Reduction of Scour Around Bridge Piers using Combined Cylindrical Protector and Riprap

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ABSTRACT

Local scour around bridge piers, especially during floods, can lead to bridge destruction. The usual method for controlling scour is to use rockfill around bridge footings. Despite proper design, the protective layer gradually becomes unstable and destroyed due to edge erosion. In this study, the use of cylindrical protector, which is a new method for controlling scour around the base, has been investigated to protect the riprap layer. Two series of experiments carried out. first, a control experiment (experiment A) was conducted using a cylindrical pier of 4.5cm in diameter without using any protection. Then, a cylindrical protector (CP) of 13.5 cm in diameter was used as pier protector (experiment B1), the results of which showed that the maximum scour depth decreased by 12.8% compared to experiment A. Subsequent tests included a 4.5 cm radius of riprap covering around the pier (Test B2), a 13.5 cm radius of riprap covering around the protective cylinder only (Test B3), and Test B4 with a 18 cm radius of riprap covering around the pier as well as the CP and was tested under the same flow conditions. The results of these experiments showed that the maximum scour depth was reduced by 81, 31, and 100 percent, respectively, compared to the Test A. The rocks particles were stable throughout the test and edge erosion was negligible. In Test B2, the gravel surface in front of the pier was depressed due to the extrusion of fine bed particles (0.7 mm in diameter) from the pores of the rocks, which was due to the lack of using a layer of filter between the rocks and the sand bed, but no edge erosion was observed. In Tests B2 and B4, negligible edge erosion was observed.

KEYWORDS

Hydraulics, protective cylinder, rock pile, scour, bridge foundation protection.

1. Introduction

Localized scour around bridge piers has been reported to be one of the main causes of bridge failure, with half of all bridge failures in the United States due to scour around bridge piers, and similar results have been reported in Europe and Asia as seen in [1], [2], [3], [4], [5] and [6]. Due to the importance of the issue and the need for prevention of damage, extensive studies have been conducted over the past three decades to find the maximum scour depth in order to predict the necessary measures for the stability of bridges under construction, and at the same time to find methods to stabilize or control (reduce) the scour depth around the piers of existing bridges.

Control methods aim to modify the flow pattern in a way that reduces the strength of the flow components that are the main cause of scour, including sacrificial piles, submerged plates or sills, and upstream diverters [7] and roughening bridge [8]. Stabilization methods that are most commonly used for existing bridges involve the use of materials that are placed on the riverbed around the foundation so that the bed material is not directly under the influence of the flow. These methods include techniques such as rock piles, concrete aprons, gabion mats, articulated concrete blocks, and geobags. Among these methods, riprap covering remains the most widely used measure due to its adaptability and cost-effectiveness over a wide range of hydraulic conditions as demonstrated in [9]. By reducing flow velocity and absorbing turbulence near the bed, riprap covering also acts as an energy dissipator, thereby limiting the development of localized scour as demonstrated in [10], [11] and [12]. If the riprap layer is well designed (including size, shape, grain size, type of arrangement, and appropriate filter), it can both protect the aggregates from erosion and prevent the penetration of the vertical component of velocity into the rock layer and the under washing of the riprap covering as stated by [3], [9], [10], [11], and [13]. However, in certain conditions, the riprap layer can lead to instability of the edge aggregates and sinking into the bed due to edge erosion (erosion of the sedimentary bed around the riprap layer), which, if continued, can lead to failure of the entire riprap layer [11]. A recent laboratory study was conducted by [14] on the effect of riprap covering around single, tandem, and stepped piers on a non-uniform moving bed under clear flow condition. They found that for a single pier, rock guarding eliminated local scour around the bridge pier but resulted in moderate edge scour downstream of the pier. And in all configurations, rock protection reduced the maximum scour depth by an average of 64–67%. A new riprap covering design to reducing bridge pier scour was studies by [6] in which they found that the new method can reduce the depth and volume of scour depth up to 81.0% and 92.3%, respectively, and it was found that quires 18% less riprap material. A new countermeasure including the roughening geometric elements (RGEs) made of materials like wood, plastic, or metal have been found to reduce the maximum scour depth of up to 35% compare to unprotected piers [8]. The combined countermeasures also have been successfully studied by researchers. Combination of collar and Geobag [15], combined riprap and collar [16], Combination of vertical slot and collar showed reduction of 100% in scour depth and combined use of collar plates and vanes as reported in [7].

