# Dimensional Analysis and Multiple Regressions of Experimental Results to Predict the Equilibrium Scour Depth Around Circular Pier in Mixed Cohesive Beds

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**Abstract**

New experimental data on scouring to predict the maximum equilibrium scour depth around circular pier embedded in clay-sand mixed cohesive beds are reported. Existing literatures on scouring around circular pier in pure cohesive clay beds suggested that the maximum equilibrium scour depth is almost similar to that of sand bed, while increase in the clay fraction for clay mixed sand beds reduced maximum equilibrium scour depth. The present study attempted to fill this contradiction of observations made by different investigators on scour around circular pier in pure clay and clay-sand mixed cohesive sediment beds, by analyzing a wide range of flume based experimental data. Dimensional analysis of major parameters responsible for pier scour around bridge pier was done to propose empirical equations to estimate non-dimensional maximum equilibrium scour depth around circular pier embedded in clay-sand mixed cohesive sediment beds through, as functions of pier Froude number, clay content of the sediment bed, water content, and bed shear strength.

**Keywords -** Scour depth, Clay-sand, Dimensional analysis, Mixed cohesive beds, Multiple regressions, Pier scour.

## Introduction

The perturbation of the flow field caused by a cylindrical obstruction (e.g., circular bridge pier) in rivers and streams introduces a complex flow field marked by turbulent structures such as horseshoe vortex, surface rollers, and wake vortices (Ettema *et al.*, 2006). Thus, high concentration of velocities, bed shear stresses, vortices, down-flows, and turbulence occur at the nose of the pier, which propagates downstream. The combinations of these factors lead to the removal of bed sediments from the base of the pier and form a local scour hole. For example, this phenomenon causes undermining of bridge foundations and has resulted in more bridge failures than all other causes in history (Briaud *et al.*, 1999). Under-prediction of scour depth can lead to costly bridge failures, while over-prediction can result in unnecessary expenditure in terms of construction costs. Therefore, an accurate estimation of maximum equilibrium scour depth around bridge piers is required for the stability of bridge and also to make a precise construction cost with no extra expenditure. Therefore, the prediction of maximum equilibrium scour depth is of immense importance for both the engineers and geo-scientists. Figure 1 reveals the conceptual model of flow patterns and components responsible for the development of scour hole around circular bridge pier.

From scouring experiments on circular piers in pure clay beds Briaud *et al.* (1999) and Ting *et al.* (2001) concluded that the obtained maximum equilibrium scour depth from different experimental runs was similar to that of sand bed for similar background conditions (e.g., pier diameter, approach flow velocity, approach flow depth). Experiments on scouring around circular pier models using clay-sand mixed cohesive beds were reported only by Molinas and Hosny (1999) and Ansari *et al.* (2002), with clay fraction (C) in the range 0.05 - 0.4 and 0.1 - 0.6, respectively. Molinas and Hosny (1999) concluded that maximum scour depth decreased as clay content increased, while increase in antecedent water content (WC) in general increased maximum equilibrium scour depth. Ansari *et al.* (2002) reported that the maximum equilibrium scour depth in cohesive sediments could be smaller or even more than that of non-cohesive sediments for similar experimental conditions and the antecedent water content of the sediment at the initiation of scour was the main factor governing the location of deepest scour in clay-sand mixed cohesive sediments. These contradictions of observations raise the following obvious question, why did Briaud *et al.* (1999) and Ting *et al.* (2001) observed almost similar maximum equilibrium scour depth around circular piers for both sand and pure clay beds; while Molinas and Hosny (1999) observed decreased scour depth with increase in clay content in clay-sand mixed cohesive sediments?

In the present study, an attempt has been made to address these questions and regression based equations were proposed for the estimation of non-dimensional maximum equilibrium scour depth around circular pier embedded in clay-sand mix cohesive sediments for different ranges of clay and water content, at velocities higher than the threshold velocity for the sand in the clay-sand mixed cohesive bed. Observations and results on scouring around circular pier embedded in clay-sand mixed beds are reported based on 56 laboratory flume experiments carried out on clay - sand mixed cohesive sediment beds with clay fraction (C ) = 0.2 – 1 and water content fraction (Wc) = 0.200 – 0.460.

