Underflow Spreading from an Open-Water Pipeline Disposal

PURPOSE: This technical note provides a conceptual review of the mixing and dispersion processes associated with open-water pipeline discharges from hydraulic dredging operations. This is the first step in developing improved predictive tools or models for water column suspended-sediments and turbidity impacts, and bottom spread of disposed dredged material under DOER. This note emphasizes underflow plume spreading of disposed dredged material.

BACKGROUND: "Good dredging procedures, already known but not always practiced, will reduce dredge-induced turbidity but also will result in a more economic operation" (Saucier et al. 1978). Questions have long been raised about the fate of material at a disposal site, dispersion of sediment into nearby bottoms, and/or spread of material along the bottom (Johnson et al. 1999). These issues closely connect to pipeline disposal, an economical method to place hydraulically-dredged material into a nearby open-water disposal area. Pipeline disposal, once more common, is now often restricted by environmental considerations. Turbidity has been the most common issue of concern related to pipeline discharge, and an underflow of fluid mud is created as material descends to the vicinity of the bed. Fluid-mud underflow account for the spreading of most disposed material. To justify the pipeline disposal method and to meet the goals of the Clean Water Act, information on the post-disposal behavior of the material is needed to properly select and size disposal sites, and to specify conditions of discharge.

Wherever practicable, adverse turbidity levels around a pipeline discharge should be minimized, and the spread of the material should be contained within designated disposal areas. Pipeline placement of dredged material requires engineering and operational controls on discharge conditions to accomplish some specified mound configuration. This technical note describes processes that interact with a simple pipeline disposal case as material first enters the environment. The approach is conceptual rather than practical.

PIPELINE DISCHARGE TURBIDITY: As it exits a pipeline or diffuser, dredged material generally has both high momentum and high density, and the behavior of the material will depend on many factors: slurry properties, initial trajectory, whether or not it exits into air or water, currents and shear stresses in the water column, and topography of the bottom. The geometry of discharges varies widely, and can include a variety of baffle or deflector plates, cylindrical or conical diffusers.

Alternatives for Reducing Pipeline Discharge Turbidity. Several options are available to minimize surface and near-surface turbidity around a pipeline discharge. The most viable are simply to direct the discharge vertically downward while submerging the discharge end of the pipe. This concept has been advanced with the development and application of submerged diffusers which reduce discharge velocity and entrainment.

Limited data suggest that in-air or submerged discharges normal to the water surface have lower near-surface turbidity than horizontal discharges or discharges at some angle (Schubel et al. 1978; Neal, Henry, and Greene 1978). Discharge deflector plates help reduce near-surface turbidity for a horizontal discharge (Schubel et al. 1978; Neal, Henry, and Greene 1978). An inward circulation set up near the water surface helps to contain the near-surface turbid zone to the proximity of the discharge point. Discharge into air significantly increases near-surface turbidity generation (Neal, Henry, and Greene 1978).

