Optimal Octagonal Hooked Collar Countermeasure to Reduce Scour Around a Single Bridge Pier

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Abstract

Pier modification countermeasures are essential as they play a vital role in protecting pier against local scour action. Current study investigates experimentally the scour around vertical pier of octagonal cross section with pier modification such as newly proposed octagonal hooked collar is explored, in steady uniform state, under clear water condition. The results of pier scour without any modification were used as a reference to compute the efficiency of hooked collar provision around octagonal pier. The results show that by increasing the hooked collar width up to 2.5 Wp reduced maximum scour depth significantly. However, the experimental investigation revealed that the best combination to be with a hooked collar width of 2.5 Wp, having sidewall height 0.45 Wp. The best combination minimized around 73.3 % of scour hole depth, compared to octagonal pier without any modification. Using experimental results, a new equation is proposed to predict the scour depth around a bridge pier fitted with hooked collar. Moreover, a relation was developed for maximum scour depth and scour hole volume. Results indicate that the scour hole volume around a bridge pier increases quadratically with maximum scour depth.

Keywords

scour, octagonal, hooked collar, pier shape, scour countermeasure

1 Introduction

Local scour at bridge pier is a complex three-dimensional process, mainly takes place because of strong flow-sediment-pier interaction. The scour process becomes complex due to formation of an intricate vortex system around pier. This formation of vortex system comprises of wake vortex, horseshoe vortex, bow wave vortex, and trailing vortex [1, 2]. Over the recent years, significant research has been undertaken to analyze the influence of various factor on the development of the complex intricate vortex system at the bridge piers. Such factors perhaps separated by three different groups: (i) sediment factor, for instance size distribution, sediment density, and median size; (ii) flow parameters, such as flow depth and approach velocity; and (iii) pier dimension, shape, and type [3–6]. One of the prime causes broadly recognized as scaling up the scour threat to bridges is shape of pier. Pier shape is very significant in the formation and strengthening of the vortex system [6–9]. The pier having any shape placed vertically in the riverbed and thereby immensely varies the flow fields, and it can be assumed that the large variations in the flow structures occurs due to different pier shapes, and thus varied scour patterns. The scour action and the flow formation around circular and rectangular pier shape have been comprehensively studied in the past by [1, 10–13]. Studies of pier scour on shapes other than circular and rectangular shape are rather insufficient comparatively as stated by [8, 14, 15]. Recently, Farooq and Ghumman [6] performed experiments on scour in steady uniform flow, examining the impact of different pier shapes on maximum scour depth. It was concluded that a plain octagonal pier shape turns out to be as more satisfying in reducing scour in comparison of all other pier

shapes. Nevertheless, researchers have unanimity that alone geometry of pier has not been sufficient in protecting bridge piers foundation against local scour.

Countermeasures to protect pier against scouring will certainly reduce the probability of bridge collapse. Usually, the protecting measures for pier scouring are in general classify in two categories: (i) bed-armoring countermeasures, and (ii) pier modification or flow altering countermeasures. Various flow altering measures are proposed in the literature for the protection of bridge piers against scouring such as vane plates, openings, cables and collars [16–20]. Collars of varying thickness and shapes are utilized by various researchers fitted around the piers as shielding plates against removal of sediments [2, 4, 21, 22]. According to Alabi [23], a collar having thickness equal to or less than 5 mm has no adverse effect on scour development. Mashahir et al. [24] concluded that the optimal collar width is three times that of the pier, in terms erosion control.

However, recently a new type of collar, namely the hooked collar *H*, has been examined by various researchers experimentally and numerically [6, 25, 26]. Interestingly, it is ascertained that the hooked collar performed relatively well in reducing the scour depth around the bridge pier compared to unprotected pier i.e., without any pier modifications. Although, it has limitations when explored, mainly in the context of the efficiency and utility around efficient pier geometry. First, past studies have emphasis primarily on the circular hooked collar placement within the bridge pier and considered it as sufficient to evaluate its efficiency. Second, past research did not investigate the impact of hooked collar width along with its sidewall height at bed level of the octagonal hooked collar. Therefore, current research is thus novel in the following aspect that it applies the octagonal hooked collar around octagonal pier geometry and derives experimentally the best relationship between sidewall height H_{wh}, and width H_w of octagonal hooked collar and also a scour depth predictive equation. Moreover, a relation was developed for maximum scour depth and scour hole volume.

