Some fundamental particularities on partly cohesive sediment transport in a circular test flume

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Abstract

The complex sediment transport phenomena in narrow sewer pipes are studied in a physical scale model. Since sewer deposits contain not only sand but also cohesive mud particles, the partly cohesive material will act differently than the traditional non-cohesive sediments. In recent literature, only a few studies on partly cohesive sediments have been presented. Therefore, a fundamental investigation on the erosional behaviour is set up. The major aim of the experiments is to point out essential similarities and differences in the particular behaviour of these sediments in a circular cross-section, in relation to the well-established non-cohesive sediment transport approach.

1 Introduction

The combined sewer systems collecting domestic and industrial waste waters are one of the major sources of pollution of urban environment. Research in situ reveals that sediments in sewers, mostly composed of a great proportion of sand mixed with a small amount of cohesive matter, tend to be partially cohesive. When the transport capacity is insufficient to carry sediments continuously, especially during long dry weather periods, deposits in sewers occur. By a new event of rainfall, these deposited bed materials are eroded resulting in high pollution of receiving bodies.

Since sediment movement in (narrow) circular sewer pipes differs in many ways from the usual transport phenomena in natural large rivers, experimental study on the specific behaviour of these mixtures of cohesive and non-cohesive sediments allows a basic understanding of the complex erosion processes in sewers. Therefore well-known non cohesive sediment transport experiments are used as a starting reference point for a further research of the partly cohesive material.

2 Experimental set-up

In the Hydraulics Laboratory of Gent, experiments are carried out in a straight semi-cylindrical flume with a recirculating water system. The flume, divided in four parts (an inflow region (4.60 m), a movable bed zone (4 m), a sediment trap (0.70 m) and an outflow region (1.85 m)), has a total length of 11.2 m and an inner diameter of 390 mm, covered with a sand paper whose wall roughness is evaluated to $k_w = 0.54$ mm.

All experimental tests in the sewer model are executed with sediment mixtures of four basic materials : two non-cohesive materials (a fine white sand of Mol and a medium beach sand of Knokke) and two cohesive materials (China clay (kaolinite) and pottery clay (montmorillonite). Partly cohesive sediments are modelled by mixing water, sand and a powder clay in a varying proportion. A general overview of the characteristic experimental conditions is given in table 1 below. The average wet bulk density is about 1800 kg/m^3 for all sediment mixtures.

	PURE SANDS		PARTLY COHESIVE SEDIMENT MIXTURES					
	White sand	Beach sand	White sand Pottery clay	White sand China clay		Beach sand China clay		Beach sand Pottery clay
Number of tests	10	9	14	22	7	8	6	5
Range of % clay	0	0	5 - 30	5 - 50	10 - 30	10 - 50	10 - 30	5 -20
Range of d_{50} (mm)	0.171	0.293	0.168-0.148	0.168-0.025	0.164-0.148	0.275-0.025	0.275-0.230	0.285-0.254
Range of slope (%)	0.07-1.01	0.07-1.01	0.13-0.25	0.25-0.35	0.01-0.78	0.35	0.35-0.66	0.13
Rel. bed thickness	0.10-0.21	0.10-0.21	0.10	0.10	0.10	0.10	0.10	0.10
Consolidation time (hours)	16	16	16	16	66-234	16	66-234	16

Table 1. General overview of the experiments.

During the complete testrun, an electromagnetic flow meter, a differential pressure transmitter in combination with a Pitot tube, a built-in turbidity sensor, a load cell connected to the sediment trap and water level gauges registrate all hydraulic and transport parameters of interest.

