Pergamon

Wat. Sci. Tech. Vol. 29, No. 1–2, pp. 363–372, 1994.

0273–1223/94 $7·00 + 0·00

SEDIMENTATION IN STORAGE TANK STRUCTURES

Virginia R. Stovin and Adrian J. Saul

Department of Civil and Structural Engineering, University of Sheffield, P.O. Box 600, Mappin Street, Sheffield S1 4DU, UK

ABSTRACT

Although storage tanks provide an effective means of reducing the magnitude and frequency of combined sewer overflow discharges, and thereby of alleviating urban watercourse pollution, poorly designed storage structures frequently suffer from maintenance problems arising from sedimentation. The development of design guidelines that optimise the self-cleansing operation of storage structures is clearly a priority for urban drainage research.

This paper describes a system that has been developed to study sediment deposition in laboratory model-scale storage structures. The patterns of deposition resulting from a selection of flow regimes are described, and the need for time-varying and time series storm tests is highlighted. Sedimentation patterns are shown to predominantly depend on the flow field, and the critical bed shear stresses for deposition and erosion in the model situation are identified. Hence, the potential application of numerical models to the design problem is discussed.

KEYWORDS

Bed shear stress; deposition; erosion; laboratory scale model; numerical model; Sediment; Storage tank; time-varying flow.

INTRODUCTION

Many urban watercourses are detrimentally affected by the low quality of combined sewer overflow (CSO) discharges, and increasingly storage tanks are located at CSOs in order to reduce the level of pollution that enters the watercourse. However, the occurrence of sediment deposits in storage tanks may lead to blockages, surcharging, flooding and premature CSO operation. Greater understanding of the sedimentation process is therefore required, in order that future designs of these structures can incorporate measures to reduce the volume of deposited sediment, and hence the maintenance problem.

It is considered that laboratory scale studies provide an important link between full scale observations of sewerage system behaviour, and an understanding of the fundamental processes that control sediment deposition in individual structures. In terms of the self-cleansing operation of storage tanks, Ellis (1992) produced improved design guidelines based on laboratory scale model investigations. The research outlined in this paper continues this work, and demonstrates that the velocity distribution alone is sufficient to facilitate a quick and accurate prediction of the pattern of sediment deposition in storage tanks. As a consequence, the simulation of the velocity distribution using a 2D or 3D mathematical model should allow the prediction of the self-cleansing performance of tanks of different geometry.

THEORETICAL CONSIDERATIONS

Sediment transport within storage tanks may be described in terms of the characteristics of the sediment, the characteristics of the bed surface, the properties of the fluid and the flow field. In a laboratory model study it is possible to change these parameters one at a time, and in this paper the link between sediment deposition, critical bed shear stress and the velocity distribution in the flow field was explored.

The velocity distribution was assumed to be turbulent, and the bed shear velocity, v_0, was calculated from the Prandtl-von Kármán universal velocity distribution law:

$$v = \frac{1}{\kappa} v_0 \ln\left(\frac{y}{y_0}\right) \tag{1}$$

where

- v = the velocity
- κ = the von Kármán constant, usually taken = 0.4
- y = the normal distance from the solid surface
- v_0 = the shear velocity.

Von Kármán (1930) showed that the value of κ may be taken to be 0.4, but Vanoni (1946) and Einstein and Chein (1955) suggested that, based on experimental results, κ decreased with an increase in the suspended sediment concentration. However, Coleman (1981) demonstrated that such a change in the value of κ could be attributed to a misinterpretation of the experimental data, and that κ was essentially constant over a range of flow conditions, from those with no sediment in suspension to those carrying a near capacity load. For the purpose of this investigation, therefore, κ was assumed to be 0.4, and invariant.

For a smooth surface, the constant y_0 depends solely on the shear velocity and the kinematic viscosity (υ);

$$y_0 = \frac{m\upsilon}{v_0} \tag{2}$$

where m represents the dimensionless Reynolds number of the laminar boundary layer, and is equal to about 1/9 for smooth surfaces.

