Pier Scouring under Live-Bed Condition

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Abstract

Problem of local-scar is key among bridge pier and abutments, local-scar of piers has lead to failure of many bridges in past and hence it is an active topic of investigation among various researchers. The problem of scar worsens once the stream gets flooded. When floods occur the scarring does not keep itself limited to stream, whereas it increases its extent and reaches the low-lying adjoining areas of the stream and tends to scarring the vicinity of the obstruction being offered to the flood flow. In spite of the efforts and work on the topic during the last five or six decades, the time evolution for depth of scar and its ultimate “equilibrium” value remains a subject of concern for engineers and investigators. In the thesis extensive work and analysis have been carried out to study the scarring behaviour of pier under live-bed condition, and to analyze its scar depth in relation to various parameters related to scar depth. Data from various studies conducted in past have been adopted for analysis. Dimensional analysis followed by regression analysis has been carried out to predict the scar depth. The predicted scar depth has been analyzed for different non-dimensional parameters. The data has also been analyzed for temporal variation to estimate the time run for equilibrium scar depth.

Keywords: Scour, Local scour, Scour depth, Live-Bed Condition

I. INTRODUCTION

Scour is due to the turbulence in a small reach. When an alluvial stream is partially obstructed by structures built on it generally bridge piers, abutments, spurs, etc. scar takes place in the vicinity of the structure. Thus, a bridge abutment or pier in a river bed induces an adverse pressure gradient in the flow resulting in three-dimensional separation of the boundary layer at the bed in front of the pier. This causes the formation of a system of vortices which moves around the pier in the shape of a horse-shoe and hence it is popularly known as horse-shoe vortex. Such vortex system results into the development of high local shear stresses on the river bed beneath them and hence, there is an increase in the sediment transportation capacity of the flow around the pier. It is found that generally scar is caused by a lack of balance between sediment in motion and transport capacity of flow. Thus, an increase in shear stress near the pier or abutment tends to break this balance and as a result, the stream in the process of adjustment increases the local depth by the scar of bed sediment. The increased depth of scar is termed as local scar depth and plays an important role in the analysis of scar forming for any structure. A factor in local scar at encroachments is whether it is live-bed or clear-water scar. Clear-water scar occurs when there is no transport of bed material upstream of the crossing or encroachment or the material being transported from the upstream reach is transported through the downstream reach at less than the capacity of the flow. Live-bed scar occurs where there is transport of bed material from the upstream reach into the crossing or encroachment.

Local scar is defined as the erosion of the bed around an obstruction to the flow-field over the mobile bed. Local scarforming may affect the structural integrity and stability of hydraulic structures and bridges causing failure of the foundation by foundation undermining. Local scar of piers continues to be one of the most common and frequent causes of bridge failures. The presence of a pier into the stream flow modifies the field of velocity, and hence increases the sediment entraining capacity from the vicinity of pier and originates scarforming process. The three-dimensional flow pattern and time-dependent behavior of scar combining together makes the phenomenon of scarforming more difficult and complex to assess. Determination of magnitude of scar becomes more complicated by the cyclic behavior of some scar processes adding to the complexity of scarforming. Scarring happens to be deepest near the peak of a flood, but rarely visible as scar holes gets it refilled with sediment as the floodwaters recede.

The study to be performed in this literature, which is the prediction of scar depth and analysis of the non-dimensional parameters affecting the scar depth prediction for the data available from the studies conducted by various researchers. The study is to be performed on the live-bed data so as to analyze the effect of flow intensity on scar depth. Dimensional and regression analysis have been used as the tools for the prediction of scar depth.

A. Possible Scarforming Conditions:
- General scar (Occur as either Long-term or Short-term scar)
- Contraction scar at the bridge
- Local scar at the piers/abutments
- Scour concentrated near the outside of the bend (Flow around a bend)
- Scour at confluences
- Lateral stream migration
Of the all listed scour conditions local scouring is the condition prominent in the built-up areas, and hence the paper completely focuses on the behavior of local scour.

**B. Local Scour:**

As described before local scour occurs in the immediate vicinity of the bridge piers. When flood occurs and the floodwater reaches into the built-up areas, the same process happens i.e. scouring of foundations of houses and buildings takes place progressively, exposing the foundations to flood loads leading them to partial/complete collapse. Local scour occurs around a foundation when the local flow field being developed by the flow is strong enough to remove the soil particles from the vicinity. Local scour is a time dependent process. The development of local scour is dependent on various factors which we will come across as we go further. The basic mechanism inducing local scour is the formation of vortices at the foundation. The localized scouring has been a concern to many investigators and researchers and numerous works exists on the topic. The significance of local scour can be understood by the fact that counter-measure to local scour alone can minimize the damages being caused by the flood in the built-up areas.

