



Predicting Geotechnical Parameters of Fine-grained Dredged Materials Using the Slump Test Method and Index Property Correlations

PURPOSE: This technical note describes an innovative method for estimating selected geotechnical properties of physically remolded dredged materials using the proposed laboratory slump test and correlation equations. Material property assessment requires laboratory testing of dredged material samples. The index properties (including bulk density, void ratio, porosity, water content, percent solids, Atterberg limits, and specific gravity) are ultimately needed as geotechnical parameter inputs into the engineering planning, design, construction, operational, and management aspects of dredging and dredged material placement. This technical note explores innovative, non-standardized, and expedient methods to estimate numerous material index properties and engineering behavior properties without running standardized time-consuming and expensive laboratory tests. The proposed methods are presented only as optional engineering tools based on experimental data and are not intended to usurp any standard laboratory testing protocol.

BACKGROUND: During nearshore dredging operations, the dredging process often involves a large amount of material handling, manipulation, and remolding. By the time an original undisturbed (or previously deposited) material has been dredged, transported, and re-deposited, its original geotechnical properties have changed. Dredged material is characterized by its physical and engineering properties, and the level of detail needed to fully characterize those properties is dependent upon factors such as the site geology, the dredging technique, and the dredged material management plan. Numerous options are available for managing dredged material removal, handling, and placement. For example, maintenance dredging may be accomplished by a trailing suction hopper dredge with open ocean disposal, by a cutterhead dredge with pipelined beach disposal, or by several other methods. The presence of contaminated sediments requires evaluation of additional sub-strategies exploring proper disposal and/or treatment such as confined aquatic disposal (Palermo et al. 1998).

For any dredging operation, the dredged material properties need to be measured or predicted. The material properties are input into dredging operation and water quality models (such as MDFATE, LTFATE, and ADDAMS), and accurate geotechnical parameters are required to provide realistic modeling similitude.

GEOTECHNICAL PROPERTIES OF REMOLDED SOILS: Dredged materials exhibit properties similar to those of undisturbed native soil and rock materials in a subaqueous environment, but when excavated, removed, remolded, or re-deposited, the properties change accordingly as the original material structure changes. High water contents, low dry densities, and low shear strengths typify remolded and deposited fine-grained dredged materials (Bartos 1977).

Physical Properties and Engineering Behavior. The most common physical property needed for dredged material characterization is the grain-size distribution, based on either the weight (which is the standardized method) or volume measurement. The material classification is then selected using the grain-size distribution and the Atterberg limit criteria. Other material properties include water content, specific gravity, organic content, bulk density, percent solids, and void ratio. Engineering behavior properties include shear strength, consolidation behavior, hydraulic conductivity (permeability), critical erosion stress, and viscosity.

Undisturbed native soil and rock materials exhibit mechanical properties that are influenced by the material structure. Intergranular bonding and physico-chemical effects influence the material's behavior (Mitchell 1993). As the water content in the material matrix is increased during remolding and the solid particles become more separated, the material behaves more like a slurry or suspension, and the intergranular bonding forces decrease. As the bonding and cohesive forces decrease, the resulting shear strength decreases. If fine-grained particles (silt and clay) constitute more than about 35 percent of the total matrix solids, the slurry will behave as a viscous material (Spigolon 1993). Fibrous materials, high organic content, and gas bubbles are known to affect the shear strength behavior of high-water-content soils (Klein and Sarsby 2000, Edil and Wang 2000). Examining the rheological behavior of soil slurries is not a traditional geotechnical topic, and standardized laboratory tests for determining the engineering properties of soil slurries have yet to be developed.

One objective for determining the engineering properties of soil slurry during nearshore dredging operations is to establish the navigation channel bottom location (horizon) when clayey suspended sediments are surficial to the channel bottom (Teeter 1992). The slurry threshold (yield) shear stress (or the amount of stress imposed on the material to initiate its movement) is determined as a function of slurry density and viscosity for a given sediment, and the nautical horizon is chosen based on established procedures (Dasch and Wurpts 2001). DeMeyer and Mahlerbe (1987) determined that the threshold (yield) shear stress of most clayey slurries is less than 2 psf (10 Pa), with in situ bulk densities of 72 to 84 pcf (1.15 to 1.35 kg/l). As the sediment consolidates and develops a higher density and threshold (yield) shear stress beyond its rheological behavior range, the geotechnical concept of effective stress (Terzaghi 1953) has been shown to govern and describe the material's physical and mechanical behavior.

Another reason for determining the properties of soil slurries is to quantify slurry strength during nearshore or contaminated dredged material placement operations. For example, when placing a sand cap over contaminated dredged materials, the engineering behavior of the dredged material must be predicted or known in order to achieve successful cap placement. If the soft dredged material has insufficient shear strength to resist the imposed cap stress, failure will occur and the purpose of the cap will be defeated. As the soft dredged material is allowed to consolidate from a slurry state into a non-zero effective stress state, its ability to resist imposed stresses will significantly increase. This phenomenon of strength increase was observed at a subaqueous capping site by Myre et al. (2000), where the soft dredged material was allowed to consolidate for about 5 months before it achieved a shear strength of about 20 psf (1 kPa), which allowed subsequent successful cap placement.

