6

torani

JOURNAL OF MARINE SCIENCE AND FISHERIES

No. 5 (Special Edition) Vol 18 December 2008 ISSN : 0853-4489

UNIVERSITAS HASANUDDIN
MAKASSAR

Torani, Vol. 18(5) December 2008: 390 - 397 ISSN: 0853-4489

MEASURING CRITICAL EROSION SHEAR STRESS OF INTERTIDAL SEDIMENTS WITH EROMES EROSION DEVICE

Mahatma Lanuru[1]

[1)] Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar

Received: 13 August 2008; Accepted: 11 October 2008

ABSTRACT

The critical erosion shear stress of intertidal sediments in the German Wadden Sea area was measured using the EROMES erosion device. Various physical, sedimentological and biological parameters were determined for 4 stations at the study site during 3 field campaigns in April, May and June 2001. ' These included: critical erosion shear stress, wet bulk density, mud content, water content, organic content and chlorophyll-a concentration of the surficial sediment. Characteristics erosion pattern (type-I and type-II erosion) were observed for most measurement. The critical erosion shear stress varied between 0.10 to 2.05 N m^{-2} and these values fall above Shields predicted values. Critical erosion shear stress correlated most significantly with Chlorophyll-a concentration suggesting that microphytobenthos biomass (measures by chlorophyll-a concentration) seem to be the main factors in controlling the erosion potential of the sediment surface at the study site.

Keywords: Critical erosion, intertidal sediment

INTRODUCTION

The erosion of fine-grained cohesive sediments (mud) is ubiquitous phenomenon in marine and estuarine environments Sediment erosion occurs whenever the shear stress exerted on the bed by currents and waves exceed a critical value, known as the critical bed shear stress (denoted τ_{cr}). The critical erosion shear stress is an important parameter in sediment transport mechanics. Below this value little or no erosion occurs, whereas once exceeded significant erosion may occur by a number of mechanisms (Tolhurst *et al.*, 1999).

In contrast to non-cohesive sediments (sands), it is presently not possible to predict the critical erosion stress of cohesive sediments from one or more easily measurable parameters, such as grain size, bulk density, or water or organic content (Dade *et al.*, 1992). The factors contributing to the shear strength of cohesive sediments are numerous, interact in a complex manner and remain poorly understood (Paterson, 1997). In addition, the published data show that critical erosion stress varied strongly for different geographical sites and that erodibility of cohesive sediments can not clearly be related to physical or biological parameters alone. Therefore, it is necessary to conduct erosion experiment in order to characterize the strength development of local cohesive sediments.

The purpose of this study was to determine the critical erosion shear stress using an EROMES erosion device and to investigate the main physical, sedimentological and biological factors governing the variation in sediment erodibility.

METHODS

Study site

The study was carried out at the Dornumer Nacken, a back barrier tidal flat located between the barrier island of Baltrum and the East-Frisian mainland coast, Germany. The meteorological setting is characterized by relatively calm conditions in summer and more stormy conditions in winter, being dominated by northwesterly winds between January and April. The mean tidal range at study site is approximately 2.6 m and the tides are semi diurnal. Tidal current velocities in the channels close to the inlet ranged from 0 to 70 cm s^{-1} and on the tidal flats from 0 to 25 cm s^{-1} (Krögel and Flemming, 1998).

Sampling

The sediment cores (for erosion measurement) and surface sediment samples (for sediment properties measurement) were collected at 4 stations in April, May, and June 2001. Station 1 is situated approximately 100 m from the shore line, whereas station 2, 3 and 4 are situated approximately 400 m, 1000 m and 1500 m from the shore line, respectively. Sediment cores were collected by means of 10 cm diameter perspex tube at each station. The cores were transported to a nearby mobile laboratory and carefully filled with seawater to a level of 30 cm. Despite great care being taken, this filling process nevertheless stresses the surface to a certain degree. Therefore, the cores were allowed to stand for at least one hour before the start of the erosion experiment.

