

CHAPTER 242

EROSION OF LAYERED SAND-MUD BEDS IN UNIFORM FLOW

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Abstract

In a laboratory flume the formation and erosion of stratified sand-mud beds in uniform flow was studied. The experiments showed that depending on the initial conditions of suspended sediment concentration and mixture composition, consecutive inputs of a mud/sand suspension will lead to the formation of a layered sediment bed. Peaks in the measured density profiles show the different layers and indicate a possible segregation of the sand due to differential settling. During the erosion of the stratified bed, the sediments are eroded layer by layer. This results in a sequence of suspended load (fines) and bed load (sand) transport phases.

Introduction

The sediments in estuaries and coastal areas are generally a mixture of sand and mud. Due to tidal action the sediments are periodically suspended and afterwards, during slack water, deposited. This sequence of erosion and deposition results in many cases in a layered bed structure, because the sand fraction settles faster. In the Scheldt Estuary layers of a few millimetres up to two centimetres thick are found (Bastin 1974). Also for the Humber Estuary and the Severn Estuary sediment laminations are reported (Williamson 1991). Understanding the erosion of such sediment bottoms is important for the control of navigation channels, dredging activities and pollution as well as for the modelling of sediment transport in estuaries and coastal seas.

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To study the fundamental aspects of the erosion of layered sand-mud beds, laboratory experiments in uniform flow were carried out. During these tests the whole erosion process was followed starting from the formation of the bed out of a suspension and looking at the layer thickness and the density profiles, over the incipient motion phase until the different modes of erosion of the stratified, mixed bed.

Experimental Procedure

The laboratory set up consists of a 9 m long flume with a rectangular cross section of 40 cm wide. The total length of the flume is divided into 4 different regions: a 4 m upstream inflow region with fixed bed, a 3 m long glass wall measuring section with the sediment bed, a sediment trap and a 1.5 m downstream outflow region with fixed bottom. A settling tank (1 m high) can be mounted on top of the flume, above the measuring section.

The tank is filled with salt water (3 kg/m^3). To simulate a tidal cycle, at regular time intervals - twice a day - a slurry of mud mixed with sand is pumped into the settling tank. The slurry density results in suspended sediment concentrations in the settling tank of a few grams per litre, too low for hindered settling to occur but about the order of magnitude of the near bed sediment concentration after a heavy erosion event. This filling procedure is repeated until, after deposition of all the layers, a bed thickness of $\pm 8 \text{ cm}$ is reached. For each layer the same amount of mass (same initial density and volume) is added. Exactly the same is done in a 0.1 m diameter perspex settling column of the same height. In the column the layer thickness can be read and density profiles can be measured using a gamma-densimeter. In this way both measurements are done without destruction of the sediment bed in the flume. Details on the experimental procedures can be found in Torfs (1994).

After the formation of the bed, the erosion experiment can start. The discharge in the flume is stepwise increased until the start of the erosion process is observed. The water levels upstream and downstream of the measuring section (sediment bed), the discharge and the cumulative weight of the bed load in the sediment trap are recorded continuously. At 15 minute time intervals samples of the suspended load are taken upstream and downstream of the sediment bed. With these data erosion rates and bed shear stresses can be calculated (Torfs 1994).

The sediments used in the experiments are mixtures of natural mud, dredged from the Scheldt river near Antwerp, and a uniform fine sand. In some preliminary tests, however, kaolinite and a montmorillonite pottery clay were used as cohesive fraction. Two types of natural Scheldt mud are used. Mud2 is a subtidal mud, with a sand content of about 15 %. Mud3 comes from an intertidal flat, the sand content was much higher, about 38 %. Mud3 was heavily contaminated with oil. Table 1 gives an overview of the mixtures used in the experiments.

Table 1: Used mud/sand mixtures.

Name of the mixture	Sand content	Initial density (kg/m ³)	Number of layers	Mud type
J1	24.6	1006	4	Mud2
J2	18.1	1005	3	Mud2
J3	20.7	1005	3	Mud2
J4	26.6	1005	3	Mud2
J5	28.7	1005	3	Mud2
J6	40.8	1006	5	Mud3
J7	46.2	1006	5	Mud3
J8	53.1	1006	5	Mud3

Measured Density Profiles

The different layers in the bed can be visually observed and measured in the transparent settling column. The stratification is also present in the density profiles measured using the gamma-densimeter. Fig. 1 is a typical example of a density profile for experiment J5. The profile shows density peaks indicating the layer interfaces. Part of the sand seems to be accumulated at the bottom of each layer and some of that sand probably intruded in the previous layer. In any case the peaks show that in the small time in between two inputs, the previous layer (with low densities at the top) already developed enough structural strength to carry the next denser layer. The presence of a high density sand layer depends on different factors (Toorman et al 1993 and Williamson et al 1992): the percentage of sand in the mixture (a slurry can only contain a certain amount of sand within its matrix), the density of the mixture (for higher initial densities hindered settling occurs preventing the sand of falling through the mud), the type of cohesive sediment and the supply rate. Another example of a measured density profile is presented in Fig. 2 for experiment J6, using Mud3. Also in this case the layered bed structure is clear.