Measuring the Physical Properties and Engineering Behavior of Dredged Materials. When fine-grained dredged material is remolded from a soft and highly compressible soil

into suspended sediment or slurry, and its behavior needs to be quantified, standardized geotechnical testing methods may not be fully adequate.

Testing methods are available to measure strength gain in very soft soils as a function of time. In situ methods include the field vane shear and cone penetrometer, but in situ methods require testing to be accomplished at discrete time intervals, which in itself does not provide a method to predict strength gain as a function of time for an ongoing project. Laboratory methods such as the oedometer, direct shear, and triaxial tests allow determination of strength indices, but the very soft or fluid material is generally incompatible with the test setup.

The laboratory miniature shear vane test D4648 (American Society for Testing and Materials (ASTM) 1994) has been the most common method to estimate shear strength of marine soils (Lee 1985), and works well for very soft cohesive dredged materials. Measuring the shear strength gain directly as a function of time is possible with the laboratory vane test, but a faster and more economical method is to measure the shear strength gain as a function of decreasing water content. A consolidating dredged material's water content has been shown to decrease as a function of time in a manner consistent with its self-weight consolidation curve (Cargill 1983), implying strength gain as a function of decreasing water content. For this reason, the laboratory vane test is useful for measuring the shear strength gain as a function of decreasing water content. When the need exists for a rapid and economical field monitoring method to measure or predict shear strength gain as a function of time (or water content), a method is needed to supplement the laboratory vane test, primarily because of the time required to determine the water content based on the standard test method D2216 (ASTM 1998). A simple new test method has been demonstrated that is a unique tool for monitoring changes in strength index properties and water content of physically disturbed (remolded) dredged material.

THE SLUMP TEST METHOD: The slump test is a simple procedure that basically consists of filling an upright open-ended cylinder with remolded dredged material, striking off the excess material at the top, slowly lifting the cylinder, and measuring the change in height (slump) as the material completes its outward flow. The only equipment required is an open cylinder, a smooth flat plate to rest it on, and a straightedge ruler. Minimal operator training is required for achieving consistent results.

The slump test for concrete (ASTM 2000a) has been used for years as a rapid field method to measure the consistency of freshly mixed concrete for quality control purposes. A conical upright open-ended cylinder is filled with wet concrete and tamped in three layers with a rod. After striking off the excess material at the top, the conical cylinder is slowly lifted, and the resulting change in height (slump) of the concrete is measured. The conical cylinder dimensions are 8 in. (200 mm) at the bottom, tapered 12 in. (300mm) high, with a 4 in. (100 mm) opening at the top.

The consistency test for controlled low strength materials (CLSM) (ASTM 1997) applies to flowable fills and soil-cement slurries. Instead of measuring the vertical change in material height (slump), the outward spread diameter is noted. The CLSM test's open-ended cylinder size is 6 in. (150 mm) in height with a 3 in. (76 mm) inside diameter.

Another application of the slump test has been to determine the yield stress of mine tailing waste materials (Pashias et al. 1996). For highly flocculated mineral suspensions, the test was shown to be an inexpensive method for plant operators to monitor suspension handling and transport. Especially useful was the ability to rapidly monitor changes in the slurry solids concentration.

The benefits of observing lateral displacement of dredged material samples as a function of time were first noted during a dredged capping project in the Boston Harbor (Fredette et al. 2000). Grab samples were openly placed on a flat sheet of plywood and their spread diameters and height changes were monitored for the purpose of observing dredged material consistency over a period of time. The height change values showed a better trend than did the spread values, and this simple test helped to achieve success for the subsequently placed sand cap by revealing when the dredged material had reached an optimum consistency.

For further application to dredged materials, the proposed cylinder slump test will provide a means to assess the selected material properties required for input into current and future physical and numerical models developed for both nearshore and contaminated dredging operations. As further tests are conducted on dredged materials, parameter correlation and predictability should be enhanced.

Dredged Material Slump Test. Figure 1 shows the sequence for the proposed dredged material cylinder slump test. The remolded material is placed as a thoroughly mixed homogenous mass into the slump cylinder, leveled off, and allowed to flow outward as the cylinder is slowly lifted upward with minimum disturbance to the sample. After the outward flow has visually stopped, the difference in height between the cylinder and the slumped material is noted. The outward flow spread diameter may also be noted.

Experimental Methods and Applicability. Numerous slump tests were conducted on different types of dredged material soils (coarse and fine-grained) using open-ended polyvinyl chloride (PVC) cylinders of various heights and diameters. Aspect ratios (cylinder height to cylinder diameter) of 1, 1.5, and 2 were evaluated, as well as slump/cylinder height, slump/cylinder diameter, slump/cylinder volume, and spread/cylinder volume ratios.

The slump cylinders were filled with remolded saturated soils at various consistencies. The water contents were varied to obtain consistencies ranging from viscous slurry to a soft soil. In situ pore water was removed or added as needed, and each sample was thoroughly mixed by hand to avoid air entrapment. The slump and spread diameter dimensions were noted, and the ASTM D2216 water content was taken from the slumped soil center to minimize excess pore pressure effects after shear failure. The best predictor was found to be the slump/cylinder height, also referred to as the normalized slump. Its applicability is discussed in more detail below.

