Erosion of the Upper Layer of Cohesive Sediments: Characterization of Some Properties

Ouafae El Ganaoui[1]; Estelle Schaaff[2]; Patrick Boyer[3]; Muriel Amielh[4]; Fabien Anselmet[5]; and Christian Grenz[6]

Abstract: A recent companion paper reported an experimental protocol used to analyze sediment properties. This protocol identified for both freshwater and marine sediments a surface layer with specific dynamic properties (critical erosion shear stresses in the range 0.025–0.05 N m^{-2}) and a second layer with critical erosion shear stresses about ten times larger. The present study compares these former results with recent work which extended the applicability domain of the Shields diagram to very fine particles. The surface layer is shown to consist in fine and unconsolidated sediments that behave like noncohesive material whereas the second layer is characterized as being cohesive. The surface layer is mainly representative of recent deposits of suspended particles. This points out the existence of a fluffy layer of fine sized particles resting near the bed, with specific erosion characteristics, which has to be considered separately when studying sediment properties.

DOI: 10.1061/(ASCE)0733-9429(2007)133:9(1087)

CE Database subject headings: Erosion; Cohesive sediment; Settling velocity.

Introduction

In both marine and freshwater systems, sediment dynamics play a major role for water quality. Consequently, the modeling of water quality requires the description of sediment bed properties. In practice, these properties are inferred from direct in situ measurements (Amos et al. 1992; Black et al. 2002) or using laboratory flume experiments (Schaaff et al. 2002). As natural water flows contain a wide and continuous range of granulometric sizes of particles of different types, it is also useful to identify these classes of particles and their specific dynamic behavior. At this end, a companion paper (El Ganaoui et al. 2004) presents an analytical method based on a multiclass model to determine the main classes with their associated erosion rate, critical erosion stress, and settling velocity. This work revealed the existence of two classes of particles (Table 1). A first class was associated to a surface layer of fine particles with mechanical properties close to those of a "fluff layer." The critical erosion shear stresses in the range 0.025–0.05 N m^{-2} were very similar to those already reported for the resuspension of benthic fluff layers by tidal currents in deep stratified waters (Jago et al. 2002). The second class had properties similar to cohesive sediments (i.e., critical erosion shear stresses of about 0.2 N m^{-2}). The present paper reports a refined analysis of these results aimed at determining the origin and the nature of these layers.

[1]IRSN, CE Cadarache, Bat. 159, 13108 St-Paul Lez Durance, France.

[2]Univ. de la Méditerranée, Laboratoire d'Océanographie et de Biogéochimie, 13007 Marseille, France.

[3]IRSN, CE Cadarache, Bat. 159, 13108 St-Paul Lez Durance, France.

[4]Institut de Recherche sur les Phenomenes Hors Equilibre, 49 Rue Joliot-Curie, B.P. 146, 13384 Marseille Cedex 13, France.

[5]Institut de Recherche sur les Phenomenes Hors Equilibre, 49 Rue Joliot-Curie, B.P. 146, 13384 Marseille Cedex 13, France (corresponding author). E-mail: fabien.anselmet@irphe.univ-mrs.fr

[6]Univ. de la Méditerranée, Laboratoire d'Océanographie et de Biogéochimie, 13007 Marseille, France.

Note. Discussion open until February 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this technical note was submitted for review and possible publication on December 13, 2005; approved on November 30, 2006. This technical note is part of the ***Journal of Hydraulic Engineering***, Vol. 133, No. 9, September 1, 2007. ©ASCE, ISSN 0733-9429/2007/9-1087–1091/$25.00.

Experiments

The experimental device is a 3.6 m long PVC recirculating flume described by Schaaff et al. (2002). The main channel has a width and height of 40 cm, and the velocity in the channel can be varied between 5 and 40 cm s^{-1}. During the resuspension experiments, the velocity was continuously monitored with an electroacoustic currentmeter (ME—MeeresElectronik Gmbh) operating at a frequency of 5 Hz (accuracy 0.2 cm s^{-1}). The test section, in the bed of which four PVC rings of 10 cm height containing sediment core samples are inserted, is located 2.1 m downstream of the main entry.