Substituting Eq. (2) for y_0 in Eq. (1), and using $\kappa = 0.4$:

$$v = 2.5 v_0 \ln \frac{9 y v_0}{\upsilon} \tag{3}$$

Equation (3) gives the velocity distribution in turbulent flows over a smooth surface, and may be used to calculate v_0 from measured v at depth y in the vertical profile.

The bed shear stress, τ_0, may then be calculated from the bed shear velocity using:

$$\tau_0 = \rho v_0^2 \tag{4}$$

where ρ is the density of the liquid.

LABORATORY SET UP

The Model Storage Tank

The model tank was constructed from 13 mm clear perspex, and had internal dimensions 2000 mm long by 972 mm wide and 470 mm deep, as shown in figure 1. The base of the tank was horizontal and both the 190 mm diameter inlet and the outlet, which was 150 mm in diameter, were positioned such that the invert was level with the tank base.

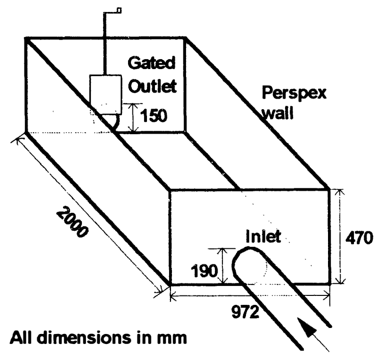

Fig. 1. The laboratory model tank

Inflow Control

Water was supplied to the tank via a recirculating system, with a control valve that was operated by dedicated computer software. The system is illustrated in figure 2. The valve could be opened or closed smoothly and automatically, and it was possible to generate steady and time-varying flow regimes.

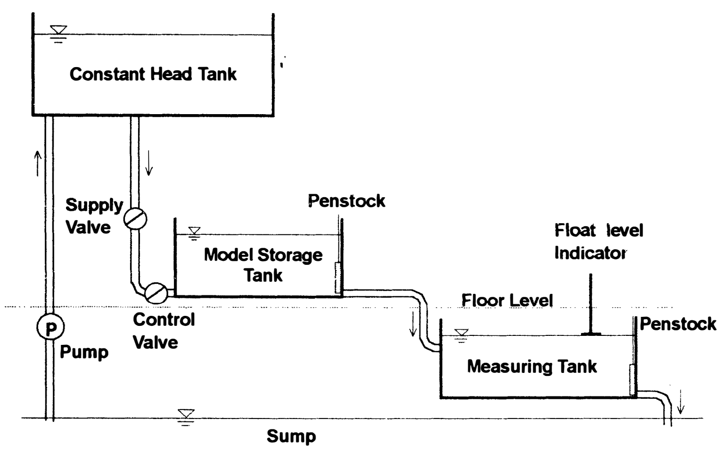

Fig. 2. Laboratory set up

Velocity Measurements

The velocity distribution in the tank was measured using a Nixon miniature propeller meter which had been pre-calibrated to relate the frequency of propeller revolutions to the velocity of flow. A supporting frame was constructed that allowed the probe to be positioned at any vertical elevation over a grid of points in the horizontal plane, as illustrated in figure 3, and such that the probe could be aligned in the direction of the maximum flow velocity.