2 Materials and methods
2.1 Experimental flume
A rectangular channel (20 meters length, 1.0 meters width, and 0.75 meters depth) having smooth surface, furnished with a recirculating water facility, is used to perform all experiments. The rectangular flume is mainly separated into three segments: inlet, working section in the middle, and outlet. The working segment includes a 6 m long and 0.3 m thick sheet of fine sand uniformly graded material having $d_{50} = 0.88$ mm, in which the wooden-pier is embedded in the center of the sand-bed. At the outlet, discharge is measured by installing a rectangular gated weir. The experimental setup is shown below in Fig. 1(a, b).

2.2 Sediment bed
The length of working segment about 6 m is filled with sand at a depth of 0.30 m (Fig. 1(a)). The median sediment grain size $d_{50} = 0.88$ mm is utilized for all the experimental runs. The friction angle and specific gravity are $\alpha_s = 32°$ and $S_g = 2.56$, for the selected sediment material. The sediment bed with computed geometric standard deviation σ_g value is less than 1.3, which is the upper limit for uniformly graded sediment [27]. Since W_p/d_{50} is more than 50 ($W_p/d_{50} = 68.2$), with Wp being the pier width, the sediment size effect on the scour hole becomes negligible [28].

2.3 Flow conditions
In all the experiments the discharge is maintained in a way that normalized shear stress of channel bed should not surpass the critical value for the incipient sediment movement of the mean sediment size ($d_{50} = 0.88$ mm). The experimental runs are carried out by keeping a constant flow discharge of 0.048 m³/s. The depth of flow d_f in all experimental runs is 15 cm, to eliminate the effect of flow shallowness i.e., $d_f/W_p > 2.5$ [29]. The Froude number $F_r = U / \sqrt{gd_f}$), where U is the mean approach flow velocity, and g is the gravity constant, against corresponding flow discharge is 0.26. Table 1 provides several flow parameters corresponding to the experimental work.

The flow intensity is maintained approximately as $U/U_c = 0.89$ (clear water condition) in all the tests, where U_c is the critical value for the inception of sediment motion. The critical shear velocity $U \times c$ for sediments used in the
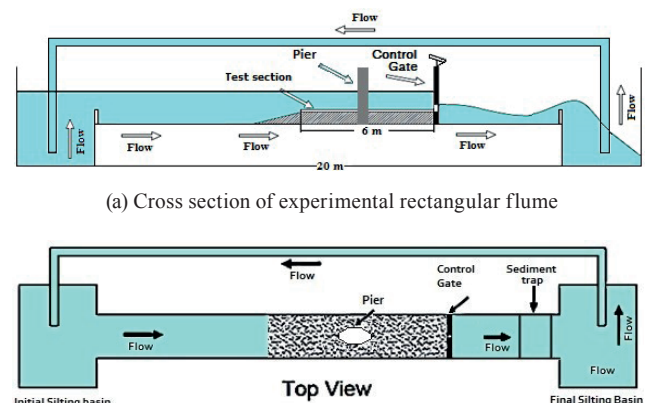

(a) Cross section of experimental rectangular flume

Fig. 1 (b) Top view of experimental rectangular flume

Table 1 Flow parameters for the sand bed

Discharge, (m³/s)	Flow epth, d_f (m)	Median Grain Size, d_{50} (m)	Mean Approach flow Velocity, U (m/s)	Critical Velocity, U_c (m/s)	Critical Shear Velocity, U_c^* (m/s)	Flow ntensity, U/U_c	Critical Shields Parameter	Reynolds Number, Ud_f/v	Froude Number, F_r
0.048	0.15	0.00088	0.32	0.36	0.021	0.89	0.033	47723	0.26

current study is determined using the Shields diagram, as shown in Table 1. The critical velocity U_c in each experiment is calculated using the logarithmic average velocity equation for a rough bed, as follows [30]:

$$\frac{Uc}{U_c^*} = 5.75\log\left(\frac{h}{k_e}\right) + 6,\qquad(1)$$

where h is the flow depth and $k_e = 2d_{50}$ is the equivalent roughness height.