Silt curtains can be used in some cases to reduce the visible surface turbidity and confine it to the immediate vicinity of the discharge (JBF 1978). Silt curtains can be used, in cases where currents are less than 0.3 m/sec (1 fps), to force the turbid layer downward to the top of the fluid-mud underflow layer as shown in Figure 1.
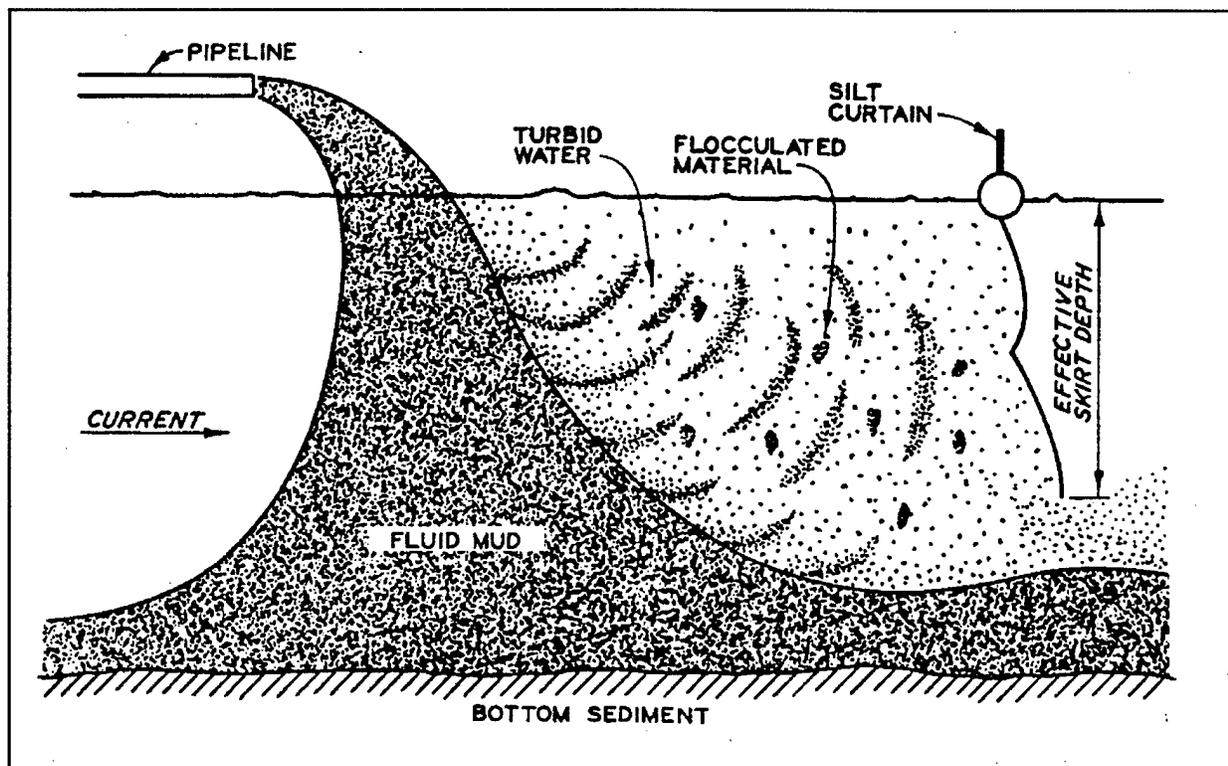
Figure 1.   Schematic representation of silt curtain acting to force a turbid plume downward to the top of the fluid mud layer (Saucier et al. 1978)

Submerged diffusers can also reduce turbidity at the surface as well as reduce overall entrainment of ambient water, and deliver material close to the bed. By reducing the entrainment of ambient water during descent to the near-bed layers, diffusers can be used to maximize fluid mud concentrations in these layers (Neal et al. 1978). Diffusers can also reduce stripping of material from the pipeline jet into the water column. Even a relatively simple vertical diffuser can help to reduce turbidity generation during descent through the water column to a very low level (Thevenot et al. 1992).

Factors Contributing to Turbidity Generation. Factors contributing to near-surface turbidity generation could include:

    a. Spreading and or stripping of material at the water surface.

    b. Gas entrained in the dredged material and released during disposal.

    c. Stripping of material by the water column during descent.

    d. Entrainment of material by the water column during underflow spreading.

The fluid mud underflow contains the greatest portion of disposed material and the greatest potential for turbidity generation by the fourth factor. Field observations indicate that at times of high bed shear-stress, entrainment of underflow material can generate a turbid plume extending some distance from the discharge and not necessarily downstream from the discharge. Thus, the area of concern with respect to water column impacts of a pipeline discharge is not confined to the vicinity of discharge, but also includes the area of the underflow that might extend hundreds or thousands of feet from the discharge.

The Entrainment Process. The entrainment of sediment from a fluid-mud layer into the water column is described, and an entrainment algorithm is proposed by Teeter (1994). A detailed theoretical and laboratory investigation of fluid mud entrainment is presented by Kranenburg and Winterwerp (1997). Density and viscosity differences between the fluid mud and the overlying water column inhibit entrainment. Thus, both fluid mud density and viscosity reduce entrainment into the overlying water column and maintain a fluid mud underflow as a distinct feature (Teeter 1994). The calculation of total entrainment depends on a reasonable estimate of the total underflow area and underflow properties.

