SEDIMENT IN SEWERS: INITIATION OF TRANSPORT

Rob A. Kleijwegt*, Robin G. Veldkamp* and Chandra Nalluri**

*Department of Civil Engineering, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands
**Department of Civil Engineering, University of Newcastle upon Tyne, Cassie Building, Claremont Road, Newcastle upon Tyne, NE1 7RU, UK

ABSTRACT

The initiation of sediment transport in sewers was investigated in field and laboratory studies. From the field studies it was concluded that some deposits in sewers are permanent due to the insufficient capability of the flow to erode the deposits. From the laboratory studies it was concluded that the upper limit of the critical shear stresses for cohesive sewer sediments may not exceed 5-7 N/m². Non-cohesive sediments are eroded at lower shear stresses than predicted by Shields' criterion. The shear stresses were calculated using the general equations of continuity and motion and Einstein's separation technique for channels of compound roughness. Experiments showed the validity of this method.

KEYWORDS

Incipient Motion; Erosion; Sediment transport; Critical shear stress; Sewer sediment; Sewer deposits; Overflow quality;

INTRODUCTION

During storm events the discharge of pollutants in combined sewers is increased by the erosion of sediment deposits with adhered pollutants. Under these circumstances overflows will be highly influenced by the erosion processes in the sewers. In order gain insight into the amounts of pollutants in overflows, the basic processes that are believed to be responsible are studied. This paper shows the results of research studies on sediment transport in combined sewers. Both field and laboratory studies were carried out and more laboratory studies are in progress. The paper starts with the identification of the problem of initiation of sediment transport in sewers and the associated research activities. The field studies are concerned with the initiation of transport, while the laboratory studies deal with the determination of the boundary shear stress, incipient motion for both non-cohesive and cohesive materials and the transport of sediment.

PROBLEM IDENTIFICATION AND RESEARCH ACTIVITIES

The pollution of surface waters is decreasing due to control measures to limit pollutant sources. As a result, the relative contribution of overflows of existing combined sewers as a source of pollution is increased. Although
from a technical point of view overflows can be controlled to any degree, for instance by means of retention basins, it is not always economically feasible. A criterion for the pollution output by overflows is needed in evaluating the operation of the system. The overflow frequency is widely accepted as a criterion, however, this is not necessarily a measure for pollution output.

Little is known about the pollution output of an arbitrary combined sewerage system. Recent field studies [NWRW, 1989a] showed that this complex problem is predominantly determined by the sediment transport in the sewers during a storm event; especially the erosion of sediments deposited during dry-weather flow, which are believed to contain a significant amount of pollutants, is important. This paper focuses on the erosion processes from the practical and theoretical points of view.

As part of the NWRW (National Working group Sewerage systems and Water quality) research programme the Delft University of Technology (TU-Delft) was involved in field studies concerning the presence of sediments in two typical Dutch combined sewer systems. The objective was to gain a better insight into the parameters that may have an effect on sedimentation and resuspension of solids [NWRW, 1989b].

In addition to these field studies and the field studies concerning overflows mentioned before, a laboratory study was initiated at TU-Delft to examine the sediment transport in sewers. Some experiments were carried out in co-operation with the University of Newcastle upon Tyne (U.K.), where similar research funded by the Science and Engineering Research Council (SERC) is in progress.

FIELD STUDIES

One of the aspects of the field study was to investigate the presence of deposits and their relation with other parameters. The field studies were performed in two sewer systems: De Muntel (urban area) and Valburg (rural area). Both system can be considered as hydraulic units. Some characteristic data of the systems are given in Table 1.

<table>
<thead>
<tr>
<th>TABLE 1 Characteristic Data Sewer Systems</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>De Muntel</td>
</tr>
<tr>
<td>Nr. of inhabitants</td>
</tr>
<tr>
<td>Runoff area (ha)</td>
</tr>
<tr>
<td>Runoff area (%)</td>
</tr>
<tr>
<td>Total sewer length (m)</td>
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<tr>
<td>Storage capacity (mm)</td>
</tr>
<tr>
<td>Pump overcapacity (mm/h)</td>
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<tr>
<td>Valburg</td>
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<tr>
<td>Nr. of inhabitants</td>
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<tr>
<td>Runoff area (ha)</td>
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<td>Pump overcapacity (mm/h)</td>
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</tbody>
</table>

During the research programme the following data were collected: water levels at different locations, rainfall, visual observations with video cameras and a range of analyses on sludge deposits. Using the rainfall data as input, the water levels and velocities were calculated with a dynamic computer program and verified against the measured water levels.