2.4 Pier modification
Present investigation intends to examine an applicable pier modification countermeasure, the octagonal hooked collar. A single octagonal cross-sectional pier having width of 6 cm is considered. Octagonal hooked collar is fitted around the pier at the bed level is explored by varying the hooked collar width H_w and sidewall height H_{wh}. Thus, various combinations considering three different widths ($H_w = 1.5\ W_p$, $2.5\ W_p$, $3.5\ W_p$ cm), four sidewall heights ($H_{wh} = 0.15\ W_p$, $0.3\ W_p$, $0.45\ W_p$, $0.6\ W_p$ cm) at bed level are analyzed. The thickness of hooked collar is maintained as 0.5 cm for all of the experiments. Since, the ratio of channel width B to pier width, B/W_p is 16.6 (see Table 2), no contraction scour or bed degradation is observed over the contracted cross section; this is in good agreement with Ballio et al. [31], who have proposed that contraction scour is negligible for $B/W_p > 10$. Accordingly, it is safe to express that contraction phenomena will not occur in our current study. The details of measuring points of the scour hole and geometric parameters along with the top and cross-sectional view of the pier fitted with the hooked collar are shown in Fig. 2(a, b). Fig. 2(a) shows the measuring points of scour pit and L_2 is location of the maximum scour depth at the pier front, whereas, Fig. 2(b) shows a sketch of a hooked collar and pier arrangement in which H_w is the hooked collar width, H_{wh} is the hooked collar sidewall height and H_{vp} is the hooked collar vertical placement. Here, x, y and z are the coordinates along the streamwise, transverse and bottom-normal to the flow direction, respectively. The origin of the coordinate system (0, 0, 0) is taken at the center of the pier along the centerline of the flume at the level of the undisturbed bed surface.
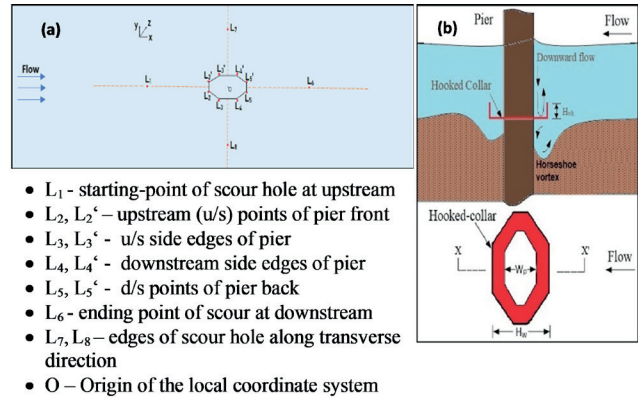

- L₁ - starting-point of scour hole at upstream
- L₂, L₂' – upstream (u/s) points of pier front
- L₃, L₃' - u/s side edges of pier
- L₄, L₄' - downstream side edges of pier
- L₅, L₅' - d/s points of pier back
- L₆ - ending point of scour at downstream
- L₇, L₈ – edges of scour hole along transverse direction
- O – Origin of the local coordinate system

Fig. 2 Schematic diagram of (a) measuring points of scour hole, (b) hooked collar around octagonal pier

2.5 Experimental procedure
Experiments are carried out in two different phases: a) a reference phase and b) an exploratory. In the first phase, a pier without any modification (run 0) and pier with collar Co (run 0') of octagonal shapes are considered. In the second phase, the size, location and sidewall of the hooked collar are varied to explore which of these combinations are more influential in protecting the pier against scour. A total of fourteen experiments are performed in the current study: a) two experiments during the first reference phase and b) twelve experiments for the second exploratory phase. Specifically, for each hooked collar width, four experiments are performed by varying sidewall height at bed level (see Table 2), to determine the best performing combination for the design and implementation of the hooked collar fitted at octagonal piers.

The experimental procedure of all the runs, performed in both phases, is the same. For instance, unprotected octagonal pier is aligned perpendicularly on the sand bed at 10.5 m from the upstream inlet end, wherein the sand bed is compacted, and its surface is levelled with the adjacent concrete bed. At the start of each experimental run, to avoid uncontrolled scour, the sand zone in the working section specifically around the pier is covered with thin metallic plates. Subsequently, the channel is gradually filled with water to allow air entrapped in the sediment to escape. The metallic plates placed in the vicinity of the pier are cautiously lifted, right after the desired discharge and depth of flow are set

out, and the experimental run gets initiated. Interestingly, the scour process occurs differently for protected and unprotected octagonal pier, and the depth of scour is determined after every 12 minutes at the sides and upstream of pier during the first hour (accuracy of +0.1 mm), by utilizing three digital level gauges. Thenceforth, the time gap between measurement readings increased. The outlet segment is at the end of the test section, where the dislodged sand particles, if any, are accumulated.

