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Technical Note

Local scour around non-circular piers in clay–sand mixed cohesive sediment beds

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ABSTRACT

Few investigations on local scour around circular piers embedded in clay–sand mixed cohesive sediment beds are available in the literature. However, no study has been reported on the local scour around non-circular piers such as round-nosed, square and rectangular piers embedded in clay–sand mixed cohesive beds. In the present investigation, laboratory flume based experimental data on local scour around round-nosed, square and rectangular pier models embedded in clay–sand mixed beds are reported. The effect of clay-content, water content and bed shear strength of the clay–sand mixed sediment bed on the scouring process, the scour hole geometry, the time variation of scour are described. In general, for circular piers embedded in non-cohesive sediment beds, equations are available in the literature for estimation of maximum equilibrium scour depth as a function of bed sediment and flow characteristics. The maximum equilibrium scour depth for the non-circular piers are obtained by multiplying the maximum equilibrium scour depth for circular piers with the correction factor for each pier shape. The data suggested that for clay and clay–sand mixtures, the shape correction factors are not constant values similar to that for the non-cohesive sediments, rather, these shape factors varied between certain ranges.

1. Introduction

Failure of bridges due to scour at their supports is a common occurrence. Many studies are available in the literature encompassing various aspects of bridge pier scour in non-cohesive sediment beds including shape effects (e.g., Tison, 1940; Chabert and Engeldinger, 1956; Laursen and Toch, 1956; Venkatadri et al., 1965; Melville and Sutherland, 1988; Breusers and Raudkivi, 1991; Richardson et al., 1993; Melville, 1997; Raudkivi, 1998 and many others). On the contrary, studies on local scour around piers on cohesive sediment beds are rather inadequate (Briaud et al., 1999; Molinas and Hosny, 1999; Ting et al., 2001; Ansari et al., 2002; Debnath and Chaudhuri, 2010a,b). All the above studies on pier scour in cohesive sediment beds were carried out on circular piers. In the literature, the equations for estimation of maximum equilibrium scour depth (y_s) around circular piers appear as function of flow and bed sediment characteristics for non-cohesive sediments (Melville, 1997). The value of y_s thus obtained for circular piers are multiplied by shape correction factor (K_{sh}) for estimation of the y_s around piers of different shapes. Thus the shape correction factor K_{sh} is defined as the ratio of y_s for a non-circular pier over the y_s for the circular pier embedded in sediment with similar characteristics and subjected to similar flow characteristics (e.g., Briaud et al., 2004).

Existing literature revealed that the shape of the obstruction to the flow can strongly affect the flow pattern around it. For example, Tseng et al. (2000) reported that the strength of the downflow, horseshoe vortex and the wake vortex are greater in the case of square piers compared to circular piers. The results in scour depths for square piers to be greater than circular piers as reported for non-cohesive [e.g., HEC-18 (Richardson and Davis, 2001)].

All studies on pier scour in cohesive beds (clay or clay–sand mixed beds) reported results for only circular piers barring Briaud et al. (2004). The study by Briaud et al. (2004) reported results of four experimental runs on rectangular piers embedded in pure clay beds (cohesive bed) with zero angle of attack. In these four runs, L/D of the rectangular pier was varied and were taken as 1 (i.e., square), 4, 8 and 12, keeping all other parameters constant, where $L=$ streamwise length of pier; and $D=$ transverse width of pier (for circular pier $D=$ diameter of the pier). Noticeable effect on y_s due to pier shape was not observed. Indeed, K_{sh} varied from 1.1 to 1.12 in their experiments. These results of Briaud et al. (2004) were consistent with the correction factor for non-cohesive sediments listed in HEC-18 (Richardson and Davis, 2001). Briaud et al. (2004) proposed a correction factor of 1.1 for rectangular piers in clay for $L/D>1$. However, the experiments reported in Briaud et al. (2004) on the effect of pier shape were conducted on pure clay beds and not on clay–sand mixtures and

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the approach flow velocity (V) was rather low ($V = 0.33$ m/s). Thus investigation on non-circular piers (e.g., square, rectangular and round-nosed piers) needs to be carried out on clay–sand mixed cohesive sediment beds with different proportions of clay.