Sediment cores were sampled at three different sites. Rhone1 is at 3 m from the bank in a calm area of the Rhone River. Rhone2 is a more turbulent zone, 10 m away from the bank, at the entrance of the previously quoted calm area. SOFI is a coastal station located on the continental shelf break (43°04N, 5°07E) where cores were sampled at a depth of 160 m. For each of these sites, eight sediment cores with an internal diameter of 15 cm were collected with a multitube corer (Minicorer Mark VI). The top 9 cm sediment layers of four of these cores were transferred into the test section using a PVC ring, the sediment-water interface being continuously in contact with overlying water. The four other cores were used to analyze water content vertical profiles and grain size distributions.

Resuspension was monitored with a turbidity sensor (AANDERAA 3712) located at 30 cm downstream of the test section

Table 1. Sediment Parameters for Rhone1, Rhone2, and SOFI

Station	Class number	τ_{ce} (N m^{-2})	W (m s^{-1})	ϕ (μm)	Particle Reynolds number	ϕ_{50} (μm)
Rhone1	1	0.05	2.80E−05	6	1.68E−04	15
	2	0.22	5.00E−05	8	4.00E−04	
Rhone2	1	0.04	4.50E−05	7	3.15E−04	55
	2	0.22	6.00E−05	8	4.80E−04	
SOFI	1	0.025	1.15E−05	4	4.60E−05	15
	2	0.2	9.00E−05	10	9.00E−04	

and 5 cm above the bed. The turbidity was continuously recorded on a computer at 0.2 Hz and related to the water load through suspended matter concentration determined from filtration of water samples collected every 3 min.

Results

Granulometry of the Uppermost Layer

The grain size distribution of the topmost sediment layer was determined by a laser granulometer Malvern Mastersizer. These distributions (Fig. 1) point out a difference between Rhone2 and the two other stations (Rhone1 and SOFI). These latter sites are characterized by a decay of the contributions from the finest to the largest grains whereas Rhone 2 displays an opposite behavior. The ϕ_{50} value is between 10 and 20 μm for Rhone1 and SOFI, and between 40 and 70 μm for Rhone2. These differences are explained by the locations of the sampling areas. Rhone1 and SOFI correspond to calm areas where the deposition of the finest particles is possible. Rhone2 is less calm and therefore less subject to fine particle sedimentation.

Water Content Profiles

Several subsamples of sediments were taken, from the top to a depth of 4 cm, from the cores that were not used for the resuspension experiments. Assuming a particle density ρ_{SS} of 2,650 kg m^{-3}, vertical profiles of the water content (p) were calculated from weight loss after freeze-drying.

Fig. 2 shows that this quantity is larger for Rhone1 than for the two other sites, Rhone2 and SOFI, which are equivalent. The values are in good agreement with those generally reported in the literature (e.g., Van Rijn 1993).

Equivalent Stokes Diameters

For particles with a Reynolds number, $\mathsf{R}=W\phi/\nu$, smaller than 1 (with W=settling velocity and ϕ=particle diameter), Stokes' law is valid

$$\phi = \sqrt{\frac{18\mu W}{g(\rho_{SS}-\rho_w)}} \tag{1}$$

The equivalent Stokes diameters deduced from settling velocities are, respectively, for Rhone1, Rhone2, and SOFI, equal to 6, 7, and 4 μm for the first class and 8, 8, and 10 μm for the second class. These diameters are smaller than the ϕ_{50} inferred from the granulometric laser analysis, which would suggest that quite a small amount of sediment has been eroded from the cores. This will be confirmed in the next paragraph.

