TEMPORAL DEVELOPMENT OF CLEAR-WATER SCOUR AROUND CYLINDRICAL PIERS

By

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ABSTRACT : Experimental results on temporal variation of scour depth around cylindrical bridge piers founded in uniform sand beds under steady clear-water flows are considered. Considering different parameters and thus non-dimensional parameters affecting scour depth, and by regression analysis of these non-dimensional parameters an equation is developed for computing the temporal variation of scour depth in cohesionless sediments. The present form of equation can be used for the estimation of the scour depth at any stage during the development of the equilibrium scour hole.

INTRODUCTION:

Scour is the local lowering of streambed elevation, which takes place in the vicinity or around a structure embedded in loose bed by constructed in flowing water. Scour takes place around bridge piers, abutments and spurs/dikes due to modification of flow pattern in such a way as to cause increase in local shear stress. This in turn dislodges the material on the streambed resulting in local scour.

The process of local scour around bridge piers is time dependent phenomena. An equilibrium between the erosive capability of the flow and the resistance to motion of the bed materials is progressively attained through erosion of the flow boundary. In cohesionless fine grained materials, the equilibrium depth of local scour is rapidly attained in live-bed condition, but rather more slowly in clear-water condition. Clear-water scour occurs for mean flow velocities (U) upto the threshold velocity (U_c) for bed sediment entrainment, i.e. $U \leq U_c$, while live-bed scour occurs for $U > U_c$. The maximum equilibrium scour depth occurs at $U = U_c$. The phenomenon of scour around bridge piers has been studied by a large number of investigators. Shen et al. (1969) distinguished between (i) clear-water scour, when upstream flow does not transport sediment, and (ii) live-bed scour; when upstream flow transports sediment.

The estimation of scour depth around bridge piers is a major concern of bridge engineers. Underestimation of the scour depth and its areal extent results in design of too shallow a foundation which may consequently get exposed to the flow endangering the safety of the bridge. Overestimation of the scour depth results in uneconomical design. Great difficulty is experienced sometimes in straightening the pier wells which tend to get tilted while sinking to large depths. Therefore, knowledge of the anticipated maximum scour depth for design discharge is essential for a proper design of the foundation of the bridge piers, abutment etc.

On the basis of dimensional analysis of different independent parameters (fluid, flow, sediment characteristics, pier size and time) affecting scour depth, different non-dimensional parameters has been found such as time scale, pier Froude number, flow depth to pier diameter ratio, Shields sediment grain entrainment parameter. With the regression analysis of these non-dimensional parameters affecting scour depth, an expression for rate of scour depth has been obtained. This relationship provide time variation of scour depth. The present form of equation also allow estimation of local scour depth at any stage throughout the development of a scour hole.

FUNCTIONAL FORM OF SCOUR DEPTH ANALYSIS:

The functional relation between the local scour depth around bridge piers, D_s and its dependent parameters can be written as

$$D_s = \phi[\text{flow } (\rho, \nu, U, H, g), \text{ sediment } (d_{50}, \sigma_g, \rho_s, U_c), \text{ pier geometry } (b, K_s, K_\theta), \text{ time } (t, t_e)] \qquad \ldots\ldots\ldots\ldots..(1)$$

where ρ and ν = fluid density and kinematic viscosity, respectively, U and H = mean approach flow velocity and depth, respectively; g = gravitational acceleration; d_{50} and σ_g = mean size and geometric standard deviation of the sediment particle size; ρ_s = sediment density; U_c = critical mean approach flow velocity for entrainment of bed sediment; b = pier width; K_s and K_θ = parameters describing the shape and alignment of the pier; t = time; t_e = time for equilibrium scour depth to develop; and ϕ represent "a function of".

Considering Shields sediment grain entrainment parameter, $\theta_c = \tau_{oc} / (\gamma_s - \gamma)\, gd_{50}$ where τ_{oc} is the critical shear stress of the flow at which sediment grain starts moving from its rest position and γ_s and γ are unit weight of sediment and water, respectively. Considering above parameters in the formulation of non-dimensional parameters for the evaluation of scour depth variable with time.

