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MODELLING (PARTLY) COHESIVE SEDIMENT TRANSPORT IN SEWER SYSTEMS

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ABSTRACT

Although the basic mechanisms of sediment transport in sewers are the same as in rivers, it is not necessarily appropriate to use the many models that have been developed for sediment transport in rivers also in sewers. Different reasons are: 1) sewer sediments are often mixtures of cohesive and non cohesive material, and the bed is often stratified; 2) due to consolidation of the (partly cohesive) bed material, the erosion resistance of the bed may vary with time; 3) the flow conditions in sewers are usually unsteady, which is not accounted for in the classical sediment transport models; 4) existing models have been derived from experiments in rectangular flumes: the results are not directly applicable to sewers with circular cross section where the distribution of bed shear stress may be completely different from a rectangular section; 5) the limited availability of erodible material and the varying supply of sediments add additional difficulty to the modelling of sediment transport in sewers. Copyright © 1996 IAWQ. Published by Elsevier Science Ltd.

KEYWORDS

Cohesive sediments; numerical modelling; sediment transport; sewer sediments; shape effects.

INTRODUCTION

The numerical simulation of the hydraulic behaviour of sewers has become common practice since about ten years, both for sewer system design and for trouble shooting in existing systems. Several commercial software packages are widely used, e.g. MOUSE (Danish Hydraulics), SPIDA/HYDROWORKS (Wallingford Software) and SWMM (EXTRAN/HYSTAN) (E.P.A./University of Hannover). The hydraulic parameters (e.g. Manning's n) can be estimated with enough accuracy. For existing systems of course calibration is preferred but not absolutely necessary to obtain approximate but still useful results.

Following the same evolution as in river modelling, recently attempts have been made to model sediment transport and water quality parameters (e.g. BOD/COD, D.O., nutrients, etc.) in sewer systems. In combined sewers (and to a lesser extent also in storm sewers), sediments are usually deposited during dry weather periods (or in periods with limited precipitation) and subsequently (partly) resuspended and conveyed through the system during storm conditions. Predicting sediment deposition and erosion is important from a hydraulic point of view, since sediment deposits affect the hydraulics of the system by reducing the flow area and increasing the flow resistance. Since suspended sediments (SS) and the pollutants attached to them, influence strongly the "quality" of the stormwater discharged from combined sewer overflows (CSO's), the modelling of sediment transport becomes also very important for the prediction of water quality in the receiving waters and for the assessment of the efficiency of different measures to reduce this pollution load.

Although there are many similarities between the sediment transport processes in rivers and sewers, a number of particular problems arise in sewer pipes which make the simulation of sediment transport in sewers an ever trickier business than in rivers.

EXISTING SEDIMENT TRANSPORT MODELS

Many (semi) empirical formulae exist and are being used for the transport of **coarse, sandy sediments** in rivers, i.e. sediments with an average grain size larger than 63 µm. They are derived either from laboratory experiments in straight rectangular flumes or from field measurements. Popular formulae used nowadays can be found e.g. in (Ackers 1991), (Engelund-Hansen, 1967), (Van Rijn, 1984) and (Yang, 1973).

Most of these models require a preliminary assessment of the bed roughness since only part of the hydraulic energy can be used for sediment transport, the other part being dissipated in bed form resistance due to the presence of "bed forms" (ripples and dunes). Both erosion and sedimentation is related to a critical bed shear stress (Shields, 1936)

It has been shown that, without calibration, one may be happy if sediment transport rates can be predicted less than double and more than half the measured values. Relative accuracies have been reported as:

	(Van Rijn, 1984)	(White *et al.*, 1973) and (Yang, 1976)
Ackers-White	77%	64 %
Van Rijn	77%	-
Yang	-	91%
Engelund Hansen	76%	58%

Erosion and sedimentation of **cohesive sediments** are also related to bed shear stress. Cohesive sediments are usually a mixture of clay and non-clay minerals in the silt- (2-63 µm) and clay-size range (< 2 µm); the finest particles are mainly responsible for the cohesion. The critical bed shear stress for erosion of cohesive sediments depends on many properties of both the sediment and the eroding fluid. Erosion rates (E) are calculated with formulae of the type (Parchure *et al.*, 1985, Mehta, 1991):

$$E = C(\tau_b - \tau_s)^n \qquad (1)$$

In which τ_b is the actual shear stress on the bed and τ_s is the bed shear strength or yield stress. C and n are constants.

