay fraction will not be sticky and a granular soil will be friable at all clay contents. If the granular soil has a low liquidity index (water content near or below the plastic limit) the clay fraction will break into small, hard clods along with the coarse grains. For granular soils (cobbles, gravel, sand) with Plasticity Index greater than 7 and with a liquidity index between, say, 0.1 to 0.9 the friability will be dependent on the amount of -No. 40 screen material and its plasticity (see also the discussion of Dumpability presented below). Based on this discussion, the important geotechnical properties for determining friability are grain size distribution, clay content, clay plasticity, and water content (liquidity index).

Cuttability during excavation

38. Cutting, ripping, plowing, or jetting are used to dislodge granular soils that are too dense or too fine to scour, friable soils, and cohesive soils.

The resulting particles, clumps of particles, or clods can then be entrained in a high velocity, high volume water stream. Cuttability is the relative ease with which a sediment can be excavated by shearing with a blade, knife, or plow. This is a direct function of the in-situ shear strength of the soil or rock, the imposed stress conditions, the hydrostatic pressure, the orientation of the cutting surface, and soil friction with, or adhesion to, the cutting surface.

39. The cutting forces on a saturated sand have been theoretically studied by Miedema (1984, 1985, 1986, 1989), Steeghs (1985a, 1985b), and van Os and van Leussen (1987). During the rapid cutting of a sand or any other granular soil, there is an attempt to dilate, i.e., increase in volume. If the permeability is low, volume change is inhibited and a water suction (negative pore water pressure) develops, causing an increase in shear strength. This effect is greater the lower the permeability of the soil; the finer the soil the lower the permeability.

40. The underwater cutting of soils during dredging is very similar to the structural behavior of soils during agricultural tillage (Gill and Vanden Berg 1968; Dalin and Pavlov 1970). Tillage involves large plastic deformations. The soil resistance to tillage is a function of the shear strength of the soil, which in turn is a function of grain size, grain shape, compactness or consistency, density, and water content.

41. Miedema (1989) explained that at very low cutting velocities, there is no cavitation and the cutting force is a linear function of relative compactness, density of water, velocity of cut, square of cut height, width of cut, shear strain, and varies inversely with permeability. Miedema then stated:

> ". . . for cutting velocities in the range from 0.5 to 5 m/sec the cutting force is dominated by the phenomenon dilatency (cavitation), so the contributions of gravitational, cohesive, adhesive, and inertial forces can be neglected. . . . "When the cutting velocity increases, the pore pressure will decrease until the absolute pore pressure reaches vapor pressure, when cavitation starts . . . [and the cutting force will] . . . remain at a constant level, which depends on water depth . . . ." i.e., cutting force increases linearly with depth.

At cavitation velocities, the required excavation energy (force per unit of volume) is a function only of shear strength, adhesion angle, blade angle, and blade height/cut thickness ratio, and hydrostatic pressure (depth x unit weight of water).

42. Reporting on a laboratory investigation of the cutting of clay underwater, Joanknecht and Lobanov (1980) and Lobanov and Joanknecht (1980)

indicated that the important soil parameters were in situ shear strength, plasticity, water content, density, and adhesion of clay to the steel blade.

43. Cuttability is directly related to the in-situ shear strength (compactness/consistency/cementation) which, in turn, is directly affected by in-situ density, degree of saturation, grain size distribution, clay content and clay mineral type (reflected in the Atterberg limits), adhesion to the cutting surface, and amount of cementation, if any.

Scoopability during excavation

44. A scoop (bucket, clamshell, etc.) uses a cutting edge to dislodge a mass of soil mechanically. As described above, the resistance of granular soil is affected by negative pore water pressure caused by rapid shear; the finer the granular soil the greater the resistance. The cutting resistance of a cohesive soil is directly related to shear strength as measured by its consistency. Properties that govern scoopability are shear strength, grain size distribution, percent fines, low plasticity (low stickiness), and adhesion to the metal cutting surface.

45. The energy required to scoop soils is a function of the in-situ compactness or consistency, adhesion to the cutting surface, in-situ density, grain size distribution, clay content, clay type (Atterberg limits), and cementation.

Slope instability (flowability) during excavation

46. Soil slopes that are undercut by a dredging machine (such as a rotary cutter head) to slope angles steeper than their natural angle will probably experience slope failures and will flow into the excavation. Cohesionless soils will temporarily stand on slopes up to about one vertical to one horizontal, dependent on relative density, the denser the soil, the steeper and longer before failure and flow. Stiff to hard cohesive soils will stand on steep slopes, approaching vertical, for long periods of time before degrading. Soft soils will fail when a critical height is reached.

47. Underwater slopes of homogeneous soils will be stable at slope angles that are dependent on the type of soil (cohesive or cohesionless), the in situ shear strength, and the water depth.

Pumpability of sediments in a hydraulic pipeline

48. Hydraulic removal and transport involves the use of a high volume, high velocity water stream in a tube (pipeline) in which soil particles are moved as a slurry. This requires that the soil be friable, or easily disintegrated or

dispersed into individual grains, flocs, or small aggregations. Harbor muds, because they already exist as a low density slurry, act as a friable soil. Clods or clumps of sedimented cohesive soil, if sufficiently small and coherent, can also be moved hydraulically and some may degrade in the slurry to individual particles or to a pumpable paste.

49. Pumpability factors. The factors that directly affect the energy needed (pumpability) for pipeline transport of sediments are (Herbich 1975 and others):

a. Factors of the sediment SOLIDS:
(1) Median grain size (d50);
(2) Maximum grain size (must be capable of passing through the pump);
(3) Degree of dispersion, or uniformity, of the grain size distribution (which indicates the relative amounts of the various grain size fractions present);
(4) Grain angularity and shape;
(5) Amount of silt and clay, (which affects the rheologic properties of the slurry); and
(6) Plasticity of the -0.42 mm (-No. 40 screen) fraction (which determines the tendency to form clay balls).

b. Factors of the transporting FLUID:
(1) Fluid density; and
(2) Fluid viscosity.

c. Factors of the EQUIPMENT GEOMETRY:
(1) Pipe diameter;
(2) Pipe length;
(3) Configuration (no. of elbows);
(4) Interior surface texture (roughness); and
(5) Pipe material.

d. Factors of the SLURRY:
(1) Concentration;
(2) Distribution of grain sizes over the pipe cross-section;
(3) Presence and amount of clay balls (lumps); and
(4) Velocity profile of the fluid.

50. Rheologic properties of a slurry. A viscous fluid has properties that are a function of the *rate* of shear deformation. Both initial (threshhold) shear strength and viscosity are functions of the shear rate; therefore, the energy needed to pump a viscous fluid varies as the slurry velocity. According to Verhoeven, de Jong, and Lubking (1988), the rheologic properties of a pipeline slurry are of concern when mud content (-63 micron, No. 230 screen) exceeds about 35 percent of total solids content and the slurry density is between about 1200 and 1400 grams/litre. A soil slurry with a density below about 1200 grams/litre

behaves like plain water. Threshold shear and viscosity increase with total
solids concentration and with mud content between 35 and 100 percent.

Abrasiveness in a hydraulic pipeline

51. The factors that determine the wear behavior, or abrasion, of
hydraulic dredge parts are (de Bree, Begelinger, and de Gee 1980):

  a. Shape and design: shaping, assembly of components, surface
      condition;

  b. Materials used: composition, structure, mechanical properties;

  c. Slurry velocity: local relative velocity between water-soil mixture
      and dredge part;

  d. Slurry direction: local angle of attack;

  e. Soil concentration: in the slurry/mixture; and

  f. Composition of the soil: grain size distribution, grain shape,
      grain mineralogy (hardness).

52. The wear of cutting surfaces, pumps, and pipelines due to abrasion
was directly related to the angularity and hardness (mineralogical composition)
of soil grains by the dredging operations personnel and contractors interviewed
for this report (see Appendix A). Frequent reference was made to the excessive
wear of pipelines and equipment encountered during the massive dredging
operations of volcanic ash from the Columbia River following the eruption of
Mount St. Helens in 1980. Turner (1984a, 1984b) references his experience, and
that of others, with Mississippi River dredging regarding wear factors related
to grain shape. He indicated that wear increases with grain angularity.

53. According to Turner (1984a), wear varies as the 0.8 power of median
diameter, D_{50}; i.e., the larger the particle the greater the wear, at a slightly
less than linear rate. When comparing soils of two different median grain sizes,
the ratio of the median size, to 0.8 power, is the relative wear. As an example,
a fine gravel will cause 24.2 times as much wear as a fine sand, all other
factors remaining the same.

54. A study of wear in dredge equipment parts was summarized in a
research report by Addie and Pagalthivarthi (1989):

  a. Wear increases as velocity increases to the third power.

  b. Wear decreases linearly as concentration increases.

  c. Wear of 1.0 mm particles compared to 0.1 mm was 20 times (1.3 power)
      greater; 0.3 versus 0.1 mm, wear was 6 times (1.65 power) greater.

55. Turner (1984a) also indicates that the relative abrasiveness for a
change in grain angularity from well rounded to angular is a factor of two. This

appears to be a minor consideration when compared to the relative changes in abrasiveness that occur for the normal random variation of median grain size within a fairly "homogeneous" granular deposit.

Clay ball formation in a pipeline

56. Sediments containing little or no clay (-0.002 mm) are friable, i.e., they will crumble or degrade easily. Clay particles have an affinity for each other, the larger the proportion of clay in the sediment, the greater the cohesiveness. For equal amounts of clay sizes, the intensity of the cohesiveness is a function of clay mineral type. This is reflected in the Atterberg limits of the clay--the liquid limit and the plasticity index. Plastic clays (high PI) excavated by cutting or scooping do not degrade friably; rather, they remain as small clods or clumps. As the clumps are moved in a hydraulic pipeline, the flow pattern forms them into clay balls. They may retain their original size, or two or more may aggregate into a larger clay ball.

57. Based on an ongoing research effort by Richter and Leshchinsky (1991), clay ball formation in a pipeline is a function of plasticity, in situ consistency, velocity of the slurry, and the length of pipeline and number of bends. Clay ball formation in a hopper is a function of both plasticity and in-situ consistency. At high relative consistency (relatively hard), the clay will degrade at a plasticity index (PI) less than 25, but there is virtually no degradation at PI greater than 25, i.e., the clay soil will form clay balls rather than degrade to smaller particles. At low relative consistency (softer soil), there is rapid degradation at PI less than 25, slow degradation at PI between 25 and 35 and no degradation at PI greater than 35.

58. According to Verbeek (1984), and a companion statement by Sorensen (1984): "Clay balls . . . are likely to be formed when the liquid limit is between 35 to 50 percent and 80 to 120 percent, the plastic limit is higher than 20 to 30 percent, the density of the soil is higher than 1500-1700 (grams/litre) and shear strength is greater than about 25 Kpa." (Author's Note: These statements are quoted here as they were published; however, the assertions are not considered fully valid and should not be accepted without verification).

Mechanical removal and transport

59. Mechanical removal methods use bucket-type containers, such as scoops, shovels, or grabs to move the soil as a wet, coherent mass. These are mainly used when the soil is not friable or otherwise cannot effectively be carried in a fluid stream. In close quarters, such as around existing docks,

bucket systems may be used to remove granular materials also. Invariably the container for removal is the same one used in soil loosening process. The bucketwheel dredge unites the mechanical and hydraulic methods, producing a high solids density slurry for further pipeline transport, thereby increasing efficiency (Arkema and Elshout 1980; Hahlbrock 1983; and McDowell 1988).

60. Mechanical transport can include hopper ships, bottom-dump barges, and land-based equipment such as trucks or conveyor belts. The sediment is usually recovered as a wet, coherent mass and is transported in the same manner, without the addition of water.

Sedimentation rate in a hopper during transport

61. If a soil slurry is placed in a hopper, or hold, on a vessel the settlement characteristics depend on grain or floc sizes and on the stillness of the water. Large particles will settle rapidly, permitting overflow of most of the slurry water. If particle sedimentation is too slow, then some or all of the water must be transported.

62. The rate at which a particle will settle in *still* water is a function of grain diameter and the viscosity of the settlement medium; larger particles settle faster. During hydraulic removal, the water is continually agitated; therefore, silt particles can take hours to settle and clay may not settle at all. Salinity of the water may cause flocculation of fine particles into coarser ones, hastening settlement. Assessment of settleability requires knowledge of grain size distribution, percent silt, percent clay, plasticity of the fines, and salinity of the water.

Bulking in a hopper

63. The volume of soil that can be placed in the hopper, for that portion of the sediment that settles rapidly, is measured by the bulking factor for that soil for that sedimentation condition. The initial deposition volume of a fine-grained material depends on: grain size distribution, flocculation capacity (related to water salinity), percentage of fines (silt and clay), plasticity of the fines, and the initial and deposition water contents (DiGeorge and Herbich 1978). Bulking factors can range from 1.0 to over 2.0.

Dumpability during disposal

64. Cohesive soils that are transported in bulk, using a barge or scow, or moved in a cutting scoop, such as a bucket or grab, must be discharged from the container. Clayey soils, particularly those that are moist and are of medium to high plasticity, tend to be sticky and adhere to the container. Some cohesive

soils tend to bridge in the container and not flow out without water jetting, mechanical scraping, or other form of dislodgement.

65. Adhesion is the molecular attraction of unlike particles. Adhesion may occur between soil and metal. Two components of soil-metal adhesion have been defined as: (1) "adhesion"--the force required to pull a metal blade over a soil parallel to the contact surface, and (2) "stickiness"--the force required to pull a metal blade away from a soil perpendicular to the contact surface (Gill and Vanden Berg, 1968). The force needed to destroy the bond between a soil and metal is the resultant of the adhesion and the stickiness. Adhesion occurs in non-friable soils, i.e., in clayey soils where the plasticity index is greater than 15.

66. The affinity of metal for water attracts the available water in the soil, forming a bond. The frictional resistance to the sliding of metal over soil is a function of the type of soil and its liquidity index, the type of metal and its surface roughness, and the normal force (perpendicular to the surface of sliding). The adhesive bond is the equivalent of additional normal force, increasing the force needed to cause sliding.

67. When the water content of a clayey soil is low, at a liquidity index of 0.1 or less, there is insufficient free water to cause an adhesion bond with the metal, and sliding occurs easily. As the water content of a saturated clay becomes greater than the plastic limit (liquidity index greater than zero) the availability of free water for metal adhesion becomes greater. The adhesion force becomes greatest at a water content below the liquid limit. At a water content just below the liquid limit, the so-called "sticky limit", the shear strength of the soil becomes less than the adhesion and stickiness is lost (Nichols, 1931). Therefore, adhesion and stickiness appear to be functions of the clay content (as reflected in the liquid limit and plasticity index) and in the water content relative to the plasticity (liquidity index of about 0.1 to 0.9). These relationships are not well established.

68. Tests for adhesion and stickiness are not well established. One test definition given by Atterberg (quoted by Casagrande, 1932) is: "The 'sticky limit' [is the water content] at which the clay loses its adhesive property and ceases to stick to other objects, such as the hands or a metal blade."
Bulking during disposal.

69. Excavated (dredged) sediments tend to have a volume increase upon removal from their in-situ position and to retain the larger volume during

deposition, unless they are mechanically compacted in the containment area. The bulking factor is the ratio of the volume occupied by a given amount of sediment in a containment area after deposition by a dredging process to the volume occupied by the same amount of the sediment in-situ.

70. Bulking factors are a function of type of soil, grain size distribution, method of excavation, and method of deposition. Mechanical dredging (scooping) cause minimum change in volume; fine cohesionless materials may actually be densified slightly by the scooping process. For hydraulic dredging, bulking will vary with in-situ density, dilution (slurry density), plasticity (tendency to form clay balls) and, in a hopper, the hopper size.

71. In a dredged material disposal area on land, the volume occupied by the sediment will decrease:

   a. with time as self weight consolidation takes place; or

   b. with the amount and type of mechanical compaction energy applied.

Sedimentation rate during disposal.

72. The rate at which a particle will settle in *still* water is a function of grain diameter; larger particles settle faster. Silt and clay particles take hours and days to settle. Salinity of the water may cause flocculation of fine particles into coarser ones, increasing their apparent size, hastening settlement. Assessment of settleability requires knowledge of grain size distribution, percent fines, plasticity of the fines, and salinity of the water.

73. Soil factors of importance in some aspects of the confined disposal of dredged material are given in a Corps of Engineers manual (HQUSACE 1987). Sedimentation characteristics are determined by grain size distribution, plasticity of fines, water content, organic content, grain specific gravity, and salinity of the water. The same characteristics are necessary for evaluation of the soil for construction of confining dikes.

Compactability during disposal

74. Mechanical compaction in a land disposal area requires either granular soil or low plasticity cohesive soil which has been dried to approximately the plastic limit water content. Therefore, knowledge is needed of the grain size distribution, plasticity, and water content.

75. There are basically three techniques for placement and possible densification of a dredged material in a land disposal area:

    a.   *Hydraulic fill*--placement as a hydraulic slurry; no mechanical manipulation except for grading or any attempt at densification; excess water drains away or evaporates;

    b.   *Partial (machine) compaction*--some mechanical manipulation by the grading machinery; mechanical densification due to the weight of the machinery; no attempt to densify to a specified value; and

    c.   *Full (specification) compaction*--mechanical densification using vibrating rollers or mechanical compacting rollers, in thin layers, to achieve the specified degree of densification.

76. The type of equipment that is appropriate for mechanical compaction depends on soil type:

    a.   *Cohesionless* (clean granular) soils have little or no cohesive binder that will inhibit free response to vibration. Densified is achieved by using vibration (vibratory rollers); usually not sensitive to moisture content.

    b.   *Cohesive* (clay, silty clay, and "dirty" granular) soils are any soil containing enough plastic clay to inhibit grain-to-grain contact during shear and therefore will not densify by vibration. Densified using weighted rollers; highly sensitive to water content and to plasticity of clay; required roller energy directly related to water content; excess water content may prevent achieving desired amount of densification. "Optimum" densification occurs when the combination of water content and roller energy produce a degree of saturation in the soil of 90 to 95 percent.

77. The definition of a soil as cohesionless or as cohesive, or as coarse grained or fine grained depends primarily on the purpose for which the definition exists. Any attempt to represent the expected behavior of a soil by definitions using grain size alone appears futile. Sowers (1979) has observed:

> ". . . for soils containing clay minerals, the volume of fines controls soil behavior, although they [may] comprise considerably less than 50% by weight. For example, a well-graded, sand-silt-clay mixture in which the fines exhibit low plasticity may behave like a clayey or fine-grained soil with only 30% fines. If the fine fraction is highly plastic, 10 to 20% fines may be sufficient for the soil to behave as a fine-grained material. Therefore, no fixed percentage of fines can distinguish predominantly coarse-grained or fine-grained behavior..."