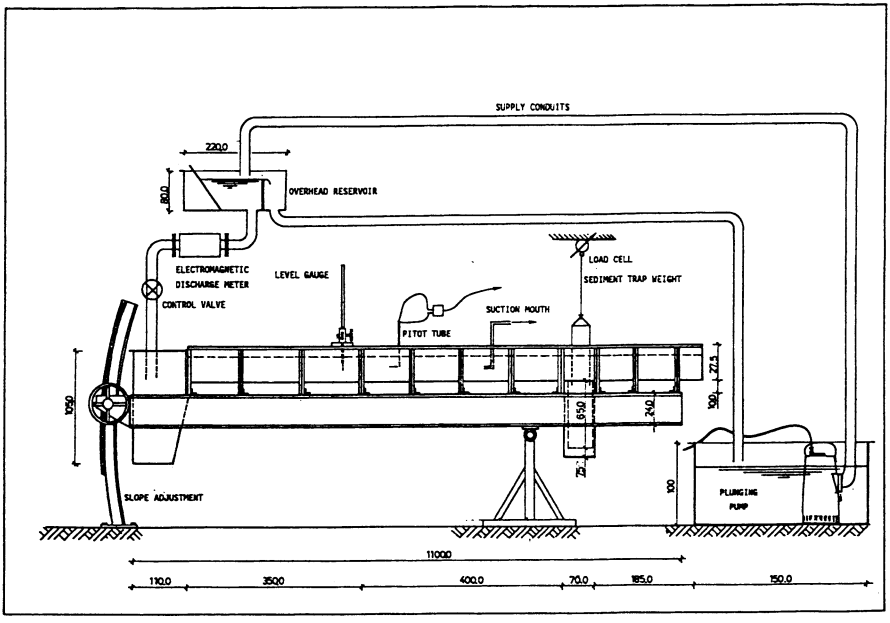


Fig. 1. Experimental set-up. Circular flume.

3 Bed shear stress and secondary currents

As the bed shear stress appears to be one of the fundamental parameters used in the definition of the erosion criteria, the quantification of the bedforms and the sediment transport, it is necessary to find an appropriate technique which gives a good estimation of this bed shear stress. Due to the narrowness of the cross section, the bed shear stress is commonly calculated using the side-wall elimination technique based on the well known Einstein hypothesis of the ponderable wetted perimeter. It appears that the Vanoni-Brooks and the alternative Kleijwegt techniques (Kleijwegt [2]) give more tight relationships with the measured bed shear stress from the registered velocity profile on a flat bed (Huygens et al. [5]). The traditional Einstein side wall elimination method generally overestimates the bed shear stress.

Due to the secondary currents generated by the turbulent flow and the geometry of the flume, the measured bed shear stresses are observed to vary in the transverse direction. As a result of the strong side wall interactions, typical local dune wings and deep holes at the intersection of sediment bed and flume walls are observed during the experiments. The side wall interaction and the

non-uniform shear distribution along the bed result in extra transport capacity in the circular sewer. As shown in figure 2 local maximum shear stresses occur at the points where the isovels bulge significantly toward the bottom (z = 11 cm) while local minimum shear stresses occur at the points where the isovels move away from the bottom (z = 0 cm).

These observations confirm the general findings from literature indicating the local maximum and minimum shear stresses to be produced by downflow and upflow secondary currents respectively (Tominaga et al. [4]). Due to this secondary order phenomena, at first sight cohesive sediments don't react as one should expect in the circular flume. Secondary currents introduce specific actions and transport developments in the narrow, circular test flume.

In all model tests, a gradual erosion process is noticed. Non-cohesive sediments move individually along the bottom while some flocculation of grains occurs with partly cohesive sediments. The sediment character as well as the sectional flume shape determine the resulting transport capacity. For low clay fractions (< 15 %), similar dune formations (figure 3) as with the non-cohesive

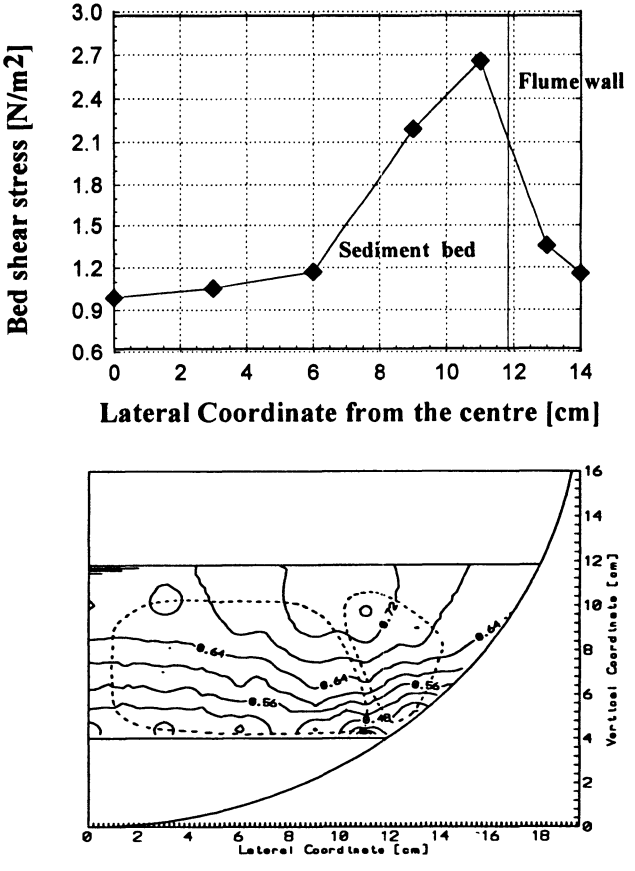


Fig. 2. Bed shear stress and velocity distribution over circular cross-section

sands are registered in the circular test flume. Due to the strong secondary currents generated by the interaction between sediment bed and the flume walls, pronounced erosion spots result in the early mentioned dune wings and local holes, propagating along the flume reach. All experiments with pure sands and mixtures of lower clay contents show a sudden increase of the bed shear stress