After completion of each experimental run, water is drained out from the flume heedfully to prevent profile of scour hole from the drawdown flushing. The depth gauge is then used to calculate precisely and carefully the scour holes and scour pattern profiles in the vicinity of the pier. The measuring section of the scour hole profile is selected approximately 1.0 m long along the upstream and downstream with the pier at the center (Fig. 1). The time length of each experimental run is considered as 24 hours, whilst the equilibrium scour depth is reached during this duration [28]. The details of experimental work carried out in the smooth rectangular flume are shown in Fig. 3.

3 Results and discussion
3.1 Temporal evolution
Fig. 4 illustrates the temporal evolution of scour depth at the location of maximum scour depth for pier with octagonal cross section (unprotected) and pier with collared and hooked collar (protected), under the same flow conditions.

Fig. 3 Details of experimental work performed

Here, results are presented only for the protected piers having hooked collar sidewall height 0.45Wp i.e., run 7 to 9 (see Table 2), which are similar to all the other tests. For the unprotected pier, the depth of scour hole initially increases, reaches a peak value and then it approaches asymptotically to a stabilized state. Thus, it can be stated that the increment of scour depth reduces temporally. From the observed data, it may be noticed that almost 72 % of the maximum scour depth is achieved within the first 5 hours of the experimental run.

Table 2 Characteristic control for the governing flow, pier and collar parameters and resulting scour metrics for all of the experimental runs

Run	Pier width W_p (cm)	Flow depth d_f (cm)	B/W_p	d_f/W_p	Hooked collar		H_{wh}/H_w	t_d (hrs)	d_s (cm)	d_s/d_s'	Efficiency E (%)
					Sidewall height H_{wh} (cm)	Width H_w (cm)					
0	6	15	16.7	2.3	-	-	-	24	11.6	-	0
0'	6	15	16.7	2.3	-	-	-	24	6.3	0.54	45.7
1	6	15	16.7	2.3	0.9	9	0.1	24	4.8	0.41	58.6
2	6	15	16.7	2.3	0.9	15	0.06	24	4.1	0.35	64.7
3	6	15	16.7	2.3	0.9	21	0.04	24	3.9	0.34	66.4
4	6	15	16.7	2.3	1.8	9	0.20	24	4.4	0.38	62.1
5	6	15	16.7	2.3	1.8	15	0.12	24	3.6	0.31	69.0
6	6	15	16.7	2.3	1.8	21	0.09	24	3.5	0.30	69.8
7	6	15	16.7	2.3	2.7	9	0.30	24	4.1	0.35	64.7
8	6	15	16.7	2.3	2.7	15	0.18	24	3.1	0.27	73.3
9	6	15	16.7	2.3	2.7	21	0.13	24	3.1	0.27	73.3
10	6	15	16.7	2.3	3.6	9	0.40	24	4.3	0.37	62.9
11	6	15	16.7	2.3	3.6	15	0.24	24	3.5	0.30	69.8
12	6	15	16.7	2.3	3.6	21	0.17	24	3.4	0.29	70.7

d_s = maximum scour depth, d_s' = maximum uncontrolled scour as reference (11.6 cm), t_d = time duration in hours

Moreover, a detailed overview of time variation of pier modifications when applied individually for the cases of the collar and the hooked collar at the octagonal pier, are also examined under the same flow conditions. Interestingly, the octagonal hooked collar showed much more satisfactory results in terms of scour reduction compared to protected collared pier. For both protected piers, the downward flow is weakened, and scouring is initiated relatively slowly with a delay during this phase, whilst the provision of hooked collar sidewalls performed relatively well, effectively weakening the downward flow and formation of a horseshoe vortex.

This is because the hooked collar blocked further the downward movement of water for a greater duration, thereby reducing the downward impact of horseshoe vortex formation at the upstream and scour generation, as shown in Fig. 4.