Total Height Eroded from the Cores

The total height, h_{ero}, eroded from the cores at the end of each set of experiments was calculated from the water content of the first layer of the cores, and $SS_{\max}$, the maximum value of the suspended matter concentration measured in the flume

$$h_{\text{ero}} = \frac{V_f}{S_c}\left(\frac{SS_{\max}}{\rho_{SS}} + \frac{SS_{\max}}{\rho_w}\frac{p}{p-1}\right) \tag{2}$$

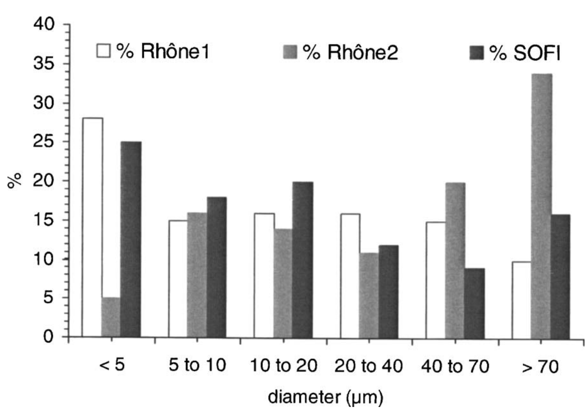

Fig. 1. Histograms of the particle diameters in the uppermost layer of the cores for Experiments Rhone1, Rhone2, and SOFI

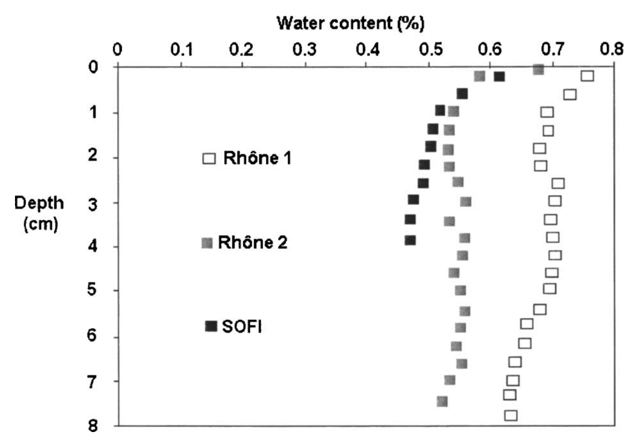

Fig. 2. Water content profiles in the sediments from the three stations

where S_c=total surface of the four cores ($0.07\ m^2$) and V_f=water volume of the flume ($0.3\ m^3$).

The values are 130, 90, and 72 μm for Rhone1, Rhone2, and SOFI. The contribution of the dry matter to these heights is estimated to be 14 μm for all experiments. This very small quantity of eroded matter validates a posteriori the assumption that no large aggregates of matter were eroded, as well as the range of diameters obtained with the Stokes formula from the settling velocities. The eroded particles could not have a diameter larger than the eroded matter height.

Discussion

Using a multicorer, sediments were sampled together with an overlying water column of depth (h_c) varying between 0.2 and 0.3 m. This water volume included suspended particles deposited on the sediment surface during transport of the cores to the lab. These particles constitute probably the first class. Unfortunately, this load has not been measured. To validate this assumption, a calculation of the available quantity of particles of this class is used to assess the suspended matter concentration that was initially trapped in the overlying water volume.

Considering S_c, the total surface of the four cores, the water volume, V_c, sampled with the four cores was between 0.014 and $0.021\ m^3$. Considering $SS_{1,\max}$, the maximum suspended load obtained in the flume for the first class, we can deduce the total eroded mass of this class, by $(SS_{1,\max}V_f)$. SS_0, the suspended matter concentration initially present in the overlying water volume, can be calculated by $(SS_{1,\max}V_f/V_c)$. The obtained values vary from 40 to $60\ mg\ l^{-1}$ for Rhone1, from 93 to $140\ mg\ l^{-1}$ for Rhone2, and from 64 to $95\ mg\ l^{-1}$ for SOFI. For the Rhone experiments, these data are in agreement with the mean load observed in this part of the Rhone River (Pont 1997). For the SOFI station, two explanations can be given for the suspended matter trapped with the cores: the existence of a more or less permanent fluff layer at the sediment water interface that has often been observed at this site or the sampling of parts of the benthic nepheloid layer close to the seabed (Naudin and Cauwet 1997).