The next section reviews underflow characteristics and some methods of analysis.

UNDERFLOW SPREADING: Whatever the configuration of the discharge port and its orientation, most discharged material reaches the bed in shallow water (less than about 4.5 m (15 ft)) shortly after disposal. Once near the bed, sediments form fluid mud layers which flow away from the point of discharge, depending on bottom slope, ambient currents, and their initial discharge trajectory. As the bottom layer quickly thickens at the point of discharge, it behaves as a density flow and spreads under the influence of gravity (Neal, Henry, and Greene 1978). The higher the thickness and solids content of the layer, the greater the density effect. It has been estimated that 95-99 percent of discharged sediment mass descents to the bottom layers with 30 m (100 ft) or so of the point of a pipeline discharge (Schubel et al. 1978; Neal, Henry, and Greene 1978). In Mobile Bay, for example, 99 percent was found to be dispersed along the bottom in the form of fluid mud (Nichols and Thompson 1978).

Fluid mud is also a term used in conjunction with channel navigability as those mud concentrations which do not inhibit navigation. The interaction of mud and a vessel comes about primarily through viscosity, though density can also have an effect (Teeter 1992a). The range of concentrations is similar for the fluid mud definition used here, roughly 10 to 400 dry-g/L (corresponding roughly

to 1,026 to 1,270 wet-g/L density). However, concentrations at the upper end of this range may not be navigable, and the term 'fluid mud' used here is not meant to imply navigability. Solids in the pipeline are generally about 15 percent by weight or 150-200 g/L (Schubel et al. 1978).

Underflow spreading controls the configuration of the final deposit. Limited observations indicate that the final deposit is a series of strata laid down as the underflow shifts and grows larger in response to bottom topography. Maximum deposit thickness was about 0.3 m (1 ft) for a typical 2-day disposal operation in Mobile Bay and about 1.8 m (6 ft) for a 10-day disposal in the James River (Nichols and Thompson 1978).

Underflow Classification. A fluid mud underflow can be characterized by its density, and speed, and can behave as a turbulent turbidity current, or laminar slowly-spreading underflow, as shown in Figure 2. The turbulent or laminar condition is critical to underflow characteristics and concentrations. Laminar flows have smooth particle trajectories while turbulent flows have chaotic motions, in addition to the mean flow, which change flow properties. Turbulent underflows or turbidity currents have lower friction and a characteristic billowing head just behind their leading edge. Turbulent underflows have velocity profiles that, unlike open-channel flows, have highest velocities near the bed. Since turbulent underflows generally entrain ambient water, they grow vertically and tend to have lower concentrations than laminar underflows. Since one goal is to avoid turbidity generation, low-density turbulent underflows are to be avoided in most cases as they are readily entrained into the overlying flow. Entrainment of water into the underflow, and growth in underflow thickness, can occur under turbulent underflow conditions. As noted earlier, density and viscosity differences between the fluid mud and the overlying water column inhibit entrainment.
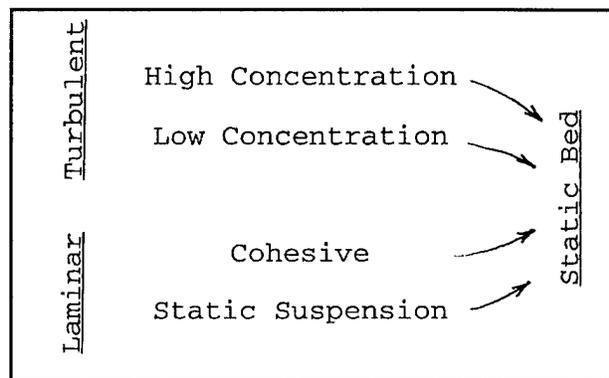
Figure 2. An underflow classification scheme using local flow and concentration conditions

