INCIPIENT MOTION OF SEDIMENT IN OPEN CHANNEL: A COMPARISON BETWEEN LABORATORY DATA AND SITE OBSERVATION

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Abstract: This paper aims at evaluating whether the design criteria based on critical velocity or critical shear stress is more suitable for the purpose of self-cleansing in open concrete drain. Experimental work on incipient motion was done in rectangular flume with two different widths namely 0.3 m and 0.6 m. The results from the incipient motion experiment were compared with a short-term on-site observation on the erosion and deposition pattern in a stretch of urban open concrete drain located in a residential area in Kuching, Sarawak, Malaysia. Comparison with site observation has shown that the relationship between mean critical velocity with median grain size; $V_c = 0.075d_{50} + 0.246$ developed from the experimental work predicts reasonably well when erosion starts to occur on site. The critical shear stress values obtained from the experimental work tend to under predict when compare with the values from site observation. Thus, the mean critical velocity is a much better criterion to be used in the design for open concrete drain for self-cleansing purpose.

Keywords: *critical velocity, critical shear stress, deposition, incipient motion*

Introduction

Sediment deposition in urban open drain which reduces the hydraulic capacity of the drain has been identified as one of the factors causing flash flooding in urban area. To reduce sedimentation, a constant minimum velocity of 0.9 m/s has been recommended by the Department of Irrigation and Drainage (DID) Malaysia for self-cleansing design purposes (Ab. Ghani *et al.*, 2008). The adoption of a constant minimum value might be successful in many cases; however it does not take into account the characteristics of the sediment and the hydraulic aspect of the channel (Butler *et al.*, 2003).

In determining the suitable constant minimum value for self-cleansing design, a number of researchers have attempted to quantify velocity or shear stress threshold for sediment deposition and erosion. The study in Germany has shown that significant deposition occurs for shear stress below 1.8 N/m^2, while no sedimentation for shear stress exceeding 4 N/m^2 (Stotz and Krauth, 1984, Stotz and Krauth, 1986). Study in Dundee also shows that bed shear stress of about 1.8 N/m^2 is responsible for bed erosion while subsequent reduction in bed shear stress will results in deposition (Ashley *et al.*, 1992). The American Society of Civil Engineers has proposed 0.9 m/s for storm sewer while the British Standard proposed 0.75 m/s and 1.0 m/s respectively for storm and combined sewer (Nalluri and Ab. Ghani, 1996). However, it is argued that since the rate of sediment transport cannot be uniquely determined by shear stress, it is questionable whether critical shear stress should be used as the criterion for incipient motion (Yang, 1996) in self-cleansing design.

This paper presented the incipient motion results through experimental work in two rectangular channels with different width using sediment size commonly found in Malaysian urban concrete drain. The critical velocity and shear stress results from the experimental work were compared with the short-term monitoring of sediment erosion and deposition pattern in an urban concrete drain. The findings will determine whether the criteria based on critical velocity or critical shear stress is much suitable to be adopted.

Methodology

The experimental work involves a rectangular open channel flume with the dimensions 6 m (L) x 0.6 m (W) x 0.4 m (D) as show in Figure 1. The velocity and discharge values in the channel was obtained from an electronic current meter which could be further verified with the discharge calculated from the V-notch installed downstream of the channel.

Figure 1: General overview of the flume

The non-cohesive sediment used has d_{50} sizes of 0.81 mm, 1.53 mm and 4.78 mm with a specific gravity of 2.54, 2.55 and 2.57 respectively. The sediment used has a geometric standard deviation σ_g value of 1.31 for d_{50}=0.81 mm (uniform sand); σ_g value of 2.63 for d_{50}=1.53 mm (slightly nonuniform for mixture of sand and gravel) and σ_g value of 1.27 for d_{50}=4.78 mm (uniform gravel). The experiment was run at four different slopes (1/200, 1/350, 1/500 and 1/1000) and at four different sediment deposit thickness (d_{50}, 5 mm, 10 mm, 24 mm). The selection of sediment size, slope and sediment deposit thickness was based on site observations at 68 urban locations around the state of Penang, Kuching city and surrounding urban areas in the state of

Sarawak, Malaysia done prior to the experiment so as to simulate on-site condition as close as possible.

