Effects of adsorbed natural organic matter on the erosion of kaolinite sediments

Keith E. Dennett, Terry W. Sturm, Appiah Amirtharajah, Talat Mahmood

ABSTRACT: The erosion of kaolinite sediments with various concentrations of adsorbed natural aquatic organic matter was studied. Experiments were conducted in a recirculating flume under uniform flow conditions. The erosion rates were generally lower at the lowest and highest concentrations of adsorbed natural organic matter (NOM) tested. The erosion rates for the intermediate concentrations of adsorbed NOM were slightly higher. As the concentration of adsorbed NOM increased, the water content of the sediment decreased dramatically. This was probably the result of the reorientation of the sediment particles from mostly edge-to-face associations at lower NOM concentrations to mostly face-to-face associations at higher NOM concentrations. The erosion rates increased linearly as bed shear stress increased for all concentrations of adsorbed NOM. The critical shear stress generally decreased as the concentration of adsorbed NOM increased. This result is significant because sediments with higher concentrations of organic matter may be more reactive with environmental contaminants and may also be more susceptible to erosion. *Water Environ. Res.*, **70,** 268 (1998).

KEYWORDS: cohesive sediment transport, natural organic matter, kaolinite, erosion.

Introduction

To assess the water quality effects of eroding sediments, a critical research need is to predict the rate at which fine cohesive sediments are resuspended into the water column under specific hydrodynamic conditions. However, determining the erosion or resuspension flux relationship remains one of the most challenging aspects of modeling the bed-exchange process (Bedford, 1992). The expression proposed by Kandiah (1974), Arulanandan (1975), and Ariathurai and Arulanandan (1978) is the most commonly used equation to determine erosion rates because of its apparent general applicability (Mehta, 1991), and it is often incorporated into sediment transport models (for example, Hayter and Pakala, 1989, and Lee *et al.*, 1994). The erosion rate of cohesive sediments depends on the excess shear stress in an expression of the form

$$E = M\left(\frac{\tau_b}{\tau_c} - 1\right) \tag{1}$$

where

E = erosion rate per unit area, kg/m$^2\cdot$s;
M = erosion rate coefficient, kg/m$^2\cdot$s;
τ_b = bed shear stress exerted by the fluid, N/m^2; and
τ_c = critical shear stress at which erosion begins, N/m^2.

In this expression, erosion is related to macroscopic bed shear stress τ_b by means of empirical coefficient M and critical shear stress τ_c. The usefulness of this relationship depends on the determination of M and τ_c, which is often unique to a given sediment and water system. The values of M and τ_c are related to physicochemical parameters like the type of clay, sediment water content, total salt concentration, ionic species in the water, pH, and temperature (Mehta *et al.*, 1989). Values of M may range from 10^{-4} to 10^{-2} g/cm$^2\cdot$min, and τ_c can range from almost zero for organic-rich flocs to 10 N/m^2 for hard soil deposits (Lavelle and Mofjeld, 1987, and Mehta, 1988). Other relationships for erosion and sediment transport have been proposed (for example, Ariathurai and Krone, 1976, and Parchure and Mehta, 1985), but these also require the determination of empirical coefficients, which depend on the surface chemistry of the sediment particles and the water chemistry of the eroding fluid.

The clay mineral particles that compose cohesive sediments have net surface charges resulting in electrostatic (attractive or repulsive) forces as well as van der Waals (attractive) forces. Cohesion of particles is caused by net attractive interparticle forces. In addition, most clay mineral particles that are suspended in natural aqueous systems are negatively charged as a result of the adsorption of natural organic matter (NOM) (Davis, 1982; Tiller and O'Melia, 1993; and Tipping and Cooke, 1982). Natural organic matter is a complex mixture of decomposing plant and animal residues, viable and nonviable microorganisms, and other microbiologically synthesized substances (Schnitzer and Khan, 1972, and Thurman and Malcolm, 1983).

Adsorbed NOM can significantly affect the behavior of colloidal particles composing fine-grained cohesive sediments by influencing the strength of interparticle bonds in clay sediments (Bennett *et al.*, 1991). Interactions of NOM with clay mineral particles affect the stability of sediments by causing either aggregation or dispersion, depending on the properties of both the particles and the NOM. Also, clay particles with organic coatings have a high adsorptive capacity for metals and hydrophobic organic contaminants (McCarthy, 1993; Murphy *et al.*, 1994; and Stevenson, 1985).

A comprehensive review of the literature indicated that the influence of aquatic NOM has not been adequately addressed in previous studies of the erosion of cohesive sediments. The few studies that have attempted to assess the effects of organic matter (for example, Kandiah, 1974, and Otsubo and Muraoka, 1988) have been inadequate primarily because of the use of organic materials, such as steer manure, starch, and agar, that are not representative of the aquatic NOM present in all natural waters.

Continuing research is attempting to link the behavior of clay particles on a microscopic level to the hydrodynamic conditions that cause erosion on a macroscopic level. Specific objectives of the research are to investigate the effects of NOM, ionic strength, and pH on the erosion and transport of cohesive sedi-

ments and relate the results to microscopic, interparticle forces including electrostatic, van der Waals, Born repulsion, and hydration forces (Dennett *et al.*, 1995; Mahmood, 1996; Raveendran and Amirtharajah, 1995; and Sturm *et al.*, 1994). This research has applications in the areas of transport and fate of adsorbed contaminants, sediment transport, reservoir management, maintenance of navigation waterways, and disposal of channel dredging spoils.

Methodology

This investigation examined the effects of aquatic NOM on the erosion and transport of kaolinite sediments. A suspension of pure kaolinite (Hydrite Flat D, Dry Branch Kaolin Company, Union, New Jersey) was prepared by mixing 800 g of dry clay with 3.2 L of a solution of tap water (pH 6.6 and ionic strength = 0.001 M) and various volumes of concentrated dissolved organic matter (0 to 2.8 L). The suspension was mixed for 1 hour and then poured into a sample tray with dimensions of 30 cm × 10 cm × 2.5 cm deep. The suspension was allowed to settle quiescently into the sample tray for 24 hours. After settling, the sediment sample tray was placed into the bed of a recirculating flume.