Pipeline discharges originate as turbulent flows, but empirical evidence suggest that they transition to laminar underflow after spreading a short distance along a relatively flat bottom (Thevenot et al. 1992). Deceleration brings a low- or high-concentration turbulent underflow into the laminar regime. Slow-spreading laminar undeflows have a velocity profile with 0 velocity at the bed, a concentrated zone of relatively high fluid shear, and often a plug-flow or 0-shear zone near the surface. Further description of laminar underflow properties will be provided in the next section. Laminar underflows do not entrain ambient water. In fact, evidence suggests that they increase in concentration as they spread, apparently as the result of settling. Underflows of both turbulent and laminar types can be entrained into the overlying water column under certain conditions. Static beds are generally formed by deposition from any of the underflow types as shown in Figure 2.

A Reynolds number (R) criteria for the turbulent-laminar transition has been proposed for Bingham plastic materials (Liu and Mei 1990), and found to be applicable to mud flows. R is composed of viscous (R_μ)and yield-stress components (R_τ) depending on underflow conditions, and:

$$R = \frac{1}{\left(1/R_\mu + 1/R_\tau\right)}$$
(1)

where

$$R_\mu = 4\bar{\rho}\,q/\mu \quad \text{and}$$

$$R_\tau = 8\bar{\rho}\,q^2\big/\tau_y h^2$$

where

ρ = the underflow density, the overbar indicates a layer-averaged density

q = the underflow discharge per unit width

μ = the apparent viscosity

τ_y = the yield stress

h = the underflow thickness.

The yield stress is defined here as the stress below which no flow occurs, but in practice it is dependent on the stress history of the material and flow conditions for the case at hand. Measured values are method-depend. Experimental evidence indicates that the turbulent-laminar transition occurs at R's of about 2,100 (Liu and Mei 1990; Van Kessel and Kranenburg 1997).

Fluid Mud Underflow Models. To predict underflow behavior, a set of equations must be solved that is appropriate to its classification. The study of fluid mud flow properties is known as rheology, and two notable flow features are plasticity and shear-thinning. Deformation in a plastic material is limited to conditions where the imposed shear stress is greater than some threshold value, a yield stress. A Bingham model is usually used to represent the stress-strain relationship of a plastic material. A shear-thinning material's apparent viscosity decreases with increased shear-rate (Teeter 1992a). A Newtonian fluid such as water has a linear stress-strain relationship. Both yield stress and shear thinning are non-Newtonian characteristics of fluid muds.

Recent studies on laminar fluid mud underflows have used Bingham (Liu and Mei 1990; Van Kessel and Kranenburg 1997) or Herschel-Bulkley (Coussot and Proust 1996; Huang and Garcia 1998) rheological models where shear stress (τ) is:

$$\tau = \tau_y + \mu\dot{\gamma}^n \ , \tau > \tau_y$$
(2)