Looking at the shape of the measured density profiles, there is a clear difference between the experiments with Mud2 (Fig. 1) and the experiments with Mud3 (Fig. 2). In both sets of density profiles some sort of segregation is visible. The density profiles from Mud2 mixtures however show a pronounced high density peak at the bottom of each layer and then a fairly uniform zone of constant density (around 1.06 kg/dm³). At the top of each layer some sort of low density peak can be seen as well. A similar feature

has been reported by Edge et al (1989). For Mud3 the density is decreasing throughout the whole layer. This could indicate that in this case sand is also withheld within the mud matrix and that there is a smooth evolution of sand content over the layer thickness. Mud3 already contained a high sand content, it could be that this sand is held within the mud and that only the additional sand falls through. Mud2 has a low natural sand content and here more (all?) sand falls through. Williamson et al (1992) showed that segregation increased with increasing sand content. They found for their experiments a sand content of about 47 % as maximum limit of sand held within the matrix. Above the limit segregation occurs. In the experiments of Huysentruyt (1994) on Mud2 the segregation limit was less than 10 % sand added (i.e. about 25 % total sand content). This agrees well with these tests: the sand content in the Mud2 mixtures was around 25 % and always segregation occurred.

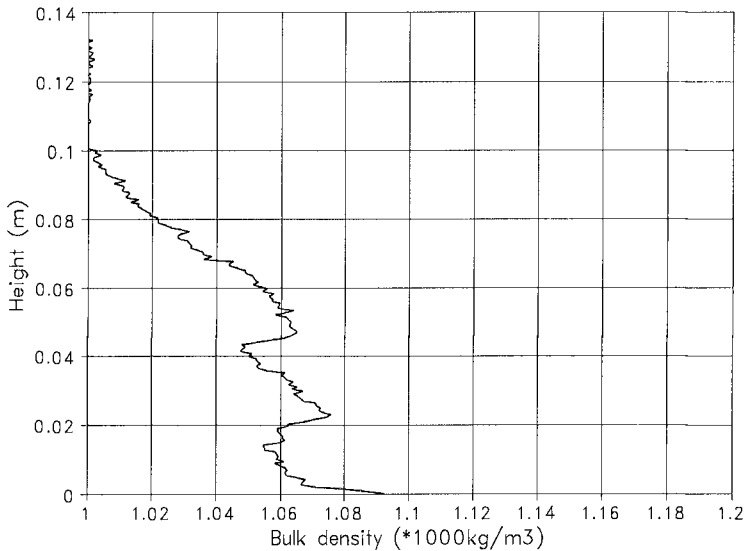


Fig. 1: Density profile for experiment J5.

A comparison of all the density profiles shows higher peak densities in the case of Mud3 mixtures. For those mixtures the density in a layer varies between 1.08 and 1.14 kg/dm³. For Mud2 (with a lower sand content) the density in a layer goes from 1.05 to 1.12 kg/dm³. Williamson et al (1992) stated that an increase in the sand content leads not only to a higher segregation but also to a greater and faster consolidation and thus to higher densities. The higher permeability of the sand layer enhances the drainage of the pore water.

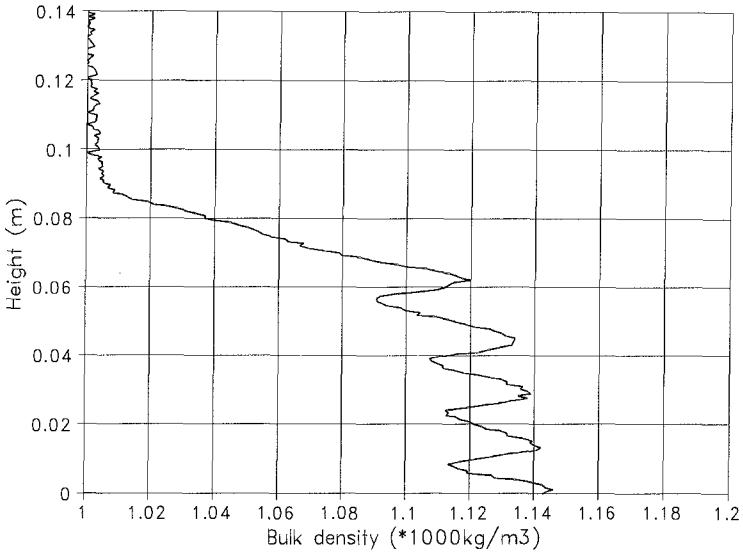


Fig. 2: Density profile for experiment J6.

