An Experimental Study on Local Scour Protection for Round Slotted Bridge Piers with Collar Variations

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ABSTRACT

Structural collapse in bridges frequently results from localized scouring around piers induced by downflow and horseshoe vortices. This study examines the impact of collar diameter and installation height on scour reduction in a cylindrical pier model with circular gaps. A laboratory experiment was performed in a flume utilizing a clear-water scour methodology. The experiment employed a cylindrical pier with a diameter of 3 cm and an average flow velocity of 0.23 m/s. The collar design modifications comprised three outer diameters (2*D*, 2.5*D*, and 3*D*) and two installation heights (*hc* = 0 cm and *hc* = 3 cm). The protection efficiency (*β*) was assessed by evaluating the decrease in the maximum scour depth (ds_{max}) following an estimated equilibrium period of 45 min. The results demonstrate that the application of collars markedly decreased the scour depth. An inverse relationship exists between the collar installation height and protection efficiency. Specifically, positioning the collar at the channel bottom (*hc* = 0 cm) was more effective in reducing scouring than positioning it at *hc* = 3 cm. Moreover, the protection from scouring increases with the outside diameter of the collar. The main findings indicated that the collar with the greatest diameter of 3*D* and positioned on the channel bottom surface (*hc* = 0 cm), attained the highest efficiency, namely a scouring reduction exceeding 51.93% relative to unprotected pillars. It was concluded that a large diameter and low placement are essential for effectively disrupting the water vortex, providing a viable solution for bridge pillar scouring issues.

Keywords-local scour; round slotted piers; collar; protection efficiency

I. INTRODUCTION

The structural failure of bridges often occurs due to scouring at the piers and abutments, so scour mitigation studies are critical in bridge design to prevent major losses [1]. Scouring is the continuous erosion (long-term degradation of the base) that removes material around bridge foundations, gradually weakening the structure and making it susceptible to damage [2]. Scouring is generally classified into three types: general (unrelated to structures), local due to channel narrowing, and local around structures caused by specific flow patterns [3].

One of the main factors causing bridge foundations to collapse is the formation of scour holes around the bridge piers. The lowering of the riverbed around bridge piers is known as local scour [4]. The main causes of local scouring around bridge piers stem from three flow phenomena: increased longitudinal flow velocity on the pier sides, the combined action of momentum and gravity creating an erosive downflow in front of the pier, and horseshoe vortices that actively suction sediment around the structure [5].

Scouring around bridge piers is a complex hydraulic problem. To mitigate the latter, various prevention methods have been developed and studied, including the use of riprap, submerged plates, slots, and collars [6]. There are two main ways to control scouring: reducing the its force and increasing the riverbed resistance. The first method involves using riprap, gabions, tetrapods, dolos, and concrete blankets to increase the protection of the riverbed from water pressure. The second method is to change the flow pattern of water around bridge pillars using piles, collars, and slots to reduce the water vortices that cause scouring [7].

Water vortices are formed when the flow interacts with bridge piers, directly causing local scouring. Therefore, an effective strategy for scouring control is to change the pier geometry, and so disrupt vortex formation [8]. A collar is a horizontal plate placed on a pier primarily to prevent base scouring by deflecting the downflow vortex. This action effectively reduces the force of the horseshoe vortex, thereby minimizing the depth and volume of the scour holes [9]. The implementation of slots as a scour mitigation strategy seeks to redirect the downflow from the pier base, thus diminishing the likelihood of scouring. Positioning slots near the base is similarly effective in disrupting horseshoe vortices [10].

Various experiments have been conducted using circular collars of varying diameters and placed at various positions. Specifically, Authors in [11] discovered that the collar efficiency varies based on the position and configuration. A hooked-collar positioned below the channel base reduced the maximum scour depth by 24%. Meanwhile, single collars placed directly at the base provided better results by reducing the final scour depth by 42%. The most significant results were achieved using the double collar configuration, with one collar placed at the base and the other at a higher elevation, resulting in a 50% reduction in scour rate. Authors in [12] investigated the mitigation of erosion around circular bridge piers by implementing rectangular slots and circular collars to facilitate transparent water flow with a uniform sediment distribution. The slots were successful in reducing erosion, particularly when placed at the bottom of the river. However, the former were inefficient when the flow approaching them exhibited a steep angle of inclination. Larger diameter collars positioned at or near the bottom demonstrated greater efficacy. Authors in [13] analyzed the effect of the external diameter and collar installation elevation on local scour depth. Focus was given on the protective effect of an active prevention measure called an "anti-scour-collar" (collar) on local scour around cylindrical bridge piers, and the findings indicate that collars are an effective method for decreasing the local scouring in pier areas. Authors in [14] investigated the effect of the collar shape and orientation on reducing the erosion depth in front of bridge piers in clear water conditions. The collars were tested using two asymmetrical shapes at three installation levels relative to the base: directly at the base, 1 cm above the base, and 2 cm above the base. According to [15], the optimal location for installing collars is at the base and below the river base. Simple collars can control erosion by up to 100%, whereas mesh collars can control erosion by up to 92%. At the position below the base, both types of collars showed comparable performance, with a reduction in erosion depth of 88%.

Other approaches include the use of collars and ripraps. For instance, authors in [16] investigated the application of independent (discrete) and continuous collars combined with riprap to reduce local scouring around various groups of bridge piers. The data showed that for two parallel piers, the integration of continuous collars and riprap achieved the greatest scour reduction (approximately 50% for the front pier and 60% for the rear). However, in separate tests on parallel pillars, discrete collars proved superior to a single continuous collar encircling both pillars. It was also found that collar efficiency was better on rectangular piers aligned with the flow compared to the parallel configurations. Conversely, collars were deemed ineffective when applied to two transverse bridge pillars. Authors in [17] examined the dimensions and surface area of stable riprap to safeguard rectangular piles against scouring. Several aspect ratios and inclination angles of the pillars, with and without collars, were explored. The collars employed were three times the width of the pillars and were affixed to the riverbed.