and $\dot\gamma$ = fluid shear-rate. The two models are equivalent when the Herschel-Bulkley exponent $n = 1$. Viscous characteristics of channel muds are discussed by Teeter (1992a). Yield stress data are shown in Figure 3 for kaolinite clay preparations and two natural sediments. Kaolinite is a model clay often used in laboratory experiment, but, as can be seen in the Figure 3, its yield stress is much lower for a given solids content than the natural muds from Rotterdam Harbor, Netherlands, or Calcasieu Channel, LA. Data in Figure 3, with the exception of that of Huang and Garcia (1998), were obtained using controlled stress rheometry. The Herschel-Bulkley model allows for shear thinning and yield stress which have been observed in natural muds.
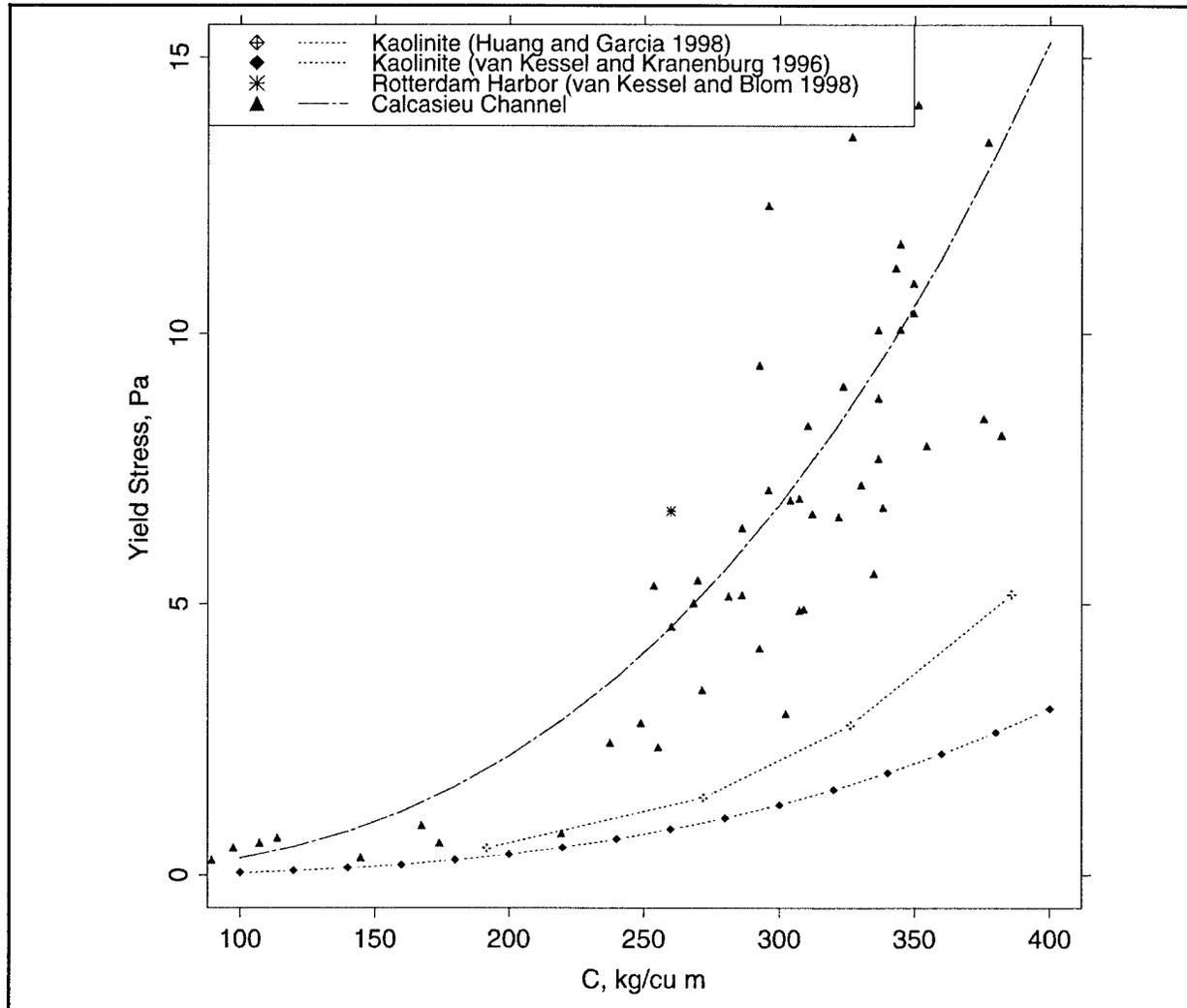
Figure 3. Yield stresses for some natural muds and kaolinite

As mud flows slowly, a yield surface appears above which there is plug flow (no shear) as in the laminar velocity profile described earlier. Shear stress at the yield surface is equal to the yield stress of the material. Shear in the flow occurs between the bottom of the plug-flow zone and the bed. When the yield surface intersects the bed, the mudflow "freezes." That is, the minimum shear stress required for flow to occur is equal to the yield stress.

