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Dredging Research Technical Notes

Geotechnical Descriptors for Dredgeability

Purpose

An investigation was made to identify the geotechnical properties of sediments that must be known for estimating, planning, and executing dredging projects and to define standard dredging-related descriptors that will indicate, or readily infer, the dredgeability of the in situ sediments. This technical note summarizes the findings of that study, which was conducted as part of the U.S. Army Engineer Waterways Experiment Station's Dredging Research Program.

Background

There is no standard, universal system of descriptors that will directly indicate, or infer, the dredgeability of subbottom sediments. 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. The various world-wide groups involved in dredging do not agree among themselves on a common system for characterizing and describing sediment properties. The cost to the dredging industry, both the Corps of Engineers and other owners, and to dredging contractors—in claims, litigation, lost time, and the other effects of incomplete understanding or misunderstanding of sediment description and classification terminology—is a contributing factor in contract claims.

Additional Information

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Dredging Mechanisms

Dredgeability has been defined (Spigolon 1993) as "the ability to excavate underwater, remove, transport, and deposit sediments with respect to known or assumed equipment, methods, and in situ material characteristics." An understanding of dredgeability descriptors requires an understanding of the dredging processes and how sediment properties affect them. Dredging is typically conducted in four stages, as outlined below.

Excavation

Loosening or dislodgement of individual material grains or of a cohesive group of particles from the in situ state.

Mechanisms of excavation include the following:

- *Direct suction*—suction is applied to a pipe inserted into a very soft or nearly fluid soil; external pressure causes the soil to enter the pipe as a plastic mass with no excess water.
- *Hydraulic or pneumatic erosion (scour)*—the flow of a high-velocity, high-volume water or air stream across the surface of a clean granular material causes scour, which pushes and lifts the grains into the water stream.
- *Mechanical cutting*—cutting the sediment 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 scooping*—using the cutting edge of a shovel, clamshell, dragline, or bucketwheel.

Removal

Moving the sediment from the bottom to the surface.

Mechanisms of removal include the following:

- *Hydraulic pipeline*—a suction pipeline is used to move the plastic mass or the hydraulic slurry from the excavation area at the bottom to the surface pumping system.
- *Mechanical containers*—a bucket, scoop, shovel, clamshell, bucket ladder, 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

Movement of the material to a disposal site by means of a slurry pipeline or mechanical conveyances.

Mechanisms of transport include the following:

- *Hydraulic pipeline*—individual particles, clumps of material, or clay balls are pumped in a pipeline as a soil-water slurry.
- *Mechanical containers*—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

Deposition of the material on land or into a water disposal area. Basic processes for performing these tasks are hydraulic, pneumatic, and mechanical.

Mechanisms of disposal include:

- *Hydraulic pipeline*—pipeline slurry is directly discharged into a land or water disposal area.
- *Mechanical devices*—materials are discharged by bottom discharge from hopper ship or barge, direct dumping from the transport unit, or mechanical removal using a scraper, bucket, clamshell, or high-pressure water stream.

Sediment Characteristics Affecting Excavation

The dredgeability of a sediment during excavation is directly dependent on its in situ shearing resistance. When cutting or scooping is used, the adhesion between the soil and the metal cutting surface is also a shearing resistance. In both cases, the shearing resistance is given by

$$s = c + (\sigma - u) \tan \phi$$

where

s = shearing resistance

c = cohesion

σ = force normal to the shearing plane

u = pore water pressure

ϕ = angle of internal friction

If a sediment is cohesionless (that is, free of cohesive fines), the cohesion term is zero and the total shearing resistance is a function of the normal force and the friction angle, which is directly related to the relative density (compactness) and the grain size distribution. The friction angle depends on the interparticle interference during shear, with larger and more angular particles having a higher friction.