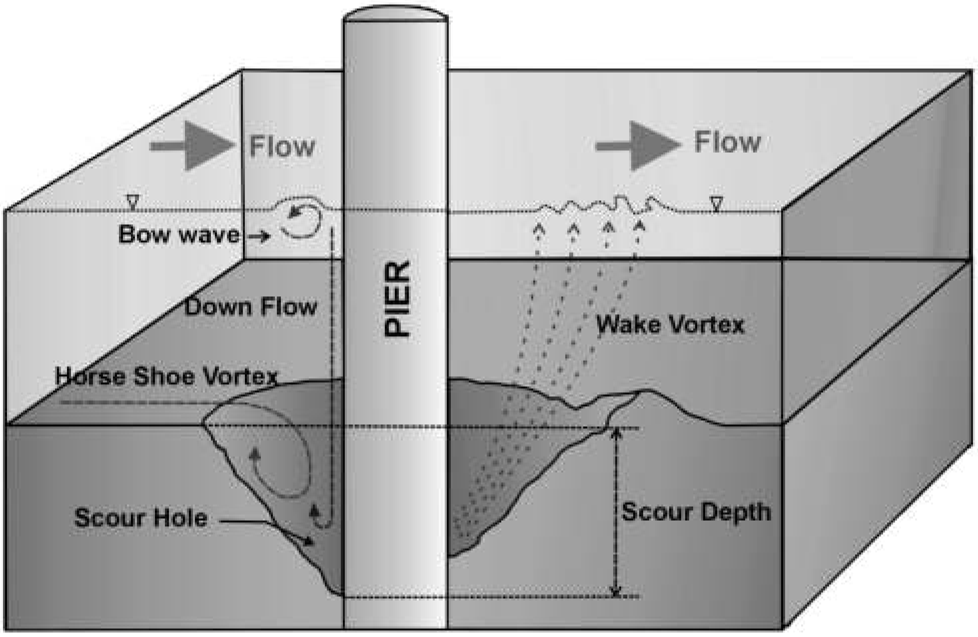


**Figure 1:** Conceptual model of flow pattern within scour hole around a circular pier.

**Experimental Set-up and Data Acquisition**

Experiments reported in this paper were conducted at the 18.3m long, 0.9m wide and 0.9m deep tilting flume (kept at constant slope = 0.001) located in the Fluid Mechanics and Hydraulics Laboratory, Bengal Engineering and Science University, Shibpur, India. The sediment recess was 0.25m deep and 2.5m long located at 10m downstream from the flume entrance. Water was re-circulated into the flume by one vertical turbine pump of 0.3 m3 s-1 capacity from a sump 57m long, 3m wide and 2m deep. A point gauge and a 16 MHz MicroADV, SonTek Inc. mounted on instrument carriage were used to measure scour hole profiles and flow characteristics, respectively.

The discharge into the flume was controlled with a flow control valve. Circular bridge pier models made of perspex (transparent) having diameter (D) of 12cm with vertical graduated tapes glued at 0° (front), 90° (left side), 180° (behind), 270°( right side) of pier were used for the experiments. Figure 2 reveals a schematic diagram of the experimental flume.