The transition between low- and high-concentration is less distinct than the laminar-turbulent transition, and depends on the grain-size and cohesive characteristics of the material. A break can occur at about 160-220 g/L where yield stress and viscosity increase sharply with increased concentration (see Teeter 1992a). High-concentration underflow solids are supported by grain interactions or cohesion (Lowe 1982). Individual grains become frozen in a suspension when the shear stress on particles is less than that which permanently deforms the visco-elastic suspension. Van Kessel and Kranenburg (1997) found a concentration breakpoint at about 200 g/L for the underflow behavior of their kaolinite experiments, with laminar flow occurring at higher concentrations.

The bed shear stress τ_b can be derived from the steady, quasi-uniform flow by means of a momentum equation for the direction of flow and assuming a linear vertical shear-stress distribution (Van Kessel and Kranenburg 1997):

$$\tau_b = \left(\overline{\rho} - \rho_w\right) gh\cos\theta \left(\tan\theta - \frac{\partial h}{\partial x}\right) \tag{3}$$

where

ρw = the water density

g = the acceleration of gravity

θ = the bed slope

x = the direction of flow

It appears that both the bed slope and $\partial h/\partial x$ terms can be important in field situations. The local mud-flow rate q can be derived by integrating the velocity profile over both the plug and shear-flow regions of the laminar profile yielding:

$$q = \frac{\tau_b h^2}{2\mu}\xi^2 \left(1 - \xi/3\right) \tag{4}$$

where $\xi = 1 - \left(\tau_y / \tau_b\right)$.

Other Underflow Model Considerations. Pipeline discharges generally last hours or days at a location, adding another dimension to the problem of predicting underflow spreading extent. As noted earlier, the final deposit builds by deposition from the underflow. Thus, bed slope θ can change appreciably during the disposal operation.

Even after underflow deposits become dense enough to resist entrainment by the overlying water column, they can still be eroded particle-by-particle under the action of waves and currents. A discussion of various erosion modes is given in Teeter (1992b). The erodibility of channel mud after being slurried and allowed to settle has been observed in the laboratory to increase by a factor of 4 or more over that of the original channel material (see Chou et al. 1998; Johnson et al. 1999).

The time required for the material to completely recover its original hydraulic shear strength is apparently on the order of months, but appreciable decreases in erodibility occur after a week or so of standing. Thus, the underflow and deposit are most susceptible to erosion during and shortly after the disposal operation.

CONCLUSIONS: Presently some generalizations can be made about underflow spreading, but more definitive information requires site-specific information and analytic procedures. Important factors include: sediment composition, rheological and erosional characteristics, bed topography, ambient currents and waves. As mentioned earlier, cohesive underflow can freeze, and thus deposit en masse. Particle deposition can also occur from an underflow depending on bed shear stress.

Under DOER a work unit "Modeling Dispersion from Pipeline Disposals," methods of analysis for pipeline discharges are being developed into a numerical model that will include many of the aforementioned processes. Products from this work unit will combine available process description for stripping during descent, jet entrainment and trajectory, turbulent and laminar underflow spreading, entrainment of water into the turbulent underflow, entrainment of the underflow into the water column, consolidation by settling of the underflow, deposition from the underflow, age, and grain characteristics of the deposited strata, and consolidation and erosion of the deposited bed. An important factor is bed slope and it will be described in a spatially- and temporally-varying manner. Interfaces will be developed between these products and the newly developed SSFATE such that multiple-grain-class suspended plumes can be predicted.

POINTS OF CONTACT: For additional information, contact Mr. Allen Teeter (601-634-2820, *teeter@hl.wes.army.mil*), or the Program Manager of the Dredging Operations Environmental Research Program, Dr. Robert M. Engler (601-634-3624, englerr@mail.wes.army.mil). This technical note should be cited as follows:

> Teeter, A. M. (2000). "Underflow spreading from an open-pipeline disposal," *DOER Technical Notes Collection* (ERDC TN-DOER-N7), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/dots/doer*

REFERENCES

Chou, L., Cialone, M., Dorth, M., Ebersole, B., Fleming, B., Gailani, J., Gravens, M., Hall, R., Johnson, B., Letter, J., Nail, G., Scheffner, N., Smith, J., Teeter, A., Thompson, E., and Vemulakonda, R. (1998). "Dredged Material Management Plan (DMMP) for the Port of New York and New Jersey - modeling studies to support island CDF and constructed CAD pit design," Draft Interim Report, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Coussot, P., and Proust, S. (1996). "Slow, unconfined spreading of a mudflow," *Journal of Geophysical Research*, 101(B11), 25, 217-25,229.