Cohesive sediments are fine-grained materials that do not change volume during shear, and thus behave as though $\phi = 0$ (that is, the strength is independent of the normal force on the shear plane and is characterized only by "cohesion"). The shear strength of clayey soils and of rock is in this category. The clay mineral type and content of cohesive soils affect the strength as well as the plasticity of the soil; therefore, the strength and plasticity are related.

Direct suction will work only if the sediment is fine grained and is extremely soft and plastic; that is, grain-to-grain friction does not occur. *Scour* (erosion) is inhibited by the interparticle attractive forces of cohesion found in clayey soils. The energy to cause scour is also affected by particle size; the easiest particles to scour are fine sands and silts.

Cutting or plowing is usually done with very little overburden. If the sediment is cohesionless, the normal force on the shear plane is very low, and shearing resistance is then a function of the pore water pressure, which is a function of permeability, which in turn is a function of grain size distribution, the relative packing of the grains, and the speed of cutting.

Scooping, or digging, usually involves a deeper shearing action than cutting; therefore, the normal force increases the shearing resistance, as does the grain size. In both cutting and scooping, cohesive soils and rock are not affected by overburden pressure, only by the cohesion, which is related to consistency. For rock, the blasting or ripping characteristics are directly related to strength. Adhesion of the soil to the cutting surface, whether cutting or scooping, depends on the soil type, its liquidity, the type and roughness of the cutting surface, and the pressure of the sediment against the cutting surface (normal force).

Turbidity occurs around a cutterhead, draghead, or scoop during excavation or during water disposal. The sedimentation rate of grains varies inversely as the square of the diameter, the smaller grains settling much more slowly than large ones. Large grains, such as rock fragments, gravel, and coarse sand, will settle in a matter of minutes. Friable silts and clayey silts will remain in suspension for hours and even days, especially in turbulent water.

The soil properties significant for evaluating the excavation dredgeability of sediments include the in situ shear strength, the overall grain size distribution, the angularity of coarse grains, and the plasticity of the fines. In the case of rock, the grain size distribution/angularity of the blasted or ripped rock fragments is a significant factor.

Sediment Characteristics Affecting Removal, Transport, and Deposition

Pumpability of a sediment is a function of the median size, grain shape, and organic content. The maximum size of particle determines the required pump clearance. The rheologic behavior of the slurry depends on slurry density and "mud" (fines) content. The *abrasiveness* of the sediment on the pipeline and pump parts is related to the angularity and hardness of the grains and on the grain sizes present. The potential for forming *clay balls* in the pipeline is a function of the amount of fines present, the in situ density, and the amount and type of clay minerals, which determine the plasticity of the clay.

Sedimentation rate and *bulking* in a hopper or other slurry bulk transport are determined by the grain size distribution and plasticity of the fines. The *stickiness* of a clayey soil to the metal surface of a scoop depends on the plasticity of the soil and its wetness. The *dumpability* of a sediment from a mechanical transport, such as a hopper, barge, or truck, depends on its stickiness and its tendency to arch. *Bulking* in the disposal area depends on grain size distribution, plasticity of fines, slurry concentration, and in situ density. *Compactability* is also a function of grain size distribution and plasticity of fines.

Once the sediment is dislodged from the bottom, the undisturbed, in situ strength characteristics are destroyed and only the properties of the individual grains are of interest. Therefore, the properties that govern are the grain size distribution, including the maximum size, median size, and amount of fines; the hardness and angularity of the grains; the plasticity of the fines; and the organic content.

Significant Geotechnical Properties for Dredgeability

Based on the discussion given above, the geotechnical sediment properties of greatest value in evaluating the dredgeability of a sediment are (Spigolon 1993):

- In situ shear strength—defined in terms of consistency, compactness (relative density), or cementation.
- Grain size distribution—including maximum size, median size, and amount of fines.
- Angularity of coarse grains.
- Plasticity of fine grains—based on the Atterberg limits.
- Organic content—ash content or other indicator.
- Presence of shells, debris, or other nonsoil materials.