Previous studies have generally focused only on the application of collars to standard piers (cylindrical/square). In contrast, the current work concentrates on testing collars with other mitigation methods, such as riprap or different slots, and on groups of piers. This research is novel because it attempts to analyze the synergistic effect between the passive modification, represented by collars, and the active modification of round slotted piers. The latter are a scour mitigation method (geometric modification), with the present study examines how these modified piers respond to the addition of collars with varying dimensions and placement heights.

II. EXPERIMENTAL SETUP

A. Testing Facilities

A flow flume at the Hydraulics Laboratory of Hasanuddin University was used for the experiment. The flume, as illustrated in Figure 1, has dimensions of 9 m (length), 30 cm (width), and 40 cm (height).

Steel frames and fiberglass sidewalls enabled comprehensive visual observations during the flume experiments. The scour test section was placed inside the flume, with dimensions of 2 m (length) × 30 cm (width) × 8 cm (depth).

The scour depth was studied in a recirculating sediment flume channel by controlling the flow rate, valves, channel slope, and downstream gates to achieve the desired flow depth. At the upstream and downstream ends, a 40 cm thick rigid base layer was installed to prevent the initial scouring of the base material due to height reduction. In the middle section, a uniform bed material (movable bed) with a thickness of 8 cm was distributed along the length of the recirculating sediment flume channel.

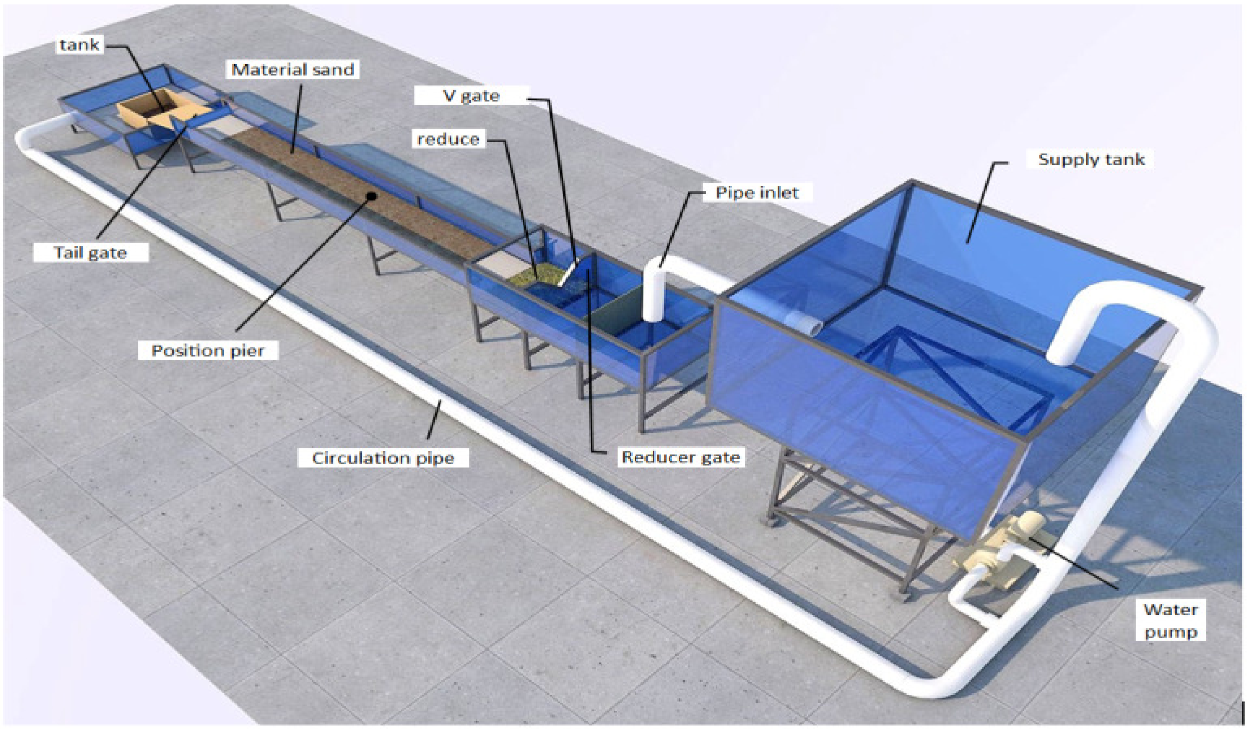


Fig. 1. Recirculating sediment flume.

Figure 2 displays the layout of the scour testing facility. The round slotted pier model, as shown in Figure 2(a), was installed at a depth of 8 cm into the bottom of the channel. The bottom of the pier model was glued to ensure structural stability during the testing process.

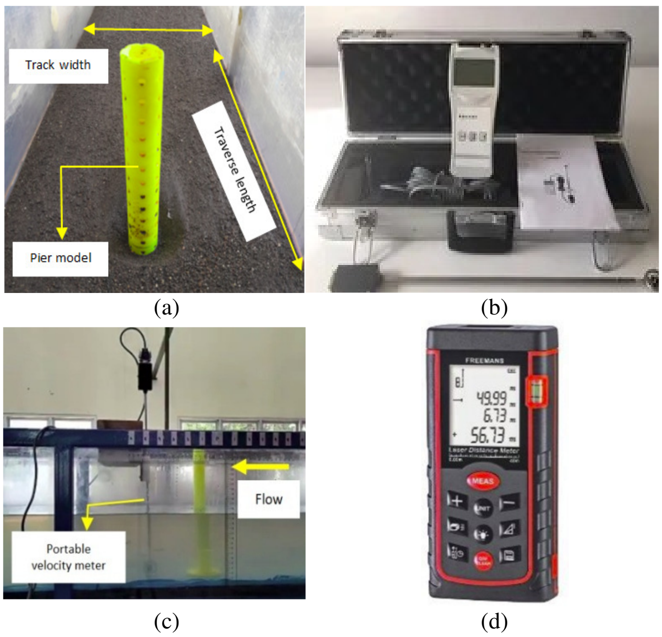


Fig. 2. Layout of the testing facilities: (a) installation of the test model, (b) the portable flow velocity meter Ls-300, (c) velocity measurement, and (d) scour depth measurement by the laser distance meter.