**C. Mechanism of Local Scour:**

Vortex formation and down-flow are the major cause of local scour and the fundamental theories of local scour are based upon them only. The vortices are formed at the base of the pier and down-flow occurs at the upstream face of the pier. The flow loses the acceleration as it move towards the pier becoming stagnant at the face of the pier. The pressure increases at the pier face as the approach flow velocity reduces itself to zero at the upstream side. The associated pressures are highest near the surface, where the deceleration is greatest, and decrease downwards. With the decrease in the velocity from surface to bed, the pressure accordingly decreases resulting in the formation of downward pressure gradient. The pressure gradient forces the flow down the face of the pier, resembling of a vertical jet. The flow resulting due to the pressure gradient impinges the streambed and creates a cavity/hole in the proximity of pier base. This flow impinging on the bed is the main scouring agent.

Figure 2 shows the scour pattern at a circular pier under the action of currents. In the figure, the vortex motion induced by the existence of the pier carries along the bed sediments within the vicinity of the base of pier. The flow rolling up continues to create a hole and, due to interaction with the oncoming flow, it develops into a vortex system, a complex vortex system. The vortex then extends itself downstream along the sides of the pier base. This vortex is referred as horseshoe vortex because of its great similarity to a horseshoe. The horseshoe vortex is effective in transporting the dispersed particles away from the pier. In context with the development of the vortex, the scour depth increases and the strength of the horseshoe vortex tends to diminish, which leads to a reduction in the rate of sediment transport from the base of the pier. Wake vortices, are the vertical vortices which are also formed in the vicinity of the pier base besides the horseshoe vortex, reason for their development is the separation of flow at the sides of the pier. Although, both the horseshoe and wake vortices erode the material from the base region of the pier, however it should be acknowledged that the intensity of the wake vortices reduces with the downstream distance of the pier, as a result it is seen that for a long pier immediately downstream there is a deposition of material.
D. Scour Depth:

Scouring is defined as the process due to which the soil particles around the foundations (piers and abutments) gets eroded and washed over a certain depth called scour depth. The scour depth can be computed by the summation of general scour and localized scour i.e. contraction scour at the bridge and local scour at bridge and abutments as discussed before.

E. Local Scour Depth:

Local scour is caused due to the interference of bridge foundations to the flow of water. The significant data for estimation of local scour depth are:

1) Approach Flow 
2) Sediment of bed 
3) Geometry of foundation 
4) Geometry of channel (in case of abutments only)

F. Framework for Analysis:

The scour depth ($d_s$) of a cylindrical pier at any given instant ($t$) can be expressed as

$$d_s = \text{function}\left[\text{flow}(y, S_f, g), \text{fluid}(\rho, \nu), \text{bed sediment}(d_{50}, \sigma_g, \rho_s), \text{pier}(b, K_w, K_s)\right]$$

or,

$$d_s = \text{function}(v, \rho, \nu, \gamma, d_{50}, \rho_s, V_c, b)$$

On application of π-Buckingham theorem, the set of nine independent variables can be reduced to six non-dimensional parameters,

$$\frac{d_s}{b} = \text{function}(R_e, Fr_{pa}, \rho', V/V_c, y/b, b/d_{50})$$

where,

- $R_e = \frac{vd_{50}}{\nu}$, particle Reynolds’s Number;
- $Fr_{pa} = \frac{\sqrt{g}d_{50}}{V^2}$, particle Froude Number;
- $\rho' = \frac{(\rho_s - \rho)}{\rho}$, relative density;
- $V_c = \text{flow intensity};$
- $\frac{y}{b} = \text{relative flow depth};$
- $\frac{d_{50}}{b} = \text{relative sediment roughness};$

Assumption made, that the sediment mobility under the effect of turbulent flow is described by a dimensionless grain diameter ($D^*$), as presented by Bonneville (1963), Ettema et al. (2009) the non-dimensional parameters $R_e, Fr_{pa}, \rho'$ are substituted by $D^*$ hence we get the functional relationship as

$$\frac{d_s}{b} = \text{function}(D^*, V/V_c, y/b, b/d_{50})$$

where,

$$D^* = \left(\frac{R_e}{Fr_{pa}/\rho'}\right) = \left[\left(\frac{\rho_s g}{\nu^2}\right)\right]^{1/3}d_{50}$$
As the non-dimensional grain diameter $D^*$ is kept constant in all the experiments keeping the focus on the effect $(V/V_c, y/b, b/d_{50})$ on $(d_{s50}/b)$, the possible significance of the non-dimensional parameters being considered in sequence:

- $(d_{s50}/b)$ is the most basic relationship. Experiments clearly indicate that if time effects are discounted by confining attention to the final or equilibrium scour depth ($d_{eq}$), and if the flow is strong enough to produce active scouring, then the ratio $(d_{s50}/b)$ is relatively insensitive to other factors and usually falls within the range of 1.0 to 3.0. The scour depth is determined primarily by the horse-shoe vortex, the dimensions of which are closely related to pier width.