Because the sediment suspension was allowed to settle under quiescent conditions, the bed structure was more representative of a natural, partially consolidated deposit. A review of previous investigations of cohesive sediment transport by Hunt and Mehta (1985) demonstrated that placed beds, compacted beds, and remolded beds have a more uniform bed structure with depth, unlike the stratified bed structure typical of natural, partially consolidated deposits.

Because the settling period for sample preparation was limited to 24 hours, most of the sediment samples behaved as partially consolidated samples. In general, partial consolidation results in a high initial rate of erosion that gradually tapers to zero when the bed is eroded down to a layer where the critical shear stress approaches the bed shear stress exerted by the flow (Hamm and Migniot, 1994).

Dissolved NOM from the Suwannee River in Georgia was used for this study because the river is designated by the International Humic Substances Society (Denver, Colorado) as the source water for a reference stream humic substance (Averett *et al.*, 1994), and it has been used extensively in previous research (Amirtharajah *et al.*, 1993; Dennett, 1990; Dennett *et al.*, 1995; and Perdue, 1989). The organic matter was isolated and concentrated by reverse osmosis to 850 mg C/L using the procedure of Serkiz and Perdue (1990).

The amount of NOM adsorbed to kaolinite, expressed as percent organic carbon, was determined from a carbon balance by measurement of the organic carbon concentration of the supernatant after the 24-hour settling period using a Dohrmann DC-180 carbon analyzer (Rosemount Analytical Division, Santa Clara, California). (The organic carbon could also be expressed as milligrams carbon per gram sediment.) Experiments were performed at 11 different concentrations of adsorbed NOM ranging from 0 to 0.091% organic carbon (0 to 0.91 mg C/g sediment) and with bed shear stresses ranging from 0.97 to 1.67 N/m^2. For comparison, Murphy *et al.* (1994) studied the sorption of organic compounds on kaolinite with concentrations of adsorbed humic substances ranging from 0.01 to 0.5% organic carbon.

Properties of the kaolinite suspensions tested are given in Table 1. The dramatic decrease in the sediment water content from approximately 180% to approximately 60% as the amount of adsorbed NOM increased should be noted. Possible effects of the variations in pH and ionic strength of the kaolinite suspensions are described later in the Discussion.

Experiments were conducted in a rectangular recirculating flume, which was 0.38 m wide and 6.1 m long. Plan and profile views of the flume are shown in Figure 1. Experiments were performed under uniform flow conditions at two different bed slopes (0.002 and 0.003 m/m) and three different flows (6.2, 8.3, and 9.8 L/s). The flow was controlled by a variable-speed Moyno progressing cavity pump (Robbins and Meyers, Inc., Springfield, Ohio). The depth of flow ranged from 42 to 67 mm, the velocities ranged from 0.33 to 0.45 m/s, and the bed shear stresses ranged from 0.97 to 1.67 N/m^2.

Velocity profiles were measured along the flume at various stations using a pitot tube connected to a pressure transducer. These stations were located at distances of 3.7 to 4.6 m downstream from the flume inlet, and the test section for sediment samples was located 4.3 m downstream from the flume inlet. The measurement of the centerline velocity profiles in the vicinity of the test section indicated that the boundary layer was fully developed. The centerline velocity profiles were used to determine the shear stress in a central core of the flow at the test

Table 1—Properties of kaolinite suspensions with adsorbed NOM.

Volume of NOM added to suspension, mL	Organic carbon in sediment, %	Ionic strength, *M*	Suspension pH	Sediment water content, %	ζ-potential, mV
0	0.000	0.004 8	5.03	183.1	−31.6
30	0.002	0.005 1	4.92	187.1	−32.1
60	0.004	0.005 5	4.87	174.8	−28.8
90	0.006	0.005 1	4.82	163.9	−28.9
120	0.009	0.005 4	4.78	156.6	−29.0
150	0.011	0.005 1	4.71	137.7	−32.3
180	0.012	0.005 2	4.69	61.8	−31.6
700	0.038	0.006 5	4.11	57.9	−28.7
1 400	0.061	0.006 8	3.52	69.6	−32.2
2 100	0.077	0.008 2	3.33	78.8	−22.7
2 800	0.091	0.009 6	3.13	83.3	−15.5

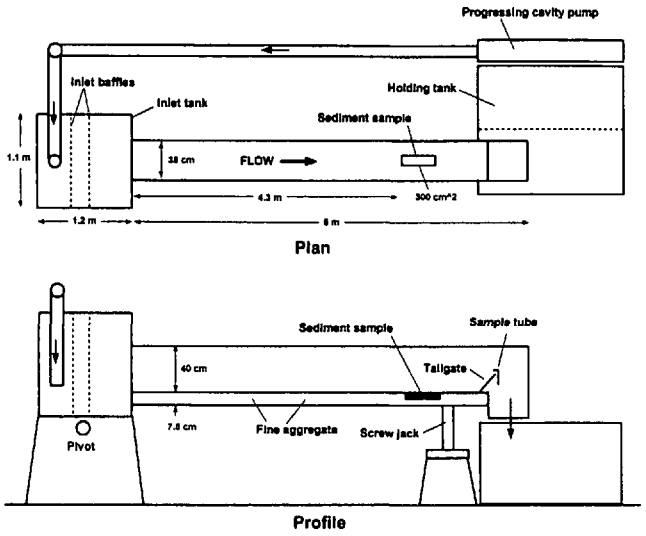


Figure 1—Plan and profile of recirculating flume.

section by measuring the slope of the semilogarithmic velocity profile near the bed (Vanoni [Ed.], 1975). The shear stresses so determined agreed with the values calculated from the uniform-flow formula.