For the measurement of surficial sediment properties, a surface scrape of the top 1 mm of sediment was taken. The samples were homogenized and sub-samples were taken to measure wet bulk density, mud content (fined-grained sediment fraction < 63 μm), water content, organic content, and chlorophyll-a concentration of the bed material. The cores and surface sediment samples were generally sampled on the tidal mudflats about 1 - 3 hour after the sampling stations were exposed.

Erosion measurement

The erosion device used for determination of critical erosion shear stress and erosion rate is the EROMES equipment (Cornelisse *et al.* 1994). The EROMES system uses artificially induced turbulence to erode the samples and to keep the eroded matter in suspension. The erosive force is induced by a rotating propeller 3 cm above the sediment surface. Six evenly spaced baffles suppress the rotational component of the water movement. The induced turbulence exhibits significant and randomly varying bursts and sweeps thus resembling the conditions of turbulent flow and wave action typical at the bed of rivers, estuaries and shallow coastal seas. The propeller rotations have been converted to bed shear stress by use of a calibration based on erosion of quartz sands with known critical erosion shear stress up to values 3 N m^{-2}.

During each erosion experiment, the bed shear stress was increased in steps of 0.1 N m^{-2} every 5 min. The concentration of eroded material in the system is determined in a bypass loop using the recorded light attenuation converted into concentrations with a calibration relationship.

Erosion shear stress is determined by significant increase of the erosion rate. The determination of the erosion shear stress requires a detailed study of the erosion rate progress during the experiment because in most case there are two distinct shear stress values where the erosion rate increase significantly. Firstly, smooth increase in the erosion rate indicates erosion of small aggregates and flocs or non-consolidated material deposited on the surface during low tide. Secondly, at stronger increase in the erosion rate indicates the onset of erosion of the consolidated bed. A linear function is fitted to the erosion rate in this region. The erosion shear stress is computed from the intersection of the fit function with a critical erosion rate level of 0.01 g m^{-2} s^{-1}

(Riethmüller *et al.* 1998, Lanuru et al.2007). The evaluation procedure to compute critical erosion shear stress is illustrated in Figure 1 for a sample taken at station 2.

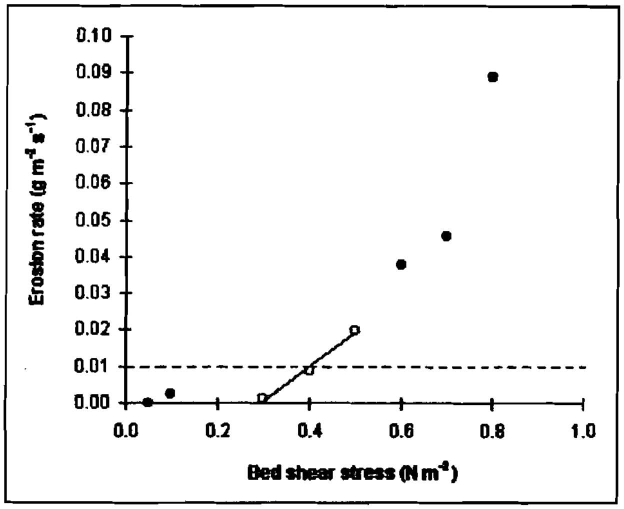

Figure 1. A plot of erosion rate versus bed shear stress for an erosion experiment.

To determine the critical erosion shear stress a linear function is fitted to the data in the region around the critical erosion rate of 0.01 g m^{-2} s^{-1} (open circles). Critical erosion shear stress of 0.4 N m^{-2} is found for this experiment

Sediment properties measurement

Chlorophyll-a concentration was measured to estimate the microphytobenthos biomass. Chlorophyll-a concentration was measured using the acetone extraction and reverse-phase column HPLC technique of Wright *et el.* (1991). Grain size analyses were done on samples pre-treated with H_2O_2 to eliminate organic material, sieved at 300 µm and weighed. On the fraction < 300 µm the determination were done by means of a Galai Cis-1 laser particle size analyzer, with a specific analytical size intervals of 1 micron. The water content of the sediment was determined by drying to constant weight for 24 hours at a temperature of 105 ° C. The organic content was measured by loss of ignition of the samples at 550 °C in an oven for 1 h.