3.2 Comparison of hooked collar provisions

The performance of the octagonal hooked collar is explored by varying its width and sidewall height at bed level around the octagonal cross-sectional pier. Three different widths (9, 15, and 21 cm) and four sidewall heights (0.9, 1.8, 2.7 and 3.6 cm) are investigated. A total of twelve experiments related to hooked collar are conducted. Fig. 5(a, b) shows a detailed overview of the results, for instance, when the hooked collar is placed at the bed level, three different hooked collar widths and four different sidewall heights are varied. It is observed that with minimum sidewall height (i.e., 0.15 W_p) by varying the hooked collar width from 1.5 W_p to 3.5 W_p, runs 1 to 3, the maximum scour depth at the upstream of the pier reduced impressively
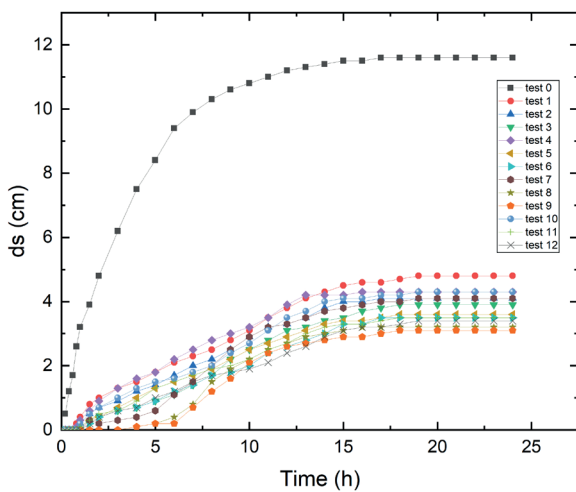

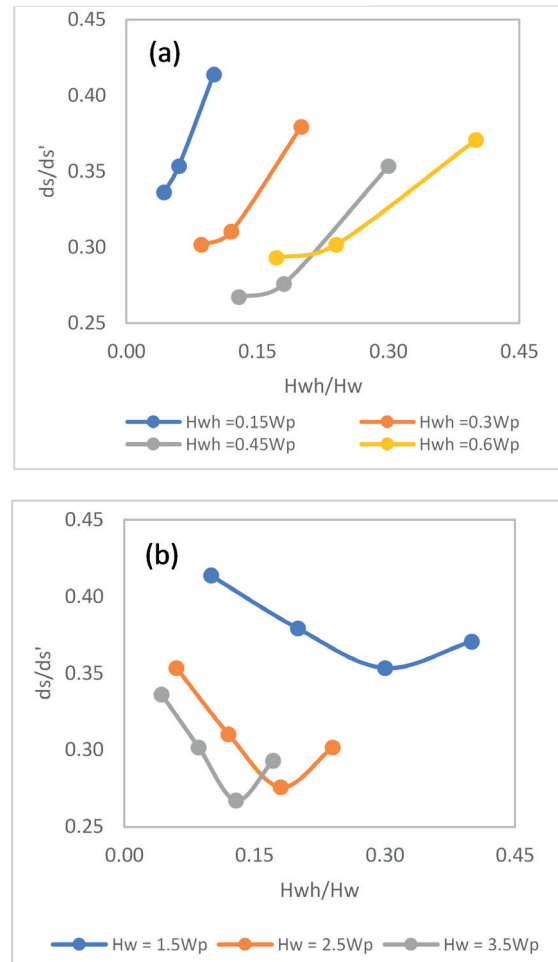**Fig. 4** The scour time history of unprotected (run 0) and protected hooked collar pier

Fig. 5 Results for hooked collar with varying sidewalls height and widths at bed level

for largest hooked collar width. In fact, by testing all other sidewall height by varying hooked collar width, this observation was same. Interestingly, the trend of reducing scour with the increase of hooked collar sidewall height was monitored up to 0.45 W_p, beyond this height the scour depth increasing. From run 9 onward this trend can be seen as well. Probably, the main reason of this increase of the scour depth is that beyond 0.45 W_p, the sidewall height acts as obstruction for the approaching water and therefore downward flow starts, causing vortex formation. Overall, the sidewall height of 0.45 W_p is the most efficient and effective in terms of reducing maximum scour depth. Therefore, the best combination in terms of reducing scour is found when the hooked collar is placed at the bed level having a width of 2.5 W_p and a sidewall height of 0.45 W_p. Although, in some cases, the scour depth reduced with further increase in the hooked collar width, but this reduction is very nominal and might be uneconomical as hooked collar width and side-wall height are increased.