Assuming a constant value of relative density of sand and the non viscous flow. An expression for equilibrium scour depth around a cylindrical pier of diameter, D for a uniform cohesionless sediment can be written using Eq. (1) as follows.

$$D_s / D = \phi\left[Ut/D,\ H/D,\ F_p,\ d_{50}/D,\ \theta_{cr}\right] \quad \ldots(2)$$

In Eq. (2) Ut/D represents the dimensionless time parameter also termed as the time scale; H/D the flow depth relative to the pier diameter, termed the flow shallowness; F_p the pier Froude number defined as $U/(gD)^{0.5}$; and d_{50}/D sediment mean size to pier diameter, termed sediment coarseness. As per Ettema (1980), for uniform sediments and $D/d_{50} \geq 50$, local scour depths are unaffected by sediment size unless the sediment is relatively coarse. In present study D/d_{50} varies from 42, to 156, hence D/d_{50} term has been dropped from Eq.(2). Thus Eq. (2) can be written as

$$D_s/D = \phi\ \{Ut/D,\ Fp,\ H/D,\ \theta_{cr}\} \quad \ldots.\ (3)$$

In Eq. (3) Shields sediment grain entrainment parameter, θ_c can be evaluated as given by van Rijn (1984). van Rijn has given the empirical relations for θ_c in terms of particle parameter (D_*) :

$$D_* = d_{50}\left[\frac{(G_s - 1)g}{\nu^2}\right]^{1/3} \quad \text{with} \quad \nu = \frac{40\text{x}10^{-6}}{20 + T} \quad \ldots.(4)$$

in which d_{50} = mean sediment diameter; g = gravitational acceleration; ν = kinematic viscosity; and T = temperature in ^{0}C.

$$\theta_{cr} = 0.24\ D_*^{-1} \quad ;\ \text{for } D_* \leq 4 \quad \ldots.5(a)$$

$$\theta_{cr} = 0.14\ D_*^{-0.64} \quad ;\ \text{for } 4 < D_* \leq 10 \quad \ldots.5(b)$$

$$\theta_{cr} = 0.04\ D_*^{-0.10} \quad ;\ \text{for } 10 < D_* \leq 20 \quad \ldots.5(c)$$

$$\theta_{cr} = 0.013\ D_*^{0.29} \quad ;\ \text{for } 20 < D_* \leq 150 \quad \ldots.5(d)$$

$$\theta_{cr} = 0.055 \quad ;\ \text{for } D > 150 \quad \ldots.5(e)$$

EXPERIMENTS :

In order to clarify the effect of time on the development of scour depth around cylindrical bridge piers in uniform cohesionless sediment under clear-water condition was considered. In the present study, experiments were performed in laboratory channel to collect the data on temporal variation of clear-water scour depth. A glass walled rectangular channel 5m long, 0.50m wide and 0.75m deep with suitable stilling arrangements at its upstream end was filled with fine sand (d_{50} = 0.16mm) and coarse sand (d_{50} = 0.60mm), respectively for performing experiments with two different size of sand particles. The sand was 0.30m deep with upstream and downstream gravel curtains, and a sediment trap at the downstream gate. The channel gets its water supply continuously through out the experiment an overhead tank. A tail gate at the downstream end of the channel was used to adjust the flow depth in order to maintain uniform flow depth. The flow discharge Q was measured with a previously calibrated weir placed downstream of the experimental section. Cylindrical piers made from clear Perspex tubes with diameters, D = 25, 32.5, 50, 78, 92, 132 and 165mm were used in the study. The flow conditions are maintained at or very near to the critical flow conditions. This is because at this state of flow the scour depth will be maximum. Two types of sediments were used in the present experimental study viz. fine sand (d_{50} = 0.16mm), where sediment transport in suspension mode is dominating, and coarse sand of size (d_{50} = 0.60mm) where the bed load is the dominating mode of transport. The experiment were run for more than 100 hours for different pier diameter for d_{50} = 0.16mm sediment size and 10 hours for d_{50} = 0.60mm sediment size, respectively. The sediments with a median size of 0.16mm and 0.60mm and a standard deviation ($\sigma_g=[d_{84}/d_{16}]^{½}$) of 1.38 and 1.72 was used. The specific gravity of these sand used in experiments were taken as 2.65. It was observed that scour depth increases with increase in time in general.

PREDICTION OF SCOUR DEPTH :

As an initial attempt to correlate scour depth with time, a curve was obtained from the regression analysis in functional form.

$$D_s/D \quad = \quad \phi\ \{Ut/D,\ Fp,\ H/D\} \qquad \text{.... (6)}$$

is plotted in Fig. 1. From this figure it can be observed that the scour depth is tending to reach equilibrium at long time of run of experiment. The data plotted in Fig.1 provide relationship in terms of different functional form as given in Eq. (6). This equation shows that scour depth varies with time in logarithmic scale in the mid range. In the initial and at the final stages, the scour depth follows non linear pattern with logarithmic time as a variable. This leads to observe the rate of scour as a function of time.

A curve was plotted between rate of scour, d (D_s/D)/d (Ut/D) versus non-dimensional time parameter (Ut/D) as in Fig. 2. From this figure it can be observed that the rate of scour is very high in the beginning and it goes on decreasing as the scour depth increases with time. An expression for rate of scour depth from regression analysis was obtained as.

$$d\,(D_s/D)/d\,(Ut/D) \quad = \quad 0.365\ \{Ut/D\}^{-1.12} \qquad \text{.... (7)}$$

In order to predict the values of relative scour depth (D_s/D), Eq. (7) was integrated, and following equation was obtained.

$$D_s/D \quad = \quad -\,3.041\ (Ut/D)^{-0.12} + C \qquad \text{.... (8)}$$

where C is the integration constant.

