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Dredging Research Technical Notes

Erosion of Cohesive Dredged Material in Open-Water Disposal Sites

Purpose

This technical note presents an overview of various erosion processes that can contribute to the dispersion of cohesive material placed in open-water dredged material disposal sites and describes in detail the surface erosion process. This information is given for guidance for scoping a cohesive-sediment dispersion study.

Background

Cohesive sediments are a special class of sediments that exhibit interparticle cohesion and are composed of particles less than 0.074 mm in diameter. Erosion of cohesive sediment is defined as the various processes by which stationary particles become available for transport. Once mobilized, the fine particles are generally transported for long durations and distances due to their low settling velocities.

Assessment of the dispersion of disposed material is often required to establish or manage open-water disposal sites. Dispersion mainly comes from the erosion and transport from the bed or mound under the action of waves and currents. A variety of predictive tools, including numerical models, may be used to perform assessments. Regardless of the tool used, a good assessment of cohesive erosion will require appropriate process descriptors or functions, good measurement techniques, and laboratory and field data.

Cohesive sediment erosion is not controlled by gravitational forces as is coarse-grained transport. Assessment is complicated by the importance of interparticle forces and the fact that fine-grained sediments exist in various states, change with time, and have highly variable erodibilities. Because of this variability and the diverse processes that can operate in the field, the erosion of cohesive sediments is difficult to predict. The erodibility of fine-grained sediments can be related to a number of sediment and fluid conditions, the most important of which are described in *Dredging Research Technical Notes* DRP-1-03 (Teeter 1990).

This technical note describes a number of processes, any of which can dominate under certain conditions and contribute to overall sediment dispersion. Particular attention is paid to surface erosion. Future Dredging Research Program (DRP) technical notes will address cohesive sediment entrainment, fluidization, and other aspects of behavior. Cohesive sediments are complicated materials, and those technical notes will be correspondingly technical in content.

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Cohesive Sediment Structure and Time-Dependent Behavior

A brief description of important cohesive sediment flow and deformation properties is presented to establish concepts before considering mechanisms by which erosion takes place. Erosion is related to breakage of cohesive bonds and structural changes in fine-grained sediments. How a given sediment responds to hydraulic shear stress depends on a number of characteristics, such as those described in Technical Note DRP-1-03, that together establish a sediment's structure. These characteristics generally include the type and amount of clay, other inorganic and organic solids present, density, temperature, pH, and pore and eroding fluid electrolyte strength and composition. An understanding of fundamental cohesive flow and deformation properties is necessary to understand erosion processes.

When clay and water (plus other organic and other inorganic materials) are mixed together, they form a visco-elastic material having two ideal behaviors: elastic deformation and viscous flow properties. Elastic deformation is reversible, while viscous flow is nonreversing, dissipative, and structure altering. A pure, uniform clay suspension can form a near-ideal elastic gel with a continuous three-dimensional interparticle bond network supported by adsorbed water. A small stress will deform the gel, but as long as interparticle bonds do not break, deformation will be limited and the gel will rebound when the stress is removed. A linear (Hookean) elastic material will strain in proportion to the imposed stress.

Particle volume increases sediment viscosity by forcing pore fluid to move in concentrated regions between particles. More important viscous effects are caused by electrostatic layers that surround clay particles and aggregates, making the effective solids volume much greater than the space they actually occupy and cushioning or restricting interparticle collisions. A small stress will continue to deform an ideal viscous suspension. A linear (Newtonian) fluid will strain at a rate proportional to the imposed stress.

Natural cohesive sediments have a combination of elastic and viscous behaviors. Unfortunately, they almost always exhibit non-Newtonian and non-Hookean behavior when subjected to a range of shear stresses representative of a disposal site. Nonlinearity is an important aspect of mud behavior. Some pure clays have yield stresses or critical shear stresses for erosion below which no irreversible strain or erosion takes place. The concept of yield stress has therefore been used to describe cohesive mud behavior in terms of a plastic model and has been related to a critical shear stress for erosion. However, this concept may not be general enough for all cohesive muds. Yield stress is a difficult quantity to measure and depends on the time scale being considered. Cohesive muds generally have viscosities that depend strongly on the shear rate, usually being shear thinning over three to six decades of viscosity. Constant high- and low-shear viscosity plateaus are often observed, and the viscosity can be idealized into high- and low-shear stress regimes separated by a critical shear stress. In many cases, a high low-shear viscosity describes the behavior of muds under low (below critical) shear stresses better than the plastic model (showing flow above a yield stress).