The flume bed was filled with a fine aggregate having a mean particle size of 3.5 mm. For all of the flows and flume slopes tested, the boundary Reynolds number, R_*, had a value of more than 100, indicating fully rough turbulent flow, which would be expected in the natural environment. The critical shear stress was determined by extrapolating the linear erosion rate versus shear stress relationship to zero erosion rate, and these values of critical shear stress also resulted in R_* values of more than 100, indicating fully rough turbulent flow.

As a further check on whether the turbulent boundary layer was fully developed at the test section, a momentum integral analysis was performed using a one-sixth power law approximation for the velocity profile and the Keulegan equation for the friction factor in fully rough turbulent flow in open channels (Henderson, 1966). The analysis indicated a fully developed boundary layer at lengths greater than approximately 20 depths for all flows and slopes tested, while the test section was located at least 50 depths downstream for all tests.

During an erosion event, a sample stream was taken continuously at the centerline of the flume tailgate downstream from the sediment sample tray and was passed through a dynamic light obscuration particle monitor (Model PM 2500, Chemtrac Systems, Inc., Norcross, Georgia). Voltage readings from the particle monitor continuously indicated the relative concentration of particles and were transmitted to a computer data acquisition system. The voltage readings were converted to the concentration profile for an erosion event using a calibration curve for the kaolinite suspension. A typical concentration profile is shown in Figure 2. The concentration profile was subsequently used to construct the cumulative mass curve shown in Figure 3. Because the flow was being recirculated through the flume, samples were also taken upstream from the sediment sample tray to monitor the background concentration of particles. When the background concentration and the centerline concentration were equal, erosion of the sediment sample had stopped.

Other parameters that were routinely monitored included particle size distribution, pH of the sediment suspension, temperature, total suspended solids, specific conductivity, ζ-potential, nonpurgeable organic carbon, and water content of the sediment samples. Additional details of the experimental methodology were provided by Dennett (1995).

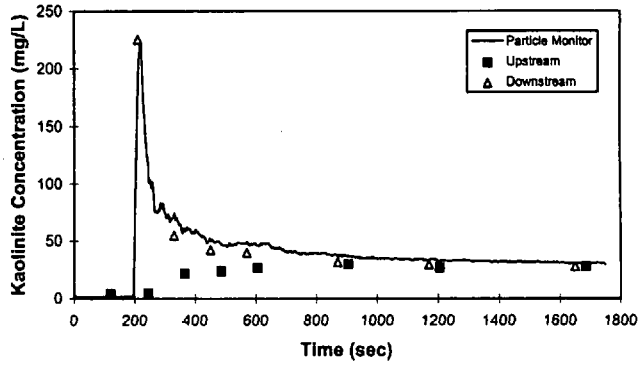


Figure 2—Typical concentration profile for an erosion event.

Results

The focus of the current research was on a surface layer of sediment (Stolzenbach *et al.,* 1992) and the physicochemical changes in its structure, and thus its erodibility, resulting from the addition of organic matter. Typical applications include peaking hydropower releases in rivers for a few hours per day and tidal flows in estuaries, for which settling time is approximately 1 day or less with the formation of a thin surficial sediment layer (approximately 1 cm or less) that is subject to repeated deposition and resuspension cycles. Because sediment deposits that form under these hydrodynamic conditions will be partially consolidated, physicochemical parameters will likely have more influence than the degree of consolidation on the erodibility of the surficial layer of these sediments. For these types of sediment deposits, it was found that Equation 1 was applicable with parameters that were responsive to physicochemical changes in terms of an average critical shear stress and a constant initial erosion rate for the surface layer. The total mass eroded was also analyzed and exhibited similar trends to the initial erosion rate. Erosion rates occurring later in the experiment might have been influenced by changes in the ap-

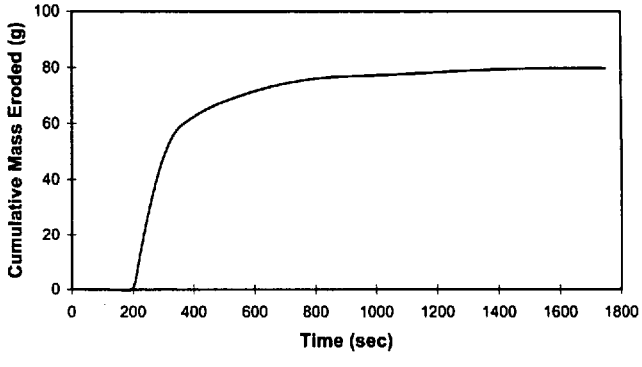


Figure 3—Typical cumulative mass curve for an erosion event.

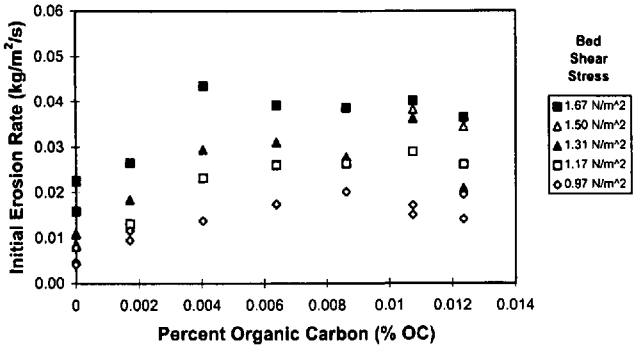


Figure 4—Variation of initial erosion rates with adsorbed NOM concentrations of 0 to 0.012% organic carbon.