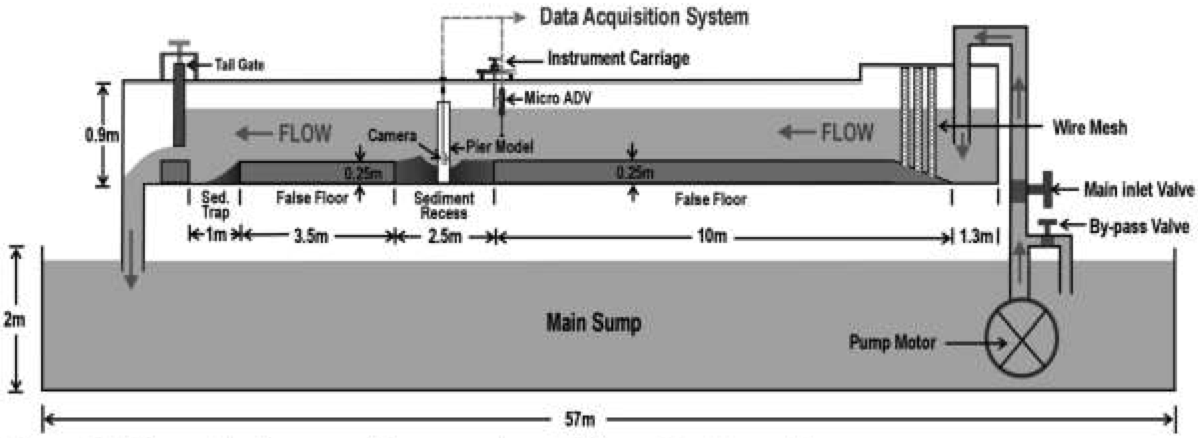


**Figure 2:** Schematic diagram of the experimental flume (not to scale).

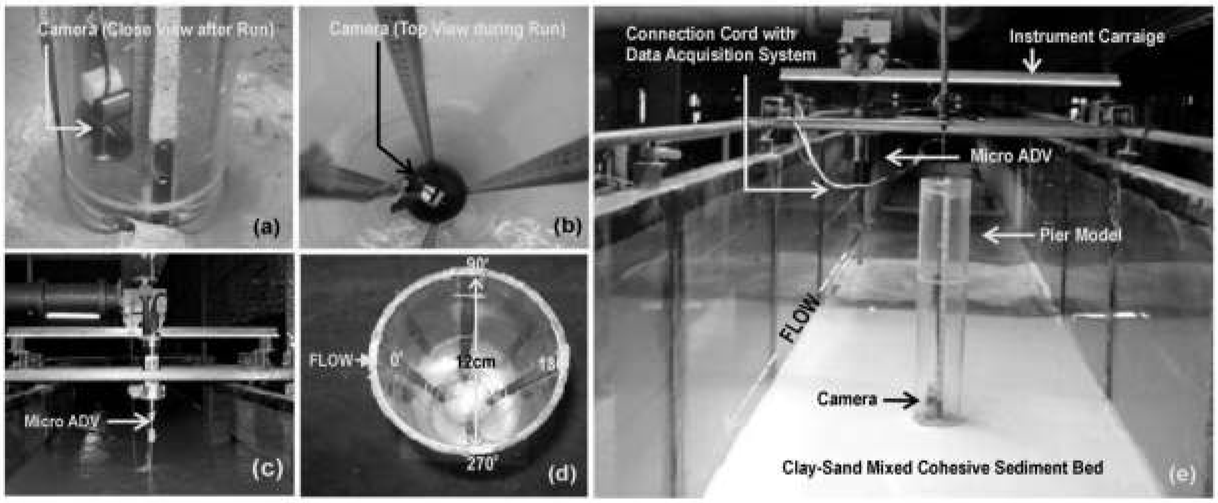


**Figure 3:** Different components of the experimental set up:(a) Close view of inserted camera after an experimental run, (b) View of camera from the fop of the pier model during an experimental run, (c) Micro ADV measuring the flow velocity, (d) Top view of the circular pier model showing the positions of attached scales (e) View of the test section of the flume just before an experimental run (view from the downstream end).

The mean velocity profile could be approximated well by the log law. Therefore, V was approximated by averaging the longitudinal mean velocity measured with Micro-ADV at 0.2y and 0.8y similar to Ting *et al.*, (2001) and is given in Table 1 for different ranges of experimental conditions. An NB Pro-Logitech camera connected to computer and installed inside the pier model from a specially designed camera holder was used in recording time variation of scour depth at regular time intervals against the four scales. The instantaneous scour depth was measured by observing the position of base of the scour hole by sliding the camera up and down within the pier. Equilibrium condition of scouring processes was assumed when at least for successive 5 hours no scouring was seen in any of the attached scale. The largest value of the scour depths recorded at different graduated scales at equilibrium condition was taken as the maximum equilibrium scour depth (ys). Figure 3(a-e) reveal the photographs, of the different components of the experimental set-up and a view of test section of the flume just at the start of experimental run.

**Preparation of Clay - Sand Mixed Cohesive Sediment Bed**

The cohesive materials that were used in the experiments comprised of kaolinite clay (KC). The cohesive material was mixed with fine sand (d50 = 0.182mm; specific gravity = 2.65; and $\sigma_g = (d_{84}/d_{16})^{0.5} = 1.37$) in different proportions for different experimental runs as given in Table 1, where d16 = 16% finer particle diameter; and d84 = 84% finer particle diameter.

At first, the cohesive material was manually mixed homogeneously with fine sand in proportions by weight as given in Table 1, respectively, in dry condition. Water by weight in fractions of dry mixture was then added to the homogeneous mixture in a container and mixed thoroughly by hand and finally, laid at the sediment recess in layers of approximately 0.05m. Each layer was compacted manually by dropping 500 times (approximately) a 2.55Kg hammer of base diameter 0.075m. 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 0.01m thick) was chiseled off and finally made smooth with the help of a wooden trowel.

Before an experimental run was commenced, the shear strength of the bed sediment was measured by vane method and sample was collected from a downstream location at the corner of the sediment recess to measure the bulk density ($\rho_b$), dry density ($\rho_d$) and Wc of the bed, using standard laboratory procedure. Detailed procedure and steps followed to prepare sediment beds can be found in Debnath and Chaudhuri (2010a; 2010b), Chaudhuri, (2010).

**Experimental Procedure**

At the beginning of the each experimental run the flume was allowed to fill up with water until a depth of approximately 0.35m was achieved. The discharge valve was gradually opened and the tail gate was simultaneously operated in order to achieve desired discharge to ensure the desired approach flow depth (y) = 0.35m (fluctuations < 1.6%). This flow depth was monitored throughout the experimental run against graduated scales attached to the glass flume wall. Total 56 experimental runs were carried out on clay-sand mixed beds for C = 0.20 – 1 where C = clay fraction in the clay-sand mixture. Experiments were carried out on four different antecedent water content ranges, Wc = 0.200 - 0.232, 0.280 - 0.335, and 0.378 - 0.460 and henceforth will be referred to as WR1, WR2, and WR3, respectively; and also on four different approach flow depth averaged velocity ranges, V = 49.76 - 54.71 cm/s, 57.31 - 62.92 cm/s, 68.03 - 72.78 cm/s, and 78.98 - 82.73 cm/s and henceforth will be referred to as VR1, VR2, VR3 and VR4, respectively. It is to be noted that WR1<WR2<WR3; and VR1<VR2<VR3<VR4. The time for which each experiment was carried out (Tc) and the time after which no scouring was observed (Te) are given in Tables 1.