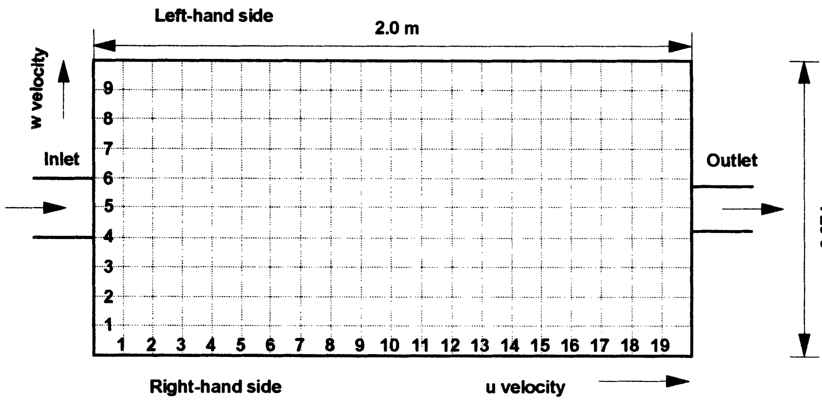

Fig. 3. Tank grid reference notation

The Model Sediment

The selection of an appropriate sediment for the model tests was based on the findings of Ellis (1992). He noted that when crushed olive stone was input into a hydraulic scale model chamber, the location and depth of deposition compared well to that observed in a full scale chamber. Hence, 150 μm crushed olivestone was selected as the model sediment. The physical characteristics of this sediment are summarised in table 1.

TABLE 1 Physical Characteristics of 150 μm Crushed Olive Stone Sediment

Size fraction	Diameter (μm)	Stokes' settling velocity (m/s)	Specific density (kg/l)
D_{20}	28	1.3×10^{-4}	
D_{50}	47	3.7×10^{-4}	}1.5
D_{80}	88	1.3×10^{-3}	

Sediment Input

The crushed olive stone was mixed with water to a concentration of up to 400 g/l, and transferred to the model using a variable speed peristaltic pump. The concentrated sediment suspension was maintained in a well mixed state by a mechanical stirrer. The pump speed was controlled using the computer software, and, as with the valve, a calibration relationship was established between output signal and pump speed to allow the control of sediment input in real time. Hence, in the same way that time-varying flow hydrographs could be defined, time-varying pumping rates were defined to simulate, for example, constant concentration, constant load or a first foul flush effect in the sediment input. The sediment concentrations used in the tests were representative of those monitored in full scale tanks (Thornton and Saul, 1986).

EXPERIMENTAL PROGRAMME

Three sets of experiments are described in this paper: a) steady flow tests; b) time-varying flow; and c) time series tests. Values of the critical bed shear stress for deposition and erosion of suspended sediment were established and compared for each flow regime.

STEADY FLOW TESTS

Experimental Conditions

A steady flowrate of 15.9 l/s was used in the tests. The mean velocity in the inflow pipe was 0.561 m/s, with a corresponding Reynolds number of 1.066 x 10^5. Similarly the depth of flow in the tank was 0.196 m, with a corresponding mean flow velocity at any tank cross section of 0.083 m/s.

Velocity Measurements

The velocity was recorded in a series of cross sections, positioned at longitudinal grid lines 1, 2, 4, 8, 12, 16, 18 and 19, at all 9 grid lines in the transverse direction, and at depths 10, 20, 40, 80, and 160 mm. Hence, the velocity was recorded at a total of 360 positions. At each measuring point the velocity was averaged over a period of at least 30 seconds, and at points of low velocity a minimum of 300 propeller revolutions was counted. The *u* (longitudinal) and *w* (transverse) components of velocity were derived trigonometrically from the recorded velocity and the corresponding probe alignment.

Velocity Distribution and the Flow Pattern

An example of the velocity distribution at a flow depth of 80 mm is illustrated in figure 4. The flow field was dominated by a clockwise circulation, with the inflow jet moving to the left wall of the tank, then across the outlet, and returning towards the inlet in the right hand section of the tank. A small anticlockwise circulation in the upstream left hand corner of the tank was also identified, while the minimum velocities were observed in the centre of each circulation, and in the upstream right hand corner of the chamber.