In running the experiment, the sediment was placed and levelled to the required thickness at the location as shown in Figure 2. The test section/observation section for the sediment samples was of 0.6 m (L) x 0.6 m (W) while an extension of about 1 m of the sediment samples upstream of the test section was to reduce the effect of sudden change of channel bed material. Before the pumps were turned on, the sediment sample was moistened by filling the flume with water from a water hose so as to minimise the initial filling surge. Water level and discharge was slightly increased while uniform flow was maintained. This was repeated until some particles moved. The definition used in this experiment is of general movement as defined by Kramer (1935) via visual observation.

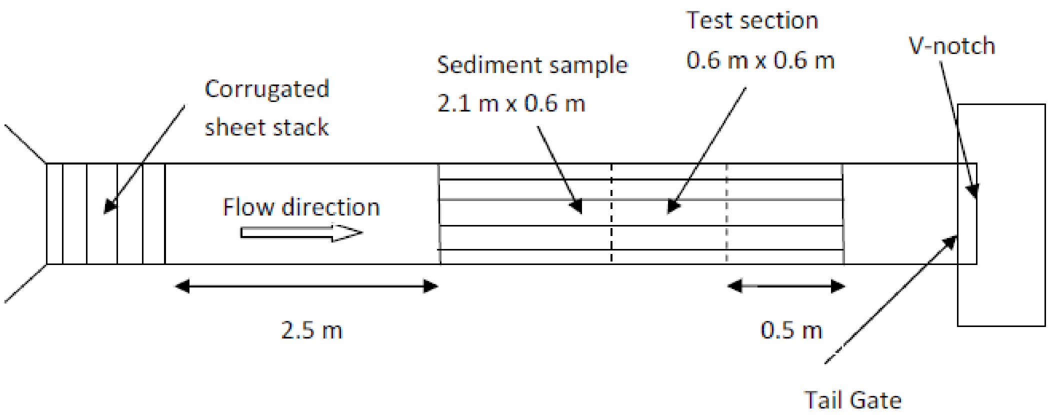

Figure 2: Schematic diagram for the flume

Another set of experimental data was obtained from Salem (1999) where a rectangular flume with dimensions 10 m (L) x 0.3 m (W) x 0.45 m (D) was used. In Salem (1999) data, the non-cohesive uniform sediment used has d_{50} sizes of 0.55 mm, 0.97 mm, 1.80 mm, 3.09 mm and 4.78 mm and specific gravity ranging from 2.301 to 2.569. The experiment was run at six different slopes (1/500, 1/600, 1/750, 1/1000, 1/1200 and 1/1700) with four different thickness (d_{50}, 5 mm, 10 mm, 24 mm). The definition used by Salem (1999) for incipient motion was also of general movement as defined by Kramer (1935).

For the on-site short-term monitoring and observation, a residential area in Kuching, Sarawak was chosen (see Figure 3). The chosen stretch of concrete drain has a length of 10 m where greywater from the households as well as partially treated blackwater from septic tanks and also stormwater flows into this drainage system. The catchment area for the chosen stretch of drain is about 1.5 hectares comprising of 26 houses (14 semi-detached and 12 detached houses). About 75% of the catchment area is impervious.

The slope of the chosen drain was determined as 0.00716 m/m and the drain is of trapezoidal shape with the dimensions of 0.82 m (depth) x 0.224 m (bottom width) x 1.13 m (top width). Some sediment samples were also taken for sieve analysis and specific gravity test. During the monitoring, sediment depth and water level was measured three times daily for the period of 20th August 2011 to 27th August 2011 using a simple stick. The measurement was made at 6.30 am, 12.30 pm and 6.30 pm daily. Rainfall data was obtained from the Department of Irrigation and Drainage (DID), Malaysia website (http://infobanjir.water.gov.my) which provide hourly rainfall data for the closest rainfall station (Kuching Third Mile, Station ID: 1503083) which is about 5 km away from the site.

Figure 3: Satellite image of the site with insert photo showing the chosen drain stretch

Results and Discussion

Figure 4 shows a plot of the median grain size d_{50} used in this study against the mean critical velocity V_c when general movement was observed in the experimental flumes. A region of incipient motion was also developed showing the upper bound and lower bound of the data where incipient motion occurred. The lower bound of the region (black color line) provided in Equation (1) and Equation (2) could be use for self-cleansing design purposes provided the size of the expected sediment is known.

$$d_{50} = 13.258V_c - 3.263 \quad (1)$$

or

$$V_c = 0.075d_{50} + 0.246 \quad (2)$$

The distance between upper bound and lower bound line shows the range of median diameters that could be associated with a single mean critical velocity value. Figure 4 also shows that the data of mean critical velocity from the wider rectangular flume (0.6 m width) seems to still falls within the incipient motion region of the data from the narrower rectangular flume (0.3 m width). This means there was no geometric influence in terms of the flume dimensions towards the mean critical velocity.