In this regard, the present study investigates the combined effect of a permeable CP, as a new method of modifying flow pattern, and using riprap cover, as a method of riverbed reinforcement, on the maximum scour depth in front of a single bridge pier under clear water flow condition. By comparing the performance of different riprap covering arrangements around the bridge pier as well as the CP, the best arrangement is introduce.

2. Materials and Methods

2. 1. Experimental setup

The present study was conducted in the Physical Models Laboratory of the Faculty of Water and Environmental Engineering, Shahid Chamran University of Ahvaz, in a rectangular flume with a slope of 0.001, 10 meters long, 76 cm wide, and 60 cm high. The side walls of the flume are made of plexiglass and its skeleton is in metal. Figure (1) - a, schematic view of the flume, Figure (1) – b, view of the position of the stone lining, and Figure (1) - c, plan view of the riprap lining is shown.

The experiments were carried out with the presence of a pier in a 1.7 m long sedimentary bed located at a distance of 2.8 m from the beginning of the flume. The thickness of the sedimentary bed is 18 cm, which is filled with alluvial materials with

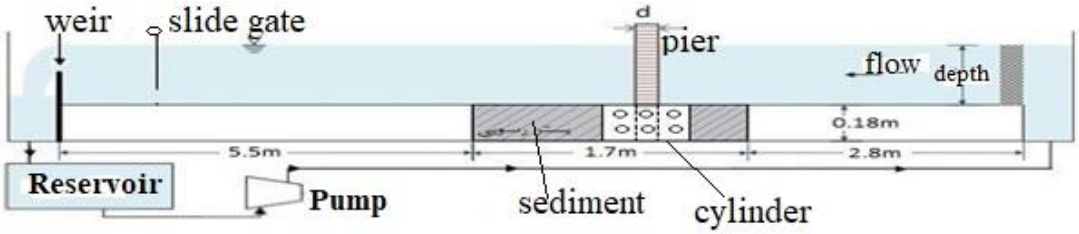
an average size of d_{50} = 0.7 mm. The size of the materials was chosen so that the bed form is not developed. In addition, the geometric standard deviation of the bed sediments ($\sigma = \sqrt{(d_{84}/d_{16})}$) is 1.22, which is consistent with the theory of [17] that the bed sediments are uniform.

In the present study, following the findings of [9] and [18] the basic parameters of the aggregate cover for bridge piers were considered, including the average diameter of aggregate stones (d_{50r}), the thickness of the aggregate layer, and the radius of the aggregate layer surface (b_r) around the pier. The average aggregate diameter (d_{50r}) was calculated using the following equation given in [7] and [18].

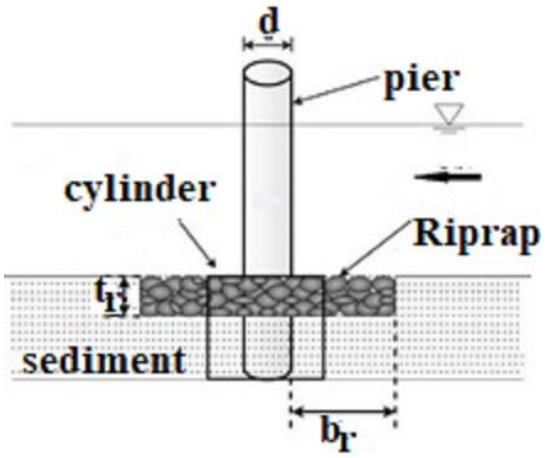
$$d_{50r}=0.692[kV^2/(S_g-1)g] \quad (1)$$

where, k is a coefficient that depends on the shape of the pier and is equal to 1.5 for a cylindrical pier, V is the average velocity of water flow (m/s), S_g is the specific gravity of aggregate (2.6), and g is the acceleration due to gravity (9.81 m/s^2). The experiments of this research were conducted at a constant flow discharge of 0.035 m3/sec and flow depth of 0.15 meters. As a result, considering the flume width (0.76 meters), the average flow velocity was determined to be 0.307 meters per second and by applying a safety factor of 1.2, the average diameter of the size of the stone for riprap layer was determined to be 4.4 mm. In order to prepare the desired granulation, sieves No. 4 and 5 with particle diameters of 4.75 and 4 mm were used. The riprap layer was placed with thickness of 8.8 mm, considering the recommended range of 2 to 3 times the average diameter of median stone size as demonstrated by [7], [12], [19] and [20], the experiments were conducted with three different arrangements of riprap cover with radii b_r = 4.5cm (inside the CP), 13.5 cm (around CP only) and 18 cm (around both pier and CP).

