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Scouring around different shapes of bridge pier

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ABSTRACT

Scouring is a complex process dependent on several factors, and local scour is more complex than general scour. This study was an attempt to predict local scour round bridge piers based on general scour in the water stream. Three obstacle shapes were used – circular, round-nosed, and elliptical – as they are predominant in hydraulic structures like bridge piers. For each obstacle shape, scour depth was measured around the periphery for five gradually increasing discharges and in two types of bed material. The local scour results were analyzed to relate them to general scour. Lacey's equation was used to estimate general scour. Models were developed for the three common shapes, by which local scour for any particular shape can be predicted based on general scour in the stream.

Key words: bridge pier, discharge, Lacey, local scour, shape, silt factor

HIGHLIGHTS

- Correct estimation of local scour depth.
- Incorporation of shape factor for a better scour depth estimation.
- Improvement over Lacey's theory.
- Relating local scour estimation with general scour.
- Better design and safety of hydraulic structures.

INTRODUCTION

Scour is the removal of soil and rocks from the beds and the banks of streams under the action of flowing water. As water passes around any obstruction in the flow path, scouring occurs. The obstruction, commonly a bridge pier, causes the water to change direction, producing turbulence. This in turn detaches soil particles and becomes suspended in the water stream. The United States Geological Survey (USGS) defines scour as the hole left when sediment is washed from the bottom of a river (Leopold & Maddock 1953). Although scour may occur at any time, scour action is especially strong during floods because swiftly flowing water has more energy than calm water to lift and carry sediment.

The flow of water over an erodible surface, such as the bed of a natural stream or an unlined channel, can cause scouring. This is accelerated if the water channel/stream is constricted by any hydraulic structure component such as a bridge pier. In such a case, the general scouring is accompanied by substantial local scour around the pier, which may prove detrimental to the latter's stability. The extent of scour is greatly affected by the presence of structures encroaching the channel (May *et al.* 2002; Abdul Aziz 2011). Many studies (Melville 1992; Landers & Mueller 1996; Melville & Coleman 2000; Hong *et al.* 2012; Akib & Rahman 2013) report that hydraulic structures fail mostly because of scouring around a structural element, most commonly a pier, in the case of bridges, especially during large floods. This highlights the importance of local scour depth estimation to reduce the probability of structural failure. Mohammadpour *et al.* (2021) conducted experiments to predict local scour around complex abutments and compared the results with complex piers. Inamdeen *et al.* (2021) studied riverbed scour to focus on the fundamental mechanisms and patterns governing bridge scour; a bathymetric survey was

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used to map the scour holes downstream on the Ronne River, Sweden to analyze the possible causes of scouring. Local scour is a function of many variables involving flow, channel, and pier/obstacle parameters (Raudkivi & Ettema 1983; Mir *et al.* 2017, 2018; Link *et al.* 2020). Channel scouring and its estimation are substantially governed by various phenomena including runoff, sediment transport mechanisms, etc. (Fakhri *et al.* 2014; MohammadzadeMiyab *et al.* 2017; Zalaki-Badil *et al.* 2017).

Lacey's model (1930) estimates general scour, and is extensively used for scour estimation and protection works design in India, with suitable factors. Almost all relevant IS/IRC/RDSO codes recommend this method. Shahriar *et al.* (2021) investigated five statistical scour estimation models; all based on deterministic approaches, to predict scour depth for clear-water conditions, and compared the results with the measured data base. The models were assessed in terms of uncertainty in predictions and were found satisfactory.

It is likely that the factors affecting general scour also affect local scour, but in addition, the shape of the obstacle may also affect it (Mir *et al.* 2017). Baghhbadorani *et al.* (2018) investigated scouring for complex pier shapes that arise when scouring exposes pile caps and piles. Fifty-two tests were conducted on four different complex pier models, in clear-water conditions, to help improve the accuracy of the published HEC-18 equations (Richardson & Davis 2001). Aly & Dougherty (2021) investigated the effect of bridge pier geometry on local scour, and the results indicated how pier geometry could reduce the bed shear stress considerably leading to reduced scour depth around the piers. Thus, there is scope to develop the local scour model, depending on the shape of the obstacle and general scour capacity of a flowing stream. In this study, Lacey's general scour model was used because of its relevance and extensive use. The aim of the study was the physical modeling of local scour for piers of commonly encountered shapes (circular, round-nosed, and elliptical) and to develop the relationships of local and general scour.