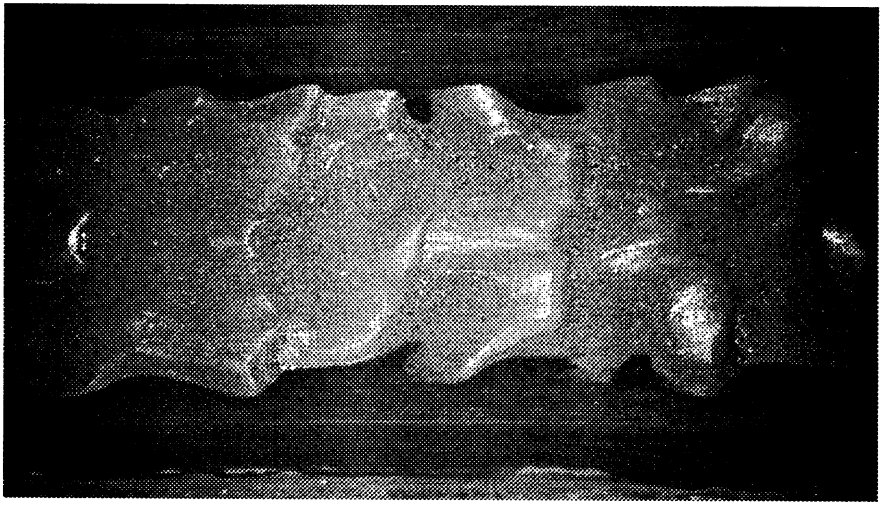


Fig.3. Dune propagation of partly cohesive sediments in circular test flume.

with the development of the typical bed forms. Indeed, with the ripple or dune formation the bed roughness increases and the flow exerts higher bed shear stresses to overcome both grain and form resistance. Further increase of the clay content leads to a more cohesive sediment mixture, characterized by ripples of limited height during transport (Perrusquia [1]).

The critical shear stresses corresponding to the incipient motion of the respective pure sands are comparable with the traditional Shields values. For the fine white sand of Mol, a critical bed shear stress of 0.157 N/m^2 from the Shields diagram can be compared with the experimental figuration of 0.183 N/m^2. The critical bed shear stresses of partly cohesive sediment mixtures vary linearly with the clay contents uptill 30 %. For higher cohesive sediment mixtures, a slight decrease of the critical bed shear similar to Alvarez experimental results [6] is noticed in figure 4. The cohesive clay particles cause a significant increase in the resistance to erosion. The major parameters influencing the critical shear stress-values are the nature and percentage fines of the cohesive fraction. As flow depths in our experimental set-up are always smaller than half the pipe diameter, channel shape effects on critical conditions can be neglected.

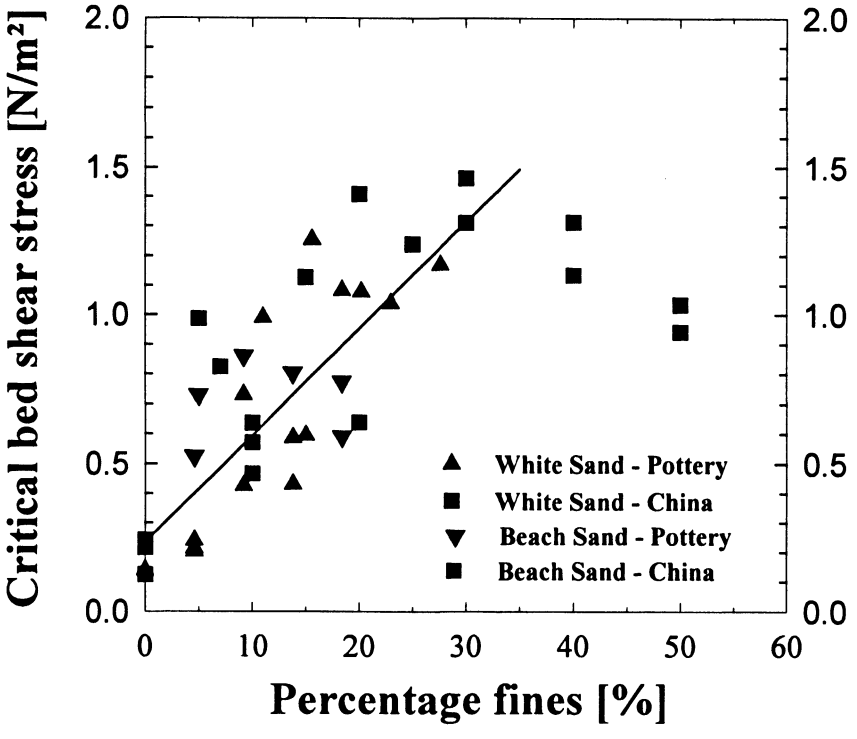


Fig. 4. Critical shear stresses of partly cohesive sediments.

