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SCOUR HOLE CHARACTERISTICS AROUND A VERTICAL PIER UNDER CLEARWATER SCOUR CONDITIONS

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ABSTRACT

A series of clear water scour experiments have been conducted in a tilting flume with a circular pier under different conditions of densimetric Froude number and inflow depths. Tests used a single pier of 50 mm diameter embedded in a sand bed of mean particle size d_{50} = 0.365 mm. It was observed that the entire scour geometry (scour depth, length, width, area and volume) depended on the densimetric Froude number (F_{D50}) and inflow depth (h). On the basis of the obtained results, empirical equations are proposed for scour depth, scour length, scour width, scour area and scour volume. Scour hole parameters calculated from the proposed equations have been compared with those obtained from experimental results and are found to be very close to each other.

Keywords: scour, tilting flume, vertical pier, threshold condition, densimetric froude number.

INTRODUCTION

Local scour is recognized as one of the prime reasons for failure of hydraulic structures. Though there have been extensive studies by several researchers on the effect of local scour around bridge piers, it is very rare to find any single analytically derived equation for prediction of scour. Due to the complex nature of the problem, such as combined effects of complex turbulent boundary layer, time-dependent flow pattern, and sediment transport mechanism in the scour hole, complete prediction of local scour depth around bridge piers becomes difficult. Raudkivi and Ettema (1983) studied relationship of local scour depth with particle size distribution of bed sediment, mean particle size of the bed sediment relative to pier diameter in clear-water conditions. The authors also presented a formula for estimating the maximum depth of local scour.

Numerous studies have been conducted with the purpose of predicting scour, and various equations have been developed (Laursen and Toch, 1956; Liu *et al*., 1961; Shen *et al*., 1969; Breusers *et al*., 1977; Jain and Fischer, 1979; Raudkivi and Ettema, 1983; Melville and Sutherland, 1988; Froehlich, 1989; Melville, 1992; Abed and Gasser, 1993; Richardson and Richardson, 1994; Lim, 1997 and Heza *et al*., 2007). Most of these empirical equations were based on laboratory results and field data and they differ from each other with respect to the factors considered in constructing the scour model, parameters used in the equation, laboratory or site conditions, etc. Among these equations, one of the most commonly used pier scour equations in the United States is the Colorado State University equation recommended in the Hydraulic Engineering Circular No. 18 of U.S. Department of Transportation (HEC-18 Federal Highway Administration, 1993). While these proposed equations have been demonstrated to be applicable with good accuracy for a certain set of data, there has been considerable uncertainty when using these equations to predict scour in field practice. To test the accuracy of the developed bridge scour equations, comparative studies have been conducted by many researchers (Jones, 1984; Johnson, 1995; Mueller, 1996 and Landers and Mueller, 1996).

Oliveto and Hager (2002) presented a scour equation and the authors found that densimetric Froude number is the dominant parameter governing the scour process. The proposed equation for temporal scour evolution was further justified with a large set of experimental results (Oliveto and Hager, 2005).

Yanmaz (1989) indicated that the relative scour depth (d/b) is a function of relative approach flow depth (h/b), where d_s is the equilibrium scour depth and b is the pier diameter. The author presented a relationship between relative scour depth and relative approach depth through curves. Earlier, such curves were developed by Melville (1975), Chiew and Melville (1987), Melville and Sutherland (1988), Gűnyakti (1989) and Breusers *et al*. (1977).

The purpose of the experimental program was to investigate the scour hole characteristics around a single vertical pier in Clearwater conditions and to develop empirical relationships on the basis of obtained results.