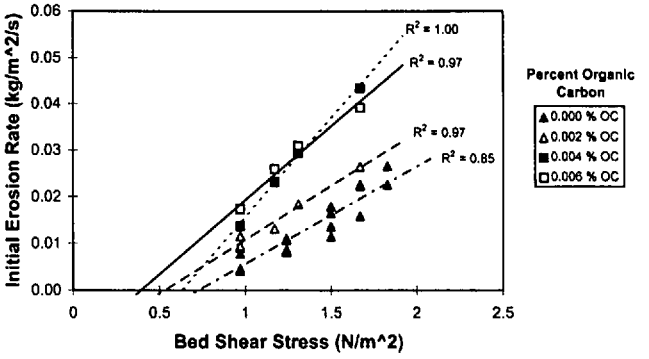


Figure 6—Estimation of critical shear stress for lower NOM concentrations.

plied shear stress because of localized changes in depth caused by lowering of the sediment surface as erosion progressed, as well as by some stratification within the sediment sample.

For each experiment, the initial erosion rate E in Equation 1 was calculated from the initial slope of the cumulative mass curve. In Figure 3, for example, the initial erosion rate is 450 mg/s or 0.015 kg/m^2/s, based on the 300-cm^2 surface area of the sediment sample exposed to flow in the flume.

The variation in initial erosion rate with concentration of adsorbed NOM in the sediment over a range of bed shear stresses is shown in Figure 4. As the bed shear stress, τ_b, increased, the initial erosion rates also increased. For each bed shear stress, erosion rates were typically lowest when no NOM was adsorbed. Erosion rates generally increased to a maximum at NOM concentrations of approximately 0.006 to 0.009% organic carbon and then declined as the concentration of adsorbed NOM increased further. Figure 5 shows the variation in initial erosion rate for concentrations of adsorbed NOM up to 0.091% organic carbon at a bed shear stress of 0.97 N/m^2. The erosion rates at and above an adsorbed NOM concentration of 0.038% organic carbon were similar to those at no adsorbed NOM.

For each concentration of adsorbed NOM in Figure 4, the variation of the initial erosion rate with bed shear stress is shown in Figure 6 for lower concentrations of adsorbed NOM (0 to 0.006% organic carbon) and in Figure 7 for higher concentrations of adsorbed NOM (0.009 to 0.012% organic carbon). The coefficients of determination (R^2) for the linear plots in Figures 6 and 7 range from 0.831 to 0.998. The critical shear stress, τ_c, required to initiate sediment erosion can be estimated from these plots by extrapolating to an erosion rate of zero (that is, x-intercept). The variation of critical shear stress τ_c with the concentration of adsorbed NOM is shown in Figure 8.

By using the values for the critical shear stress with Equation 1, erosion rate coefficient M can be determined for each of the adsorbed NOM concentrations from the slopes of the lines shown in Figures 9 and 10. Variation in erosion rate coefficient M with the concentration of adsorbed NOM is illustrated in Figure 11. If a linear relationship is assumed for the change in critical shear stress with the concentration of adsorbed NOM (that is, best-fit straight line shown in Figure 8), then the variation of M is reduced.

Discussion

Results of the flume experiments indicated that the intermediate concentrations of adsorbed NOM (approximately 0.006 to 0.009% organic carbon) increased the initial erosion rates of the kaolinite sediments. When the concentration of adsorbed NOM was increased further, the initial erosion rates declined as shown in Figures 4 and 5. This suggests that settled kaolinite existed in a relatively stable state for adsorbed NOM concentrations greater than 0.038% organic carbon up to 0.091% organic carbon because there was no significant variation in the initial erosion rates in this higher range of adsorbed NOM concentrations. In terms of comparison with other research on kaolinite, it was noted previously that Murphy *et al.* (1994) studied the

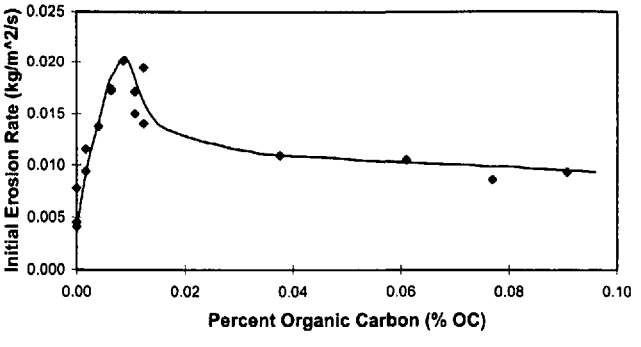


Figure 5—Variation of initial erosion rates with adsorbed NOM concentrations of 0 to 0.091% organic carbon at τ_b = 0.97 N/m^2.

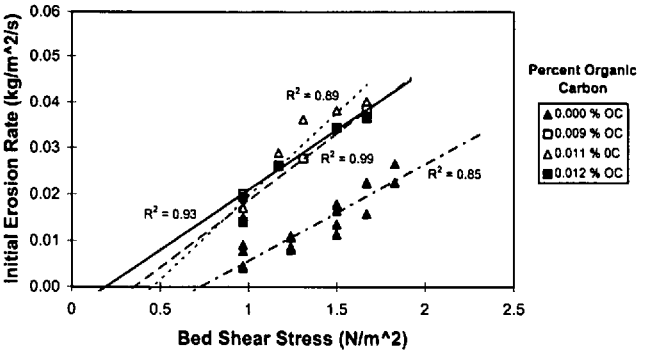


Figure 7—Estimation of critical shear stress for higher NOM concentrations.

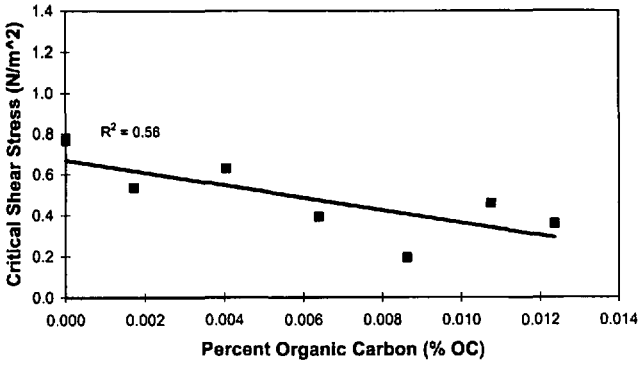


Figure 8—Variation of critical shear stress with amount of NOM adsorbed.