Geotechnical Soil Properties for Estimating Dredgeability

78. From the discussion given above, and the literature cited, several soil behavior characteristics emerge as significant in the dredging processes. In the excavation stage, the soil is in its deposition (in situ) state. The in situ shear strength and/or erodability (scourability) of the soil governs. If

the fine gravel, sand, or coarse silt is free of cohesive fines and is relatively loose, it can be easily scoured. If the soil is dense, or if it contains plastic fines, then it must be mechanically agitated to loosen it. If it is not friable, and cannot be loosened into discrete particles, then the soil must be cut, ripped, or torn. The energy required to loosen and/or cut a soil is a function of the in situ strength, which in turn is a function of the in situ density or relative density. Boulders and cobbles require extraordinary hydraulic flow for movement and may be better loosened and removed using mechanical methods. Because payment is measured by change in channel volume measured in situ, and production is gaged by weight, particularly in a slurry, there is a real need by the contractor to know the density of the soil in situ.

79. During removal and transport, the in situ structure has been altered and the undisturbed shear strength properties no longer govern. Hydraulic methods can be used if the soil is friable and has been loosened into discrete particles. The maximum size of particle must be known for pump clearance, and the median size (d50) must be known to determine pump capacity (Turner 1984a, 1984b). If boulders and cobbles are present, the question of hydraulic versus mechanical removal and transport arises. Uniformity of the soil gradation in the slurry affects pump performance (Herbich 1975). Angularity and hardness of coarse grains are factors in causing wear of pumps and pipelines. The rheologic properties of a slurry containing fines determine the energy needed to pump the soil-water mixture. Transport in a hopper is enhanced by the rapid sedimentation of the soil. This is a function of the grain sizes and the flocculation of cohesive soils, which is affected by the salinity of the water. If the soil is not friable, then bulk removal using a scoop or bucket may be needed.

80. Disposal of a clayey soil is influenced by its stickiness, which affects the ease with which it can be discharged from its container. The grain size characteristics of any soil affect its capability for being used in beach nourishment projects, and greatly influence the ease with which the soil can be dried and compacted, if necessary, for the project.

81. The literature reviewed and the perspectives of persons interviewed regarding significant geotechnical soil properties for estimating dredgeability are summarized in Table 3. The table reflects those soil characteristics that are directly amenable to geotechnical testing, in the field or in the laboratory, or to reasonable estimation by means of alternative field or laboratory tests or by visual-manual methods.

82. A number of standardized laboratory and field tests are used to evaluate the geotechnical properties given in Table 3. Many of the tests were developed to meet the needs of geotechnical engineers; others were developed by geologists and other scientists. Where a shear strength test is not available, feasible, or economical, the in situ strength (compactness or consistency) may be reasonably estimated by the geotechnical index properties tests, which correlate with the fundamental properties they represent. Some index properties tests measure a soil characteristic, such as grain size distribution, directly. Other tests are used as indicators of other, more difficult to determine, properties. As an example, the Atterberg plasticity tests are indicators of the amount of clay present in the soil, of the type of clay mineral, and of the nature of the ions adsorbed on the clay surface (Peck, Hanson, and Thornburn 1974). Standard laboratory or field test methods exist for the evaluation of each of soil index properties. In some instances, alternative standard or nonstandard methods for performing the tests are in common use. A detailed discussion of soil testing methods is beyond the scope of this report.

83. An appropriate perspective to the significance of soil strength and material identification tests is that of Huston (1970) who stated in his textbook:

> "Materials can be given tests for shear . . . grain size . . . (other soils tests)--ad infinitum. However, the fundamental reason for obtaining the sample is to determine what the dredge will do in it. Any test that is not comparable with dredging results in material similarly tested is highly speculative, and actually is not worth much regardless of how [well] it is made."

Table 3

Geotechnical Soil Properties for Dredgeability Estimation

Geotechnical Property	Applications to Dredgeability
In Situ (Undisturbed) Soil Mass Properties	
In situ shear strength.	Extremely soft or loose soils can be suctioned; energy needed for cutting or scooping directly related to in situ strength.
In situ density.	Used for calculation of in situ solids content; density is correlated with shear strength.
Soil Material Properties	
Grain size distribution.	Clean granular soils can be easily scoured; energy for pumping slurry is related to median size; need maximum size for pump clearance; possibility of rheologic behavior in slurry related to fines content; amount of fines is indicator of settlement capability in hopper and in disposal area; indicator of compactability; correlated with shear strength.
Plasticity of the -no. 40 screen fraction.	Indicator of friability; correlated (with water content) with in situ strength and with potential stickiness; indicator of settlement capability in hopper and in disposal area; indicator of clay ball potential in pipeline; indicator of compactability.
Grain angularity, shape, and hardness.	Factors affecting the in situ shear strength of cohesionless soils; directly affect pumping energy and abrasiveness in a pipeline slurry.
Water content and specific gravity of grains.	With bulk density, used in calculation of solids and gas content, either in situ or in any other condition; used in settlement calculations.
Organics and type of cementation.	Factors in evaluation of in situ strength; indicators of potential for friability and for degradation during pumping; directly affect pipeline gas content and pumping energy.
Sedimentation rate - in fresh and salt water.	Direct tests for sedimentation rate, or estimation using grain size distribution and plasticity; used for estimating settlement rate in hopper or in disposal area.
Rheological properties of slurry.	For fines content greater than about 35%, the shear strength and viscosity of slurry are functions of slurry velocity, slurry density, fines content, and clay content.
Bulking capacity.	Bulk volume change during manipulation of the soils is a function of initial density, grain size distribution, plasticity, organic content, water content, and method of deposition.

84. The function of a soil description is to disclose, by means of words, symbols, and numbers, those soil characteristics that dominate and are responsible for the behavior of a soil under a given set of controlling conditions (Burmister 1951) and to permit correlation with experiences with similar soils. Geotechnical descriptors must indicate all of the properties shown in Table 3 so that a complete estimate of the dredgeability of the soil can be directly made or readily inferred. The geotechnical test methods by which these and other important properties can be determined are shown in Table 4. The description of a soil sediment using only the properties of the disturbed soil material is not sufficient; for evaluation of the excavation dredgeability the in situ shear strength must also be included. There are basically only two methods for communicating a complete sediment description for directly indicating or readily inferring dredgeability: (1) as numerical soil identification test data, and (2) as word or symbol descriptors.

85. All geotechnical descriptors are based on some form of grouping, with all soils in a group sharing the common characteristic(s) by which they are defined. The word description of something as a silt or a clay, or as a coarse or a fine sand, signifies the material has been identified, by observation or test, as belonging to a certain group of soil materials, according to certain agreed upon rules or criteria, even though the actual numerical values implied may be fuzzy. A soil classification as used in geotechnical engineering practice is a grouping that provides an indication of expected or probable behavior in a specific engineering application.

86. Burmister (1951) argued for a distinction in the meanings of soil identification and soil classification, stating:

> ". . . identification is *factual* information, whereas classification is *interpretive* information." Therefore, ". . . soil test data, and actual observed or measured soil behavior are factual information. . . . "Classification . . . really is . . . a *rating* of soils with regard to [a] certain limited number of qualities and potential behavior characteristics only, . . . that are considered to be significant and important in a particular field of soil work . . . based upon criteria established by interpretations of experience." And, ". . . the classification or rating of soils should never be given alone, as now done, but should be attached to the identification as an interpretive qualifying term."

Table 4
Geotechnical Tests for Determination of Soil Properties

Geotechnical Property	Geotechnical Tests
In Situ (Undisturbed) Soil Mass Properties	
In situ shear strength of cohesionless soil.	Direct shear test of re-formed laboratory sample; In situ standard penetration test (SPT); In situ cone penetration test (CPT).
In situ shear strength of cohesive soil.	Unconfined compression test of undisturbed sample; In situ standard penetration test (SPT); In situ cone penetration test (CPT); In situ vane shear test (VST).
In situ density.	Density of undisturbed tube sample of cohesive soil; In situ nuclear density test; Remolded density test of cohesionless soil sample.
In situ structure of cohesive soil.	Visual observation of relatively undisturbed sample.
Soil Material Properties	
Grain size distribution.	Particle size analysis test (sieves and hydrometer) to establish: maximum size, median size, percentage of fines (-No. 200 screen), and uniformity.
Plasticity.	Liquid limit, plastic limit, and plasticity index of the -No. 40 screen fraction.
Angularity, shape, and hardness of coarse grains.	Visual-manual tests; comparison with standard shapes; hardness using Moh's scratch test or striking with hammer.
Water content.	Standard laboratory oven dry test for water content; Nuclear gauge or calcium carbide water content tests;
Specific gravity of grains.	Laboratory specific gravity of grains test.
Peat or other organics.	Observation of odor and/or of vegetable matter; Ash content test in laboratory.
Color	Visual observation; comparison with standard colors.
Cementation	Laboratory test for lime or iron oxide content.
Sedimentation rate - in fresh and salt water.	Direct laboratory tests for sedimentation rate; Estimation using grain size distribution and plasticity.
Rheological properties of slurry.	Series of laboratory viscosity tests to determine threshold shear and viscosity (for fines content greater than about 35%), correlated with slurry density, fines (- No. 200) content, and clay content.
Bulking capacity.	Bulk volume change as result of empirical test (function of initial density, grain size distribution, plasticity, organic content, water content, and method of deposition).

Soil Description by Numerical Identification Test Data

87. The simplest and most direct method of communicating a soil description is a report of only the numerical identification test results, both field and laboratory, without interpretation or grouping. Virtually all formal soil identification tests and methods have a numerical result, and the description of a soil using numerical information is both appropriate and basic (Terzaghi and Peck 1967) and inherently superior to words. Numbers and well-defined symbols, including music, constitute the only real international language. International communication of soils data is enhanced because of the lack of a language or terminology barrier.

88. Given numerical soil description data, each group involved in using the data in dredging activities may evaluate the soil properties reported by using its own knowledge and experience without the need for a specific, universal soil descriptor system.

89. Numerical soil identification data do not directly indicate or readily infer dredgeability because the large groups of numbers are difficult for humans to assimilate. Without a well established theoretical model, or empirical correlations of summaries of the numerical soils data with dredging performance, numerical data by themselves become difficult to interpret.

Describing Soils Using Descriptors

90. The use of a descriptor, i.e., a word, a phrase, or a symbol, conjures an image of a familiar object and implies a general behavior related to experience, usually far better than numerical data by themselves. Descriptors permit a simplified data representation on boring logs, soil profile drawings, and in project specifications. Three basic types of descriptor systems have been identified in this study:

a. *Descriptive terms*--using words to represent the numerical soil identification test data without a specific dredgeability grouping.

b. *Classification groups*--using symbols to indicate a rating of soils according to specific characteristics that directly indicate or readily infer dredgeability; and

c. *Special testing devices*--test results from special devices that will infer the engineering properties or the dredgeability.

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<u>Descriptors using descriptive terms</u>

91. A descriptive term provides a word equivalent to the numerical data it represents. All persons familiar with soil sediments recognize the inherent variability in identification test data, mostly stemming from the natural variation of the physical properties from point to point in a relatively homogeneous soil deposit. Harr (1977) compiled a listing of variability of several soil properties, including average and standard deviation, from various published sources. The coefficient of variation, (i.e., the ratio of the standard deviation to the arithmetic mean) for most common parameters was on the order of 10 to 20 percent. Therefore, several samples taken at random from a "uniform" soil deposit can have numerical identification test values somewhat different from each other. The use of a descriptive word or phrase, because of its inherent lack of precision, tends to group the various test values, all presumably sharing the same general contiguous range of soil characteristics, into one relatively broad descriptive term.

92. For consistency, it is imperative that the descriptive term descriptors have uniform, well defined meanings related to the numbers, or other identification sources, they represent. Some form of the descriptive term method of describing soils is used by nearly everyone involved with dredging. It appears that nearly all such descriptors in common use have between four and seven categories of terms for each soil property characteristic. This descriptor method is exemplified by typical geotechnical textbook soil word/phrase descriptions and by the PIANC Soil Classification System.

93. The Permanent International Association of Navigation Congresses (PIANC) developed a "Classification of soils and rocks to be dredged" in 1972, which is a descriptive term system. This system was later revised (PIANC 1984) by the Working Group of the Permanent Technical Committee II. A copy is contained in Appendix B. The PIANC System defines descriptive terms for soils based on grain size and strength. Size fractions are defined for boulders and cobbles, gravels, sands, silts, and clays. Particle shape and texture terms and fine-grained soil plasticity terms are given but not defined. Shear strength is defined in visual-manual terms and in laboratory unconfined compressive strength terms. As stated under General Comments (PIANC 1984):

"Every description of soil should contain some indication as to the following characteristics: structure (e.g., resistance to penetration, compactness); for granular soils: [the] quantitative distribution of grain sizes and . . . indication of the shape of the grains; for cohesive soils: shear strength; smell and colour; for peats, . . . the extent of decomposition."

94. The PIANC system includes all of the word terms necessary for the description of a soil for dredging purposes. A major failing of this system is that, while the use of the Atterberg limits is mandatory in the Unified Soil Classification System (USCS) for distinguishing silt and clay, they are only suggested in PIANC. Silts can be identified using either grain size or plasticity terms. This can be confusing. Terms such as structure, resistance to penetration, compactness, and grain shape are not clearly defined, leaving much room for ambiguity.

95. To the extent that the descriptive terms represent a known (at least to the individual user) soil property numerical range, this method gives fairly complete information. The information can then be interpreted and applied according to the accumulated knowledge and experience of the individual contractor or engineer, somewhat in the same manner as if the numerical data were presented. The major problem with this descriptor system is that the meanings of the terms are not standard, not even within the Corps of Engineers.

96. Descriptive terms do not lend themselves to easy grouping or categorization on soil profile drawings or simple description in specifications or project records because of the length of the phrase needed to completely describe the sediment. All attempts to use this method have resulted in the use of abbreviations for the various terms. Furthermore, this method does not indicate dredgeability directly or readily infer it. As with numerical data, the individual user must use his own knowledge and experience to interpret the information. Further discussion of descriptive terms as a possible descriptor system is given in Part IV of this report.

Descriptors using a soil classification system

97. Alphanumeric index terms may be used to indicate a rating or grouping of soil properties into predefined classes according to expected or potential behavior in a specific application. Examples of soil classification systems used in geotechnical engineering in the United States are the Unified Soil Classification System (USCS), the American Association of State Highway

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and Transportation Officials (AASHTO) highway soils classification system, and the Federal Aviation Agency (FAA) airport soils system. Each of these classifies soils as a structural material for a specific end use and they involve dry-land excavation. The USCS and the others do not include all of the necessary information for evaluation of dredgeability and, therefore, do not directly indicate or readily infer dredgeability. What is needed, then, is a classification system based on dredgeability, i.e., using ratings of the expected interaction between a soil type and a dredging equipment type.

98. There are advantages in using a dredgeability classification system. If soil identification data are used only in the description of the geotechnical properties of the soil using numbers or descriptive terms, then the interpretation and application of this information requires either comprehensive technical knowledge or extensive experience or both. Because of the variable and complex nature of soils, the utilization of a simple, straightforward, and easily defined dredgeability classification system can be expedient and practical, particularly when used by lesser experienced, and presumably less knowledgeable, personnel. This type of descriptor can provide a grouping of soils of equal or known dredgeability on soil profile drawings or in a group description in specifications or project records. If the criteria are selected properly, the classification groups may directly indicate or readily infer dredgeability.

99. Classification groups do not present complete soil properties descriptions in the same manner as numerical or descriptive term data. The information is not presented for interpretation by individual contractor or engineer except as broad categories defined by the symbols. The implementation of a dredgeability classification system will require extensive time and money for research, experimental and/or empirical, to establish the criteria for class properties limits. There are other potential disadvantages in using a dredgeability-based system of classification of soils. The establishment or use of such a system implies a statement of the expected behavior, with all of the legal ramifications of such a statement. Stating, or implying, that a given soil is expected to behave in a given manner, especially on the part of the owner in a contract document, may lead to litigation if the soil behaves differently. Further discussion of a dredgeability classification system as a possible descriptor system is given in Part V of this report.

Descriptors using special testing devices

100. Descriptors may be based on the test results from a specific device, or suite of devices, which will directly indicate or readily infer the dredgeability of the soil. The interpretation of the results of tests with such devices must be based on empirical or experimental correlations between significant soil properties and dredge equipment performance. Special testing devices may simulate any one, or a group of, the normal dredging mechanisms of Table 1. In effect, each device could become a form of "test dredging" for a specific dredging system, such as cutting, ripping, or suctioning tests. The use of such devices may even be of assistance in placing a soil sample into one or another dredgeability classification group if a classification system is adopted.

Reporting and Using a Descriptor Database

101. It may be desirable to present soil identification test data to all interested parties (e.g., contractors, engineers, estimators) in the form of a database on a computer data diskette or tape. The database could contain either (1) numerical identification test data, (2) standard descriptive terms, or (3) a combination of these. This will permit each involved party the opportunity to analyze the data in its own manner, using its own expertise and experience. No interpretation of the data would be required on the part of the project owner. This may have some positive effect in reducing the misunderstandings that often result in claims.

102. Computer software already exists, or existing software can be adapted, to permit easy and direct manipulation of data in a database format. Grain size distribution curves, grain size analyses, automatic classification according to any well-defined system, graphical representation of boring logs and soil profiles, and quantities of specific soil types can presently be accomplished. All of this presupposes a standardized format and terminology. Correlations can then be made readily, using project records from a given locality, between soil test properties and dredgeability, either for general industry-wide use or for use by an individual organization.

103. A database management program presently developed for use within the US Army Corps of Engineers is the "Geotechnical Application Programs for CADD Systems" (CAGE CADD Support Task Group 1991) developed at WES. The

program contains three units. Unit I contains a boring log database system written in dBase III Plus. Unit II is a boring log plotting program and Unit III is a cell library and matrix menu; both units are intended for use with Computer Aided Design and Drafting (CADD) systems.

104. It should be recognized that a computer database, of the types discussed above, has merit simply because it is expeditious. It certainly is not the only way of recording and reporting soil identification data; conventional paper records and graphical boring logs have been used and possibly will continue to be used. The use of a computerized database record does not improve the information--it just makes it more accessible and usable. The analyses or correlations it permits are only as good as the input data.

