SOIL PROTRUSION APPARATUS FOR EROSION RATE PREDICTION WITH SMOOTH AND ROUGH SEDIMENT BEDS

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Abstract: A series of 2D small-scale physical experiments were performed in the Ahlborn sediment model bed tank (4.0×0.6×0.2 m) to investigate the influence of flow and sediment properties on soil erodibility. A Soil Protrusion Apparatus (SPA) was developed to investigate the soil-hydrodynamic phenomena under wet and dry conditions with smooth plastic bed tank (Jayaratne et al., 2010a). A simple mathematical model on soil erosion rate for smooth bed was proposed using dimensional analysis and a best-fit technique (Jayaratne et al., 2010b). The proposed paper discusses the extended investigation on soil-hydrodynamic behaviour by increasing the mobile bed roughness to greater values used in earlier experiments by the authors. A low cost technique involving spraying separate solutions on to a drained flume will be used to freeze the soil bed geometry (Benson et al., 2001). Proposed experimental work will lead to the comparison, calibration and development of predictive curves of erodibility for different soils and verify the proposed mathematical model. Furthermore, erosion rate prediction analysis will be investigated using computer programmes to simulate interrelated changes in sediment bed topography for the better representability of the proposed mathematical and physical model.

1. Introduction

In many cases where hydraulic structures such as bridges, levees and embankments have collapsed, the failure is attributed to erosion associated with a soil-hydrodynamic interaction phenomenon. When a hydraulic structure is built on a sand or gravel bed, the racing water flow may erode away the bed just around the piers on which it rests. At the same time there is immense force on the structure from the fast flowing water which may cause structural failure.

In the UK, incidents such as the collapse of railway bridges in Inverness in 1989, and at Glanrhyd in 1987, with the loss of four lives as part of a train dropped into the River Towy now have enhanced understanding of hydraulic structures get swept away in floods due to soil erosion.

Another example of the erosion in practice is where the impacts of sea-level rise due to climate change particularly increase coastal flooding. A rise in sea level produces major geophysical impact in coastal areas which include erosion of shorelines (Bijlsma et al., 1996). In 2006, several houses had been lost to the sea and many of those remaining were in a precarious position in Happisburgh, Norfolk, UK (http://www. happisburgh.com, 2006).

The frequent failures of coastal and river structures necessitate both quantitative and qualitative understanding of erosion processes. For this purpose, a series of 2D small-scale physical experiments were performed in the Ahlborn sediment model bed tank (4.0×0.6×0.2 m) in the hydraulic laboratory of the University of East London (UEL) to investigate the influence of flow and sediment properties on soil erodibility.

Sediment characteristics for five average soil diameters collected from various locations around the UK with the guidance given in Wijeyesekera (1998, 2001) under wet and dry conditions with smooth plastic bed tank were studied intensively (Jayaratne et al., 2010a). To investigate the soil-hydrodynamic phenomena under fully controlled turbulent flow conditions a Soil Protrusion Apparatus (SPA) was developed by re-fabricating the Ahlborn model bed tank. Using dimensional analysis and best fit technique a simple mathematical model for soil erosion rate was proposed for the smooth plastic bed (Jayaratne et al., 2010b).

The current paper is an extension to the previous studies (Jayaratne et al., 2010a & 2010b) increasing the sediment bed roughness to a higher value for the comparison, calibration and development of proposed physical and mathematical models maintaining the natural condition in a small scale.

2. Previous Work

Sediment transport is often difficult to be studied without proper knowledge of measuring instruments. The accuracy of the data is strongly related to the type of instrument applied. Various types of laboratory apparatus have been developed to measure erodibility of fine and coarse grained soils.

The rotating cylinder apparatus was proposed by Moore and Masch (1962). It consists of an outer cylinder rotating around a stationary inner cylinder. The inner cylinder is made of a soil sample wrapped around a centre rod. The gap between the two cylinders is filled with the eroding fluid. The rotating outer cylinder imparts motion to the eroding fluid, which in turn applies a shear stress generates a torque that is measured on the centre rod.

The drill hole apparatus was proposed by Rohan et al. (1986) in order to improve upon the rotating cylinder test. The test consists of drilling a 6.35 mm diameter hole through a sample, fitting the sample in a tube, and circulating water through the 6.35 mm hole. This test is a more sophisticated version of the pinhole tests (ASTM, 1999). The shear stress applied at the water-soil interface is calculated from the head loss in the drill hole, and the erosion rate is obtained by weighing at regular time intervals the soil collected in a sedimentation tank.