The flume water circulation system is a closed circuit, consisting of an underground tank, pump, valves and pipes. In all



a) Flume section view



b) View of pier CP and riprap layer



c) permeable cylinder(CP)

Figure 1. Experimental apparatus: a) section view of the flume b) View of pier, CP and riprap c) view of the CP

experiments, the constant inlet flow discharge was measured with an electromagnetic flow meter model Mega 3000 manufactured by Iran-Morad Company with an accuracy of 0.25%. At the beginning of the flume, there was a flow stilling tank that reduced the turbulence of the entering flow. At the end of the flume, there was a gate to control the flow depth within the flume. In selecting the diameter of the pier, the side effect of the width of the flume walls on the scour of the bridge pier should be considered. Therefore, according to the recommendation of [5], the ratio of the pier width to the channel width should be a maximum of 0.16. Also, according to the recommendations of [4] the maximum diameter of the pier should be equal to 10% of the flume width. Therefore, a diameter of 4.5 cm was chosen for the pier. Based on the recommendation of [21], two points were also considered for choosing the height of the pier. First, it should not be submerged in water and second, the height of the pier should be less than the flume height so as not obstruct the longitudinal movement of the bed profiler (an instrument for measuring the bed surface profile). Therefore, considering the height of the flume, the height of the pier was considered to be 52 cm (>33 and <60cm). The bridge pier made of Plexiglas was installed at a distance of 1.1 m from the beginning of the sedimentary bed (or 3.9 m from the beginning of the flume) so that a fully developed flow was established before the pier. In these experiments, a permeable CP made of galvanized sheet with a thickness of 0.7 mm, height of 18 cm (equal to the height of bed sediment) and diameter of 3d=13.5 cm with a circular mesh of 0.5 cm in diameter was made. To determine the depth and velocity of the flow, according to [4] and [5] and [18] in order to avoid the effects of the flow depth on the scour depth, the flow depth should be more than three times the width of the pier. Also, according to [18], when the average flow velocity is in the range $V_c > V$ in which V_c is the threshold flow velocity of the bed sediment (is equal to 0.3m/sec in this study), scouring occurs in clear water conditions and if the average flow velocity is more than the V_c, scouring occurs in live bed conditions. Therefore, to establish clear water conditions, initial experiments, without the presence of bridge pier, were conducted at a constant flow discharge and graduate lowering the flow depth to find out the threshold velocity of bed sediment particles. Therefore, the rest of experiments were conducted at a flow discharge of 35 l/s, flow depth of 15 cm, $V/V_c = 0.92$ and Froude number of 0.26.

2. 2 Experimental procedures

At the beginning of each experiment, the sediment surface was first leveled using an iron profile (iron can) measuring 2 × 4 × 280 cm and controlled by a Leica X310 laser meter with an accuracy of ±1 mm. To level the sediment surface, the upstream and downstream parts of the sediment surface were leveled by first tapping the sediment surface and then moving the iron can back and forth simultaneously on both sides. Then, the desired radius for placing riprap stones on the sediment bed was drawn and dug to the desired depth equal to the desired riprap thickness, and then the covering stones were placed around the bridge pier. Then, the sliding gate was completely closed and water entered the flume at a low flow discharge to prevent initial erosion which can make errors in the final scour depth. After a few minutes, the flow discharge was gradually increased till the desired flow discharge is reached and simultaneously the downstream gate was gradually opened till the flow depth reached 15cm. Once the flow was established the flow condition kept constant for few hours and during this time the flow discharge and flow depth was measured periodically and videotaped, using an endoscopic video camera, used to measure the maximum scour depth during the experiment inside the water flow. We also observed any possible movement of rock particles from the sides of the corner of riprap cover. After the experiment duration is over, the

pump was turned off and then the water inside the flume was gradually drained. when the bed sediments are dried enough, the riprap surface and bed topography was measured using a digital bed profiler with accuracy of ±0.001m. A laser meter also was used to determine the scour depth at specific point around the pier. Three-dimensional images and bed topographic maps as well as longitude and transvers bed profile were plotted using MATLAB software.