To measure the flow velocity, a portable velocity meter (Ls-300) with an operational range of 0.01–4.0 m/s was used (Figure (2b)). The maximum flow velocity applied in this test was 0.23 m/s. As depicted in Figure 2(c), the device can be positioned vertically to obtain a velocity distribution profile along the water depth. Additionally, a laser distance meter was used to measure the scour depth and model the geometry of the scour hole around the pile. The setup of the laser distance meter for scour depth measurement is shown in Figure 2(d).

B. Description of Round Slotted Pier and Collar

The dimensions of the piers in this investigation were determined according to the parameters set by prior research. This study employed an aspect ratio range of $1.7 \leq B/H \leq 2.9$. To prevent wall impacts on scour, the pier diameter was limited to no more than 10% of the flume width [18]. The pier and collar models were constructed from a plastic material compatible with 3D printers utilizing Fused Filament Fabrication (FFF), as depicted in Figure 3.

A cylindrical pier was employed with the following specifications: diameter (D) 3 cm, height (H) 30 cm, and slotted with 0.5 cm diameter holes, a distance of 1 cm between holes, and a depth of 0.25 cm. The pillar is portrayed in Figure 3(a). The collar had a thickness of 0.02 mm and was fabricated using the FFF method. Three collar diameter design parameters were tested ($2D$, $2.5D$, and $3D$), with the neck tilted at 45°. This configuration is illustrated in Figure 3(c). The installation height of the collar at the bottom of the channel (h_2) and the distance between the collar and bottom of the channel (h_1) were set to 3 cm, as presented in Figure 2(b). Meanwhile, the water level (H) was maintained at 15 cm.

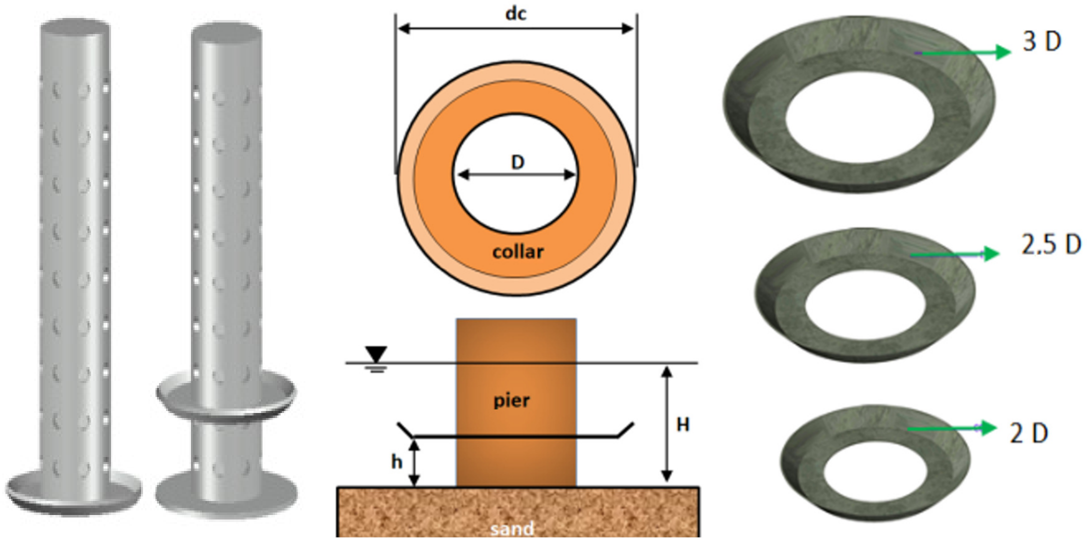


Fig. 3. Schematic diagram of round-slotted piers and collars: (a) pillars with 2 different collar positions, (b) the installation of collars in pier, and (c) collars with different diameters.

C. Flow Velocity Determination

The flow velocity in open channels exhibits significant spatial variations. The flow is described by three directional components (vertical, lateral, and longitudinal), but the vertical and lateral components are often considered negligible and can be ignored. Therefore, only the longitudinal velocity component (in the direction of flow) was considered in the analysis [19].

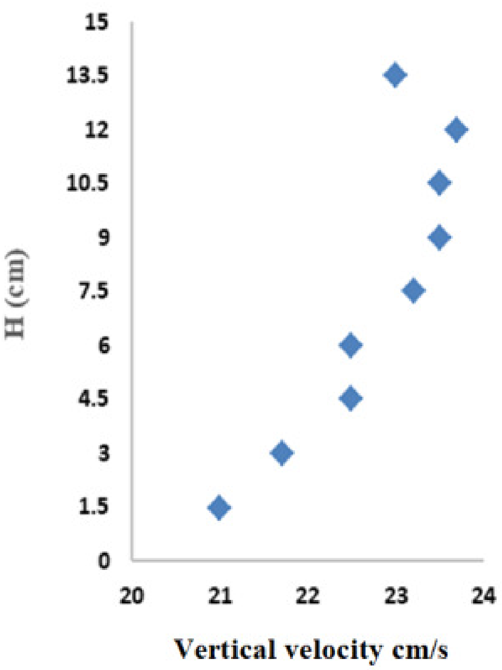


Fig. 4. Measured distribution of velocity in water depth.

Before the scour test was conducted, the flow velocity profile was measured at the point where the pillar model would be placed. This measurement was taken after the flow reached a stable condition for 10 min. This measurement was carried out by dividing the flow cross-section into nine observation points. Figure 4 displays the vertical results, with measurements taken at three depth points: 0.2*H*, 0.6*H*, and 0.8*H*, where *H* represents the water depth. Horizontally, measurements were taken at three points: the left edge, center, and right edge. These measurements yielded an average flow velocity of 23 cm/s.

