Sedimentology (2005) **52,** 183–189 doi: 10.1111/j.1365-3091.2004.00686.x

Dewatering effects on the erodibility of newly deposited cohesive beds by unidirectional currents

EDUARDO A. GÓMEZ* and CARL L. AMOS†
**Instituto Argentino de Oceanografía, Complejo CRIBABB, Camino 'La Carrindanga' km 7·5, Casilla de Correo n°. 804, 8000 Bahía Blanca, Argentina (E-mail: gmgomez@criba.edu.ar)*
†Southampton Oceanography Centre, European Way, Dock 4, Southampton, Hampshire SO14 3ZH, UK

ABSTRACT

A series of laboratory experiments on cohesive sediments under inorganic conditions was undertaken in order to evaluate the impact of fluid bed shear stress on the build-up of bed resistance to erosion with time. The importance of small pressures due to flowing water to increase bed strength is presented. It is also shown that the susceptibility of a cohesive bed to changes in its erodibility is related to deposited bed thickness due to sediment disturbance caused by dewatering from the consolidating bed. Laboratory experiments that use beds deposited from suspension should thus report the thickness of the bed prior to resuspension.

Keywords Annular flume, bed thickness, erosion rate variability, kaolinite, physical alterations, subcritical flows.

INTRODUCTION

The behaviour of cohesive sediment beds under steady, unidirectional currents is of great importance in engineering, biology and chemistry (Lick *et al.*, 1994; Ziegler & Nisbet, 1995 Statham, 2000). Predictions of erosion and deposition of cohesive sediments are important in the evaluation of nutrient, chemical or pollutant mobilization from beds (Boudreau, 1997), in the evaluation of the morphodynamics of navigation channels (in tidal rivers, estuaries and water ways; Nichols, 1986, 1993; West, 1994), and in the evaluation of water quality and consequent effects on aquatic organisms (Wiltshire *et al.*, 1998).

In nature, a cohesive bed is affected by many variables that influence the behaviour of that bed (Partheniades, 1993). In order to measure and predict these complex effects, it is necessary to know how a particular sediment will behave under inorganic conditions. Once this is known, the complicating biochemical effects may be examined; the latter being a condition more typical of nature (Yingst & Rhoades, 1978; Ruddy *et al.*, 1998).

According to Parchure (1984) and Parchure & Mehta (1985), a settled cohesive sediment bed subjected to a constant bed shear stress will exhibit an exponential decay in erosion rate with time (Type I erosion). This is due to an increase in sediment strength with eroded depth to a position where bed strength equals the applied bed shear stress. An artificially placed bed, however, is usually homogeneous with depth, resulting in a constant erosion rate with time (Type II erosion, *sensu* Villaret & Paulic, 1986). Estuariane sediments usually display Type I erosion in the uppermost 5 mm which reflects the surface fine-grained layer and collapse zone of Droppo & Amos (2001) or the unconsolidated new deposit of Hayter, 1985); that is, a region of rapid strength increase with depth. Type II erosion is more common for lower sediment layers (usually below 5 mm) and higher flow velocities (rough turbulent). The present study focuses on laboratory settled beds that exhibit Type I erosion.

MATERIALS AND METHODS

The experiments were carried out in Laboratory Carousel which is a laboratory equivalent of the Sea Carousel (Amos *et al.*, 1992). The Carousel is an annular flume 2 m in diameter (Fig. 1). The duct is 15 cm wide and 40 cm high. Flow in the flume is driven by eight paddles fixed equidistantly to