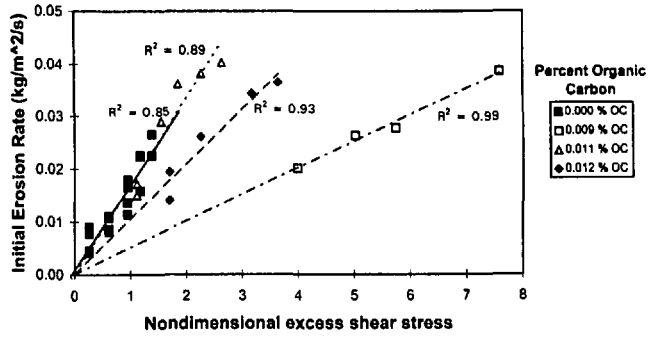


Figure 10—Determination of erosion rate coefficient *M* for higher NOM concentrations.

sorption of hydrophobic organic compounds on kaolinite coated with humic substances, and the organic carbon content resulting from the sorbed humic substances ranged from 0.01 to 0.5%. Edwards *et al.* (1994) conducted a study on sorption of organic compounds to sediments with organic content ranging from 0.034 to 0.053% organic carbon. In a study by Kile *et al.* (1995) on the sorption of organic contaminants to numerous different natural sediments, values for the organic carbon content varied widely, from approximately 0.1% up to more than 6%. Thus, the higher range of organic carbon content in this study falls well within the ranges studied by Murphy *et al.* (1994) and Edwards *et al.* (1994), while falling in the lower range of values found by Kile *et al.* (1995).

These experimental results can be explained on the basis of the types of particle associations that occur for platelike clay particles such as kaolinite. The three possible particle associations are edge-to-face (EF), edge-to-edge (EE), and face-to-face (FF) (van Olphen, 1977). Characteristic properties of sediments with the various particle associations are shown in Figure 12. Bennett *et al.* (1991) reported that on initial aggregation, particles typically have an EF orientation that is controlled by variations in charge density on the particle surfaces. A sediment with EF associations is characterized by a random arrangement of multiplate particles with minimal area of particle contact, a high porosity, and, therefore, a higher water content. If bonding at the point of particle contact is not strong, particles may reorient to an FF configuration in which van der Waals forces become more significant. A sediment with FF associations has a more dense, tightly packed arrangement with a lower water content.

The rapid settling of the suspension during preparation of the sediment samples and the relatively high water content of the sediment when no NOM was added (approximately 180% [see Table 1]) suggest that the kaolinite was flocculated with mainly EF particle associations. From unpublished results of Ghosh and Varadachari reported by Wershaw (1991), and the study by Murphy *et al.* (1994), it may be inferred that the negatively charged macromolecules of NOM adsorb mainly at the positively charged edge sites of kaolinite. Therefore, as the concentration of NOM was increased, the number of EF associations that formed was reduced. At high concentrations of adsorbed NOM, mainly FF associations would be expected.

As the NOM concentration increased, the water content of the settled deposits decreased dramatically, from approximately 180% to approximately 60% as indicated in Table 1. The minor variation in ζ-potential over the range of NOM concentrations tested suggests that the kaolinite particles in the suspensions continued to flocculate. A very low porosity sediment exhibits a relatively high packing density and low water content, characteristic of FF particle associations. This would suggest that the clay particles reoriented from an EF association at low NOM concentrations to FF associations at higher NOM concentrations. For the intermediate concentrations of NOM, a mixture of EF and FF particle associations would result in a nonuniform sediment bed structure and, therefore, higher erosion rates.

In general, the critical shear stress decreased as the concentration of adsorbed NOM increased, as shown in Figure 8. This suggests that kaolinite sediments with higher concentrations of adsorbed NOM are less resistant to erosion because a lower

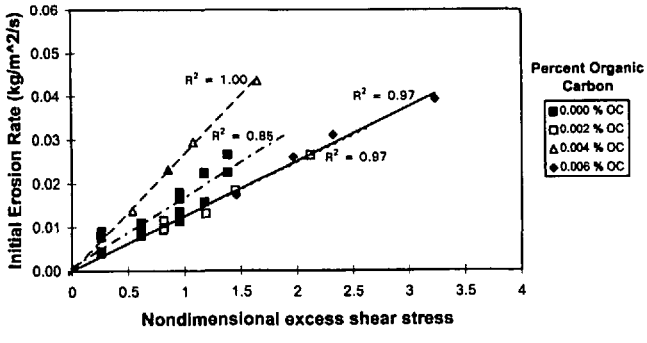


Figure 9—Determination of erosion rate coefficient *M* for lower NOM concentrations.

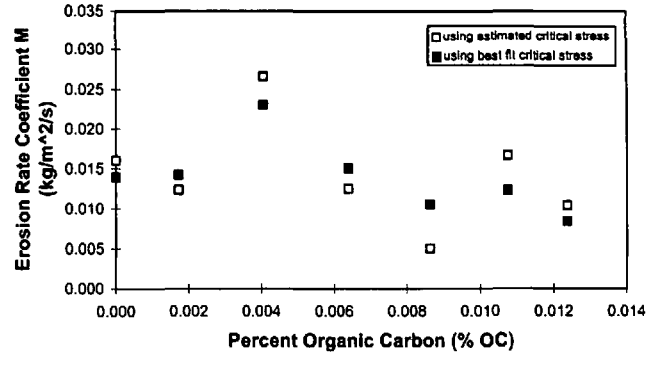


Figure 11—Variation of erosion rate coefficient *M* with amount of NOM adsorbed.