EXPERIMENTAL SETUP

The experiments were conducted in a flume 10 m long, 0.81 m wide and 0.60 m deep, located in the Fluvial Hydraulics Laboratory of School of Water Resources Engineering, Jadavpur University, Kolkata, India. Water was supplied to the flume from a recirculating tank with the help of a centrifugal pump. The flow rate in the flume was adjusted using a valve provided in the inlet pipe. The selected water depth for each run was maintained with the help of a adjustable vertical slit type tailgate provided at the downstream end of the flume. A mobile bed (stilling basin) zone 3 m long, 0.81 m wide and 0.25 m depth was prepared at a distance 1.7 m downstream of the flume beginning, and was filled with sediment of median particle size d_{50}=0.365 mm and standard deviation of particle size distribution, $\sigma_g = (d_{84}/d_{16})^{0.5} = 1.7$. A vertical circular pier of diameter 50 mm was placed in the center of the stilling basin. A schematic diagram of the experimental setup is shown in (Figure-1). The mobile bed was compacted and leveled before the starting of each test run. During the test run the flow discharges and the flow depths were kept constant, so as to attain a fixed inflow Froude number. Three different flow depths (0.06m, 0.07m and 0.08m) were tested and for each inflow depth three different discharges were tested. It was observed that after about 28 hours, there was no significant change in the scour depth and profile. Hence it was considered that equilibrium scour depth was obtained after about 28 hours. A point gauge was then used to measure the scour depth at various points across transverse and longitudinal cross sections. Transverse measurements were taken at every 10 mm intervals while in the longitudinal direction; intervals of 20 mm to 40 mm were used and were continued till about 1 m downstream of the pier. Table-1 gives the summary of conditions for the tests performed.

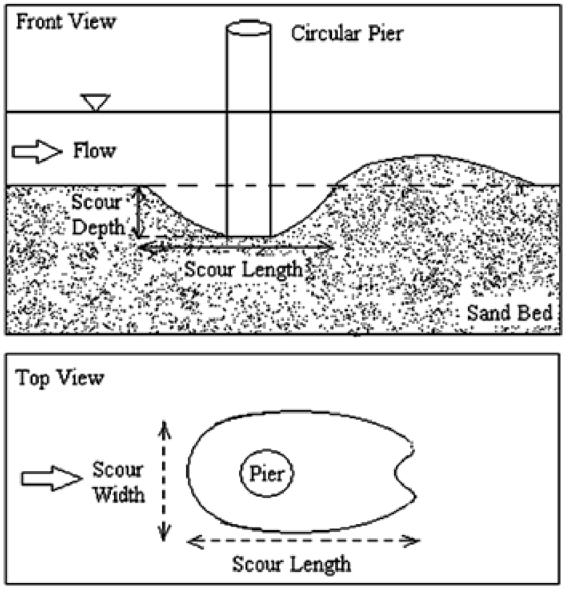


Figure-1. Schematic diagram of the experimental setup.

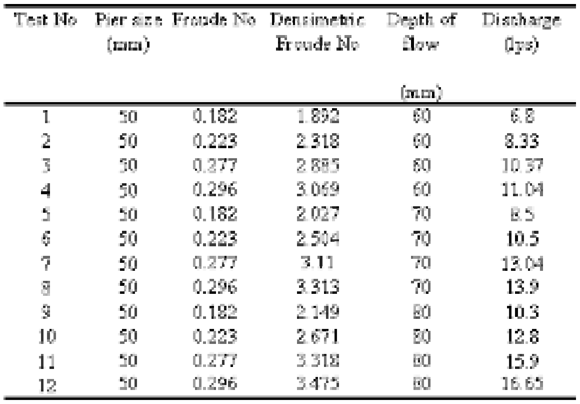
DIMENSIONAL ANALYSIS FOR SCOUR HOLE CHARACTERISTICS

Scour at piers is influenced by various parameters (Breusers *et al*., 1977), such as size of pier, sediment characteristics, approaching flow conditions, fluid properties, and time etc.

The relationship showing the influence of various parameters on the equilibrium scour depth d_s at piers can be given in functional form as follows:

$$d_s = f\left(U, h, \rho, \rho_s, g, \nu, b, d_{50}, \sigma_g, t\right) \tag{1}$$

Table 1: Summary of Test conditions



Test No	Pier size (mm)	Froude No	Densimetric Froude No	Depth of flow (mm)	Discharge (lps)
1	50	0.182	1.892	60	6.8
2	50	0.223	2.318	60	8.33
3	50	0.277	2.885	60	10.37
4	50	0.296	3.069	60	11.04
5	50	0.182	2.027	70	8.5
6	50	0.223	2.504	70	10.5
7	50	0.277	3.11	70	13.04
8	50	0.296	3.313	70	13.9
9	50	0.182	2.149	80	10.3
10	50	0.223	2.671	80	12.8
11	50	0.277	3.318	80	15.9
12	50	0.296	3.475	80	16.65

where,

f = Function symbol
d_s = Equilibrium scour depth
U = Inflow velocity
h = Inflow depth
ρ = Water density
ρ_s = Sand density
g = Acceleration due to gravity
ν = Kinematic viscosity
b = Pier diameter
d_{50} = Particle mean diameter
σ_g = Particle size distribution [= $(d_{84}/d_{16})^{0.5}$]
t = Time