III. EXPERIMENTAL PROGRAM

A. Threshold Velocity Calculation of Natural Sediment

Only one sand size, flow depth, and average flow velocity were used in this study. Table I provides a summary of the parameters utilized in this study. The critical Shields parameter was calculated using the following empirical equation [20]:

$$\theta_{cr} = \frac{0.30}{1+1.2D_*} + 0.055[1 - \exp(-0.020D_*)] \qquad (1)$$

where the non-dimensional particle size D_* is defined as $D_*=[g(s-1)v^2]^{1/3}d_{50}$, with $v=10^{-6}$ m^2/s representing the kinematic viscosity of water. The Shields parameter due to the total friction, was obtained according to the measured velocity profile. The Shields parameter θ_s due to friction is defined as:

$$\theta_s = \frac{\tau_s}{\rho g\,(s-1)d_{50}} = \frac{U_{fs}^2}{g\,(s-1)d_{50}} \qquad (2)$$

where τ_s is the shear stress caused by friction at the base, ρ is the density of water, g is the specific gravity, s is the specific gravity of sand, d_{50} is the size of sand particles, and $U_{fs}=(\tau_s/\rho)^{1/2}$ is the friction velocity associated with the pile. The shear stress due to pile friction is calculated using the following empirical formula [20]:

$$\tau_s = \rho\, C_D\, U^2 \qquad (3)$$

where the logarithmic relationship for the Coefficient of Drag (CD) is $CD = \{\kappa/[\ln(z_{0s}/h)+1]\}2$, κ=0.4 is Karman's constant, U is the average flow velocity depth, $z_{0s}=d_{50}/15$ is the roughness caused by friction, and h is the water depth.

TABLE I. PARAMETERS USED IN THE TESTS

Median particle size of sand d_{50} (mm)	0.287
d_{10} (mm)	0.131
d_{30} (mm)	0.206
d_{60} (mm)	0.344
Uniformity coefficient $Cu = d_{60}/d_{10}$	0.2624
Coefficient of curvature $Cc = d_{30}^2 /(d_{60}* d_{10})$	0.935
Specific gravity s	9.81
Critical Shields parameter θ_{cr}	0.038
Water depth h (m)	0.15
Approximate depth averaged velocity U (m/s)	0.23
Shields parameter due to skin friction θ_s	0.048
Logarithmic relationship for CD	0.0027
Roughness length for skin friction z_{0s} (m)	2.39×10^{-5}

B. Calculation of Equilibrium Scour Time

Scour is the erosion of the riverbed or material around a structure caused by water flow. The scour depth continues to increase over time until it reaches a point where the scour rate becomes very small or stops. This condition is referred to as the equilibrium scour depth [21, 22]. The time required to reach this condition is known as scour equilibrium time. Theoretically, this time can approach infinity. However, in engineering practice, what is observed is the time required to reach a quasi-equilibrium condition or a condition approaching stability, where changes in scour depth become very minimal.

The scour testing in this study was conducted under subcritical turbulent flow conditions, which were influenced by the Froude number. All experimental tests used the same water depth and pillar size, but with different collar diameters and heights. A series of preliminary experiments were conducted to obtain representative times. Therefore, an equilibrium time of 30 min was selected for each test (Figure 5).

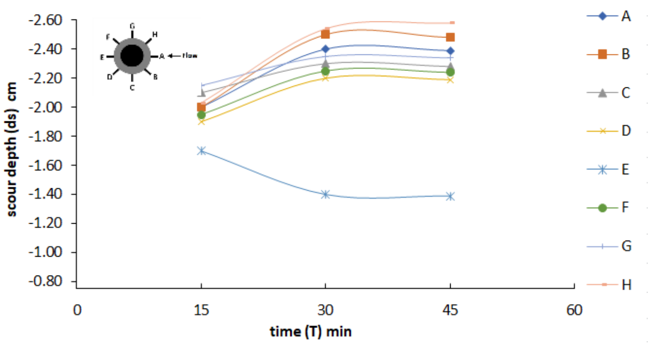


Fig. 5. Equilibrium was achieved after 30 min for the pier without collar.

C. List of Testing Conditions

This experiment investigated the influence of collar parameters, namely, the installation height and outer diameter, on the maximum scour protection efficiency of a single cylindrical pillar with a circular gap. A clear-water scour test scheme was utilized based on the results of scour velocity and equilibrium time tests. The general and specific testing conditions are detailed in Tables I and II. Based on a series of preliminary tests, the flow velocity was set at 0.23 m/s and the flow depth at 0.15 m for all experiments.

TABLE II. PARAMETERS FOR THE TEST CONDITIONS

Test	**Round slotted pier**	**Installation height *hc* (cm)**	**External diameter *dc* (cm)**
1	without a collar	-	-
2	with collar	0	9
3	with collar	3	
4	with collar	3	6
5	with collar		7.5
6	with collar		9

As illustrated in Figure 6, eight observation points and 40 measuring points were placed in a circle around the pier at 45° intervals. This placement was intended to obtain representative scour depth data from various sides of the pier. Data recording and collection were conducted using a camera and a laser distance meter. To gradually capture the initial dynamics and long-term evolution of the scour hole, monitoring was conducted for 15 min to track the rapid scour rate in the initial phase. After 30 min, it was assumed that the scour development rate began to slow down and approach equilibrium conditions. After 90 min, the flow was stopped to record the final scour development results.