Statistical Analysis

Level of significance of correlation between variables was analyzed with the Pearson correlation statistics (Fohler and Cohen, 1990).

RESULTS AND DISCUSSION

Modes of sediment erosion

The critical erosion shear stress for the erosion of the sediment varied between 0.16 to 2.05 N m^{-2}. The wet bulk density of the top layer of the bed varied between 1.46 to 1.94 gr cm^{-3}. The mud content ranged between 46.32 to 97.07 %. The water content ranged between 24.7 to 52.46 %. The organic content varied between 1.30 to 6.81 %. The chlorophyll-a concentration ranged between 8.72 to 144.19 mg m^{-2} at the study site. Two types of erosion were observed during the erosion experiment, i.e. type-I and type-II erosion.

The erodibility of cohesive sediment bed is commonly expressed by means of critical erosion shear stress or erosion threshold and by erosion rate. In this study, the erosion potential (erodibility) of the sediments was measured in term of critical erosion shear stress and it was determined by significant increase of the erosion rate. Several descriptions of the initiation of cohesive sediment erosion have been reported in other erosion studies. For example, the erosion threshold of sediment has been defined as the velocity at which 10 or more mineral grains are moving simultaneously (Heinzelmann & Wallisch, 1991). Madsen *et al.* (1993) defined critical erosion shear velocity as the velocity when both attached organic material and mineral grains were moved. Whereas Paterson (1989) defined erosion threshold as the velocity when resuspended sediment leads to a substantial reduction (> 30%) in light transmission.

Modes of sediment erosion that observed in this study can be classified as type-I and Type-II erosion. At relative low bed stresses, erosion was manifested by surface creep or bedload transport of small organic aggregates, loose flocs, pellets, shell debris, and mineral grains. Afterward, erosion was evident as a non-linear increase in suspended sediment concentration. This typical erosion pattern can be classified as type-I erosion, where the erosion process peaks rapidly once it has begun and then decreases with time (Amos *et al.* 1997). Whereas at higher bed stresses, the suspended sediment concentration increased steadily and this pattern can be classified as type-II erosion.

Factors influencing sediment erodibility

The data were pooled from different stations and different sampling periods and correlated (Pearson product moment) to determine which sediment properties had the strongest co-variation with sediment erodibility (Table I). A significant correlation was accepted when P = 0.01. There was no significant correlation between wet bulk density, water content, and mud content with erosion shear stress (P = 0.01) suggesting that those variables were not dominant factors influencing sediment erodibility at study site (Table I). Chlorophyll-a concentrations were highly correlated with critical erosion shear stress (Table 1, Figure 2). This observation suggests that microphytobenthos (measured by chlorophyll-a) seem to be one of the main factors in controlling the erosion potential of the surface sediment at study site. Another parameter that significantly correlated with critical erosion shear stress was organic content (Table I).

Table I. Pearson correlation coefficient (r) of the correlation analysis of the data

	Wet bulk density	Mud content	Water content	Organic content	Chlorophyll-a concentration
Mud content	-0.68				
Water content	-0.99	0.65			
Organic content	-0.97	0.71	0.97		
Chlorophyll-a concentration	-0.68	0.62	0.73	0.75	
Critical erosion shear stress	-0.50	0.48	0.53	0.58	0.80

Number in bold: significant at P = 0.01

One parameter which related strongly with the critical erosion shear stress is the sediment bulk density (Amos *et al.*, 1997). However, it was observed that the effect of wet bulk density on critical erosion shear stress less pronounced. As shown in Table I, there was no significant relationship between bed density and erosion shear stress. This suggests that the bed density was not a dominant factor influencing sediment erodibility in the study site. The proposed relationship between bed density and erosion shear stress seems to be based on sediment mixture with high percentage of mud by weigh in combination with a high organic content (Houwing, 1999). At the study site, the bed densities and mud content were relatively high, but the organic contents were low. Therefore, this relationship might not be valid in this particular situation. In addition, the effect of biostabilization by microphytobenthos might be larger than the expected increasing erosion shear stress due to high bed density.