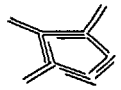
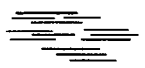
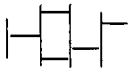
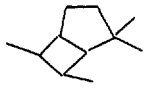
Particle Association:	E-F	E-E	F-F
Flocculated particles (low zeta potential)			
Dispersed particles (high zeta potential)			
Mechanism of Particle Interaction:	electrostatic: + edges to - faces	electrostatic and van der Waals	van der Waals between faces
Area of Particle Contact:	low	low	high
Bed Structure:	voluminous, porous, high void ratio	voluminous, high void ratio	dense, tightly packed arrangement
Relative Water Content:	high	intermediate to high	low

Figure 12—Characteristics of particle associations.

bed shear stress is needed to initiate erosion. This finding is significant because sediments with higher concentrations of adsorbed organic matter may be more reactive with environmental contaminants and may also be more susceptible to erosion.

The decline of critical shear stress with increasing concentration of adsorbed NOM is consistent with the concept of reorientation of sediment particles from EF to FF particle associations. The increase in FF associations apparently resulted in a weaker overall bed structure, causing sediments with more adsorbed organic matter to begin eroding at a lower shear stress.

The linear increase in the erosion rates with increasing nondimensional excess shear stress, as shown in Figures 9 and 10, suggests that Equation 1 is suitable for predicting the erosion of the kaolinite sediment. However, specific reasons for the irregular trend in M shown in Figure 11 are unknown. Perhaps the increase in M for the NOM concentration of 0.004% organic carbon may be the result of an intermediate particle configuration or physicochemical environment that provided more stability than the other concentrations of NOM that were tested.

Differences in the pH and ionic strength of kaolinite suspensions can affect the adsorption of NOM and may have introduced some variations into the results. The extent of adsorption of NOM is controlled by the properties of the mineral surface and the structural configuration of organic molecules in solution before adsorption and on the mineral surface following adsorption (Murphy *et al.*, 1994). The extent of coverage on a mineral surface by adsorbed NOM is dependent on pH, the relative amounts of surface area and adsorbable organic compounds, the mineralogy of the solid surface, and the inorganic electrolyte composition (Davis, 1982, and Stevenson, 1985).

Variations in ionic strength from approximately $I = 0.005$ to $I = 0.01$ and suspension pH from approximately pH 3 to pH 5 (see Table 1) likely had some effects on the structure of macromolecules in the NOM and, subsequently, the surface coverage by adsorbed NOM on kaolinite. Higher pH (pH 5) and lower ionic strength ($I = 0.005$) conditions likely resulted in a more extended, open formation that allowed macromolecules to adsorb on the mineral surface in an elongated configuration that maximized surface coverage (Ghosh and Schnitzer, 1980, and Murphy *et al.*, 1994). Lower pH (pH 3) and higher ionic strength ($I = 0.01$) conditions likely promoted a more coiled configuration with incomplete surface coverage (Murphy *et al.*, 1994). When surface coverage is incomplete, with open sites available for adsorption, dangling tails can adsorb to the surfaces of adjacent clay particles, leading to aggregation by polymer bridging (O'Melia and Tiller, 1993, and Sumner, 1992). Because this type of particle aggregation may not occur uniformly or predictably at a given NOM concentration, some variation in the results should be expected.

However, the data set used for analysis of critical shear stress τ_c and erosion-rate constant M in Figures 4, 6, 7, 8, 9, 10, and 11 includes only samples with lower organic carbon contents, ranging from 0 to 0.012%. For this portion of the data set, variations in pH and ionic strength were minor, with pH ranging from 5.03 to 4.69 and I ranging from 0.004 8 to 0.005 2 M, respectively.

Conclusions

The results of these flume experiments can be explained on the basis of how the concentration of adsorbed organic matter affected the types of particle associations that occur in clay sediments. Without the addition of organic matter, associations among kaolinite particles were predominantly edge-to-face between the positively charged particle edges and the negatively charged particle faces. Settled suspensions with edge-to-face associations had a relatively high water content. With the addition of organic matter to the suspension, negatively charged organic molecules adsorbed to the positively charged edges. As the concentration of organic matter increased, the pH decreased from 5 to 3 and the organics had fewer negatively charged sites and coiled conformations. These effects resulted in face-to-face associations in the settled suspensions becoming more common. Sediments with face-to-face associations had a low porosity and low water content.

The initial erosion rates of kaolinite sediments with no adsorbed organic matter were the lowest because of the predominance of edge-to-face associations. The erosion rates were the highest for the intermediate concentrations of adsorbed organic matter (approximately 0.006 to 0.009% organic carbon) because the sediments consisted of a nonuniform mixture of particles with both edge-to-face and face-to-face associations. These particle structures resulted from the additional negative charges and steric effects of the NOM. At higher concentrations of adsorbed organic matter (0.038 to 0.091% organic carbon) and lower pH conditions (pH < 4), the structures collapsed to face-to-face associations and the erosion rates were similar to those with no organic matter. Without the addition of organic matter, face-to-face associations will only predominate at high pH (pH > 7).

For the lower concentration range of adsorbed organic matter (0 to 0.012% organic carbon), the critical shear stress decreased as the concentration of adsorbed organic matter increased. This result is consistent with the gradual reorientation of particles from mainly edge-to-face associations to more face-to-face associations as the concentration of adsorbed organic matter increased. The increase in face-to-face associations apparently resulted in a weaker overall bed structure that caused sediments with more adsorbed organic matter to begin eroding at a lower shear stress.

The values of the erosion rate coefficient M did not vary predictably, perhaps because of the different conformational

states of NOM that may occur with changes in pH, ionic strength, and the concentration of organic matter. Changes in the conformational state of organic macromolecules with pH will influence particle aggregation resulting from polymer bridging.

