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Transport of sediment mixtures

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Abstract Sediments form mixtures of non-cohesive and cohesive materials in rivers, reservoirs or sewer systems. Both erosion and transport phenomena will differ completely from those observed in cases of "traditional" non-cohesive sediment transport. The erosion and transport of cohesive sediment mixtures is still not completely understood. Laboratory flume tests with artificial mixtures of non-cohesive and cohesive sediments are presented in this paper. Erosion rates are assessed as a function of the percentage of the cohesive binder. Rheology data are linked with erosive behaviour. The influence of a transient flow situation on the transport capacity is being examined for these mixtures.

INTRODUCTION

The erosion of cohesive sediments (<63 μm) has been extensively studied during the last decades because there is a growing environmental concern that small particles are transport vectors for a large number of contaminants (Torfs, 1995). These sediments stick together due to electrochemical forces and bioagglutination. Recently several empirical equations for erosion and transport of cohesive sediments have been developed (Parzonka *et al.*, 1997).

Cohesive sediments show a completely different erosive behaviour from non-cohesive sediments. For this reason they are often studied separately (Parzonka *et al.*, 1997). In natural environments, mixtures of non-cohesive sediments and cohesive sediments are found in estuaries, coastal zones and river systems as well as in combined sewer systems. The interactions between the two fractions are sometimes important, depending on the composition of the mixture. Sediments found in sewer pipes tend to be partially cohesive. In the United Kingdom, sewer sediments are mainly composed of a mixture of gravel (33%), sand (61%) and silt/clay (6%) with a mean organic content of 7%. On top of this layer, a mobile and highly organic layer with finer sediments (55% sand and 45% silt/clay) is usually found. In the Zwalm, a small catchment basin in Flanders, river bed material ranges from fine sand (D_{50} = 300 μm) to silt/mud material (D_{50} = 40 μm) and the mean grain size of the suspended material is given as D_{50} = 25 μm with a mean organic content of about 4% (Huygens *et al.*, 1998).

The objective of this study is to investigate the erosional behaviour of sediment mixtures. The results of flume erosion studies and rheological tests are compared. This study further aims to assess the influence of an unsteady flow regime on the erosion and transport behaviour of mixtures of non-cohesive and cohesive material.

MEASURING EQUIPMENT AND METHODS

Erosion experiments were conducted in an 11 m long tilting flume that is integrated in a closed circuit system. The tilting flume has a semicircular cross-section with an internal diameter of 0.39 m. The roughness coefficient (K_w) of the flume wall, which is covered with abrasive paper, was determined as 0.40 mm. The bed slope of the tilting flume is fixed at 0.3%. Measurements were made in the central section (4 m).

An EM flux meter was fitted onto a horizontal tube between the buffer reservoir and the tilting flume. Two pressure transducers were used to measure upstream and downstream water levels. An accurate and reliable discharge control is achieved because of electronic adjustment of the opening angle of a butterfly valve. This valve is located in a horizontal tube next to the discharge meter.

A load cell with an accuracy of ±35 g records the accumulated weight of a sediment trap that is situated at the end of the measuring section. Material that enters this trap is considered bedload while sediment remaining in the flow forms the suspended load. Suspension transport is measured using an infrared Partech 15 transmission sensor and a Staiger Mohilo backscatter sensor, both of which are positioned inside the sediment trap to ensure a minimal flow obstruction. Sensor response depends essentially on the surface area of particles where the larger surface area of samples composed of smaller particles generates greater sensor sensitivity (De Sutter *et al.*, 1999b). A sediment sampling system was constructed for the experiments in unsteady flow. This sampling array was placed directly downstream of the sediment trap, thus allowing to pump five samples simultaneously on different levels over the central water column.

The sieve analysis of the respective components of the partly cohesive mixtures is given in Fig. 1. The size distribution of the non-cohesive sands was determined via a Tyler RO-Tap sieve. A Malvern Mastersizer S particle size analyser was used to measure the size distribution of suspended kaolin clay samples via laser diffraction analysis. A TA Instruments Ltd CSL² 500 plate-to-plate rheometer with temperature control was used to study the rheological behaviour of mixtures of non-cohesive and cohesive material.