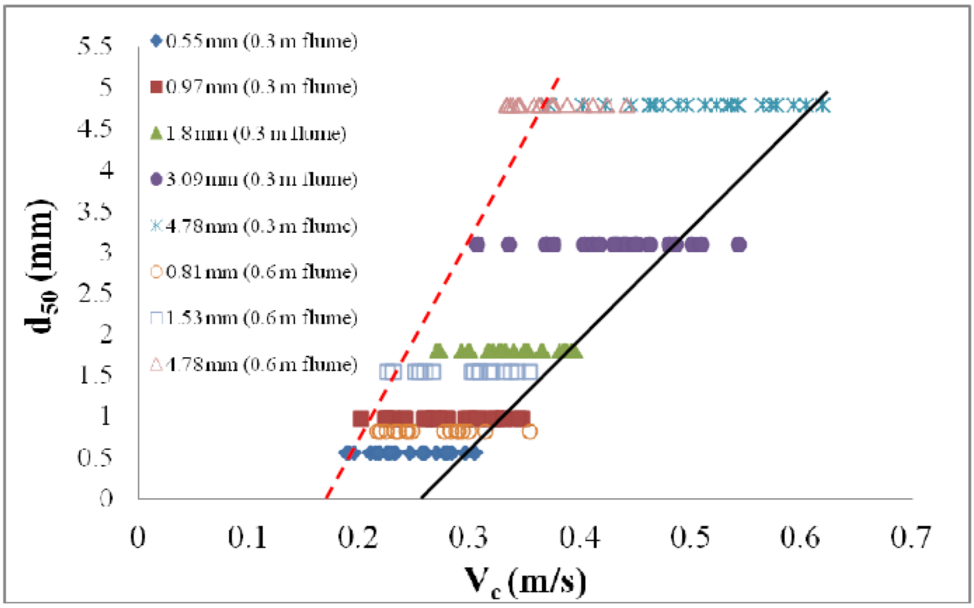

Figure 4: Mean critical velocity as a function of median sediment size

Figure 5 shows the plot for median grain size d_{50} against the mean critical shear stress. The mean shear stress was calculated using the relationship $\tau_c = \gamma RS$; where τ_c is the mean shear stress, γ is the specific weight of fluid, R is the hydraulic radius and S is the channel slope. Much higher mean critical shear stress values were observed in the wider rectangular flume. This could be due to the steeper slopes used in the wider flume experiment making the value calculated for τ_c becomes larger. Existing literatures actually suggest that the critical shear stress values increase with increasing slope (Neill, 1967, Lamb *et al.*, 2008) which contradicts with theoretical models which suggest that sediment should become more mobile as slope increases due to increased in the component of gravity in the downstream direction (Wiberg and Smith, 1987). Lamb *et al.* (2008) suggested the grain emergence and changes in local flow velocity and turbulent fluctuations might be the reason for the slope dependency due to the coincident increase in the ratio of bed roughness scale to flow depth. Incipient motion was also found to be slope dependent even on low slopes $(S < 0.01)$ and small particles size $(\mathrm{Re}_p < 10^2)$ (Shvidchenko and Pender, 2000, Shvidchenko *et al.*, 2001). However, detail study on the influence of channel bed slopes on the critical shear stress values is beyond the scope of this paper.

