Sewer sediment transport studies using an environmentally controlled annular flume

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Abstract This paper provides an overview and some preliminary results of a collaborative project recently completed at WL Delft Hydraulics. It describes tests in an annular flume, in which sediment deposits were formed under carefully controlled and monitored environmental conditions. The deposits were then subjected to a series of time steps in which the rotational speed of the flume’s top and bottom plates was increased, progressively increasing the bed shear stress. The sediment deposits were formed using three different types of sediment. An artificial organic sediment, together with a uniformly sized sand were selected as surrogate sewer sediments. The deposits in the remaining experiments were real in-sewer sediments, from catchments in the UK (Dundee) and The Netherlands (Loenen). During the erosion tests, total and volatile suspended solids concentration, particle size distribution of the eroded sediment, and COD and DO levels were recorded. The bed surface topography was also measured so that the influence of the deposit formation condition on bedforms could also be examined. Where bed consolidation times were least 24 hours a biologically active surficial layer was observed to develop at the sediment/water interface. The initial deposit conditions (temperature and deposit duration) were both found to have a significant impact on the subsequent erosion of the deposit.

Keywords Annular flume; deposition; erosion; laboratory experiments; sewer sediments

Introduction

Most sewer systems in the EU are combined as they carry both foul water and rain water. During periods of high rainfall, these sewer systems cannot transport all the runoff from the urban catchment to the treatment plant and are therefore designed to discharge excess flows via overflows to natural watercourses. Pollutants within these discharges can have a significant environmental impact on the receiving waters. High suspended sediment concentrations have been commonly observed in these overflows during the initial periods of storms and have been termed “first foul flushes”. One of the main causes of these “flushes” is the erosion of existing in-sewer deposits.

In an attempt to retain sediment within sewer systems, large computational sewer network models with sediment transport rate modules have been developed, e.g. MOUSE (DHI) and INFOWORKS (Wallingford Software) to simulate the hydraulic and sewer flow quality performance of these sewer systems. In general these models can simulate accurately the time varying hydraulic performance of these complex networks providing suitable and sufficient field data is used to initially calibrate the model (Clemens, 2001). However, the ability of these commercial models to predict water quality changes is much more limited. The sediment transport rate modules employed have generally utilised transport rate relationships originally developed in fluvial environments. In-sewer deposits have been represented as homogeneous and generally granular, whereas in reality they comprise a
wide range of sediment types (organic/inorganic) and can exhibit significant cohesive-like properties. This oversimplification and the use of inappropriate sediment transport relationships has led to poor simulation of suspended sediment transport and as a consequence low end-user confidence. It is clear that a better understanding is required of how in-sewer sediments form deposits and how these deposits can develop strength. There have been few studies in which the parameters which control the strength development of in-sewer deposits have been systematically varied in order to develop robust process based erosion relationships. This is a major failing in many of the existing sediment transport models.

Field based studies have clearly demonstrated that a significant proportion of in-sewer deposits contain large amounts of organic material and cannot therefore sensibly be described as purely granular (Crabtree, 1989; Verbanck et al., 1994). The most recent design approach in the UK, produced by CIRIA (Ackers et al., 1996) brings together knowledge about sediment transport that has largely evolved from laboratory studies in pipe channels using single sized granular sediments (May, 1993). Attempts to relate current predictive approaches for sediment transport to observations from real systems have proven difficult (Jack et al., 1996; Arthur et al., 1999). It is believed that, given the heterogeneous nature of many in-sewer deposits, cohesion may be one physical reason for such poor predictions. The CIRIA design method recommends a single critical value of bed shear stress of 2 N/m², to account for the influence of cohesion.

Some early attempts to develop an adequate model for sewer sediment erosion utilised field data collected in the main Dundee interceptor sewer (Wotherspoon, 1994; Ashley, 1993). Field based research has continued by extending data collection to further sites and to a wider range of hydraulic conditions and sewer sediment types e.g. near bed solids (Arthur, 1996), near bed organic layers (Ahyerre, 1999) and fluid sediment/dense undercurrents (Ashley et al., 1994; Verbanck, 1995). Several empirically based relationships have been developed to describe the transport behaviour of different types of sediment at various sites, for example near bed solids (Arthur and Ashley, 1997) and granular sediments (Lin and Le Guennec, 1996). The results of these studies lack wider applicability due to their site specific nature and the inability in the field to control the hydraulic conditions sufficiently to investigate specific sediment parameters systematically.