Also the layer thickness is influenced by the sand content of the sediment mixture. Fig. 3 gives the average layer thickness for each experiment, including the preliminary tests, as a function of sand content. A general decreasing trend over all experiments is visible. But also the type of sediments can be partly responsible for that. If only the data for Mud2 are considered, a decrease of layer thickness with increasing sand content is noticed but the decrease seems to be much less pronounced. An extensive set of consolidation experiments with amongst others Mud2 by Huysentruyt (1994) showed that the settling behaviour is only affected by the addition of sand up to a certain maximum percentage of sand added. In the case of Mud2 an addition of 10 % and more sand does not change the settling behaviour any more. Segregation takes place and the thickness and density peak of the bottom layer remain the same. An addition of 10 % sand means a total sand content of about 25 %, the results of Fig. 3 again confirm this limit.

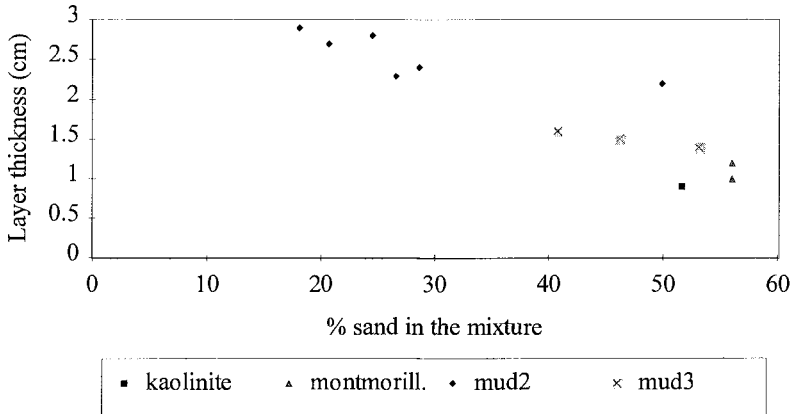


Fig. 3: Mean layer thickness as a function of sand content.

Results of the Erosion Experiments

Fig. 4 gives an overview of an erosion experiment. The discharge in the flume is slowly increased, step by step. During the first step a thin film (only fine material) is lifted of the bed surface and goes into suspension. On the surface longitudinal fine lines appear. Increasing the discharge (step 2, Fig. 4), the erosion of the first layer (mainly mud) starts. The suspension concentration increases suddenly (suspended load downstream minus suspended load upstream = eroded material). At the beginning of this step, no bed load erosion occurs (slope of cumulated bed load in Fig. 4 is zero). After a while, the mud erosion decreases. Two different factors can cause this decrease. Due to the increasing bed density with depth, also the erosion resistance of the surface material increases during the erosion. Depending on the magnitude of the applied bed shear stress as compared to the erosion resistance, the erosion can eventually stop. Another possibility is that a sand layer is reached. That is the explanation in this case. The sediments in this layer are transported mainly as bed load. Hence, the slope of the curve of the measured bed load increases, whereas the difference between suspended load concentrations measured upstream and downstream decreases. Also the formation of sand ripples on the bed can be observed. These bed forms move towards the downstream end of the flume. Increasing the discharge (step 3, Fig. 4) increases the bed load transport of the sand until all the bed forms reach the downstream reservoir. Meanwhile at the upstream end of the sediment bed, the next mud layer becomes available and goes into suspension. The bed load decreases... For all experiments on layered sediment beds a similar sequence of suspended load and bed load transport is encountered, indicating a layer by layer erosion of the bed.

