Comprehensive Analysis of Compound Bridge Pier under Clear Water Conditions: An Experimental Investigation of Scouring Countermeasures

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Abstract: **Apart from the natural calamities, bridge pier scouring has proved to be the foremost reason for the failure of over 600 bridges so far around the world. Scouring has ascertained to be an inevitable process around hydraulic structures. Many countermeasures were designed and implemented to cope with this critical phenomenon so far, from advancements in shapes to the flow altering countermeasures. However, there lies a huge void in investigating compound piers (piers with non-uniform cross section) that can be seen lying amidst major rives in South Asian region. This study aimed at experimental testing of the circular compound bridge piers and their comparative analysis with circular piers. A series of experiments were performed keeping constant discharge and flow depth following clear water conditions. This study showed valuable results as the compound pier significantly reduced the scouring depth at upstream side of the pier up to a maximum of 52.4 % as compared to a circular pier. Also, the results helped in devising the suitable position for the placement of the footing of compound pier to minimize the vortex.**

***Keywords*: compound pier, experimental work, flow altering countermeasure, local scouring.**

I. INTRODUCTION

Anything that comes across a river flow decreases water flow cross section affecting the morphology of rivers causing the flow to strike the piers, diverting streams and giving rise to vortices, a leading cause of local scouring around bridge piers [1]. Scour is an important concept that plays a central role in almost all river engineering applications, since it is the most probable cause for failure of river structures. Local scouring under a bridge pier primarily occur due to the down flow that generates along the upstream side of the pier resulting the generation of a horseshoe vortex at the base of the pier [2]. This mechanism has been shown in the Fig.1. Briaud, Hurlebaus [3] analyzed over 1000 bridge failures in the history of united states revealing that local pier scouring was the major reason behind 60% of these structural failures. To alleviate the risks of local scouring, protection measures are often applied to control the scouring depth at upstream and downstream faces of the structures. Numerous studies have been led so far for the assessment and development of countermeasures. These countermeasures have been divided by the scholars into two methods i.e. direct and indirect method.

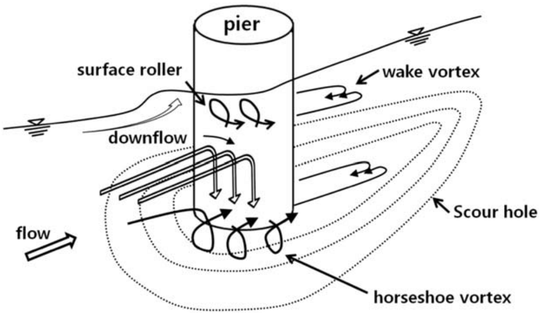

Fig. 1: Schematic diagram of Scouring Mechanism.

Direct methods, leads to increase flow resistance in the stream bed. This is commonly done by employing riprap around the bridge piers [4-6]. Another widely applied countermeasure is the construction of sequenced sills to alleviate excessive erosion [7]. Even though bed sills play an important role in controlling the scouring problem, they also impact the stability of the downstream channel negatively. Some of the countermeasures are challenging and difficult to apply practically in the rivers or show minor efficiency under live bed conditions [8]. Indirect methods tend to change the flow configuration around the bridge piers resulting the reduced shear stresses on the stream bed, consequently reducing the scoured depth around. Geometry and shape of the pier, among direct methods, has become one of the leading research area within the last decades. Bridge piers are built in different types of geometries along their heights and cross sections i.e. uniform and non-uniform [9]. Such piers are categorized as compound piers or non-uniform piers. Kumar, Kothyari [10] targeted at computing a model for studying the scour depth and its temporal variation around circular compound piers with the placement of the top surface of the footing ‘caisson’ at three different levels with respect to level of the channel. These types of circular compound piers can be seen under the bridges mostly in the Asian subcontinent as shown in Fig. 2.

Fig. 2: Bridge on river Sutlej, *Pakistan* having circular compound bridge piers.