The influence of kinematic viscosity (*v*) is insignificant for a turbulent flow over rough beds (Yalin, 1977). In sediment- water interaction, the parameters *g*, *ρ* and ρ_s are combined into one parameter where $\Delta = (\rho_s/\rho)-1$ (Dey and Debnath, 2001 and Dey and Raikar, 2005). Since in the present study only one bed material is used and equilibrium scour depth is being considered, the term σ_g, and *t* can be ignored. Therefore equation (1) can be written as:

$$d_s = f\left(U, h, \Delta g, b, d_{50}\right) \tag{2}$$

Using Buckingham's π-theorem, the relative scour depth D_s=(*d*/*b*) can be expressed in non-dimensional form as a function of densimetric Froude number (=$U/(\Delta g d_{50})^{1/2}$) and relative flow depth. Densimetric Froude number F_{D50} can be considered as a very important parameter since it takes into account the both the mean particle size of the sediments and inertia force.

$$D_s = f\left(F_{D50}, h/b\right) \tag{2(a)}$$

Similarly for scour length (l_s)

$$L_s = f\left(F_{D50}, h/b\right) \tag{2(b)}$$

and scour width (w_s)

$$W_s = f\left(F_{D50}, h/b\right) \tag{2(c)}$$

Multiplying equations 2(b) and 2(c), the resulting equation can be regarded as non-dimensional area of scour hole, $A_s = (a_s/a_p)$ where a_s and a_p are the areas of scour hole and pier, respectively.

$$A_s = f\left(F_{D50}, h/b\right) \tag{2(d)}$$

Further, multiplying 2(a), 2(b) and 2(c), a new non-dimensional term known as relative volume of scour hole, $\cancel{V}_s = \cancel{v}_s/\cancel{v}_p$ can be introduced where $\cancel{v}_s$ and $\cancel{v}_p$ are the volumes of scour hole and pier, respectively.

$$\cancel{V}_s = f\left(F_{D50}, h/b\right) \tag{2(e)}$$

INCIPIENT MOTION CONDITION

Figure-2 shows the Shields' experimental results which relate critical Shields parameter (Θ_c) and critical shear Reynolds number (R_{*_c}) and is known as *Shields diagram*. The threshold of sediment motion occurs when $\Theta > \Theta_c$ or $\tau_0 > \tau_{0_c}$ or $u_* > u_{*_c}$. From the above figure it is clear that the discharge measured during each experimental run was lower than the minimum discharge required for the incipient motion or threshold conditions of the bed particles. Therefore, it can be said that all the experiments were carried out under clear water scour condition. In all the experiments, the flow was hydraulically rough [Shear Reynolds number $R_* \geq 70$ by Nikuradse (1933)] in nature. Therefore viscous sub-layer does not exist here. Yalin (1977) also mentioned that the influence of kinematic viscosity (v) is insignificant for a turbulent flow over rough beds.

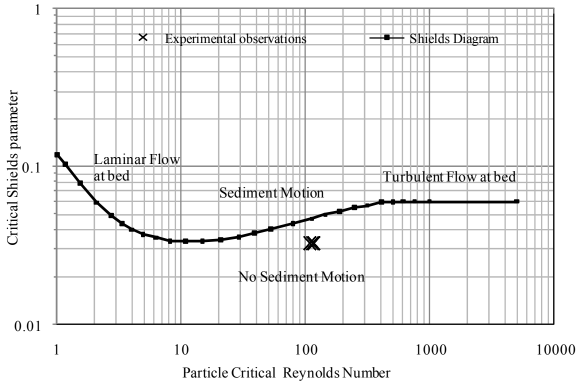


Figure-2. Experimental data plotted on shields diagram.