4. Results and Discussion

The main goal of this study is to investigate the effect of CP on stability of riprap cover. To achieve such goal, different experiments were conducted, as was presented in material and methods, then the maximum scour depth around the pier was measured and analyzed. The percentage variation in maximum scour depth for different arrangements of experiment compare to the control experiment (Experiment A) was calculated using the following equation.

$$R= [(d_{s1}- d_{s2})/d_{s1}] \times 100 \quad (2)$$

In this relation, d_{s1} and d_{s2} are the maximum scour depth for Experiment A and for other Experiments (B1, B2, or B3).

4.1. Experiment A

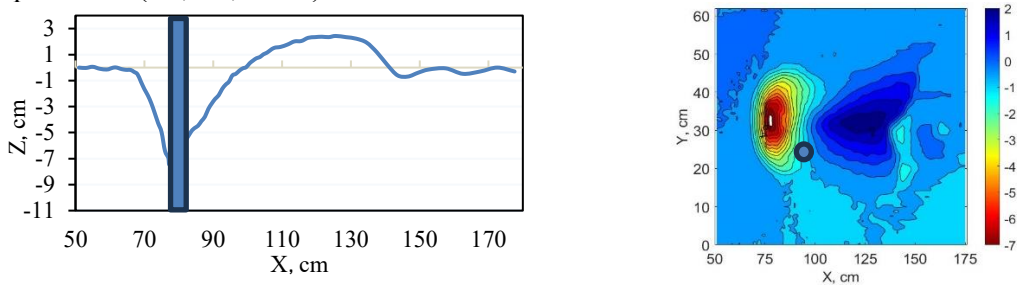
This experiment was conducted to monitor the movement of sediment particles in the vicinity of the bridge pier. The maximum measured scour depth in the front of the pier was used for comparison with the results of other experiments. In this experiment, the scour process started at the initial moments of the experiment and rapidly expanded with the formation of horseshoe vortices. The scour process began symmetrically with respect to the pier axis and sediments were gradually washed from the front and around the pier and accumulated at a short distance downstream of the pier. With the passage of time, the rate of change of scour depth decreased significantly and the scour hole reached almost unchangeable. The duration of this experiment was 12 hours. Figure 2 shows a picture before and after the end of Experiment A.



a) before test b) after test

Figure 2. Bed topography a) before and b) after Experiment A

Figure (3) shows the erosion and sedimentation status of the bed in the Experiment A. In this experiment, the maximum depth of the scour hole closed to the front of the pier was measured to be 7.8 cm.



a) longitudinal bed profile b) bed topography

Figure 3. longitudinal bed profile and bed topography after Experiment A

4.2. Permeable CP Without riprap (Experiment B1)

Recently, CP, as a new measure to control scour around the pier, has been introduced by [22]. Therefore, in this experiment, a permeable CP around the pier was installed so its top lip is at the bed level. Figure 4 shows the conditions before and after the test.

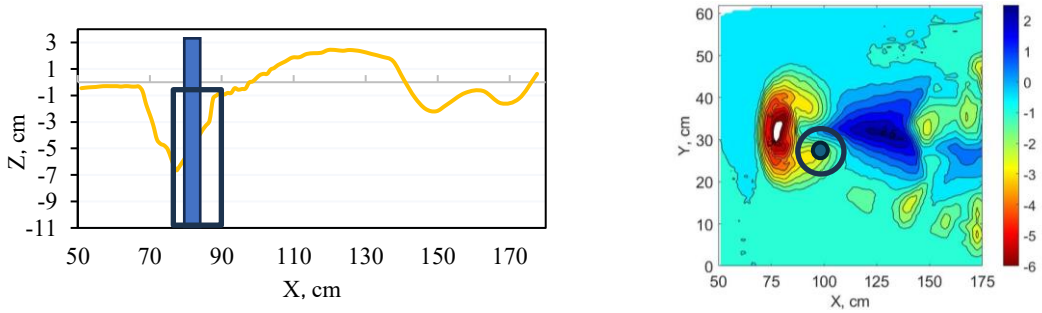
In this experiment, the maximum depth of the scour hole was measured to be 6.8 cm. The installation of the CP reduced the maximum scour depth by 12.8% compared to the Experiment A without CP. Figure (5) shows the longitudinal profile of the sedimentary bed topography in the experiment with CP. This figure also shows the position of the bridge pier and the CP.