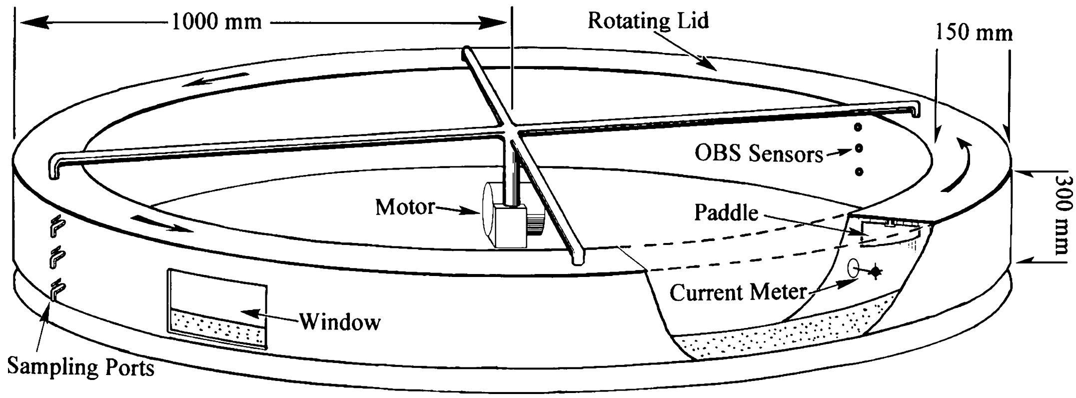

Fig. 1. A schematic diagram of the annular flume 'Laboratory Carousel' used in this study.

the underside of a rotating lid. Flow is controlled by lid rotation that is programmed by a script file and downloaded to a computer-controlled motor. Mean tangential and radial current speeds were measured using a Marsh-McBirney® electromagnetic current meter (ECM) located at the centre-line of the channel at a height of 8·5 cm above the bed. Three optical backscatter sensors (OBSs) were mounted through the flume wall at heights of 10, 20 and 30 cm to monitor turbidity. Three sampling ports were located on the outer wall at the heights of the OBSs. Samples were taken regularly from these ports in order to calibrate the OBSs. Measured volumes of water were filtered through 25 mm, Whatmann® GFC glass fibre filters to determine dry-weight suspended mass during the experiments on bed erosion.

A Campbell Scientific® CR10 data logger/controller read, transformed, and stored the measurements made by the sensors which logged at 1 Hz. The time-series of data so derived was de-spiked and time-averaged over 10 s intervals in order to smooth results.

The material used in the experiments was Glomax® kaolinite. A grain size distribution is shown in Fig. 2. The kaolinite was a well-sorted clay with a disaggregated median size (D50) equal to 1·9 microns. The flume was filled with fresh water and brought to a salinity of 35·3‰ by introducing Instant Ocean® synthetic sea salt. Synthetic sea salt was used instead of natural sea water in order to minimise organic contamination. The flume was maintained biologically neutral by using NaN_3 (sodium azide) at a concentration of 0·01 g l^{-1}. The effectiveness of this measure to prevent growth of microorganisms was checked weekly in triplicate. This was done by measuring dissolved oxygen (O_2) through titration of samples incubated over four days. The results were compared to similar analyses undertaken on sterilized water samples (controls) that reflect inorganic changes. Departures from the controls reflect the loss of O_2 due to organic activity. The water temperature was held constant (17 °C) by means of an external cooling system. The saturated sediment bed within the flume was formed by settling sediment slurry that was mixed thoroughly in the water column at an azimuthal velocity of 0·6 m s^{-1}. It was left to consolidate in still water for 20 h.

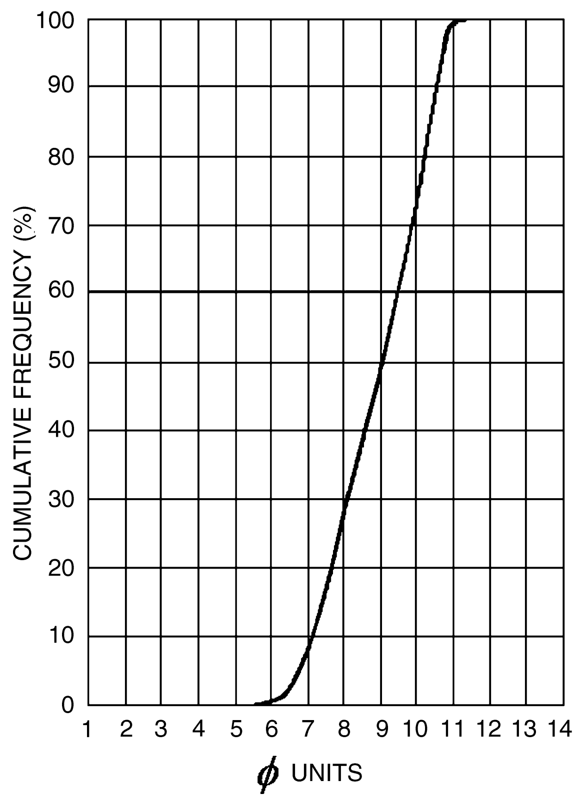

Fig. 2. A grain size distribution of the kaolinite sediment used in this study.