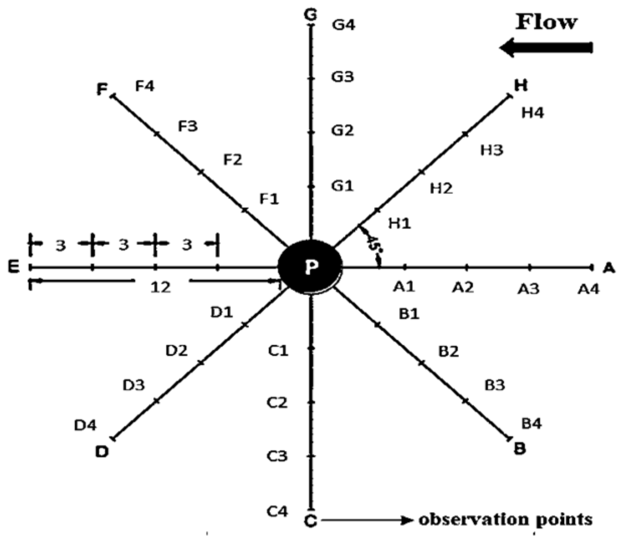


Fig. 6. Layout of the measuring points around the slotted pier.

IV. RESULTS AND DISCUSSION

The maximum scour depth was determined by taking the maximum value from all measurement points. The testing steps were: First, the pillar model was tested without a collar to obtain baseline data. These data were used for comparison. Subsequently, this work tested the pillar fitted with a collar. The results were compared to calculate the effectiveness of the collar in preventing scouring. This effectiveness is expressed by the β value in percentage, which indicates the ability of the collar to reduce the scouring depth. The higher the β value is, the better is the collar's performance.

A. Characteristics of Local Scour for a Round Slotted Pier without a Collar

In [23], observations were conducted to understand the effect of pillar shape on scouring. The scour depth was plotted sequentially at eight measurement points over different scour times, as shown in Figure 7(a). The erosion depth around the pillar model was symmetrical to the direction of the current flow. The erosion depth decreased from the upstream side (A) to the downstream side (E) because the flow velocity and shear stress behind the pillar were smaller than those in front of it due to the pillar's shadowing effect.

The scour depth increased continuously throughout the test. After 10 min of scouring, the maximum scour depth occurred on the side of the pillar at position G, whereas the minimum scour depth appeared at position E, which was directly behind the pillar. After 10 min, the measured maximum scour depth gradually shifted from the side to the front of the pillar, and the final maximum scour depth at 45 min occurred at the front of the pillar.

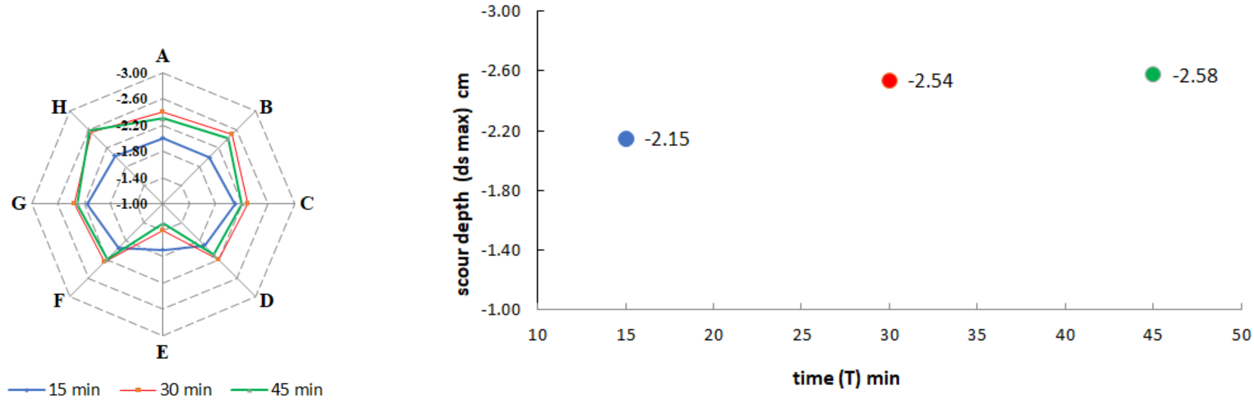


Fig. 7. Scour depth data of a round-slotted pier: (a) the time-varied scour development at eight measurement points, and (b) the maximum scour depth of a single pier.

The maximum scour depth around the pile as a function of scour test time is presented in Figure 7(b). In the first 30 min, scour develops rapidly, with the maximum scour depth, as well as the length and width of the scour hole, increasing rapidly. The development rate of the maximum scour depth slows down as the test time increases and approaches zero at the approximate equilibrium condition. A similar phenomenon has also been reported in [24]. The maximum scour depth around the pillar was -2.15 at 15 min and increased to -2.54 at 30 min. Although scouring continues in the subsequent period, the growth in scour depth and hole extent is very small. The minimum scour depth occurred at position E after 45 min. As demonstrated by the photos in Figure 8, at 45 min the minimum scour depth was approximately 50% of the maximum scour depth at the final scour hole. Based on the scour depth development as a function of experimental time for all operating conditions, although the scour depth continues to increase after 45 min in the test, the increase in depth is very small, and the rate of increase is significantly slower than that in the first 15 min. Therefore, this time can be considered the time required to reach an approximate equilibrium condition.

The maximum base shear stress and scour depth occurred at the front of the upstream side of the pier [22]. Owing to the shear stress, turbulent flow was generated around the pier and accelerated the scour development in front of the pier. Therefore, the position of the deepest scour depth is always associated with the area where the base shear stress of the channel and flow turbulence reach their peak, namely at the upstream section directly in front of the pillar.

