# EXPERIMENTAL INVESTIGATION OF SQUARE-SHAPED SACRIFICIAL PILES ON SCOUR DEPTH OF COMPOUND BRIDGE PIER

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***Abstract-*** A non-uniform pier, also known as a compound A pier, is characterized by varying cross-sectional dimensions along its length. Depending on the exposure of their foundation to the flow field, the behavior of many bridge structures is non-uniform. There are numerous causes for the bridge's failure, including design flaws and construction errors. In contrast, scouring is the most hazardous reason. The primary objective of this experimental research is to reduce the scour depth around a compound bridge pier by using a square-shaped sacrificial pile as its countermeasure in clear water scour conditions. A constant flow rate of 30 l/s. was maintained throughout the experiment. and each trial was run for about 3 hours. Scour depth was measured using a point gauge as the measurement tool. Three experimental sets were carried out by using two, four, and six sacrificial piles on the front side of the pier in different locations for each case. The results show that by using sacrificial piles, scour depth was reduced significantly. With an increase in the number of piles and varying distances from the pier, the reduction in scour depth became increasingly noticeable. Case C-4 exhibited the most significant percentage reduction in scour depth among all the cases studied, which was 47.6%. In this case, six sacrificial piles were installed u/s of the pier at a distance equal to between 5,5.67 and 6.33 times the diameter of the pier (Dp = 76.2 mm).

***Keywords-*** Compound bridge pier, Countermeasures, Sacrificial piles, and Scour depth

## 1 Introduction

For scientists and professionals working in the domain of hydraulic structures, understanding pier scouring around bridge piers holds great significance. Scouring is the result of a complicated vortex system. This system of vortices includes a wake vortex, a horseshoe vortex, a trailing vortex, and a bow wave vortex [1]. More than 1000 bridges have failed in the United States, with 60% of these failures attributable to scour and only 2% attributable to earthquakes [2]. Fig. 1 depicts a fundamental local scour mechanism near a bridge pier. [3].

There are two kinds of local scour countermeasures around the bridge pier: Armoring and flow-altering devices [4]. Armoring devices consist of riprap, tetrapods, dolos, cable-tied blocks, etc. Flow-altering countermeasures consist of sacrificial piles, Iowa vanes, and pier-mounted flow detectors such as collars. This research aims to examine the impact of square sacrificial piles near the compound bridge pier.

Sacrificial piles serve as a protective measure upstream of the bridge pier, shielding it from local scour. These piles redirect the fast-flowing water, creating a wake area behind the pier. The effectiveness of this approach depends on factors such as the number and size of the piles in relation to the pier, the arrangement of the piles relative to one another and the bridge pier, and the projection of the piles (i.e., whether they are partially or completely submerged) [4]. Different authors have used sacrificial piles in their research work for pier scour reduction for instance, [5], [6], [7]. The presence of sacrificial piles reduces scour depth by up to fifty percent as stated in these studies. By using collars around multi-vent bridge piers, current deflectors, and sacrificial piles on the upstream side of bridge piers Mohammed et al., 2015 [8] concluded that local scour depth around the piers can be reduced by more than 90% as compared to the unprotected bridge piers.

Manes et al. 2015 [9] suggested a new formula based on the phenomenological theory of turbulence and empirical observations for predicting scour depth. Farooq et.al 2021 [10] examines the scour around rectangular pier under clear water conditions by applying rectangular hooked collar as a scour countermeasure. The author concluded that the most effective dimensions for hooked collar which reduces scour depth to maximum extent are width of 1.5 $W_p$ and side wall height of 0.3 $W_p$ ($W_p$ is the pier width). Farooq et.al 2023 [11] investigated the effect of hooked collar around a vertical pier with a lenticular cross-section. The experimental results revealed that the equilibrium scour depth decreased with the ratio of hooked collar to the pier width when $W_c$ (width of collar) is 2 times of the pier width.

Temporal variation and maximum scour depth were significantly affected by variations in the foundation and pier geometry [12]. In addition, when the top surface of the bridge pier is maintained below the general riverbed level, maximum scour depth was reduced as compared to uniform piers. Environmental and climate change is an emerging and necessary research in every aspect of life for the future generation [13]. Nimbalkar et al., 2022 [14] developed a scour model for a compound bridge pier which is based on artificial intelligence (AI). Scouring is a time-dependent phenomenon. Over time, the scour depth will increase until it reaches equilibrium [15].