Similar apparatus have been developed and were described in Lee and Mehta (1994), and Philogene and Briaud (1996). They included the vertical grid oscillator, the EROMES System, the rotating disk device and the submerged jet. In addition, several flume systems have been used: straight flumes, racetrack flumes, annular flumes and rocking flumes (Briaud et al., 2001).

The Soil Protrusion Apparatus (SPA) described in this paper was developed at UEL with the following specific goals in mind: (1) to be able to perform site specific erosion studies, (2) to minimize sample disturbance; (3) to study the behaviour of the soil samples, (4) to incorporate the test results in a erosion prediction method.

2.1 Soil Protrusion Apparatus (SPA)

The UEL laboratory testing facility was contained with Ahlborn sediment mobile bed tank. The tank was purposefully re-fabricated in order to install a SPA that takes 100.0 mm diameter sediment core samples (see Fig.1).

The apparatus was placed at a distance of 1.5 m from the upstream end of the tank, and along its centre line. The sample tube was fitted to be pushed at a preset protrusion (z=1.0-10.0 mm) in 1.0 mm thick intervals.

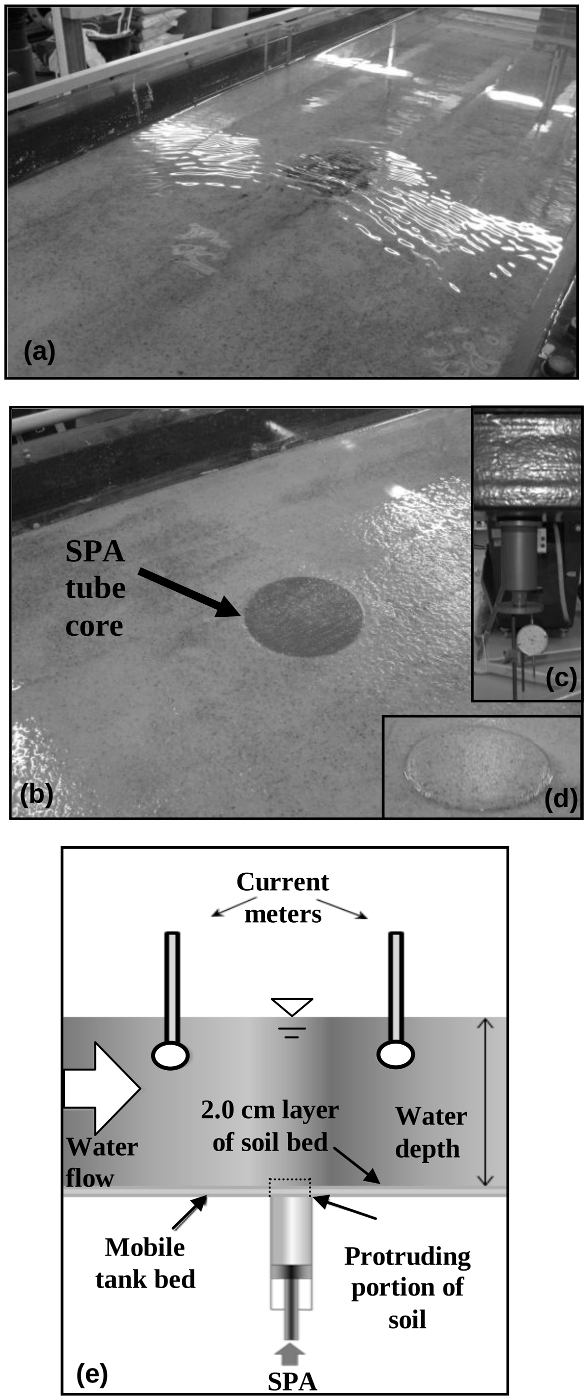

Figure 1. (a) Modified Ahlborn sediment bed tank at UEL, (b) SPA tube core with rough bed, (c) SPA piston with dual gauge (d) 5.0 mm thick soil protrusion in rough bed, and (e) Schematic diagram of SPA.

Preliminary tests were carried out for average grain size diameter, d_{50}=0.303 mm sample under wet conditions as outlined in Table 1. Experiments were repeated at least 3 times for each test condition to ascertain reproducibility and representability of observations. Longitudinal (l_1) and lateral (l_2) erosion spreading of the sediment plumes were recorded via a HD Sony digital video camera (1920×1080, 24 frames per second). This facility enabled observations to be recorded at preset times and hence the sediment transport rate and scour patterns were continuously monitored. The flow rate (Q) was adjusted as desired through a control of the voltage input into the pump. Propeller type current meters (0.06-1.5 m/s) were used in the upstream and downstream of the tank to monitor the uniformity of the flow and its measurements. Detailed experimental set-up and procedure is explained in Jayaratne et al. (2010b).