Cohesive sediments have time-dependent rigidity and viscosity that correlates to the shear history of the material. Shearing breaks cohesive bonds, rearranges particles and aggregates, and alters microstructure. The material is weakened with respect to resisting imposed shear stress; this process is reversible, and the material recovers with time once shearing stops.

Aggregate bond strength is vitally important to flow and deformation behavior, as well as to the erodibility of cohesive muds. The main aggregation force between cohesive particles is electrostatic (Van der Waals forces). When particles come together with sufficient force, they can form tight, primary bonds that are not easily broken by shear. Particles can aggregate at greater interparticle distances, but the bonds are much weaker and easily broken. Clays consist of platey particles, and bonds can be edge-to-face, edge-to-edge, or face-to-face. Organic filaments and mucilage add to mud structure. Natural muds are composed of silt and clay mineral and organic particles arranged in a variety of aggregation orientations, and have a corresponding range of bond strengths.

Dredging and Disposal Effects on Cohesive Sediment

Dredging can have a variety of effects on mud. Hydraulic dredging can dilute muds with water and shear sediments, greatly decreasing strength relative to original in situ conditions. On the other hand, maintenance hopper dredging can maintain high densities in the dredge stream, and flow in pipes can be quite laminar. Disruption under these conditions is partial, with some remaining sediment structure left intact. Likewise, mechanical dredging usually causes little dilution and only a moderate disruption to sediment.

During disposal, muds are diluted and sheared (disrupted) to various degrees. The depth of water at the disposal site, method of disposal, ambient currents, and characteristics of the disposed material affect dilution and disruption. Short-term fate models can be used to estimate dilution and velocities attained during convective descent, bottom encounter, and spreading. A sense of the sediment disruption can be obtained from such model predictions.

Dilution rate during disposal can be related to the density of cohesive material, with less dense muds undergoing more rapid dilution due to viscosity and cohesion effects. Dilution during dredging is therefore compounded or magnified during disposal: the greater the dilution during dredging, the greater will be the dilution during disposal.

If muds are sufficiently diluted during dredging and disposal, a low-density sediment plume will result at the bed surface of the disposal site. However, mechanically dredged or clumped material may be deposited at the disposal site in the same condition it left the dredging site. Thus, mud density can vary widely at a disposal site.

A disposal site deposit is generally nonuniform with respect to properties that affect erodibility. Deposits formed out of a dense cohesive suspension are likely to have grain-size mixtures and densities that will make the erodibility vary with vertical position in the deposit. Even uniform deposits will consolidate to an extent depending on their position in the mound, and the mound will be nonuniform. A key to predicting erosion accurately is recognizing the temporal and spatial variation in cohesive erodibility.

Overview of General Dispersion Processes

Cohesive muds are evidently most susceptible to erosion immediately after disposal, and erodibility decreases rapidly during the first few days after disposal. Thus, starting immediately after the disposal of material, a number of erosion processes can mobilize cohesive sediment particles as described below. Some additional process-related references are given in the Bibliography. Erosion processes involve shear stress force applied to sediment by waves, currents, or the weight of sediment acting along a slope.

Entrainment

When a residual low-density suspension is generated by the disposal, two situations can arise. If a slope is present, the suspension can form a turbidity current and be carried away from the disposal site immediately. If no slope is present, the suspension will level itself by flowing radially and forming static suspensions with horizontal surfaces. This material can be relatively easily entrained or redispersed by the overlying flow. The entrainment process is analogous to mixing between density layers and is depicted in Figure 1. Entrainment rates are similar to corresponding dense-liquid systems at Richardson numbers of about 5, but entrainment falls off rapidly relative to dense-liquid systems at Richardson numbers greater than about 20. Note the interfacial wave shown in Figure 1 is superimposed on a horizontal surface of dense suspension (with densities of 1.05 to 1.15, or solids contents of 50 to 200 g/L). At low densities, a cohesive suspension acts much like a liquid and will not stand on a slope. Entrainment is a rapid erosion process, with vertical mass flux rates on the order of 0.1 to 20 kg/sq m/sec for field conditions of 5 m depth, 125 g/L suspension concentration, and currents of 0.3 to 1 m/sec.