Laboratory investigations

Investigations were carried out in a laboratory flume for the three obstacle model shapes – circular, round-nosed, and elliptical. The data were analyzed to determine the relations between the local and corresponding general scour.

Experimental set-up

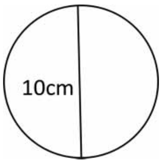
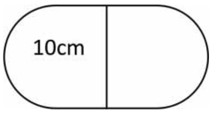
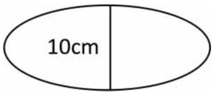
The experiments were done in a tilting flume 21.5 m long, with a height of 0.6 m and width of 1 m (Figure 1), like that used by Mir *et al.* (2019). The slope was fixed at 1 in 114 m, as commonly found in valleys. The discharge variations were managed using a regulatory valve at the flume's influent section and the measurements made using a sharp-crested weir at the downstream end. Water levels and scour hole depths were measured with a data logger system attached to the flume.

Figure 1 | Experimental set-up.

Obstacle models and bed material

As stated earlier, three commonly encountered shapes of the obstacles were used in the present study. These were circular, round-nosed, and elliptical. Wooden models of the three obstacle shapes, whose cross-sections are given in Table 1, were prepared. The obstacles' standard section was taken as 10 cm, in accordance with previous studies (Chiew & Melville 1987), which state that the maximum channel obstruction should not exceed 10% of its width to study scouring free from channel side effects.

Table 1 | Obstacle shapes used

Shape	**Designation**	**Obstacle shapes**
Circular	S_1	
Round-ended	S_2	
Elliptical	S_3	

Two non-cohesive soils of different gradations were used as bed materials to fill the glass-sided flume, both having varying particle distribution characteristics. Both materials were studied to find their characteristics and determine their effect on local scour depth around the obstructions. Table 2 gives the bed material parameters.

Table 2 | Bed material parameters

Parameter	**Symbol**	**Material 1**	**Material 2**
Size at 10% passing	D_{10}	0.2	0.3
Size at 30% passing	D_{30}	0.39	0.7
Size at 50% passing	D_{50}	0.4	1.5
Size at 60% passing	D_{60}	0.5	1.9
Coefficient of curvature	C_c	1.52	0.86
Coefficient of uniformity	C_u	2.5	6.33
Silt factor	f	1.11	2.15

Experimentation

The study was limited to local scour depth in non-cohesive bed material. The bed material was properly compacted and leveled to achieve results approximate to natural conditions. Discharge variation was brought about using a sharp-crested weir downstream end connected to a sensor and gave the head over the crest directly (Equation (1)).

$$Q = \frac{2}{3} C_d B \sqrt{2g} (H)^{\frac{3}{2}} \tag{1}$$

The scouring along the obstacle model peripheries was noted down for different discharges using a laser meter. That discharge has the main effects in scouring is already well known and widely reported. In this study, discharges were varied using discharge heads between 0.4 and 4.5 cm, for each obstruction type and both types of bed material. The flow parameters of the study are given in Table 3.

Table 3 | Flow parameters of the study

S. No.	Head over crest H (cm)	Discharge coefficient C_d	Discharge intensity q (m^2/s)
1	0.4	0.647	0.0008631
2	1.4	0.647	0.005237
3	2.5	0.647	0.012331
4	3.5	0.647	0.020329
5	4.5	0.647	0.0296370

Experimental data

During the experiments, it was clear that scour showed dependence on pier shape. Changes in obstacle shape cause considerable variations in scour depth. The maximum scour depths for each obstacle for different discharges are given in Table 4.