Cylinder height dimensions ranged from 5 cm (2 in.) to 20 cm (8 in.), and diameter dimensions ranged from 5 cm (2 in.) to 15.2 cm (6 in.). Slightly better correlation between water content and normalized slump was found in cylinders with aspect ratios of 1:1 and 2:1, but many 2:1 samples had a higher tendency to topple over before slumping. The lateral spread was also measured in numerous samples, but better correlations were observed using the vertical deformation (slump) measurement. Deformations were measured to the nearest 0.32 cm (0.125 in.).

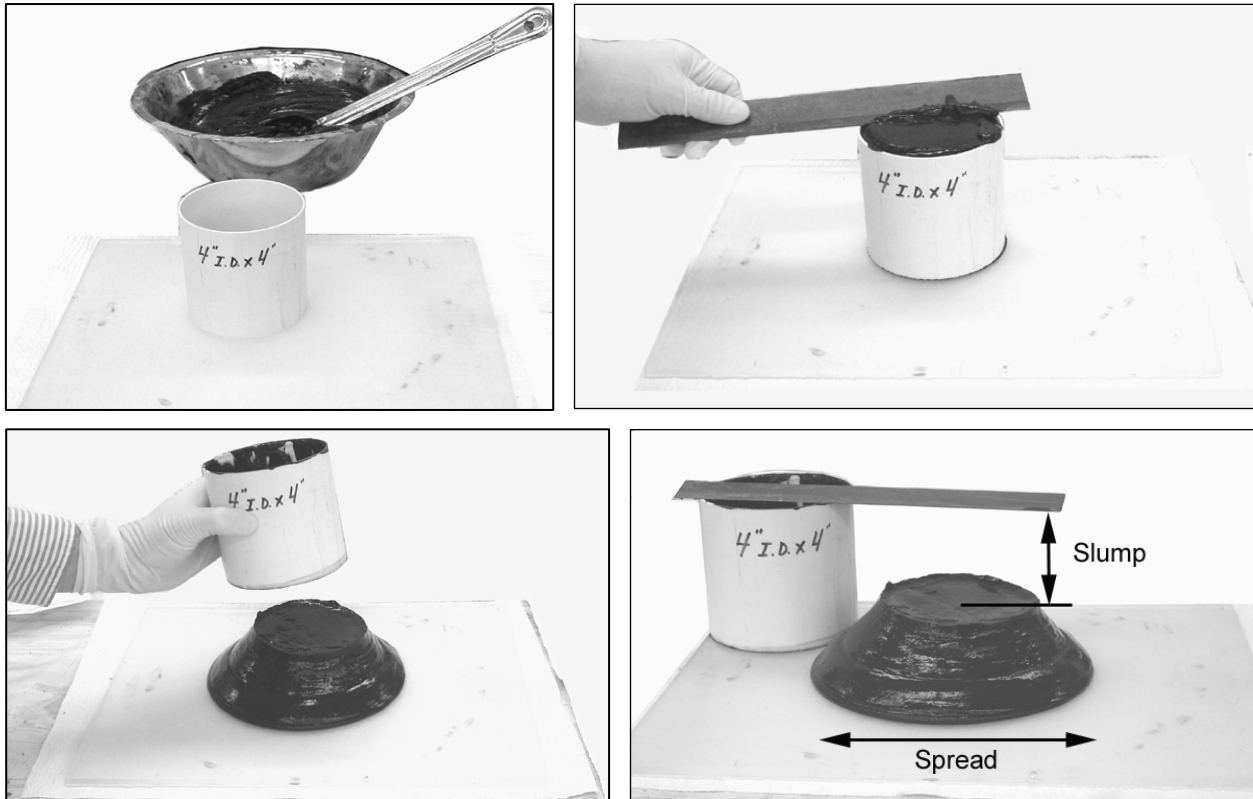


Figure 1. Dredged material slump test sequence

For each soil sample, the slump test was conducted as quickly as possible to avoid thixotropic effects, but each cylinder was lifted in a slow manner to avoid tensile failure and to prevent toppling. Pre-wetting the cylinder walls had no appreciable effect on the slump height but it helped prevent material sticking to the walls while lifting the cylinder. Each cylinder was removed in less than approximately 7 seconds after leveling off the top. Elapsed time during each test, from the sample preparation to final slump measurement, was typically less than 1 minute.

Figure 2 shows the normalized slump versus water content for various types and locations of dredged materials. Note that the test results vary as a function of soil type, and since the coarser-grained soils have less water content variability, the test is most useful for finer-grained soils.

Index property correlations for dredged materials were established by conducting other laboratory tests and identifying correlations to normalized slump. When the slump test is combined with index property correlations, it becomes a useful tool not only to rapidly monitor an individual material's properties as a function of time, but as a characterization tool for estimating an unknown dredged material's index properties.