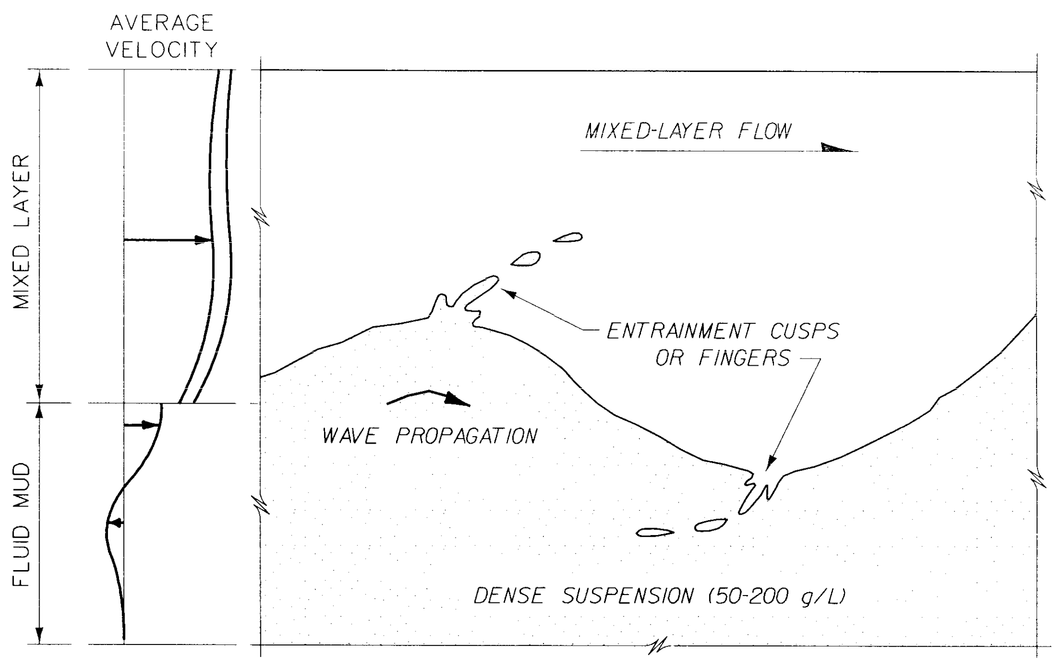


Figure 1. Entrainment of fluid mud into a mixed layer by interfacial wave instabilities

Sagging

Dense suspensions will consolidate by settling and accumulate higher density material in the range of 200 to 450 g/L (1.15 to 1.3 g/cu cm). At the higher densities, cohesive muds will flow very slowly on relatively small slopes. Figure 2 shows how slow flow can occur in thin layers where forces are low enough that the viscosity is in the low-shear range. In this range of densities, low-shear viscosities are in the range of 10 to 10,000 Pa-sec. Typical flow rates for thin layers may be on the order of 10 to 1,000 m/day. (Notations used in Figures 2 and 3 are defined in Table 1.)

Mass Erosion

Thick layers of partially consolidated sediments can suddenly mobilize by a mass erosion mechanism. Mass erosion occurs when a layer within the sediment bed fails. This can occur if large hydraulic shear stresses are applied to the surface, the layer has fluidized (discussed later), or the layer builds on a slope as a result of successive disposal operations. Figure 3 shows the latter situation, equivalent to a submarine slope failure, where the weight of the material increases shear stress within the layer to a level where the material fails or reverts to a much lower viscosity. A sheet slide is thus formed; the mud breaks through a vertical section on

Table 1
Notation Definitions for Figures 2 and 3

Notation	Definition
g	Gravity, m/sec^2
h	Layer thickness, m
z	Depth, m
E	Erosion rate, $g/m^2/min$
R_i	Richardson number = $h\,\Delta b/\overline{V}^2$
$\overline{V}$	Layer-averaged velocity, m/sec
Δb	Buoyancy difference = $g(\rho_m - \rho_o)/\rho_o$
ρ_o	Reference density, kg/m^3
ρ_m	Density of mud, kg/m^3
θ	Slope
η_o	Low-shear viscosity, Pa-sec
τ	Bed shear stress, Pa
$\tau(z)$	Shear stress at depth z, Pa
τ_c	Critical shear stress for erosion, Pa
τ_r	Reference shear stress, Pa
τ_s	Origin point shear stress, Pa