All particles in the natural environment are exposed to organic matter. Because NOM can have a significant effect on particle behavior, further study of its effects is warranted.

Acknowledgments

Credits. This research was funded by the U.S. Environmental Protection Agency Hazardous Substance Research Center, South and Southwest, and was conducted in the School of Civil and Environmental Engineering at the Georgia Institute of Technology, Atlanta. The contents of this manuscript are based on a paper presented at WEFTEC '95, the 68th Annual Water Environment Federation Technical Exposition and Conference, held in Miami Beach, Florida, October 21–25, 1995.

Authors. Keith E. Dennett is an assistant professor in the Department of Civil Engineering at the University of Nevada, Reno. Terry W. Sturm is an associate professor and Appiah Amirtharajah is a professor in the School of Civil and Environmental Engineering at the Georgia Institute of Technology, Atlanta. Talat Mahmood is a postdoctoral scientist at the Institute of Paper Science and Technology, Atlanta, Georgia. Inquiries should be sent to Keith E. Dennett, Department of Civil Engineering, Mail Stop 258, University of Nevada, Reno, NV 89557-0152.

Submitted for publication August 14, 1996; revised manuscript submitted January 22, 1997; accepted for publication July 17, 1997.

The deadline to submit Discussions of this article is September 15, 1998.

References

Amirtharajah, A.; Dennett, K.E.; and Studstill, A.E. (1993) Ferric Chloride Coagulation for Removal of Dissolved Organic Matter and Trihalomethane Precursors. *Water Sci. Technol.*, **27**, 11, 113.

Ariathurai, R., and Arulanandan, K. (1978) Erosion Rates of Cohesive Soils. *J. Hydraul. Eng.*, **104**, HY2, 279.

Ariathurai, R., and Krone, R.B. (1976) Finite Element Model for Cohesive Sediment Transport. *J. Hydraul. Eng.*, **102**, HY3, 323.

Arulanandan, K. (1975) Fundamental Aspects of Erosion of Cohesive Soils. *J. Hydraul. Eng.*, **101**, HY5, 635.

Averett, R.C.; Leenheer, J.A.; McKnight, D.M.; and Thorn, K.A. (1994) Humic Substances in the Suwannee River, Georgia: Interactions, Properties, and Proposed Structures. U.S. Geological Survey Water-Supply Paper No. 2373, U.S. Gov. Printing Office, Washington, D.C.

Bedford, K.W. (1992) Sediment Exchange Process Parameterization. In *Chemical Dynamics in Freshwater Ecosystems.* F. Gobas and J. McCorquodale (Eds.), Lewis Publishers, Boca Raton, Fla., 63.

Bennett, R.H.; O'Brien, N.R.; and Hulbert, M.H. (1991) Determinants of Clay and Shale Microfabric Signatures: Processes and Mechanisms. In *Microstructure of Fine-Grained Sediments, From Mud to Shale.* R.H. Bennett, W.R. Bryant, and M.R. Hulbert (Eds.), Springer-Verlag, New York, N.Y., 5.

Davis, J.A. (1982) Adsorption of Natural Dissolved Organic Matter at the Oxide/Water Interface. *Geochim. Cosmochim. Acta* (G.B.), **46**, 2381.

Dennett, K.E. (1990) Coagulation of Natural Dissolved Organic Matter Using Ferric Chloride. Unpublished Master's thes., Ga. Inst. Technol., Atlanta.

Dennett, K.E. (1995) Flume Studies on the Erosion of Cohesive Sediments. Ph.D. diss., Ga. Inst. Technol., Atlanta.

Dennett, K.E.; Sturm, T.W.; Amirtharajah, A.; and Mahmood, T. (1995) The Erosion of Cohesive Sediments in Uniform Flows. *Proc. 1995 Ga. Water Resour. Conf.*, Univ. Ga., Athens, 221.

Edwards, D.A.; Zafar, A.; and Luthy, R.G. (1994) Distribution of Nonionic Surfactant and Phenanthrene in a Sediment/Aqueous System. *Environ. Sci. Technol.*, **28**, 1550.

Ghosh, K., and Schnitzer, M. (1980) Macromolecular Structures of Humic Substances. *Soil Sci.*, **129**, 266.

Hamm, L., and Mignoit, C. (1994) Elements of Cohesive Sediment Deposition, Consolidation, and Erosion. In *Coastal, Estuarial, and Harbour Engineer's Reference Book.* M.B. Abbott and W.A. Price (Eds.), Chapman and Hall, London, G.B., 93.

Hayter, E.J., and Pakala, C.V. (1989) Transport of Inorganic Contaminants in Estuarial Waters. *J. Coastal Res.*, spec. issue no. 5, 217.

Henderson, F.M. (1966) *Open Channel Flow.* Macmillan, New York, N.Y., 13.

Hunt, S.D., and Mehta, A.J. (1985) an Evaluation of Laboratory Data on Erosion of Fine Sediment Beds. In *Particulate and Multiphase Processes, Vol. 3: Colloidal and Interfacial Phenomena.* Hemisphere Publishing Corporation, Washington, D.C., 503.

Kandiah, A. (1974) Fundamental Aspects of Surface Erosion of Cohesive Soils. Ph.D. diss., Univ. Calif., Davis.

Kile, D.E.; Chiou, C.T.; Zhou, H.; Li, H.; and Xu, O. (1995) Partition of Nonpolar Organic Pollutants from Water to Soil and Sediment Organic Matters. *Environ. Sci. Technol.*, **29**, 1401.

Lavelle, J.W., and Mofjeld, H.O. (1987) Do Critical Stresses for Incipient Motion and Erosion Really Exist? *J. Hydraul. Eng.*, **113**, 3, 370.