**Table 1:** Ranges of experimental conditions and maximum equilibrium scour depths.

| Exp. Run No. | Nos. of Runs | $C$ | $\tau_s$ (N/cm$^2$) | $\rho_b$ (gm/cm$^3$) | $W_c$ | $\rho_d$ (gn/cm$^3$) | $V$ (cm/s) | $T_e$ (hr) | $y_s$ (cm) |
|---|---|---|---|---|---|---|---|---|---|
| 1 & 2 | 2 | 2.00 | 0.57 - 0.59 | 1.84 - 1.86 | 0.226 - 0.286 | 1.45 - 1.50 | 52.86 - 53.91 | 36 - 41 | 20.0 - 22.4 |
| 3 to 14 | 12 | 0.35 | 0.68 - 0.92 | 1.80 - 1.91 | 0.200 - 0.392 | 1.30 - 1.59 | 51.39 - 81.68 | 52 - 66 | 6.2 - 20.5 |
| 15 to 25 | 11 | 0.50 | 0.86 - 1.11 | 1.71 - 1.88 | 0.207 - 0.397 | 1.23 - 1.53 | 49.77 - 81.47 | 56 - 68 | 5.1 - 17.6 |
| 26 to 37 | 12 | 0.70 | 0.92 - 1.07 | 1.59 - 1.72 | 0.213 - 0.421 | 1.15 - 1.41 | 52.32 - 81.59 | 52 - 73 | 3.3 - 14.7 |
| 38 to 48 | 11 | 0.85 | 0.7 - 1.12 | 1.53 - 1.63 | 0.219 - 0.46 | 1.08 - 1.33 | 52.86 - 81.21 | 48 - 73 | 3.0 - 15.3 |
| 49 to 56 | 8 | 1.00 | 0.61 - 0.78 | 1.4 - 1.53 | 0.306 - 0.458 | 1.03 - 1.13 | 52.69 - 82.73 | 40 - 53 | 10.5 - 17.3 |

In general, an experiment was terminated when at least for successive 5 hours no scouring was observed in any of the four scales. At the end of each experimental run, the flow was gradually reduced until it was stopped by controlling the flow control valve and tail gate to avoid any distortion to the final scour hole. The water from the scour hole was drained out by siphoning. Then, detailed geometry of the scour hole was recorded with point gauge with graduated traverse arrangement in all three co-ordinate directions. Maximum equilibrium scour depth ($y_s$) as viewed by the camera for a particular experimental run was recorded in the data acquisition system (Chaudhuri *et al.*, 2009; 2010).

**Results and Discussions**

Figure 4 (a-c) shows the plot of maximum non-dimensional scour depth $\hat{y}$ ($\hat{y} = y / \mathrm{D}$) as a function of C in different flow velocity regime and water content (i.e. WR1, WR2, and WR3) respectively. For cohesive beds with low water content (WR1), $\hat{y}_s$ decreased steadily with increase in C (Fig. 4a). For cohesive beds with higher water content (WR2 and WR3,) as a function of C first decreased and thereafter steadily increased after a certain value of C was reached (Fig. 4b-4c).

 

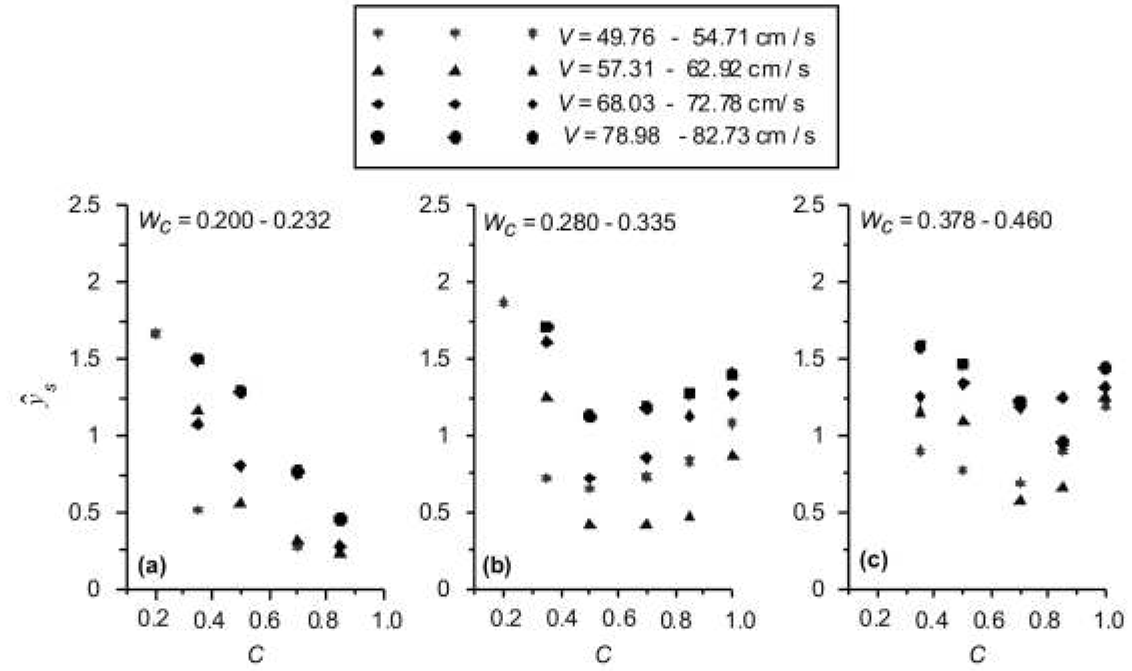


**Figure 4** Comparison of $\hat{y}$ as a function of C for clay-sand mixed sediments using (a) $W_c$ = 0.200 - 0.232, (b) $W_c$ = 0.280 - 0.335, (c) $W_c$ = 0.378 - 0.460.