Table 4 | Local scour depths for different obstacle shapes (mm)

Discharge Q	Silt factor f	Circular S_1	Round-nosed S_2	Elliptical S_3
Q_1	1.1	4.3	0.3	0.5
	2.2	1.7	1.9	5.9
Q_2	1.1	7.6	3.3	6.0
	2.2	4.1	4.6	7.6
Q_3	1.1	10.9	7.8	12.4
	2.2	5.2	7.6	16.5
Q_4	1.1	16.5	10.0	18.6
	2.2	7.5	17.6	20.5
Q_5	1.1	21.6	14.3	22.7
	2.2	13.5	24.1	29.8

The circular cross section was found to have the greatest scour, the round-ended the least. The trend was similar at all five discharge flows and with both types of bed material.

DISCUSSION

It is clear from the literature that the uncertainty in estimating general scour is less than that in local scour. Extensive research has been done on this and the complex nature of local scour is the main reason for this uncertainty. Compared to local scour, general scour is defined much more broadly. Local scour has varied characteristics and is also subject to changes in site conditions; most commonly, the models developed are site-specific. The models for general scour are well established and are not subject to a wide range of variations with changes in the conditions under which they were formulated. So, general scour estimation is an efficient tool for the determination of local scour depth. In this study, local scour depth models were developed for the three pier shapes by relating to general scour. Local scour depths observed against general scour for the three obstacle shapes are given in Figures 2(a)–4(b).

The best-fit models for the shapes follow a power trend. The models' statistical results are given in Table 5.

The data indicate a trend between local and general scour. Equations (2)–(4) were developed by analyzing the experimental data for the three shapes used in the study. In the equations, S_L stands for local scour, S_G for general scour.

Circular

$$S_L = 0.943 S_G^{1.209} \tag{2}$$

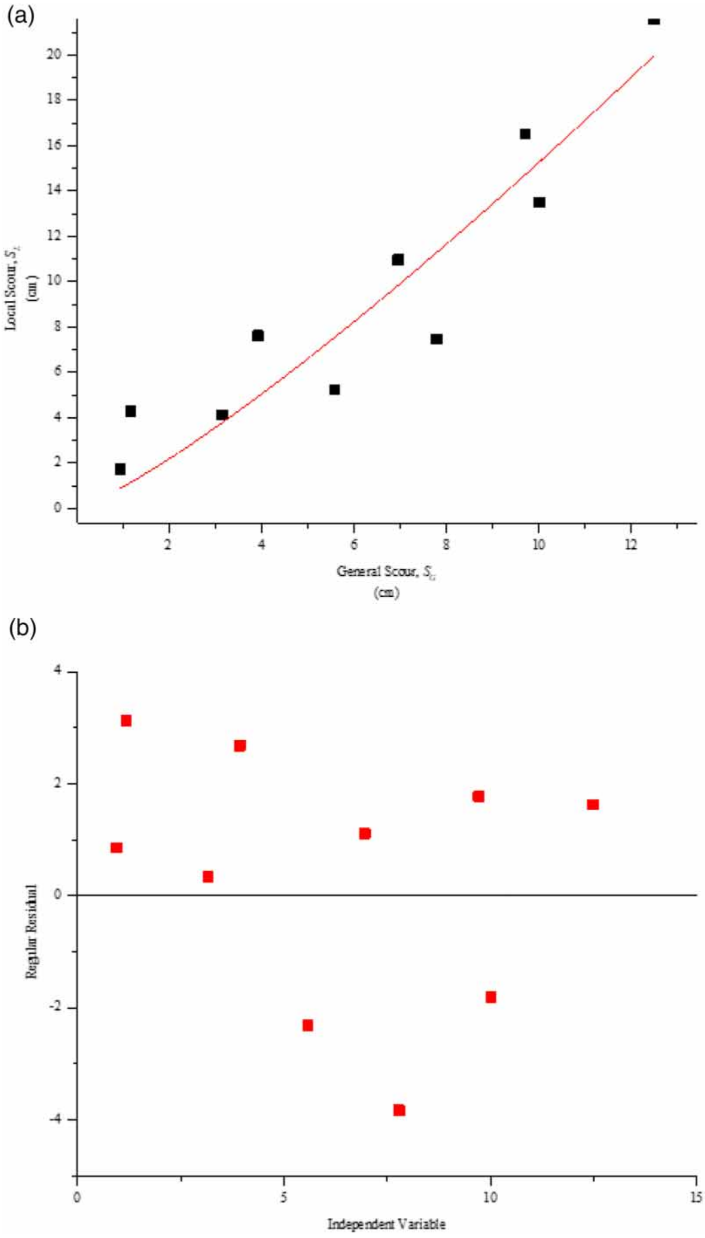


Figure 2 | (a) Local versus general scour for circular piers (S_1). (b) Residuals versus independent plot for S_1.