Table 1. Test conditions used in the preliminary experiments.

Parameter	Value/ Condition
Average grain diameter, d_{50} (mm)	0.303
Soil condition (-)	Wet
Soil protrusion, z (mm)	1.0-5.0
Flow rate, Q (l/s)	1.65-3.57

2.2. Physical Model

Previously, laboratory experiments on soil-water interaction for 3 different diameters of soils under wet and dry conditions were carried out in the same moveable sediment tank (Jayaratne et al., 2010a). Based on the experimental results, it was found that the soil of same diameter under wet and dry conditions gives significant changes in sediment transport rate and to its erosion pattern. Transport rates were much slower in dry condition than that of wet condition. It was observed that for the same flow condition, different soils give different long term equilibrium deposition patterns due to the grain size distribution and particle shape.

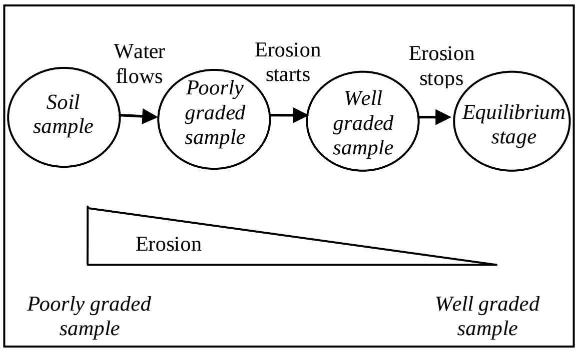

Figure 2. Identification of different erosion stages during experiments.

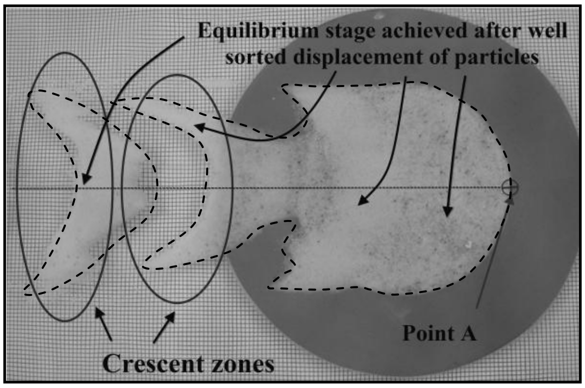

Figure 3. A photographic view of 'crescent' deposition zones developed on smooth bed (d_{50}=0.303 mm, Wet soils, z=5.0 mm, Q=3.57 l/s).

Wake vortices were generated behind the soil samples which resulted in forming a series of 'crescent' zones. The process of sediment deposition during scour process was identified through the laboratory observations on smooth plastic sediment bed (see Figs. 2 & 3).

2.3. Mathematical Model

A simple mathematical model was developed for erosion rate in terms of measured flow and sediment parameters using dimensional analysis and best-fit technique (Jayaratne, 2004). Calibration coefficient for this model is applicable for smooth bed flow calculations and model dimensionless parameters are given in Eq. (1).

$$\frac{q_s}{d_{50}\sqrt{d_{50}g(s-1)}} = f\left[\frac{\tau_s}{\rho g d_{50}(s-1)}, \frac{z}{d_{50}}\right] \quad (1)$$

where:

d_{50} = Median particle size of soil sample (m)

g = Acceleration of gravity (m/s^2)

q_s = Volumetric total sediment transport rate (m^2/s) per metre width

s = Specific density (ρ_s/ρ)

z = Thickness of the sample (m)

ρ = Density of water (kg/m^3)

τ = Bed shear stress (N/m^2)

3. Current Practice

To extend the investigation of the proposed physical and mathematical models described in previous papers by the authors, modification of the SPA was urgently required. To increase the roughness of the plastic flume to a greater value, a low cost technique involving spraying separate solutions of sodium silicate (Na_2SiO_3) and sodium bicarbonate ($NaHCO_3$) on to a drained sediment bed will be used to freeze the soil bed geometry (Benson et al., 2001).

The benefits of using this low cost technique are (1) equipment and materials costs are low, and (2) less hazardous from a health and safety point of view.