4 Sediment transport

Some well-known formulae (Einstein, Peter-Meyer and Müller, Ackers-White, Van Rijn), found succesful for non-cohesive sediment transport calculations in rivers, seem to overestimate the partly cohesive sediment transport in the narrow, circular flume (Tito et al [3]). On one hand, the cohesive fraction of the sediment material reduces the transport capacity of the mixture; while on the other hand the side wall interaction in the narrow circular cross-section introduces extra (lateral) transport capacity. Therefore, a more particular approach will lead to a general figuration tool for sediment mixtures. Using the Buckingham Π-theorem, several dimensionless parameters can be selected. Various combinations are tried to optimize the transport calculations. Appropriate results are found using a multiple regression with at least three independent variables of suitable significance. The transport of both non-cohesive and partly cohesive sediments is found to be related to the dimensionless bed shear stress θ_b, the dimensionless Chézy coefficient C_{b*} and the dimensionless unit stream power US_f/u_{*cr} (Yang [7]), where u_{*cr} is the critical shear velocity obtained from Shields diagram for pure sands while it is varying with clay content for partly cohesive sediments. The bed load transport of pure sands, as the only transport regime for the non-cohesive bottom material is expressed as:

$$\phi_b = 0.089\ \theta_b^{2.11}\ C_{b*}^{2.10} \left(\frac{US_f}{u_{*cr}} \right)^{0.84} \qquad (r^2 = 0.761)$$

where $\theta_b = \dfrac{\tau_b}{g\ (\rho_s - \rho)\ d_{50}}$ = dimensionless bed shear stress = bed mobility parameter

$C_{b*} = \dfrac{C_b}{\sqrt{g}}$ = dimensionless Chézy coefficient

U = mean flow velocity

S_f = energy slope

The total transport (as a sum of bed load and suspension fraction) of partly cohesive mixtures is given by (figure 5) :

$$\phi_t = 0.002\ \theta_b^{1.67}\ C_{b*}^{0.95} \left(\frac{US_f}{u_{*cr}} \right)^{-0.81} \qquad (r^2 = 0.725)$$

The transport parameter ϕ_t is related to the effective transport in the flume by the following expression :

$$\phi_t = \frac{g_t}{\rho_s \sqrt{g\ (s - 1)\ d_{50}^3}}$$ where g_t = transport per unit width [g/s/m]

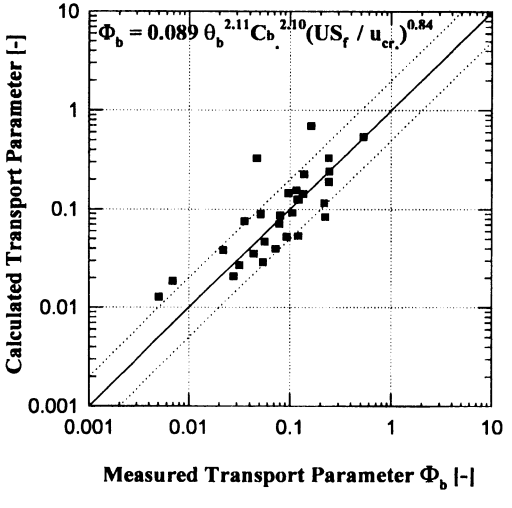


Fig. 5. Bed load transport of non-cohesive sands.

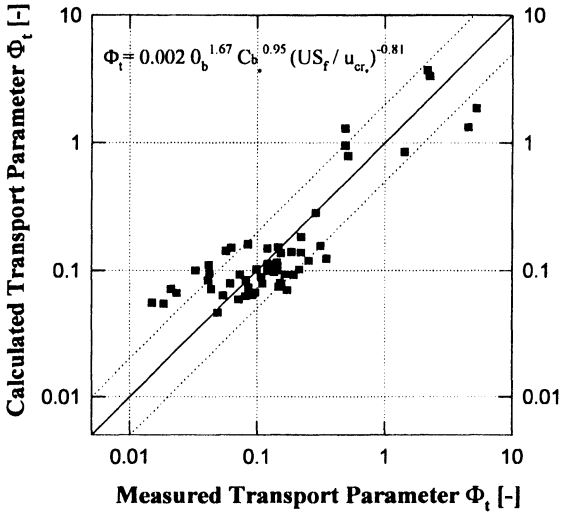


Fig. 6. Total transport of partly cohesive mixutres.