Here, R_* = shear Reynolds number, that is $u_* d_{50}/v$; where u_* = shear velocity, that is $u_* = \sqrt{\frac{\tau_0}{\rho}}$

RESULTS AND DISCUSSIONS

A design method for the estimation of equilibrium depths of local scour at bridge piers was presented by Melville and Sutherland (1988). A functional relationship was proposed using laboratory data in the form:

$$d_s/b = K_I K_y K_d K_\sigma K_s K_\alpha \tag{3(a)}$$

Where K_I = flow intensity factor, K_y = flow depth factor, K_d = sediment size factor, K_σ = sediment gradation factor, K_s = pier shape factor and K_α = pier alignment factor. To validate the present work data, the scour depth d_s calculated with equation 3 is plotted with measured scour depth of the present work as shown in Figure-3. It can be seen from Figure-3 that the data of the present work matches well with the equation recommended by Melville and Sutherland (1988).

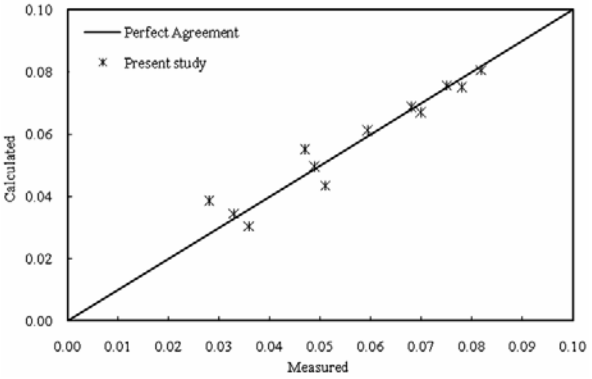


Figure-3. Comparison between calculated Eq. 3(a) scour depth and measured scour depth (author data).

For Design purpose, an envelope curve was also recommended by Melville and Sutherland, 1988:

$$K_I = 2.4\left|\frac{U-\left(U_a-U_c\right)}{U_c}\right|, \text{ if } \frac{U-\left(U_a-U_c\right)}{U_c} < 1 \tag{3(b)}$$

Where, U= Approach flow velocity, U_c = Approach flow velocity at threshold condition and U_a = Approach flow velocity at armor peak (= 0.8 × approach flow velocity beyond which armoring of channel bed is impossible).

The data of the present work was plotted with this envelope curve as shown in Figure-4 and it is evident that the scour depth obtained in the present work is less than the scour depth obtained from the design curve (Figure-4).

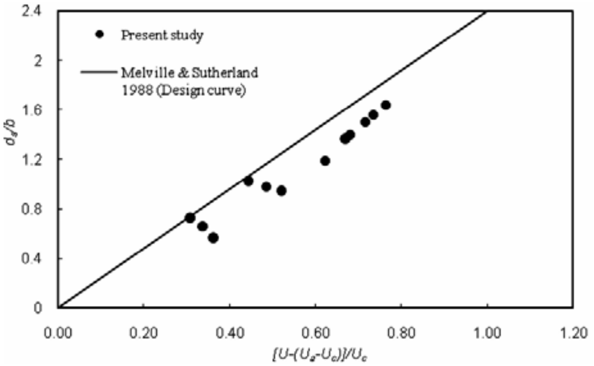


Figure-4. Comparison of scour depth (author data) with design curve of Melville and Sutherland (1988) Eq. 3(b).

Scour Depth

From dimensional analysis, it has been observed that the scour depth is a function of densimetric Froude number and inflow depth. In order to establish a relationship among them, relative (non-dimensional) scour depth (D_s) is plotted against densimetric Froude number (F_{D50}) with inflow depth (h) as parameter as shown in Figure-5.

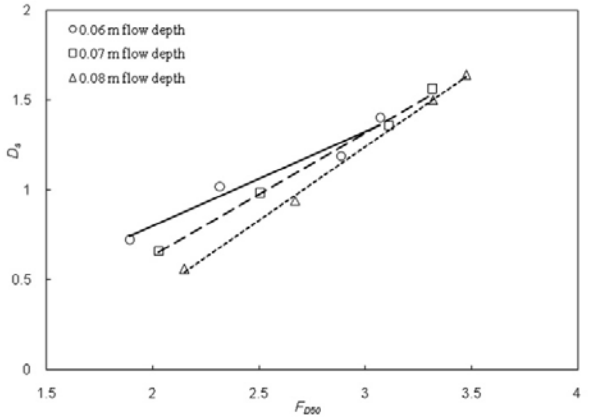


Figure-5. Scour depth D_s versus densimetric froude number F_{D50}.