Fine-grained materials were tested using the laboratory vane shear apparatus to determine their undrained shear strength as a function of water content. Correlation curves for slump, shear strength, water content, and other properties were then generated for each material tested. Figure 3 illustrates the laboratory vane undrained shear strength as a function of water content and liquid limit.

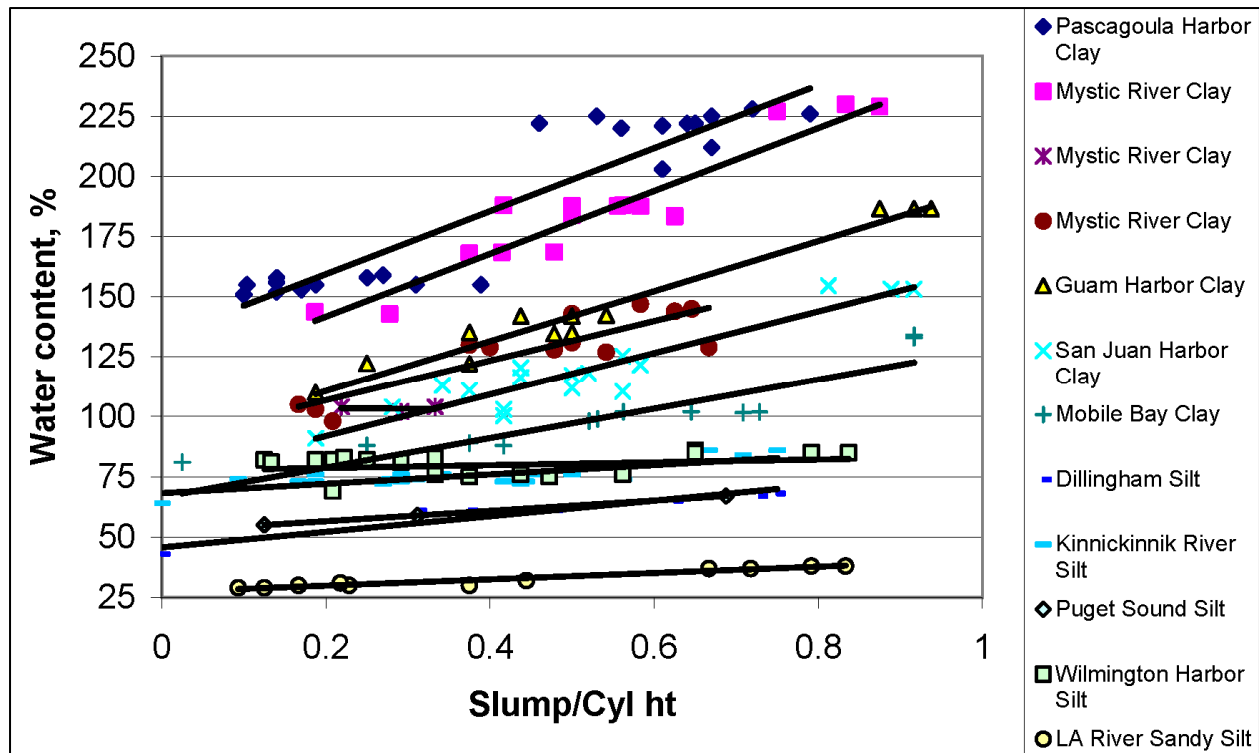


Figure 2. Normalized slump versus water content for several dredged materials

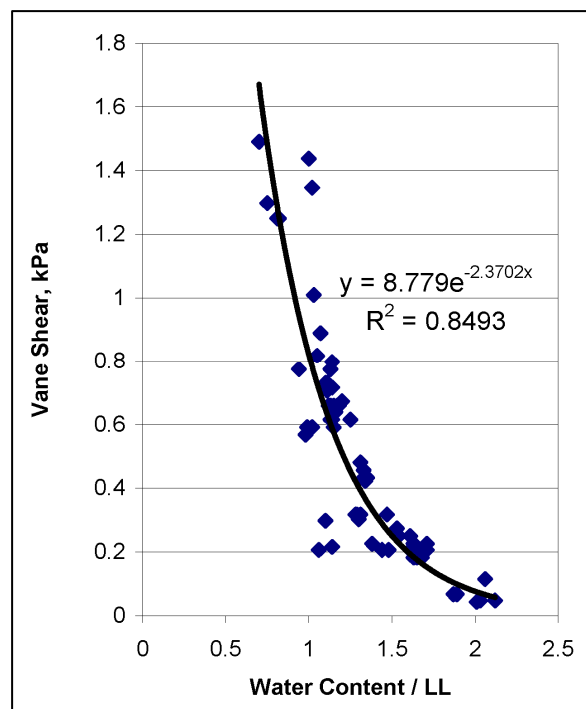


Figure 3. Plot of vane shear strength as a function of water content and liquid limit LL for Pascagoula Harbor material (to convert kPa to pounds per square foot (psf), multiply kPa by 20.8)

A set of correlation curves may be generated for any particular dredged material. The slump test method then becomes useful for monitoring changes in the remolded material properties either in the field or in the laboratory, based on the pre-generated curves. As an example, the engineering behavior properties of shear strength and self-weight consolidation stress may be monitored using a pre-generated slump test curve correlated to shear strength and consolidation. By conducting a series of simple slump tests and generating a function curve for a parameter such as water content (or void ratio, bulk density, solids content, etc.), the curve may be compared with another function containing the common parameter. Subsequent remolded material monitoring for changing shear strength or effective stress requires only a single slump test.