With the boundary conditions that at $t = 0$, the constant was not in a position to be evaluated and the other boundary condition when t is very large, the value of D_s is not known. Due to this, scour depth at intermediate value of time t, is chosen for the evaluation of integration constant C. Evaluating the integration constant, C at a mid range value of $Ut/D = 10^5$ for all the pier diameters. D_s/D at $Ut/D = 10^5$ with the other non-dimensional parameters Fp, and θ_c by regression analysis of present data following equation was obtained from Fig. 3.

$$\begin{aligned} D_s/D \quad &= \quad 10.55\ (Fp \times \theta_{cr}^{1.76})^{0.625} \\ &= \quad 10.55\ Fp^{\,0.625}\ \theta_{cr}^{1.10} \qquad \text{....(9)} \end{aligned}$$

From Eq. (8) and at $Ut/D = 10^5$

$$D_s/D \quad = \quad -0.764\ + C \qquad \text{....(10)}$$

Thus the value of integration constant, C at $Ut/D = 10^5$ can be obtained as.

$$C \quad = \quad 0.764 + Ds/D \qquad \text{....(11)}$$

Substituting the value of Ds/D at Ut/D = 10^5 from Eq. (9) into Eq. (11)

$$C = 0.764 + 10.55\, Fp^{0.625} .\, \theta_{cr}^{1.10} \qquad ....(12)$$

Thus from Eq. (8) and (12), the equation for temporal variation of scour depth can be obtained as follows

$$D_s/D = 10.55\, Fp^{0.625} .\, \theta_{cr}^{1.10} - 3.041\, (Ut/D)^{-0.12} + 0.764 \qquad ....(13)$$

The agreement between the experimental data and predicted value of D_s/D from Eq.(13) is found to be reasonably good.

Melville et al. (1999) have expressed the ratio of local scour depth (D_s) at any time, t and local scour depth at equilibrium (D_{se}) at time (t_e) as-

$$D_s/D_{se} = \exp. \{-0.03\, |Uc/U\, (t/t_e)|^{1.6}\} \qquad ....(14)$$

The application of Eq. (14) required knowledge of equilibrium time, te Relation for which was also given by Milville et al. (1999) as follows

$$t_e\ (\text{days}) = 48.26\, D/U\, (U/U_c - 0.4) \quad ;\ \text{for } H/D > 4 \qquad ....15(a)$$

$$t_e\ (\text{days}) = 30.89\, D/U\, (U/U_c - 0.4)\, (H/D)^{0.25};\ \text{for } H/D \leq 6 \qquad ....15(b)$$

Thus scour depth at any time (t) can be obtained from Eq. (13) and for the prediction of equilibrium scour depth Eq. (13) can be used along with Eqs. (14) and (15).

The critical mean flow velocity, U_c in Eq. (15) can be computed as

$$U_c = 2.5\, [\theta_c\, (G_s\text{-}1)\, gd_{50}]^{0.50} \ln\, (6H/d_{50}) \qquad ....(16)$$

CONCLUSIONS :

The study is limited to clear-water local scouring around cylindrical bridge piers in uniform noncohesive sand beds. It was found that a clear-water scour around a cylindrical bridge pier was a time dependent phenomena. The Eq. (13) allow estimation of local scour depth at any stage throughout the development of a scour hole. For the prediction of equilibrium scour depth, knowledge of design flood hydrograph is necessary to assess the time of scouring (t). The relations given were not confirmed at prototype scale. Thus, it is suggested to confirm above equations at prototype scale before applying in the field.

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NOTATIONS

D = diameter of cylindrical pier;
D_* = particle parameter;
d_{50} = median size of particle size distribution;
D_s = local scour depth at time t;
D_{se} = local scour depth at equilibrium;
F_p = pier Froude number;
g = acceleration of gravity;
G_s = relative density of sediment;
H = mean approach flow depth;
K_s = pier shape factor;
K_θ = pier alignment factor;
t = time;

t_e = time to develop equilibrium scour depth;
U = mean approach flow velocity;
U_c = mean approach flow velocity at threshold condition for sediment movement;
U_{*c} = critical shear velocity;
ν = kinematic viscosity of water;
ρ = density of water;
ρ_s = sediment density;
θ_c = Shields sediment grain entrainment parameter;
τ_{oc} = critical shear stress of the flow of which sediment grain dislodges from the movement;
σ = geometric standard deviation of sediment particle size distribution.