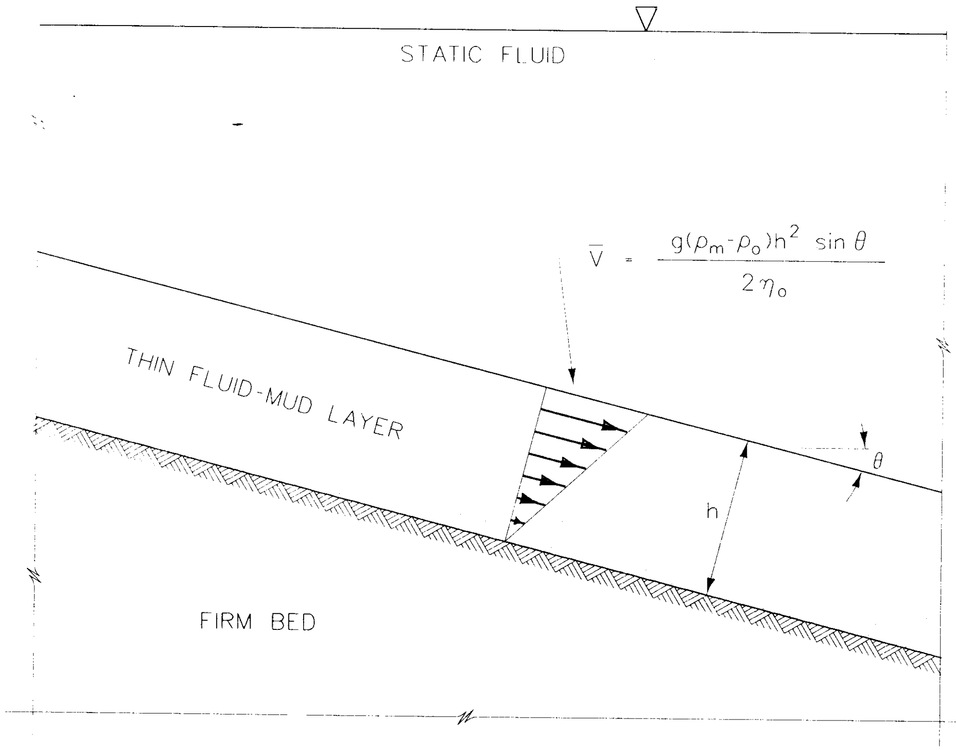


Figure 2. Slow, thin-layer fluid mud flow on a slope

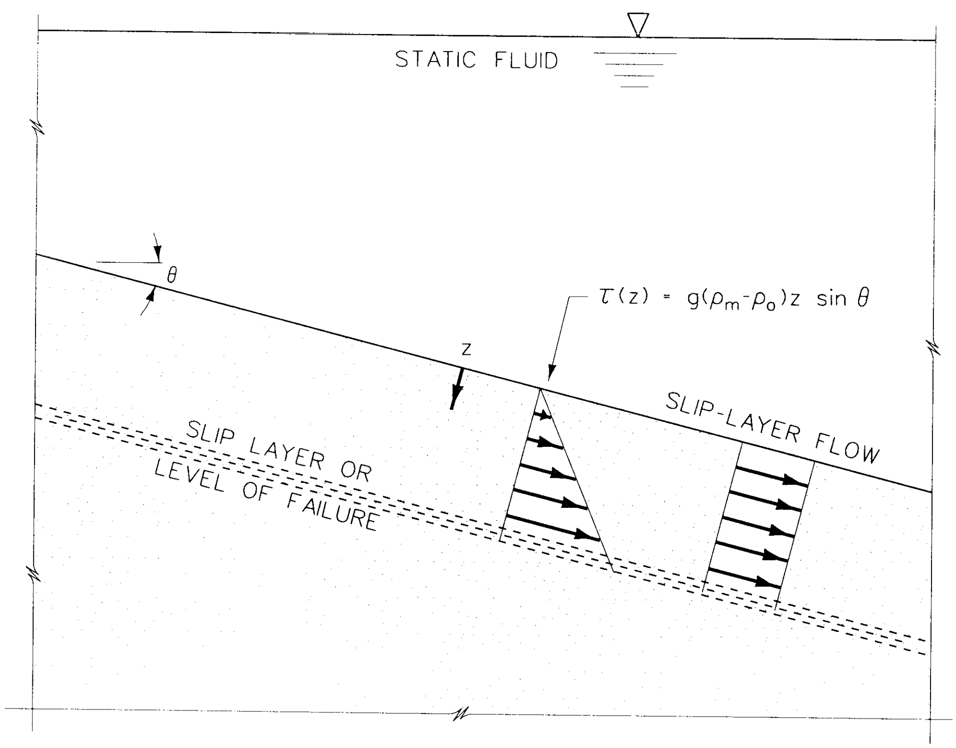


Figure 3. Sheet slide of thick fluid mud after slip layer failure

the upslope end; a slip layer forms at a uniform depth in the mud; and the mud slides downslope. The layer thicknesses where this occurs within man-made reservoirs and on the continental slope are in the 1- to 10-m range. These failures have been observed on slopes ranging from 1 to 8 deg and may occur depending on the sediment density and critical stress. When such failures occur, much material moves, and a turbidity current can be triggered.