PREDICTING UNKNOWN MATERIAL INDEX PROPERTIES: Correlations useful for predicting unknown index properties were derived from experimental geotechnical data collected from geographically diverse fine-grained dredged

materials. The correlations discussed below enable prediction of material properties including water content, wet bulk density, percent solids, void ratio, porosity, specific gravity, and Atterberg limits without conducting time-consuming and expensive standardized laboratory testing. Combining these experimental property correlations with published correlation equations enables expedient screening-level assessment of engineering behavior properties including undrained shear strength, consolidation, and permeability (saturated hydraulic conductivity) parameters without waiting for the prerequisite laboratory testing.

Method for predicting unknown water content. Given a dredged material with an unknown water content (defined as the weight of water divided by weight of dry solids), the standard procedure to determine water content involves an oven or microwave for drying to a constant mass (ASTM 1998). An alternate and much faster method is to measure the wet bulk unit weight (commonly called the bulk density) using a simple mud balance device (ASTM 1984) and apply the Equation 1 correlation (also shown in Figure 4):

$$\text{Water content \%} = 2 \times 10^{11} \gamma^{-4.7128} \quad (1)$$

where γ = saturated wet bulk density, lb/cu ft

Equation 1 was experimentally obtained using 146 data points from fine-grained dredged material.

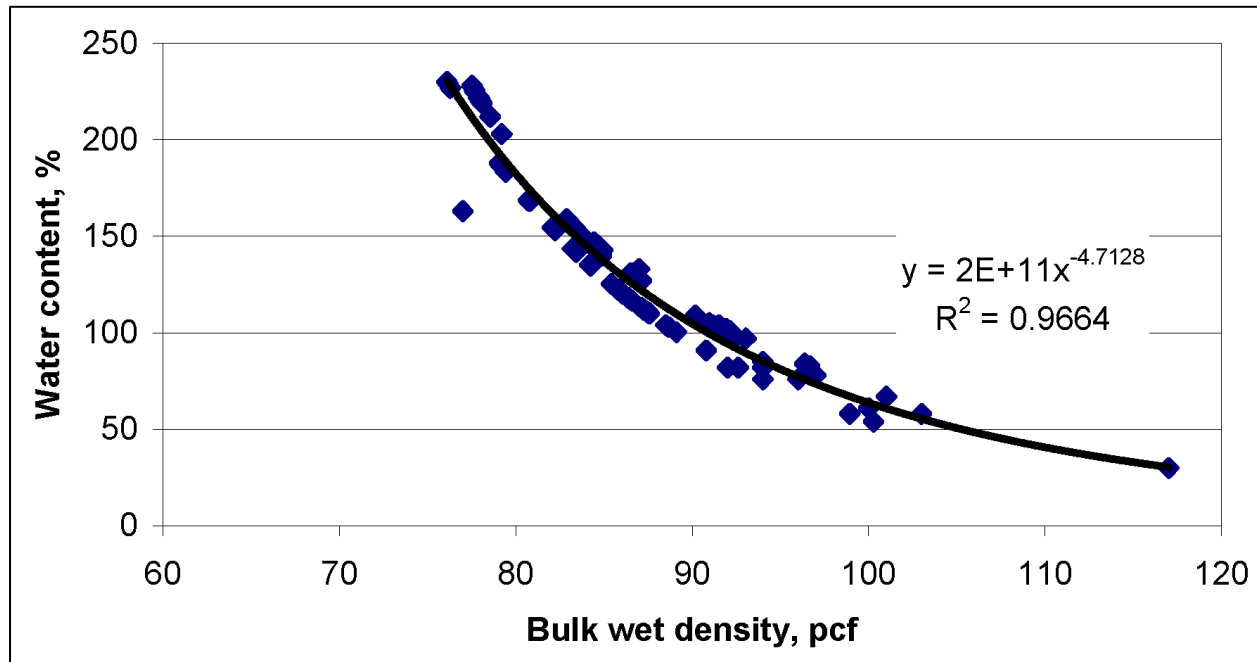


Figure 4. Dredged material water content as a function of bulk wet density (same as bulk unit weight) (to convert pounds per cubic foot (pcf) to Newtons per cubic meter, multiply by 157)

Method for predicting unknown Atterberg limits. Atterberg limits are defined by the shrinkage, plastic, and liquid limit water contents of fine-grained soils, along with the plasticity index and the liquidity index. The shrinkage limit is of little concern for dredged materials, but

the plastic and liquid limits impact not only the classification but the behavior as well. As an example, knowing the Atterberg limits enables prediction of the clumping capability in mechanical dredging, which is needed for numerical models such as MDFATE. Laboratory testing (ASTM 2000b) is required to determine the Atterberg limits. An expedient prediction method is to conduct a single slump test and apply the following equations:

$$LL = 52.74 + 0.526W - 59.97N \quad (2)$$

where

LL = liquid limit percent

W = water content percent

N = normalized slump = slump / cylinder height

Equation 2 is based on a multiple linear regression of 126 data points with $R^2 = 0.86$.