PART IV: DESCRIPTIVE TERMS FOR SEDIMENTS TO BE DREDGED

105. A phrase containing a group of descriptive terms may be used to characterize the soil properties described in Tables 3 and 4. Each of the descriptive terms represents a property, having well defined criteria, acting as a word equivalent to the numerical test data. Unfortunately, the descriptive terms and definitions used by the various members of the dredging community differs at present, causing communication difficulties. If a descriptor system using words is to be adopted for worldwide use by the dredging community, it will be necessary that the terms and their definitions be standardized.

106. This section of the report discusses terms that may be used as descriptors. A complete descriptive term phrase to describe a sample of soil for dredging operations should contain at least the following terms (Terzaghi and Peck 1967; Sowers 1979; PIANC 1984):

a. In situ shear strength--compactness of cohesionless soils; consistency of cohesive soils; degree of cementation of cemented soils;

b. Grain size distribution of the soil:

(1) Maximum grain size;
(2) Median grain size (for hydraulic pipeline);
(3) Principal soil type name, based on median grain size; and
(4) Modifiers to the principal soil type to indicate uniformity of gradation.

c. Plasticity of the -no. 40 screen fraction;

d. Grain shape and hardness (granular soils only);

e. Structure of in situ soil (cohesive soils only);

f. In situ density and water content;

g. Color and odor (if any); and

h. Presence and estimated amount of peat, other organics, cementation, shells, and debris.

In addition, the following information is often of importance and may be reported separately:

a. Rheologic properties of slurry at various densities.

b. Sedimentation rate in salty water.

c. Bulking factor.

107. Where more than one definition of a descriptive term is commonly being used within the dredging industry, or a term has more than one criterion

in common use, the several definitions are described below. Selection among the alternatives will ultimately require discussion and agreement among, and adoption by, the practitioners of the dredging profession.

Descriptive Terms for Properties of the Undisturbed Soil Mass

108. The undisturbed soil properties of Tables 3 and 4 are those relating to the arrangement of the material components in a soil mass. The soil mass properties are a result of the relative positions of the soil materials, their structure, and mass density. The properties of the soil materials and the properties of the soil mass are independent of each other. The same soil material can exist in a number of different arrangement states, and different soil materials can have the same water content, density, and other soil mass characteristics. Basically, the mass properties are measures of the strength of the soil. They include angle of internal friction, cohesion, adhesion to cutting surfaces, and permeability. Generally, the denser a soil, the greater the strength and the lower the permeability.

Strength (compactness) of granular soils

109. The shear strength of granular soils, measured by the angle of internal friction, derives from grain-to-grain contact. The friction angle is a function of the normal force on the shear plane and, primarily, of the relative compactness (relative density) of the grains. The grain size distribution and grain angularity also affect the shear strength. The direct measurement of friction angle may be made in the laboratory using either a direct shear test or a triaxial compression test. Undisturbed sampling of cohesionless soils is practically impossible; therefore, the laboratory tests are made on re-densified samples. This requires that the in situ density be known and be reproduced exactly, a condition that is also difficult to accomplish.

110. Correlations have been developed between the angle of internal friction and relative density for cohesionless soils. The determination of relative density requires measurement of the in situ density and the performance of a laboratory procedure for determination of the maximum and minimum densities possible for the same soil in the laboratory (ASTM 1992). The spread in density between the maximum and minimum values rarely exceeds 320 grams/litre (20 lb/cu ft) and the error in determination of in situ

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density can be 15-30 grams/litre (1-2 lb/cu ft). It is extremely difficult to obtain an undisturbed sample of granular material from a test boring for density testing. Therefore, the direct determination of relative density, except on surface soils, is virtually impossible. As a consequence, two field tests that correlate reasonably well with relative density have been developed. The first, and most used, is the Standard Penetration Test (SPT) (ASTM 1992). The Quasi-Static Cone Penetration Test (CPT) (ASTM 1992) has also been used to estimate the relative density of sands indirectly, mainly by correlation with the SPT.

111. An early definition of terms for relative density based on the Standard Penetration Test (SPT) was given by Terzaghi and Peck (1948). Gibbs and Holtz (1957) gave the terms their present somewhat arbitrary definitions based on percent relative density, as given in Table 5. This terminology now appears to be almost universally accepted, both in a number of geotechnical

Term	Relative Density, percent	Normalized[*] SPT N-values		
		Natural Deposits[**]	Recent Fills[**]	Laboratory Test Fills[**]
Very loose	0-15	0-3	0-2	0-2
Loose	15-35	3-8	2-6	2-5
Medium (firm)	35-65	8-25	6-18	5-16
Dense	65-85	25-42	18-31	16-27
Very dense	85-100	42-58	31-42	27-37

Table 5

Compactness of Sands Based on Standard Penetration Test
After Skempton (1986)

[*] Corrected to 60% of free-fall energy of standard hammer weight and drop and normalized to unit effective overburden pressure of 100 kPa (1 Tsf).

[**] Natural deposits have been in place (undisturbed) for over 100 years
Recent fills have been in place for about 10 years
Laboratory test fills have been in place for less than one month

engineering textbooks and by both United States and European geotechnical engineers. Skempton (1986) presented the results of an extensive investigation of SPT and relative density. The values in Table 5 for SPT

values are for normally consolidated sands, normalized to account for overburden pressure and impact energy. The N-values should be multiplied by the ratio 55/60 for fine sands and by the ratio 65/60 for coarse sands.

Strength (consistency) of cohesive soils

112. The shear strength of cohesive soils is derived from inter-particle forces rather than grain contact. For a given cohesive soil, the strength is a direct function of density and of stress history. At the high strain rates encountered in dredging excavation, undrained shear conditions prevail. The simplest, and most used, measure of the shear strength of cohesive soils is the unconfined compressive strength. There are several descriptive terms systems for defining the unconfined compressive strength of cohesive soils using relative consistency as the basis. Two of the most common are shown in Table 6.

Table 6 Consistency of Cohesive Soils			
Consistency Term	Unconfined Compressive Strength		
	USCS (HQUSACE 1960)		PIANC (1984)
	Tons/sq ft	kPa	kPa
Very Soft	< 0.25	< 25	< 40
Soft	0.25 - 0.50	25 - 50	40 - 80
Medium (Firm)	0.50 - 1.00	50 - 100	80 - 150
Stiff	1.00 - 2.00	100 - 200	150 - 300
Very Stiff	2.00 - 4.00	200 - 400	
Hard	> 4.00	> 400	> 300

113. Recently sedimented in situ cohesive soils are encountered in dredging operations, at the surface of the bottom, in a fluid or semi-fluid state; these are often referred to in the literature as "mud". Mud is a fine-grained soil of such a high water content that it loses its structure and takes on the properties of a quasi-liquid. The quantity of water needed for this state varies with the surface area (liquidity index greater than 1.0) and angularity of the particles. The shear strength is so low that it is not determinable by the unconfined compression test and, therefore, does not fit into the system of Table 6. Therefore, a new category in Table 6 that may be

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called *fluid mud* should be defined. Skempton and Northey (1953) reported the shear strength of some English clays at the liquid limit to be about 1.1 kPa (0.01 tons/sq ft). Wroth and Wood (1978) indicated the shear strength at the Atterberg liquid limit is at about 1.7 kPa (0.02 tons/sq ft) and the shear strength at the plastic limit is about 100 times that at its liquid limit. Carrier and Beckman (1984) show that the actual value at the liquid limit varies over an order of magnitude for clays of different activities.

114. Because of its extensive usage in the United States and elsewhere, both by Corps of Engineers personnel and by private engineering consultants, it is recommended that the WES version of the USCS (USAEWES 1960) definition of consistency based on unconfined compression test, as shown in Table 6, be adopted as a universal standard. This conforms to the usage directed by TM 5-818-1 (DOA/AF 1983) and in the Navy Design Manual DM 7.1 (NAVFAC 1982). However, serious consideration should be given to the use of the "firm" rather than "medium"; the latter term appears to be an overworked word in soil descriptions.

In situ density of sediments

115. There are no generally used descriptive terms for in situ density. The bulk density is typically stated in numerical terms, either as pounds per cubic foot, kilograms per litre, or grams per litre. Values calculated from density, water content, and specific gravity of grains include porosity, void ratio, and degree of saturation (gas content). These values are also expressed as numbers rather than as descriptors.

In situ structure of cohesive soils

116. The in situ, or undisturbed, structure of a cohesive soil cannot be easily described using numbers. Yet, it is essential in understanding the probable behavior of a soil to know if a soil deposit is homogeneous, contains lenses of dissimilar soil, or is laminated or stratified. The structure and consistency terms in Table 7 were assembled from several sources, including Sowers (1979), ASTM D 2487 (ASTM 1992); the sub-terms under "stratified" are from the Navy Design Manual DM-7 (NAVFAC 1982).

Table 7	
Undisturbed Structure of Cohesive Soils	
Term	Descriptive Details
Banded	Alternating layers in residual soils.
Blocky	Brittle failure into discrete blocks.
Concretion	Hard inorganic mass different from surrounding soil.
Fissure	Crack, as from shrinkage or frost.
Homogeneous	Having uniform properties, such as the same color, texture, and appearance.
Jointed	Regular, parallel cracks.
Laminated	Repeating alternate layers less than 1/4 in. (6 mm) thick.
Lens	Layer, thick in middle and thinning toward edges.
Nodular	Having small, round concretionary bodies.
Slickensides	Former failure (slippage) planes.
Stratified (a) Parting (b) Seam (c) Layer (d) Occasional (e) Frequent	Alternating layers of different soils (or color). (a) 0 to 1/16 in. (0 to 2 mm) thickness. (b) 1/16 to 1/2 in. (2 to 13 mm) thickness. (c) 1/2 to 12 in. (13 to 300 mm) thickness. (d) One or less per ft. (30 cm) thickness. (e) More than one per ft. (30 cm) thickness.
Stratum	Layer greater that one ft. (30 cm) thick.
Varved	Alternating thin layers of silt and clay, usually found in present or former lake bottoms.

Descriptive Terms for Properties of the Soil Material

117. The soil material properties of Tables 3 and 4 are those of the soil components without reference to their arrangement in a soil mass, i.e., the properties of the individual grains, the pore water, or the other materials present. The soil tests are performed on a representative sample of soil whose in situ, mass structure has been completely disturbed.

Grain size distribution

118. The primary, and perhaps only, purpose for describing the grain size distribution of a soil for dredging purposes is, as given in Tables 3 and

4, to define the maximum size, the median size, and the uniformity. Descriptive terms for defining grain size characteristics are of value only if they provide the desired information. The use of specific numerical grain sizes to define the terms gravel, sand, silt, and clay has been part of every textural classification system for over 80 years, and there has never been general agreement on the definitions (Casagrande 1948). Several grain size classification systems are shown in Table 8. The lack of general agreement between the Unified Classification System (USCS) (ASTM 1992) commonly used in the United States, including the U.S. Army Corps of Engineers, and the European definitions (PIANC 1984) are clearly shown.

119. The Wentworth scale (Wentworth 1922) is used extensively by geologists and other scientists and, because it may appear in their writings, is presented here for comparison and reference. One feature of the Wentworth scale often encountered in non-engineering literature is the Wentworth coefficient ϕ which is the negative logarithm (base 2) of the grain size in millimeters (Krumbein 1934, 1938) and is related to logarithms (base 10) by:

$$\phi = -\log_2 D(mm) = -3.3219 \log_{10} D(mm)$$

This terminology was introduced in pre-computer time to facilitate calculation of the statistical moments of the grain size frequency distribution. Today, the ease of electronic calculation negates the advantage of this term and its continued use is not justified.

120. The equivalent spherical diameters that are used to distinguish the groups for communication using descriptive terms must be defined. Table 8 gives a starting point for discussion. The USCS uses specific U. S. Standard screen sizes as limits between gravel, sand, and fines, and their subdivisions (USAEWES 1960; ASTM 1992) as does Al-Hussaini (1977). This choice of subdivisions has served a useful laboratory data analysis function, eliminating the need for plotting a grain size distribution curve for defining percentages in each group.

121. If the test data are available as a grain size curve, the actual screen sizes used to subdivide the soil mass into groups are immaterial. Computer-based calculation and/or graphical reporting methods can be used to determine the size fractions meeting any system of descriptive term definitions. It is only necessary that a sufficient number of screens be used in the gradation tests to provide the desired sensitivity.

Group Name	Screen Opening, mm (U. S. Standard Sieve Size) Defining Upper Limit of Group			
	Wentworth (1922)	Al-Hussaini (1977)	USCS (ASTM 1992)	PIANC (1984)
Boulder	--	--	--	--
Cobble	256	--	300 (12 in.)	200
Coarse Gravel	64	75 (3 in.)	75 (3 in.)	60
Medium Gravel	16	19 (3/4 in.)	--	20
Fine Gravel	8	4.76 (No. 4)	19 (3/4 in.)	6
Coarse Sand	2	2.00 (No. 10)	4.76 (No. 4)	2
Medium Sand	0.500	0.850 (No. 20)	2.00 (No. 10)	0.600
Fine Sand	0.250	0.212 (No. 70)	0.425 (No. 40)	0.200
Coarse Silt	0.063	0.074 (No. 200)	0.074 (No. 200)	0.060
Medium Silt	0.031			0.020
Fine Silt	0.016			0.006
Clay	0.004	(0.002)	(0.002)	0.002

Table 8
Grain Size Classification Systems

122. It is recommended that the grain size limits and terminology presented in Table 8 derived from the ASTM version (ASTM 1992), and the equivalent WES version (USAEWES 1960), of the USCS be adopted as the standard for a descriptive term system because of extensive present usage in the United States. If the data are also presented numerically or graphically the user could establish his own limits and definitions for his own personal interpretation.

Primary soil name

123. Using a grain size distribution , a primary name can be determined using the frequency, or percentage, present of any primary soil group (i.e., boulders, cobbles, gravel, sand, silt, or clay), or one of its subdivisions if the soil is primarily coarse-grained, and naming the soil after the largest group. Another approach to defining the primary soil name is to use the median grain size, D_{50}. The fine-grained fraction of a soil should only be distinguished, silt from clay, using the Atterberg plasticity tests.

124. The criteria for differentiating coarse- and fine-grained soils and for establishing the primary soil name are not consistent among the several engineering soil classification systems presently being used in the United States. For the purpose of examining some existing methods, several typical grain size distribution curves are shown in Appendix F, Figures F-1 to F-12. The figures were derived from Plates 3 through 8 of "The Unified Soil Classification System", (USAEWES 1960). A description/classification of each soil is given by: (a) the Waterways Experiment Station descriptive terms description; (b) USCS Classification; (c) AASHTO Classification; (d) FAA Classification; and (e) the median grain size (D_{50}). The USCS and D_{50} descriptions include the modifiers given in ASTM D2487 (ASTM 1992) described in Table 9 below.

125. None of the classification systems used in Appendix F is clearly superior to any of the others in matching the WES soil description. The use of the median grain size, D_{50}, to establish the primary noun to describe a soil has merit because is serves a dredging-related purpose. Herbich (1975) and Turner (1984a, 1984b) indicate that the median grain size, D_{50}, is a major factor in assessing the pipeline transport of dredged material. The primary noun would then give a usable approximate value for the median grain size.

Modifiers to Primary Soil Name

126. Virtually all natural soils are a mixture of various sizes. The PIANC (1984) classification system requires some form of word description using adjectives and/or suffixes. The objective of the adjectives to the primary noun is to describe the uniformity of grain sizes by indicating the relative amounts of the various grain size fractions. The latest version of the USCS in ASTM D 2487 (ASTM 1992) requires that a word description be used to supplement the symbols, and that the words include modifiers. Table 9 gives some definitions of soil name modifiers from the published literature. It is evident that there are no general "rules" for adjectives or suffixes.

127. The modifiers described in Table 9 are not intended to be exhaustive of those proposed for use by various writers. If grain size and Atterberg limits data are available for a given soil or can readily be estimated, and a general idea of uniformity is available, then the Unified Soil Classification System modifiers of ASTM D2487 (ASTM 1992) have much merit because of simplicity. A more complex system of modifiers, such as some of those in Table 9, should only be adopted in case of real, demonstrated need.

Modifier Term	Percent of Total Sample				
	Burmister (1951)	Sowers (1979)	ASTM D2487 (ASTM 1992)		Visual-Manual ASTM D2488 (ASTM 1992)
			Coarse Grained	Fine Grained	
Adjectives to Primary Name					
trace	1-10	0-15			0-5
few					5-10
little	10-20				15-25
some	20-35	16-30			30-45
Suffix to Primary Name					
with			≥ 15 sand or gravel	15-29 coarser than No. 200	
sandy or gravelly				≥ 30	
-----y		31-45			
and	35-50	45-50			
mostly					50-100

Table 9

Soil Name Modifiers

Plasticity of cohesive soils

128. The Atterberg limits reflect the mineralogy and surface chemistry of fine grained soils, silt and clay, which are major factors in determining cohesive soil behavior. Although they are of value stated numerically, a word description to convey a general experience with similar soils is often useful. Table 10 contains descriptive terms used in the published literature for the various liquid limit fractions. The symbols shown are intended to be used, as in the USCS, as modifiers for the two terms: silt (M) and clay (C).

129. It is suggested that the A-line of the plasticity chart of the USCS (Appendix D) continue to be used to differentiate silt from clay using the results of Atterberg limits tests, and that the level of plasticity within the chart be defined using the terms of Casagrande (1948), i.e., adding the

medium plasticity term to the USCS. Then soil names can be used to define the plasticity of the fine-grained fraction of granular soils or the plasticity of cohesive soils (e.g., silty fine sand, non plastic; clayey gravel, medium plasticity fines; and high plasticity clay).

Table 10 Plasticity Groups for Cohesive Soils					
Plasticity Term	Symbol	Liquid Limit, percent			
		Casagrande (1948)	Dumbleton (1968)	USCS ASTM (1989)	Carrier (1988)
Nonplastic	N		< 20		
Low	L	0-35	20-35	< 50	0-35
Intermediate (Medium)	I	35-50	35-50		35-50
High	H	> 50	50-65	≥ 50	50-100
Very high	V		65-80		100-150
Extremely high	E		> 80		
Ultra high	U				150-200
Super high	S				> 200

Shape of coarse grains

130. The angularity, shape, and hardness of coarse grains is a factor in pumping energy requirements and in equipment wear (Turner 1984a). A chart by Krumbein and Sloss (1963) was presented by Al-Hussaini (1977) as a suggestion for a simple visual comparison chart for angularity and shape, easy to use in laboratory or field. Verbeek (1984) has presented a similar chart by Russel and Taylor (reference not disclosed). Mather (1965) presented a rather thorough discussion of particle shape as applied to concrete aggregates.