In spite of a widespread work being done on local scouring around circular bridge piers, little work has been found on non-circular shaped piers with non-uniform geometries to apprehend the scour geometries and the physical nature of turbulence characteristics. Regardless of the fact that these type of experimentations have potential to find the nonlinear interactions of flow on a mobile sediment bed. The water flow around non-circular bridge piers show a modified behavior due to such interactions between the embedded pier in the bed and the flow, making it more difficult to predict scour depth. However, after Kumar, Kothyari [10], research work on the effects of compounds piers on scouring is found to be scarce. This research aims at experimentally testing the circular compound pier with respect to circular pier and compare scour depth and patterns around them.

II. MATERIALS & METHODS

A. Flume

The flume used in the experimental research was positioned in the University of Engineering and Technology, Taxila. This water flume was consisted of a primary tank for supplying water; an underground masonry tank for circulation and a trapezoidal weir at the end for measurement of the discharge. The flume had specifications of 20 m length,1 m width and 0.7 m deep glass-sided flume with an adjustable tailgate at the channel-end to regulate the flow depth. Fig. 3 shows a view of the used laboratory flume. A metric scale (accuracy of ±0.1 mm) was fixed to the side glass of hydraulic flume to determine water depth h and bed level. 75 PVC pipes were placed at the entrance of the channel in order to reduce the turbulence and circulations at the upstream.

Fig. 3: A view of the flume provided by Hydraulic Lab of University of Engineering and technology, Taxila.

B. Pier

A circular compound pier made out of PVC having a ratio of footing diameter (b*= 6.1 in) to pier diameter (b=3.5 in) such as 1.84 is used as model of the bridge foundation. A pictorial view of circular compound pier has been shown in Fig. 4. Due to the variable diameters, the average diameter of the pier is taken i.e. (4.8 inches) to study its design in contrast to the criteria used in former studies. The featured pier average width was taken less than one-sixth of the width of the flume in order to minimize the adverse effects of side walls, as recommended by Frostick, McLelland [11]. The other pier with uniform diameter (3.5 inches) is used as a reference pier for the comparison in scour depth respectively.

Fig. 4: Definition diagram and pictorial view of circular compound pier used in the experiment.

C. *Sand*

The entire study was accomplished using a bed of uniform sand having a median diameter ‘d_{50}’ = 0.51 mm and geometric standard deviation ‘σ_g’ = $(d_{84}/d_{16})0.5 = 1.74$. Fig. 5 shows the grading diagram of the used sediments. The sand size considered in this study stood in compliance to the condition of $D/d_{50} > 50$ in order to dominate the sediment size effect on the scour evolution process guaranteeing non–ripple-forming sand [12].

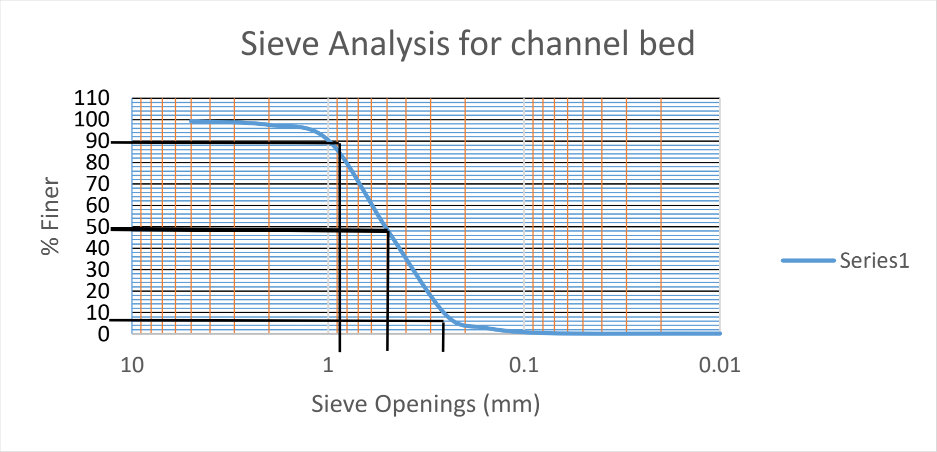

Fig. 5: Grading diagram of materials used as the channel bed.