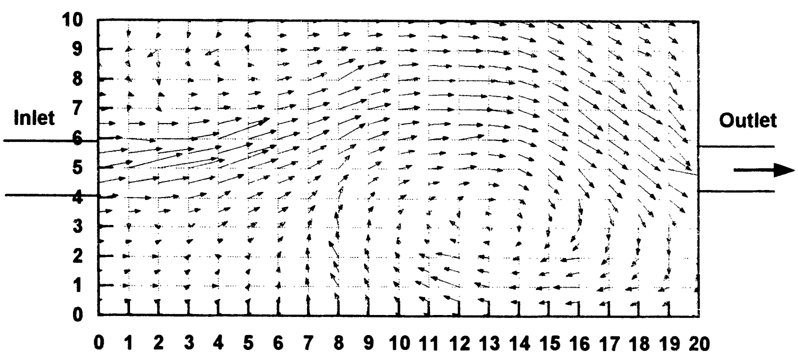

Fig. 4. Steady flow velocity distribution at 80 mm depth

Bed Shear Stress

At each grid location the maximum measured velocity in the vertical profile was identified, and this was used to calculate the value of τ_0, assuming that the vertical velocity profile was logarithmic and using equations (3) and (4). A contour plot of the distribution of τ_0 is presented in figure 5.

Sediment Deposition

The 150 μm crushed olivestone was injected into the inflow at a constant concentration of approximately 250 mg/l for a 10 minute period. After this time a clear pattern of sediment deposition on the bed was observed, and this is illustrated in figure 6. It is clear that the zones of deposition apparent in figure 6 correspond to zones of minimum bed shear stress in figure 5. By comparing the position of the boundary of the sediment-free area in figure 6 to the corresponding value of bed shear stress it was possible to identify the critical bed shear stress (τ_{cd}) below which deposition occurred. For the 150 μm crushed olivestone used in the tests, τ_{cd} was found to lie between 0.03 and 0.04 N/m^2.

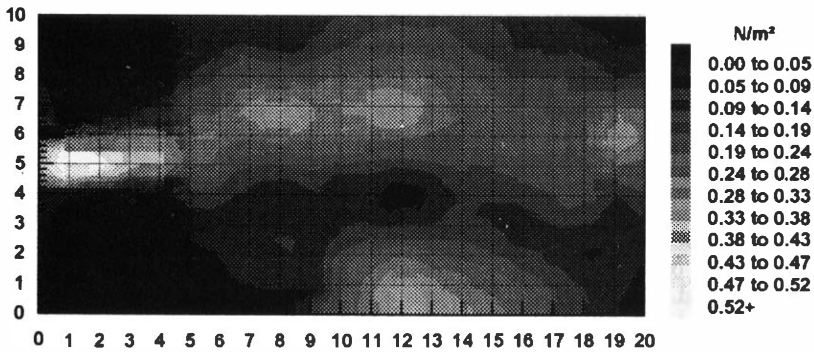

Fig. 5. Steady flow bed shear stress distribution

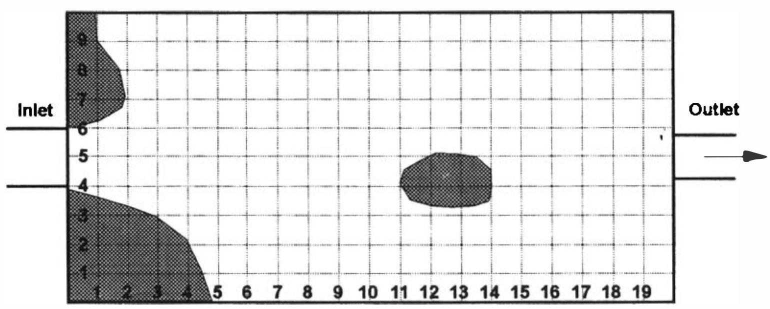

Fig. 6. Sediment deposition for the steady flow regime

TIME-VARYING INFLOW TEST

Test Procedure

Observations of flow velocity and sediment deposition were also made during a 20 minute duration time-varying inflow hydrograph, termed HYDRO1. The profile of this inflow hydrograph is shown in figure 7, along with the resultant profile of flow depth in the tank.