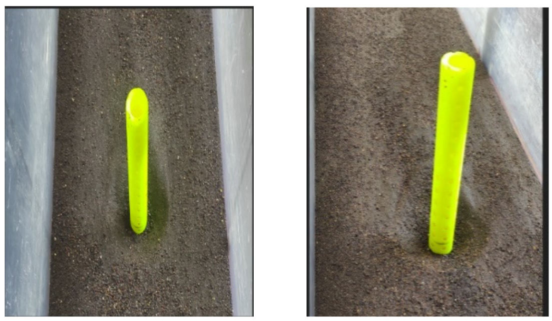


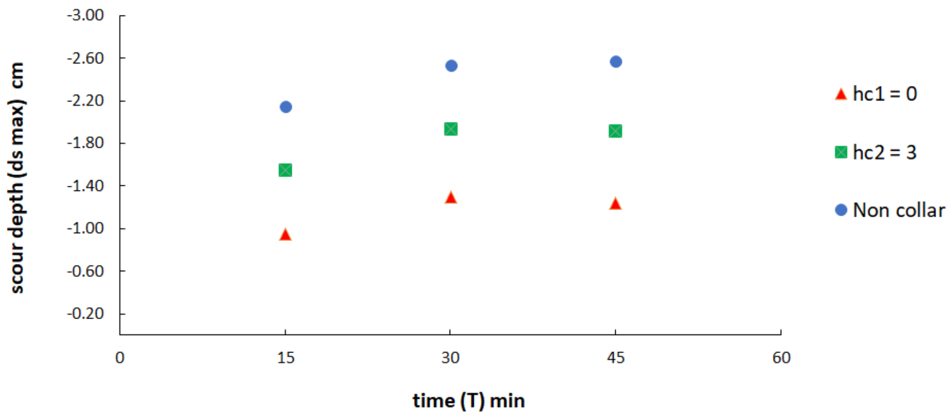
Fig. 8. The scour hole in the approximate equilibrium condition.

B. Effect of Collar Installation Height

Tests 2 and 3 (Table II) were conducted to investigate the effect of the collar installation height on scour protection. In this experiment, the outer diameter of the collar (*dc*) was set to 9 mm. The collar installation height (*hc*) was set to either 0 or 3. The development of the maximum scour depth (ds_{max}) at different collar installation heights is shown in Figure 9(a). The collar reduced the local scour depth and had a protective effect on the circular slotted pile, regardless of its installation height. The scour depth as a function of the collar installation height was consistent with the results of the experiment conducted in [25].

To evaluate the efficiency of the protector (collar), a protection efficiency factor β was defined, where $\beta = (ds_{max} - ds_i)/ds_{max}$. In this formula, ds_{max} is the maximum scour depth from the unprotected case test after 45 min, and ds_i is the maximum scour depth for case *i* after 45 min. The larger the value of the β factor is, the better is the protective effect. The relationship between the protection efficiency factor β and the installation height is presented in Figure 9(b). Photos of the scour holes for tests 2 and 3 at t=45 min are displayed in Figure 10. The development of scour depth around the pillar model as a function of the collar installation height is demonstrated in Figure 11.

(a)



(b)

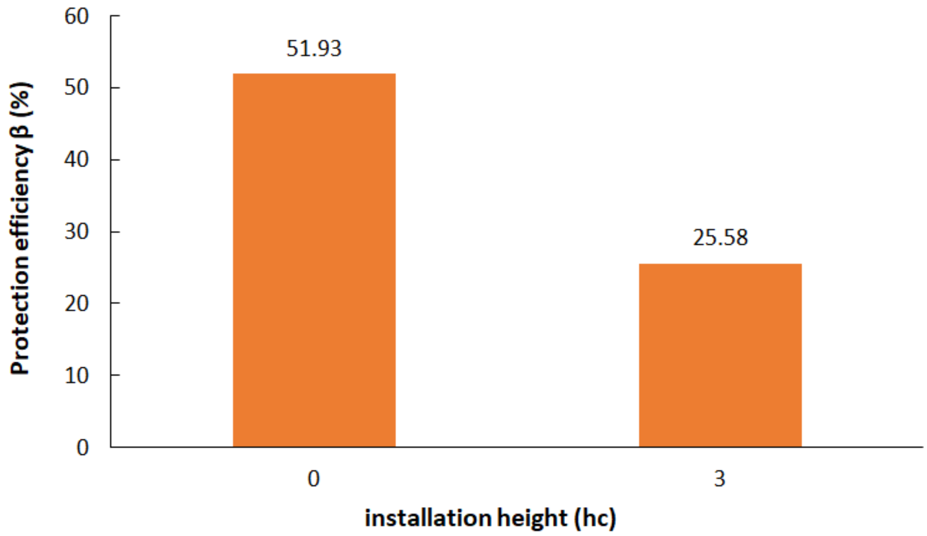


Fig. 9. Scour protection effect at different collar installation heights (*hc*): (a) the maximum scour depth development and (b) the protection efficiency.

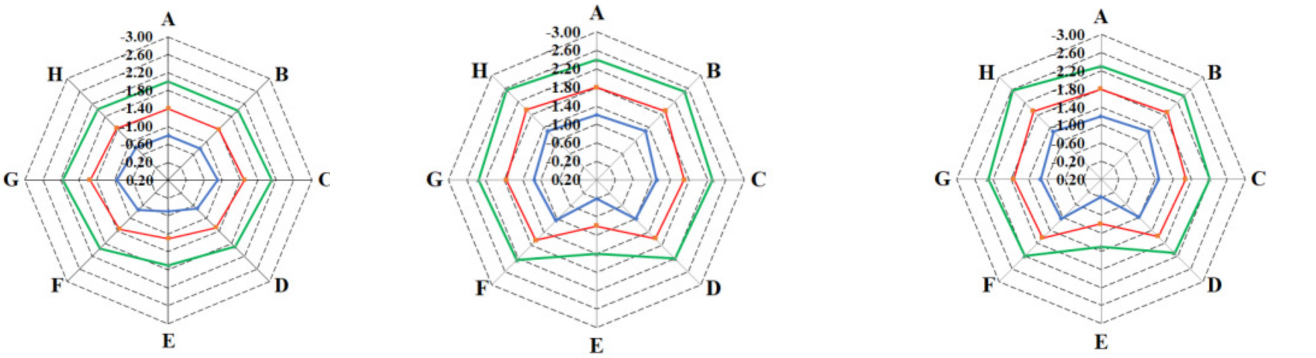
(a) *hc* = 0 cm

(b) *hc* = 3 cm

Fig. 10. Scour hole shape at different installation heights of collars.