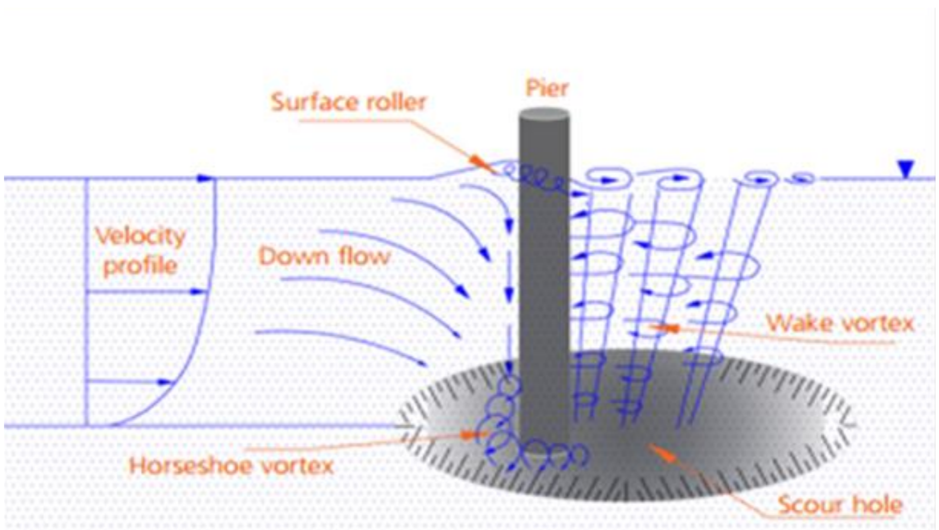


Figure 1: Local scour mechanism around a bridge pier [3].

Using an acoustic Doppler velocimeter, Kumar & Kothyari, 2012 [16] conducted experiments on turbulence characteristics and flow patterns around circular and compound bridge piers. Melville & Raudkivi, 1996 [17] describe three scour zones for the compound bridge pier that is: In Zone 1, the foundation top lies below the scour hole's bottom, having no influence on the scour process. Zone 2 is characterized by the foundation top being inside the scour hole, leading to scour reduction. On the other hand, in Zone 3, the foundation top is above the bed level, causing increased scouring compared to a uniform pier. Moreover, scour depth is dependent on the geometry of the bridge pier and also on the size and shape of the pier's foundation diameter [18]. By investigating the effect of sacrificial piles in different configurations in front of circular bridge pier using FLOW-3D [19], the author concluded that the efficiency of sacrificial piles depends on their arrangement to be used as scour countermeasure, which influences the formation of horseshoe vortex and eventually the scouring around the pier.

From the previous studies, it can be seen that a sacrificial pile is an important technique to reduce scour around the bridge pier. Although, a lot of research has been done on uniform bridge piers combined with sacrificial piles. In the present study, a compound bridge pier with square-shaped sacrificial piles as its countermeasure was used at constant discharge under clear water conditions to investigate the impact of square sacrificial piles on scour reduction. For the design of bridges, scour consideration is an important factor. Because failure of the bridge affects the transportation system and may cause loss of life and properties. So, it is necessary to use countermeasures such as sacrificial piles to reduce scouring and eventually protect the bridge.

## 2 Experimental Procedures

The experiments were conducted in a recirculating channel measuring 20 meters in length, 0.75 meters in depth, and 1 meter in width. The entire channel was made of concrete except for the walls which are made of 12 mm thick glass sheet. All the experiments were conducted in the UET Taxila Hydraulics Laboratory. In addition, the experimental work was conducted in conditions of clear water. For each test of the experimental program, the 10m length of the flume was leveled with sand using a wooden screed of equal width to the flume. Using a point gauge, the sand level was examined at random locations. The water channel was slowly filled until it reached the required depth. After turning on the pump and gradually increasing its speed until the required flow rate was reached, the tailboard was adjusted to achieve the desired water depth. After the test, the pump was turned off and the flume was slowly drained in order to preserve the scour topography. All the experiments were run for a duration of 3 hours. Because according to (Chiew and Melville) [20], After 10% of the equilibrium time, 80% of the equilibrium scour depth was achieved.