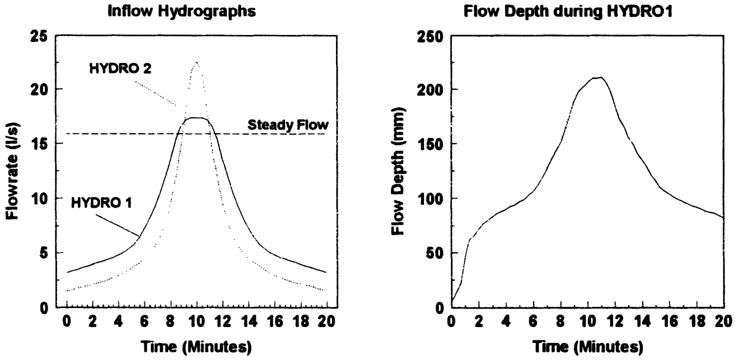

Fig. 7. Flow profiles

Again, a constant concentration of approximately 250 mg/l of 150 μm crushed olivestone was input into the tank over the duration of the hydrograph, and photographs of sediment deposition were taken at intervals of one minute.

Velocity measurements were made continuously at all odd numbered longitudinal and transverse grid locations, except for points (1,1) and (1,9). At these two points the magnitude of the flow velocity was too low to be recorded using the miniature flow meter. Further measurements were made in the region of the inflow jet, where horizontal velocity gradients were large. The velocity was therefore recorded at a total of 59 grid points in the horizontal plane. The length of time required to monitor each location made it impractical to consider investigating more than one depth. In addition, it was required that the probe should be submerged throughout the duration of the hydrograph, and hence a flow depth of 50 mm was arbitrarily selected for the velocity measurement during the time-varying flow test.

Results

The pattern of the final sediment deposition following the discharge of HYDRO1 is shown in figure 8. A comparison of the results of the steady and time-varying flow tests showed that when sediments of similar concentration and load were introduced into the tank during each test, the total quantity of sediment deposited was far greater in the time-varying test. This excess deposition was caused by the reduced flow velocities which occurred during the recession limb of the hydrograph.

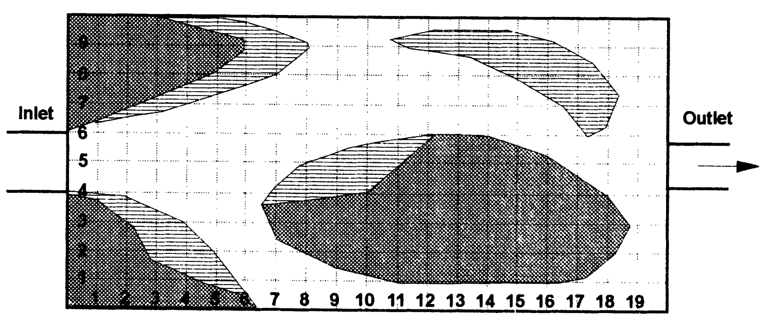

Fig. 8. Sediment deposition following HYDRO1

A comparison of figures 6 and 8 clearly demonstrated that there were considerable differences between the pattern and extent of sediment deposition in steady and time-varying flow tests, and hence it was concluded that in any assessment of the performance of a storage tank structure the flow regime under which it was tested must be fully qualified.

Using the measured velocity results from the time-varying flow tests, equations (3) and (4) were used to estimate the bed shear stress distribution at one minute time intervals over the duration of the hydrograph. These results were compared with the observed zones of deposition. Two conclusions were drawn from the results: firstly, deposition occurred at a bed shear stress of less that 0.04 N/m^2, which agreed with the findings of the steady flow tests; and secondly, that re-erosion of sediments occurred at a higher bed shear stress, $\tau_{ce} = 0.06$ N/m^2. Once deposited, the sediments required a higher bed shear stress to initiate movement than that required to simply maintain the sediments in suspension. This phenomenon may be explained in terms of interparticle forces and cohesion, and has been well reported in the literature (Hjulström, 1935).

These results were then used to develop a critical bed shear stress model for sediment deposition. A FORTRAN program was written that used the values of τ_{cd} and τ_{ce} to predict the presence, or absence, of sediment on the bed for all monitored points, at any specified time during the discharge of HYDRO1. It was assumed that whilst the bed shear stress was less than 0.04 N/m^2, deposition would occur. Once the velocity increased such that the bed shear stress exceeded 0.06 N/m^2, then it was assumed that the bed would be free of sediment, but that as soon as the velocity decreased to produce a bed shear stress below 0.04 N/m^2 deposition would again occur.