131. The simplest and most straightforward determination of angularity, shape, and hardness is given in ASTM D 2488, Visual-Manual Procedure (ASTM 1992). The ASTM document contains a photograph for visual identification of particle angularity by comparison. Soil angularity is classified as: rounded, subrounded, subangular, and angular according to Table 11. Grain shape is

defined as: flat, elongated, or flat and elongated, as shown in Table 12.
When gravel size particles are struck a strong blow with a hammer, "hard"
particles do not crack, fracture, or crumble. A more detailed definition of
these terms is not of great value in dredging-related activities.

Table 11	
Angularity of Coarse Grained Particles	
(ASTM D2488)	
Term	Criteria
Angular	Particles have sharp edges and relatively plane sides with unpolished surfaces.
Subangular	Particles are similar to angular description but have rounded edges.
Subrounded	Particles have nearly plane sides but have well-rounded corners and edges.
Rounded	Particles have smoothly curved sides and no edges.

Table 12	
Shape of Coarse Grained Particles	
(ASTM D2488)	
Term	Criteria
Flat	Particles with width to thickness ratio greater than 3
Elongated	Particles with length to width ratio greater than 3
Flat and Elongated	Particles meeting criteria for both flat and elongated.
Spherical (typically not stated in description)	Particles having width to thickness ratio and length to width ratio less than 3.

Soil color

132. Soil color, while not of great consequence in the dredgeability of
soils, is of considerable help in correlating soil samples from location to
location during geotechnical analysis of the site investigation. Soil colors
are often useful in (a) detecting different strata, (b) defining soil type
based on experience in a local area, and (c) possible identification of

materials. Dark or drab shades of brown or grey, and almost black, soils are typically organic. However, some soils are black from other minerals. Brighter colors are associated with inorganic soils (Terzaghi and Peck 1967). Red, yellow, and yellowish brown suggest iron oxide, whereas white or pink indicate silica, calcium carbonate, or aluminum compounds. The standard group of colors used in current US Army Corps of Engineers documents (CAGE CADD Support Task Group 1991) is given in Table 13.

Table 13 Suggested Standard Soil Colors			
Color	Symbol	Color	Symbol
Tan	T	Brownish-Gray	br Gr
Yellow	Y	Grayish-Brown	gy Br
Red	R	Greenish-Gray	gn Gr
Black	Bk	Grayish-Green	gy Gn
Gray	Gr	Green	Gn
Light Gray	lGr	Blue	Bl
Dark Gray	dGr	Blue-Green	bl Gn
Brown	Br	White	Wh
Light Brown	lBr	Mottled	Mot
Dark Brown	dBr	Reddish	rd

Organic Content

133. Sediments may contain organic matter that will affect the excavation and pumping processes. The organic content of a soil sediment may be established in the laboratory by dry combustion or wet combustion or by using the ASTM D2487 (ASTM 1992) Atterberg limits procedure. In the ASTM procedure, the Atterberg liquid limit is determined on a sample that has not been previously dried and again on the sample after it has been oven dried. If the liquid limit, oven dried, is less than 75% of the liquid limit, never dried, the soil is defined as organic. The *ash content* is the un-combusted residue, mostly clay minerals, after the sample has been dried at a sufficiently high temperature to burn all the organics. Landva (1986) defined

terms for highly organic soils on the basis of ash content; they are given in Table 14. ASTM D4427 (ASTM 1992) defines peat as having less than 25% ash. Therefore, Landva's definition of peat has been increased in Table 14 from 20 to 25 percent.

Table 14 Highly Organic Soils (After Landva 1986 and ASTM D4427)	
Soil Type	**Description**
Peat	Ash content less than 25%. Derived from plants. Very fibrous.
Peaty Organic Soils	Ash content 25 to 40%. Part fibers and part colloidal organics.
Organic Soils	Ash content 40 to 95%. All colloidal organics.
Soils With Organic Content	Ash content over 95%. All colloidal organics.

Cementation

134. Granular and mixed-grain soils may be cemented with various natural cementing agents. These agents are primarily compounds of iron or alumina, or are calcium or magnesium oxides or carbonates. The only cementing agents for which terminology has been developed are those that will react with hydrochloric acid, mostly calcium carbonate (limestone) or calcium oxide (lime). The descriptive terms from ASTM D2488 (ASTM 1992) are in Table 15.

Table 15 Reaction of Sediments with Hydrochloric Acid (HCl) From ASTM D2488 (ASTM 1992)	
Description	**Criteria**
None	No visible reaction
Weak	Some reaction, with bubbles forming slowly
Strong	Violent reaction, with bubbles forming immediately

PART V: A PROPOSED DREDGING CLASSIFICATION SYSTEM

135. Soil classification systems have been established, and are described in the geotechnical engineering textbooks, for various construction-related uses to *rate*, i.e., to indicate the suitability, of soils for use in a specific application. Most of them utilize the soil material properties of the disturbed soil as the basis for class grouping, without concern for the original in situ mass properties, because they are involved with the use of the soil as a construction material. None of the existing systems indicates dredgeability either directly or indirectly because none of them include the in situ strength in the classification nor do they consider the any other direct needs of the dredging mechanisms.

136. Either the geotechnical properties data, numerical or descriptive terms, or the results of empirical testing devices may be used in a system that groups sediments on the basis of extensive, statistically valid correlations between soils having those properties and accumulated dredging experience. The correlation of soil test properties with dredging experience can best be effected if (a) a consistent set of standardized soil properties tests, field and/or laboratory, or a standardized empirical test device, is used, and (b) a consistent, universally understood terminology, words and/or symbols, is used (or if a good inter-language dictionary exists!).

Existing Soil Classification Systems

137. Several soil classification systems have been used or are presently in use by geotechnical engineers, each of them serving a special purpose (Casagrande 1948; ASTM 1951; PCA 1962; Al-Hussaini 1977). Four of them: the PIANC, the USCS, the AASHTO, and the FAA Systems are reproduced in Appendices of this report for easy reference. The PIANC System is not a rating-type classification system, but is basically a descriptive term descriptor system. The USCS, AASHTO, and FAA Systems are all rating-type classification systems. Each system was devised for a different application than dredging and therefore none is directly applicable as it now exists.
Unified Soil Classification System.

138. The Unified Soil Classification System (USCS) is of special interest to the dredging industry. The USCS is the classification system of

the geotechnical engineer, both because of formal training and because of required use within the geotechnical branches of the US Army Corps of Engineers and the US Bureau of Reclamation. By contrast, the PIANC system has been highly recommended for use within the European dredging community.

139. The USCS, given in Appendix C, is published in a Corps of Engineers document (USAEWES 1960) and as ASTM Standard D 2487 (ASTM 1992). This is a performance rating system. The Corps of Engineers document contains two appendices that rate the characteristics of the several soil groups as they pertain to (a) embankments and foundations, and (b) to roads and airfields construction. The system was developed for use by the US Army Corps of Engineers in military airfield construction during the early 1940's and was later (Casagrande 1948) published for general use. Soils are classified first according to grain size. Soils with more than 50 percent retained by weight on the United States Standard No. 200 screen (0.074 mm) are classified as coarse-grained: either gravel or sand. Soils containing 50 percent or more fines (material passing the No. 200 screen) are fine-grained soils: either silt and clay. The fraction of a soil finer than the No. 40 screen is used for the plasticity tests: liquid limit (LL) and plastic limit (PL), and the plasticity index (PI) which is the numerical difference between the LL and the PL. Only two levels of plasticity are recognized: LL equal to 50 percent or less means low plasticity and LL greater than 50 percent is high plasticity. The USCS was a significant improvement over previous textural soil classification systems by its introduction of the Atterberg limits to describe and classify fine-grained soils using the A-line chart (Casagrande 1948; Terzaghi and Peck 1967; Al-Hussaini 1977).

140. Although widely used, the USCS has had some criticism, both from the general geotechnical engineering and the dredging-related standpoints. Even in the original publication (Casagrande 1948) the author proposed a third plasticity term, intermediate plasticity, with a liquid limit between 35 and 50 percent, because of the wide range of soil behavior within the low plasticity range. The USCS is based on laboratory tests of remolded soils and does not reflect in situ soil characteristics. Therefore, strength of the soil is not a factor in the soil groupings or in the ratings. Sowers (1948), in his discussion of the Casagrande paper, indicated that two important foundation engineering soil properties were not considered in the system: the water content and the consistency. Cooling, Skempton, and Glossop (1948) also

discussed the need to add the: ". . . strength and structural features of the soil as it exists in the ground." The excavation phase of dredging is dependent on the in situ, undisturbed properties of the soil. Furthermore, the disturbed soil group properties are so broad, especially within the sand and gravel groups, that no estimate of pipeline pump capacity or of settlement capability in a hopper can be made without analysis of the actual grain size distribution curve. In several sections of the United States the material being dredged, either for maintenance or new work, ranges from a fine sandy silt to a silty fine sand within the same deposit. The USCS groupings therefore show the material is either a sand (SC, SM, or SP) or a silt (ML), even though the differences among samples are trivial. This has been the source of misunderstanding on a number of dredging projects.

AASHTO Classification System

141. The American Association of State Highway and Transportation Officials (AASHTO) Classification System for highway soils is shown in Appendix D. This is a rating system based on expected load carrying capacity and serviceability of the soil when used in the construction of a highway base or subgrade. It is assumed in the classification that the final in situ soil properties will have specified values, i.e., the soils will be suitably compacted in place. Because it assumes the soils will be remolded prior to use, the system uses only soil material data (grain size and Atterberg limits) for classification. To a minor extent, it recognizes the relative difficulty of excavating, manipulating, and compacting each of the various soil groups. Granular soils are those having 35 percent or less finer than the No. 200 screen (0.074 mm). Among the silt-clay materials (more than 35 percent passing the No. 200), silty soils are those with a plasticity index of 10 or less; clayey soils have a plasticity index of 11 or more.

FAA classification system.

142. As shown in Appendix E, the Federal Aviation Agency (FAA) Classification System for airfield soils was used to rate soils according to expected behavior when used to construct the base of an airfield runway, taxiway, or parking apron. This system, like the AASHTO System, relies only on material properties (grain size and Atterberg limits), assumes the remolded soil will be suitably compacted in place, and is concerned with the relative ease of compacting the soils. Granular soils have less 45 percent passing the No. 200 screen (0.074· mm) whereas fine-grained soils have more than 45 percent

passing. The fine grained soils are rated by a combination of liquid limit and plasticity index, with classification number increasing (indicating poorer soil) as the combined values increase. For liquid limits below 60, clayey soils (higher PI) are preferred to more silty soil (lower PI), often because of frost effects.

Proposed Dredging Classification System

143. A classification, or rating, system for directly indicating or readily inferring the dredgeability of in situ sediments should be based on the dredgeability properties of paragraph 22 above:

<u>a</u>.   *Excavation* properties: suctionability, erodability (scourability), cuttability (affected by friability), scoopability, and flowability (underwater slope instability);

<u>b</u>.   *Removal and transport* properties: pumpability (affected by rheologic properties of slurry), abradability (abrasiveness in a pipeline), clay balling (affected by stickiness), sedimentation rate in a hopper, and amount of bulking; and

<u>c</u>.   *Disposal* properties: dumpability (affected by friability and stickiness), sedimentation rate in a disposal area, amount of bulking, and compactability.

Some type of formal or informal grouping of soils, recognizing the interaction of soil properties and needs of the processing equipment, is now being used by designers, estimators, and contractors based on their own, or their organization's, knowledge and experiences whether they realize it or not.

144. Based on the published literature and interviews conducted for this study, it is suggested that sediments may be placed into eight groups, shown in Table 16, each with different fundamental dredging characteristics. The major sediment groups of Table 16 are:

<u>a</u>.   Group R: Rock and Coral (after pretreatment)

<u>b</u>.   Group S: Shale and Cemented Soil

<u>c</u>.   Group B: Boulders and Cobbles

<u>d</u>.   Group G: Clean Granular Soil

<u>e</u>.   Group F: Friable Mixed-Grain Soil

<u>f</u>.   Group C: Cohesive Soil

<u>g</u>.   Group O: Highly Organic Soil

<u>h</u>.   Group M: Fluid Mud

Maintenance dredging will deal mainly with Groups G, F, and M. New work dredging can encounter any of the eight major groups. The methods for pretreatment of rock are not included here. It is assumed in this Classification System that the rock, and the shale or cemented soil when appropriate, have been pretreated by blasting, ripping, or other suitable method. At that point, the material becomes a group of broken, angular fragments and can be dredged using one or another of the equipment systems described in Table 2.

145. Subgroups will be needed to show the various grades of geotechnical properties significant in each major group. It is suggested that letters be used to designate the major sediment group and that numbers be used to designate subgroups to prevent possible confusion with the two-letter designators of the USCS. For example, Class B (Boulders and Cobbles) may be subdivided into B-1, B-2, and B-3 to show small, medium, and large sizes. Or Class M (Fluid Mud) may be grouped as M-1, M-2, M-3, and M-4 to signify various levels of slurry density and clay content. Other groups may be subdivided according to other properties, singly or in combination. It remains for future research studies to establish soil test properties criteria for the various soil groups of Table 16.

Table 16
Proposed Dredging Classification System

GROUP R: Rock and Coral	
Geotechnical Properties	Rock is massive, solid (non-granular), inorganic mineral matter with an unconfined compressive strength exceeding 1000 kPa (10 Tsf) Coral consists of living calcareous organisms usually formed into a massive offshore reef.
Excavation Properties	Hard rock and coral require blasting to break the mass into fragments that can be removed by normal dredging equipment. Softer rock and coral capable of being easily cut or ripped into small fragments. Cut slopes are stable.
Removal and Transport Properties	Blasted or ripped rock fragments behave like Group B: Boulders and Cobbles. Hard rock fragments can be abrasive in pipeline.
Disposal Properties	Blasted or ripped rock fragments behave like Group B: Boulders and Cobbles.
GROUP S: Shale and Cemented Soils	
Geotechnical Properties	Highly compressed clays (shale) or rock-like soils cemented with iron oxide, lime, silica, calcium, or magnesia; have unconfined compressive strength below that of hard rock.
Excavation Properties	Require cutting, ripping, or blasting; usually breaks up into small particles. Cut slopes are stable.
Removal and Transport Properties	Fragments can be removed and transported using either hydraulic or mechanical methods; energy requirement is function of fragment size distribution. Hard angular fragments can be very abrasive in pipeline.
Disposal Properties	Behavior similar to cobbles or coarse gravel; shale fragments may soften appreciably in air or water.
(continued) (page 1 of 4)	

Table 16 (continued)

GROUP B: Boulders and Cobbles	
Geotechnical Properties	Material is dominantly blasted rock fragments, or natural boulders and cobbles; deposit typically contains mixture with gravel, sand, and fines; usually insignificant amounts of nonplastic fines. Usually dense and shear strength derives almost entirely from grain to grain contact.
Excavation Properties	Usually excavated by mechanical methods (scooping). Hydraulic methods are usually inefficient.
Removal and Transport Properties	Not easily moved hydraulically. Requires high velocity/high volume hydraulic removal methods or mechanical (bucket) removal and transport methods.
Disposal Properties	Dumping is easy and coarse particles settle very fast. Very difficult to compact beyond dumped density because of grain-to-grain contact. Low bulking factor.
GROUP G: Clean Granular Soils	
Geotechnical Properties	Material is gravel, sand, or coarse silt with little or no plasticity; will not stand unconfined if dry. Shear strength derives from relative density, grain angularity, and lack of fines.
Excavation Properties	Excavate easily under hydraulic erosion (scour). Have high friability. Easily cut or scooped. Slopes not stable; tend to flow easily to angle of underwater repose.
Removal and Transport Properties	Easily removed and transported hydraulically. Particles settle very quickly in a hopper. Readily transported in a pipeline slurry; energy required is function of median grain size. Large particles contribute to pipeline wear. Bulking factors are low.
Disposal Properties	Dump easily. Settle quickly in disposal area. Clean granular soils (few or no plastic fines) will densify with vibration. Typically do not respond well to mechanical compaction.