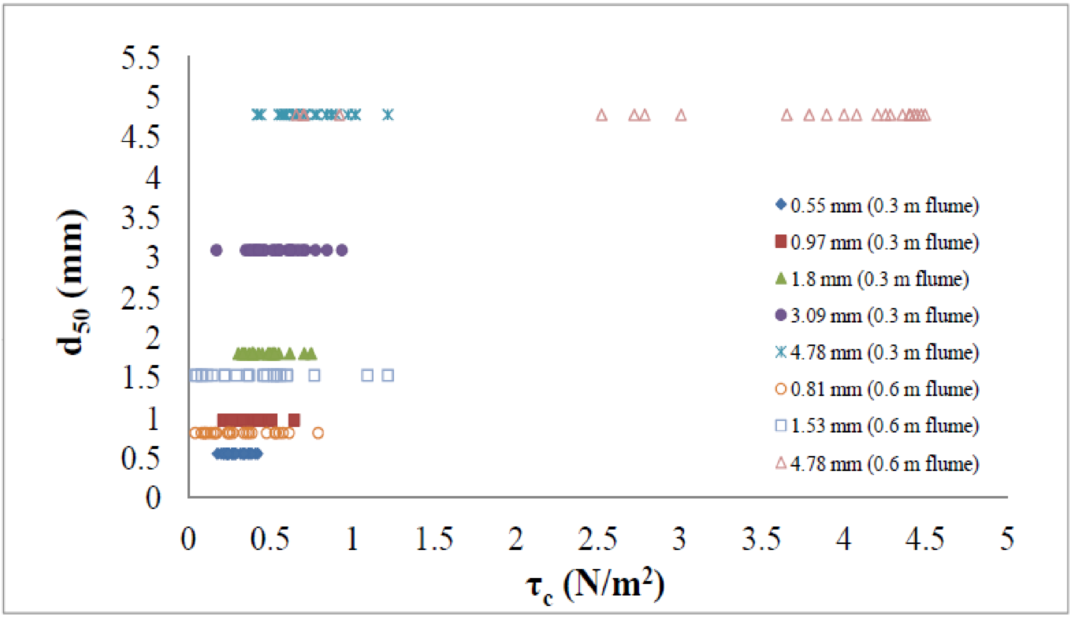

Figure 5: Mean critical shear stress as a function of median sediment size

Figure 6 shows the sediment characteristics from the study area. The sample has a median grain size d_{50} of 0.75 mm. The component of the sample was 67.8% sand, 31.8% gravel and 0.4% silt and clay with the specific gravity of 2.5.

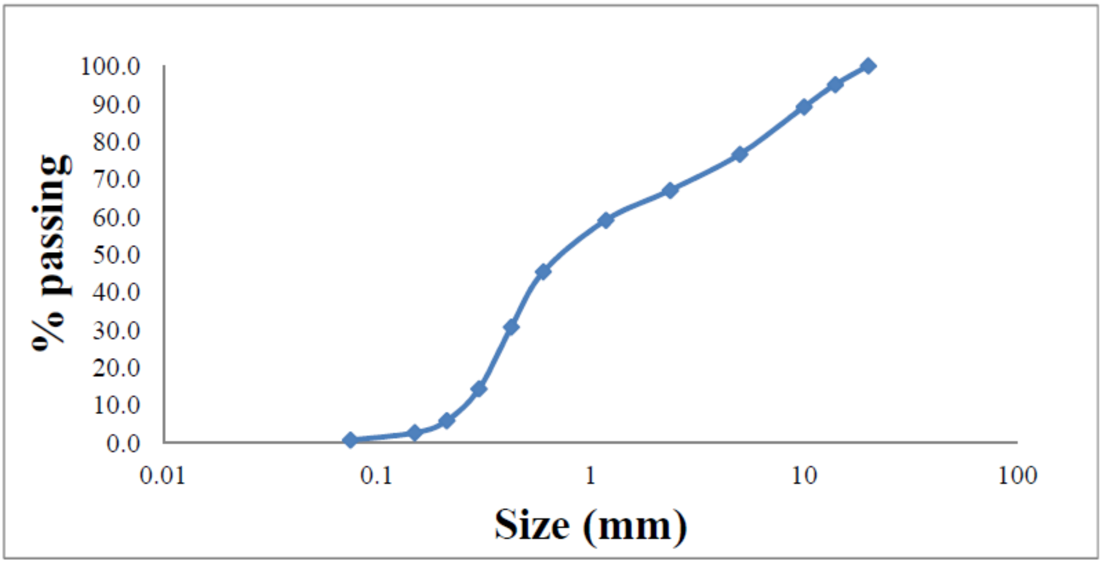

Figure 6: Size distribution of sample from the study area

From the drain geometry, slope and water level, the mean velocity during certain time of observation could be calculated using the Manning's equation by assuming the Manning's roughness coefficient as 0.030 due to the presence of sediment deposits (Ab. Ghani et al., 2008). Figure 7 shows the variation of sediment depth with mean velocity and mean shear stress between the periods of 20th August 2011

(Saturday) to 27th August 2011 (Saturday). Higher mean velocity and shear stress was observed on 23rd August 2011 (Tuesday) which was due to rainfall. Erosion was observed for mean bed shear stress value higher than 2.6 N/m^2 with the reduced in sediment depth. Except for on the 23rd August 2011 at 6.30 pm; the mean velocity on the rest of the observations varies between 0.27 m/s and 0.34 m/s and the mean bed shear stress between 2.1 N/m^2 and 3.0 N/m^2.