In parallel with field-based work a number of laboratory studies have been carried out (Alvarez, 1992; Torfs, 1995; Skipworth, 1996; DeSutter, 2000; Rushforth, 2001) to examine the erosion processes from cohesive-like deposits. These studies have been conducted under more controlled conditions and have included both steady and time varying flows. However they have generally used surrogate, artificial sewer sediments and so any extrapolation of the outcomes is open to the criticism that the artificial sediments selected may not behave in the same manner as real in-sewer sediments. These studies have, however, clearly demonstrated that significant correction factors are required to modify purely granular based transport relationships to account for fine-grained cohesive sediment (De Sutter et al., 2000). Laboratory studies have also suggested that organic fine-grained cohesive-like deposits can exhibit a vertical deposit structure, with erosion resistance increasing with depth. By incorporating this type of structure into a model the erosion from in-sewer deposits can be simulated reasonably (Skipworth et al., 2001) providing sufficient field data is available to calibrate the variation in erosional strength with depth. Unfortunately this type of model can not simulate the processes within the deposit that lead to such changes in bed strength.

The adjustment of erosion thresholds by the transformation of organic sediment has been observed in the natural environment. Sutherland et al. (1998) reported that the critical value of shear stress for entrainment increased as levels of colloidal carbohydrate increased, indicating biological activity, in a small number of estuarine mud samples.
Vollertsen and Hvitved-Jacobsen (2000) reported on a small number of laboratory flume tests in which the erosional strength from remoulded sewer sediment samples left a small flume for 1–4 days was roughly estimated. Although no direct measurements of the threshold of erosion were made, observations of the total mass removed from the beds indicated that bed strength diminished with time and that DO measurements suggested that these changes were linked to the bio-transformation of the organic fractions within the sewer sediments.

Major difficulties have been encountered in trying to develop understanding of the erosion phenomena associated with in-sewer sediments. Two groups of researchers have emerged: one group has attempted to identify surrogate sediments, whose characteristics, they believed, would accurately simulate the behaviour of real in-sewer sediments, and then conduct a series of tests systematically changing hydraulic conditions to observe the erosion and transport potential of the sediments (e.g. Torfs, 1995; Skipworth et al., 1999; De Sutter, 2000; Rushforth, 2001). The second group has maintained that only by the study of real in-sewer sediments can one observe and understand the physical processes which control the movement of in-sewer sediments (e.g. Arthur and Ashley, 1998; Ahyerre et al., 2001). The first type of study has been unable to demonstrate clearly that the surrogate sediment selected will faithfully describe the behaviour of in-sewer sediments. Tests in laboratories have also tended to ignore the importance of the environmental conditions in which in-pipe deposits form. These are believed to have a significant effect on the way in which organic sediments can transform and thus influence deposit strength (Vollertsen and Hvitved-Jacobsen, 2000; Camuffo, 2001). Any results produced by these studies are heavily dependent on the initial conditions (type of surrogate sediment, mode of deposit formation). It is therefore difficult to apply the results obtained and relationships derived in a more general context.

Other studies have relied on observations of the behaviour of real sewer sediment in-situ. Although this type of study uses real sewer sediments, typically the hydraulic control is poor and there is limited opportunity for examining the repeatability of observations. Field studies are expensive in terms of resources and the collection of data physically problematic. This has led to field data sets having limited ranges of hydraulic conditions and measured determinants. The lack of control also means deposit formation cannot be controlled and is rarely monitored. The outputs from this work tend to be very site specific and in the form of only locally applicable empirical relationships.