(continued)   (page 2 of 4)

	Table 16 (continued)
GROUP F: Friable Mixed-Grain Soils	
Geotechnical Properties	Material is mixed-grain soils or low plasticity friable soils, such as small gravel, sand, silt with appreciable clay content. Strength derives from combination of grain-to-grain friction and cohesion due to clay. Friable due to low plasticity of -No. 40 fraction.
Excavation Properties	Not easily suctioned; too dense or too much clay for easy erosion; typically suitable for cutting or ripping process. Easily scooped. Well suited to cutter suction or bucket-wheel suction processes. Underwater slopes do flow easily; are fairly stable.
Removal and Transport Properties	The soil is friable and will disintegrate during excavation and hydraulic removal; will enter easily into a pipeline slurry. Clay balling is normally not encountered. Sedimentation rate in hopper is typically fast, although disintegrated fines may not settle quickly.
Disposal Properties	Usually will respond well to mechanical compaction but not to vibration.
GROUP C: Cohesive Soils	
Geotechnical Properties	These are massive fine-grained soils, typically firm to hard clays and silty clays of medium to high plasticity. Not friable. Have sufficient density and clay content to have unconfined compressive strength. Exhibit plasticity, cohesiveness, and dry strength. Little or no grain-grain contact; shear strength derives from density, stress history, and amount and type of clay.
Excavation Properties	Not friable (will not crumble easily); will not suction or erode; may be excavated using cutting or scooping. Underwater slopes are usually stable except for very soft clays.
Removal and Transport Properties	Probably form clods during mechanical transport or clay balls in hydraulic pipeline. Low abrasion in pipeline. Will not settle rapidly in hopper; will usually overflow.
Disposal Properties	Often sticky when water content is high. Take appreciable time to settle in land disposal area. The "cohesiveness" of the clay prevents the soil from densifying with vibration. Bulking is fairly high.
(continued)	(page 3 of 4)

Table 16 (concluded)	
GROUP O: Highly Organic Soils	
Geotechnical Properties	Peat, humus, and swamp soils are examples. Typically have a spongy consistency, a high water content, and are dark brown to black color, although the color alone is not an indicator. Usually have an organic odor in a fresh sample or in wet sample that has been heated. Have a fibrous to amorphous texture and often contain vegetable matter (sticks, leaves, etc.).
Excavation Properties	May be cut or scooped. Behaves like a soft to firm cohesive soil (Group C), unless fibrous matter interferes with cutting.
Removal and Transport Properties	High gas content may interfere with hydraulic suction. Fibrous matter content may interfere with pipeline transport. Easily moved mechanically.
Disposal Properties	Organic matter is not usually desirable in a disposal area. Ocean disposal may leave some fibrous matter floating or in suspension. Not easily compacted because of sponginess.
GROUP M: Fluid Mud	
Geotechnical Properties	"Muds" - found at or near the surface of the "bottom" in harbors and other areas of slow current. Extremely low shear strength; has no unconfined compressive strength; physically behaves like a fluid, i.e., sample will not retain its shape. The solids are mainly silt and clay of low to high plasticity, but may have some very fine sand. Invariably has a very low density and very high water content in situ.
Excavation Properties	Easily suctioned at or near in situ density without dilution water. Erodes easily with very little dilution water added. Will not stand on slope.
Removal and Transport Properties	Easily transported in a pipeline; may require addition of dilution water for improved flowability. Fine grains will not settle quickly in a hopper or in a disposal area.
Disposal Properties	Fine-grained soils do not settle quickly in disposal area.
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146. The denotation of test criteria for classification grouping is in itself a form of descriptive terminology. The criteria for inclusion in a classification group and subgroup should be defined in terms of numerical soil identification test data, in the same manner as the USCS, the AASHTO, and the FAA classification systems. The user will then know that an M-6 soil has certain properties that differentiate it from an M-5 soil and from a C-1 soil, and will know what those properties are--either in number values or descriptive terms. Assuming the Dredging Classification System of Table 16 is to be implemented, then the following factors may be considered, without any presumption of completeness, for establishing the criteria for each of the groups of Table 16:

a. GROUP R, ROCK AND CORAL -- What is the grain size distribution of the rock fragments? What is the maximum size? Can the fragments be excavated and removed with normal sizes of buckets? Are the fragment sizes small enough to be transported hydraulically?

b. GROUP S, SHALE AND CEMENTED SOIL -- What is the grain size distribution of the shale or cemented soil fragments? What is the maximum size? Can the fragments be excavated and removed with normal sizes of buckets? How friable are the fragments? Can they be economically crushed to a smaller grain size distribution? Are the fragment sizes then small enough to be transported hydraulically? Will the shale soften appreciably, causing a problem in the disposal area?

c. GROUP B, BOULDERS AND COBBLES -- How many (percentage?) boulders and cobbles need be present before we classify this soil as Type B? Should we have a minimum size criterion to establish hydraulic versus mechanical removal? Should there be subgroups to indicate amount and type of granular and cohesive soil present?

d. GROUP G, CLEAN GRANULAR SOIL -- Which combinations of relative density and grain size distribution govern erodibility? Does in situ density enter into the factor list? What about various amounts of fines? How will the soil behave in a pipeline? What is the median diameter? How much relative wear can be expected? It may be desirable to include a third symbol to indicate grain angularity/shape/hardness, perhaps a lower case letter as in the AASHTO system (Appendix D).

e. GROUP F, FRIABLE MIXED-GRAIN SOIL-- Friable soils can range from dense granular material with little or no soil binder to a granular material with some binder, such as a clayey gravel, to a dense silt with no clay, to a soft clay which is capable of being cut and removed hydraulically without formation of clay balls. What are the various combinations of grain size distribution, plasticity (Atterberg limits), compactness or consistency. and in situ density (relative density applies only to clean granular materials) for the subgroups to define ease of cutting? To define

ease of crumbling or disintegrating (friability)? If the material is cohesive, what are the limits of consistency and plasticity? Is there to be a maximum size definition? How will the soil behave in a pipeline? Will the angularity/hardness of the granular component cause wear?

f.   GROUP C, COHESIVE SOIL -- When the material becomes non-friable, i.e., it will not crumble or disintegrate into small fragments, or will form large clay balls, then mechanical bucket methods are needed for excavation and removal. What is the dividing line between this group and Groups F and M? Can we use consistency (strength) and Atterberg limits as the criteria? Is the soil a massive coherent clay or simply a soil having a significant clay binder - not loose and not friable, and not boulders and cobbles?

g.   GROUP O, HIGHLY ORGANIC SOIL -- What amount of peat or other organics is needed before the soil requires special handling? How should cementation be defined? Based on strength, as though it were a soft rock? Should debris be a factor? How much debris, and of which types, should place a soil in this category? Which other soil types should be placed in this "special handling" category? How to define their properties?

h.   GROUP M, FLUID MUD -- Should fluid mud be rated according to density or to density and some measure of grain size? We are interested in pumpability (viscosity and threshhold shear) which varies by grain size and density. What are its settlement characteristics in a hopper?

147. As part of the Dredging Classification System, it should be possible to develop a tabulation of "Characteristics of Soil Groups Pertaining to Dredging," similar to the tables contained in Appendices A and B in the WES publication titled "The Unified Soil Classification System" (USAEWES 1960). Consideration should be given to listing, for each subgroup, either numerical or relative word term characteristics for: amount of large particles, grain size, relative density, relative consistency, in situ density, suctionability, erodibility (scourability), cutting energy, friability, gas content, settlement rate, grain angularity and hardness (abrasion potential), etc.

148. The implementation of this system will require the establishment of the specific physical properties criteria for each group and subgroup. This problem can be approached empirically or experimentally. An experimental approach can be expensive in time and money. The empirical approach appears more fruitful; useful information exists in project files around the world. The geotechnical and operations data from several completed projects could be compiled using a computer data base as described earlier in this report. Data base manipulation can then be done to establish the soil properties criteria

needed to define each group and subgroup. If desired, the selected group boundaries can then be verified experimentally. With a new system such as this, we can hope to achieve international usage because there are no established descriptor systems in conflict.

PART VI: SUMMARY AND RECOMMENDATIONS

149. This study is part of the US Army Corps of Engineers Dredging Research Program. The objective of the study is the development of "standard descriptors for directly indicating or readily inferring the dredgeability of in situ material." The term *dredgeability* is given to mean the ability to excavate underwater, remove to the surface, transport, and deposit sediments with respect to known or assumed equipment, methods, and in situ material characteristics.

150. This report is the result of a literature survey, the first phase of a study of geotechnical soil descriptors as they apply to dredging operations. The literature survey consisted of a survey of the geotechnical and the dredging-related literature and of interviews with knowledgeable persons from the dredging industry. Its objectives were to:

a. Identify the physical properties of sediments that directly affect the performance (dredgeability) of the dredging process;

b. To identify the geotechnical engineering properties of sediments to be dredged that will directly indicate or readily infer the dredgeability properties of the sediments; and

c. To identify the available methods for describing and possibly classifying the geotechnical properties of sediments to be dredged in a standard, internationally understood manner.

Summary

xxx. The dredgeability properties of a sediment are those that relate to the mechanisms used for excavation, removal, transport, and deposition of the sediment. They are the:

a. *Excavation* properties--suctionability, erodability (scourability), cuttability (affected by friability), scoopability, and flowability (underwater slope instability);

b. *Removal and transport* properties--pumpability (affected by rheologic properties of slurry), abradability (abrasiveness in a pipeline), clay balling (affected by stickiness), sedimentation rate in a hopper, and amount of bulking; and

c. *Disposal* properties--dumpability (affected by friability and stickiness), sedimentation rate in a disposal area, amount of bulking, and compactability.

151. The geotechnical soil properties that are significant for estimating soil behavior when subjected to specific dredging processes are: (a) the soil mass properties, those related to the in situ arrangement of the individual components in a soil mass--cohesion, angle of internal friction, adhesion to cutting surfaces, tendency to dilate, bulk density, degree of saturation (gas content), and structure of cohesive soils; and (b) the soil material properties, those of the soil components, without reference to their arrangement in a soil mass--grain size distribution, plasticity of the fines, grain shape and hardness, specific gravity of the grains, and salinity of the pore water. In addition, certain other properties are often of value--the rheologic behavior of the soil in a slurry, the sedimentation rate of the slurried soil in water of a given salinity, and the density or bulking factor of the redeposited soil for any given manner of deposition.

152. The objective of a soil description for dredging is to relate those characteristics, based on soil identification test data, that dominate and are responsible for the behavior of the sediments when acted on by the various dredging processes and to permit correlation with experiences with similar soils. Soils can be described (a) using only the numerical results of soil identification tests, and/or (b) using descriptors. The presentation of numerical data alone is fundamental and is not associated with a specific descriptor system. This method of soil description requires that the individual user apply his own knowledge and experience to analyze the data for estimating dredgeability. Therefore, this method does not indicate or infer dredgeability directly.

153. The descriptors for dredgeability prediction can be either (a) a group of descriptive terms, i.e., word equivalents to the numerical data, that completely and concisely define the significant soil properties, which can then be related to dredgeability on the basis of theoretical model analysis or empirical correlations, (b) classification, or rating, of soil into groups having similar properties, with each group indicating a rating of probable behavior when used with a specific dredging process, (c) test results from a specific test device, or suite of devices, which will directly indicate the dredgeability, or (d) some combination of these.

139. Descriptors using descriptive terms based on soil properties should use a consistent and standardized system of names. Various commonly used descriptor terms for the significant geotechnical properties have been

tabulated in the report. However, there is no general agreement on the meanings of the descriptive terms being used by the various groups involved in dredging. Descriptive word term descriptors, like the numerical data they represent, do not indicate or infer dredgeability directly.

140. Classification is a format for rating soils, using a systematic arrangement into groups, according to established procedures by reason of common characteristics. Various systems exist in the geotechnical engineering and related fields for classifying soils in groupings of soil of similar material properties according to their expected suitability for a construction use. None of these address the unique needs of the dredging industry although two of them, the Unified Soil Classification System and the PIANC System, are being used by the industry at this time.

141. A recommendation has been made in the report for the establishment of a Dredging Classification System. Eight major sediment groups are proposed: Group R, Rock and Coral; Group S, Shale and Cemented Soil; Group B, Boulders and Cobbles; Group G, Clean Granular Soil; Group F, Friable Mixed-Grain Soil; Group C, Cohesive Soil; Group O, Highly Organic Soils; and Group M, Fluid Mud. It is suggested that each group be subdivided into several subgroups. The soil identification test criteria for each group, and subgroup, remains to be established, either experimentally or empirically.

Recommendations for Further Work

142. This report has documented three possible methods for describing soils for dredging purposes. As the first step beyond this report, a decision must be made regarding which method appears most likely to meet the objectives of this study and the needs of the dredging industry:

> a. A reporting system for numerical soil identification test data in which each user group or firm decides for itself on how to apply its own accumulated experience and research data to the sediment properties described;

> b. A descriptive term system, using standard word equivalents to numerical soil identification test data, in which each user group or firm decides for itself on how to apply its own accumulated experience and research data to the properties described;

> c. Use the accumulated knowledge and experience of the dredging industry to develop the criteria for the Dredging Classification System proposed in this report, or for a similar one, that will

indicate or infer probable behavior for specific dredging mechanisms directly;

d. A combination of two of the systems given above, either numerical data or descriptive terms, supplemented with the symbols of the dredging classification system, with all information reported in a standard computer data base.

Implementation of a descriptive terms system

143. A review or advisory group could be appointed to make recommendations regarding a soil description system based on the information contained in this report. The group ideally should be representative of the Corps of Engineers, port authorities, and dredging contractors. University and private consultants, and perhaps European and Asiatic dredging experts, may be used as consultants to the group. If the advisory group recommends the use of either the numerical data or descriptive terms systems, it may be possible for the advisory group to also recommend a tentative computer data base format for recording and reporting data. The basis for such a data base already exists in the Corp' Computer Applications in Geotechnical Engineering (CAGE) program. Several Corps of Engineers District offices are now using a form of such a data base for recording site exploration data. A listing of suggested "field" headings for such a data base has been suggested in this report.

Dredging classification system

144. A dredging-related soil classification system may be developed, using a major grouping of soils such as that presented in Table 16. The development can be experimental or empirical. The empirical approach is suggested. This will require accumulation of data for a wide variety of soils and the analysis of that data for consistent relationships. This has a good prospect of being accomplished in a reasonable time because much of the background data now exists in the project files of the Corps of Engineers and other agencies. It should only be necessary to form the computerized data base suggested above, combining it with performance records, and find where soil property boundaries are for each of the various dredgeability criteria.

Dredgeability testing devices

145. It may be possible to develop a new testing device, or suite of devices, that will directly indicate dredgeability. The device(s) must be capable of indicating the difference between the soil groups similar to those shown in Table 16, and also exhibit a value that can be calibrated with the

difficulty of dislodging and removing the soil. In effect, each device can be a form of "test dredging." This is an ideal that may take much time, effort, and money to perfect and field test.

Pilot program

146. If a tentative standard set of descriptors and a descriptor recording and reporting system is determined by the advisory group, the system could be implemented in one or more Districts as a demonstration, or pilot program. All of the existing geotechnical information in a given harbor area could be entered into a computerized database. A suitable software program can then manipulate the data, make quantity estimates, and even display the total information as a three-dimensional profile.

147. Implementation of such a pilot program will require (1) the instruction of personnel in each District in the proper use of the system by means of lectures/seminars, (2) supervision of the District personnel in the installation of the database and the recording of data; and (3) evaluation of the potential of the existing data in the District for solving other problems such as a correlation of soil properties with performance characteristics.

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APPENDIX A: PERSONS INTERVIEWED
FOR THIS STUDY
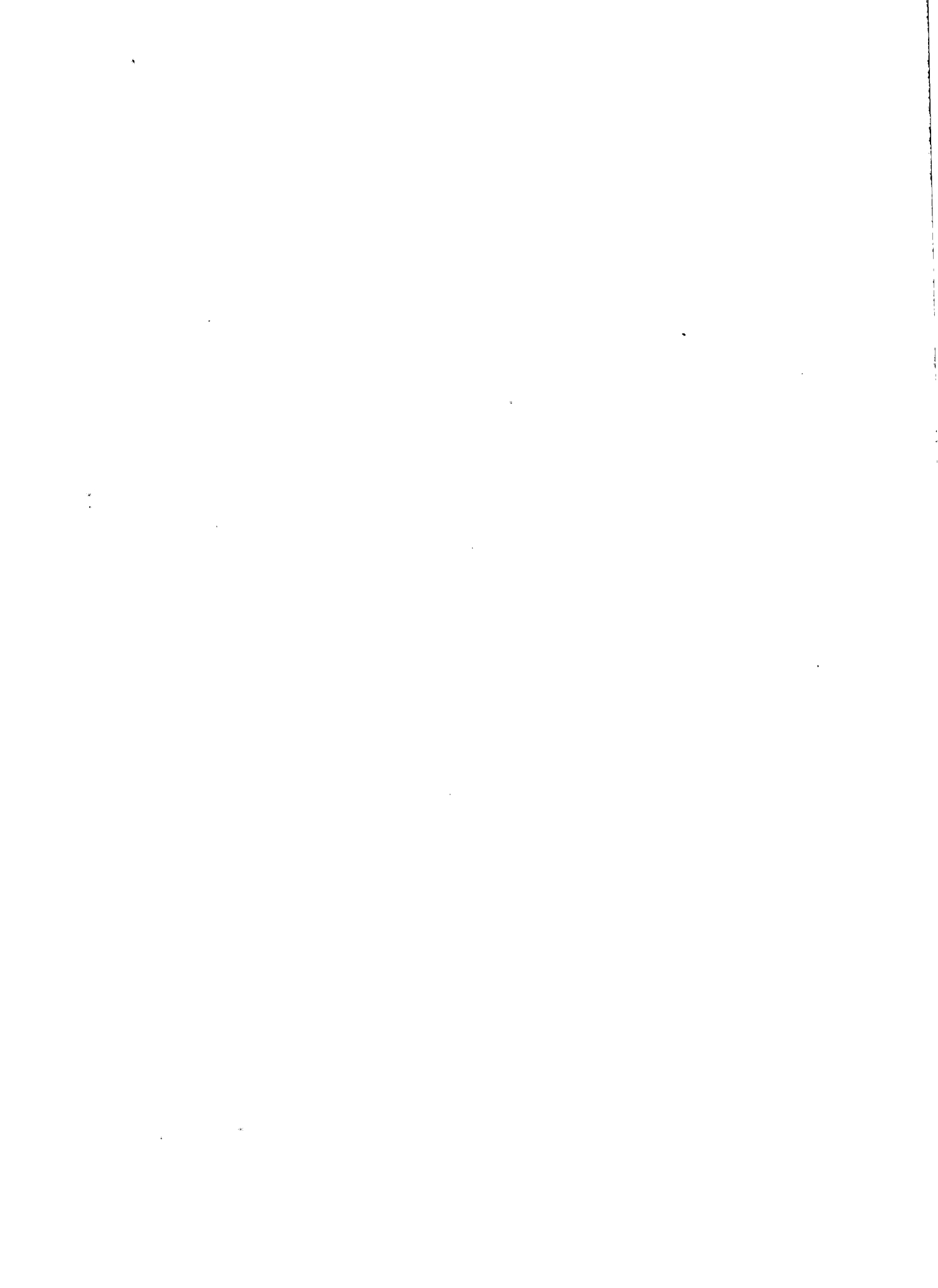
APPENDIX A: PERSONS INTERVIEWED FOR THIS STUDY

1.   The following persons were interviewed for this study:

USAE Division, North Pacific (Portland, Oregon).
    04/15/88   Tim Seeman, Chief, Soils Section, NPD Laboratory, Troutdale,
                Oregon.

USAE District, Portland (Oregon).
    03/28/88   Ron Henry, Captain, Dredge "Essayons".
    03/29/88   Ronald N. Oberst, Operations Section.
    03/29/88   A. Rudder Turner, Jr., Environmental Specialist.
    06/16/88   Nancy L. Case, Formerly Chief, Operations Section.

USAE District, Seattle (Washington).
    08/08/88   Charles Fradenberg, Waterways Maintenance Section.
    08/08/88   Kenneth Graybill, Chief, Soils Section.
    08/08/88   Robert M. Parry, Chief, Waterways Maintenance Section.

USAE Division, South Pacific (San Francisco, California).
    06/21/88   Dan Parrillo, Chief, Geotechnical Branch.
    06/21/88   Robert Siessen, Geotechnical Branch.
    06/21/88   Byongmu Song, Geotechnical Branch.
    06/21/88   William Bechtell, Geotechnical Branch.
    06/21/88   Glen Roycroft, SPD Laboratory, Sausalito, California.
    06/21/88   Douglas Pirie, Construction Operations.

USAE District, Los Angeles (California).
    06/17/88   Vernon Minor, Chief, Geology Section.
    06/17/88   Thomas Mitchell, Chief, Navigation Section.
    06/17/88   Christopher Sands, Civil Engineer.