For *WR*2, $\hat{y}_s$ decreased up to $C = 0.5$ and thereafter increased (Fig. 4b). Similarly, for *WR*3 (Fig. 4c) $\hat{y}_s$ decreased up to $C = 0.7$ and thereafter increased. The clay fraction in the clay-sand mixed sediment beds after which the maximum equilibrium scour depth increased was consistent for different velocity ranges for a particular range of water content (Figs. 4b-c). Briaud *et al.*, (2004 ) and Ting *et al.*, (2001) reported $\hat{y}_s$ that around circular piers for sand or pure clay beds were not much different, while Molinas and Hosny (1999) observed that $\hat{y}_s$ decreased with increase in $C$ for the range C = 0.05-0.4. Ansari *et al.*, (2002), concluded that for a given flow and pier characteristics, $\hat{y}_s$ in cohesive sediment could be lesser or even greater than non-cohesive sediments. This observation further added to the ambiguity. Fig. 4b, 4c possibly explain this discrepancy. No study reported in literature on local scour around circular piers covered the entire range of clay content in the clay-sand mixed sediments and the present study filled the gap. It can be seen, that the inflection point in the $\hat{y}_s$ as a function of clay content shifts position for different water content ranges in the clay-sand mixture (Fig. 4b, 4c). Possibly the functional relationships, as observed in Fig. 4a, 4c, can be explained based on the bed shear strengths of the clay-sand mixed sediment beds. Vane shear strength as a function of clay content and water content for different runs also showed similar trend (Fig. 5a, 5c). Fig. 5a reveals that $\tau_s$ increases steadily with increase in C for *WR*1. The inflection in the vane shear strength as a function of clay content occurs for similar clay contents as observed for . For e.g., experimental runs using clay-sand mixed sediments with *WR*2 showed inflection at about 0.5 clay fraction (Fig. 5b) while with *WR*3 showed inflection at about 0.7 clay fraction (Fig. 5c).

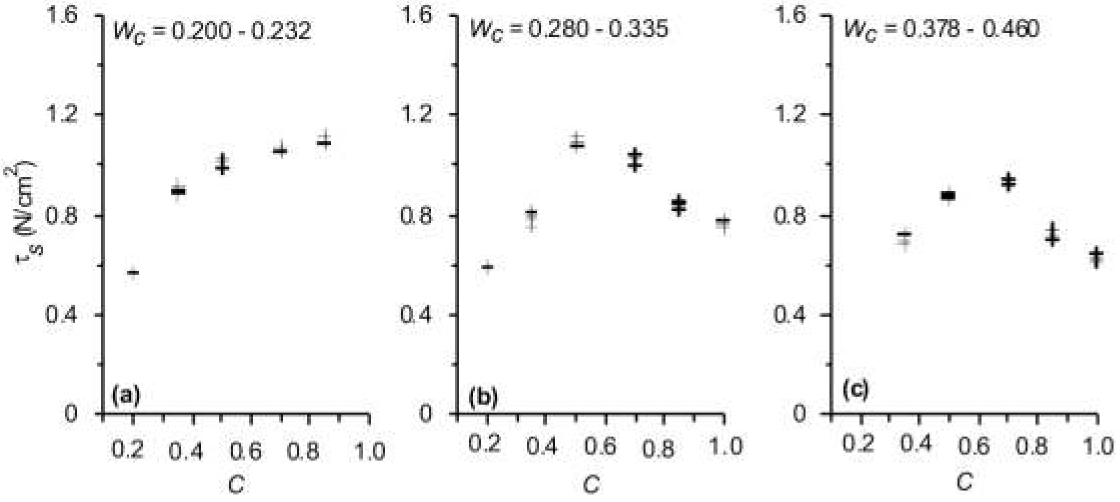


**Figure 5:** Comparison of $\tau_s$ as a function of $C$ for clay-sand mixed sediments using (a) $W_c$ = 0.200 - 0.232, (b) $W_c$ = 0.280 - 0.335, (c) $W_c$ = 0.378 - 0.460.

*Dimensional Analysis*

For non-cohesive sediment beds (e.g., sand), it is mainly the submerged weight of the sediment particles that resist its dislodgement. The parameters influencing the maximum equilibrium scour depth ($y_s$) for circular pier in uniform non-cohesive sediments is given by (Ettema *et al.*, 1998).

$$y_s = f_1(\rho, \mu, V, y, g, d, V_c, D) \quad \text{... (1)}$$

where $\rho$ = fluid density; $\mu$ = dynamic viscosity of water; $V$ = depth averaged approach flow velocity along x-direction; $y$ = approach flow depth; $g$ = acceleration due to gravity; $d$ = sediment particle diameter; $V_c$ = critical value of $V$ generating the critical threshold shear stress ($y_c$) associated with threshold of movement of particles on bed surface; and $D$ = pier diameter.