Another parameter that is supposed to have great influence on the erodibility is water content (Amos *et al.* 1998) and mud content of the bed. However, no significant relationships were observed between water content and mud content with erosion shear stress in this study (Table I). Again the larger effect of microphytobenthos on the sediment erodibility might be responsible for lack of correlation between water content and mud content with erosion shear stress.

A strong positive correlation between microphytobenthos biomass (measured by chlorophyll-a concentration) and erosion shear stress was observed (Table I and Figure 2). It can thus be concluded that microphytobenthos (mainly diatom) seems to be one of the main factors in controlling the erosion potential of the upper most sediment surface at the study site.

Diatoms therefore tend to be effective in stabilizing muddy sediments (Sutherland *et al.* 1998). The secretion of extracellular polymeric substance (EPS) by benthic diatom during locomotion might be the main binding mechanism that influences the stabilization of sediment. These EPS binds sediment particle together at the mud surface, hence reducing the susceptibility for erosion (Paterson, 1989). In addition, the diatom covers present on the sediment reduces the flow induced shear stress by smoothing the surface. The results of this study suggests that sediment with high chlorophyll a concentration will be more stable and not easily eroded than sediment with low level of chlorophyll-a.

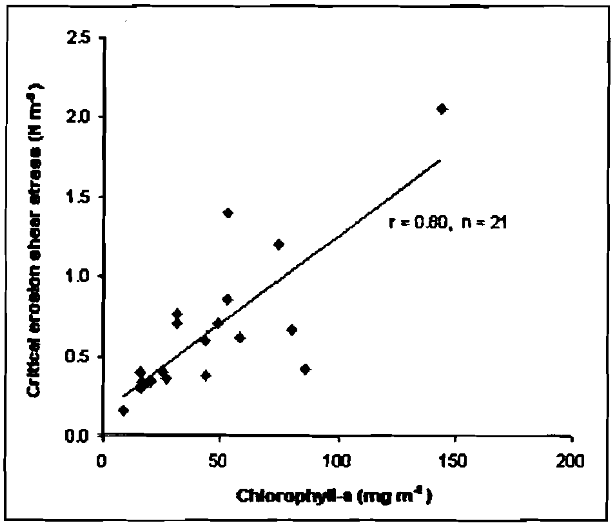

Figure 2. Correlation between chlorophyll-a concentration and erosion shear stress of the surface sediments.

Comparison with abiotic sediment erosion

The measured critical erosion shear stresses can be compared to the critical erosion shear stress of abiotic non-cohesive sediment, which can be determined from knowledge of grain density and size and the fluid properties by using one of the version of the Shields parameters. Here, the threshold Shields parameter for cohesionless grains θ_{cr} was calculated using a formula proposed by Soulsby and Whitehouse (1997):

$$\theta_{cr} = \frac{0.30}{1+1.2D_*} + 0.055\left[1 - \exp(-0.020D_*)\right]$$

with dimensionless grain-size, $D_* = \left[\frac{g\,(s-1)}{\nu^2}\right]^{1/3} d$

With the Shields parameter the abiotic non-cohesive sediment critical erosion shear stress ($\tau_{cr\text{-}Shields}$) can be calculated as follows:

$$\tau_{cr-Shields} = \theta_{cr}\left[(\rho_s - \rho)g d\right]$$

where ρ and ρ_s are fluid and sediment density, respectively, $s = \rho_s / \rho$, g is acceleration due to gravity, d is grain diameter, and ν is kinematic viscosity of water. For this purpose, ρ_s was taken as 2650kg m^{-3}, ρ as 1027kg m^{-3}, g as 9.81m s^{-2} and ν as 1.36 x 10^{-6} m^{2}s^{-1}.