The reason for the reduction in the scour depth around the pier can also be stated as follows. The longitudinal flow, when hitting the pier and reduce its kinetic energy, and as a result, creating a reverse pressure gradient, forms a downward vertical flow velocity component in front and sides of the pier, which changes its direction upward when it hits the bed and lifts sediment particles. At the same time, a spiral-shaped flow is formed from the intersection of the downward velocity component and the longitudinal component of the flow velocity. The lifted sediment particles are trapped in this spiral flow and transported downstream. However, due to the presence of CP, firstly, the strength of the spiral flow is reduced, and secondly, these particles are deposited inside the CP. Also, the presence of CP will cause the wake vortex to shift away from behind the pier further downstream, resulting in less scour behind the pier. As seen in Fig.6 During the experiment, erosion of bed material around the CP also is visible (Fig. 6b). However, no edge erosion of the riprap cover can be observed. This is because the rocks are completely compact inside in the CP. Maximum scour in front of CP (maximum of 5.9cm in this experiment) compare to the scour around bridge is about 15% less, although the CD diameter is 4.5 times pier diameter. This is because the maximum height of CP above the bed (5.9 cm) is low compare the pier height (15 cm) and since the near bed flow velocity which attack the CP is low, the strength of downward velocity component is low enough and thus scouring around the CP is low. The results of this study have shown that CP alone, can only reduce the scour depth up to 12.8%. In addition, as can be seen in Fig, 4b, although scouring occurs around the CP although less, it may eventually cause failure of the CP and or bridge pier. Therefore, the present study's aim is to investigate the combined CP with riprap to improve the application of CP for the sake of safety.



a) before test **b) after test**

Figure 4. Bed condition a) before and b) after Experiment B1



a) longitudinal bed profile **b) bed topography**

Figure 5. longitudinal bed profile and bed topography after Experiment B1

4.3. Combined CP and riprap, b_r = 4.5 cm (Experiment B2)

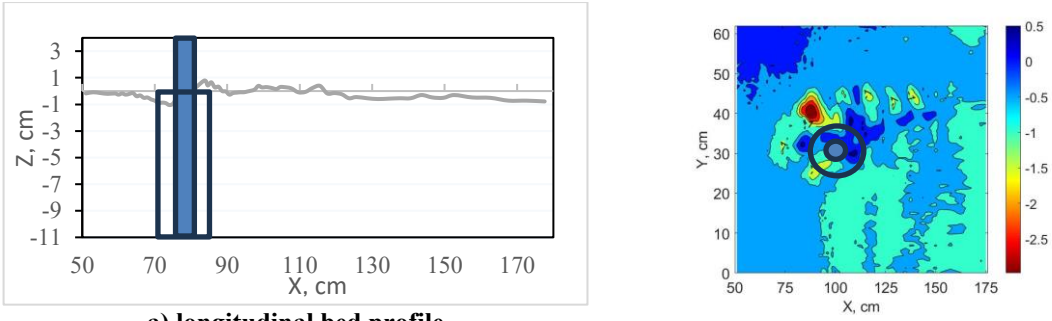
The bed conditions in this experiment before and after the test are shown in Figure 6.

At the end of this experiment, the surface of the stone in front of the pier was lowered by 1.5 cm compared to the control condition without stone. During the experiment, the aggregates did not move around the pier, although a few aggregates had slight jumps, but no horizontal movement was observed. The reason for the decrease in the level of the gravel surface can also be caused by the escape of fine bed particles through the pores of the gravel particles because no filter was used in this experiment. In practice the riprap may failed due to undermining which this type of failure which is called winnowing failure. However, if a suitable filter is used between the gravel layer and the sedimentary bed, it will not be possible for the bed sedimentary particles to escape through the riprap's pores, and practically the level of riprap surface around the pier will remain stable. By comparing with the control test, placing this riprap cover has reduced the maximum scour depth by 81%. Fig. 7b also shows that scour around CP is much lower than in Experiment B1. Figure (7) shows the longitudinal profile of the sedimentary bed and the topography of the sedimentary bed around the pier and CP.