Scouring around circular pier in non-cohesive sediment beds is extensively studied for the last few decades (Raudkivi and Ettema, 1983; Melville, 1997; Sheppard *et al.*, 1997; Ettema *et al.*, 1998). However, local scour around bridge piers on cohesive (muddy) sediments is not yet clear and till date, very few investigations are reported with its quantification. Fine sediment particles ranging in size from less than 1 μm to 63 μm (i.e., particles in clay and silt range) are mainly responsible for the muddy or the cohesive nature of these sediments (Mitchener and Torfs, 1996; Debnath *et al.*, 2010a). 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 inter-particle bonds connecting an aggregate or floc or individual particle in its neighbourhood. At present, the existence of cohesive sediment erosion threshold is still in question and two schools of thought are found in literature. The first promotes that erosion threshold does not exist for cohesive sediments and some particles erode at any value of bed shear stress (Lavelle *et al.*, 1984; Parchure and Mehta, 1985), while the second theory advocates the existence of erosion threshold (Amos *et al.*, 1992; Ravens *et al.*, 1999; Tolhurst *et al.*, 2000; Kothyari and Jain, 2007). Debnath *et al.*, (2007a) found that at very small values of bed shear stress some particles always erode in cohesive sediments. Therefore, further understanding is required before $V_c$ (for clay-sand mixtures) can be used in Eq. (1) as an easily usable parameter in estimation of maximum scour depth in cohesive material sand mixtures. Thus, instead of Vc we used bed shear strength ($r_s$) of clay-sand mixtures, which is a more easily measurable parameter in Eq. (1) similar to that of Molinas and Hosny (1999).

Briaud *et al.*, (1999) and Ting *et al.*, (2001) reported results from scouring experiments on circular piers using cohesive sediments having particles in the clay and silt size range (presence of sand sized particles was negligible). Both concluded that the obtained maximum equilibrium scour depth from different runs was similar to that of sand for similar background conditions (e.g., pier diameter, approach flow velocity, approach flow depth).

Scouring experiments around circular pier using clay-sand mixtures were only carried out by Molinas and Hosny (1999) and Ansari *et al.*, (2002) with clay fraction ($C$) in the range 0.05 - 0.4 and 0.1 - 0.6, respectively. Molinas and Hosny (1999) concluded that maximum scour depth decreased as clay content increased, while increase in water content ($Wc$) in general increased maximum equilibrium scour depth. Ansari *et al.*, (2002) reported that the maximum equilibrium scour depth in cohesive sediments could be smaller or even more than that of non-cohesive sediments for similar experimental conditions and the water content of the sediment antecedent to the initiation of scour was the main factor governing the location of deepest scour in cohesive sediments.

Thus for clay-sand mixtures Eq. (1) becomes

$$y_s = f_2\left(\rho, \mu, V, y, g, d, D, C, W_c, \tau_s\right) \qquad \text{... (2)}$$

Using dimensional analysis and selecting V, D and ρ as repeating variables we get from Eq. (2),

$$\hat{y}_s = f_3\left(R_{ep}, \hat{y}, F_{rp}, \hat{d}, C, W_c, \hat{\tau}_s\right) \qquad \text{... (3)}$$

where $\hat{y}_s = y_s / D$ = non-dimensional maximum equilibrium scour depth; $\hat{y} = y/D$ = non-dimensional approach flow depth ; $F_{rp} = V/(gD)^{0.5}$ = pier Froude number; $\hat{d} = D/d$ = non-dimensional particle size; and $\hat{\tau}_s = \tau_s/(\rho V^2)$ = non-dimensional bed shear strength.

Pier Reynolds number $(R_{ep})$ is not an important parameter if the viscous effects are concerned but $R_{ep}$ influences the frequency of vortex shedding[1]. $R_{ep}$ is not a significant parameter if the flow around the pier is fully turbulent and is generally neglected in pier scour studies (Ettema *et al.*, 1998). Therefore, we neglect $R_{ep}$ in Eq. (3). The pier Froude number can be expressed as the ratio $H/D$ where $H$ = the stagnation head $V^2/2_g$ along the leading edge of the pier13. Further, Ettema *et al.*, (1998) showed that $V^2/gD$ is in effect a normalized expression of vorticity of wake vortices. Therefore, the pier Froude number is useful for describing the flow and flow gradients around a pier. Therefore, Eq. (3) reduces to

$$\hat{y}_s = f_3\left(\hat{y}, F_{rp}, \hat{d}, C, W_c, \hat{\tau}_s\right) \qquad \text{... (4)}$$

*Estimation of* $\hat{y}_s$

For non-cohesive sediments in clear water[26] and in live bed condition[27] for $\hat{d} > 50$, the maximum scour depth is independent of the sediment size. The present experimental runs were carried out at $\hat{d} > 50$.

Further Melville and Sutherland (1988) showed that scour depth is independent of approach flow depth for $\hat{y} = y/D > 2.6$. In the present study, $y = 0.35$m which gave $\hat{y} = 2.91$ corresponding to shallowest case making the scouring process independent of $y$.

Therefore, Eq. (4) reduces to

$$\hat{y}_s = f_4\left(F_{rp}, C, W_c, \hat{\tau}_s\right) \quad \text{... (5)}$$