The relationship between height and efficiency exhibits an inverse correlation between the height of the collar installation and its protective efficiency. This indicates that to achieve the maximum protection, the collar should be placed as close as possible to the bottom of the duct. The effectiveness of the system significantly increased with a reduction in the installation height. As portrayed in Figure 11, the maximum scour position is indicated at the deepest scour depth, which always occurs at point A, at the front of the pier (or the area most directly exposed to the water flow). The fact that the location did not change with or without the necklace shows that it does not fundamentally alter the water flow pattern; it merely reduces erosion in critical areas.

When the collar was installed on the channel bed (hc=0), minimal sediment scour was observed at all eight measurement points during the first 45 min of testing. This demonstrates the immediate and highly effective performance of the protector in the initial phase. This protector successfully reduces the speed of the water flow, thereby reducing the shear stress that typically causes significant erosion around the pole, thus reducing sediment erosion. The collar protects the sediment beneath it from being carried away by the flow, but the sediment on the downstream edge of the collar undergoes scouring. This phenomenon is known as secondary scour. The collar alters the flow distribution, causing local acceleration and strong vortices at the downstream edge. As a result, the concentrated energy of the flow in this area causes the erosion of unprotected sediments. The collar is not absolute or permanent. Over time, scour around the collar's edge can develop and creep downward, though possibly at a much slower rate. The maximum scour depth always occurs at two points on the outer sides of the collar, directly behind the pillar. This location is usually where the horseshoe vortex and tail vortex interact and become the most intense. These results indicate that while the collar reduces the scour intensity at the front, it may not completely eliminate or shift the center of the most damaging vortex. This position is the weakest point in the protection system and is the primary focus of designing a better protective structure.



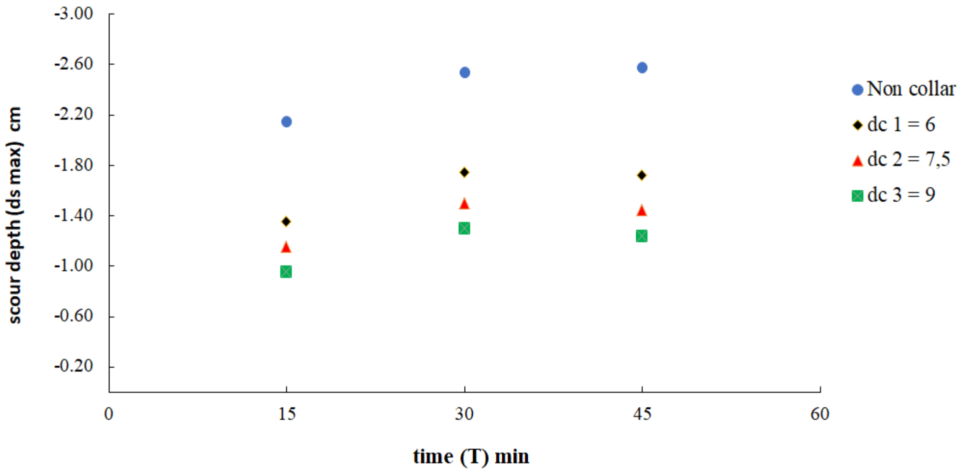
(a) (b) (c)

Fig. 11. The dimensionless scour depth development of different collar installation heights (hc) at each measuring point. t = (a) 15 min, (b) 30 min, (c) 45 min. Green: no collar, blue: hc = 0, red: hc = 3.

C. Effect of Collar External Diameter

The effect of the outer diameter of the protective collar on scour protection was investigated experimentally at a specific collar installation height (hc = 3 cm). Three scour protection collars with different outer diameters (dc = 6, 7.5, and 9) were used. The development of the maximum scour depth, ds_{max}, as a function of the outer diameter of the protector is plotted in Figure 12(a). The protection efficiency factor β (defined as $ds_{max}–ds_i)/ds_{max}$ in the previous section) versus the outer diameter is illustrated in Figure 12(b). The collar with the larger diameter (dc=9) provided the maximum protection compared to the collar with a smaller diameter. From a scientific perspective, a larger collar is more effective because it can break and shift the horseshoe vortex from the base of the pier, thereby reducing the shear stress that causes scouring. The larger surface area of the neck allowed for a more effective distribution of the flow energy in the upstream area, thereby preventing the formation of destructive vortices. It is clear that the outer diameter of the protector (collar) affects the protective effect against erosion. The protection effect increases with the increase in the outer diameter of the collar at the eight measurement points. This statement provides external validation (scientific validity) by referencing existing scientific literature. This indicates that the findings of this study are consistent with the results of other studies, thereby strengthening its reliability [26]. Sequential photos of the scour holes after 45 min of scouring during the three tests are presented in Figure 13. Based on Figure 14, increasing the outer diameter of the collar not only reduced the maximum scour depth but also the scour hole range. A very large collar effectively breaks the horseshoe vortex and changes the flow behind the pillar. When the outer diameter (dc) was set to 9.0, the edge of the scour hole was within the collar range and sediment was deposited behind the pillars. As the outer diameter of the collar decreased, its protective effect diminished. When the outer diameter of the collar was 7.5, the scour hole range was similar to the protector size, which was larger than that in the case with a diameter of 9.0. As the outer diameter of the collar decreased, the scour hole became larger than the protective size, and its range became wider. An adequate collar size not only reduces the scour depth but also minimizes the affected area and can even trigger sediment deposition in areas previously prone to scour. The development of scour depth as a function of scour time at the eight measurement points is shown in Figure 14 for different outer collar diameters. The maximum scour depth occurred in front of the pier, regardless of the outer collar diameter. Although collars with larger diameters provide better protection, it is not possible to install protectors with an infinite outer diameter due to hydraulic and economic reasons. Based on this study, a collar with an outer diameter equal to three times the pillar diameter can reduce scour by more than 51.93% compared to a pillar without protection. However, there must be a balance between the scour reduction and costs due to increased protector diameter, especially when applied to long-span bridge piers with large diameters in the field [27].