$$LI = 1.601(W/LL) - 0.612 \quad (3)$$

where

LI = liquidity index

W/LL = water content percent / liquid limit percent

Equation 3 is based on a linear regression of 139 data points with $R^2 = 0.98$.

$$PL = \frac{(LI)(LL) - W}{LI - 1} \quad (4)$$

where

PL = plastic limit percent

LI = liquidity index

LL = liquid limit percent

W = water content percent

Equation 4 is the standard soil mechanics textbook equation for liquidity index (Atkinson and Bransby 1978) rearranged for determining the plastic limit. The plasticity index (PI) is then calculated as the liquid limit minus the plastic limit, or

$$PI = LL - PL \quad (5)$$

Thus by calculating the liquid limit using the slump test correlation (Equation 2), one may determine the liquidity index, plastic limit, and the plasticity index. Although Equation 2 is based on limited data to date with evident variance, there exists a strong correlation between water content, normalized slump, and the liquid limit.

For a quick assessment of a dredged material's liquid limit consistency without using the standard test method, insert the sharpened tip of a common No. 2 pencil (with the tip shaved to an

approximately 60-deg angle) into the surface of the material and observe if the pencil remains in a vertical position. The maximum water content at which the pencil freely stands without toppling over is the approximate liquid limit.

Methods for predicting unknown phase relationships. Phase relationships include void ratio, percent solids, bulk density, porosity, and dry density, among others. They are calculated from parameters such as water content, percent saturation, and specific gravity, which generally require laboratory testing to determine.

To predict the saturated wet bulk density (or the bulk unit weight) of a dredged material when only the water content is known, the following equation may be used:

$$\gamma = 233.21W^{-0.2051} \quad (6)$$

where

γ = bulk unit weight (commonly called the bulk density), lb/cu ft
W = water content percent

Equation 6 is based on 146 data points with $R^2 = 0.96$.

To predict the void ratio (volume of voids / volume of dry solids) when the water content is known, but specific gravity is not, conduct a single slump test and use:

$$e = 0.028W - 0.055N - 0.065 \quad (7)$$

where

e = void ratio
W = water content percent
N = normalized slump = slump / cylinder height

Equation 7 is based on 185 data points with $R^2 = 0.99$, which is an excellent correlation.

If water content and specific gravity are both known, and the material is fully saturated, use the textbook equation:

$$e = WG_s/100 \quad (8)$$

where

W = water content percent
G_s = specific gravity of solids

Combining Equations 7 and 8 allows estimation of the specific gravity, G_s:

$$G_s = 2.8 - 5.5N/W - 6.5/W \quad (9)$$

Another useful relationship is the percent solids by weight as a function of water content, illustrated in Figure 5.