USAE District, San Francisco (California).
    06/23/88   George Altenberg, Design Branch.
    06/23/88   Hector L. Cordero, Design Branch.
    06/23/88   Steven Kakihara, Design Branch.
    06/23/88   Julie Sharp, Design Branch.
    06/23/88   Ted Bruch, Construction Management Branch.
    06/23/88   Mark Dettle, Water Resources.

USAE Division, Southwestern (Dallas, Texas).
    05/18/88   George Johnson, Chief, Operations Branch.
    05/18/88   Carlos Aguilar, Operations Branch.

USAE District, Galveston (Texas).
    05/20/88   David Campbell, Chief, Geotechnical and Survey Branch.
    05/20/88   Tim Few, Geotechnical & Survey Branch.
    05/20/88   Richard Medina, Operations and Maintenance Branch.
    05/20/88   Dale Petersen, Operations and Maintenance Branch.

USAE District, New Orleans (Louisiana).
    05/24/88   Gerrard S. Satterlee, Foundations and Materials Branch.
    05/24/88   Burt Kemp, Foundations and Materials Branch.
    05/24/88   Jay L. Joseph, Foundations and Materials Branch.
    05/24/88   Lowrey Williamson, Design Branch.
    05/24/88   K. C. Clark, Design Branch.

Naval Civil Engineering Laboratory, Port Hueneme, California.
    06/14/88   James Miller, Acting Division Director.
    06/14/88   Barbara Johnson, Civil Engineer.
    06/14/88   Craig Conner, Civil Engineer.
    06/14/88   Jack DeVries, Coastal & Estuarine Engineer.

Bean Dredging Corporation, New Orleans, Louisiana.
    05/24/88   Arthur R. Burgoyne, Engineer.
    05/24/88   Ancil Taylor, Engineer.

Ogden Beeman & Associates, Portland, Oregon.
    06/06/88   Ogden Beeman, President.

CPN Corporation, Martinez, California.
    06/20/88   William Mancuso, Vice President.
    06/20/88   Patrick N. Corcoran, Sales Engineer.

Dutra Dredging Co., Rio Vista, California.
    06/24/88   Douglas D. Comstock, General Manager.

Great Lakes Dredge & Dock Co., New Orleans, Louisiana.
    05/25/88   Lee Jones, Estimator.
    05/25/88   Philip M. Pearse, Gulf Coast Division Manager.

Great Lakes Dredge & Dock Co., Oakland, California.
    06/22/88   W. E. Hannum, Manager, Pacific Division.

Great Lakes Dredge & Dock Co., San Pedro, California.
    05/25/88   Paul Siebert, Superintendent.

T. L. James & Co., Inc., Kenner, Louisiana.
    05/25/88   Charles Harris, Dredging Department.

Louisiana State University, Baton Rouge, Louisiana.
    05/26/88   Dr. Jack Hill

Moffatt & Nichol Engineers, Long Beach, California.
    06/17/88   Andrea Bertolotti, Coastal Engineer.

Port of Portland, Portland, Oregon.
    07/07/88   Cmdr. Lawrence M. Patella, Manager, Navigation.

Riedel International, Inc., Portland, Oregon.
    06/07/88   Robert W. Lofgren, Senior Vice President.

Slotta Engineering Associates, Inc., Corvallis, Oregon.
    03/27/88   Dr. Larry S. Slotta

Smith-Rice Dredging Co., Alameda, California.
    06/22/88   William H. Mueser, Jr.

Stuyvesant Dredging Co., Metairie, Louisiana.
    05/23/88   Frans Bloos

Texas A&M University, College Station, Texas.
    05/19/88   Dr. Wayne Dunlap, Dept. of Civil Engineering.
    05/19/88   Dr. William Bryant, Dept. of Oceanography.
    06/07/88   Dr. John Herbich, Center for Dredging Studies.

Williams-McWilliams Construction Co., Metairie, Louisiana.
    05/23/88   Donald Miller

APPENDIX B: PIANC SOIL CLASSIFICATION SYSTEM

APPENDIX B: PIANC SOIL CLASSIFICATION SYSTEM

PERMANENT INTERNATIONAL ASSOCIATION OF NAVIGATION CONGRESSES CRITERIA
(PIANC 1984)

DESCRIBING SOILS
GENERAL COMMENTS

In practice no soil will fall precisely within a single predetermined main type, so combinations of types must be described accurately and intelligibly.

It is possible to do so by using a noun to denote the chief constituent of the complex soil and adjectives to denote other constituents that are present in smaller quantities. The noun should be regarded as denoting the principal constituent i.e. the one that determines the behaviour of the soil.

Every description of soil should contain some indication as to the following characteristics :

a) structure (e.g. resistance to penetration, compactness);
b) for granular soils : quantitative distribution of grain sizes, preferably indicated as a grading curve, descriptive indication of the shape of the grains;
c) for cohesive soils : shear strength;
d) smell and colour;
e) for peats, note should be made of the extent of decomposition.

Furthermore for composite soils the major characteristics should be given, depending on the predominant nature of the soil.

Whenever possible a full grading curve should be provided but if grading curves are not given or are limited in extent the percentage by weight of the several soil fractions should be stated.

Clear descriptions should be given, e.g.

1) stiff, fissured, grey clay;
2) loose, yellow, rounded, fine medium gravel and coarse sand containing shells;
3) soft, grey/blue, sandy silt;
4) soft, black, clayey, fibrous strong-smelling peat;
5) brown, rounded slightly compact fine sand;
6) compacted, coarse, angular sand mixed with scattered, irregular gravel;
7) hard, brown clay containing sand and gravel.

Even though a full soil description is made, representative samples should be kept in airtight containers so that further examination can be carried out at a later date on fresh samples.

FINE SOIL

In fine soil, the engineering behaviour is better related to a description which takes account of marked influence of the silt and clay fraction. For example, a small proportion of clay-sized material can confer cohesive properties to a composite soil and can then be sufficient to warrant description of the soil as a clay. Distinction between the silt and clay fractions is important since they behave differently. The property most indicative of the relative proportion of silt and clay in a fine soil is its plasticity.

In this respect fine soil may often be categorised according to plasticity properties, on a basis of the relation between plastic limit and liquid limit of the soil. Use may then be made of the well-known plasticity chart where mineral and organic soils fall on either side of a dividing 'A' line (after Casagrande). Soils which plot below the 'A' line are predominantly silt and those that plot above are more predominantly clay. For further details reference may be made to British Standard 5930 'Site Investigations' (1981).

In many cases (in particular in the Scandinavian area) the inclusion of boulders and cobbles gives rise to problems in dredging work. Unfortunately, the investigation of such deposits is difficult and the correct prediction and assessment of the boulder and cobble content is therefore important.

Indirect estimations of the boulder and cobble content can be assisted by considering the mode of formation, composition of laboratory samples and sounding results.

In this respect valuable comments are found in the publication "Soil Classification and Identification" (issued by the Swedish Council for Building Research, Stockholm, Sweden, 1981), as follows :

a) Mode of formation

The mode of formation provides a good indication of the boulder and cobble content of a soil. For example, the boulder content of tills (i.e. material transported by the ice sheet and deposited when the ice has melted) can be assumed to correspond to the following table :

Till type	Boulder content
Course-grained	High
Mixed-grained	Medium to high
Fine-grained	Low to medium

It should be noted that fine-grained tills can have a high cobble content even if a boulder content is low. For a full discussion on guiding values for the division of mineral soils on the basis of the contents of the various fractions, reference should be made to the Swedish publication mentioned (especially tables 5, 6 and 7).

b) Composition of laboratory samples

The composition of laboratory samples can also improve the estimation of the boulder content. Due to the limited capacity of the sampling device, the samples give no direct indication of the possible presence of boulders or cobbles in the soil. However, it is possible to draw some indirect conclusions.

If a soil sample is classified as gravelly or if it contains small cobbles, there may be reason to suspect the presence of larger cobbles and boulders. Without special investigation and designation (e.g. eolian sand), even sand cannot be assumed to be completely free from cobbles. However, the boulder content is usually very low. If the uniformity coefficient C_U (i.e. $\frac{d60}{d10}$) is high (> 10) however, the possible presence of gravel cobbles and boulders may be suspected even in a sand deposit.

c) Results of penetration tests

Light sounding probes are stopped by boulders and large cobbles. The following conditions can therefore indicate the presence of boulders and cobbles :

- if the probe stops at varying depths in adjacent holes,
- if increased resistance occurs irregularly (necessitating impact driving),
- if the probe stops at a lesser depth than the assumed bedrock.

The probe is unlikely to encounter cobbles or boulders if they only occur to a minor degree. Just a few stops can therefore be taken to indicate a considerable content of cobbles and boulders.

Main Soil Type	Particle size identification Range of size (mm)	Identification	Particle nature and plasticity	Strength and Structural Characteristics	
Boulders Cobbles	Larger than 200 mm Between 200 - 60 mm	Visual examination and measurement (3)	Particle shape : Rounded Irregular Angular Flaky Elongated Flaky and elongated Texture : Rough Smooth Polished	N.A.	
Gravels	Coarse 60 - 20 Medium 20 - 6 Fine 6 - 2 mm	Easily identifiable by visual examination		Possible to find cemented beds of gravel which resemble weak conglomerate rock. Hard-packed gravels may exist intermixed with sand.	
Sands (4)	Coarse 2 - 0.6 Medium 0.6 - 0.2 Fine 0.2 - 0.06 mm	All particles visible to the naked eye. Very little cohesion when dry.		Deposits will vary in strength (packing) between loose, dense and cemented. Structure may be homogeneous or stratified. Intermixture with silt or clay may produce hard-packed sands.	
Silts (4)	Coarse 0.06 - 0.02 Medium 0.02 - 0.006 Fine 0.006- 0.002 mm	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 dilatancy (1). Material may have some plasticity, but silt can easily be dusted off fingers after drying and dry lumps powdered by finger pressure.	Non-plastic or low plasticity	Essentially non-plastic but characteristics may be similar to sands if predominantly coarse or sandy in nature. If fine 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 into "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.	Clay exhibits strong cohesion and plasticity, without dilatancy. Moist sample sticks to fingers, and has a smooth, greasy touch. Dry lumps do not powder, shrinking and cracking during drying process with high dry strength.	Intermediate plasticity (Lean clay) High plasticity (Fat clay)	**Strength** V. Soft May be squeezed easily between fingers. Soft Easily moulded by fingers. Firm Requires strong pressure to mould by fingers. Stiff Cannot be moulded by fingers, indented by thumb. Hard Tough, indented with difficulty by thumb nail. Structure may be fissured, intact, homogeneous, stratified or weathered.	**Shear Strength (2)** Less 20 kN/m^2 20-40 " 40-75 " 75-150 " Above 150 "
Peats and Organic soils	Varies	Generally identified by black or brown colour, often with strong organic smell, presence of fibrous or woody material.		May be firm or spongy in nature. Strength and structure may vary considerably in horizontal and vertical directions. Presence of gas should be noted.	

NOTES ON TABLE 1

N.A : Not applicable

(1) Dilatancy is the property exhibited by silt as a reaction to shaking. If a moistened sample is placed in an open hand and shaken, water will appear on the surface of the sample giving a glossy appearance. A plastic clay gives no reaction.

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

(3) Though only visual examination and measurement are possible an indication should be given with respect to the particles as well as to the percentages of different sizes.

(4) "Sands" and "Silts" are terms denoting a particle size. Sands are not necessarily restricted to quartz sands but may include lime sands, iron ores, etc. Also silts denote a grain size, not a consistency. Therefore consistency terms such as "fresh harbour silts, muds", etc. should not be used.

APPENDIX C: UNIFIED SOIL CLASSIFICATION SYSTEM
CRITERIA FOR GROUP SYMBOLS AND GROUP NAMES
(HQUSACE 1960)

UNIFIED SOIL CLASSIFICATION
(Including Identification and Description)

Major Divisions			Group Symbols	Typical Names	Field Identification Procedures (Excluding particles larger than 3 in. and basing fractions on estimated weights)	Information Required for Describing Soils	Laboratory Classification Criteria
1		2	3	4	5	6	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.)

	Group Symbols	Typical Names	Field Identification Procedures	Laboratory Criteria
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.	$C_u = \dfrac{D_{60}}{D_{10}}$ Greater than 4 $C_c = \dfrac{(D_{30})^2}{D_{10} \times D_{60}}$ 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 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.
	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.)

	Group Symbols	Typical Names	Field Identification Procedures	Laboratory Criteria
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.	$C_u = \dfrac{D_{60}}{D_{10}}$ Greater than 6 $C_c = \dfrac{(D_{30})^2}{D_{10} \times D_{60}}$ 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.	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

Column 6 (Information Required for Describing Soils) – Coarse-grained:
For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions, and drainage characteristics.

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.

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).

Column 7 note:
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.

Fine-grained Soils (More than half of material is smaller than No. 200 sieve size.)

Identification Procedures on Fraction Smaller than No. 40 Sieve Size

	Group Symbols	Typical Names	Dry Strength (Crushing characteristics)	Dilatancy (Reaction to shaking)	Toughness (Consistency near PL)
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
	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
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

Column 6 (Information Required for Describing Soils) – Fine-grained:
For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions.

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.

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

	Group Symbols	Typical Names	Field Identification Procedures
Highly Organic Soils	Pt	Peat and other highly organic soils.	Readily identified by color, odor, spongy feel and frequently by fibrous texture.

Plasticity Chart:
Comparing Soils at Equal Liquid Limit Toughness and Dry Strength Increase with Increasing Plasticity Index.
(Plasticity Index vs Liquid Limit; A Line; regions CL, CH, ML, MH & OH, CL-ML, OL)
PLASTICITY CHART — For laboratory classification of fine-grained soils.

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

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(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.
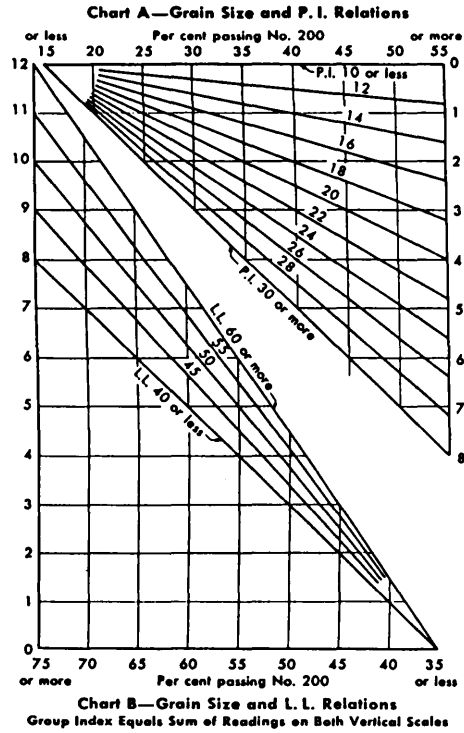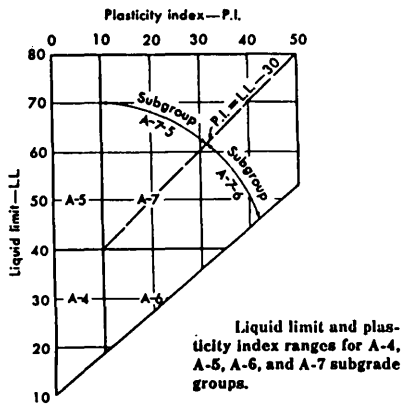
Dilatancy (reaction to shaking)

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 larger 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.

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APPENDIX D: AASHTO SOIL CLASSIFICATION SYSTEM

APPENDIX D: AASHTO SOIL CLASSIFICATION SYSTEM

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS CRITERIA
(PCA Soil Primer 1962)

Group index charts.

Chart A—Grain Size and P. I. Relations

Liquid limit and plasticity index ranges for A-4, A-5, A-6, and A-7 subgrade groups.

Chart B—Grain Size and L. L. Relations
Group Index Equals Sum of Readings on Both Vertical Scales

Classification of Highway Subgrade Materials (with Suggested Subgroups)

General classification	Granular materials (35 per cent or less of total sample passing No. 200)							Silt-clay materials (More than 35 per cent of total sample passing No. 200)			
Group classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5, A-7-6
Sieve analysis, per cent 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.		NP	10 max.	10 max.	11 min.	11 min.	10 max.	10 max.	11 min.	11 min.*
Group Index**	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 chart; 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.
*P.I. of A-7-5 subgroup is equal to or less than L.L. minus 30. P.I. of A-7-6 subgroup is greater than L.L. minus 30 .
**See group index formula   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.
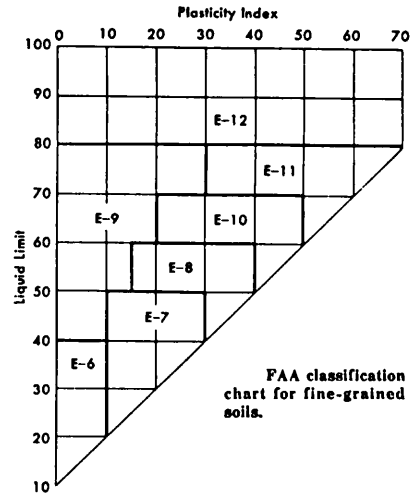
D3

APPENDIX E: FAA SOIL CLASSIFICATION SYSTEM

# APPENDIX E: FAA SOIL CLASSIFICATION SYSTEM

FEDERAL AVIATION AGENCY CRITERIA
(PCA Soil Primer 1962)

FAA Classification of Soils for Airport Construction

Soil group	Mechanical analysis				L.L.	P.I.
	Retained on No. 10 sieve*	Material finer than No. 10 sieve				
		Coarse sand passing No. 10, retained on No. 60	Fine sand passing No. 60, retained on No. 270	Com-bined silt and clay passing No. 270		
	per cent	per cent	per cent	per cent		
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 limit shown in the table, a raise in classification may be allowed provided the coarse material is reasonably sound and fairly well graded.

FAA classification chart for fine-grained soils.