Fluidization

Soft cohesive muds can be fluidized by waves. Wave motion is transmitted to the mud according to its stress-strain properties. The mud deforms and endures pressure fluctuations. The water waves, especially short waves, are damped by viscous dissipation in the mud. The mud structure can fatigue, and the strength of the mud disintegrates. A fluidized layer develops at the mud surface (Figure 4) and deepens with duration of wave exposure. The density of the fluidized layer does not necessarily change, but pore pressure becomes equal to the total vertical stress, particles become fluid-supported, and rigidity decreases drastically. The fluidized mud is much more susceptible to mobilization via surface erosion, entrainment, or mass-erosion mechanisms. This time-dependent behavior reverses when wave action ceases, and the strength of the mud returns.

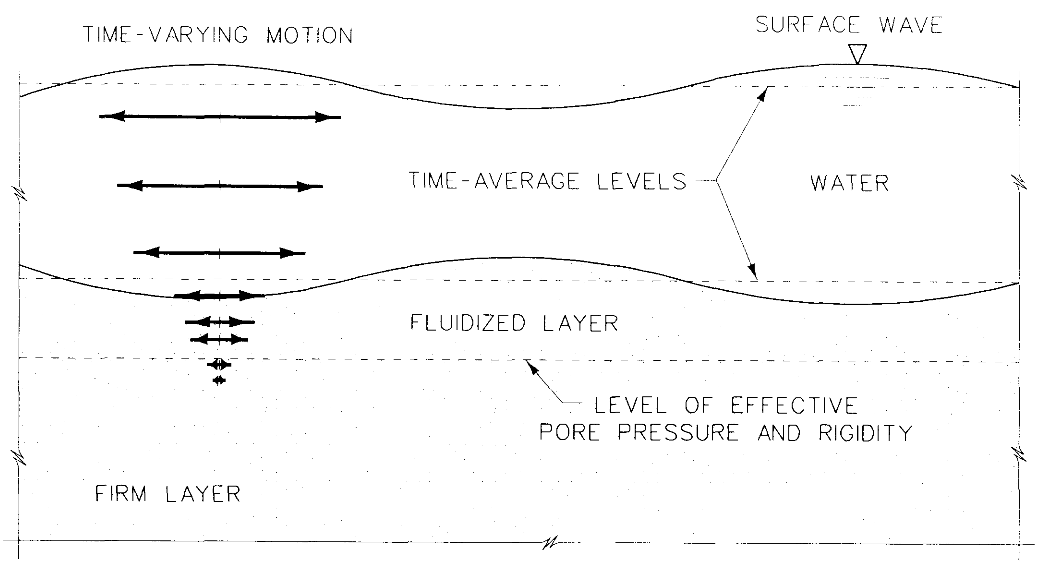


Figure 4. Mud layer fluidization by waves

Abrasion

Consolidated cohesive sediments are extremely erosion resistant. They can have clear-water erosion thresholds of 20 Pa or greater and can withstand flows that normally transport sand and larger particles. However, flows capable of transporting sand-sized particles can abrade stiff cohesive sediments if such materials are available to the flow. Experimental data suggest that in areas where sands are available and being transported in the eroding stream, the cohesive erosion threshold should be assessed as if it were for the granular material.

For cohesive beds with densities greater than about 1.15 g/cu cm with a space-filling structure, currents can erode the surface of the bed. Surface erosion is the final dispersion process and is described below.

Surface Erosion

Surface erosion occurs at the surface of a well-settled cohesive bed. Particles or small aggregate groups are removed from the sediment surface individually during surface erosion. This mode of erosion has been the most widely studied and is driven by hydraulic shear stress, τ, generated by the overlying flow. Surface erosion is probably the predominant mode of erosion in nature and occurs at low-to-moderate shear stresses. Surface erosion process descriptors are based on physical reasoning but have a large empirical content.