Whatever its origin, the upper layer can be associated with recent deposits characteristic of a fluff layer and which can be easily resuspended under low bed shear stress. Among others, Gust and Morris (1989) and Maa et al. (1998) noted the importance to consider this fluff layer because it plays an important role in the determination of the erosion critical shear stress. The fluff layer is also significant for the benthic pelagic exchanges (Jago et al. 2002).

A quantitative interpretation of these results can be obtained by considering the work by Pilotti and Menduni (2001), who derived an analytical relation to extend the Shields diagram to the finest particles. Shields' diagram involves two nondimensional parameters

$$X=\frac{u*\phi}{\nu},\quad \theta_{cr}=\frac{\tau_{ce}}{(\rho_{SS}-\rho_w)g\phi} \tag{3}$$

Used to characterize noncohesive sediments (Graf 1984), it can also be used as a reference for the analysis of the properties of any natural matter. It allows one to: (1) discriminate the properties of their cohesive part, which will be associated with critical shear stresses much larger than those displayed by Shields' diagram; and (2) check the validity of the diameters inferred from the experimentally determined settling velocities. The Shields parameter θ_{cr} should not be smaller than the semiempirical curve, as "it is not possible to be more noncohesive than noncohesive matter."

Our experimental data are plotted in terms of X and θ_{cr} in Fig. 3. For one set of data, we used ϕ and τ_{ce} actually determined by resuspension experiments. For the second set of data, τ_{ce} was inferred, for each value of ϕ, from the semiempirical relation given by the Yalin method as reported by Li and Amos (2001). The ellipses connect the pairs of associated points with the same value of ϕ. Their major axes have a slope of 2 in this log-log diagram, since the diameter ϕ=same, while the two τ_{ce} values deduced by the two different approaches correspond to two values of u^{*2}.

For the particles of the first class, the two sets of data are in rather good agreement and very close to the relation derived by Pilotti and Menduni (2001) as shown in Fig. 3. Conversely, for the second class, the measured critical shear stresses are significantly larger than those given by the analytical relations. This demonstrates that the first class, associated to a fluffy layer, behaves like noncohesive and nonconsolidated sediments, which probably mostly originate from the deposition of suspended matter contained within the water column that was sampled together with the sediments. Conversely, the second class of particles corresponds to the cohesive and consolidated sediments that actually constitute the cores. This is rather similar to the two-layer concept of the sediment interface already discussed by Thomsen and Gust (2000) but for aggregates. The different origins explain the rather large increase in critical shear stresses (from about 0.02 to $0.2\ N\ m^{-2}$) for rather small diameter increase (from about 5 to 10 μm).

On Fig. 3 are also plotted the points calculated with the ϕ_{50} of the uppermost layer of the sediment cores. In all cases, the fact that these points are below the semiempirical curves suggests, here also, that these diameters are not representative of the real diameters of the resuspended particles. These latter diameters are necessarily smaller than the ϕ_{50} and therefore closer to the values inferred from the experimental settling velocities. Moreover, it can also be assumed that the real diameters cannot be larger than the calculated matter eroded heights (14 μm), which are smaller than the values of ϕ_{50}.