D. *Methodology*

The experiment was carried out with a 10 m sediment bed having a thickness of 27 cm. The pier was aligned and ranged perpendicularly with the centerline. The ratio of W/D was equal to 8.2. According to the criterion given by Ballio, Teruzzi [13], the contraction effects on scour depth exists when $W/D < 3$. The flow discharge was 42 *l/s* and was kept constant in all experiments. A trapezoidal weir placed at the end of the channel was used to measure the discharge with the help of equation derived by Martinez, Reca [14]. The flow velocity was measured by digital velocity meter averaging the mean values at 0.4h and 0.6h of the test section. Flow depth, h, for each set of the experiments is kept equal to 13 cm and remained constant (Fig. 6 (a)). A precise point gauge of 0.1 mm accuracy mounted on a leveled carriage (Fig. 6 (b)) was utilized to quantify the scour depth and geometric features of the scour holes around the pier.

Fig. 6 (a) and (b): Flow depth kept equal to 13cm & Point gauge mounted on a levelled carriage.

Initially, reference tests were performed on uniform circular pier of 3.5 in dia. The next test runs were performed on circular compound pier having controlled parameter as in the reference test. The channel was slowly drained off at the end of every test before the depths of scour holes were measured. Hydraulic conditions of experiments are presented in Table 1. Here, D = pier width; Q = flow discharge; h = depth of approach flow; B = width of approach flow (flume width) and ds= maximum measured scour depth.

Table 1: Hydraulic conditions and characteristics of scour experiments

Scenario	Pier diameter 'D' (inches)	Q=flow discharge (l/s)	Flow depth 'h' (cm)	Width of approach flow 'B' (meters)	Scour depth max 'ds' (mm)
1	3.5	42	13	1	75-80
2	4.8	42	13	1	35-40

III. RESULTS

In the present study, the following series of the experimental runs have been performed:

1. Experimentation of the scour around the pier with a uniform circular section having diameter= 3.5 inches (R1).
2. Experimentation of the scour around the compound pier with variable circular sections having pier diameter = 3.5 inches and footing diameter = 6.1 inches (R2).

Clearwater condition was maintained during all the experimental runs ensuring the flow velocity to get itself adjusted for the experiments under threshold movement of the sediments. In the first phase of analysis, detailed measurements were recorded regarding scour depth at eight vertical profiles in different radial planes were taken (θ =0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°, and 360°) using point gauge (Fig. 7). The first experimental run R1 was conducted with a uniform circular pier having the flow discharge of 42 l/s and flow depth=13 cm. The bed profiles for the scoured holes were measured after gradually draining the water off the channel once the equilibrium time has been achieved. Fig. 8 shows experimental results of the scour depth for the uniform circular pier.

Visual observation of the scour process exhibit accelerated transport of the sediments at both upstream and downstream sides of the pier simultaneously at the initial stages of the scour process. Most importantly the erosion around the area between 270°-360° was quite prominent showing the scouring depth of i.e. 75-80 mm. At the upstream side of the pier, the pattern of bed was eroded carrying the sediments towards the downstream by wake flow. In such a transport towards the downstream side of the pier, wake vortices appeared to have played the primary role. The configuration of the scoured pattern is found in accordance with the results of Vaghefi, Akbari [15].

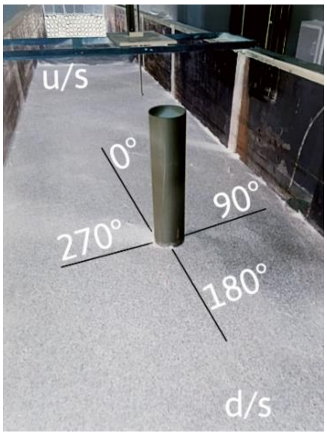

Fig. 7: Radial divisions around the pier for the measurement of vertical profiles.