In each area sewers were selected to record the quantity of deposits. The selected sewers were subdivided according to their function: laterals, transport sewers, storage sewers, sewers to spillways and sewers to pumping stations.

The sludge deposits were subdivided in 3 categories: light solids such as paper and fibrous material, sludge and sand. The easily transportable light solids were found at several locations. In most cases the sludge was already decomposing. This material, being easily erodible, may probably be the major contribution to surface water pollution. Sand is mainly present in main sewers. Sometimes it was mixed with organic matter, resulting in a cohesive mixture of sand and mineralized organic matter. At different locations in both areas these deposits were found to be permanent.
From statistical analyses it can be seen that the majority of the sewers do not contain much deposits. Some sewers, however, contain deposits in excess of the average. These sewers are selected from the total and presented in Table 2.

<table>
<thead>
<tr>
<th>Function</th>
<th>Total nr.</th>
<th>Excess deposits</th>
<th>Paper</th>
<th>Sludge</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>lateral</td>
<td>11</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>lateral + transport</td>
<td>13</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>transport</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>transport to spillway</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>transport + transport to spillway</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>transport + storage</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>transport to pumping station</td>
<td>4</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Problems with deposits are mainly found in sewers where the transport function is combined with another function. Of the laterals with a transport function 4 of the 13 sewers contained solids in excess, up to 12.5 L/m paper, 18.5 L/m sludge and 34.5 L/m sand, all in 600 mm pipes. The maximum sand content is thus 12.2 % by volume in these sewers. In all transport sewers and sewers to spillways sand was found in excess, up to 24 L/m (700 mm). In all transport + storage sewers deposits of all categories were found in excess, up to 12 L/m paper, 16 L/m sludge and 20 L/m sand, all in 1000 mm pipes. In these sewers the maximum sand content was 2.5 % by volume.

From the results of the computer output some shear stresses were calculated by hand. Water levels at different moments during heavy rainfall were the basis for these calculations. In most cases the shear stresses were far below the values (as found in the laboratory studies) needed for resuspension of cohesive deposits.

LABORATORY STUDIES

Field studies alone are insufficient for understanding the fundamentals of erosion processes. Due to the lack of existing theories laboratory experiments are necessary to study the erosion processes of sediment beds in sewers. Primarily the driving force behind the erosion, the bed shear stress, has to be studied. A method to calculate the bed shear stress, based on the general equations of continuity and motion and Einstein's separation technique, is checked by determining the bed shear stress from velocity measurements. The incipient motion of non-cohesive and cohesive sediment can be analysed using this calculation method.

Experimental-layout

The experiments concerning shear stress determination and incipient motion of non-cohesive sediments were carried out by the first author at the University of Newcastle upon Tyne. The equipment consisted of a circular PVC pipe of 302 mm diameter, 12 m length with a flat sediment bed of 20 mm thickness in the centre. The pipe was divided into three sections: an inflow section (6.0 m), a test section (0.7 m) and an outflow section (5.3 m). The pipe slope varied between 1 and 4.5 per thousand. The water depth varied up to 90% of the pipe diameter.

While doing velocity measurements (with a micro propeller currentmeter), the whole sediment bed was fixed with vaseline. The shear stress was determined by measuring vertical velocity profiles at several points in the transverse direction of the flat sediment bed.

While doing incipient motion experiments the test section was filled with sand only. The discharge was increased step by step, keeping the flow uniform in longitudinal direction, until the sediment was being transported. A sediment trap at the end of the test section caught the transported sediment (figure 1). A similar PVC pipe of 150 mm diameter was used by the third author with both non-cohesive and cohesive sediments.
Determination of shear stress

Calculation method. For rectangular and circular channels with constant roughness the mean boundary shear stress can be determined using the general equations of continuity and motion. Usually the maximum shear stress is determined by multiplying the mean shear stress with an empirical coefficient [Replogle, 1966]. Integration of the three-dimensional basic equations leads to:

- equation of continuity: \[ \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \]

- equation of motion: \[ \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( Q \frac{\partial^2 A}{\partial z^2} \right) + gA \frac{\partial z}{\partial x} + \frac{P r}{\rho} = 0 \]

with A and P as functions of z₁ and z₂.