**Experimental work**

Given the above difficulties, carefully controlled experiments in which the antecedent depositional environment as well as the hydraulic conditions during the erosion test are controlled are extremely rare in sewer sediment studies. This paper will introduce a series of tests in which the conditions of deposit formation are carefully controlled. The second “erosion” part of the tests is carried out using a high level of control so that a systematic data set can be obtained. The tests were carried out in an annular flume at WL Delft Hydraulics in which the hydraulic conditions and many of the significant environmental parameters within the flume (DO and temperature) could be controlled. The ability to control the environment within the flume means that this facility has significant advantages over many other laboratory facilities. The annular flume is also sufficiently large so that the Reynolds numbers that are generated are of the same order of magnitude as observed in real sewers. The circular nature of the facility will cause the moving granular bedload to be “re-circulated” allowing the bedforms to attain equilibrium. In this way the annular flume will represent a “long” length of sewer pipe in which a stable bed morphology can develop. The temperature-controlled environment allows for the separation of the processes caused by
physical consolidation of the sediment deposits and by the biological transformation of the fine-grained organic sediment, present in many in-sewer deposits.

**Experimental equipment**
The tests were carried out in an annular flume that has an external diameter of 2.2 metres and an internal diameter of 1.8 metres. The flume is located in a room in which the air temperature and humidity can be controlled. During these tests the air temperature was set to either 14°C or 4°C. Both the top and bottom plates of the flume rotated. This was done so that the lateral flow circulations within the flume could be minimised so as uniform a shear stress pattern as possible was applied to the sediment bed.

The flume was equipped to measure bed shear stress, suspended sediment and dissolved oxygen concentrations and temperature at a frequency of 2 Hz. A web camera was installed on the lower plate and viewed a vertical section of the bed. Images from the web camera were recorded at one-minute intervals during the depositional and erosional phases of each test. This gave a visual record of what happened to the bed at one location. Examination of the images proved useful in examining the mechanisms of erosion and in estimating the celerity of bedforms if they were present. The flume was also equipped with an automatic sampling device that allowed recovery of discrete samples of 250 ml of fluid at any time. The draw off point for the suspended sediment concentration devices, the DO probe and the discrete samples was located approximately 30 mm above the sediment bed. Sampling at this position was believed to provide depth averaged values of suspended sediment and DO concentration.

**Procedures**
Each test comprised three parts – a deposit formation phase, a controlled erosion test and then the measurement of “equilibrium” bedforms. During the first part, the deposit formation phase, a 5 cm deep sediment bed was carefully placed in the flume and then gently scraped flat. The flume was then slowly filled with tap water. The water constituted a form of “sewage” as there was some mixing with the placed sediment, although the filling of the flume did not disturb the bulk bed. In each test the upper flume plate was 270 mm above the level of the sediment bed. The temperature of the room had already been set as required. In each test the DO level was set at 70% of saturation and this was achieved by recirculation of water through an oxygenation column that was continuously aerated. During the deposit formation phase the upper plate rotated slowly to ensure adequate mixing of the dissolved oxygen throughout the water in the flume. The deposit was then left for a pre-determined amount of time to consolidate.

After the consolidation period was over the deposit was then subjected to a controlled erosion test. The speed of the lower and upper plates of the flume were increased in a step-wise manner so that the bed was subjected to a series of shear stress steps in which the shear stress was steady but increasing from step to step. The suspended sediment concentration and dissolved oxygen levels were measured continuously during each step which lasted approximately 30 minutes. One of the advantages in using an annular flume over field studies to investigate erosion behaviour is that any sediment found in the water column must have been removed from the bed. In the field it is difficult to isolate the influence of upstream sediment supply. Therefore any sharp increases in total suspended sediment concentration with time, in the flume, indicates high erosion rates from the deposited bed. Discrete samples (250 ml) of the “sewage” containing eroded material were recovered approximately every 300 seconds. These samples were used to determine total and volatile suspended solids (TSS and VSS) concentrations and particle size distributions using a Malvern particle size analyser. Images from the side viewing web camera were also recorded, at one-minute inter-
vals, so that the response of the bed could be observed visually. At the end of the erosion test, detailed topography measurements were made of the entire deposit surface so that the bed-forms created during the mobilisation of the deposit were quantified.

**Test programme.** The test programme had two parts. The first series of tests used surrogate sediment; the second used real in-sewer sediments. The levels of temperature and DO were selected to resemble the extremes encountered in a northern European sewer. The sediment deposits were left in these conditions for periods of approximately 18, 42, 56 and 80 hours before being subjected to the stepwise increases in boundary shear stress to assess the erosional stability of the deposit (Table 1).