Hence, a common expression for the sediment transport in the circular model sewer with adapted parameters is developed for both sediment types. The visual similarity in transport behaviour is expressed in a general transport formulation for all sewer deposits. A preliminar distinction in cohesive and non-cohesive sediments, based on any artificial (visual) description is no longer necessary to figure the transport rate. The largest scatter in the calculations is observed near the critical situation where the sediment trap shows a great time delay in its registrations and for steep slope conditions (S = 1.01 %) where a non-uniform flow regime is established. By interpreting these multiple regression results, the specific form and dimensions of the experimental set-up of the circular test flume must be kept in mind since shape effects and side wall interaction play an important role in the transport process.

5 Impact of consolidation

The influence of consolidation of sediment mixtures is qualitatively identified in an extra series of experiments. While the normal deposits in the model sewer are consolidated during 16 hours, supplementary tests with sediments consolidated over 3 days (± 66 hours), respectively 10 days (± 235 hours) reveal some specific transport characteristics. During the consolidation process, a scaly surface peeling is formed above the settled sediment layer. After an initial wash-out of this fine surface layer (suspension transport), the underlying dense sediment bed becomes more resistive with the consolidation time; leading to a general increase in the critical bed shear stress. This consolidation process also reflects in the sediment transport evolution (Figure 7).

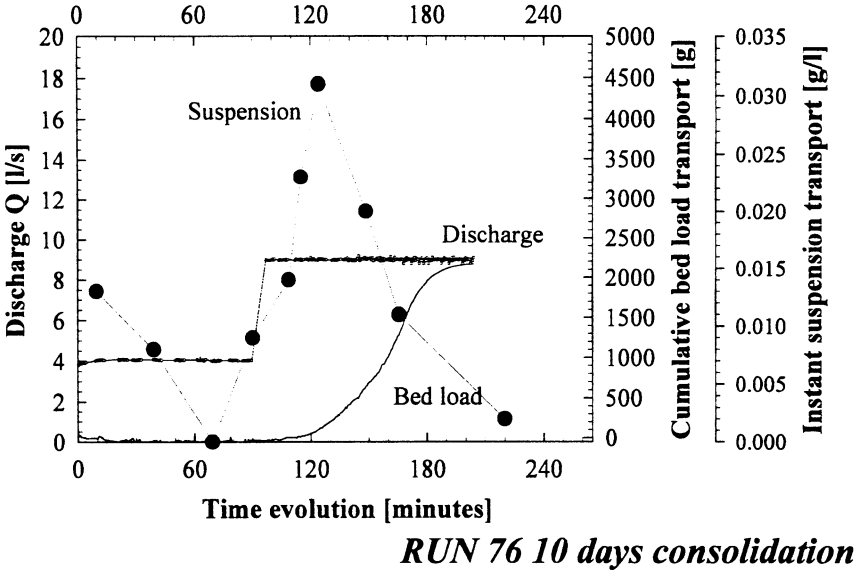


Fig. 7. Transport sequence for a consolidated sediment bed.

An initial mass transport removes the finer, unconsolidated upperlayer; while the dense, settled underlayer resists the constant shear force. A further increase in shear action (second discharge stage) leads to a general transport activity. The less consolidated upper layer of fines again goes in suspension, while the underlying, more consolidated bed is mainly transported as bed load. This bed load transport is characterized by a typical S-curve : after an initial establishment, a fully developped stage is followed by a decrease in transport due to a more consolidated aspect of the remaining sediment bed. For higher clay fractions, the cohesion develops with the consolidation time, leading to a massive sediment bed. The sediment bed is paved during the bed load transport of the underlying more consolidated sediment bed.

6 Conclusion

Laboratory tests in a circular scale model reveal some interesting knowledge on the specific comportment of typical sediment mixtures in sewer systems. The impact of the cohesive fraction on the transport behaviour and the shape of the circular cross section on the shear characteristics is indicated for a wide range of sand-clay mixtures. A general transport calculation, based on a multiple regression analysis, covers all sediment mixtures. A first impression on the impact of consolidation is formulated. Based on these experimental results, some practical suggestions can be formulated for a proper design, operation and maintenance of circular sewers.

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