In steady flow experiments the time-dependent terms in the above equations can be neglected. Using the equations of continuity and motion and the experimental data, the mean shear stress can be calculated. In the analysis of the results, \( \alpha' \) appeared to be less than 1.16 giving a maximum error of 2 % when the shear stress is calculated with \( \alpha' \) equal to unity. Because in most cases the flow is not uniform in the longitudinal direction of the flow (but nearly uniform), the shear stress is not proportional to the bed slope. Therefore the calculated shear stress is taken as proportional to a so called effective slope, which will be used in the following separation technique.

In case of different roughness factors for channel wall (smooth) and bottom (rough), the mean shear stress has to be separated in order to know the shear stresses at the wall and bottom. A well known hypothetical separation technique was developed by Einstein. Yassin [1953] demonstrated the validity of this technique for rectangular channels with different roughness factors for bed and walls. Einstein's separation technique separates the cross-section in parts related to the perimeters with different roughnesses. For uniform flow Einstein assumed velocity and slope to be similar in each part, thus giving (using the Chézy formula \( u = C/(Ri) \)):

\[ i = \frac{u^2}{C^2R} = \text{constant} \]

for each part and with constant velocity:

\[ C^2R = \text{constant} \].
The non-uniform flow can be corrected using the effective slope in stead of the bed slope.

The resistance coefficient and the hydraulic radius of the total cross-section can be determined from the experimental data. Knowing the resistance coefficient of the wall or the bottom the unknown coefficient and hydraulic radii can be determined. Using a wall roughness from literature resulted in a large scatter due to the relatively large influence of small disturbances in the wall surface. The scatter could be reduced with an average value for the bottom roughness which was determined from the measured velocity profiles.

Results. The shear stress at several points on the sediment bed is determined using measured vertical velocity profiles and a formula based on a logarithmic velocity profile:

$$u(z) = u_r 5.75 \log (32z/k_w). \quad (3)$$

The shear stress determination at different positions in the cross-section shows that the bed shear stress differs in the transverse direction. It also shows that the maximum shear stress occurs at different positions. When a maximum is defined as the shear stress somewhere in the cross-section larger than the shear stress in adjacent points, it is possible to have more than one maximum. The experiments show three possibilities: one (in the centre), two (close to the centre on each side) or three maxima (in the centre and close to the walls).

When the results for one bed slope are considered, they show one maximum to exist at smallest depths, three maxima at average depths and two maxima at the highest depths. In case of three maxima it appeared to be dependent on the bed slope whether or not the maxima near the wall exceeded the central maximum. Referring to the studies of turbulence phenomena in trapezoidal and rectangular channels [Knight, 1985] a theoretical explanation may be found by studying this phenomenon. The measurements are not suitable for checking this and the number of experiments was not large enough to deduce an empirical relation for instance between average and maximum shear stress with parameters like bed slope and water depth.

Validity of the calculation method. In figure 2 the calculated shear stresses are compared with the 'measured' bed shear stresses (averaged over the bed). As can be seen some difference exists between the calculated and measured shear stresses, although the points give a straight line relationship with a correlation coefficient of 0.99.

The calculated shear stresses do not represent the mean measured shear stresses. Better results are obtained when the calculated shear stress is compared with the maximum measured shear stress (figure 3). If both shear stresses are set equal, the standard deviation of the difference between the calculated and 'measured' values is 0.12.
Incipient motion

Definition. The critical shear stress for incipient motion has to be a point between motion and no motion. The Shields diagram is widely accepted as a criterion for the incipient motion of uniform non-cohesive sediment on a flat bed.

Shear stresses at the bed surface are subject to random fluctuations in time. Incipient motion will be caused by the occasional peak values of the bed shear stress that can be almost twice the mean value in a rectangular channel and even higher in a circular channel due to the complex flow structure.

Calculating time-averaged shear stresses, it is apparent that incipient motion may occur at low values of the mean shear stress and hence the bedload versus shear stress curve must be very flat for small values of the bedload. So it is practically impossible to decide where to fix the point of incipient motion. Motion of particles for a mean value of the bed shear stress is therefore interpreted as a shear stress above the critical value and no motion means a value below the critical value, thus resulting in a range of critical values.

Critical shear stresses for non-cohesive sediments. Knowledge of the equivalent roughness of Nikuradse of the sediment bed is required to calculate the bed shear stress with Einstein's separation technique. Usually the equivalent roughness of a flat bed is related to the largest particles in the bed. Van Rijn [1982] found an average value which can be used for the equivalent roughness of Nikuradse:

\[ k_s = 3 \ D_{90} \]  \hspace{1cm} (4)

The constant in this formula was found to be correct after comparison of the corresponding wall roughnesses with the expected wall roughness based on literature.