Three different types of sediment mixtures were used. Initially artificial organic sediment, crushed olivestone, was used to represent the fine-grained organic sediment found in many deposits within combined sewers. This was mixed with single size sand to form a granular/organic sediment mix, with an organic content of 20% by mass. The other two types of sediment mixture were sourced in combined sewer systems, from Dundee in the UK and from Loenen in The Netherlands. Typical physical characteristics of the sediment mixtures used are given in Table 2.

**Experimental results**
Comparison between results obtained in the first (surrogate) and second (real sediment) series of tests will indicate the suitability of surrogate sediments for sewer sediment studies. The second series of tests will provide, for the first time, comprehensive data on the influence that various environmental parameters have on the development of deposit strength for in-pipe deposits composed of real sewer sediments. The data will also provide high quality observations necessary to understand how real in-sewer sediments transform in a sewer between high flow events.

**Erosion of sewer sediment deposits**
Similar surficial features could be observed for all deposits (surrogate and real sediments) that had consolidated for at least 24 hours at 14°C. Figure 1 shows diagrammatically the

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<th>Table 1</th>
<th>Summary of experimental tests and deposit formation conditions</th>
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<tr>
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<td>Sand:olivestone</td>
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<td>Loenen</td>
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<td>4</td>
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<tr>
<th>Table 2</th>
<th>Average sediment characteristics of original sediment mixes used to form deposits</th>
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<td>Sediment</td>
<td>Inorganic characteristics</td>
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<td>$D_{50}$ (mm)</td>
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<td>Dundee</td>
<td>0.48</td>
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<td>Loenen</td>
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existence of an active organic surface layer, which was seen to develop by the web camera as a lighter coloured material. This corresponds with field observations of sediment deposits where there is frequently a grey-whitish (aerobic) surface layer overlying a black (presumably anaerobic) bulk deposit. This grey-whitish layer was observed in all tests with sewer sediments at 14°C.

In all the sewer sediment deposit tests that were formed at 14°C, a characteristic pattern of erosion was observed. Erosion was initiated in each case at bed shear stresses lower than 0.5 N/m². Figure 2 indicates the erosional pattern observed in test 4 (Dundee sediment). As the bed shear stress increased, the TSS increased very slowly at first. After approximately 5,000 seconds the TSS started to rise sharply. This continued for a further 500 seconds and then the TSS values remained fairly constant even though the shear stress being applied to the bed continued to be raised in a stepwise fashion. In the final stage of the test the bed started to erode very rapidly and, as a consequence, the TSS values rose sharply. A similar pattern was observed in Test 3 (Figure 3), which used Loenen sewer sediments deposited under identical environmental conditions. In this test the TSS rose slowly for the first 12,000 seconds before increasing very rapidly, for a period of 30 minutes. The TSS then

Figure 1 (Left) Schematic illustration of the biologically active surface layer observed in all sediment tests for which consolidation was at least 24 hours and temperature was 14°C. (Right) Side view photograph of bed deposit during erosion test 001 showing surface layer during erosion test.
dropped and remained rather stable before it started to rise rapidly again after 20,000 seconds had elapsed, indicating the start of a second phase of bed erosion.

Comparison between tests 4 (Figure 2) and test 5 (Dundee sediment at 4°C, Figure 4) indicates the influence of temperature on the development of resistance to erosion by a sewer sediment deposit. In these tests, the sediments used were taken from the same location, and had very similar particle size distributions and organic content. They were consolidated for identical periods of time and the DO level in the overlying water was maintained at 70% saturation. The only environmental difference was the temperature of the water. In test 4 this was set to 14°C which was taken to resemble the conditions in a northern European sewer in summer, 4°C was selected for test 5 so that any biochemical processes would be negligible. When exposed to a similar pattern of shear stress steps it is clear that

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**Figure 3** Total suspended solids and volatile solids from discrete sampling, along with upper plate rotational speed, for a sewer sediment deposit, formed using sediment from Loenen, at 14°C with a DO level of 70% of saturation.