3.1 Preparation of the Freeze Sediment Bed (Rough Bed)

The quantities of chemicals per coat estimated to be used for immobilising are given in Table 2. Two separate sprayers will be used in applying the chemicals, one for the sodium silicate solution (Na_2SiO_3) and one for the sodium bicarbonate solution ($NaHCO_3$). The tank which will be frozen is drained. After 12–24 hours, while the sediment will remain visibly slightly damp, the first coat will be applied over the whole area. Sodium silicate and water will be mixed in the sprayer itself, but the sodium bicarbonate solution will be made separately beforehand in order to prevent un-dissolved lumps entering the sprayer. Care will be taken to achieve a fine spray and keep the spray moving across the bed so as not to disturb the loose sand, especially on the first coat. It is essential that the two mixtures would be applied directly to the sand with separate sprayers to avoid mixing the chemicals until they are actually in the sediment.

	Sodium silicate mixture (Na_2SiO_3)	Sodium bicarbonate mixture ($NaHCO_3$)
Volume of chemical	0.33 litres	-
Mass of chemical	0.48 kg	12 g
Volume of water	0.27 litres	0.21 litres
Approx. total volume	0.6 litres	0.21 litres

Table 2. Relative quantities of chemicals used for bed freezing, sufficient to cover 2.4 m^2 (4.0×0.6) with one coat.

3.2 Preliminary Test Results

A complete set of preliminary experiments for d_{50}=0.303 mm sample was performed to compare and further investigations on soil-water interaction under rough bed. The soil sample was visualised initially by introducing Potassium Permanganate ($KMnO_4$) dye into the soil (see Fig. 4). The preliminary experiments were conducted without freezing the soil geometry.

Physical observations on preliminary tests showed an integration of crescent zones formed (see Fig. 5 & 6) while draining the sediment bed as described in Jayaratne et al. (2010a).

The hydraulic shear stress, τ_s exerted by the water flow on the bed sand is as given in Eq. (2) and can also be obtained graphically using the diagram given by Moody (1944).

$$\tau_s = \frac{1}{8}\lambda\rho U^2 \qquad (2)$$

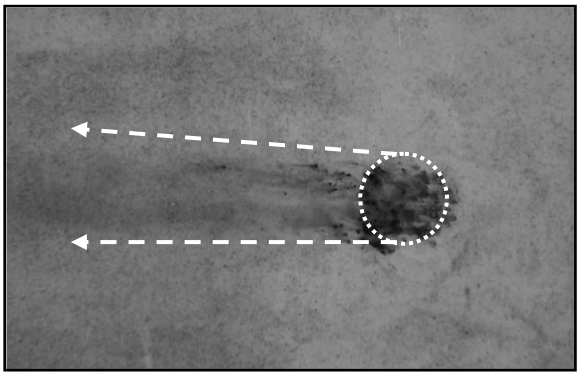

Figure 4. Visualised soil sample using $KMnO_4$ dye.

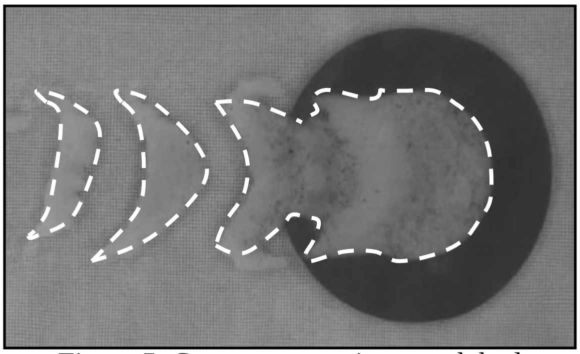

Figure 5. Crescent zones in smooth bed (d_{50}=0.303 mm) at equilibrium stage.

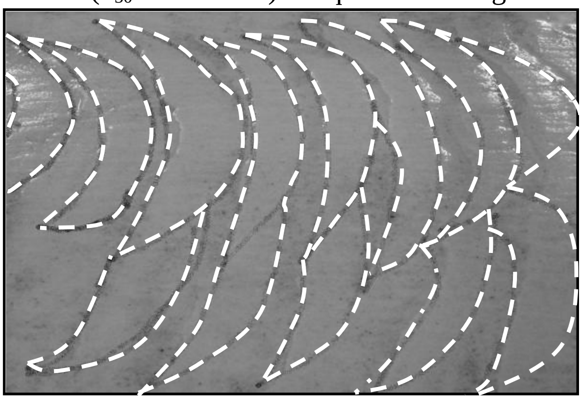

Figure 6. Integrated crescent zones in rough bed (d_{50}=0.303 mm) at equilibrium stage.