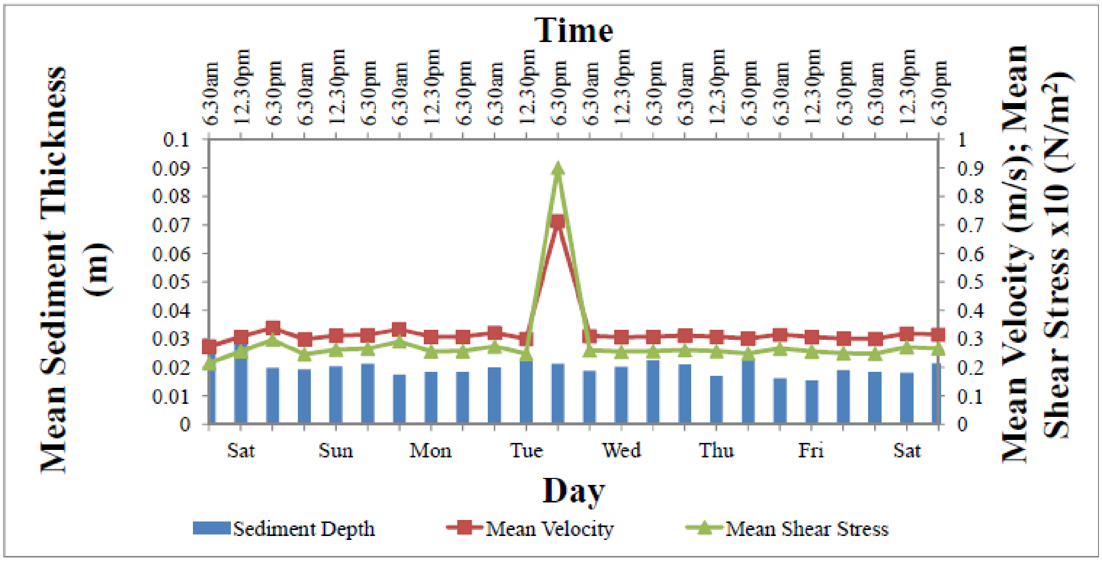

Figure 7: Mean sediment depth with mean velocity and mean bed shear stress

By using Equation (2), for median grain size d_{50} of 0.75 mm, the critical velocity for erosion of sediment is 0.3 m/s. Evaluating Figure 7 will shows that sediment depth in the observed drain will be reduced when the velocity is above 0.31 m/s such as on the first Saturday (6.30 pm), Monday (6.30 am), Tuesday (6.30 pm), Wednesday (6.30 am), Thursday (12.30 pm) and Friday (6.30 am). This confirm that the graph from Figure 4 on mean critical velocity as a function of median sediment size and Equation (2) developed from experimental work could be used to predict when erosion starts in the design of open concrete drain.

As for the use of critical shear stress to predict erosion, the site observation shows that erosion starts to happen when mean bed shear stress is above 2.6 N/m^2. However, from the results of the experimental work, the value of critical shear stress obtained from the 0.3 m wide flume shows that for median grain size of 0.97 mm (the closest value to the size from the study area of 0.75 mm), is between 0.21 N/m^2 to 0.64 N/m^2. If these values were used in the design of open concrete drain, it will under predict the incipient motion value for the sediment. The values given by the wider 0.6 m wide flume which is between 0.04 N/m^2 to 0.79 N/m^2 for median sediment size of 0.81 mm (the closest value to the size from the study area of 0.75 mm) also under predict the mean critical shear stress.

Conclusions

The results from experimental work when compare with site observation had shown that the relationship obtained for the mean critical velocity with median sediment grain size $V_c = 0.075 d_{50} + 0.246$ from the experimental work predicts reasonably well when erosion starts to occur on site. In contrast, the critical shear stress values obtained from the experimental work under predict the occurrence of erosion on site. Thus, the mean critical velocity is a much better criterion to be used in the design for open concrete drain for self-cleansing purpose.

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