Fig. 8 :Scour Pattern around circular pier in case R1

The second experimental run R2 was conducted with a compound pier keeping the flow discharge and other parameters same as in R1. The scour results have been shown in Fig. 9. The rate of evolution of scour depth around compound pier considerably differs in depth size and pattern. At the upstream side of the pier i.e. 0° the scour depth was recorded 38 mm, showing a 52.4% decrease in scour depth comparative to the results of the circular pier when the footing ‘caisson’ part of the pier was placed below the bed level. However, the sediment transport from the upstream side of the pier is to some extent larger comparative to the sediment transport in case of the circular pier at the initial stages of the scour development. A slight heap of deposition at the downstream side of the compound pier was developed due to continuous sediment transport towards the downstream side of the pier primarily by wake vortices. The results were recorded and found in accord with Kumar, Kothyari [10].

Fig. 9: Scour Pattern around compound pier in case R2.

The second phase of the analysis show the combined scour cross sectional plots of the measured data in the XY planes at different radial angles i.e. (θ =0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° and 360°) for the experimental runs R1 and R2 respectively (Fig. 10). The depth cross sectional profiles were drawn at the radial distances of 1 cm division in X component and corresponding vertical depth in Y component. The magnitude of combined trends was plotted in MS Excel 2016. Along the plane at θ =0°, the flow was observed to be unidirectional outside the scour hole among all the runs. In the case of the circular pier (R1), the downward flow exhibited to grow stronger while approaching the pier. Owing to this downward flow, rotations inside the developing scoured pits started to accelerate near to the bed giving rise to backflow in the direction of the upstream side of the scour hole. As a result, a rotational flow was originated at the nose of the pier inside the scoured pit called as principal vortex of the horseshoe vortex system (HVS). However, the principle vortex was observed to be smaller and weaker in the case of the compound pier (R2) owing to its footing-top placed below the bed level in comparison with the vortex formed around the circular pier.

Along the planes at 45° and 90°, a downward flow adjacent to the pier was observed among the runs during the experiment except in R2. However, the flow configuration in the planes for R2 were similar to that of a compound pier in the plane at 0°. In the downstream plane of the pier at 180°, it was interesting to see the flow direction was towards the water surface in all the experimental runs. However, the flow direction was observed to be moving away from the pier below the general bed level downstream. In the plane at 135°, a smaller vortex was observed with weakening strength close to the bed level of scour hole among all the runs during experiments. In the case of the compound pier, the flow magnitude was higher than that in the circular pier but the maximum scour depth showed an interesting reduction in R2.

Most importantly, a heap of sediment deposition was found in R2 at the downstream side of the pier due to the wake vortices playing the main role in sediment transportation. As per observations and characteristics of a circular shape exhibiting similarities, the behavior in the other half shows similarity in terms of scouring depth profiles. To summarize the observations, the principal scour reduction at upstream side of the compound pier in R2 is found to be reduced up to the maximum 53.08% in contrast with circular pier which was credited to the vortex supporting capability of the footing-top surface keeping the footing surface level below the sediment bed level.