Figure 4 shows the limits for incipient motion in the circular channel and the Shields curve. It can be seen that in the case of a flat sediment bed in a circular channel, the diagram has to be evaluated. Even the upper limits of the critical ranges are found to be below the Shields curve. The critical (bed) shear stress for incipient motion is found to be around 70% of the value that Shields suggested.
Critical shear stresses for cohesive sediments. The sediment movement in sewers is a function of physical and chemical characteristics of the sediment and of the spatial and temporal characteristics of the flow. The variables describing the characteristics of the sediment were extended with cohesion. Cohesion can occur when organic materials are present in the sediment bed. Williams (1988) analysed sewer sediment samples collected from different locations within the U.K. Sediments composed of a synthetic clay gel and sand were identified as rheologically suitable analogues for combined sewer sediment deposits. A synthetic sewer sediment was used in erosion tests with differing percentages of sand and clay gel in order to express the range of characteristics found by Williams. The results suggest that the upper limit of the critical shear stress may not exceed 5-7 N/m² [Nalluri, 1989].

Transport

The experimental studies were mainly concerned with the incipient motion but some observations were related to the transport of bed material. As was expected a further increase of the shear stress resulted in dune formation of the non-cohesive sediment bed. The form of the bed corresponded to the shear stress distribution. The erosion process of a cohesive bed appeared to start with the formation of small spots of erosion at critical shear stresses, a further increase in shear stress made the whole sediment bed collapse very rapidly resulting in a short peak value of the transport and a washed out sediment bed (Nalluri, 1989).

Present and future studies

The next step in studying the fundamentals of sediment movement in sewers will be the investigation of the transport phenomena in combination with the erosion of both non-cohesive and cohesive sediments in channels of circular cross section. At Delft University of Technology experiments are being carried out with sand in a transparent circular pipe of 150 mm diameter and 30 m length. At the University of Newcastle upon Tyne experiments are being carried out with cohesive sands in transparent circular pipes of 154 mm diameter and 20 m length and of 302 mm diameter and 12 m length.

CONCLUSIONS

From the field studies it may be concluded that some deposits in sewers are permanent because of the insufficient capability of the flow to erode the deposits. Cementation of sand with organic matter intensifies the permanent character.

The shear stress on the flat sediment bed is found to differ in the transverse direction. The predicted bed shear stresses (using the equations of motion and Einstein's separation technique) along the flat sediment bed compare reasonably well with the maximum measured (using velocity profiles) shear stresses. The theory was expected to be applicable in the calculation of the average bed shear stress, but appeared to be applicable in the calculation of the maximum bed shear stress.

Shields' criterion for incipient motion of non-cohesive sediments is not applicable in channels of circular cross section with a flat sediment bed. The particles tend to move at much lower shear stresses (than predicted by Shields' criterion). The erosion studies on the investigated cohesive sewer sediments suggests that the upper limit of the critical shear stress may not exceed 5-7 N/m². Once the critical shear stress is exceeded the sediment bed will be washed out. Further studies to investigate the transport mechanisms of both non-cohesive and cohesive sediments are in progress at both TU-Delft and the University of Newcastle upon Tyne.
ACKNOWLEDGEMENTS

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NOTATION

A area of cross section (L^2);
C Chézy-coefficient (L^0.5T^{-1});
D_{50} 50% particle size (L);
D_{90} 90% particle size (L);
g acceleration of gravity (LT^{-2});
i slope;
k_e equivalent roughness of Nikuradse (L);
R hydraulic radius (L);
P perimeter (L);
u longitudinal flow velocity (LT^{-1});
u(z) longitudinal flow velocity as a function of z (LT^{-1});
w_{b} bed shear velocity (LT^{-1});
z vertical coordinate (L);
Z_{b} bottom level (L);
Z_{w} water level (L);
ν kinematic viscosity coefficient (L^2T^{-1});
ρ density of fluid (ML^{-3});
ρ_s density of sediment (ML^{-3});
τ shear stress (ML^{-1}T^{-2});
D_e = D_{50} \left( \frac{(\ell_{50}/z)\ell}{\nu^2} \right)^{1/3} particle diameter (-);
θ = \frac{w_{b}^2}{(\rho_s/\rho - 1)gD_{50}} mobility parameter (-);