The experimental data given in Tables 1 were used for multiple regression analysis for obtaining equations for non-dimensional equilibrium scour depth based on Eq. (5) for different ranges of clay content and water content in the clay-sand mixture as below:

$$\hat{y}_s = 2.05 F_{rp}^{1.72} C^{-1.29} \hat{\tau}_s^{-0.37} \quad \text{for } W_c = 0.200 - 0.232 \text{ and } 0.2 \leq C \leq 0.85 \quad \text{... (6)}$$

$$\hat{y}_s = 3.64 F_{rp}^{0.22} C^{-1.01} \hat{\tau}_s^{-0.69} \quad \text{for } W_c = 0.280 - 0.335 \text{ and } 0.2 \leq C \leq 0.5 \quad \text{... (7)}$$

$$\hat{y}_s = 20.52 F_{rp}^{1.28} C^{0.19} \hat{\tau}_s^{-0.89} \quad \text{for } W_c = 0.280 - 0.335 \text{ and } 0.5 \leq C \leq 1 \quad \text{... (8)}$$

$$\hat{y}_s = 3.32 F_{rp}^{0.72} C^{-0.62} W_c^{0.36} \hat{\tau}_s^{-0.29} \quad \text{for } W_c = 0.378 - 0.460;\ 0.2 \leq C \leq 0.7 \quad \text{... (9)}$$

$$\hat{y}_s = 8 F_{rp}^{0.61} C^{0.58} W_c^{1.24} \hat{\tau}_s^{-0.19} \quad \text{for } W_c = 0.378 - 0.460;\ 0.7 \leq C \leq 1 \quad \text{... (10)}$$

In Eqs. (6) - (8), $W_c$ was neglected because multiple regression analysis gave negligible exponents for $W_c$. Comparison of experimental data of $y_s$ with that of computed using Eqs. (6) - (10) are shown in Fig. 6.

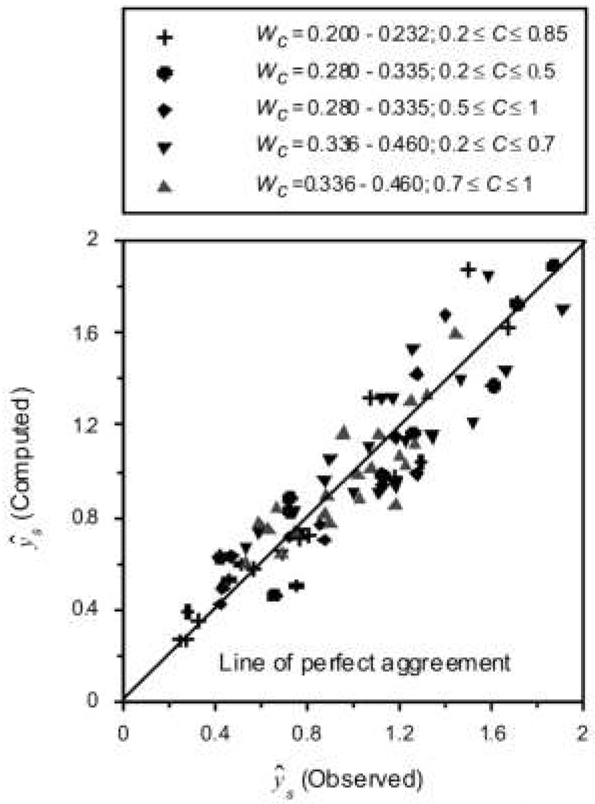


**Figure 6:** Comparison of experimentally observed $y_s$ from present data that obtained using Eqs. (6) - (10).

The R2 between the experimentally obtained $y_s$ and that computed with Eqs. (6) - (10) were 0.91, 0.82, 0.85, 0.80 and 0.73, respectively. This suggested that the above equations reasonably describe the data obtained from experiments.

## Conclusions

The present study investigated the effects of clay content and water content on maximum equilibrium scour depth. Diverse observations were made in the previous investigations by different researchers on local scour around circular pier in cohesive beds such as: (a) the maximum equilibrium scour depth in cohesive beds was similar to that of sand; (b) the maximum equilibrium scour depth in cohesive beds was smaller or even more than that of sand; and (c) the maximum equilibrium scour depth decreased with increase in cohesive material content. The present study suggested that for water content less than 0.240 the maximum equilibrium scour depth decreased with increase in clay content of the clay-sand mixture. For water content greater than 0.270, with increase in clay content, at first the maximum equilibrium scour depth decreased up to 0.5 - 0.7 clay fraction and thereafter increased. The clay fraction corresponding to the point of inflection is a function of water content of the clay-sand mixed sediments. It was also evident that vane shear strength is a significant parameter in describing the maximum equilibrium scour depths in clay-sand mixed sediments.

Dimensional analysis of major parameters influencing the scouring process was done to propose regression based equations for the estimation of non-dimensional maximum equilibrium scour depth around circular pier embedded in clay-sand mixed cohesive sediments as functions of pier Froude number, clay content, water content, and bed shear strength. These equations are valid for clay-sand mixed cohesive sediments having clay fraction in the range 0.20 - 1 and water content in the range 0.200 - 0.460. Considering, the large number of parameters that can influence cohesive sediment erosional properties Eqs. (6)-(10) can be used with ease in estimation of scour depth and scour hole extension for clay-sand mixtures for $0.2 \leq C \leq 1$; $0.200 \leq Wc \leq 0.460$.

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## References

Amos, C. L., Daborn, G. R., Christian, H. A., Atkinson, A., Robertson, A. 1992. In-situ erosion measurements on fine-grained sediments from the Bay of Fundy. *Marine Geology*, 108, 175-196.

Ansari, S., Kothyari, U. C., Ranga Raju, K. G. 2002. Influence of cohesion on scour around bridge piers. *Journal of Hydraulic Research*, 40(1), 717-719.