Sediments with a Distinct Critical Shear Stress

For cohesive sediments with a distinct threshold shear stress for erosion, a critical shear stress, τ_c, can be used to scale shear stress and surface erosion rate per unit area, E, by:

$$E = M\left(\frac{\tau - \tau_c}{\tau_c}\right) \qquad \tau > \tau_c > 0 \tag{1}$$

where M is the erosion-rate parameter. This erosion expression has been used in a number of US Army Corps of Engineers sediment models since 1977. This expression with constant parameters applies only to cohesive beds of uniform properties, such as density or other characteristics that affect erodibility. In this case, τ_c and M are indices of erodibility. Thus both τ_c and M vary with those properties described in Technical Note DRP-1-03. The observed range for M is from about 30 to about 300 g/sq m/min, and for τ_c is about 0.05 to about 2.5 Pa for typical dredged material. To determine τ_c and M experimentally, erosion is measured over a range of shear stresses; results are extrapolated to 0.0 E to estimate τ_c; and M is determined as E at 2 τ_c.

Two ranges of surface erosion (particle and significant) have been observed, separated at some shear stress in excess of τ_c. The slope of the erosion rate versus shear stress curve becomes much greater. The process proceeds in the same manner as Equation 1, except that at a second critical shear stress, τ_{ch}, erosion becomes more significant. Thus to cover a wider range of shear stresses, a second functional form is required, such as:

$$E = M_h \left(\frac{\tau - \tau_{ch}}{\tau_{ch}} \right) \qquad \tau > \tau_{ch} > \tau_c > 0 \tag{2}$$

where M_h is the erosion-rate constant equal to E at 2 τ_{ch}, τ_{ch} is usually greater than 0.3 Pa, and M_h has values at the higher end of the range for M. It is important that test data be used to assess erosion over an appropriate shear stress range, because extrapolating low-stress erosion data to a higher stress range may underestimate erosion. Equation 2, like Equation 1, is for uniform sediment conditions.

Nonuniform Sediments

Laboratory and field observations of mixtures of clay and silt have indicated that erosion does not progress at a constant rate for a constant shear stress, as implied by Equations 1 and 2. Erosion decreases with time, and suspension concentrations above the cohesive bed become constant. These steady-state concentrations could be the result of simultaneous erosion (independent of concentration) and deposition (varies directly with suspension concentration). This also can occur if the bed is nonuniform with respect to density, grain size, and other factors, and erosion is limited by changes in erodibility as erosion proceeds to degrade the bed. The value τ_c can approach 0.0 Pa at the surface of a deposited bed. Various similar expressions have been used to describe erosion proceeding through a nonuniform bed; perhaps the most general form is:

$$E = A_1 \left(\frac{\tau - \tau_c}{\tau_r} \right)^n \qquad \tau > \tau_c \tag{3}$$

where A_1 is a constant found to vary between 0.05 and 0.4 g/sq m/min for different sediments, τ_r is a reference shear stress (0.1 Pa, for instance), and n is an exponent that varies between 2.5 and 4. Thus, erosion is characterized by A and n for any given sediment. The exponent n has been related to hydrodynamic factors such as critical wave height and is undoubtedly also dependent on sediment conditions. Equation 3 can be applied if τ_c = 0.0 Pa. The experimental procedure used in conjunction with Equation 3 has been to measure suspension concentrations above a deposited bed subjected to progressively higher shear stresses, usually over a rather narrow bed depth range (~ 1 cm). Erosion in this case is determined by removing the deposition effect from the suspension concentration. The application of Equation 3 to substantial erosion, such as for a disposal site mound under storm conditions, has yet to be verified.

Variation of Surface Erosion with Sediment Characteristics

A number of sediment characteristics affect mud erodibility, and the parameters in Equations 1 through 3 depend on sediment conditions. The expense and time required for laboratory experiments have limited the availability of data sets with which to construct functional relationships between sediment characteristics and erosion-process parameters. In addition, much of the available data are either poorly documented with respect to sediment characteristics that affect erodibility or were performed under conditions that were not representative of erosion at a disposal site, thereby limiting their usefulness. Erosion testing is difficult. For instance, if a cohesive bed does not erode uniformly over its surface, secondary flows evolve that can attack the bed locally, and misleading erosion test data may be produced. Yet often the sediment bed condition is not observable during testing. Test repeatability appears, from the small amount of data available, to be no better than ±15 percent. Still, erosion test data are the major source of erosion information. A data base of previous laboratory erosion tests is being compiled into the DRP PC program for COhesive sediment eRODibility assEssment (CORODE) to aid in the selection of parameters.

For a given coastal sediment composition, conditions having the greatest effect on mud erodibility at a disposal site are most likely to be sediment density or related parameters, clay content, and temperature.