a) before experiment **b) after experiment**

Figure 6. Bed conditions a) before and b) after Experiment B2



a) longitudinal bed profile **b) bed topography**

Figure 7. longitudinal bed profile and bed topography after Experiment B2

The main reason for the reduction of scouring depth was due to the stone covering around the pier, which were designed in the right size and the stone particles did not move. In addition, the presence of aggregates causes the strength of the vertical component to decrease when it reaches the sedimentary bed, and the roughness of the aggregates leads to a decrease in the strength of the spiral flow around the foundation, which reduces the amount of sedimentary particle transport. These factors have also helped to reduce the amount of scour around the CP, so that when compared with the Experiment A, the amount of maximum scour depth 81% reduction. One of the advantages of using CP is, that the riprap material cannot escape from the CP by edge erosion. In comparison with other study [5], the new methods, need less riprap material with almost the same performance.

4.4. Combined CP and Riprap only around the CP, b_r=13.5cm (Experiment B3)

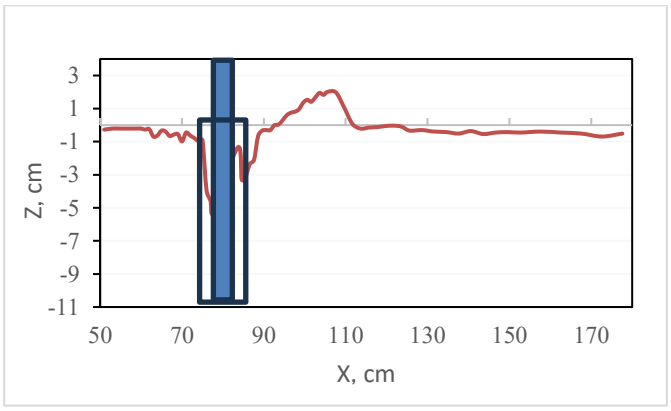
The conditions of this experiment are shown in Figure 8. The layer of crushed stone is placed only around the CP with b_r=13.5cm.

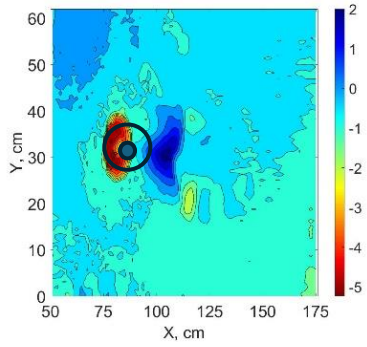
As it is clear from Figure 8, at the end of the experiment, scouring occurred around the pier inside the CP, and the maximum depth of the hole was measured as 5.4 cm in front of the pier. Compared to the Experiment A, the maximum scour depth has decreased by 31%. Figure (9) shows the longitudinal profile of the sedimentary bed and the leveling curves of the sedimentary bed of this experiment.



a) before experiment **b) during experiment** **c) after experiment**

Figure 8. Bed conditions a) before experiment, b) during Experiment and c) after Experiment





a) longitudinal bed profile **b) bed topography**

Figure 9. longitudinal bed profile and bed topography after Experiment B3

The reduction of scouring depth around the pier inside the cylinder by 31% compared to Experiment A, can be due to the decrease in the strength of the vortices due to the presence of roughness caused by the aggregates around the protective cylinder. As it is clear from Figure 8b, the transported sediment is deposited downstream of the CP and on top of the riprap layer. In addition, it can be seen that the bed sediments at the edge of the protective layer have slightly eroded and created a small groove. Comparing experiment B1 with experiment B2 shows that the effect of placing riprap inside the cylinder has a greater effect on reducing the scour depth around the pier, while placing riprap around the cylinder, protects the bed scour around the CP. Therefore, experiment B4 was conducted.