### *2.1 Sediment Bed*

In this study, uniformly graded sand was used. The calculated geometric standard deviation was determined to be 1.21 for the sediment size $d_{50}$ = 0.613mm; calculated as $\sigma_g = (d_{84}/d_{16})^{0.5}$ ($d_{84}$ and $d_{16}$ were the sediment sizes with a finer mass, at 84% and 16%, respectively). According to [21] if the standard deviation of soil is less than 1.3 then the sand will be classified as uniformly graded. The size of the sediment has no discernible effect on scour holes since $D_p/d_{50}$ was > 50 ($D_p/d_{50}$ = 120.95) [22]. The thickness of the sand bed was 0.203 m and was completely horizontal. The bed was properly leveled before the commencement of each trial.

### *2.2 Compound pier Models*

The model of a compound circular pier was made up of wood. The footing top of the bridge pier model was put 25.4 mm below the general bed level, having footing diameter (b* = 152.4 mm) and pier diameter (b=76.2 mm) such that the ratio of footing diameter to pier diameter is 2. A pictorial view of a compound circular pier has been shown in Fig. 2a. Fig. 2b illustrates the schematic diagram that represents the circular compound bridge pier, where b = the diameter of the pier, b* = the diameter of the foundation or footing, Y = the depth of the top surface of the footing (foundation) below the channel's initial bed level and h = flow depth. The pier's average width was taken to less than one-sixth of the width of the flume to minimize the adverse effects of side walls as recommended by [23]. No changes in the bed level were observed along the contracted cross sections, suggesting the absence of any bed degradation, contraction scour appeared to be absent; this was consistent with the findings of [24]. Contraction scour is not significant when the ratio of the channel width to the pier diameter (B/Dp) equals or exceeds 10. As a result, it is safe to conclude that in the current investigation contraction effects were not present.

Table 1: Hydraulic conditions for the scour experiments.

| **Diameter of Pier (mm)** | **Diameter of foundation (mm)** | **Flow depth (mm)** | **Discharge (l/s)** |
|---|---|---|---|
| 76.2 | 152.4 | 127 | 30 |

### *2.3 Flow Conditions*

To avoid incipient sediment movement at the plane sand bed with mean grain size ($d_{50}$ = 0.613 mm), the flow discharge was selected to ensure that the bed shear stress remained below a critical threshold. The experiments were carried out under a constant flow discharge of 0.030 $m^3$/sec. The Froude number $Fr = \frac{U}{\sqrt{gh}}$ was 0.213 where h represents the depth of flow above the sediment bed, g represents the gravitational constant and U represents the approach flow velocity. In order to ensure the condition of clear water scours, the flow intensity was consistently maintained at approximately U/Uc = 0.694 in all the conducted tests. Here, U represents the velocity of the approach flow, and Uc signifies the critical velocity required for the sediment to start moving. The shields diagram was used to calculate the critical shear velocity $U_{*c}$ for the sediments used in the current study.

In each experiment, to calculate critical velocity $U_c$ the logarithmic average velocity equation for a rough bed was used [25].

$$\frac{Uc}{U*c} + \frac{c}{d} = 5.75 \log\left(\frac{df}{ke}\right) + 6$$

In the above equation, '$k_e = 2d_{50}$', the term 'ke' represents the equivalent roughness height and $d_f$ is the depth of flow. The clearwater condition prevails when the flow velocity U is smaller than the critical velocity Uc (i.e., $U < U_c$) and the live bed condition prevails when the flow velocity exceeds the critical flow velocity i.e. ($U > U_c$) [26].

## *2.4 Sacrificial Pile*

A square sacrificial pile measuring 38.1 mm in dimensions was used in the study. To evaluate the efficiency of these piles, the scour depths around the pier were measured both with and without countermeasures. The reduction in scour depth under equilibrium conditions is then calculated by [27]. Table 2 and Fig. 3 depicts various arrangements of sacrificial piles.

$$R = \frac{Yp-Ys}{Yp}100\ (\%) \tag{1}$$

In the absence of sacrificial piles, compound piers exhibit a maximum scour depth of $Y_p$, whereas compound piers with sacrificial piles show a maximum scour depth of $Y_s$ and R is the %age reduction of scour depth. The scour depth around the compound pier was measured for each trial. The depth of scour was determined by measuring from the original sediment bed level to the maximum depth of erosion around the base of the pier.