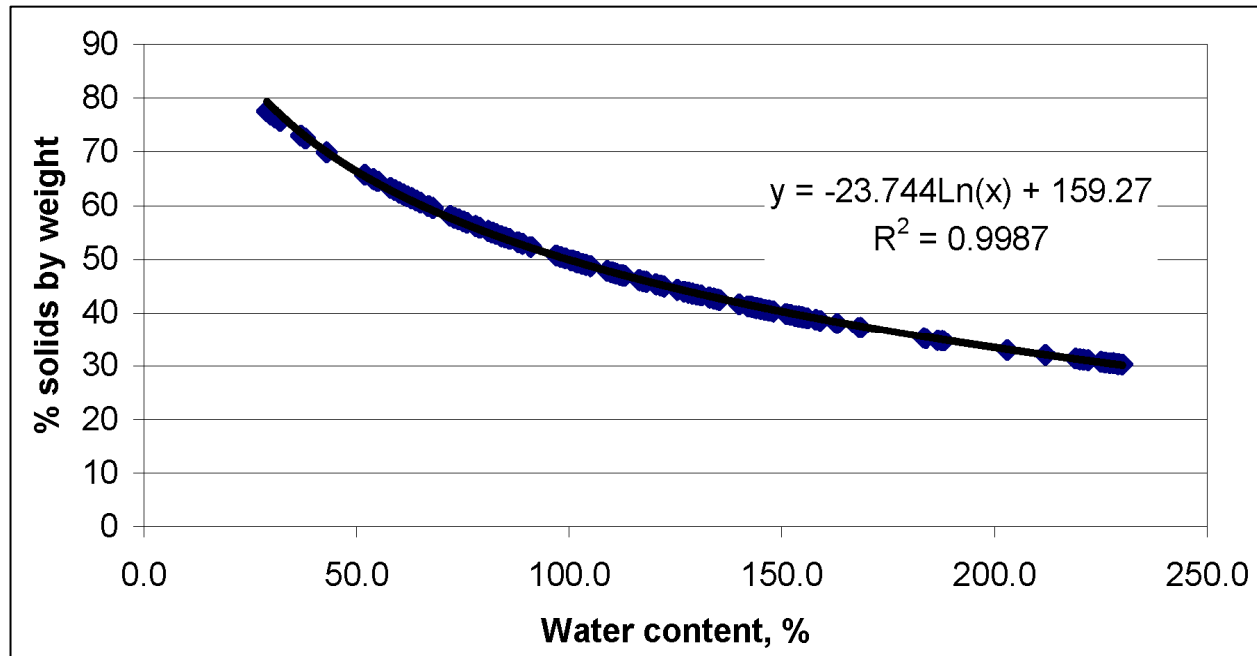


Figure 5. Percent solids by weight as a function of water content

The general equation for percent solids by weight is

$$\% \text{ solids by weight} = 10000 / (W+100) \quad (10)$$

where W = water content percent

To convert percent solids by weight to percent solids by volume, the specific gravity needs to be known. An approximate conversion without knowing the specific gravity is

$$\text{Solids concentration by volume, grams/liter} \sim 10 \times \% \text{ solids by weight} \quad (11)$$

Other conversions for solids content are given in EM 1110-2-5027 (Department of the Army 1987). Several geotechnical parameters may also be calculated using phase relationships found in soil mechanics textbooks such as Bardet (1997).

Methods for predicting unknown engineering behavior properties. For determining undrained shear strength knowing only the water content and liquid limit of the material, an approximate equation is:

$$\text{Vane shear strength psf} = 183 e^{-2.3714(W/LL)} \quad (12)$$

where

$$e = 2.718$$

W/LL = water content percent / liquid limit percent

A relatively low R^2 value of 0.85 based on 72 data points likely precludes usage of Equation 12 for anything other than general screening and rapid estimation purposes. Figure 6 shows the regression curve.

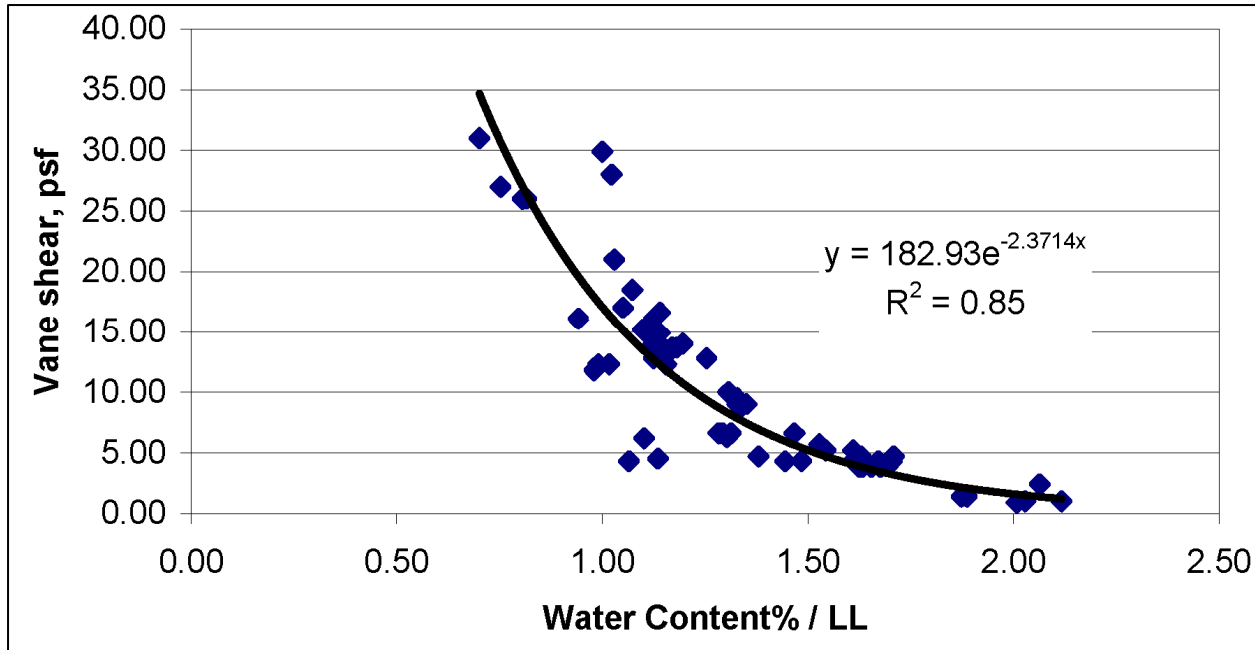


Figure 6. Vane shear strength as a function of water content and liquid limit (to convert pounds per square foot (psf) to kPa, divide psf by 20.8)

For estimating an unknown effective stress–void ratio relationship for a cohesive dredged material, Figure 7 was generated based on data from 10 self-weight consolidation tests combined with standard oedometer (fixed ring) consolidation tests. The ratio of water content to water content at the liquid limit for each material provided the best correlation to effective stress. A relatively low R^2 value of 0.83 based on 166 data points likely precludes usage of this equation for anything other than general screening and estimating purposes, similar to the vane shear equation above.