Flow in the flume was equated with mean bed shear stress using results presented by Amos *et al.* (1992) from Sea Carousel. These results showed that the root-mean-square friction velocity (U_{*rms}) is related to the mean azimuthal velocity (U_x) measured by the EMCM through the relationship: $U_{*rms} = 0{\cdot}045U_x$ (drag coefficient, $C_d = 0{\cdot}002$). This relationship accounts for the changing bed stress radially, but does not include the radial component of stress, which is about 0·1 of the tangential component and so it is thus within the noise of the methods of detection. Thompson *et al.* (2003) evaluated drag coefficients and bed stresses within Laboratory Carousel using eight differing methods (five proxy and three direct). In this fashion, the total drag coefficient was shown to vary with Reynolds number and bed roughness and was between 0·0007 and 0·008. The value of $C_d = 0{\cdot}002$ fell within the range of values determined by Thompson *et al.*, 2003 and hence is justified in this study.

The influence of suspended sediment concentration (C) on the fluid density and on the applied bed shear stress was neglected. Thus, bed shear stress (τ_o) was derived as follows:

$$\tau_o = (0.045U_x)^2\rho \qquad (1)$$

where ρ is the density of the saline water (1025·5 kg m^{-3}). Observations made during the present study have shown that mass erosion (bulk erosion of Mehta, 1984) starts to take place at flow speeds of the order of 0·5 m s^{-1}. So, the experimental current speed range was maintained below this value, while the speed increments were between 0·046 m s^{-1} and 0·064 m s^{-1}.

Grain size spectra of suspended material were evaluated from samples collected during the experiments using a Coulter Counter® (model T & TA). The purpose of this was to determine if the bed was graded, which would likely influence bed stability. The results, shown in Fig. 3, indicate that there was no significant difference in the grain size distributions of successively eroded layers. Hence the bed was considered uniform. The depth-averaged dry bulk density (ρ_b) was determined from: (1) the total starting suspended mass M_0 [30·26 and 2·37 g l^{-1} for a bed thickness (d) of 19 and 2 mm respectively]; and (2) dividing this mass by the volume of deposited bed derived from measuring the thickness of the consolidating