Although sediments found in sewers are predominantly coarse, extensive studies on "real sewer sediments" over the past 5 to 10 years (Williams *et al.*, 1989, Wotherspoon, 1994, Verbanck *et al.*, 1994) have recognised that combined sewer deposits possess cohesive characteristics, although this cohesion primarily arises from agglutination due to tars and greases, chemical cementation and biological processes in the combined sewer, rather than the classical concepts of electrostatic cohesion which is found in e.g. estuarine sediments. Hence sewer sediments exhibit rheological properties which are similar to those present in cohesive materials, in particular the deposits may have an apparent yield stress τ_s up to 2 Pa.

(Combined) sewer sediments thus very often are **mixtures of cohesive and non-cohesive material**. Field studies have also demonstrated that the sediment bed is often highly **stratified** in density and thus also in strength.

EROSION OF MIXED SEDIMENTS

The erosion of sewer sediments is described as continuous mass erosion by the removal of large pieces of the bed, similar to the turbulent bursting in estuarine environments (Ashley *et al.*, 1992). Surface erosion has only been reported during dry weather conditions, when only the surficial layer of the bed is eroded and a "heavy fluid layer" (Verbanck *et al.*, 1994) or a "fluid sediment" layer (Ashley *et al.*, 1993) is formed. In storm conditions bed shear stresses higher than 4 to 6 Pa lead to the complete erosion of the upper layers (Wotherspoon, 1994).

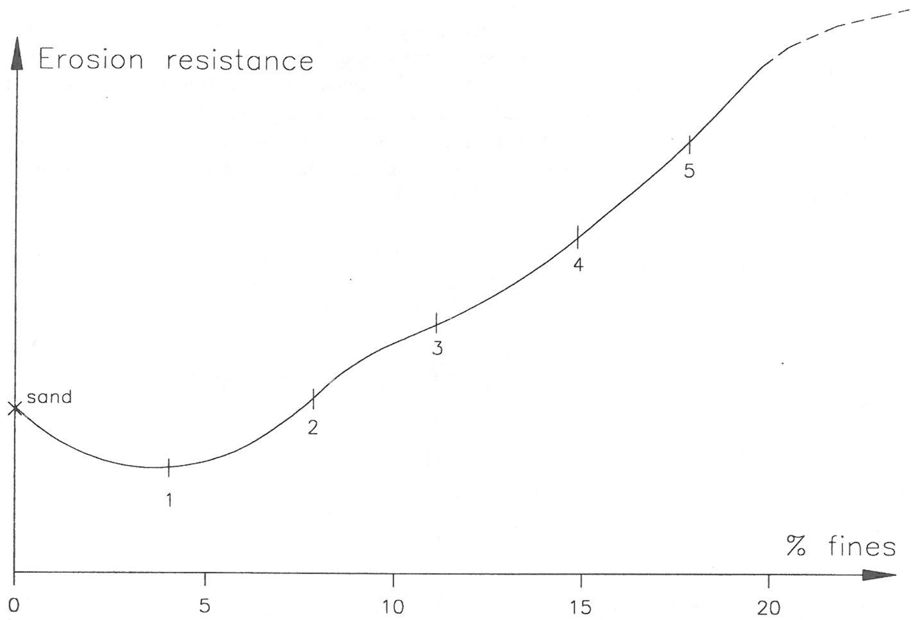

Figure 1. Erosion resistance (e.g. critical shear stress) of partly cohesive sediments as a function of mixture composition expressed as the content of fines, i.e., the amount of material smaller than 63 μm.