Scour depth increases with densimetric Froude number for all the tested inflow depths. Linear trend lines for the curves indicate their dependence on inflow depths which take the following form:

$$D_s = (C_1) F_{D50} + (D_1) \quad (4)$$

Where, C_1 and D_1 are constants depending on inflow depths.

Generalized equations for C_1 and D_1 are further obtained by plotting the different values with their corresponding inflow depths.

The proposed equation for scour depth takes the final form as reproduced below which is a function of densimetric Froude number and inflow depth.

$$D_s = \{0.744(h/b) - 0.367\} F_{D50} + \{-2.438(h/b) + 2.683\} \quad (5)$$

Length and Width of Scour Hole

Dimensional analysis has indicated scour length as a function of densimetric Froude number and inflow depth. However, it has been shown in the preceding section that scour depth is dependent on densimetric Froude number as well as inflow depth. Hence, measured relative (non-dimensional) scour lengths (L_s) are plotted against the calculated relative scour depths with inflow depth as variable parameter. Linear trend lines for the relative scour lengths for different inflow depths assume the following form:

$$L_s = (C_2) D_s + (D_2) \quad (6)$$

Where, C_2 and D_2 are constants which depend on inflow depths.

Further, values of C_2 and D_2 for different inflow depths are plotted against non-dimensional flow depth (h/b) and equations for C_2 and D_2 are obtained. Finally, relative scour length is proposed as follows:

$$L_s = \{3.958(h/b) - 2.371\} D_s + \{-2.649(h/b) + 5.082\} \quad 6(a)$$

Similarly empirical equation for width of scour hole can also be analyzed using plots between relative (non-dimensional) scour width (W_s) and non-dimensional scour depth (D_s). Relationship to evaluate non-dimensional scour width is proposed as

$$W_s = \{6.204(h/b) - 5.412\} D_s + \{-4.435(h/b) + 7.597\} \quad 6(b)$$

Area of Scour Hole

For developing proposed equation for scour hole area, the measured scour area is plotted as a function of calculated scour depth with inflow depth as parameter and it is noticed that scour area increases with increasing scour depth. However, it also varies with inflow depth. Hence the scour area is expressed as a function of non-dimensional scour depth.

$$A_s = (C_3) e^{D_3 D_s} \quad (7)$$

After finding C_3 and D_3 in similar manner as explained earlier, the scour area can be expressed as a function of calculated scour depth D_s and inflow depth h/b, as shown in equation 7(a).

$$A_s = \{-3.041(h/b) + 7.087\} e^{\{1.229(h/b) + 0.158\} D_s} \quad 7(a)$$

Volume of Scour Hole

The observed scour hole volume is plotted as a function of calculated scour depth for different inflow depths and in this case also it is observed that the scour volume increases with increasing non-dimensional scour depth. Moreover, for the same non-dimensional scour depth, the scour volume increases with decreasing inflow depth. Hence the scour volume is expressed as a function of non-dimensional scour depth.

$$\cancel{V} = (C_4) e^{D_4 D_s} \quad (8)$$

After determining and substituting for C_4 and D_4, scour volume is expressed as a function of calculated scour depth D_s and inflow depth h/b, as shown in equation 8(a).

$$\cancel{V} = \left\{-1.520\left(h/b\right)+3.661\right\} e^{\left\{1.568\left(h/b\right)-0.716\right\}D_s} \tag{8(a)}$$

Comparison of Calculated and Measured Values

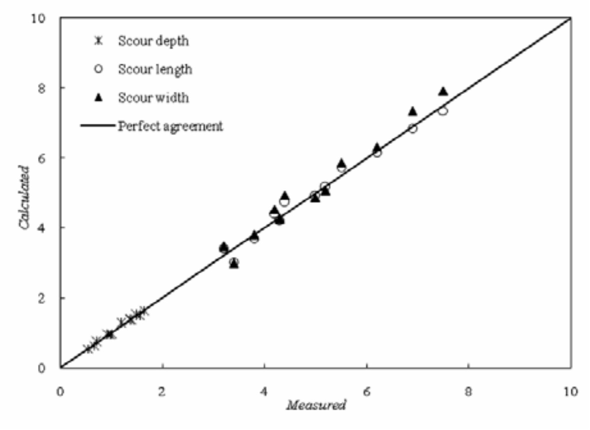


Figure-6(a). Comparison between measured and calculated values of scour depth, length and width.