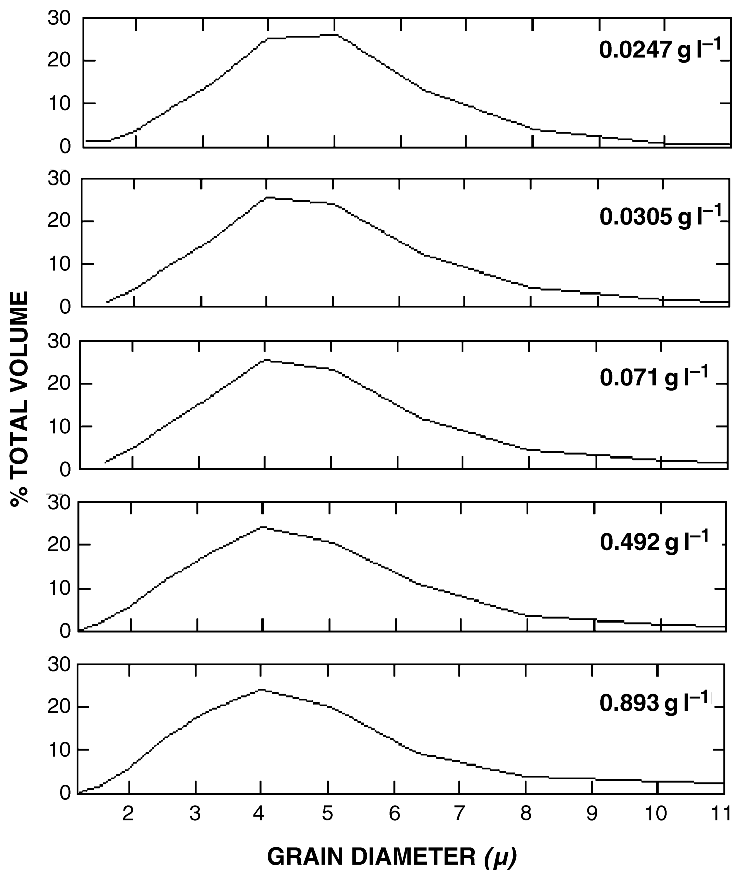

Fig. 3. A suspended grain size spectra of successively eroded bed layers.

bed (d) multiplied by the area of the Laboratory Carousel (0·874 m^2): $\rho_b = \frac{M_0}{0.874d}$ kg m^{-3}. Depth-averaged dry-weight densities of 503 and 374 kg m^{-3} were derived for the kaolinite at d = 19 and 2 mm respectively.

RESULTS AND DISCUSSION

An applied bed shear stress_ can affect the physical properties of the soft, topmost sediment layers, leading to measurable changes in the erodibility (Kusuda *et al.*, 1985). Working with placed cohesive beds with different water contents, Kusuda *et al.* (1985) noted a significant decrease in the erosion rate (ε) after 10 to 30 min from the test start caused mainly by the hardening of sediments as the result of the applied shear stress, while on the contrary, selective erosion has not much influence in such decrease of ε.

A series of experiments was designed and carried out on a newly settled kaolinite bed to test if the hardening effect of subcritical bed shear stresses on bed stability was significant. Here, subcritical bed shear stresses are defined as those values that over one hour do not produce measurable erosion. In the experiments, the bed was left to consolidate for 20 h (to a thickness of 19 mm). As shown in Fig. 4A, the bed was subjected to the action of three increasing successive subthreshold bed shear stresses (0·008, 0·018 and 0·052 Pa) over time intervals ranging from 5·4 to 67 min. Then, the bed was subjected to an erosive shear stress of 0·102 Pa and the evolution of suspended sediment concentration through time was measured (Fig. 4B). It is evident that erosion rates (curve steepness) show differences among the experiments of the series, with a reduction in the erosion rate up to 50%. This reduction on the observed ε is related to the length of the time over which the subthreshold bed shear stresses were applied. Such great differences in bed response may make laboratory experiments inconsistent; perhaps more so if the hardening effect of the applied shear stress continues throughout the period of erosion.