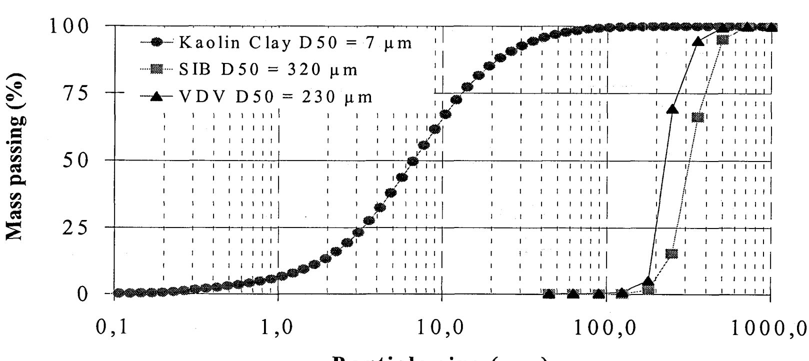

Fig. 1 Sieve distributions of non-cohesive sand and cohesive clay.

RESULTS AND DISCUSSION

Critical bed shear stress (τ_{bcr})

The critical bed shear stress τ_{bcr}, which is a main indicator for erosion resistance, is expressed as a function of the cohesion of the sediment mixture. Previous attempts to relate τ_{bcr} to one or more physical parameters (e.g. grain size, water content, density) were not very successful (Torfs *et al.*, 1994).

Different approaches are used in the literature to define the conditions for incipient motion. All sediments must be in motion over the entire length of the bed, including small and larger diameter particles (Lavelle & Mofjeld, 1987). Visual observation was used for sediment entrainment (Tito, 1995). It is also possible to determine τ_{bcr} as the bed shear stress, τ_b, related to the moment when a significant increase in suspension transport (whatever method is used to determine this) is remarked. However, in this paper the following procedure is used. At one particular flow rate, there is no erosion: the load cell indicates a constant weight of the sediment trap and the turbidity sensors record no suspension. At the next step, with slightly increased discharge, there is erosion, either consisting of sediment falling in the trap or of suspension transport detected by the sensors. The critical stage is defined as the one in between both stages and τ_{bcr} is defined as the average of both τ_b values. By using this procedure, the values of τ_{bcr} are determined in flume erosion tests for mixtures of two types of sand (VDV and SIB) and 10, 20, 30 and 40% clay (Table 1). Each test was performed twice.

The maximum difference between the τ_{bcr} values of two tests for one mixture is 0.14 N m^{-2}. For a particular percentage of clay, there was no significant difference between τ_{bcr} for a mixture with VDV sand and τ_{bcr} for a mixture with SIB sand. In the literature, the particle size of the sand has been shown to have only limited influence on the τ_{bcr} of cohesive mixtures (Skipworth, 1996; Trask, 1959). The maximum values for τ_{bcr} are obtained for mixtures with 20 or 30% clay. Adding more clay does not further increase the strength of the bed, which suggests that the strongest matrix of fine sand and clay is formed for a mass ratio of 75/25. A similar behaviour of τ_{bcr} with varying percentages of clay was observed for erosion tests on mixtures of sand and Laponite clay (Alvarez-Hernandez, 1990).

Table 1 Critical bed shear stress values.

Mixture	τ_{bcr} (N m^{-2})*	Ave. τ_{bcr} (N m^{-2})	Density (g cm^3)
VDV 10%	1.28, 1.40	1.36	1.86
VDV 20%	1.98, 1.92	1.95	1.92
VDV 30%	1.74, 1.88	1.80	1.88
VDV 40%	1.73	1.73	1.97
SIB 10%	1.35, 1.42	1.38	1.90
SIB 20%	1.79, 1.92	1.85	1.91
SIB 30%	1.95, 1.95	1.95	1.95
SIB 40%	1.78	1.78	1.88

* τ_{bcr} measured for the two tests that were performed for each mixture composition.

Experimental data on mono-sized sediments suggest that erosion rates are a very strong decreasing function of bulk density for the finer cohesive particles and that they are essentially independent of bulk density for the larger non-cohesive sediments (Lick, 1999). Table 1 shows there is no relationship between τ_{bcr} and the bulk density of mixtures of non-cohesive and cohesive sediments. A lack of relationship between both parameters was also found during erosion tests on similar mixtures in a rectangular flume (De Sutter *et al*, 1999a; Torfs, 1995). Few studies have been conducted to relate the yield stress obtained in rheology experiments to τ_{bcr} from flume experiments (Migniot, 1989). Therefore, the rheological behaviour of sand/clay mixtures was tested using a plate-to-plate rheometer. Figure 2 gives an overview of the sand/clay ratio and of the water content of the different samples, which were chosen in such a way as to avoid rapid settling or fracture problems (Coussot, 1997). The minimal shear stress, corresponding to the lowest shear rate ($<0.003\ 1\ s^{-1}$) observed during stress controlled experiments, is considered to be the yield stress. Figure 3 clearly shows the influence of water content and clay content on the yield stress value *YS* (Coussot, 1997; Trask, 1959). This results in the following equation:

$$YS = 23042\exp(-0.409W)\exp(0.123C) \tag{1}$$

where *YS* is yield stress, *W* is water content, and *C* is clay content.