$$\sigma' = 129.77(W/LL)^{-4.7044} \quad (13)$$

where

σ' = effective stress, psf

W/LL = water content percent / liquid limit percent

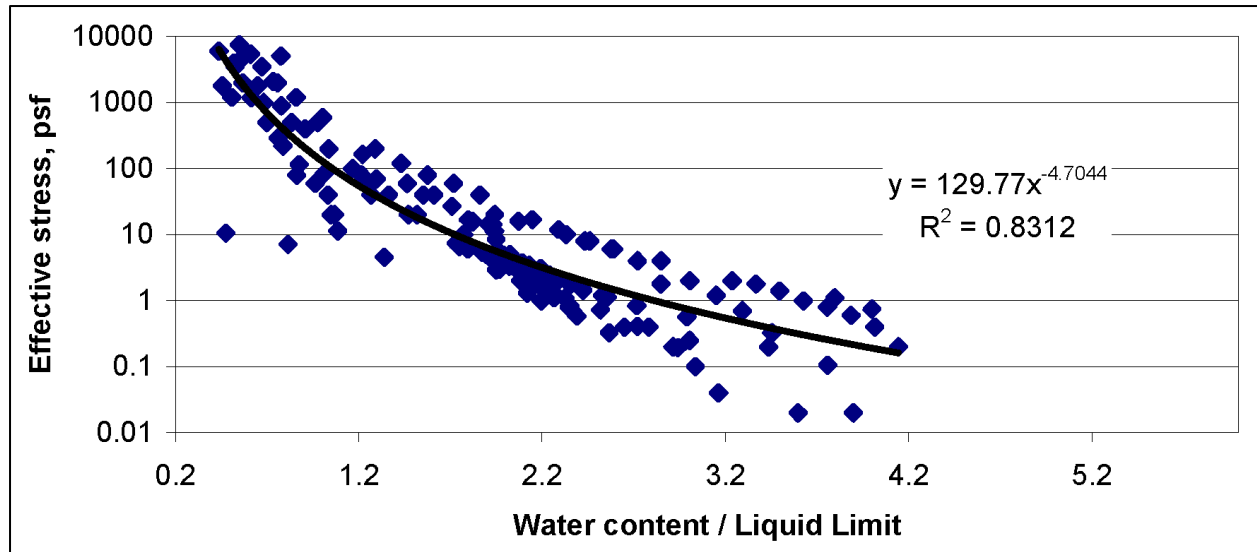


Figure 7. Predictive curve from dredged material self-weight and fixed-ring consolidation data (to convert pounds per square foot (psf) to kPa, divide psf by 20.8)

Numerous correlations between physical index properties and engineering behavior properties are available based on published data. For example, Wroth (1979) has shown that

$$LI = \log(170/c_u) / 2 \quad (14)$$

$$c_u = 170 e^{-4.6LI} \quad (15)$$

where

LI = liquidity index
 c_u = undrained shear strength, kN/m^2
 $e = 2.718$

For the soil compression index C_c , Terzaghi and Peck (1967) showed that

$$C_c = 0.009 (LL-10) \quad (16)$$

and Wood and Wroth (1978) showed that

$$C_c = G_s PI / 200 \quad (17)$$

where

C_c = compression index = change in void ratio per effective stress log cycle change
 LL = liquid limit percent
 G_s = specific gravity of solids

To estimate permeability (saturated hydraulic conductivity), Carrier and Beckman (1984) proposed the following equation for remolded clays:

$$k = 0.0174 [e - 0.027 (PL - 0.242PI) / PI]^{4.29} / (1+e) \quad (18)$$

where

k = permeability, m/sec

e = void ratio

PL = plastic limit percent

PI = plasticity index

SUMMARY: Geotechnical parameters required for numerical models may be easily predicted or estimated using material property correlations obtained from both standardized and innovative geotechnical tests. Both published and experimental correlation equations are presented herein for application to typical fine-grained remolded dredged materials (i.e., in a physically disturbed state such as that imposed by mechanical or hydraulic dredging operations). The following geotechnical parameters may be rapidly estimated based on dredged material test data, using one or more of the approximately 18 equations listed heretofore:

- Water content
- Bulk wet unit weight (commonly referred to as bulk density)
- Atterberg limits (liquid limit, plastic limit, plasticity index, and liquidity index)
- Specific gravity
- Void ratio and porosity
- Percent solids (by weight or volume)
- Undrained shear strength
- Effective stress
- Compression index
- Permeability

Obtaining geotechnical parameters using the above correlation equations does not substitute for standardized laboratory testing requirements. All correlations and non-standardized test methods presented herein are intended to be used as guidance for estimating purposes only, due to their empirical origins.

ADDITIONAL INFORMATION: Questions about this technical note can be addressed to Mr. Landris T. Lee (601-634-2661, Fax 601-634-3453, e-mail: Landris.T.Lee@erdc.usace.army.mil). This technical note and associated research work is funded by the Dredging Operations and Environmental Research (DOER) Program 12B Nearshore Focus Area Work Unit 33292 titled "Geotechnical Properties of Dredged Material." Program Manager of the DOER is Dr. Robert M. Engler (601-634-3624, Robert.M.Engler@erdc.usace.army.mil), and the Nearshore Focus

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