Experimental study: bridge pier protection against local scour using guide panels

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Abstract. The most important cause of failure in hydraulic structures is local scour. Local scour around a bridge pier is generally the result of the actions of a complex vortices system that appears due to the modification of flow patterns caused by obstructions associated with the bridge pier. Experimental studies have always been considered to be a powerful tool for understanding and analysing the performance of these complicated flow conditions, and for examining the effect of countermeasures which otherwise could not be subjected to theoretical analysis. This study was thus conducted to determine the efficiency of the proposed method of reducing the depth of scour under laboratory conditions. This was done by conducting scour studies for a pier protected by a guide panels of various heights under different hydraulic conditions suffering from clear water scour. The results showed that as the height of panels decreased, the scour depth also decreased, with a maximum reduction of scour depth equal to 93%, with negligible side effects on the guide panels' scour. Dimensional analysis was used, and based on the laboratory results, an empirical formula was derived using IBM SPSS v.24 with a coefficient of determination $R^2 = 0.967$; this indicates considerable convergence between predicted and observed data.

Key-Words: Local scour, Experimental studies, Guide panels, Dimensional analysis.

1. Introduction

The scour process can be defined as the action of flowing water causing erosion, which excavates the river bed and carries away sediments from around bridge piers (Figure 1). Bridge scour must be considered a dynamic phenomenon and it is affected by several factors, including flow depth, flow velocity, pier shape, pier width, and sediment properties. The performance and safety of bridges can be affected by three types of scour: general, contraction, and local scour [1]. General scour is defined as the exclusion of sediments from the river bottom by flowing water. The development of general scour exists regardless the presence of a bridge, and it is considered a natural process; however, a lot of sediment may be removed over time. Contraction scour refers to sediment removal from the sides and the bottom of the river. It occurs as a result of an increase in flow velocity as the water flows across a bridge opening which is narrower than the channel of the river. Local scour is defined as the removal of bed sediment from around bridge piers or abutments, which leaves a hole in the bed known as a scour hole (as shown in figure 1).

The development of flow in the area surrounding a circular bridge pier has been studied by many researchers [2-6]. Figure 2 shows a schematic of flow pattern around a circular bridge pier in a scour hole. It can be seen that the approach flow separated by the pier converges at its downstream to form wake vortices. Also, as the flow approaches the bridge pier, a portion of the flow is forced to move down the front surface of the pier to form a horseshoe vortex at the base of the pier, which carries away bed materials from the base of the pier, causing local scouring around it. The higher the depth of the scour, the lower the strength of the horseshoe vortex, which reduces the transfer rate from the base area.
One of the methods used to reduce the scour around a pier is to combat the corrosive action of the horseshoe vortex by arming the river bed using solid engineering materials such as guide panels.

The purpose of this study is to investigate local scour around circular piers protected by such guide panels. The experimental data gained in this way is then used to derive a formula to predict the maximum scour depth around a circular pier.
2. Dimensional analysis

For a smooth pier of circular shape with diameter $D_p$ located at a centre of rectangular flume with a movable sand bed; under clear, steady, and uniform water flow conditions; and protected by a guide panels, the maximum scour depth at a pier nose $ds$ during time $t$ is a function of following parameters:

\[ (ds) = f(y, v, v_c, g, p, \mu, d_{50}, \rho_s, \sigma_g, D_p, S, B, t, X_{gp}, W_{gp}, h_{gp}, \alpha_{gp}, T_{gp}, O_{gp}) \]  \hspace{1cm} (1)

where $f$ is an unknown function, and the other parameters included in the equation are described as follows:

i) Flow variables: $y$=flow depth, $v$=velocity of flow, $v_c$=critical velocity, $g$= gravity acceleration.

ii) Fluid variables: $\rho$= water density; $\mu$= dynamic viscosity.

iii) Bed sediment variables: $d_{50}$=median particle grain size, $\rho_s$= sediment density, $\sigma_g$=geometric standard deviation, where $dx$ = is the sieve opening size that allows passage of x% (by weight of sediment) of fine sediment.

iv) Pier variables: $D_p$=pier diameter.

v) Channel geometry variables: $S$=channel slope, $B$=channel width.

vi) Time variable: $t$=scouring time.

vii) Guide panels variables: $X_{gp}$=spacing between pier and guide panels; $W_{gp}$ =width of guide panels; $h_{gp}$=height of guide panels above the sand bed; $\alpha_{gp}$ = interior angle between panels; $T_{gp}$=thickness of guide panels; and, $O_{gp}$= leading opening between panels.