**Figure 4** Total suspended solids and volatile solids from discrete sampling, along with upper plate speed, for a sewer sediment deposit, formed using sediment from Dundee, at 4°C with a DO level of 70% of saturation.
the overall mobility is lower, with TSS values approximately 50% less, and the pattern of erosion of the deposit formed at 4°C is significantly different. No grey-whitish surface top layer was observed to form. In test 5, after 10,000 seconds the TSS values rise slowly and then more quickly, in a similar pattern to purely granular sediment deposits. No "two peak" pattern as observed in tests 4 and 6 is observed. However once the deposit has been mobilised the proportion of inorganic sediment in the suspension rises slowly as the shear stress increases as in the previous tests. The difference in results may be attributable to the significance of the surficial layer (Figure 1).

In order to examine the impact of different deposit durations, suspended sediment concentrations were averaged for each shear stress step in the tests using Loenen sediment. Two groups of process are possible, physical consolidation or biological processes transforming the organic sediment. In test 5 the biological processes were suppressed by running the test at 4°C and the comparative data with test 4 indicated that consolidation could reduce the sediment suspension by around 50%. However in the Loenen tests it is seen that the biological processes are much more important than physical consolidation as they significantly weaken the bed with time (Figure 5). It would be expected that the physical consolidation would strengthen the bed, but the biological transformation processes seem to dominate with the weakening of the deposit continuing even after 56 hours.

Discussion

It is clear that the surficial biochemical processes have a measurable impact on the resistance to erosion that a sewer sediment deposit can develop. This is confirmed by examination of the results from tests 1 and 2 (deposits formed with the artificial organic sediment) and tests 4 and 5 in which the deposits formed at 4°C were significantly stronger. The patterns of TSS were also similar. In tests 1, 3 and 4 a “two peak” pattern in TSS values was observed. The side-view web camera images indicated that a surface layer developed during the consolidation period and that as the shear stress increased during the erosion test, the thickness of the layer increased, until particles were observed to be eroded from the surface layer. Later in the tests as the TSS values started to increase rapidly it was seen that the surface layer no longer covered the whole surface but had been breached, releasing material from below it. The high proportion of organic material in the early stages of these

![Figure 5](https://iwaponline.com/wst/article-pdf/47/4/51/422368/51.pdf)

**Figure 5** Suspended sediment concentration against top plate speed for all tests using Loenen sewer sediment. Three different deposit durations: 18 hours, 42 hours and 56 hours; all tests at 4°C.
tests indicates that the surface layer may be highly organic. From these tests it is possible to tentatively postulate the need for a new two-layer model for sediment erosion, which accounts for:

- a surficial layer which is active (aerobically) resulting in changes to the material and bed strength characteristics at the oxygen-rich interface;
- a “bulk” sediment layer underlying the above which may be anoxic/anaerobic – erosion of this material depends upon the initial removal of the surface layer.

The bulk layer may erode in different ways depending on the transformation of its fine organic sediment in relation to physical consolidation. It appears that in biologically active sewer beds significant weakening of the deposit occurs with time and this conflicts with traditional concepts of deposit strengthening due to consolidation normally associated with fine-grained deposits.

Conclusions
A series of laboratory tests were carried out to examine the erosion of sewer sediments and artificial materials that had been used previously as sewer surrogates. Both sediment types exhibited similar patterns of erosional behaviour, particularly when comparing deposits formed at 4°C and 14°C. Initial comparison of shear stress levels observed in the field in Loenen and Dundee at the threshold of erosion with those observed in the flume suggest similar threshold conditions, thereby suggesting that the deposits formed in the flume developed similar levels of stability to those in the field.

Sewer sediment deposits formed under different environmental conditions exhibit different resistances to erosion. In conditions in which the biochemical processes are inhibited (due to low temperatures) deposits behave as though they were composed with entirely inorganic sediments. When biochemical processes are present deposits are generally weaker and appear to exhibit a two-stage erosion process.

Acknowledgements
This paper reports on a project that involved researchers from a number of institutes. The authors are the principal scientists and representative of others who helped conduct the experiments. In particular the following made significant contributions and without whose efforts the data presented would not be available: Mr Trevor McIlhatton, University of Liverpool, Mr Ruben Sakranbani, University of Bradford, Mr Robin Veldkamp and Mr Tony Schuit of TU Delft, Ir John Cornelisse, Mr John Coolegem and Mr Pierre Bosland of WL Delft. The project was funded by an EU TMR programme, project no. HPRI-CT-1999-0103 and its support is gratefully acknowledged.

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