*Figure 2a: Photograph showing the model of compound circular bridge pier used in the current study*

*Figure 2b: Compound pier with levelled bed*

*Table 2: Arrangements of sacrificial piles in different cases*

| Case Number | Number of sacrificial piles | Distance from the pier |
|---|---|---|
| C-1 | 0 | |
| C-2 | 2 | 5 times the pier diameter (Dp = 76.2 mm) |
| C-3 | 4 | 5 and 5.67 times the pier diameter |
| C-4 | 6 | 5,5.67 and 6.33 times the pier diameter |

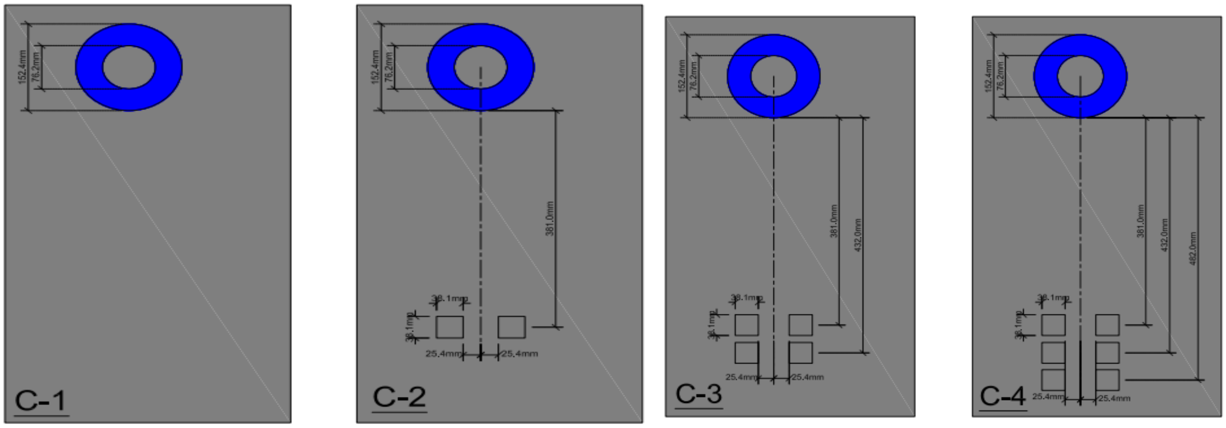


*Figure 3: Various arrangements of sacrificial piles used in the lab.*

## 3 Results

The findings revealed that the use of square-shaped sacrificial piles decreased the scour depth around the compound pier in comparison to the case without any piles. In addition, as the number of sacrifice piles increased, the depth of the scour decreased. Fig. 4 depicts the graph between maximum scour depth (mm) and no. of sacrificial piles on the u/s of the bridge pier. For case C- 2, when 2 sacrificial piles were used, scour depth reduction was observed to a minimum extent compared to the case without any piles. For C-3 when 4 sacrificial piles were used, the reduction in scour depth was more pronounced compared to C-1. The additional piles and slightly increased spacing allowed for more effective dissipation of flow energy, resulting in greater scour mitigation. Six sacrifice piles were installed upstream of the compound bridge pier for C-4, this configuration exhibited the most significant reduction in scour depth. The higher number of sacrificial piles, along with the varying distances from the pier, created a more intricate flow pattern, leading to a substantial reduction in scour. The findings indicate that square-shaped sacrificial piles can effectively reduce the scour depth around a compound pier. This is due to the disruption of the flow pattern resulting from the presence of sacrificial piles, which results in a decrease in flow velocity and turbulence near the pier. Figure 5 depicts the relationship between the %age reduction of scour depth and the number of sacrificial piles. Under C-4, the maximum %age reduction in scour depth was observed, which was 47.6%. Six sacrifice piles were installed upstream of the pier in this instance at a distance equal to 5,5.67 & 6.33 times the pier diameter (Dp = 76.2 mm). Also, the minimum %age