By using the Buckingham $\pi$-theorem, and after simplification of the formula and removal of the parameters with negligible and constant values, the following considerations were applied to Eq. (1):

(1) $\sigma_g < 1.5$ for uniform sediment with $D_p/d_{50} > 25$: this ratio can be excluded from the scour formula [8],

(2) a horizontal channel floor without any inclination,

(3) for $B/D_p \geq 10$, side-wall (or blockage), effects due to pier presence are negligible (e.g. [9]),

(4) constant spacing between the pier and guide panels, constant width and thickness of guide panels, and a constant interior angle, both in the presence of the leading opening between guide panels and without it,

(5) and the equation as a whole is independent of dimensionless time at equilibrium conditions.

In accordance with these conditions, the functional relationship which describes a depth of scour normalised with the pier diameter may be written as:

\[ \frac{ds}{D_p} = f \left( \frac{y}{D_p}, \frac{v_c}{v}, \frac{D_p g}{v^2}, \frac{h_{gp}}{D_p} \right) \]  \hspace{1cm} (2)

The above formula shows that scour depth ratio ($\frac{ds}{D_p}$) varies with flow depth ratio ($\frac{y}{D_p}$), flow intensity ($\frac{v_c}{v}$), pier Froude number ($\frac{D_p g}{v^2}$), and height of guide panels above the sand bed ($\frac{h_{gp}}{D_p}$).
3. The experimental work and guide panel models:

The experimental work was done at the university of Al-Basrah's college of engineering in the hydraulic laboratory of the civil department.

A 5.72 m-long, 0.61 m-wide rectangular flume was used. The longitudinal slope was zero. A uniform sand was used to fill a 1.8 m-long, 0.08 m-deep bed (see figure 3).

![Illustration of experimental setup.](image)

A tailgate was used to control the flow depth, which was measured using a point gauge with an accuracy of ± 0.1 mm to determine the maximum scour depths at the pier front, and the scour at the edge of the guide panels.

Three different diameters of cylindrical pier were tested: 1.9, 2.4, and 4 cm. The results showed that the strength of the horseshoe vortex is proportional to the pier diameter: the larger the diameter, the deeper scour upstream of the pier and larger deposition downstream. For test guide panels, the larger diameter (4 cm) was thus used to test the worst-case scenario.

The two guide panels used in the experiments were placed in front of the pier vertically in the bed, at either an open or closed interior angle. These were made of plywood with a constant thickness of 1.6 cm. Experiments included using three different heights of guide panels with constant width and distance from the pier (see Figure 4).
4. Results and Discussion:

4.1 Guide panels height

The experiments showed that the height of the guide panels has a direct influence on the scouring process. As the height of the guide panels increase, the scour depth increases. Three models were used with three different heights (0.5, 1, and 2 cm) to examine the effect of guide panel height on the scour depth.

A set of experiments were conducted to evaluate the relationship between guide panel heights and scour depth. These experiments are shown in figure (5).

In the experiments, the scour process began at the face of the pier and then extended to its sides. The relationship between the height of the panels and the depth of the scour was found to be such that the lower the height of the panels, the greater the impact on the down flow. Consequently, the horseshoe vortex had less strength in such cases, leading to a lower scour depth. In all guide panels tests, scour did occur around the guide panels themselves.

4.2 Interior angle between panels

In this research, guide panels without a leading opening (closed interior angle) and a guide panels with a leading opening (open interior angle) were investigated. In the case without the leading opening, panels were installed at a distance of 1.5 $D_p$ ahead of the pier; the width of panels equalled 1.5 $D_p$, and three different heights of panels were used (0.5, 1, 2 cm), with a constant interior angle equal to 45°. The efficiency of scour reduction in these cases ranged from 67 to 93%. In the second set of cases, the guide panels had a leading opening ($\frac{D_{ogp}}{D_p} = 1.15$), and all other factors were held as in the previous
case. The efficiency of reducing scour was somewhat convergent, and the scour around the edges of the panels was greater than in the first case (see figure 6). This is due to the presence of a leading opening, which represents sharp edges that can reduce the strength of the horseshoe vortex and wake vortices, which in turn leads to greater efficiency in reducing scour depth in front of a circular pier; however, it divides and diverts the vortices' paths around the pier, leading to higher scouring around the pier. Figure 5 shows the guide panels tested in both cases.