Experimental research on the erosion of mixed sediments (Torfs, 1994a, Williamson *et al.*, 1995) showed an increasing erosion resistance with increasing content of cohesive material (Figure 1). When the mixture only contains a very small amount of cohesive material (1, Figure 1) the fines (i.e., the fraction smaller than 63 μm as opposed to the sand fraction with grain sizes larger than 63 μm) are washed out of the surface layer at very low values of the bed shear stress, lower than the critical shear stress needed to move the sand particles. Adding more cohesive material, the fines fill the pore spaces in between the sand grains and make the mixture smoother and thus more difficult to erode (2, Figure 1). At some spots in the mixture the cohesive particles create bridges connecting the sand grains (3, Figure 1). With increasing % fines these bridges, originally only some threads made up of loose flocs, become stronger and stronger bonds and eventually, a cohesive network is formed in the sediment bed (4, 5, Figure 1).

A critical amount of fines exists at which the sand grains loose contact and a cohesive matrix covers the sand particles. This critical content of fines was found to be between 10 and 20% fines by weight or around 5% fines in volumetric concentrations and is a function of the sand grain size, the type of cohesive material, the clay fraction and the organic content. Below this limit, the mixture can be treated as a cohesionless sediment: friction and gravity are the forces opposing particle motion and sediment transport rates can be predicted using existing sand transport formulae. Above the critical content of fines cohesive forces determine the behaviour of the mixture: the erosion resistance is governed by the electrochemical bonds, chemical cementation or biological processes in the sediment and the erosion process can be described as mass or surface erosion, depending on the type of cohesive sediment and the bed density.

To model erosion and sediment transport rates of mixed sediments, the existing formulae for both non-cohesive and cohesive sediments can be applied, since a mixture can be seen as either cohesionless or cohesive for an amount of fines below or above the critical limit. Hence, a numerical model to simulate the erosion of mixtures can be built up of existing formulae for sand and mud erosion, provided the mixture composition of the erodible surface layer is evaluated and its erosion resistance can calculated.

When the sediment bed is formed out of a suspension, segregation can occur during the deposition process, when the initial mud concentration is below the gel point (i.e., the concentration at which the cohesive sediment forms a continuous structure) or when the settling rates are high. When segregation takes place, both the density and the composition of the sediment bed show strong variations with depth (Torfs *et al.*, 1995). This results in changing erosion characteristics (e.g. erosion resistance, mode of erosion) as well. The erosion of a layered bed is a sequence of suspended load phases, during the erosion of a muddy layer, and bed load transport, when a segregated sand layer is reached.

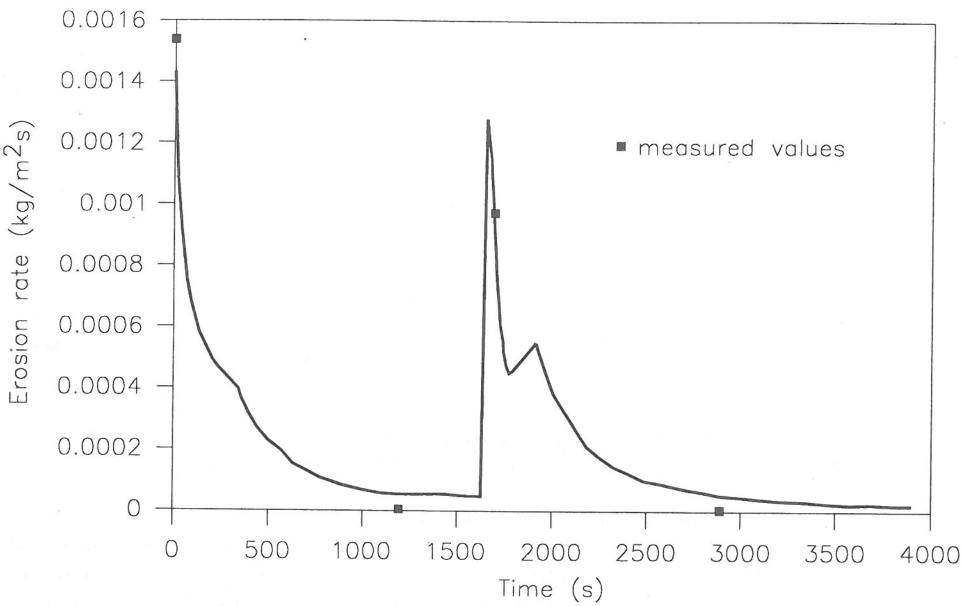

Figure 2. Modelling the erosion rates for a layered mud/sand bed (Dauwe *et al.*, 1995). During the experiment the bed shear stress was increased at 1600s.