The effects of sediment density on erodibility have been studied in laboratory tests. Power law relationships between critical shear stress and mud solids content have been based on specific experimental data:

$$\tau_c = A_2 \gamma_s^m \tag{4}$$

where γ_s is the solids content in g/cu cm, τ_c is in units of Pa, and the parameter A_2 and exponent m vary with the particular sediment. The exponent m has been found to vary between 2.3 to 5.0, and the value of A_2 has been found to fall in the range of 18 to 38.

Temperature has been shown to strongly affect mud erosion. The viscosity of some muds has about the same temperature dependence as erosion, but few measurements are available for correlations. The viscous effect is dependent on Brownian motion, which randomizes mud structure and increases with temperature. Temperature dependence is greatest for fine clay-sized particles. The value τ_c typically varies over a 30° C temperature range by a factor of 5, and the erosion slope or M varies sharply as well.

Some laboratory data sets suggest that an alternate scaling for shear stress and E may prove useful for examining the effects of certain sediment conditions, including temperature, clay content, and organic matter. When these conditions were varied, there existed an origin point with respect to erosion rate, E_o, and shear stress, τ_s. Under these conditions, erosion can be described as:

$$E = \frac{E_o}{\tau_c - \tau_s} (\tau - \tau_c) \qquad \tau > \tau_c > \tau_s \tag{5}$$

where the point (τ_s, E_o) is the virtual origin point for E versus τ curves. This position holds for variations of temperature, organic content, salinity, and clay content, but varies for sodium adsorption ratio (SAR), density, and pH. When E_o and τ_s remain constant, only τ_c changes with sediment condition variation.

An example application of Equation 5 is presented for variations of sediment temperature, organic matter, and clay content. For a test data set in which temperature was varied and other sediment conditions remained constant, τ_c was related to temperature by the empirical expression:

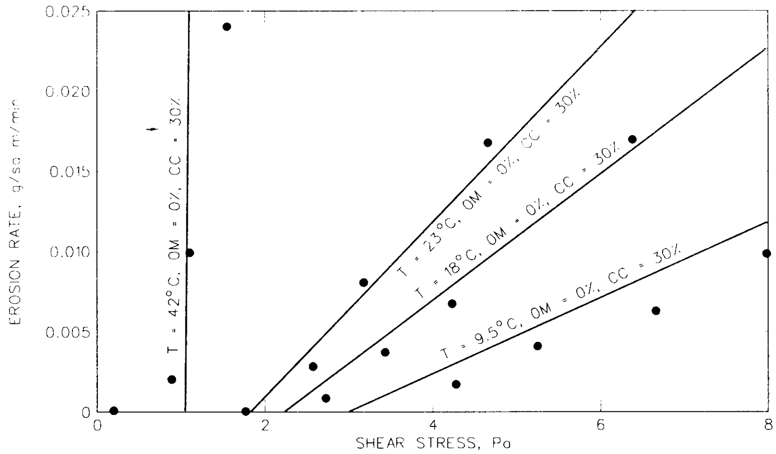
$$\tau_c = A_3 \exp (A_4 T) \tag{6}$$

where T is the temperature in degrees Celsius, and A_3 is a constant. It should be noted that an equally good and more theoretically rigorous fit to the data can be made using the inverse of the absolute temperature.

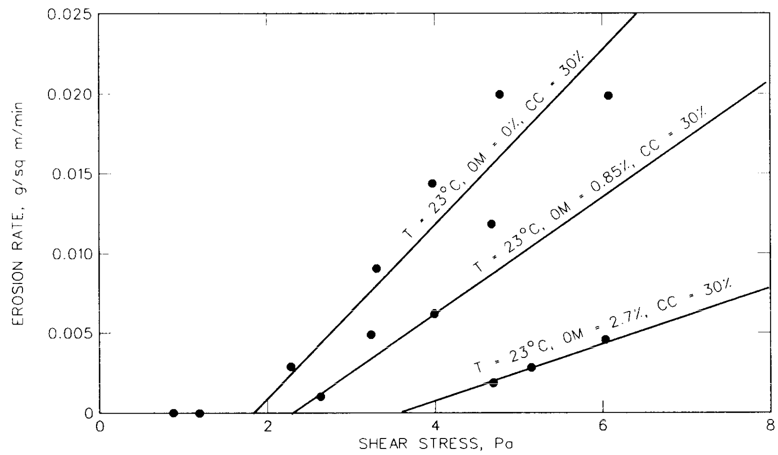
In the same study, organic matter and clay content were varied while holding other sediment conditions almost constant. All three test sets were conducted with a base condition of 23° C, 0 percent organic matter, and 30 percent clay content. Functional relationships between τ_c and organic matter and clay content can be combined to describe the dependence of τ_c on all three conditions:

$$\tau_c = A_3 \exp (A_4 T) \exp (A_s OM) \exp (A_6 (CC - 30)) \tag{7}$$

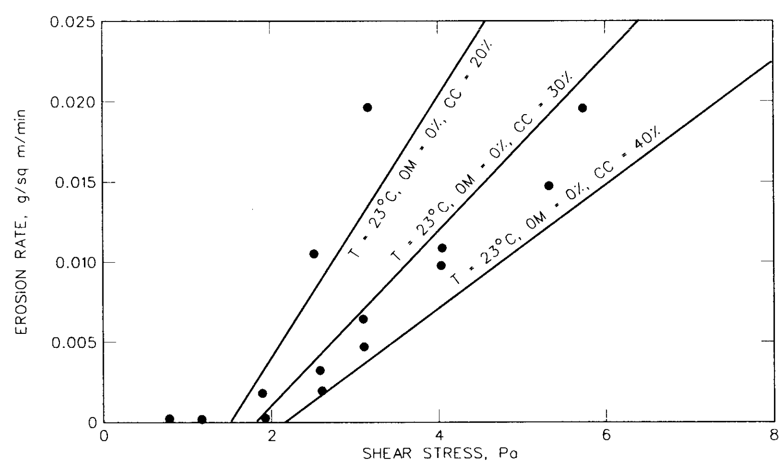
where OM is the organic content on a percent dry-weight basis, CC is the percent clay content on a dry-weight basis, and A_4, A_5, and A_6 are constants. Plots of experimental data and solutions for Equations 5 and 7 are shown in Figures 5a-c. The sediment tested was an illite clay mixed with silt-sized noncohesive silica or loess, with small variations in density and SAR. The regression coefficients for the constants A_3 through A_6 of Equation 7 are as follows: A_3: 5.64; A_4: -0.0465; A_5: 0.2451; and A_6: 0.0168.



a. Temperature: 9.5 to 42° C



b. Organic matter: 0 to 2.7%



c. Clay content: 20 to 40%

Figure 5. Example application of Equation 5 to calculate E (using τ_c calculated with Equation 7) compared to test data for three variations

Conclusions

Behavior of cohesive mud varies widely depending on composition and state. Also, behavior of a given mud varies widely with imposed shear stress, shear history, and time. Dredging dilutes mud, disturbs sediment structure, and makes mud more susceptible to erosion and dispersion, at least for a short time. Muds can be mobilized from a disposal site by entrainment, sagging, mass erosion, fluidization, abrasion, and surface erosion. Predicting erosion requires good process descriptors, measurement techniques, and laboratory and field data.

Erosion assessments depend on empirical information. The ideal situation would exist if general dependence descriptors between erosion parameters and sediment conditions were known. At present, reliance must be made on previous, sometimes poorly documented, laboratory and field test data and on engineering judgement. Laboratory test data are being compiled in the DRP PC program CORODE to guide the selection of erodibility parameters. However, erodibility still depends on a large number of sediment properties, and available test data do not cover all sediment conditions. Extended or complete erodibility characterization (see Technical Note DRP-1-03) may be required for some sediments when the erosion assessment is critical.

Because cohesive sediment behavior depends on such a large number of sediment and flow properties and also is time-dependent, adjustment of erosion process models is a difficult task, and the results are unreliable without site-specific field and characterization data. Fortunately, the variation of cohesive sediment conditions is not so wide in the coastal area. The main properties that vary are density or solids content, temperature, and clay content.

Spatial variations in sediment conditions are important to erosion assessment. Parameters for surface erosion process descriptors must be adjusted to match sediment conditions. Equations 1 and 2 are applicable for uniform sediments; τ_c and M must be adjusted for the vertical position of the sediment bed surface. Equation 3 is applicable for a given nonuniform sediment, but the parameters A_1 and n (and possibly τ_c) vary with sediment composition. Equation 5 requires τ_c adjustment for certain sediment conditions, and also adjustments for E_o and τ_s for changes in density. It must be emphasized that the relations between τ_c and sediment conditions expressed in Equations 4, 6, and 7 are only applicable to the test sediments from which they were developed; they were presented only to demonstrate an approach to defining erosion over a range of conditions. Therefore, a requirement for a good erosion assessment tool is the ability to represent spatial and temporal variations in sediment conditions and to relate sediment conditions to erosion parameters.

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