The increase in clay content, up to 50%, causes an increase in yield stress, which is contrary to the influence of clay content on τ_{bcr}. The relationship between yield stress and τ_{bcr}, as suggested by Migniot (1989), does not seem to give any quanti-

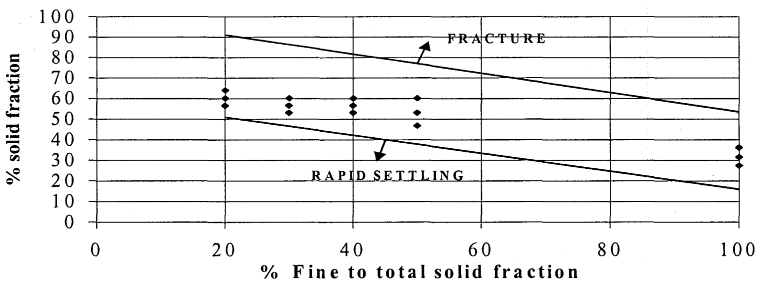

Fig. 2 Overview of rheology experiments.

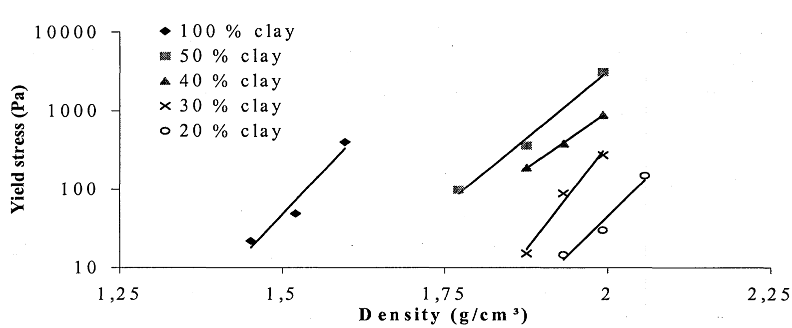

Fig. 3 Influence of sand/clay ratio and water content on yield stress.

tative agreement between the calculated and the observed τ_{bcr} (Migniot, 1989). Small differences in water content greatly influence the yield stress. Differences in water content of the sediment bed, which might not be determined with the necessary accuracy during the erosion tests, could be a reason for the lack of agreement between results of rheological and erosion experiments.

Shear stress *vs* erosion rate in steady flow

For dense, uniform cohesive beds (bed shear strength constant over the depth), the following equation was proposed to relate shear stress to erosion rate (Mehta *et al.*, 1989; Partheniades, 1965):

$$E(\mathrm{kg\,m^{-2}\,s^{-1}}) = E_m\left(\frac{\tau_b - \tau_{bcr}}{\tau_{bcr}}\right)^{\alpha} \tag{2}$$

where E_m is an erosion constant (kg m^2 s^{-1}) and α is a power coefficient (-) original value = 1.

This equation is used to describe experimental data and relate bed shear stress with either bedload transport (sand) and suspension transport (clay) separately or with the total erosion rate, E. For a particular percentage of clay, no significant difference was found between transport for a mixture with VDV sand and that for a mixture with SIB sand. In this way, data provided by four tests (two types of fine sand; each test repeated) are combined to yield the values for both parameters E_m and α for each percentage of clay (Table 2). The combination of all data yields the following relationship (R^2 = 0.61):

$$E = 2.2\cdot10^{-3}\left(\frac{\tau_b - \tau_{bcr}}{\tau_{bcr}}\right)^{1.477} \tag{3}$$

A better correlation is found using the following expression (R^2 = 0.83):

$$E = 1.1\cdot10^{-3}\left(\tau_b - \tau_{bcr}\right)^{2.65} \tag{4}$$

It is clear that high excess bed shear stress increases the scatter among data because high transport rates cause the hydraulic conditions to change quickly. Figure 4 gives an overview of experimental data, equation (4), as well as a similar formula with different coefficients proposed by Torfs using erosion experiments on similar mixtures in a flume with a rectangular cross-section (Torfs, 1995). The total

Table 2 Erosion rate coefficients.