Geotechnical Descriptors

Two types of geotechnical descriptor systems exist: *descriptive terms*—words used to represent numerical soil test results, arranged into classes without consideration of a specific engineering or dredging application, and *classification groups*—words or symbols used to show a grouping or rating of soils according to their expected behavior in a specific engineering or dredging application.

The descriptive term descriptor method is exemplified by typical geotechnical textbook soil descriptions and by the Permanent International Association of Navigation Congresses (PIANC 1984) "Classification of Soils and Rocks to Be Dredged." An example of a rating-based descriptor system is the Unified Soil Classification System (USCS) (Headquarters, U.S. Army Corps of Engineers (HQUSACE) 1960; American Society for Testing and Materials (ASTM) 1992). The USCS is based on the expected behavior of soil as an airfield base course medium after suitable compaction. Therefore, only compactability is considered in this system; in situ strength, median grain size, and other descriptive terms needed for dredgeability require information added to the basic descriptors.

Shear Strength Descriptive Term Descriptors

In situ shear strength is measured by in situ tests or by laboratory tests of undisturbed samples. The shear strength of cohesionless materials (sand and gravel) is directly related to the relative density. It is normally estimated by the Standard Penetration Test (SPT) and is expressed in compactness terms based on relative density, as given in Table 1, both in U.S. and European standard geotechnical engineering practice. Other field test methods such as the Cone Penetration Test are used, but they are correlated with the SPT values shown in Table 1.

Table 1. Compactness of Sands Based on Standard Penetration Test

Compactness Term	Relative Density, percent	SPT N-value, blows/30 cm (12 in.)
Very loose	0-15	0-4
Loose	15-35	4-10
Medium (firm)	35-65	10-30
Dense	65-85	30-50
Very dense	85-100	Over 50

The in situ shear strength of cohesive (clayey) sediments is defined on the basis of the unconfined compressive strength of an undisturbed sample. Field strength test methods such as the Vane Shear Test are sometimes used to estimate the unconfined compressive strength. Note that there is a difference between the USCS and the European-based PIANC definitions in Table 2. The newly defined term "fluid" is not part of the standard systems, but is introduced here because of its value in dredgeability evaluations.

Table 2. Consistency of Cohesive Soils

Consistency Term	Unconfined Compressive Strength		
	USCS (HQUSACE 1960)		PIANC (1984)
	Tons/sq ft	kPa	kPa
Fluid[1]	< 0	< 0	< 0
Very soft	0 - 0.25	0 - 25	0 - 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

[1]The fluid consistency occurs when a cylindrical test specimen of cohesive soil will not stand unconfined under its own weight and, therefore, may be considered to have a negative unconfined compressive strength.

The strength of intact rock, shale, and cemented soils is generally defined by the unconfined compressive strength of a core sample as given in Table 3. Once the intact rock has been broken into fragments, the dredgeability is similar to that of boulders, cobbles, and smaller grain sizes, except that the grains will be much more angular.

Table 3. Strength of Intact Rock

Relative Strength	Unconfined Compressive Strength	
	MPa	Tons/sq ft
Very weak	< 1.25	< 12.5
Weak	1.25 - 5.0	12.5 - 50
Moderately weak	5.0 - 12.5	50 - 125
Moderately strong	12.5 - 50.0	125 - 500
Strong	50 - 100	500 - 1,000
Very strong	100 - 200	1,000 - 2,000
Extremely strong	> 200	> 2,000

Grain Size Distribution Descriptors

Systems of descriptive term descriptors for grain sizes show greater diversity among users than almost every other descriptor used in geotechnical engineering. Three of the systems most commonly used in dredging operations are shown in Table 4. The Wentworth system, one of the earliest (1922), is used by nearly all scientists and engineers *except* geotechnical engineers. The USCS is used by the U.S. Army Corps of Engineers and by virtually all U.S.-trained geotechnical engineers. The PIANC definitions are based on European geotechnical engineering practice, patterned after British definitions. If it is recognized that each descriptive term is really a word-definition based on well-defined grain size limits, then by using a tabulation such as Table 4, conversion from one system to another may be done easily. Ultimately, it is the equivalent grain diameter that is of interest rather than the name, and each name simply defines a grain size range.