When the material comprising the sediment bed is coarse and non-cohesive, it is mainly the submerged weight of the sediment particles that resist erosion (Raudkivi, 1998). The erosion of clayey/muddy sediment is influenced primarily by cohesion due to physiochemical forces, which include van der Waals attraction, electrical double-layer repulsion, and the net attraction arising from chemical cementation at the grain contacts (Raudkivi, 1998). Fine sediment particles ≤ 63 μm (i.e., particles in clay and silt range according to Wentworth sediment size scale) are mainly responsible for the muddy or the cohesive nature of these sediments (e.g., Mitchener and Torfs, 1996; Debnath et al., 2007a,b). These cohesive or muddy sediments exist in the form of flocs or group of flocs (called floc aggregate) or individual particles (McAnally and Mehta, 2002). Entrainment or transportation of particles from cohesive sediment beds occurs when flow induced shear breaks all the interparticle bonds connecting an aggregate or floc or individual particle in its neighborhood. Erosional properties of combined mud and sand is a direct function of relative proportions of sand and mud (Debnath et al., 2007a,b; Debnath and Chaudhuri, 2010a,b; Debnath and Chaudhury, 2010). It was found that the mode of erosion changes from cohesionless to cohesive at low proportion of mud added to sand. This transition occurs in the range 0.03–0.15 mud by weight, depending on different compaction level of the mixture, water content and clay mineral type (Mitchener and Torfs, 1996). Here, mud is defined as particles less than 63 μm in size, i.e., clay and silt. Further, Debnath and Chaudhuri (2010a) reported results of scouring experiments on circular piers embedded in cohesive sediments (kaolinite clay) with clay fraction (C) ≈ 0.2–1 and water fraction (W_c) ≈ 0.20–0.46 of the dry weight of the clay–sand mixture. They concluded that for $W_c < 0.24$, the values of y_s decreased with increase in C of the clay–sand mixture. For $W_c > 0.27$, with increase in C, at first the y_s decreased up to $C \approx 0.5$–0.7 and thereafter increased; and these trends were consistent with the shear strength of the sediment mixtures. Detailed physical explanations of the observed trends are reported in Debnath and Chaudhuri (2010a).

Molinas and Hosny (1999), Ansari et al. (2002) and Debnath and Chaudhuri (2010b) also reported strong dependence of C and W_c on maximum equilibrium scour depth in piers. With the above, it is evident that C and W_c play significant roles in local pier scour for clay–sand mixed cohesive beds. The mechanism of scour hole development, y_s and scour hole geometry as functions of C and W_c of the clay–sand mixture has not been explored for non-circular piers. In the present investigation, we have reported data from 79 experimental runs out of which, 26 experimental runs were carried out on round-nosed pier, 30 runs on square pier and 23 runs on rectangular pier, respectively. These shapes were chosen because these shapes are the common shapes that are used in the bridge foundation design. The experiments of the present study have been carried out on cohesive sediment beds having $C \approx 0.35$–1 and $W_c \approx 0.279$–0.423 in the clay–sand mixture and with $V \approx 0.490$–0.820 m/s. The results from these experiments have been used to describe, the mechanism of scour, time variation of scour, maximum equilibrium scour depth and scour hole geometry as functions of C and W_c of the clay–sand mixture. The present local scour experimental results on round-nosed, square and the rectangular piers were compared with that of the results of circular pier. These comparisons are based on the circular pier experiments reported in Debnath and Chaudhuri (2010a).

2. Experimental set-up and procedure

Experiments reported in this paper were conducted at the 18.3 m long, 0.9 m wide and 0.9 m deep tilting flume (kept at constant slope = 0.001) located in the Fluid Mechanics and Hydraulics Laboratory, Bengal Engineering and Science University, Shibpur, India (Figure 1a). Detailed description of the experimental set-up can be found in Debnath and Chaudhuri (2010a,b).