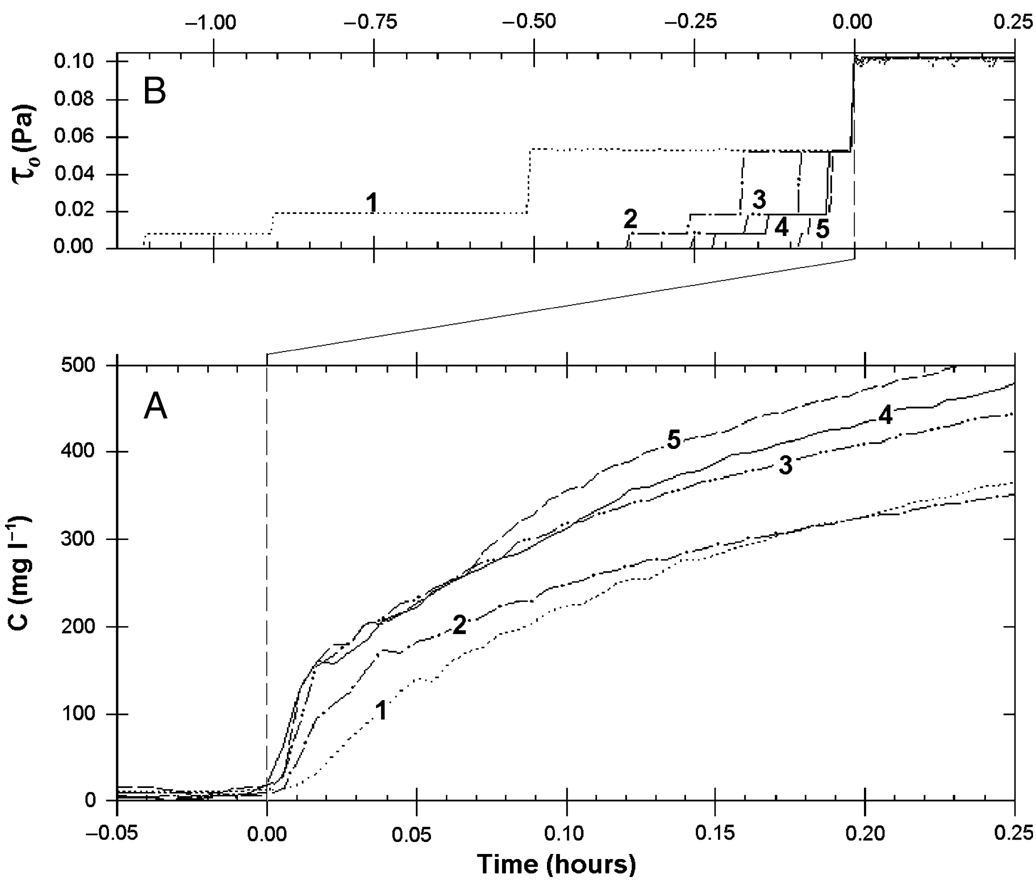

Fig. 4. Changes on erosion rate (A) due to subthreshold bed shear stresses applied over different time intervals (B).

It was observed that the sediment surface was disturbed and roughened by dewatering of the consolidating bed. This surface, instead of being smooth, showed vent cones up to 4 mm in diameter and less than 1 mm in height, with a density of the order of 10 cm^{-2}. These vents suggest that pore pressure was equilibrated with the hydrostatic pressure. In order to test if variability in bed erodibility was mainly related to sediment dewatering, a second series of experiments was carried out. In two of the experiments of this series (1 and 2), the total 19 mm of bed thickness was resuspended before settling and consolidation (Table 1), whereas in the other two experiments (3 and 4) resuspension of the first 2 mm only took place, with no visible alterations on the underlying layers. After 20 h of consolidation, a subthreshold shear stress of 0·041 Pa was applied for 30 min but only to one of each resuspended bed thickness (experiments 2 and 4). The bed in all the experiments of this series was subjected to an erosive shear stress of 0·13 Pa. This value was reached within a time interval of 2·8 min by stepping 0·0061, 0·026, 0·058 and 0·078 Pa (Fig. 5A). The evolution of suspended sediment concentration of this experimental series is shown in Fig. 5B. Large differences in ε (curve steepness) were observed among the experiments of the series, especially at the very beginning of erosion. These differences in erosion rate were smaller by 15% after 6 min from the start of the erosive step. Differences between experiments 1 and 2 are linked to 30 min of subthreshold shear stress. The same effect is evident between experiments 3 and 4. Results from those experiments, where a subthreshold shear stress was applied (2 and 4), are almost identical. In experiments 1 and 3, erosion started earlier and at a higher rate than in experiments 2 and 4 (Fig. 5C). Thus, the greater part of bed susceptibility to hardening by subthreshold shear stresses is related to bed alterations produced by dewatering, which may be linked to the consolidating bed thickness.

The observed erosive behaviour suggests that the roughened surface caused by dewatering may be providing a source of form drag that would have an effect on the bed shear stress, or the subthreshold shear stresses may cause a rearrangement of the sediment fabric. As dewatering effects diminish with bed thickness, a way of reducing response variability of a settled sediment bed to the subthreshold shear stresses would be to reduce the experimental bed thickness as much as possible. This may be more representative of what usually takes place on tidal flats, where the sediment layer eroded or deposited over a tidal cycle is commonly in the order of millimetres or less.