- $D^* = (R_e/F_{p,a} / \rho^*) = \left[\left(\frac{a}{c}\right)ight]^{1/3} d_{50}$ non-dimensional grain diameter, in the case of small or light grains it is required to specify the state of bed transport and the susceptibility of the bed to local scour. In the case of large or heavy grains it may be possible to neglect it. In case of lightweight sediments, special consent must be given to $D^*$.

- $(\frac{b}{d_{50}})$ is a necessary geometrical ratio expressed in part the geometry of the vortex system. Its influence on $(d_{s50}/b)$ has been clearly demonstrated by experiments performed. $(\frac{y}{b})$ ratio is useful for describing the interaction of the down flow into the scour hole, the horse-shoe vortex at the base of the pier, and the counter-rotating water surface roller near the top of the pier. For small values of $(\frac{y}{b})$, the surface roller interacts with and weakens the down flow into the scour hole.

- $(\frac{V}{V_c})$ the term is the pier diameter relative to sediment mean size, termed the sediment coarseness. For, uniform sediments the local scour depths are unaffected by the sediment size unless the sediment is relatively coarse. Ettema (1980) explained that for larger values of sediment coarseness ratio, individual grains are relative to the groove excavated by the down flow, and erosion is impeded because the porous bed dissipates some of the energy of the down flow.

- $\left(\frac{V}{V_c}\right)^{\frac{1}{2}}$, the variation of scour depth under live-bed conditions are the consequence of size and steepness of the bed features, at particular flow velocities. The higher and steeper the bed is formed, the lesser is the scour depth because of the sediment supplied with the passage of the bed form is not completely removed from the scour cavity prior to arrival of next bed form. At the transition flat-bed condition the live-bed peak occurs. The anti-dunes tend to dissipate some energy at high velocities and local scour depth tends to decrease again. Due to the bed form migration, the magnitude of scour depth fluctuations is approximately equal to half-amplitude of bed forms, showing that the scour depth due to the bed forms is approximately one-half the bed form height.

From the assumptions made above, the non-dimensional parameters describing the equilibrium scour depth around circular piers can be written as:

$$d_{s50}/b = \text{function}(V/V_c, y/b, b/d_{50})$$

**G. Prediction of Scour Depth:**

Various data collected have been analyzed for live-bed conditions for different different non-dimensional parameters and have been plotted for their inter-relationship. Prediction of scour depth has been done using curve-fitting method and regression analysis. From various flume experiments, an attempt to correlate scour depth with various non-dimensional parameters used in using regression analysis, we get:

$$d_{s50}/b = \text{function}(D^*, V/V_c, y/b, b/d_{50})$$

**SCOUR DEPTH FOR LIVE-BED LOCAL PIER SCOUR EXPERIMENTS:**

$$d_{s50}/b = 0.86766 + 0.130719\left(\frac{y}{b}\right) - 0.44952\left(\frac{b}{d_{50}}\right) + 0.22584\left(\frac{V}{V_c}\right)$$

The predicted scour depth from regression analysis gives the equation written above. The equation is used to compute the non-dimensional scour depth and to analyze the non-dimensional scour depth with the independent non-dimensional parameters.

- Graph 1: Relationship between Non-Dimensional Scour Depth and Flow Intensity
- Graph 2: Relationship between Non-Dimensional Scour Depth and Flow Shallowness
- Graph 3: Temporal Variation of Scour Depth

**II. Conclusion**

The detailed analysis of data has been presented in this study. In addition to the data collected in the present investigation, the laboratory and field data collected by other investigator have also been used. The scour depths computed using regression analysis and graph are plotted to their respective parameters. In this plot the data of data collected from other investigators were also used for graph plot and also for equation derivation based on regression analysis. Based on the functional relationship derived in the dimensional analysis, new method for computation of scour depth in uniform, non uniform and sediment during steady flow are developed. Firstly, the scheme for computation of scour depth for live-bed flow has been evolved. Then the scheme for computation of scour depth in sediment transporting flow is discussed.
H. Analysis of Scour Depth in Relation to Non-Dimensional Parameters:

Graph 1: Non-Dimensional scour depth – flow intensity relationship

Graph 2: Non-Dimensional scour depth – flow Shallowness relationship

Graph 3: Temporal variation of scour depth

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REFERENCE