Conclusions

A multiclass analysis of resuspension experiments allowed characterizing the properties of the uppermost layer of cohesive sediments. The fine particles present in this layer were recently deposited and behave like noncohesive matter. These small sized particles constitute a fluffy layer that can be transported in suspension-deposition loops over long distances. For the other class of eroded matter, the critical erosion shear stresses obtained in the resuspension experiments are in good agreement with commonly reported values for cohesive matter and significantly deviate from the Shields curve. These results confirm the existence of a pool of small particles with low entrainment thresholds equivalent to a fluffy layer. As this type of material contains many times the load of contaminants usually observed on large particles, the present results show that it is necessary to describe correctly the behavior of the fluffy layer when modeling the migration of hazardous contaminants in aquatic systems.

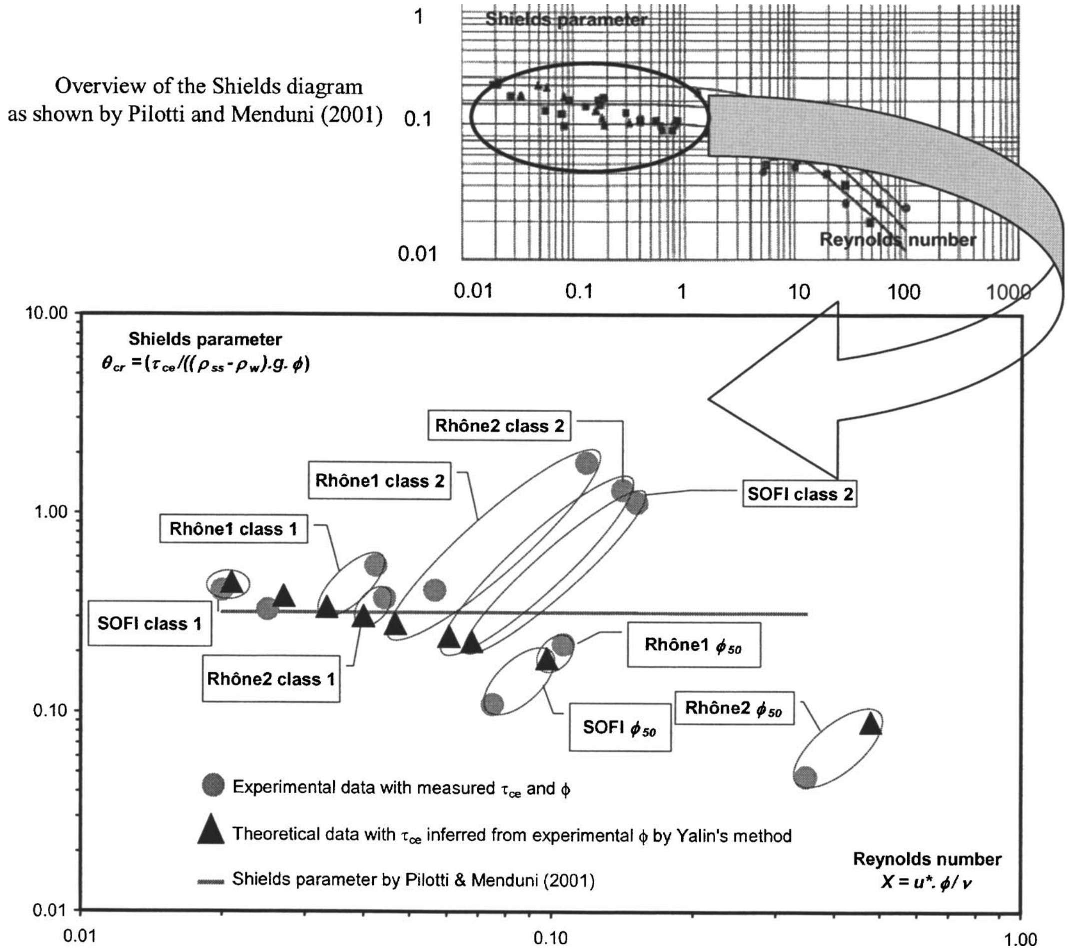

Fig. 3. Comparison between experimental results and semiempirical Shields diagram modeling

Acknowledgments

Financial support for this research was provided by the interdisciplinary "PNEC: Programme National d'Océanographie Côtière–Chantier Golfe du Lion" project. We also thank the crew of RV Tethys II for help during field sampling in the Mediterranean Sea.