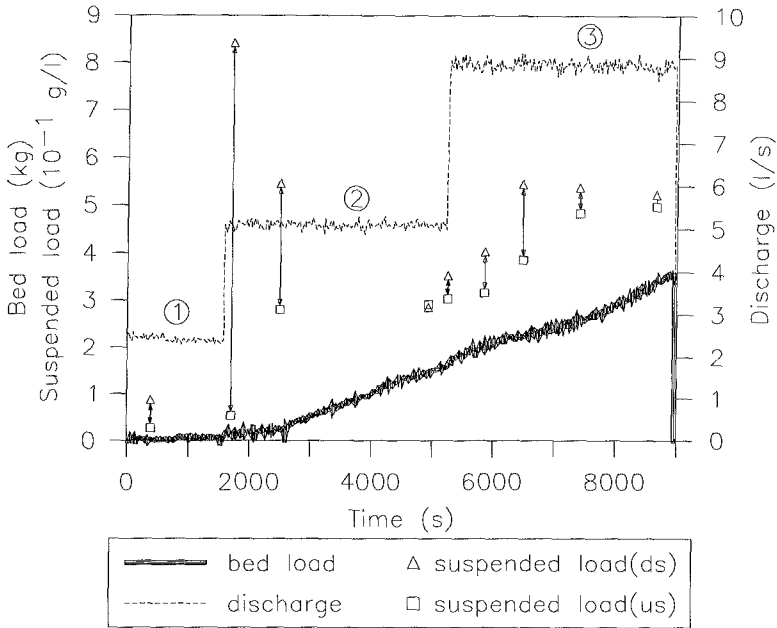


Fig. 4: Overview of an erosion experiment.
(us = upstream, ds = downstream)

Although the bed densities are very low, between 1.06 and 1.15 kg/dm³, the experiments learned that the sediment bed has a significant erosion resistance. It is not clear if this is partly caused by the presence of sand in the matrix. Using an empirical formula (Eq. 1) presented by Delo in 1988,

$$\tau_{cr} = 0.0012\rho_d^{1.2} \quad (1)$$

with τ_{cr} the critical shear stress for erosion in Pa and ρ_d representing the dry density in g/l, the calculated critical shear stresses for the surface layer lie between 0.1 and 0.2 Pa.

An important aim of this study was to look at the influence of the sand content on the erosional behaviour. For the determination of the erosion resistance, in general a higher sand content in the mixture means a faster consolidation and hence, higher bed densities that will lead to an increased erosion resistance. Of course also the type of sediment is important. During the erosion process, the presence of an important amount of sand in the sediment bed causes bed load transport. Depending on the amount of sand

in the mixture and the importance of the segregation, the bed load transport can be very significant and therefore, cannot be neglected in transport modelling.

Conclusions

Sediment layering is known in many environments ranging from the tidal reaches of rivers to the deep sea. Energy variations are the main cause for the development of layers. During a period of high energy (flood) sediment is transported either as bed load or suspended load. As the energy level decreases first the coarse and then the finer sediments settle. Laboratory experiments have shown the formation of a layered bed as a function of mud type and sand content. The presence of sand enhances the consolidation, decreases the layer thickness and increases the bed densities.

Erosion of these layered sediment beds leads to a sequence of suspended load and bed load transport phases. The sand content normally increases erosion resistance of the deposited sediment bed by enhancing the consolidation and by increasing the bed density. The presence of a significant amount of sand in the sediment bed increases the importance of the bed load transport in the total erosion and sediment transport process.

Acknowledgment

This work was carried out as part of the G8 Coastal Morphodynamics programme. It was partly funded by the Commission of the European Communities, Directorate General for Science, Research and Development, under contract no. MAS2-CT-92-0027.

References

- Bastin, A. (1974) Regionale sedimentologie en morfologie van de Zuidelijke Noordzee en van het Schelde estuarium. *Phd thesis, Katholieke Univeriteit Leuven, Faculteit der Wetenschappen* (in dutch).
- Delo, E.A. (1988) Estuarine Muds Manual. *Hydraulics Research Wallingford Report No. SR 164*.
- Edge, M.J. and Sills, G.C. (1989) The development of layered sediment beds in the laboratory as an illustration of possible field processes. *Quarterly Journal of Engineering Geology, Vol. 22*, pp. 271-279.
- Huysentruyt, H. (1994) Experiments on consolidation of natural mud. Effect of composition, mixtures with sand and layering. *4th Nearshore and Estuarine Cohesive Sediment Transport Conference INTERCOH'94*, Wallingford (poster session).

Toorman, E.A. and Berlamont, J.E. (1993) Settling and consolidation of mixtures of cohesive and non-cohesive sediments. *Advances in Hydro-Science and Engineering, Vol. 1*, Sam S.Y. Wang (ed.), pp. 606-613.

Torfs H. (1994) Erosion of sand/mud layers in uniform flow. *Progress report 1994*, Mast2 G8M, Project 4: Cohesive Sediments.

Williamson, H.J. (1991) Tidal transport of mud/sand mixtures, Sediment distributions - A literature review. *HR Wallingford, Report SR 286*.

Williamson, H.J. and Ockenden, M.C. (1992) Tidal transport of mud/sand mixtures, laboratory tests. *HR Wallingford, Report SR 257*.