CONCLUSIONS

Two series of erosion experiments have been undertaken within the controlled confines of the annular flume Laboratory Carousel. The purpose of these experiments was: (1) to determine the effect of a subcritical flow on bed strengthening of a standard kaolinite; and (2) to determine what causes bed susceptibility to the action of subcritical flows and how to reduce it.

The first experimental series showed that surface erosion rate was strongly influenced by the shear stresses applied on the bed immediately prior to erosion. Even within the limits of the experiments this rate was changed by a factor of two by varying the period of time over which the subcritical shear stresses were applied. What is not clear is whether this effect alters the critical shear stress (τ_{crit}). Thus experiments should report in detail the nature of bed preparation, and perhaps, more importantly, the stress history prior to bed erosion.

The second experimental series indicated that bed susceptibility to subthreshold shear stresses is strongly related to the amount of the settled-consolidating sediments (bed thickness). This appears to be caused by physical bed alterations generated by dewatering from the consolidating

Table 1 Procedures used in erosion experiments used to test the effect of bed thickness on its erodibility.

Experiments	Depth of resuspension (mm)	Compaction time (h)	Bed alterations due to dewatering	τ_{sbcr}/time (Pa/h)
1	19	20	Appreciable	–
2	19	20	Appreciable	0·041/0·5
3	2	20	Non appreciable	–
4	2	20	Non appreciable	0·041/0·5