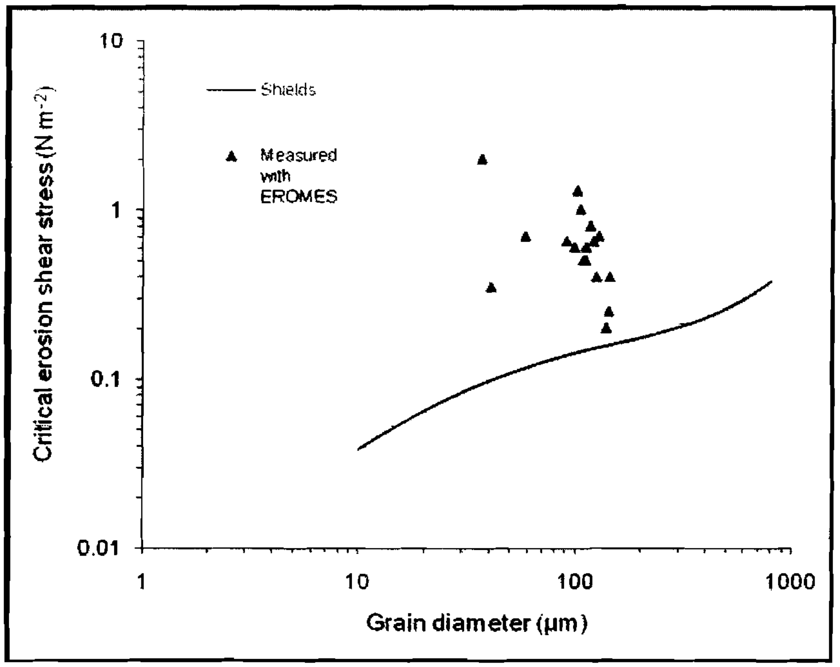

Figure 3. Measured critical erosion shear stress with EROMES and compared to $\tau cr - Shields$ of quartz grain in seawater of 10 °C and salinity 35 $^o/_{oo}$ (Soulsby and Whitehouse 1997).

As shown in Figure 3, critical erosion shear stresses at the study site fall above Shields predicted values and the divergence can not solely be attributed to difference in erosion threshold criteria. The discrepancy between the measured critical erosion shear stress and abiotic non-cohesive sediment values is most likely caused by the existence of benthic diatoms. Even in the sand flat with lack of visible diatom biofilm, Lelieveld et al. (2003) still found an increase of sediment critical shear stress relative to abiotic sediment by up to factor of 14, highlighting that visible diatom biofilms are not a prerequisite for measurable sediment stabilization. In this case the stabilization is most likely due to gluing by sessile diatoms which do not form a bioflim.

The differences in critical erosion shear stress between natural sediment and abiotic sediment may be also caused by the effect of cohesiveness associated with natural sediments, which will increase the critical shear stress. As suggested by Mitchener and Torfs (1996), the mode of erosion changes from cohesionless to cohesive behaviour at low mud contents (< 62.5 μm) added to sand, with a transition occurring in the region 3 % to 15 % mud by weight. The mud content of sediment at all stations was above the transition region of 3 - 15 % suggested by Mitchener and Torfs (1996) to impart cohesive properties on sediment.

CONCLUSIONS

The critical erosion shear stress varied from 0.10 to 2.05 N m^{-2}. Type-I and type-II erosions were observed for most measurement. Critical erosion shear stress correlated most significantly with Chlorophyll-a concentration suggesting that microphytobenthos biomass seem to be the main factors in controlling the erosion potential of the sediment surface at the study site. Critical erosion shear stresses at the study site fall above Shields predicted values. The discrepancy between the measured critical erosion shear stress and abiotic non-cohesive sediment values is most likely caused by the existence of benthic diatoms and effect of cohesiveness associated with natural sediments, which will increase the critical shear stress.

ACKNOWLEDGMENT

I thank W.Stille, K. Heyman, B.Peters, M.Janik and K.Wirth (GKSS Research Centre, Germany) for their help in the field and with the erosion and sediment properties measurements. My appreciation also goes to Dr. R. Riethmüller for his help in the data analysis and data interpretation.

REFERENCES

Amos,C.L., Feeney, T., Sutherland, T.F. and J.L. Luternauer. 1997. **The stability of fine-grained sediments from the Fraser River Delta. Estuarine, Coastal, and Shelf.** Science 45: 507-524.

Amos, C.L., Van Wagonner, N.A. and G.R. Daborn. 1988. **The influence of subaerial exposure on the bulk properties of fine-grained intertidal sediment from Minas Bay, Bay of Fundy.** Estuarine, Coastal, and Shelf Science 27:1 – 13.