Notation

The following symbols are used in this technical note:

g = gravitational acceleration;
h_c = height of water in the cores;
h_{ero} = eroded height of sediment;
h_f = equivalent height of water in the flume;
p = water content;
S_c = total surface of the four cores (0.07 m^2);
SS = suspended matter concentration;
u_* = friction velocity;
V_c = total water volume of the four cores;
V_f = volume of water in the flume (0.3 m^3);
W = settling velocity of the particles;
μ = dynamic viscosity of water;
ν = kinematic viscosity of water;
ρ_{SS} = density of the particles (2,650 kg m^{-3});
ρ_w = density of water (1,000 kg m^{-3});
τ_{ce} = critical shear stress of erosion; and
ϕ = equivalent Stokes diameter of the particles.

References

Amos, C. L., Daborn, G. R., and Christian, H. A. (1992). "In situ erosion measurements on fine-grained sediments from the bay of Fundy." *Mar. Pet. Geol.*, 108, 175–196.

Black, K. S., Tolhurst, T. J., Paterson, D. M., and Hagerthey, S. E. (2002). "Working with natural cohesive sediments." *J. Hydraul. Eng.*, 128(1), 2–8.

El Ganaoui, O., Schaaff, E., Boyer, P., Amielh, M., Anselmet, F., and Grenz, C. (2004). "The deposition and erosion of cohesive sediments determined by a multiclass model." *Estuarine Coastal Shelf Sci.*, 60, 457–475.

Graf, W. H. (1984). *Hydraulics of sediment transport*, Water Resources Publications, Highlands Ranch, Colo.

Gust, G., and Morris, M. J. (1989). "Erosion thresholds and entrainment rates of undisturbed in situ sediments." *J. Coastal Res.*, 5, 87–99.

Jago, C. F., Jones, S. E., Latter, R. J., McCandliss, R. R., Hearn, M. R., and Howarth, M. J. (2002). "Resuspension of benthic fluff by tidal currents in deep stratified waters, northern North Sea." *J. Sea Research*, 48, 259–269.

Li, M. Z., and Amos, C. L. (2001). "SEDTRANS96: The upgraded and better calibrated sediment-transport model for continental shelves." *Comput. Geosci.*, 27, 619–645.

Maa, J. P., Sanford, L., and Halka, J. P. (1998). "Sediment resuspension

characteristics in Baltimore Harbour, Maryland." *AV Commun. Rev.*, 146, 137–145.
Naudin, J. J., and Cauwet, G. (1997). "Transfer mechanisms and biogeochemical implications in the bottom nepheloid layer. A case study of the coastal zone off the Rhone River (France)." *Deep-Sea Res., Part I*, 44, 551–575.
Pilotti, M., and Menduni, G. (2001). "Beginning of sediment transport of incoherent grains in shallow shear flows.' *J. Hydraul. Res.*, 39, 115–124.
Pont, D. (1997). "Les débits solides du Rhône à proximité de son embouchure: Données récentes (1994-1995)." *Revue de Géographie de Lyon*, 72, 23–33.
Schaaff, E., Grenz, C., and Pinazo, C. (2002). "Erosion of particulate inorganic and organic matter in the Gulf of Lion." *CR Geosciences*, 334, 1071–1077.
Thomsen, L., and Gust, G. (2000). "Sediment erosion thresholds and characteristics on resuspended aggregates on the western European continental margin." *Deep-Sea Res., Part I*, 47, 1881–1897.
Van Rijn, L. C. (1993). *Principles of sediment transport in rivers, estuaries, and coastal seas*, Aqua, Amsterdam, The Netherlands.