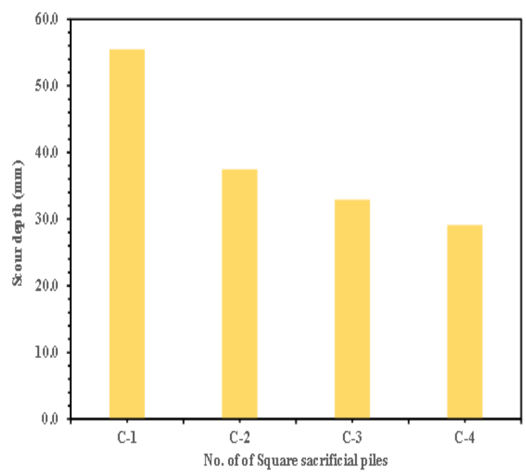


*Figure 4: Scour depth Vs No. of square sacrificial piles.*

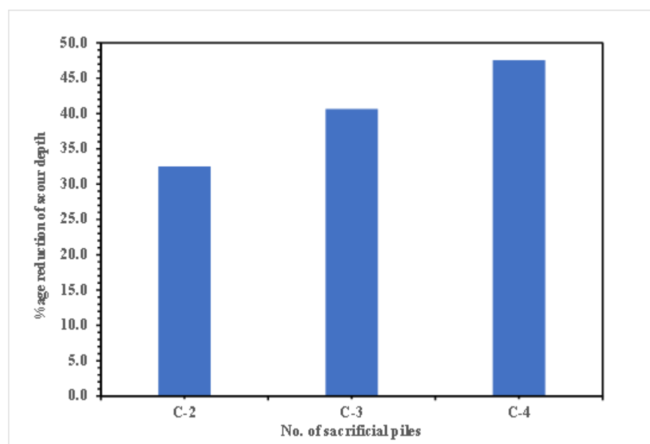


*Figure 5: %age reduction of scour depth Vs No. of sacrificial piles.*

reduction in scour depth was observed under C-2 (i.e., 32.5%). In this case, 2 sacrificial piles were installed at a distance equal to 5 times the pier diameter. The effectiveness of the scour countermeasure is influenced by the No. of sacrificial piles and their spacing distances from the pier. As more piles are used and they are placed at varying distances, a more complex flow field is created. This complex flow field dissipates energy more efficiently, leading to a greater reduction in scour depth.

### *3.1 Profiles of scour hole:*

The longitudinal profiles of scour holes for cases C-2, C-3, & C-4 are shown in Fig. 6. From Fig. 6 it is clear that as the number of sacrificial piles increases, scour depth reduces on both the upstream and downstream side.

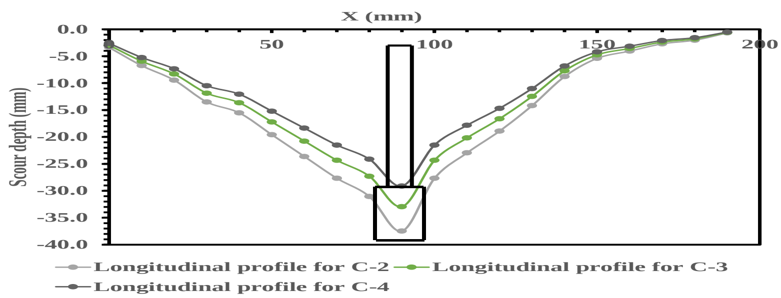


*Figure 6: Longitudinal profiles of scour hole.*

## 4 Conclusions

In this investigation, the impact of square-shaped sacrificial piles on reducing the scour depth around a compound bridge pier was evaluated.

- The maximum %age reduction of scour depth was observed under C-4 i.e., 47.6%. In this case, 6 sacrificial piles were installed upstream of the pier at a distance equal to 5,5.67 & 6.33 times the pier diameter ($D_p$ = 76.2 mm).
- The minimum %age reduction of scour depth was observed under C-2 i.e., 32.5%. In this case, 2 sacrificial piles were installed upstream of the pier at a distance equal to 5 times the pier diameter ($D_p$ = 76.2 mm).
- The use of sacrificial piles proved to be an efficient countermeasure against scour, and their effectiveness increased with the increasing number of piles and varying spacing distances.

## 5 Future Recommendations

The findings suggest that the implementation of sacrificial piles can be a viable and practical solution to alleviate scour-related issues around bridge piers and similar hydraulic structures. However, further research is needed to account for different flow conditions and pile configurations to develop more comprehensive design guidelines. Also, this study was performed on clear water scour conditions. The limitation of this research was that this study was conducted on clear water scour and not on live bed scour. In the future, the same work can also be performed for live bed scour conditions to check the efficiency of sacrificial piles on reduction of scour depth.

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