Where λ is friction factor read from Moody diagram knowing the appropriately chosen bed roughness and Reynolds number (the fluid flows in the study have Re=2.0×10^4-4.0×10^4 and therefore in the turbulent regime), ρ is the water density and U is the water velocity

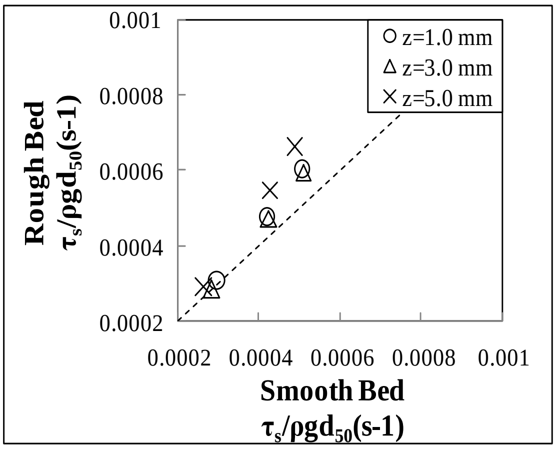

Figure 7. Comparison of dimensionless shear stress for smooth and rough beds.

Figure 7 illustrates the non-dimensional shear stress is higher in rough bed in comparison to the smooth bed over a range of different cases.

Figure 8 shows that the trend is for erosion rate to be higher for smooth bed than for rough bed, particularly for the highest protrusion cases, although little difference was noted for the protrusion cases. It should be noted that since the sediment bed was not frozen during the preliminary experiments; difficulties were encountered in collecting the eroded sand from the bed.

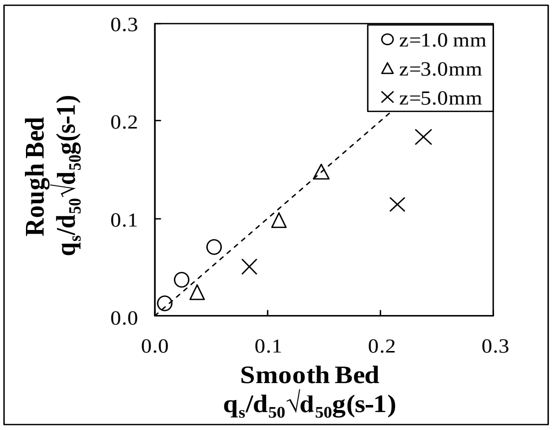

Figure 8. Comparison of dimensionless erosion rate for smooth and rough beds.

4. Conclusions

Preliminary laboratory experiments on sand-hydrodynamic interaction for d_{50}=0.303 mm sample was carried out in a movable sediment tank model rough bed conditions. Results from the tests indicate that shear stress is higher in rough sediment bed in comparison to the smooth bed. On the other hand, erosion rate is higher in smooth bed than that of rough bed. After freezing the sediment bed, soil samples with diameters will be used in the experiments which will lead to the development of a set of predictive curves of erodibility for different diameters and validate the proposed mathematical model for rough bed. Moreover, in the drained sediment tank, integration of crescent zones were observed which explains the similar behaviour of crescent zones as described in previous papers by the authors. A detailed investigation will be conducted to better understand the integrated crescent zones and to simulate the field conditions.

5. Future Investigation

The sediment bed will be frozen using low cost technique as described in Section 3 to increase the roughness of the bed. Five average grain diameters under rough sediment bed conditions will be used to propose a mathematical model and simulate prototype conditions. Quantitative parameters to define the patterns of the vertical and lateral spread of the plumes of eroded soils with respect to roughness will also be established.

Erosion rate prediction analysis will be investigated using computer programmes such as, Hydrologic Engineering Centre's River Analysis System (HEC-RAS), Mike 21 and Fluvial12 for the better representability of previous mathematical and physical model. Particle size data from previous experiments will be used in software analysis in order to analyze whether the flow induced bed shear stress is high enough for erosion or low enough for deposition, based on the size of the particles in the stream bed.

Acknowledgement

The authors are grateful for the financial support provided by the Graduate School of University of East London (UEL) to carry out the laboratory experiments in line with the extensive research project *"Mathematical and Physical Modelling of Hydrodynamic Erosion of Soils (HES)"* set up under *"UEL Promising Researcher Fellowship (2009-2010)"*.

Notation

d	average sediment diameter (subscripts indicate percent finer)
g	acceleration due to gravity
l_1	longitudinal spreading length of sediment
l_2	lateral spreading length of sediment
Q	flow rate
q_s	erosion rate
Re	Reynolds number
s	specific gravity
U	water velocity
z	soil protrusion
λ	friction factor
ρ	density of water
τ_s	bed shear stress

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