Round-ended

$$S_L = 1.537S_G^{0.991} \tag{3}$$

Elliptical

$$S_L = 2.941S_G^{0.873} \tag{4}$$

Using these models, the preliminary scour depth can be estimated with respect to the general scour in the channel. This concept is different from the conventional methods used till now. But, further comparison of the models obtained here with the previous studies after adjusting the parameters of the studies accordingly

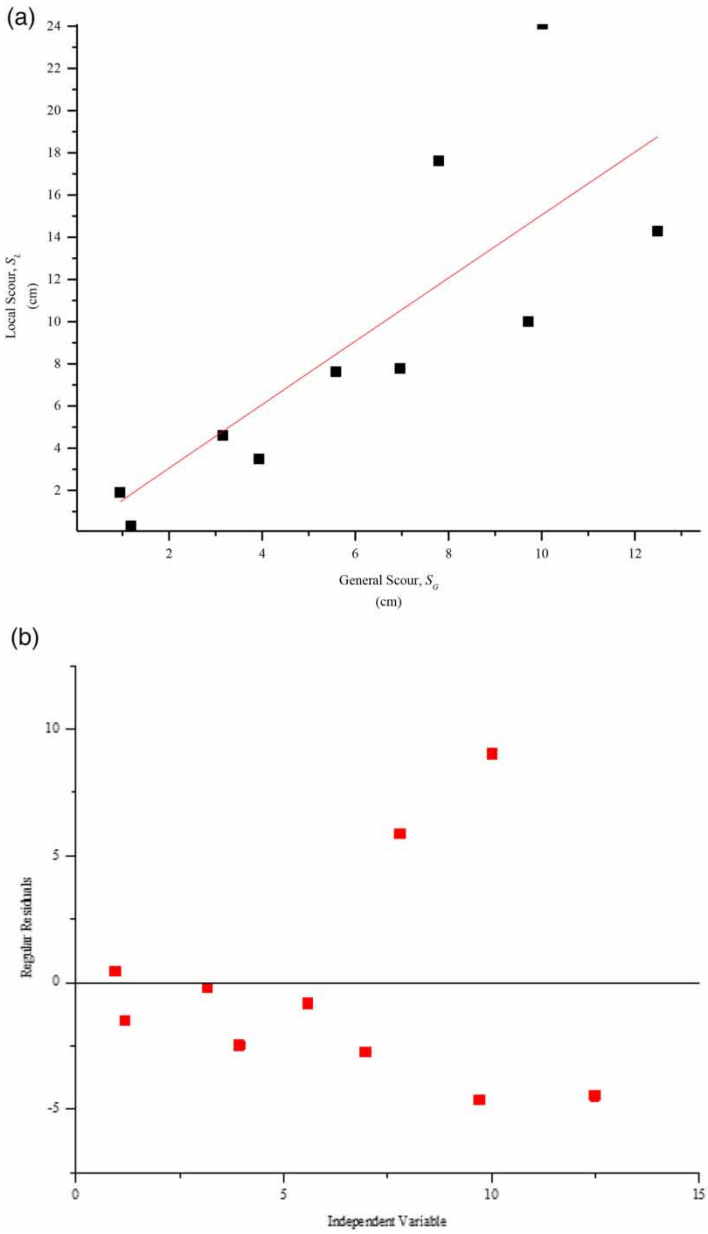


Figure 3 | (a) Local versus general scour for round-ended piers (S_2). (b) Residuals versus independent plot for S_2.

can help in scour prevention and mitigation measures to a great extent. This has been listed as the future recommendation of the present study.