Dauwe *et al.* (1995) modelled the results of erosion experiments on layered sand/mud deposits. From the measured density profiles they calculated the shear strength profiles using the following equation (Mehta, 1988).

$$\tau_s(z) = \zeta(\rho_b(z)-1) \qquad (2)$$

with ρ_b the bulk density at depth z and ζ a coefficient, usually close to 1 for pure estuarine muds.

The erosion of the soft top layer (bulk density about 1100 kg/m^3) can be described as surface erosion and can be modelled using equation 3 (Parchure *et al.* 1985).

$$E = E_f \exp\{A[\tau_b-\tau_s(z)]^{1/2}\} \qquad (3)$$

with E_f the floc erosion rate, A a coefficient and τ_b the bed shear stress. The coefficients E_f, a and ζ were adjusted to obtain the best agreement with the experimental results. At each time step the depth of erosion is calculated and hence the characteristics of the surface layer are updated. An example of the results of the modelling exercise is given in figure 2.

Comparison with data for homogeneous mud beds indicated that the coefficient ζ and hence the shear strength increases when sand is added, although the surface layer contains no sand; the passage of the sand through that layer, during the deposition of the bed, has altered its structure and strength.

SPECIFIC PROBLEMS WITH THE PREDICTION OF SEDIMENT TRANSPORT IN SEWERS

Apart from the difficulties arising due to the presence of stratified deposits consisting of mixtures of cohesive and non cohesive material, a number of other factors make the prediction of sediment transport in sewers a risky operation:

Unsteady flow

All sediment transport formulae have been derived from laboratory or field measurements under uniform and (quasi) steady flow conditions. This is most often acceptable in rivers but the hydraulics of sewer systems is always characterised by a strong unsteadiness due to the rainfall and non uniform flow conditions e.g. caused by the presence of transitions or hydraulic structures such as regulators, internal weirs or overflows.

Dimensional analysis (Kabir, 1993, Bestawy *et al.*, 1995) shows that sediment transport in general is a function of the shape and the slope of the hydrograph. Even more important is that the bed forms and consequently the hydraulic resistance and the bed shear stress are strongly dependent of dQ/dt and the sign of dQ/dt! Due to inertia, the variations of the bed forms are lagging behind the variations of the discharge, and dune or ripple heights are usually higher during the falling branch than during the rising branch of the hydrograph. More experimental work is needed to quantify these relations. Until we can introduce properly the effect of flow unsteadiness we will not be able to make correct predictions of sediment transport during storm events.

Variability of sediment supply

Bed load equations predict the transport capacity of the flow, which not necessarily equals the actual sediment transport, it obviously also depends on the sediment supply. This is also true for rivers, but in sewer pipes the sediment "source" is usually much more limited. Erosion can continue as long as the transport capacity is reached or until the complete sediment layer has been removed.

When the sediment bed is a mixture of non-cohesive sediments, "armouring" (Gessler 1965) can occur: the fine fraction is washed out from the surface layer and a relative courser bed layer is obtained, which resist further erosion and protects the underlying finer material.

When the bed is a mixture of cohesive and non-cohesive material, the fine cohesive fraction may be washed out, thereby decreasing the erosion resistance of the remaining sandy sediments, which will be eroded consequently.

Shape effects

Most sediment transport formulae are derived from laboratory tests in rectangular flumes or from field measurements in (relatively wide) rivers, where the shear stress distribution over the bed is relatively uniform. In pipes with a circular or egg-shaped cross section, the shear stress distribution may be much more irregular. That means that the shear stress may locally reach the critical shear stress for erosion for much smaller discharges than the average shear stress.

A comparison of the results of similar erosion tests in flumes with a rectangular and a semi-circular cross section revealed important differences in erosional behaviour (Torfs *et al.*, 1994). These differences are caused by the secondary flow structure, which in turn affects the bed shear stress distribution. The secondary currents are much more important in a circular cross section (Torfs, 1994b) and are responsible for the higher erosion rates compared to the rectangular section. The bed shear stress distribution in the rectangular flume is fairly constant with mostly maximum value near the centre of the flume (Figure 3). In the semi-circular cross section more extreme values can exist depending on flow depth and discharge (Figure 4), and usually an important local maximum near the side walls is found, which explains the strong erosion near the intersection of the sediment bed and the side wall.