The mean velocity profile could be approximated well by the log law for smooth boundary (e.g., Nezu and Nakagawa, 1993)

$$\frac{\bar{u}}{u_*} = \frac{1}{\kappa}\ln\left(\frac{u_* z}{\nu}\right) + 5.5 \tag{1}$$

where z = vertical distance from the bed, $\bar{u}$ = time averaged stream wise velocity at z, u_* = shear velocity, κ = von Karman constant and ν = kinematic viscosity of water. Therefore, V was approximated by measuring the mean velocity with Micro-ADV at $0.2y$ and $0.8y$ and averaging them similar to Ting et al., 2001 (Tables 1–3), where y = approach flow depth. Transparent pier models made of perspex having round-nosed cross-section (Figure 1b), square cross-section (Figure 1c) and rectangular cross-section (Figure 1d) have been used in the experiments. The stream-wise and the transverse width of the round-nosed, the square and the rectangular piers are furnished in Fig. 1b, c and d, respectively. For all the three non-circulars piers used in the present study, $D = 0.12$ m was adopted for comparison of different scour hole geometrical parameters as well as scouring processes with that of the circular pier having $D = 0.12$ m (Figure 1e). Vertical graduated tapes glued at 0° (front), 90° (left side), 180° (behind), and 270° (right side) were attached in all the pier models (Figure 1b–e). In addition, for the square (Figure 1c) and the rectangular (Figure 1d) piers additional tapes were attached at 45° (left side front corner) and 315° (right side front corner). An NB Pro-Logitech camera connected to a computer was installed inside the pier models for recording y_{st} as a function of time, t at regular time intervals against the scales where y_{st} = the scour depth at t. The camera could clearly detect the interface between the water and sediment at the locations on the wall of the pier where scales were attached for recording the time variation of scour depth.

Cohesive material (kaolinite clay), mixed with fine sand having $d_{50} = 0.182$ mm and $\sigma_g = (d_{84}/d_{16})^{0.5} = 1.37$; was used for the experiments where d_{16} = diameter for which 16% by mass of sediment is finer; and d_{84} = diameter for which 84% by mass of sediment is finer. The specific gravities of the fine sand and the kaolinite clay were 2.65 and 2.62, respectively. Particle size analysis of the kaolinite clay and the sand is shown in Fig. 2a, b, respectively. The cohesive material (kaolinite clay) used in this study also contained sand sized particles in small proportions. In general, these fine sediments will be referred to as clay as was done by others (e.g., Molinas and Hosny, 1999; Ting et al., 2001 and Ansari et al., 2002; Debnath and Chaudhuri, 2010a,b) in pier scour experiments using cohesive sediments. The other properties of the cohesive soil were: Liquid limit (W_L) = 0.49; Plastic Limit (W_P) = 0.26; Plasticity index (PI) = 0.23; maximum dry unit weight ($\rho_{d_{\max}}$) = 1830 kg/m^{-3}; Optimum moisture content (OMC) = 0.2; bed shear strength, τ_s at optimum moisture content = 12.77 kN/m^2; and specific surface area = 2.36 m^2/g. At first, the cohesive material and sand were manually mixed homogeneously in desired proportion. Water by weight in percentage of dry mixture was then added to the homogeneous mixture in a container and mixed thoroughly by hand. Finally, it was made to pass through a 5 mm sieve to ensure uniformity of mixing before laying around the pier at the sediment recess in layers of approximately 0.05 m. Each layer was compacted manually by freely dropping a 2.55 kg hammer of base diameter 0.075 m from a height of 0.3 m, 500 times (approximately). After each layer was compacted, the top surface of the compacted layer was roughened to improve bonding between layers. For the final layer, the extra sediment (approximately 0.01 m thick) was chiseled off and finally made smooth with the help of a wooden trowel. Before an experimental run was commenced, τ_s was measured by vane method, and bulk density sample was collected from a downstream location at the corner of the sediment recess (Tables 1–3). The bulk density (ρ_b), dry density (ρ_d) and W_c of the bed were determined using standard procedure (Tables 1–3) based on these samples.