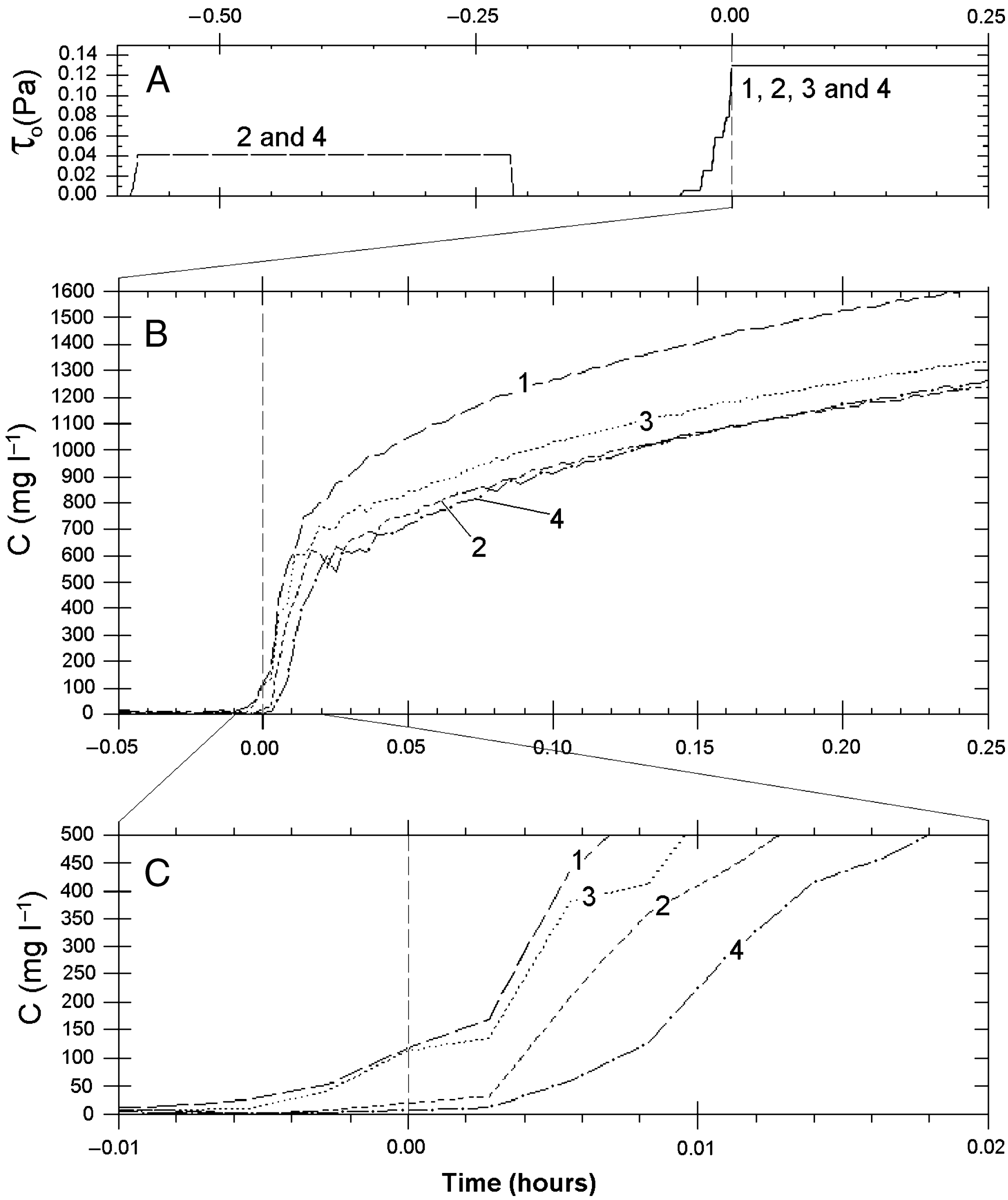

Fig. 5. Results from four experiments described in Table 1. Experiments 1 and 2, and experiments 3 and 4 were carried out on 19 mm and 2 mm bed thicknesses respectively. All experiments were performed in the same way, but on experiments 2 and 4 a subthreshold shear stress of 0·041 Pa was applied for 30 min (A). Bed susceptibility to erosion on experiment 1 is clearly increased compared with experiments 2, 3 and 4, whereas results from experiments 2 and 4 are almost identical (B). In (C) it is observed that erosion seems to start earlier and at a higher rate in experiments 1 and 3 than in experiments 2 and 4.

bed. As the magnitude of these physical alterations is directly related to the bed thickness, in order to minimize erosion rate variability experiments should be carried out reducing the bed thickness as much as possible.

ACKNOWLEDGEMENTS

The authors wish to express thanks to Drs G. R. Daborn and M. Brylinsky, Acadia Centre for Estuarine Research, and to Mr J. Gibson and Mrs V. Partridge, Acadia University, for their help during this investigation. This study was funded by the Geological Survey of Canada and the National Agency for Scientific and Technologic Promotion of Argentina (ANPCyT, PICT n°. 07–03955). E.A.G. was funded by an external fellowship from the Argentinean Research Council (CONICET). Finally, thanks go to Dr Jean Berlamont and the anonymous reviewer who significantly improved this manuscript.

NOMENCLATURE

C suspended sediment concentration (mg l^{-1})
C_d drag coefficient
M_o total suspended mass (kg)
D_{50} median diameter of disaggregated particles (microns)
d thickness of the consolidating bed (mm)
U_{*rms} root-mean-square friction velocity (m/s)
U_x azimuthal velocity (m/s)
ε erosion rate (kg $m^{-2}s^{-1}$)
ρ density of the saline water (kg m^{-3})
ρ_b bed depth-averaged dry bulk density (kg m^{-3})
τ_o bed shear stress (Pa)
τ_{crit} critical shear stress (Pa)
τ_{sbcr} subcritical shear stress (Pa)

REFERENCES

Amos, C.L., Grant, J., Daborn, G.R. and **Black, K.** (1992) Sea Carousel - a benthic, annular flume. *Estuar. Coast. Shelf Sci.* **34,** 557–577.

Boudreau, B.B. (1997) A one-dimensional model for bed boundary layer particle exchange. *J. Mar. Systems*, **11,** 279–303.

Droppo, I.G. and **Amos, C.L.** (2001) Structure, stability, and transformation of contaminated lacustrine surface fine-grained laminae. *J. Sed. Res.* **71,** 717–726.

Hayter, E.J. (1985) Esturial sediment bed model. In: *Estuarine Cohesive Sediment Dynamics*, (Ed A.J. Mehta), pp.326–359. Springer-Verlag, Berlin.