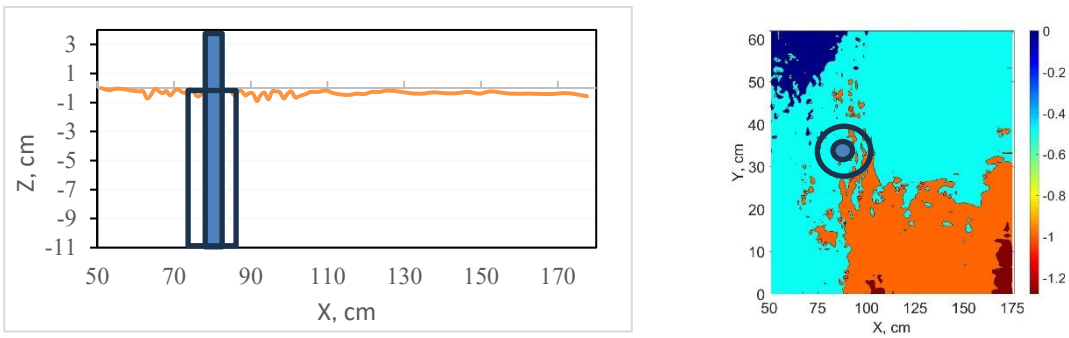


a) before experiment **b) after experiment**

Figure 10. Bed conditions a) before and b) after Experiment B4

4.5. Combined CP and Riprap br=18cm (Test B4)

In this experiment, the stone were placed both inside and around CP. The radius of the covering was 18 cm. The stone surface was the same level as the bed surface. No movement of the stone was observed during the experiment. Figure 10 shows the conditions before and after the experiment. The initial surface of riprap was the same before and after the test. Placing this covering alternative with stone completely eliminated local scour and ensured bed stability both around bridge pier and CP. Little scour downstream of the riprap layer can be observed. Although no edge movement of riprap material is visible here, further scouring can the riprap material to be unstable and collapse into the scour hole which the failure of riprap material may continue till reaches the around CP. In such cases, the riprap movement stopped by CP whilst the riprap inside the CP can safely protect the pier. In Figure (11) - the longitudinal bed topography at the end of the Experiment B4 is shown.



a) longitudinal bed profile **b) bed topography**

Figure 11. longitudinal bed profile and bed topography after Experiment B4

In this arrangement, due to the flow passing over surface area of the crushed stone layer around the pier and CP, the velocity of the flow impinging on the pier and CP decreased, as a result, the strength of the downward and horseshoe vortex decreased compared to the Experiment A.

Although the effect of CP in this experiment is not apparent, as can be seen from the Figure 10b, no particle has moved from around the pier and of course, this is due to the presence of CP. Because in cases of riprap without CP, due to the presence of strong vortices around the pier, finer aggregates can jump upwards and be transported downstream by the spiral vortex. The continuation of these conditions will create larger pores around the pier and ultimately destroy the riprap layer. Whereas as shown in Experiment B1, the stone inside CP are more tightly packed within the CP and cannot move easily. Therefore, the scour depth does not occur.

Table (1) shows the percentage reduction in scour depth around the pier in different alternatives of the riprap coverage in comparison with the Experiment A. Figure 12 shows the effect of combined CP and riprap on the longitudinal profile of the bed. This figure clearly show the reduction of the scour in front of the bridge pier with the installation of CP and the riprap compared to the control experiment (Exp. A). The minimum scour depth around the pier is related to experiment B4 and the highest scour depth is related to experiment B1 (CP without stone cover).

5. Comparison with other studies

Although similar to this study, the use of combination of CP and riprap, has not been published so far (at least to the authors' knowledge), the closest and most recent study on rockfill arrangement types was conducted by [14], where the results of the study are compared with this study, which are shown in Figure 10. According to the diagram in Figure 13 around a CP, with an increase in the ratio of rockfill coverage around the pier to the its diameter (br/d), the percentage of reduction in scour depth around the pier first increases and then with an increase in this ratio, the percentage of reduction will be insignificant. As can be seen, at a b_r/d ratio of 5 according to the results of [14] and the results of 4 experiments of this study, the percentage of reduction is maximized and the coverage radius no longer needs to be more than four times the pier diameter. In this coverage, the possibility of destruction of the rockfill layer due to edge erosion is also minimized.