Table 4. Grain Size Classification Systems

Group Name	Screen Opening, mm (U.S. Standard Sieve Size) Defining Upper Limit of Group		
	Wentworth	USCS	PIANC
Boulder	—	—	—
Cobble	256	300 (12 in.)	200
Coarse gravel	64	75 (3 in.)	60
Medium gravel	16	—	20
Fine gravel	8	19 (0.75 in.)	6
Coarse sand	2	4.76 (No. 4)	2
Medium sand	0.500	2.00 (No. 10)	0.600
Fine sand	0.250	0.425 (No. 40)	0.200
Coarse silt	0.063	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

Grain Angularity Descriptive Term Descriptors

The angularity of coarse grains, including rock fragments, boulders, cobbles, gravel, and sand, is generally described using the visual criteria of ASTM (1992) D 2488, as shown in Table 5.

Table 5. Angularity of Coarse-Grained Particles	
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

Soil Plasticity Descriptive Term Descriptors

The plasticity of cohesive soils has traditionally, and usefully, been defined in terms of the Atterberg limits tests. Casagrande (1948) defined the plasticity of cohesive soils using the A-line chart of Plasticity Index vs. Liquid Limit. The Atterberg limits tests are made only on that fraction of a soil that is finer than 0.425 mm (U.S. Standard No. 40 screen). The original Casagrande definitions were modified and incorporated into the USCS (ASTM 1992). Table 6 contains the descriptive word definitions currently used in geotechnical engineering in the United States and nearly all other nations. The U-line represents an empirically determined upper limit of Plasticity Index for natural soils. The PIANC (1984) system does not include the Atterberg limits in its cohesive soil descriptors; it formally uses only grain sizes.

Table 6. Plasticity Terms to Define Cohesive Soils		
Term	**Liquid Limit**	**Plasticity Index**
Silt	< 50	Plasticity Index (PL) less than 4 or less than the A-line[1] value corresponding to the Liquid Limit (LL).
Elastic silt	> 50	Plasticity Index (PL) less than 4 or less than the A-line[1] value corresponding to the Liquid Limit (LL).
Lean clay	< 50	Plasticity Index greater than 7 and equal to or greater than the A-line, and below the U-line,[1] value corresponding to the Liquid Limit.
Fat clay	> 50	Plasticity Index greater than 7 and equal to or greater than the A-line, and below the U-line,[1] value corresponding to the Liquid Limit.

[1]The A-line has the equation: Horizontal at PI = 4 to LL = 25.5, then PI = 0.73 × (LL -20). The U-line has the equation: Vertical at LL = 16 to PI = 7, then PI = 0.9 × (LL - 8).

Organic Soils Descriptive Term Descriptors

Terminology for organic soils has not been standardized. Therefore, it is proposed that the terms of Table 7 be used in the dredging industry. The terms were given by Landva (1986), modified by ASTM (1992) D 4427, and are based on the residue after burning the sediment at 440° C for 4 hr. Ostensibly, the organics are burned and the residue is mainly inorganic mineral solids. The USCS defines organic versions of the soils defined in Table 6 as those in which the Liquid Limit from a test made after drying the soil is less than 75 percent of the Liquid Limit of the same soil that has never been dried.

Table 7. Descriptive Terms for Highly Organic Soils

Soil Type	Description
Peat	Ash content less than 25 percent. Derived from plants. Very fibrous.
Peaty organic soils	Ash content 25 to 40 percent. Part fibers and part colloidal organics.
Organic soils	Ash content 40 to 95 percent. All colloidal organics.
Soils with organic content	Ash content over 95 percent. All colloidal organics.

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