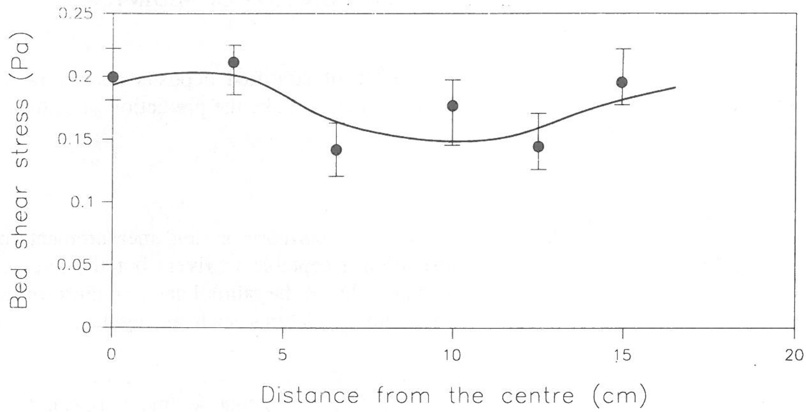

Figure 3. Typical shear stress distribution over the rectangular cross section.

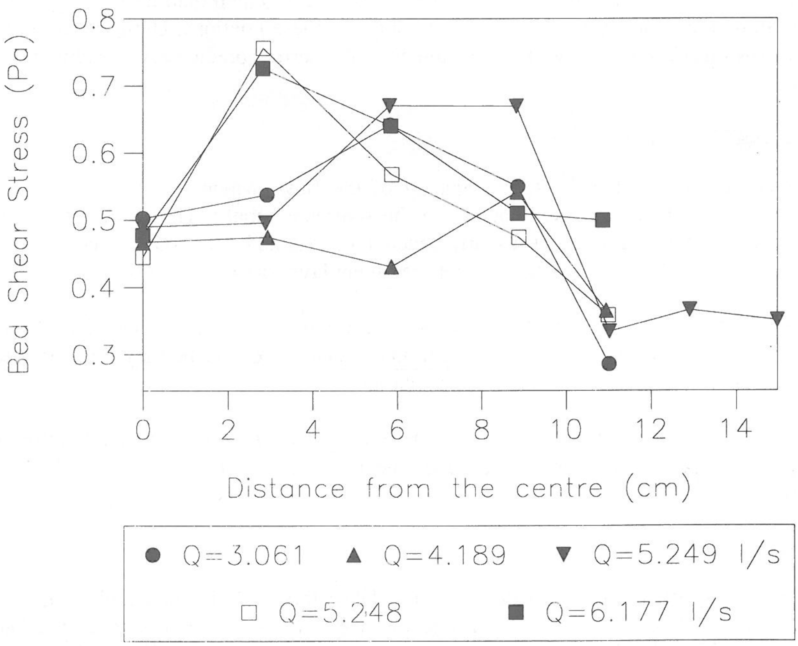

Figure 4. Measured shear stress distributions over a semi-circular cross section.

Furthermore, it was shown that the frequently used side wall elimination calculations overestimate the average bed shear stress for narrow flumes and that these methods calculate in fact the maximum bed shear stress (Torfs, 1994a).

CONCLUSIONS

Although the basic mechanisms of both non cohesive and cohesive sediment transport in sewers are very similar to the mechanisms of sediment transport in rivers, a number of differences exist which makes it difficult to use the well known sediment transport models in rivers in sewer systems. Different reasons are: the presence of mixtures of cohesive and non cohesive material, often in a stratified bed; the strongly pronounced unsteadiness of the flow in sewers, which is not accounted for in the classical sediment transport models, the limited availability of erodible sediments and the varying supply of sediments, and shape effects.

In the absence of calibration, sediment transport predictions in sewers are thus subject to a large degree of uncertainty. More experimental work is needed to clarify these matters.

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