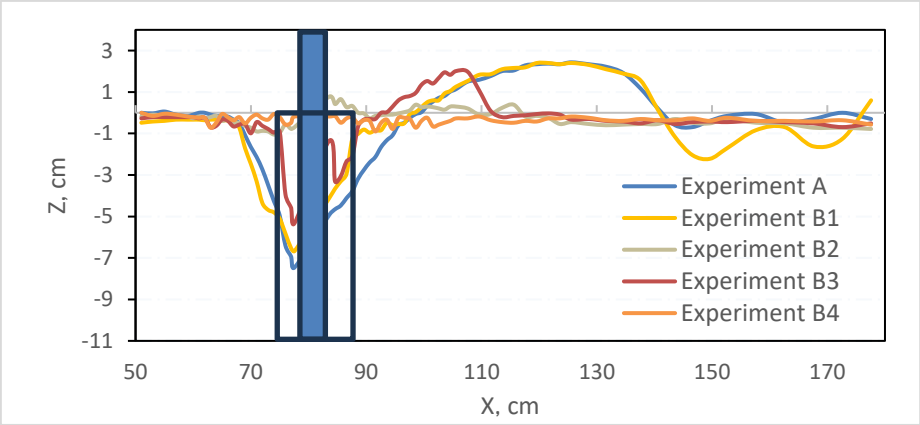


Figure 12. The longitude bed profiles for different experiment

Table 1. Percent reduction of scour depth around pier for different experiments

Experiment B4	Experiment B3	Experiment B2	Experiment B1	Test name
100	31	81	12.8	Percent reduction

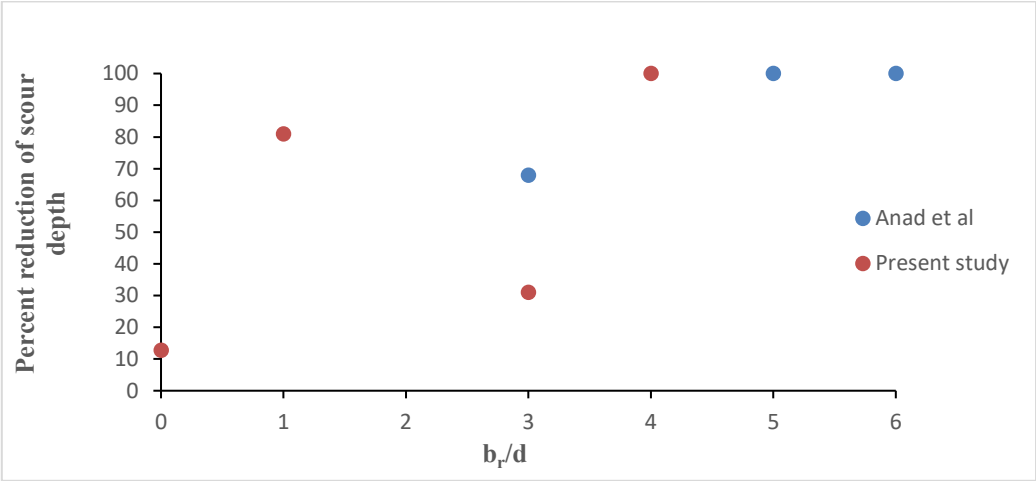


Figure 13. Percent reduction of scour depth around pier versus the ratio of $\frac{b_r}{d}$

6. Conclusion

In this study, the effect of combined installation of cylindrical protective and riprap layer on reducing the maximum scour depth around the pier bridge was investigated. The results show that although the installation of CP alone leads to a reduction in the maximum scour depth of 12.8 percent, the combined use of the CP and riprap can be more efficient. Three riprap arrangements with coverage of a) $b_r/d=1$ (inside the CP), b) $b_r/d=3$ (around the CP), and c) $b_r/d=4$ (around both pier and CP) reduced the maximum scour depth by 81, 31, and 100 %, respectively. The results also showed that the maximum cover radius of riprap layer should not be more than four times the diameter of the pier. In this condition, the amount of damage to the riprap layer from edge erosion is also minimized.

It is notable that riprap particles are quite dense inside CP cause the stone particles not to washed away especially the smaller particles which are close to the pier. In case of riprap without CP, the smaller particles are subject to the down flow velocity component and helicoidal vortices as well as wake vortex and can escape which eventually large pores are developed result in riprap failure due to winnowing. In addition, for the case of riprap without CP, once the edge erosion initiated and move toward the pier causing bridge failure. While for the case of presence of CP, the edge erosion will stop once it reaches to the CP and therefore, the bridge pier will be safe enough.

It should be noted that this paper presents a study with some limitation to introduce a new combined countermeasure against bridge pier scour. Despite the limitations of this study, the use of a combination of protective cylinders and riprap is very promising in reducing scour depth and ensuring bridge pier stability. However, before the results of this research can be used in the field, more studies with larger scales, different flow conditions, different shape and diameter of the pier and shape of CP should be conducted.

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Conflict of Interest

The authors declare that they have no conflict of interest.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by [M.SH.], [F.M.], [S.M.K], [M.B.Y.] and [K.K.]. The first draft of the manuscript was written by [M.SH.] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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