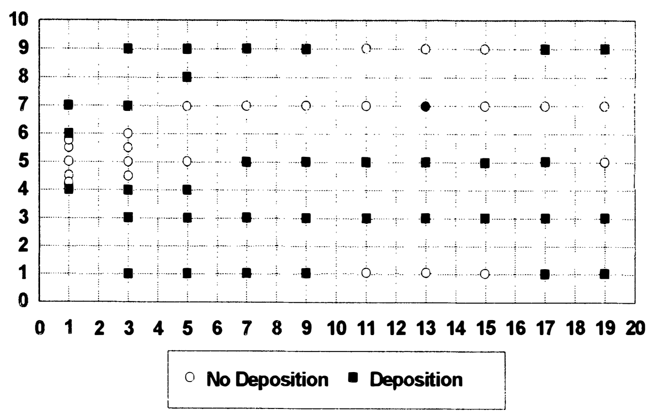

Fig. 9. Predicted sediment deposition based on measured velocities

The predicted pattern of sediment deposition, shown in figure 9, compared well with that which was observed at the end of the test (figure 8). It was concluded, therefore, that a sediment transport model based on critical bed shear values τ_{cd} and τ_{ce} is appropriate to describe the sediment retention performance of storage tanks in steady and time-varying flow conditions. However, the self-cleansing performance of the tank is likely to appear better in steady flow tests than in the real situation, where the flow is time-varying and where storms usually form a time series of events. Time series studies are described in the following section.

TIME SERIES TESTING

To study the effect of a time series of storms on the location of the sediment deposits in the tank a second flow hydrograph, termed HYDRO2 (fig. 7), which was free of sediment, was discharged through the tank immediately following both the steady flow and the hydrograph tests.

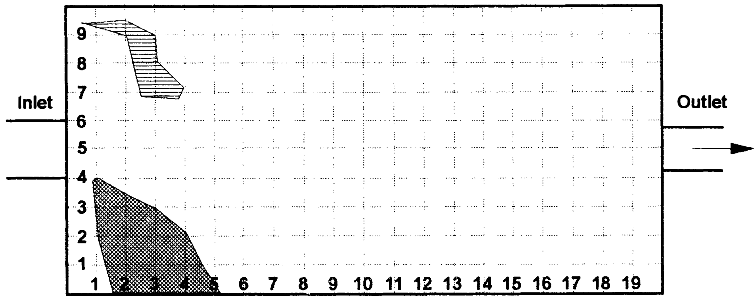

Fig. 10. Sediment deposition following HYDRO2

In both cases the erosional effects of this second storm were very similar, and the final location of each of the sediment deposits, as illustrated in figure 10, was the same. The initial effect of the hydrograph was to scour the bed along its central axis, with the upstream sediment deposits moved to locations adjacent to either side wall. Once a flow circulation developed, four zones of deposition, similar to those shown in figure 8, were observed. However, as the flow increased, the deposit in the downstream left hand section of the chamber was gradually eroded, with the subsequent erosion of the large deposit at the centre of the major flow circulation. The right hand boundary of this deposit became very well defined, and the movement of the eroded boundary towards the central axis was mapped in detail. At the peak of the hydrograph a large amount of sediment was observed in suspension. Thereafter, however, the water flowing through the tank was clear. Subsequently, only one significant area of deposition in the upstream right hand corner was observed. The shape of this deposit remained unchanged on the recession limb of the hydrograph, and it may be concluded therefore that this final pattern of sediment deposition was dependent on the flow conditions at, or immediately after, the peak flow. An identical final sediment distribution was also observed when HYDRO2 (without sediment) was discharged throughout the chamber after an evenly distributed layer of sediment had settled on the bed.