Scour hole characteristics viz. depth, length, width, area and volume have been calculated using the corresponding proposed equations presented in previous sections. These values have been compared with those obtained by measurements from the conducted experiments as shown in Figures 6(a) and 6(b). A good agreement is observed for all the characteristics as indicated in Figures 6(a) and 6(b).

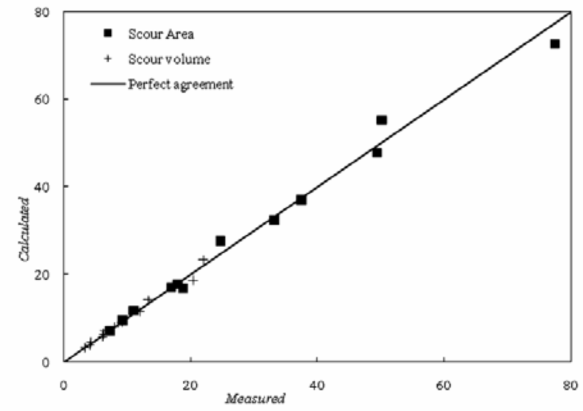


Figure-6(b). Comparison between measured and calculated values of scour area and volume.

CONCLUSIONS

Clear water scour tests have been performed on a single pier under varying inflow depths and densimetric Froude numbers. All the fourteen experimental runs satisfy the Shields Diagram where in each case the discharge measured during each experimental run was lesser than the minimum discharge required for the incipient motion or threshold conditions of the bed particles which satisfies the clear water scour condition. Primary scour hole characteristics such as depth, length and width have been measured physically while scour hole area and volume have been determined using Surfer application. Results from the tests indicate influence of densimetric Froude number and inflow depth on scour hole geometry. Dimensional analysis indicates scour hole characteristics as a function of inflow depth and densimetric Froude number. Proposed equations for scour hole parameters exhibit a good agreement with measured values.

List of symbols

The following notations are used in the present study.

h	Approach flow depth
b	Pier diameter
d_{xx}	Particle size diameter, where *xx*% material finer
d_s	Local equilibrium scour depth
l_s	Scour length
w_s	Scour width
a_s	Planar scour area
a_p	Pier plan area
$\cancel{v}_s$	Scour hole volume
$\cancel{v}_p$	Pier volume inside the scour hole
U	Approach flow velocity
σ_g	Standard deviation of sediment particle size distribution $[(d_{84} / d_{16})^{0.5}]$
ρ	Water density
ρ_s	Sand density
t	Time
g	Acceleration due to gravity
Δg	Reduced gravitational acceleration $[\{(\rho_s/\rho)-1\}\, g]$
F	Froude number $[U/ (gh)^{1/2}]$
F_{D50}	Densimetric Froude number $[U/ (\Delta g d_{50})^{1/2}]$
D_s	Relative scour depth (d_s/b)
L_s	Relative scour length (l_s/b)
W_s	Relative scour width (w_s/b)
A_s	Relative scour area (a_s/a_p)
$\cancel{V}_s$	Relative scour volume $(\cancel{v}_s/\cancel{v}_p)$
U_c	Approach flow velocity at threshold condition
U_a	Approach flow velocity at armor peak (= 0.8 × approach flow velocity beyond which armoring of channel bed is impossible)
u_*	Shear velocity
u_{*c}	Critical shear velocity
τ_0	Average shear stress at the boundary
τ_{0_c}	Threshold shear stress at the boundary
Θ	Shields parameter
Θ_c	Critical Shields parameter

R_*	Shear Reynolds number
R_{*c}	Critical shear Reynolds number
K_I	Flow intensity factor
K_y	Flow depth factor
K_d	Sediment size factor
K_σ	Sediment gradation factor
K_s	Pier shape factor
K_α	Pier alignment factor
C_x,D_x	Coefficients

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