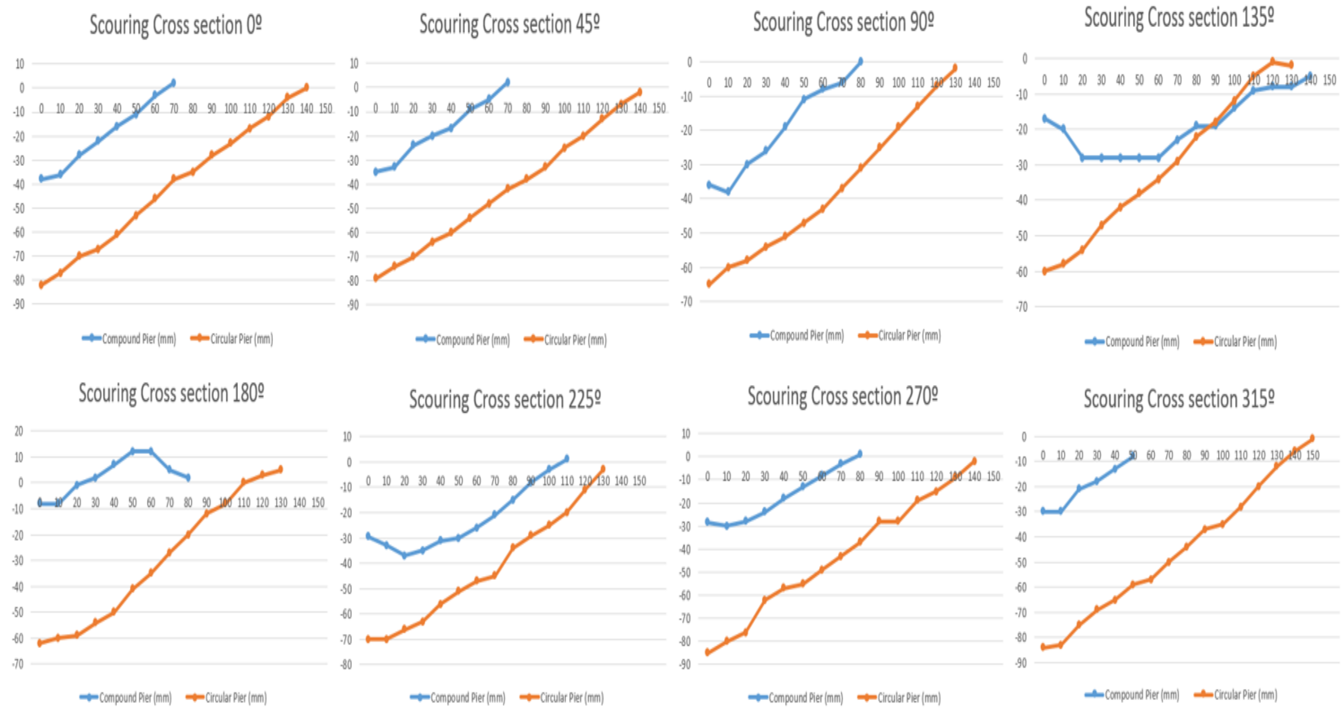

Fig. 10: Effect of circular and compound piers on longitudinal and lateral profiles.

IV. CONCLUSIONS

Witnessing the results, the shape of a pier proved to play a significant role in the scouring phenomenon. Well meticulous measurements were taken, using point gauge, around modelled compound piers placing the footing/ caisson top surface below the sediment bed level of the channel. Circular uniform piers were employed to benchmark the local scouring of bridge piers. The geometry of a pier plays a significant role in the scouring phenomenon. The location of the occurrence of maximum scour depth rests on the shape of the pier. Scoured depth at the upstream nose of the compound pier placed below the bed level was recorded 53.08% less when compared with the results in the circular pier. The measurements of scouring pits formed at the upstream side close to the pier (0°) revealed significant variations in the vertical plane among all radial profiles. This occurred due to rotating vortices inside the developing scoured pits when they started to accelerate the downward flow near to the bed giving rise to backflow in the direction of the upstream side of the scour hole. This phenomenon was acknowledged as the principal vortex of the horseshoe vortex system.

V. RECOMMENDATIONS

The dataset presented and discussed in this research can be served as the base results for flow simulation models regarding local scour. These results can also be useful in developing new measures for protection against scour around piers. However, this study presents a quantitative analysis of the development of scour depth under a series of controlled conditions. Disagreements may exist with the proposed conclusions; for example, with a sediment bed of non-uniform mixture, or for high flow intensity. When in real conditions, the flow velocity becomes much greater than its critical value for incipient sediment motion, within a very short duration the scour depth reaches its equilibrium owing to deviate with the results, and also exhibits large fluctuations induced by bed forms propagating through the scour hole. Further experiments are required to better understand the phenomenon of flow around non-circular piers with variating lengths and geometries i.e. rectangle, trapezoidal, triangular, oblong and lenticular. The impact of turbulence on scouring and its key parameters is still an open problem that is needed to be deliberated in future.

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