Furthermore, the efficiency of the proposed pier modification countermeasure is calculated in terms of percentage reduction of scour depth E (%) at the upstream base of the pier and is given as follows:

$$E(\%) = \left(d_{up} - d_{hc}\right)/d_{up} \times 100. \qquad (2)$$

In Eq. (2), dup and dhc denote the maximum equilibrium scour depth measured at the unprotected octagonal pier and pier protected with the hooked collar, respectively. From Fig. 6(a, b), it is observed that the maximum percentage reduction of scour depth for the hooked collar provision (run 9) is when it placed at bed level having width of 3 W_p and sidewall height of 0.45 W_p is 73.3 %, when compared to unprotected octagonal pier. Moreover, it is noticed that only ~1 % scour reduction was notices in run 9 compared to run 8. Therefore, it can be concluded that most efficient hooked collar provision is when it placed at bed level having width of 2.5 W_p and sidewall height of 0.45 W_p. Overall, it is noticed that efficiency of

Fig. 6 Efficiency E versus (a) H_w and (b) H_{wh} reached with hooked collar for different widths and sidewall height

hooked collar enhanced as the width and sidewall height of the hooked collar increased. Interestingly, for all hooked collar widths, the sidewall height of 0.45 W_p shows the satisfactory results and reduce the scour significantly. Furthermore, it can be concluded that hooked collar width is effective when width is 2.5 W_p, after that scour reduction is not significant. On the other hand, sidewall height is effective till 0.45 W_p, after that increase in its size results in the enhancement of the scour.

3.3 Scour pattern around pier

The development of various scour patterns around the unprotected and protected octagonal piers is quite interesting to discuss for the various cases examined herein. The pierwith protection has substantially changed the scour patterns locally around the pier. To elucidate the scour trend around pier with and without modification, Fig. 7 demonstrates the scour depth measurements along the streamwise longitudinal direction through location L1–L8 of Fig. 2. Protected pier (hooked collar) with varying hooked collar width, the scoured section length along the streamwise directions is maximum for the run 1 and minimum for run 8.

The reduction in scoured section length in streamwise directions can be noticed with the increase in hooked collar width along with sidewall height of hooked collar pier. This increase is prominent especially in the hooked collar pier when the sidewall was maintained as 0.45 W_p. Moreover, it is observed that the bed slopes in the sand pit, in front side of the pier, for all the profiles of different hooked collar tests are almost the same. Furthermore, location of the main sediment accumulation areas at the downstream, and the general shape of the deformed region, turned up due to the provision of the hooked collar. Hence, it is clearly monitored from these results that the maximum scour depth depends on the specifics of the configuration of the hooked collar.