Lee, D.H.; Bedford, K.W.; and Yen, C.C.J. (1994) Storm and Entrainment Effects on Tributary Sediment Loads. *J. Hydraul. Eng.*, **120**, 1, 81.

Mahmood, T. (1996) The Mechanics of Asymmetric Particle Release during Filter Backwashing and Migration of Colloids. Ph.D. diss., Ga. Inst. Technol., Atlanta.

McCarthy, J.F. (1993) Sub-Surface Transport of Natural Organic Matter: Implications for Contaminant Mobility. In *Organic Substances in Soil and Water: Natural Constituents and Their Influences on Contaminant Behavior.* A.J. Beck, K.C. Jones, M.H.B. Hayes, and U. Mingelgrin (Eds.), Royal Soc. Chem., Cambridge, U.K., 153.

Mehta, A.J. (1991) Review Notes on Cohesive Sediment Erosion. In *Coastal Sediments '91, Proc. Spec. Conf. Quantitative Approaches Coastal Sediment Processes,* N.C. Kraus, K.J. Gingerich, and D.L. Kriebel (Eds.), Am. Soc. Civil Eng., 40.

Mehta, A.J. (1988) Laboratory Studies on Cohesive Sediment Deposition and Erosion. In *Physical Processes in Estuaries.* J. Dronkers and W. van Leussen (Eds.), Springer-Verlag, New York, N.Y., 427.

Mehta, A.J.; Hayter, E.J.; Parker, W.R; Krone, R.B.; and Teeter, A.M. (1989) Cohesive Sediment Transport. I: Process Description. *J. Hydraul. Eng.*, **115**, 1076.

Murphy, E.M.; Zachara, J.M.; Smith, S.C.; Phillips, J.L.; and Wietsma, T.W. (1994) Interaction of Hydrophobic Organic Compounds with Mineral-Bound Humic Substances. *Environ. Sci. Technol.*, **28**, 1291.

O'Melia, C.R., and Tiller, C.L. (1993) Physicochemical Aggregation and Deposition in Aquatic Environments. In *Environmental Particles.* Vol. 2, J. Buffle and H.P. van Leeuwen (Eds.), Lewis Publishers, Boca Raton, Fla., 353.

Otsubo, K., and Muraoka, K. (1988) Critical Shear Stress of Cohesive Bottom Sediments. *J. Hydraul. Eng.*, **114**, 1241.

Parchure, T.M., and Mehta, A.J. (1985) Erosion of Soft Cohesive Sediment Deposits. *J. Hydraul. Div.*, **111**, 1308.

Perdue, E.M. (1989) Effects of Humic Substances on Metal Speciation. In *Aquatic Humic Substances: Influence on Fate and Treatment of Pollutants.* I.H. Suffet and P. MacCarthy (Eds.), Am. Chem. Soc., Washington, D.C., 281.

Raveendran, P., and Amirtharajah, A. (1995) the Role of Short Range Forces in Particle Detachment. *J. Env. Eng.*, **121**, 12, 860.

Schnitzer, M., and Khan, S.U. (1972) *Humic Substances in the Environment.* Marcel Dekker, New York, N.Y., 203.

Serkiz, S.M., and Perdue, E.M. (1990) Isolation of Dissolved Organic Matter from the Suwannee River Using Reverse Osmosis. *Wat. Res.* (G.B.), **24**, 911.

Stevenson, F.J. (1985) Geochemistry of Soil Humic Substances. In *Humic Substances in Soil, Sediment, and Water: Geochemistry, Isolation, and Characterization.* G.R. Aiken, D.M. McKnight, R.L. Wershaw, and P. MacCarthy (Eds.), John Wiley and Sons, New York, N.Y., 13.

Stolzenbach, K.E.; Newman, K.A.; and Wong, C.S. (1992) Aggregation of Fine Particles at the Sediment-Water Interface. *J. Geophys. Res.*, **97**, 17889.

Sturm, T.W.; Dennett, K.E.; Amirtharajah, A.; and Mahmood, T. (1994) Flume Studies on the Detachment of Kaolinite Clay and Associated Contaminants from a Coarse Sediment. *Proc. 20th Annu. Risk Reduction Eng. Lab. Res. Symp.*, U.S. EPA, Cincinnati, Ohio, 216.

Sumner, M.E. (1992) the Electrical Double Layer and Clay Dispersion. In *Soil Crusting: Chemical and Physical Processes.* M.E. Sumner and B.A. Stewart (Eds.), Lewis Publishers, Boca Raton, Fla., 1.

Thurman, E.M., and Malcolm, R.L. (1983) Structural Study of Humic Substances: New Approaches and Methods. In *Aquatic and Terrestrial Humic Substances.* R.F. Christman and E.T. Gjessing (Eds.), Ann Arbor Science, Ann Arbor, Mich., 1.

Tiller, C.L., and O'Melia, C.R. (1993) Natural Organic Matter and Colloidal Stability: Models and Measurements. *Colloids and Surf. A: Physicochem. Eng. Aspects*, **73**, 89.

Tipping, E., and Cooke, D. (1982) The Effects of Adsorbed Humic Substances on the Surface Charge of Goethite (a-FeOOH) in Freshwaters. *Geochim. Cosmochim. Acta* (G.B.), **46**, 75.

Vanoni, V.A. (Ed.) (1975) *Sedimentation Engineering.* Am. Soc. Civ. Eng., New York, N.Y.

van Olphen, H. (1977) *An Introduction to Clay Colloid Chemistry.* 2nd Ed., John Wiley and Sons, New York, N.Y., 95.

Wershaw, R.L. (1991) The Importance of Humic Substance-Mineral Particle Complexes in the Modeling of Contaminant Transport in Sediment-Water Systems. In *Organic Substances and Sediments in Water.* R.A. Baker (Ed.), Lewis Publishers, Chelsea, Mich., 23.