Cornelisse, J.M., Mulder, H.P.J., Williamson, H.Y., Witte, G. and E.J. Houwing. 1994. **On the development of instruments for in situ erosion measurement**, in Fourth Nearshore and Estuarine Cohesive Sediment Transport Conference :175 - 186.

Dade, W.B., Nowell, A.R.M., and P.A. Jumars. 1992. **Predicting erosion resistance of mud.** Marine Geology 105: 285-297.

Fohler, J. and L. Cohen. 1997. **Practical Statistic For Field Biology**. England. Jhon Willey & Sons. Pp.130-141.

Heinzelmann, C.H. and S. Wallisch. 1991. **Benthic settlement and bed erosion**: A review. J. Hydraul. Res. 29: 355-371.

Houwing, E.J. 1999. **Determination of the critical erosion threshold of cohesive sediments on intertidal mudflats along the Dutch Wadden Sea coast.** Estuarine, Coastal, and Shelf Science 49: 545 – 555.

Krögel, F. and B.W. Flemming. 1998. **Evidence for temperature-adjusted sediment distribution in the back barrier tidal fltas of the East Frisian Wadden Sea (Southern North Sea)", in Tidalites**: Processes and products, SEPM special publication No.61 (Alexander, C.R., Davis, R.A., and Henry, V.J. eds). Pp. 31-41.

Lanuru, M., Riethmueller. R. van Bernem, C, and K. Heymann. 2007. **The effect of bedforms (crest and trough systems) on sediment erodibility on a back barrier tidal flat of the East Frisian Wadden Sea, Germany.** Estuarine, Coastal, and Shelf Science 72: 603 – 614.

Lelieveld, S.D., Pilditch, C.A., and M.O. Grenn. 2003. **Variation in sediment stability and relation to indicators of microbial abundance in the Okura Estuary, New Zealand.** Estuarine, Coastal and Shelf Science 57, 123 - 136.

Madsen, K.N., Nilsson, P. and K. Sundbäck. **The influence of benthic microalgae on the stability of a subtidal sediment.** J. Exp. Mar. Biol. Ecol 170:159-177.

Mitchener, H., and H. Torfs. 1996. **Erosion of mud/sand mixtures**. Coastal Engineering 29, 1 - 25.

Paterson, D.M. 1989. **Short term changes in the erodibility of intertidal cohesive sediments related to the migratory behaviour of epipelic diatoms**. Limnology and Oceanography 34: 223 – 234.

Paterson, D.M. 1997. **Biological mediation of sediment erodibility: ecology and physical dynamics, In Cohesive Sediments** (Burt,N., Parker, R., and Watt, J. eds.). John Wiley & Sons Ltd.

Riethmueller, R., Haakvoort, J.H., Heineke, M., Heymann, K., Kuehl, H.and G. Witte. 1998. **Relating shear stress to tidal flat surface color, in Sedimentary Processes in the Intertidal Zone** (Black, K.S., Paterson, D.M. & Cramp,A. eds.), pp. 283 - 293.

Soulsby, R.L., and R. Whitehouse. 1997. **Thereshold of sediment motion in coastal environment**. In: Proc Pacific Coast and Ports Conf 1, University of canterbury, Christchurch, New Zealand, Pp 149 - 154.

Sutherland, T.F., Amos, C.L., and J. Grant. 1998. **The effect of buoyant biofilms on the erodibility of sublittoral sediments of a temperate microtidal estuary"**, Limnology and Oceanography 43: 225 – 235.

Tolhurst, T.J., Black, K.S., Shayler, S.A., Mather, S., Black, I., Baker, K. and D.M. Paterson. 1999. **Measuring the in situ erosion shear stress of intertidal sediments with the cohesive strength meter (CSM)**. Estuarine, Coastal and Shelf Science 49: 281- 294.

Wright, S., Jeffery, S.W., Mantoura, R.F.C., Llewellyn, C.A., Bjorland, T., Rapeta, D. and N. Welschmeyer. 1991. **Improved HPLC method for analyses of chlorophyll and carotenoids from marine phytoplankton.** Marine Ecology Progress Series 77: 183 – 196.