It is clear that the final pattern of sediment deposition depended not only on the velocity distribution, but also on the supply of sediment. On the rising limb of HYDRO2 the critical bed shear stress for erosion was exceeded over practically all of the chamber bed, and previously deposited sediments were resuspended. Some of these sediments then deposited in the upstream corners, where the bed shear stress was below τ_{cd}, but by the time velocities had fallen on the recession limb such that the bed shear stress over a larger area of the chamber bed fell below τ_{cd} no sediment was available. Hence those areas on the bed which potentially could have experienced deposition remained clean. On the other hand, when HYDRO2 was input into the chamber with a constant concentration of sediment in the inflow throughout its duration, far more extensive deposition, similar to that illustrated in figure 8, was observed. Clearly, in this case, when sediment was available on the recession limb of the hydrograph, deposition occurred where the flow velocity was sufficiently low.

In summary, the results of these tests clearly indicate that a subsequent storm may largely influence the location of sediment deposition within the storage tank, but that the variation in sediment supply over the duration of a storm is also critical. Time series storms and pollutographs should therefore be used in any analysis to predict the final location of any deposited sediment.

The reported tests have simulated the sediment retention performance of a single geometry rectangular storage tank for steady, time-varying and time series hydraulic inputs. Further work is however required which considers changes to the deposited sediments due to consolidation and a possible concreting of the sediments with age. Such processes may change the physical, chemical, and hence erosional, characteristics of the sediment, and these changes need to be addressed. Fieldwork studies in full scale chambers are, therefore, the next phase of this investigation.

CONCLUSIONS

The velocity distribution in the storage tank was the primary control on sedimentation. The distribution of deposited sediment may be predicted from knowledge of the velocity distribution in the tank and the values of the critical bed shear stresses, τ_{cd} and τ_{ce}, alone. It may be argued therefore that the velocity distributions computed mathematically may be used to predict sediment deposition in prototype storage tank designs.

The magnitude of the critical bed shear stress for the re-erosion of deposited sediment was greater than the critical bed shear stress for sediment deposition. For the laboratory sediments τ_{ce} was 0.06 N/m^2 and τ_{cd} was 0.03 - 0.04 N/m^2. The value of τ_{cd} was found to be the same in steady and time-varying flow conditions. It is stressed that these two values of critical bed shear stress depend on properties of the sediment, and of the bed. Further work is required to derive appropriate values for full scale sediments.

The extent of deposition was a function of the flow regime used in the tests. It was concluded that in order to provide a realistic assessment of the sediment retention performance of a storage tank it is essential to carry out the tests with time-varying and time series flow conditions, together with inflow suspended sediment concentrations which are representative of full scale conditions.

ACKNOWLEDGEMENT

All of the laboratory work, and a substantial part of the analysis, was carried out with the assistance of Michael Rodenbach, a visiting student from the Technical University of Aachen, Germany.

REFERENCES

Coleman, N.L. (1981). Velocity profiles with suspended sediment. *J. Hyd. Res.* **19**(3), 211- 229.

Einstein, H.A. and Chein, N. (1955). Effects of heavy sediment concentration near the bed on velocity and sediment distribution. *Univ. of Cal., Berkeley, and US Army Corps of Engr., Missouri River Div.* Rep. No. 8, 96 pp.

Ellis, D.R. (1992). The design of storm drainage storage tanks for self cleansing operation. *PhD thesis.* University of Manchester.

Hjulström, F. (1935). Studies of the morphological activity of rivers as illustrated by the River Fyris. *Bulletin of the Geological Institute, University of Uppsala.* 25. 221-527.

Thornton, R.C. and Saul, A.J. (1986). Some quality characteristics of combined sewer flows. *J. Inst. Public Health Engineers.* **14**(3), 35-39.

Vanoni, V.A. (1946). Transportation of suspended sediment by water. *Trans. ASCE.* Vol. III. pp. 67-133.

Von Kármán, T. (1930). Mechanische Aehnlichkeit und Turbulenz, Nachrichten von der Gesellschaft der Wissenschaften zu Goettingen. *Fachgruppe I (Mathematik).* Num. 5. ss. 58-76.