CONCLUSIONS

In the study, local scour was found to vary with general scour with a significant coefficient of correlation. The local-general scour relations developed for the three shapes used are different, indicating a definite effect of the obstacle's shape on local scouring.

The above relation is based on limited data and only two different bed materials, but can be used for preliminary estimation of local scour for a proposed obstacle shape that may encounter streamflow. The relations give a better estimate of local scour than multiplying general scour values with some factors, where the shape effect is usually ignored. The conclusions that can be drawn from the study are:

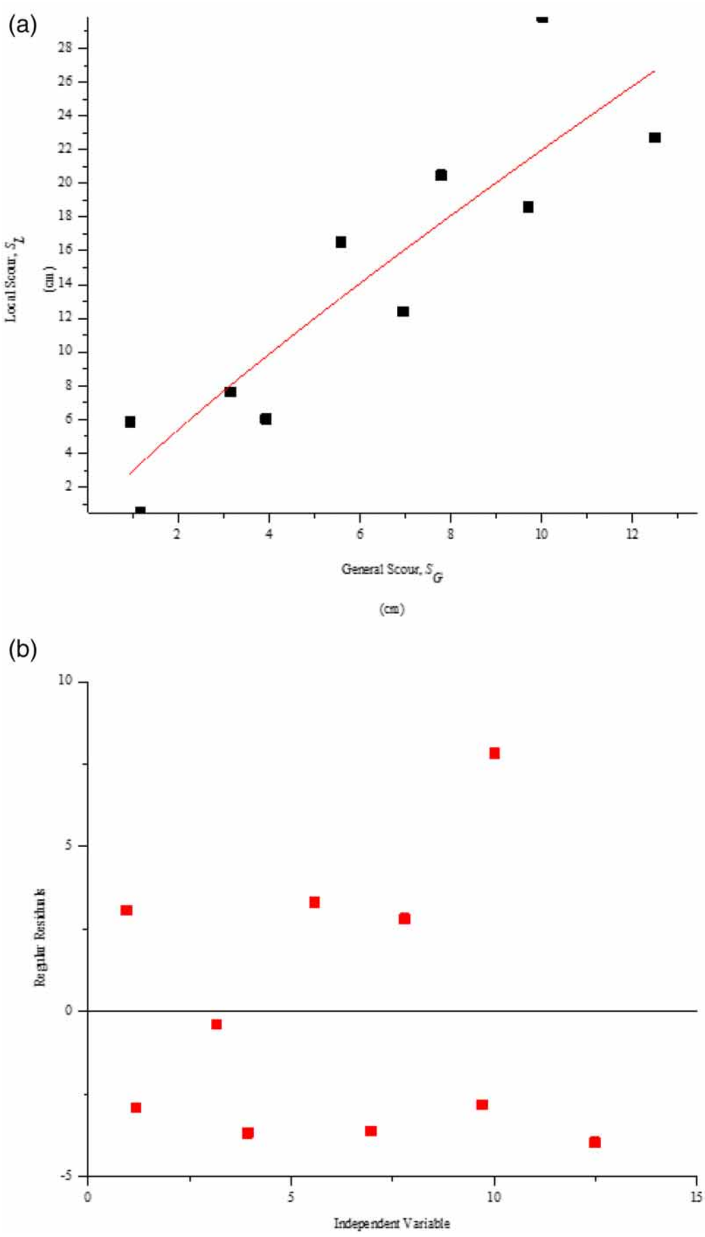


Figure 4 | (a) Local versus general scour for elliptical piers (S_3). (b) Residual versus independent plot for S_3.

Table 5 | Statistical results for the developed models

Shape	Coefficient	Value	Standard error	R^2
S_1	A	0.943	0.506	87
	B	1.209	0.236	
S_2	A	1.537	1.342	67
	B	0.991	0.391	
S_3	A	2.941	1.457	81
	B	0.873	0.224	

- General scour can be used effectively to estimate local scour.
- Local scour models are subject to greater variation with changes in laboratory testing conditions than general local scour models.
- Local scour depth is affected significantly by the shape of the obstacle encountered.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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