Kusuda, T., Umita, T., Koga, K., Futawatari, T. and **Awaya, Y.** (1985) Erosional process of cohesive sediments. *Water Sci. Technol.* **17,** 891–901.

Lick, W., Lick, J. and **Ziegler, C.K.** (1994) The resuspension and transport of fine-grained sediments in Lake Erie. *J. Great Lakes Res.* **20,** 599–612.

Mehta, A.J. (1984) Characterisation of cohesive sediment properties and transport processes in estuaries. In: *Estuarine Cohesive Sediment Dynamics*, (Ed A.J. Mehta), pp. 290–325, Springer-Verlag, Berlin.

Nichols, M.M. (1986) Effects of fine sediment resuspension in estuaries. In: *Estuarine Cohesive Sediment Dynamics.* (Ed. A.J. Mehta), pp 5–42, Springer-Verlag, Berlin.

Nichols, M.M. (1993) Response of coastal plain estuaries to episodic events in the Chesapeake Bay region. In: *Nearshore and Estuarine Cohesive Sediment Transport.* (Ed. A.J. Mehta), pp. 1–20, American Geophysical Union, Washington, DC.

Parchure, T.M. (1984) Effect of bed shear stress on the erosional characteristics of kaolinite. PhD Thesis, University of Florida, Gainesville.

Parchure, T.M. and **Mehta, A.J.** (1985) Erosion of soft cohesive sediment deposits. *J. Hydraul. Eng.*, **111,** 1308–1326.

Partheniades, E. (1993) Turbulence, flocculation and cohesive sediment dynamics. In: *Nearshore and Estuarine Cohesive Sediment Transport.* (Ed. A.J., Mehta), pp. 40–59, American Geophysical Union, Washington, DC.

Ruddy, G., Turley, C.M. and **Jones, T.E.R.** (1998) Ecological interaction and sediment transport on an intertidal mudflat I. Evidence for biologically mediated sediment–water interface. In: *Sedimentary Processes in the Intertidal Zone*, (Eds K.S. Black, D.M. Paterson, and A..Cramp). *Geol. Soc. London Spec. Pub.* **139,** 135–148.

Statham, P.J. (2000) Trace metals in water, sediments and biota of the solent system. In: *Solent Science: a Review* (Eds M.B. Collins and K. Ansell) pp. 149–161, Elsevier, the Netherlands.

Thompson, C., Amos, C.L., Jones, T.E.R. and **Chaplin, J.** (2003) The manifestation of fluid-transmitted bed shear stress in a smooth annular flume – a comparison of methods. *J. Coastal Res.* **19,** 1094–1103.

Villaret, C. and **Paulic, M.** (1986) Experiments on the erosion of deposited placed cohesive sediments in an annular flume and a rocking flume. *University Florida, Coastal Oceanographic Engineering Report UFL/COEL-86–007*, 61pp.

West, J.R. (1994) Cohesive sediment transport in estuaries. In: *Mixing and Transport in the Environment. (*Eds. K. Beven, P. Chatwin and J. Millbank), pp. 307–323, John Wiley & Sons.

Wiltshire, K.H., Tolhurst, T., Paterson, D.M., Davidson, I. and **Gust, G.** (1998) Pigment fingerprints as markers of erosion and changes in cohesive sediment surface properties in simulated and natural erosion events. In:. *Sedimentary Processes in the Intertidal Zone. (*Eds K.S. Black, D.M. Paterson and A. Cramp) *Geol. Soc., London Spec. Pub.* **39,** 99–114.

Yingst, J.Y. and **Rhoades, D.C.** (1978) Seafloor stability in central Long Island Sound: Part II. Biological interactions and their potential importance for seafloor erodibility. In: *Estuarine Interactions* (Ed. M.L. Wiley), pp. 245–284, Academic Press, New York.

Ziegler, C.K. and **Nisbet, B.S.** (1995) Long-term simulation of fine-grained sediment transport in large reservoir. *J. Hydraul. Eng..*, **121,** 773–781.

Manuscript received 24 January 2004;
revision accepted 2 October 2004.