(a)



(b)

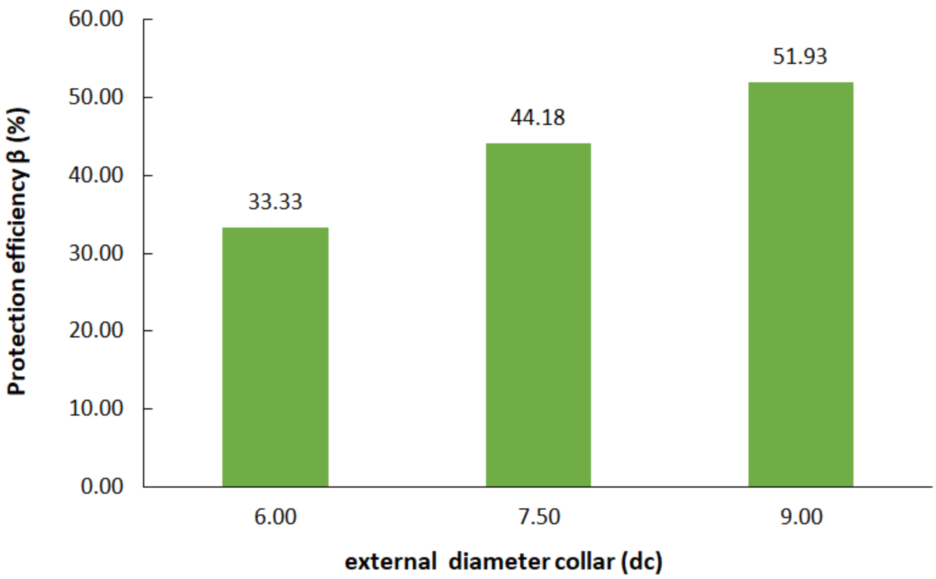
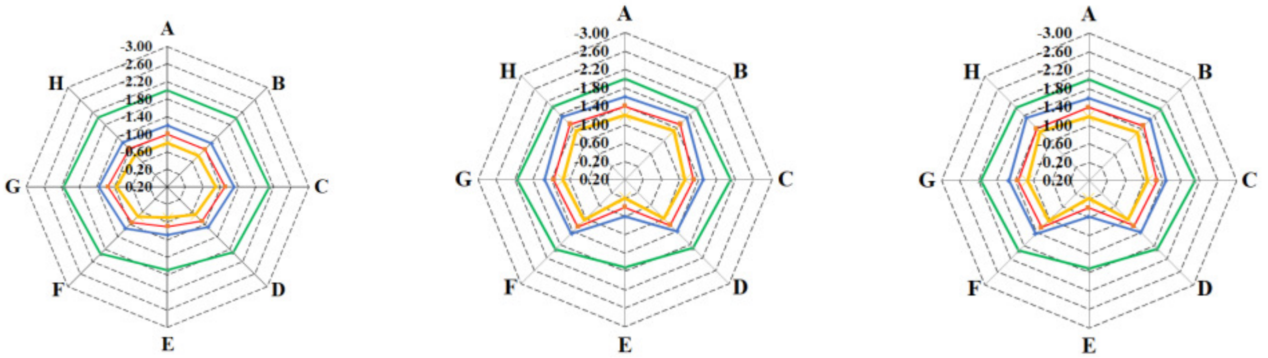


Fig. 12. Scour protection effect at different collar external diameters (*dc*): (a) the maximum scour depth development, and (b) the protection efficiency.

(a) $dc_1 = 6$ (b) $dc_2 = 7.5$ (c) $dc_3 = 9$

Fig. 13. The scour hole formed by different collar external diameters at 45 min.



(a) (b) (c)

Fig. 14. The dimensionless scour depth development of different collar external diameters at each measuring point. t = (a) 15 min, (b) 30 min, (c) 45 min. Green: no collar, blue: $dc_1 = 6$, red: $dc_2 = 7.5$, yellow: $dc_3 = 9$.

V. CONCLUSIONS

This study aims to analyze the effectiveness of combining round gap pillars (active modification) with the addition of collars (passive modification) as a mitigation effort against local scouring phenomena around bridge pillars. The experimental results indicate that the use of collars is effective in reducing the depth of local scouring on round-gap pillars.

Regarding the installation height of the collars, an inverse correlation between the installation height of the collar (hc) and scour protection efficiency (β) was found. The installation height was varied, and the results indicated that the maximum protection was achieved when the collar was installed as close as possible to the channel bottom (hc=0 cm). In this position, the collar successfully reduced the scour depth with a protection efficiency of 51.93%. Installing the collar 3 cm above the channel base resulted in a reduced protection efficiency of 25.58%.

Regarding the external diameter of the collar, it was observed that an increase in the external diameter of the collar (dc) significantly increases the protective effect against scouring. In detail, the collars with the largest diameter (three times the diameter of the pier, i.e., dc=9 cm) were the most effective in reducing scouring because they broke and shifted the horseshoe vortex, which is the main cause of erosion at the base of the pier. These collars can reduce scouring by more than 51.93% compared to unprotected pillars.

It is worth mentioning that the maximum scouring depth on pillars without collars always occurs upstream, directly in front of the pillar (point A), which is the area with the highest shear stress and flow turbulence.

In summary, collars are a highly effective mitigation method for round-slotted pillars. The optimal design is a collar with a large outer diameter (at least three times the pier diameter) installed at the bottom of the channel to achieve the maximum protection efficiency. Although effective, collars have the potential to trigger secondary scour at their downstream edges, which occurs due to changes in flow distribution and local eddies in unprotected areas.

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