Briaud, J. L., Chen, H. C., Li, Y., Nurtjahyo, P. 2004. SRICOS-EFA method for complex piers in fine grained soils. *Journal of Geotecnical and Geoenvironmental Engineering*, 130(11), 1180-1191.

Briaud, J. L., Ting, F. C. K., Chen, H. C., Rao, G., Suresh P., Wei, G. 1999. SRICOS: Prediction of scour rate in cohesive soils at bridge piers. *Journal of Geotecnical and Geoenvironmental Engineering*, 125(4), 237-246.

Chaudhuri, S. 2010. Study on Bridge Pier Scour in Clay-Sand Mixed Cohesive Beds - an Experimental Approach. Ph.D Dissertation (215 pages), *Bengal Engineering and science University*, Shibpur, Howrah, India.

Chaudhuri, S., Mukhopadhyay, B.P., Debnath, K. 2009. Volume of scour around circular cylinder in clay-sand mixed beds. *Conference proceeding, Indian Society for Hydraulics*, 7-14.

Chaudhuri, S., Mukhopadhyay, B.P., Debnath, K. 2010. Experimental study on equilibrium scour hole volume around circular bridge pier in clay-sand mixed cohesive beds. *Journal Indian Geological Congress*, 2 (1), 47-53.

Chiew, Y. M. 1984. Local scour at bridge piers. Report No.355. *School of Engineering*, The University of Auckland, Auckland, New Zealand,

Debnath, K., Aberle, J., Nikora, V., Westrich, B., Muste, M. 2007a. Erosion of cohesive sediments: re suspension, bed load, and erosion patterns from field experiments. *Journal of Hydraulic Engineering*, 133 (5), 508-520.

Debnath, K., Chaudhuri, S. 2010a. Laboratory experiments on local Scour around cylinder for clay and clay-sand mixed beds. *Engineering Geology.* 111(1-4), 51-61.

Debnath, K., Chaudhuri, S. 2010b. Bridge Pier Scour in Clay-Sand Mixed Sediments at Near Threshold Velocity for Sand. *Journal of Hydraulic Engineering*, 136(9), 597-609.

Ettema, R. 1980. Scour at bridge piers. Report No. 216. *School of Engineering*. The University of Auckland, Auckland, New Zealand,

Ettema, R., Melville, B. W., Barkdoll, B. 1998. Scale effect in pier-scour Experiments. *Journal of Hydraulic Engineering*, 124(6), 639-642.

Ettema, R., Kirkil, G., Muste, M. 2006. Similitude of large-scale turbulence in experiments on local scour at cylinders. *Journal of Hydraulic Engineering*, 132(1), 33-40.

Kothyari, U. C., Jain, R. K. 2008. Influence of cohesion on incipient motion condition of sediment mixtures. *Water Resources Research*, 44(4), 1-15.

Lavelle, J. W., Mofjeld, H. O., Baker, E. T. 1984. An in situ erosion rate for fine grained marine sediments. *Journal of Geophysical Research,* 89(C4), 6, 543-6,552.

McAnally, W. H., Mehta, A. J. 2002. Significance of aggregation of fine sediment particles in their deposition. *Estuarine, Coastal and Shelf Science*. 54, 643-653.

McLean, VA, Nezu, I., Nakagawa, H., Turbulence in open-channel flows. *Federal Highway Administration*, U.S. Department of Transportation, Balkema, Rotterdam, The Netherlands. 1993.

Melville, B. W., Sutherland, A. J. 1988. Design method for local sour at bridge piers. *Journal of Hydraulic Engineering*, 114(10), 1210-1226.

Melville, B. W. 1997. Pier and abutment sour: integrated approach. *Journal of Hydraulic Engineering*, 23(2), 125-136.

Mitchener, H. J., Torfs, H. 1996. Erosion of mud/sand mixtures. *Coastal Engineering*, 29, 1-25.

 

Molinas, A., Hosny, M.M. 1999. Effects of gradation and cohesion on bridge scour, Vol-4. Experimental study on scour around circular piers in cohesive soils. *In Publication No. FHWA-RD-99-186,*

Parchure, T. M., Mehta, A. J. 1985. Erosion of soft cohesive sediment deposits. *Journal of Hydraulic Engineering*, 111(10), 1308-1326.

Raudkivi, A. J., Ettema, R. 1983. Clear water scour at cylindrical piers. *Journal of Hydraulic Engineering*, 109(3), 338-350.

Ravens, T. M., Gschwend, P. M. 1999. Flume Measurements of Sediment Erodibility in Boston Harbor. *Journal of Hydraulic Engineering*, 125(10), 998-1005.

Sheppard, D.M., Odeh, M., Glasser, T. 2004. Large scale clear-water local pier scour experiments. *Journal of Hydraulic Engineering*, 130(10), 957-963.

Ting, F. C. K., Briaud, J., Chen, H. C., Gudavalli, R., Perugu, S., Wei, G. 2001. Flume tests for scour in clay at circular piers. *Journal of Hydraulic Engineering*, 127(11), 969-978.

Tolhurst, T.J., Black, K.S., Paterson, D. M., Mitchener, H. J., Termaat, G. R., Shayler, S. A. 2000. A comparison and measurement standardisation of four in-situ devices for determining the erosion shear stress of intertidal sediments. *Continental Shelf Research*, 20, 1397-1418.