![Figure 5](image)

**Figure 5.** Guide panels: (a) closed interior angle; (b) open interior angle (leading opening).

![Figure 6](image)

**Figure 6.** Variation of scour depth with guide panels height for each case (with and without leading opening).
4.3 Variation of Flow Depth and Velocity and Pier Froude Number:

Figures 7, 8, and 9 show the development of scour around a circular pier protected by constant dimensions of guide panels at an elevation of 0.5 cm above the bed level. The results shown that the scouing depth increases with increases in flow velocity, flow depth, and the pier's Froude number.

**Figure 7.** Variation of scour depth with flow depth.

**Figure 8.** Variation of scour depth with flow velocity.
5. Development of a new formula

IBM SPSS was used to derive the guide panel’s equation based on dimensional analysis and non-linear regression analysis. In order to generalise the experimental results to form a relationship takes into account the effects of guide panel dimensions, about 80% of the experimental data for an open interior angle (chosen due to its higher efficiency) was used to conduct analysis to develop a model:

\[
\frac{d_s}{D_p} = c_0 \times \left\{ \left( \frac{y}{D_p} \right)^{c_1} \times \left( \frac{v}{v_c} \right)^{c_2} \times (F_p)^{c_3} \times \left( \frac{h_{gp}}{D_p} \right)^{c_4} \right\}
\]

SPSS Nonlinear Regression Analysis gave the constants the following values:

\[c_0 = 0.191 \quad c_1 = 2.288 \quad c_2 = 3.680 \quad c_3 = -0.695 \quad c_4 = 0.181\]

Thus, the equation becomes:

\[
\frac{d_s}{D_p} = 0.191 \times \left\{ \left( \frac{y}{D_p} \right)^{2.288} \times \left( \frac{v}{v_c} \right)^{3.680} \times (F_p)^{-0.695} \times \left( \frac{h_{gp}}{D_p} \right)^{0.181} \right\}
\]

(3)

The determination coefficient for this formula is \(R^2 = 0.951\).

The remaining data (20% of the experimental data) was used to test the equation: a statistical comparison of equation, as shown in figure 10, was used to show the convergence of the observed values.
6. Conclusions
In the present study, local scour hole development around a circular pier protected by guide panels with and without leading openings was tested. The presence of a leading opening gives more efficiency in terms of reducing depth of scour to some extent because it reduces the strength of the horseshoe vortex and wake vortices, which in turn leads to a higher efficiency in reducing depth of scour. Different heights of guide panels were tested, and the results showed that the lower the panels, the greater the effect on the down flow, leading to more efficient reductions in scour depth. Efficiency of scour reduction ranged from 65% to 93%. However, in all guide panel tests, scour occurred around the guide panels themselves, especially in cases with a leading opening, due to the impact on vortices' patterns. The experimental results of this study also suggest that the scouring depth around a pier increases with increases of flow velocity, flow depth, and the pier's Froude number.

7. List of symbols

\[ D_p \]  Pier diameter

\[ d_{16} \]  Sediment size for which 16% of the particles are finer

\[ d_{50} \]  Median particle size

\[ d_{84} \]  Sediment Size for which 84% of the Particles are Finer

\[ d_s \]  Maximum Scour Depth below the Bed Level

\[ F_p \]  Pier Froude Number

\[ h_{gp} \]  height of guide panels above the sand bed

\[ OL_{gp} \]  leading opening between panels

\[ R^2 \]  Determination Coefficient
Slop of the Channel

$T_{gp}$ thickness of guide panels

t Scouring Time

$v$ Mean Velocity of Approach Flow

$\frac{v}{v_c}$ Flow Intensity

$v_c$ critical flow velocity for sediment entrainment

$W_{gp}$ width of guide panels

$x_{gp}$ spacing between pier and guide panels

$y$ Flow Depth

$\alpha_{gp}$ interior angle between panels

$\sigma_g$ Geometric Standard Deviation of Sediment Size Distribution

$\mu$ dynamic viscosity of fluid

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