Mixture	E_m	α	R^2
10% clay	$4.7\cdot10^{-3}$	1.79	0.95
20% clay	$36.1\cdot10^{-3}$	2.96	0.85
30% clay	$39.3\cdot10^{-3}$	3.49	0.91
40% clay	$12.9\cdot10^{-3}$	2.07	0.97

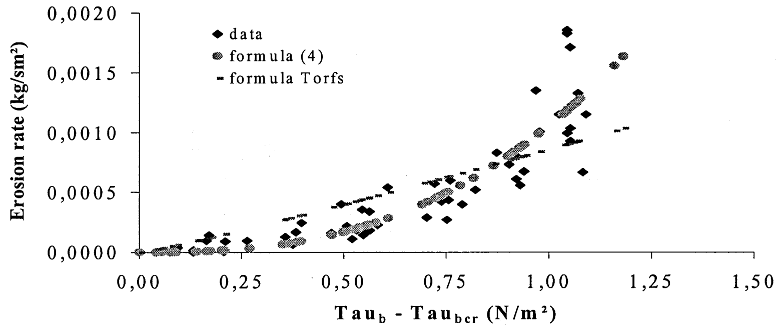

Fig. 4 Relationship between erosion rate and excess bed shear stress.

erosion rate of cohesive mixtures can be predicted with a nondimensional expression of the equation (2) type, which characterizes dense cohesive beds, or with a dimensional expression of the equation (4) type, with the possibility to use a specific formula for each percentage of clay when this parameter is known.

The influence of unsteady hydraulic conditions

The main theories and formulas of sediment dynamics are traditionally based on steady and uniform flows (Wang *et al.*, 1997). Since current sediment transport calculations are found to be in poor agreement with field observations, one might argue to identify non-stationary flow effects as an important distortion factor for traditional transport equations (Plate, 1994).

A first approach in assessing the influence of unsteadiness on sediment transport consists of a comparison of the total recorded suspended load (g) during a triangular hydrograph (rising and falling limb of 80 s) with the calculated suspension transport (using the discharge recorded during the hydrograph and the formula established for steady flow). Table 3 reveals an extra transport capacity induced by the unsteadiness of the flow. Due to the inertia of the coarser bedload material, the difference between calculation and observation is smaller for bedload transport: the influence of the flow is bigger for the finer material (suspended load).

An alternative approach identifies the unsteady flow regime by the suspension transport registrations during a trapezoidal hydrograph (rising limb of 80 s, maximum discharge for 120 s, falling limb of 80 s). The registrations of the turbidity sensor on Fig. 5 reveal a maximum concentration of suspended material when

Table 3 Comparison of suspended load (g) in steady flow and in unsteady flow conditions.

Mixtures	Steady flow: Calculation	Unsteady flow: VDV–clay	SIB–clay
10% clay	90	151	111
20% clay	61	195	143
30% clay	86	237	181

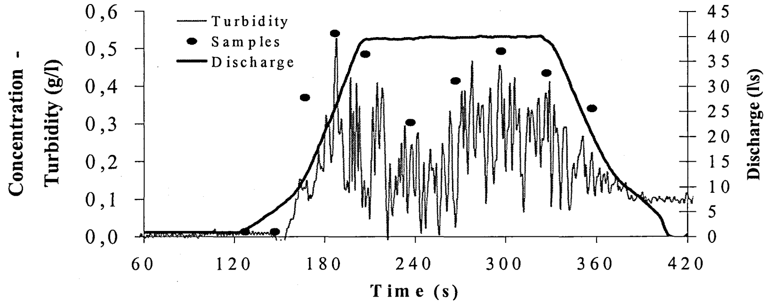

Fig. 5 Influence of unsteady flow regime on suspended load registrations.

maximum discharge is reached, but they also show a sudden concentration drop while maximum discharge is maintained. These turbidity registrations were confirmed by collecting samples. This "rise and fall" phenomenon of the concentration is also established during erosion tests in unsteady flow with non-cohesive material (De Sutter *et al.*, 1998). A reasonable explanation would be that the unsteady flow during the rising limb of the hydrograph calls for more than the transport capacity of the sediment in steady flow conditions. It is for this reason that the sediment bed cannot immediately provide the transport that corresponds to the maximum discharge when the flow conditions return to steady state (maintaining maximum discharge).

CONCLUSIONS

Flume erosion tests in steady flow conditions with artificial mixtures of non-cohesive and cohesive sediments are presented. There is a positive relationship between clay content and critical bed shear stress up to 20% clay. For higher values of clay content, the critical bed shear stress does not augment any more. A formula that relates erosion rate of sediment mixtures with excess shear stress is proposed. The comparison between rheological tests (yield stress) and flume erosion tests (critical bed shear stress) gives a disagreement. A first attempt is made to evaluate the influence of an unsteady flow regime on the transport capacity of these cohesive mixtures. In this way, the foundation is laid to tackle the erosive behaviour of natural cohesive mixtures under ambient flow conditions.

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