FAA textural classification of soils.
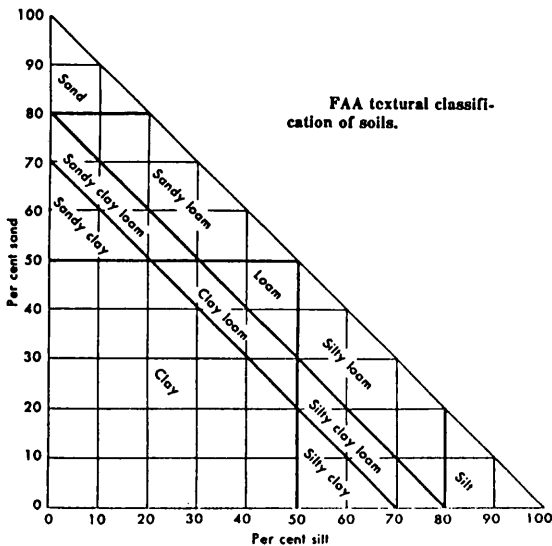
Textural class	Per cent sand	Per cent silt	Per cent clay
Sand	80-100	0-20	0-20
Sandy loam	50-80	0-50	0-20
Loam	30-50	30-50	0-20
Silty loam	0-50	50-80	0-20
Silt	0-20	80-100	0-20
Sandy clay loam	50-80	0-30	20-30
Clay loam	20-50	20-50	20-30
Silty clay loam	0-30	50-80	20-30
Sandy clay	50-70	0-20	30-50
Silty 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

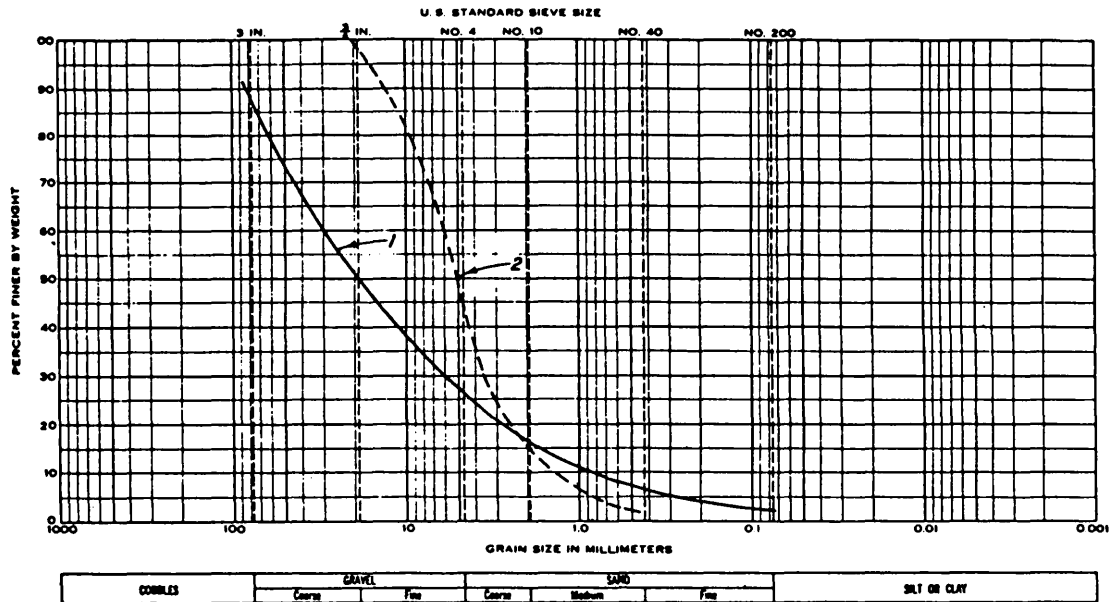APPENDIX F: COMPARISON OF SOIL CLASSIFICATIONS

Figure F1. Typical grain size distribution; well graded gravels

CURVE 1:

|	
WES -	Pit run gravel; nonplastic; well-graded; small percentage of fines
USCS -	GW, Well-graded gravel with sand
AASHTO -	A-1-a, Clean gravel
FAA -	E-1, Gravel with few fines
d50 -	19.0 mm, Coarse gravel with sand; well-graded

CURVE 2:

WES -	Sandy gravel; nonplastic; no fines
USCS -	GW, Well-graded gravel with sand
AASHTO -	A-1-a, Clean gravel
FAA -	E-1, Gravel with few fines
d50 -	5.0 mm, Fine gravel with sand; well-graded
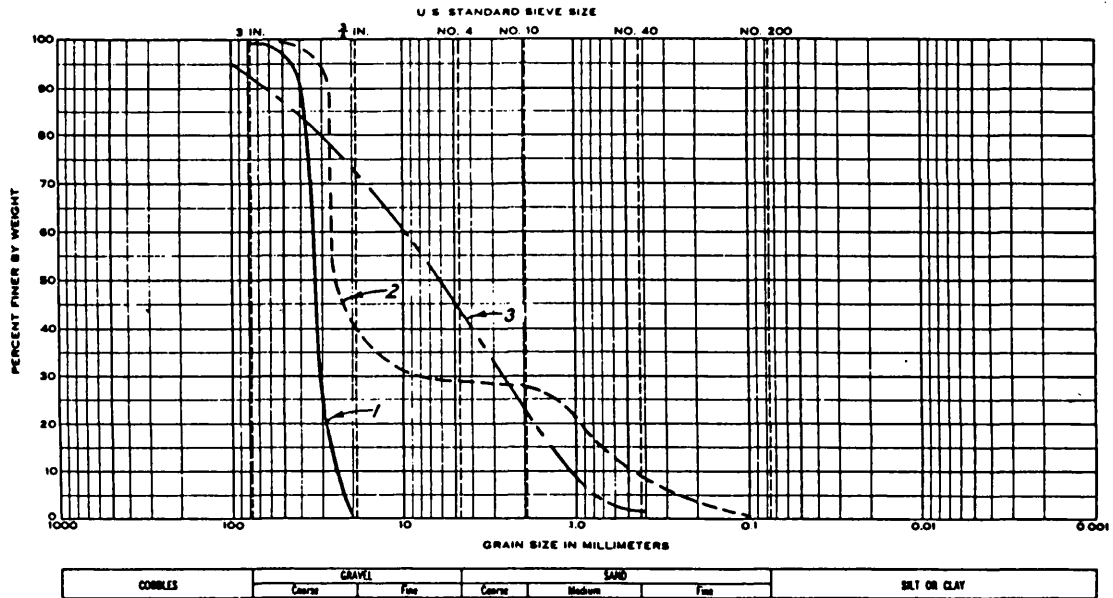
Figure F2. Typical grain size distribution; poorly graded gravels

CURVE 1:

WES -   Uniform coarse gravel; nonplastic
USCS -   GP, Poorly graded gravel
AASHTO -   A-1-a, Clean gravel
FAA -   E-3, Gravel; nonplastic
d50 -   33.0, Coarse gravel; poorly graded

CURVE 2:

WES -   Gravel-sand mixture; nonplastic
USCS -   GP, Poorly graded gravel with sand
AASHTO -   A-1-a, Clean gravel
FAA -   E-1, Gravel; nonplastic
d50 -   26.0 mm, Coarse gravel with sand; poorly graded

CURVE 3:

WES -   Sandy gravel; nonplastic
USCS -   GP, Poorly graded gravel with sand
AASHTO -   A-1-a, Clean gravel
FAA -   E-1, Gravel; nonplastic
d50 -   6.1 mm, Fine gravel with sand; poorly graded
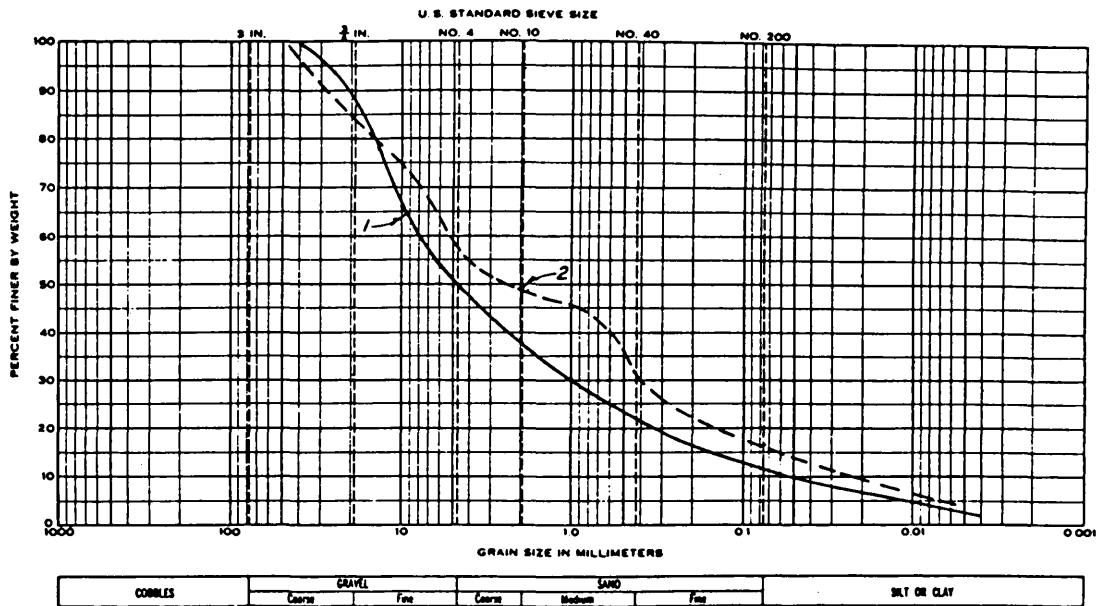
Figure F3. Typical grain size distribution; silty gravels

CURVE 1:

WES -   Crushed limestone; LL = 16, PI = 8; well graded
USCS -   GW-GM, Well-graded gravel with silt and sand
AASHTO -   Clean gravel
FAA -   E-4, Gravel; low plasticity fines
d50 -   5.0 mm, Fine gravel with silt and sand; well-graded

CURVE 2:

WES -   Gravel-sand-silt mixture; LL = 32, PI = 6; poorly graded
USCS -   GM, Silty gravel with sand
AASHTO -   A-2-4, Silty gravel
FAA -   E-4, Gravel; low plasticity fines
d50 -   2.3 mm, Coarse sand with gravel and silt; poorly graded
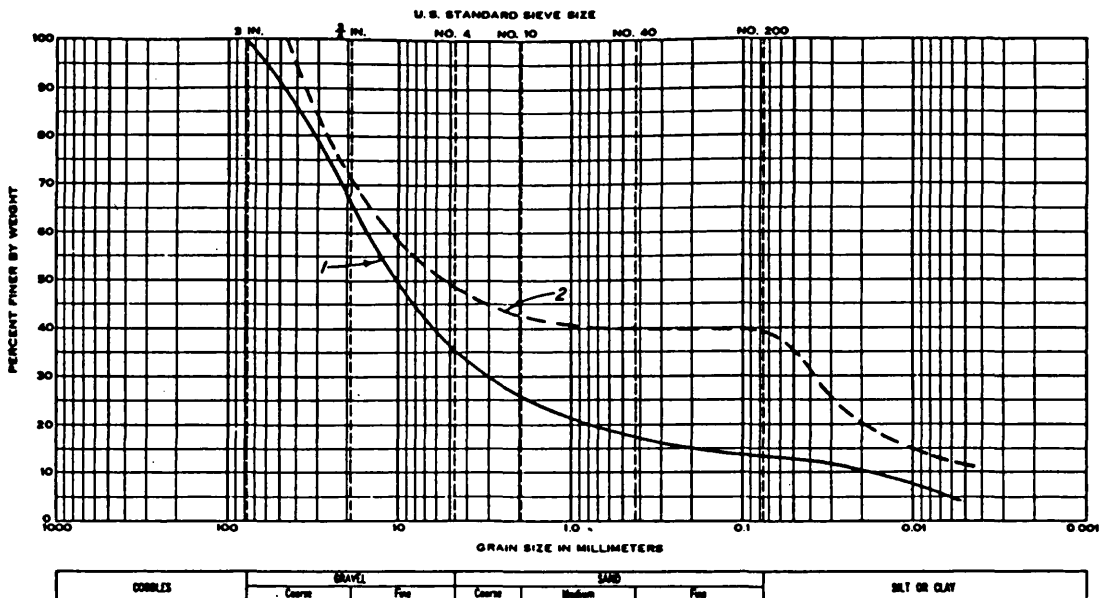
Figure F4. Typical grain size distribution; clayey gravels

CURVE 1:

WES -   Clay-gravel; LL = 40, PI = 19; low percentage of plastic fines
USCS -   GC, Clayey gravel with sand
AASHTO -   A-2-7, Clayey gravel
FAA -   E-7, Clayey gravel
d50 -   10.0, Fine gravel with sand; clayey

CURVE 2:

WES -   Natural gravel and clay mixture; LL = 46, PI = 20; almost no
           sand sizes present
USCS -   GC, Clayey gravel
AASHTO -   A-7-6, Gravelly clay
FAA -   E-7, Clayey gravel
d50 -   5.0 mm, Clayey fine gravel
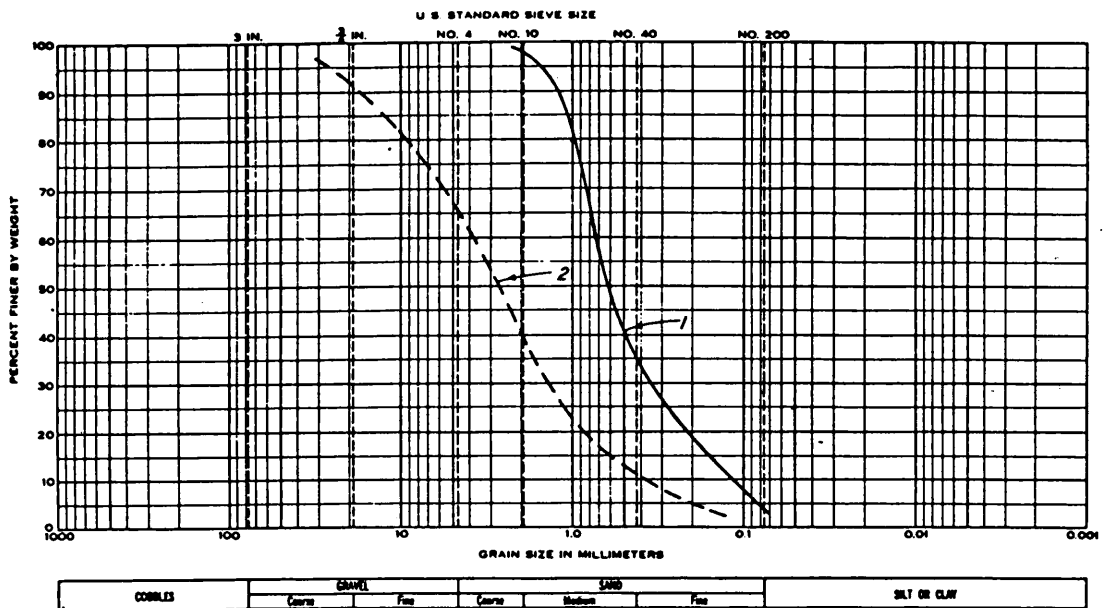
Figure F5. Typical grain size distribution; well-graded sands

CURVE 1:

WES -   Medium to fine sand; nonplastic; well graded
USCS -   SW, Well-graded sand
AASHTO -   A-1-b, Clean sand
FAA -   E-1, Sand with nonplastic fines
d50 -   0.61 mm, Medium sand; well-graded

CURVE 2:

WES -   Gravelly sand; nonplastic; well graded
USCS -   SW, Well-graded sand
AASHTO -   A-1-a, Clean gravel
FAA -   E-1, Sand; nonplastic fines
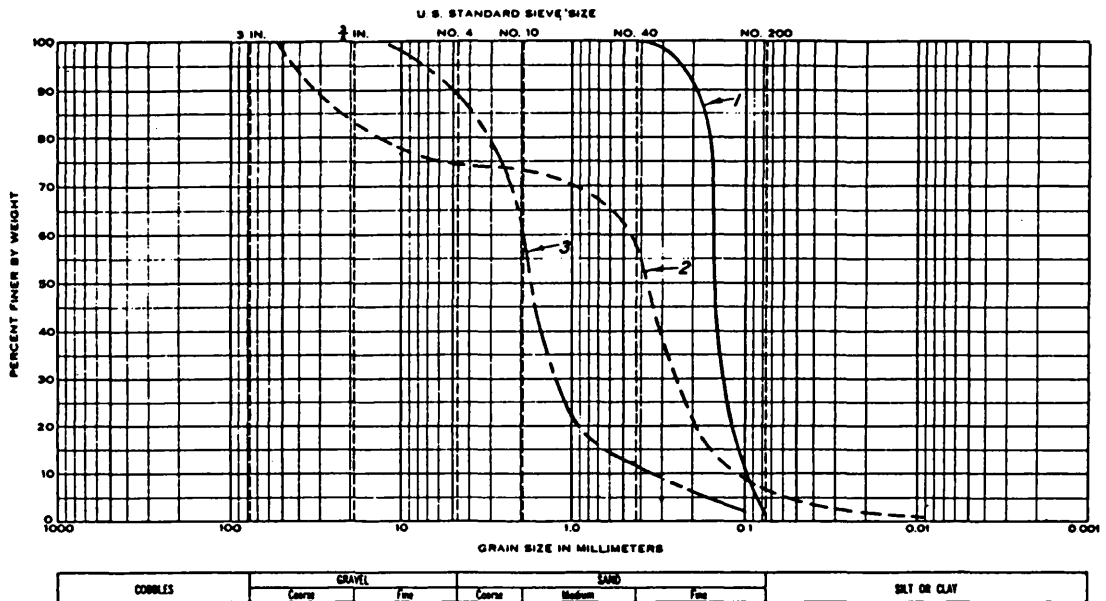d50 -   2.7 mm, Coarse sand with gravel; well-graded

Figure F6. Typical grain size distribution; poorly graded sands

CURVE 1:

WES -   Uniform fine sand; nonplastic
USCS -   SP, Poorly graded sand
AASHTO -   A-3, Fine sand
FAA -   E-3, Sand; nonplastic fines
d50 -   0.15 mm, Fine sand; poorly graded

CURVE 2:

WES -   Poorly graded gravelly sand mixture; nonplastic
USCS -   SP, Poorly graded sand with silt; nonplastic fines
AASHTO -   A-3, Fine sand
FAA -   E-2, Sand; few nonplastic fines
d50 -   0.38 mm, Fine sand with gravel; poorly graded

CURVE 3:

WES -   Coarse to medium sand; nonplastic
USCS -   SP, Poorly graded sand
AASHTO -   A-1-b, Clean sand
FAA -   E-1, Sand, no fines
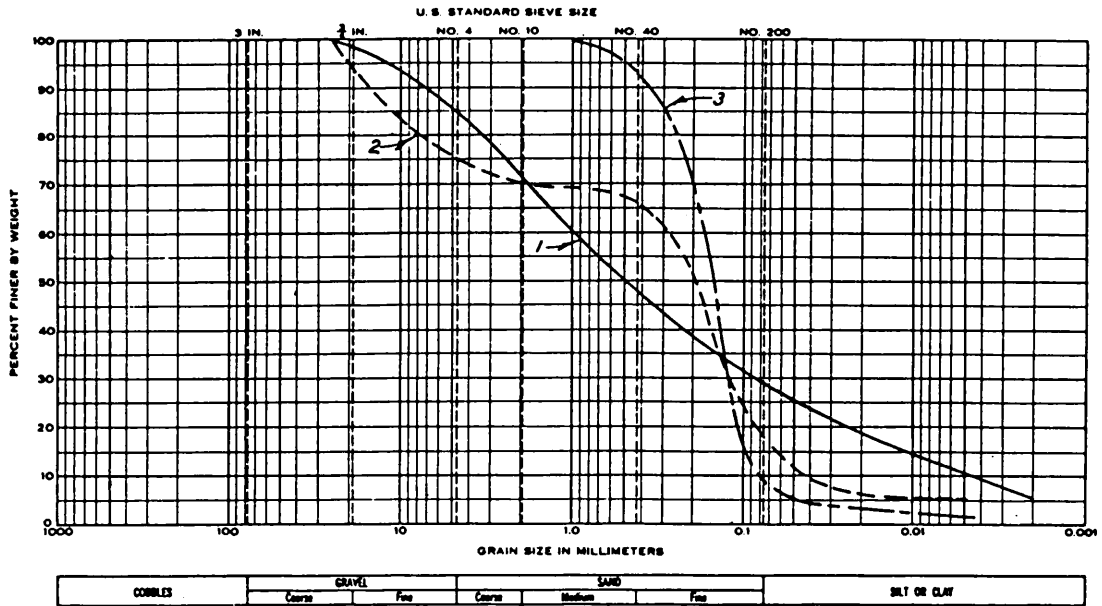d50 -   1.8 mm, Medium sand; poorly graded

Figure F7. Typical grain size distribution; silty sands

CURVE 1:

WES -   Silty gravelly sand; nonplastic
USCS -   SM, Silty sand with gravel; nonplastic fines
AASHTO -   A-2-4, Silty sand
FAA -   E-5, Sand, some nonplastic fines
d50 -   0.50 mm, Medium sand with gravel and silt

CURVE 2:

WES -   Mixture of gravel-sand and fine silty sand; nonplastic
USCS -   SM, Silty sand with gravel; nonplastic fines
AASHTO -   A-2-4, Silty sand
FAA -   E-4, Sand, few nonplastic fines
d50 -   0.19 mm, Fine sand with gravel and silt

CURVE 3:

WES -   Silty fine sand; LL = 22, PI = 5
USCS -   SM, Poorly graded sand with silt
AASHTO -   A-2-4, Silty sand
FAA -   E-3, Silty sand
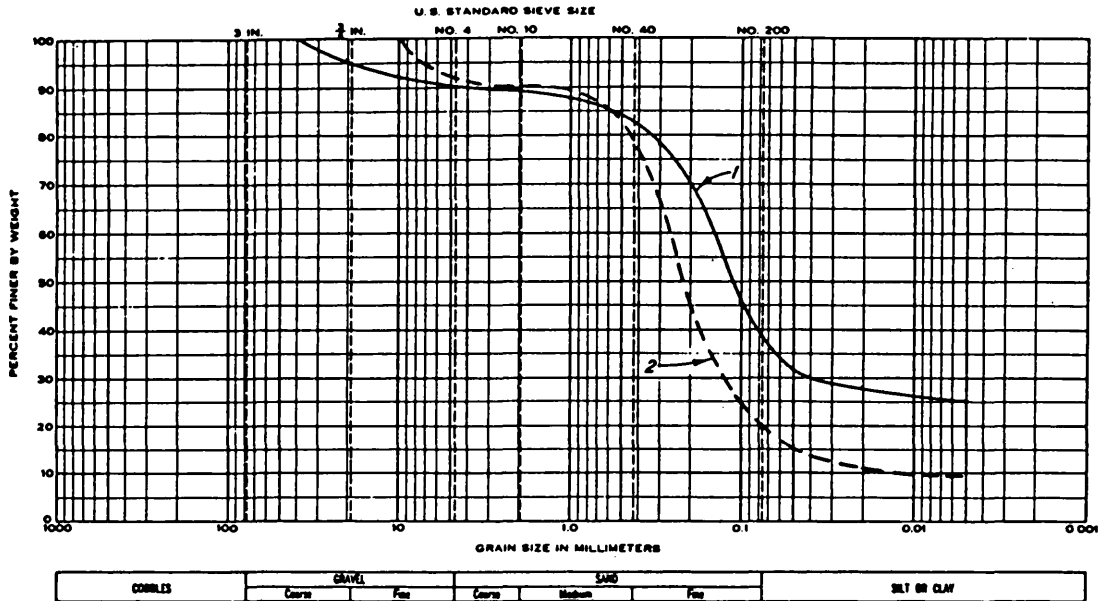d50 -   0.16 mm, Fine sand

F9

Figure F8. Typical grain size distribution; clayey sands

CURVE 1:

WES -   Clayey sand; LL = 23, PI = 10
USCS -   SC, Clayey sand
AASHTO -   A-4, Sandy silt
FAA -   E-5, Sand, low plasticity fines
d50 -   0.11, Clayey fine sand

CURVE 2:

WES -   Limerock and sand mixture, LL = 23, PI = 8; poorly graded
USCS -   SC, Clayey sand
AASHTO -   A-2-4, Silty sand
FAA -   E-4, Sand, low plasticity fines
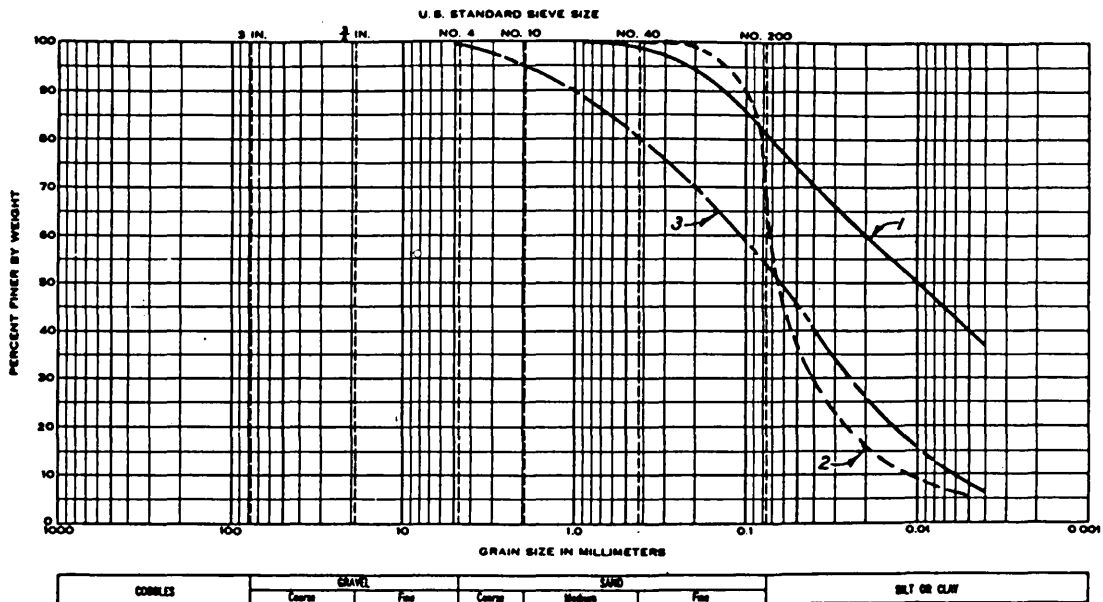d50 -   0.22 mm, Fine sand with clay

Figure F9. Typical grain size distribution; low plasticity silts

CURVE 1:

WES -	Clayey silt; LL - 46, PI - 16
USCS -	ML, Silt with sand
AASHTO -	A-6, Low plasticity clay
FAA -	E-7, Clayey silt
d50 -	0.01 mm, Low plasticity silt with sand

CURVE 2:

WES -	Uniform sandy silt; LL - 30, PI - 3
USCS -	ML, Sandy silt
AASHTO -	A-4, Low plasticity silt
FAA -	E-6, Sandy silt
d50 -	0.06 mm, Low plasticity silt with sand

CURVE 3:

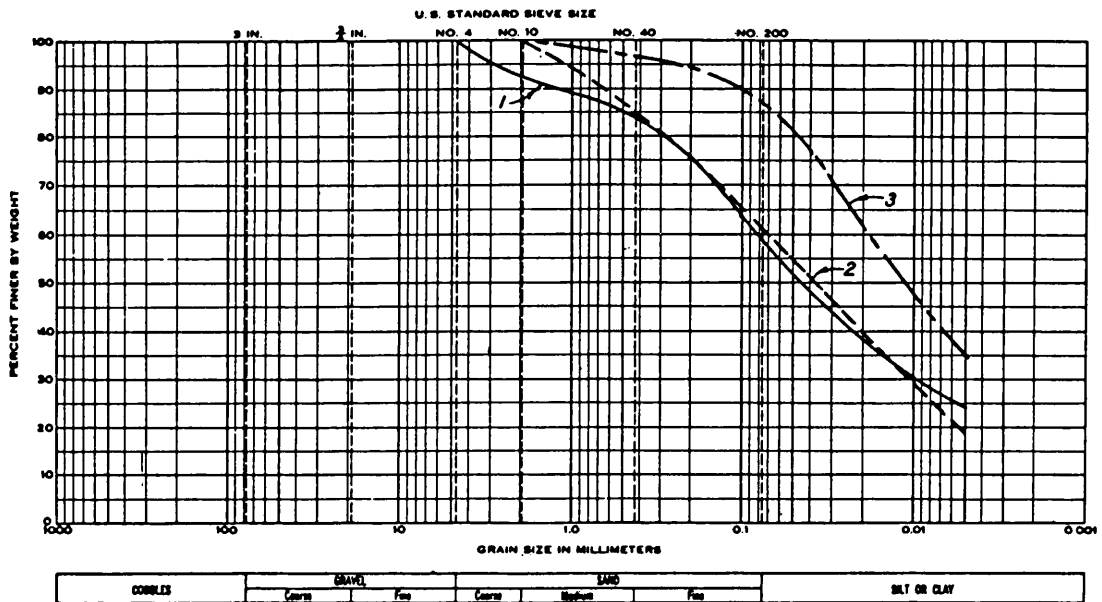|	
WES -	Sandy silt; LL - 34, PI - 3
USCS -	ML, Sandy silt
AASHTO -	A-4, Low plasticity silt
FAA -	E-6, Sandy silt
d50 -	0.06 mm, Low plasticity silt with sand

Figure F10. Typical grain size distribution; high plasticity silts

CURVE 1:

WES -   Micaceous sandy silt; LL - 55, PI - 6
USCS -   MH, Sandy elastic silt
AASHTO -   A-5, High plasticity clay
FAA -   E-9, Clayey silt
d50 -   0.04 mm, High plasticity silt with sand

CURVE 2:

WES -   Sandy silt; LL - 67, PI - 27
USCS -   MH, Sandy elastic silt
AASHTO -   A-7-5, Medium plasticity clay
FAA -   E-10, Clay
d50 -   0.04 mm, High plasticity silt with sand

CURVE 3:

WES -   Clayey silt; LL - 54, PI - 24
USCS -   MH, Elastic silt
AASHTO -   A-7-5, Medium plasticity clay
FAA -   E-8, Clayey silt
d50 -   0.01 mm, High plasticity silt
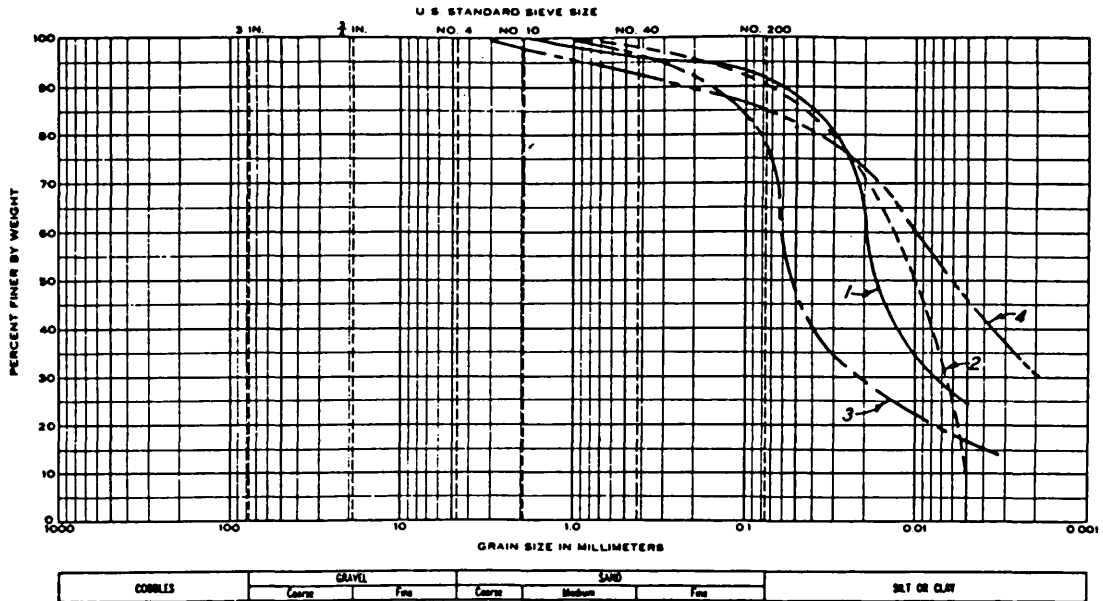
F12

Figure F11. Typical grain size distribution; low plasticity clays

CURVE 1:

WES -   Lean clay; LL = 30,
            PI = 13
USCS -   CL, Lean clay
AASHTO -   A-6, Low plasticity
            clay
FAA -   E-7, Silty clay
d50 -   0.18 mm, Low plasticity
            clay

CURVE 2:

WES -   Silty clay; LL = 25,
            PI = 6
USCS -   CL, Lean clay
AASHTO -   A-4, Low plasticity
            silt
FAA -   E-6, Silty clay
d50 -   0.10 mm, Low plasticity
            clay

CURVE 3:

WES -   Sandy clay, LL = 31,
            PI = 18
USCS -   CL, Lean clay with sand
AASHTO -   A-6, Low plasticity
            clay
FAA -   E-7, Silty clay
d50 -   0.051 mm, Low plasticity
            clay with sand

CURVE 4:

WES -   Clay; LL = 44, PI = 25
USCS -   CL, Lean clay with sand
AASHTO -   A-7-6, High plasticity
            clay
FAA -   E-7, Silty clay
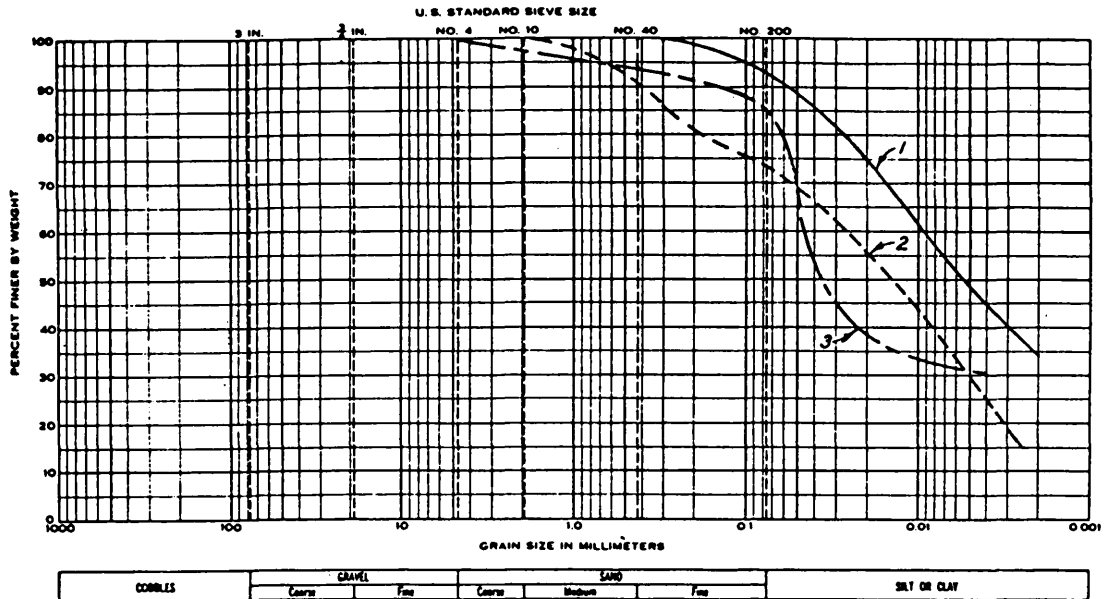d50 -   0.006 mm, Low plasticity
            clay with sand

F13

U. S. STANDARD SIEVE SIZE

Figure F12. Typical grain size distribution; high plasticity clays

CURVE 1:

WES -	Silty clay; LL - 52, PI - 25
USCS -	CH, Fat clay
AASHTO -	A-7-6, High plasticity clay
FAA -	E-8, Silty clay
d50 -	0.005 mm, High plasticity clay

CURVE 2:

WES -	Sandy fat clay; LL - 75, PI - 45
USCS -	CH, Fat clay with sand
AASHTO -	A-7-6, High plasticity clay
FAA -	E-11, Clay
d50 -	0.015 mm, High plasticity clay with sand

CURVE 3:

WES -	Sandy clay; LL - 51, PI - 29
USCS -	CH, Fat clay with sand
AASHTO -	A-7-6, High plasticity clay
FAA -	E-8, Silty clay
d50 -	0.037 mm, High plasticity clay with sand

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S. Joseph Spigolon

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13. ABSTRACT (Maximum 200 words)

Existing soil descriptor systems are not universally used, or even understood, by all groups involved in navigation dredging. As part of a 6-year study of this problem, a resource review has been conducted, which includes examination of the published literature and interviews with individuals knowledgeable in this area. The study indicates that the minimum soil identification test data necessary for the design, planning, and execution of dredging projects are as follows: (a) undisturbed soil mass properties, (b) disturbed soil material properties, (c) specific properties such as rheologic properties of a slurry, sedimentation rate in salt water, or bulking factors. Suggestions are made in the report for a standard set of descriptive terms and for a new Dredging Classification System.

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DEPARTMENT OF THE ARMY

WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
3909 HALLS FERRY ROAD
VICKSBURG, MISSISSIPPI 39180-6199

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