JBF Scientific Corp. (1978). "An analysis of the functional capabilities and performance of silt curtains," Technical Report D-78-39, U.S.Army Engineer Waterways Experiment Station, Vicksburg, MS.

Huang, X., and Garcia, M. H. (1998). "A Herschel-Bulkley model for mud flow down a slope," *Journal of Fluid Mechanics*, 374, 305-333.

Johnson, B. H., Teeter, A. M., Wang, H. V., Cerco, C. F., and Moritz, H. R. (1999). "Modeling the fate and water quality impact of the proposed dredged material placement at Site 104," Technical Report CHL-99-2, U.S.Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kranenburg, C., and Winterwerp, J. (1997). "Erosion of fluid mud layers, Part I: Entrainment model," *Journal of Hydraulic Engineering*, 123(6), 504-511.

Liu, K. F., and Mei, C. C. (1990). "Approximate equations for the slow spreading of a thin sheet of Bingham plastic fluid," *Physics of Fluids*, A2(1), 30-36.

Lowe, D. R. (1982). "Sediment gravity flows: II. Depositional model with special reference to the deposits of high-density turbidity currents," *Journal of Sedimentary Petrology* 52(1), 279-297.

Neal, R. W., Henry, G., and Greene, S. H. (1978). "Evaluation of the submerged discharge of dredged material slurry during pipeline dredge operations," Technical Report D-78-44, U.S.Army Engineer Waterways Experiment Station, Vicksburg, MS.

Nichols, M .M., Thompson, G. S., and Faas, R. W. (1978). "A field study of fluid mud dredged material: its physical nature and dispersal," Technical Report D-78-40, U.S.Army Engineer Waterways Experiment Station, Vicksburg, MS.

Saucier, R. T., Calhoun, C. C., Jr., Engler, R. M., Patin, T. R., and Smith, H. K. (1978). "Executive overview and detailed summary," Technical Report DS-78-22, U.S.Army Engineer Waterways Experiment Station, Vicksburg, MS.

Schubel, J. R., Carter, H. H., Wilson, R. E., Wise, W. M., Heaton, M. G., and Gross, M. G. (1978). "Field investigations of the nature, degree, and extent of turbidity generated by open-water pipeline disposal operations," Technical Report D-78-30, U.S.Army Engineer Waterways Experiment Station, Vicksburg, MS.

Teeter, A. M. (1992a). "The viscous characteristics of channel-bottom muds," Technical Note DRP-2-04, U.S.Army Engineer Waterways Experiment Station, Vicksburg, MS.

Teeter, A. M. (1992b). "Erosion of cohesive dredged material in open-water disposal sites," Technical Note DRP-1-07, U.S.Army Engineer Waterways Experiment Station, Vicksburg, MS.

Teeter, A.M. (1994). "Erosion by entrainment of fluidized cohesive sediments," Technical Note DRP-1-15, U.S.Army Engineer Waterways Experiment Station, Vicksburg, MS.

Thevenot, M.M., T.L. Prickett, and Kraus, N.C. (1992). Tylers Beach, Virginia, dredged material plume monitoring project: 27 September to 4 October 1991," Technical Report DRP-92-7, U.S.Army Engineer Waterways Experiment Station, Vicksburg, MS.

Van Kessel, T., and Blom, C. (1998). "Rheology of cohesive sediments: comparison between a natural and an artificial mud," *Journal of Hydraulic Research*, 36(4), 591-612.

Van Kessel, T., and Kranenburg, C. (1997). "Gravity current of fluid mud on sloping bed," *Journal of Hydraulic Engineering*, 122(12), 710-717.