3.4 Scour depth prediction

The main aim of the derived equation is to provide a tool that can be able to predict accurately the percent reduction in the scour depth around a single bridge pier in the presence of the octagonal hooked collar. Several researchers have developed the predictive equations to compute the scour depth [32, 33]. However, recently Jahangirzadeh et al. [34] proposed a novel predictive equation to determine the scour hole depth around piers protected with simple collar such as rectangular and circular shapes, that couples the theory of turbulence with empirical observations.
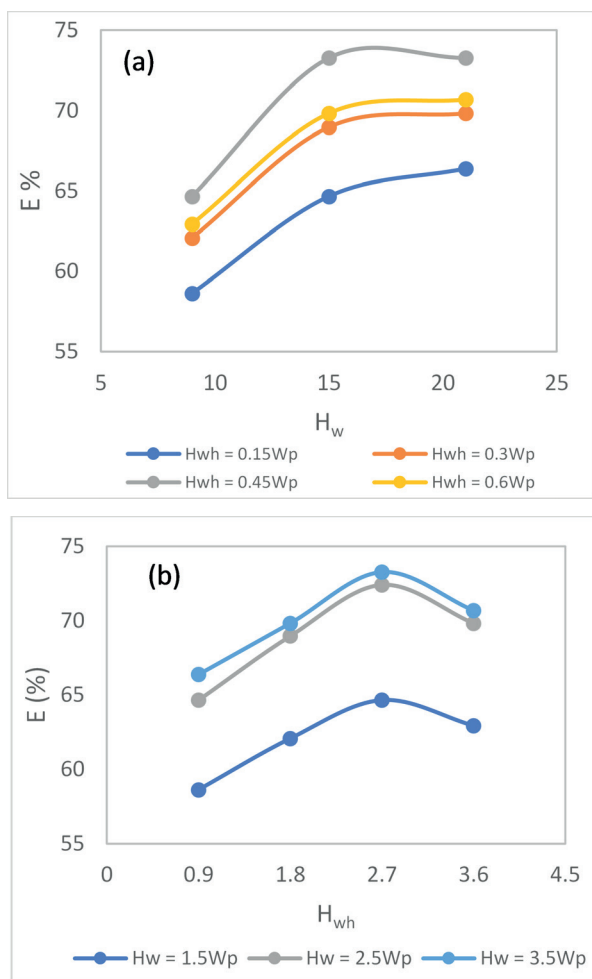
(a) $H_w = 1.5\ W_p$
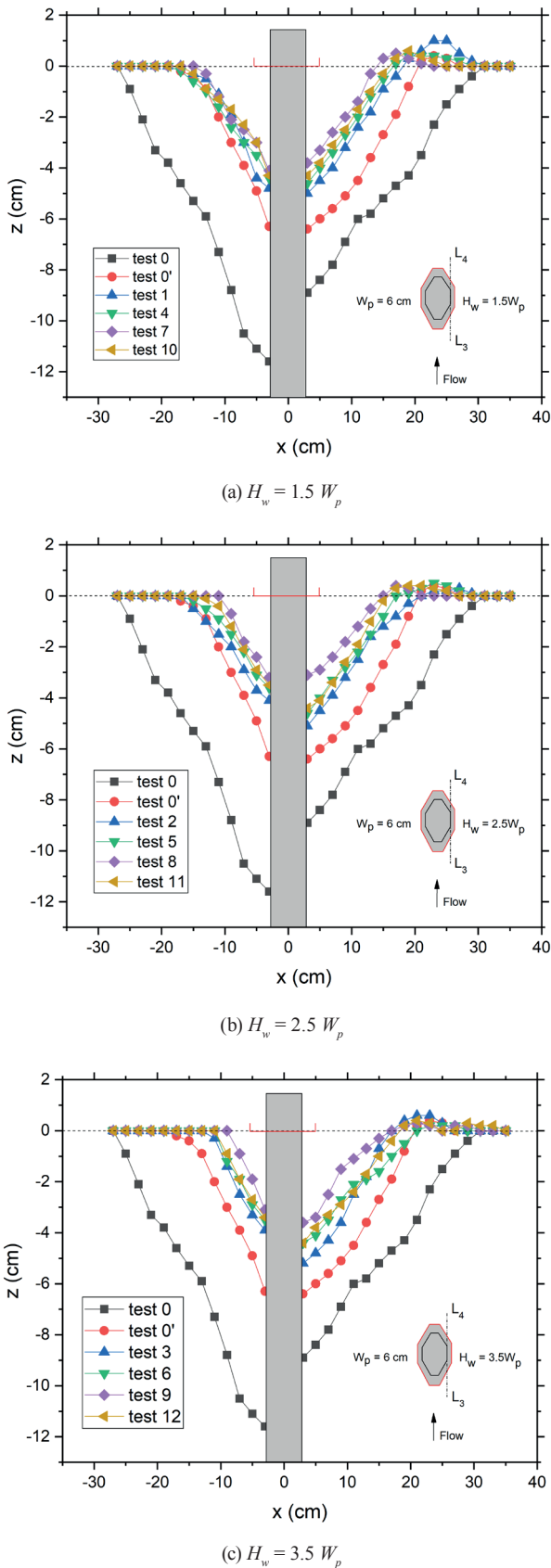

(b) $H_w = 2.5\ W_p$

(c) $H_w = 3.5\ W_p$

Fig. 7 Scour profiles aligned with section L3-L4 for different hooked collar provisions, collared pier and unprotected octagonal pier

Contrarily, research on local scour prediction on efficient pier geometry investigating optimal hooked collar are rather inadequate. It is, therefore, utmost important to drive such a relationship to further enhance the understanding of local scour phenomena around protected hooked collar pier. Thus, the dimensional analysis approach is very significant to find out the most important variables that affect the depth of scour which is the subject of this study.

The scour hole geometry around a protected bridge pier depends on flow conditions (depth and velocity), fluid parameters (density and viscosity), sediment properties (grain size, specific gravity), channel geometry (hydraulic radius, bed slope, and width), pier dimensions and shape, protective measures (pier modification and bed armoring), characteristics of collar (shape, width, and its elevation from bed, hooked collar placement, hooked collar elevation, hooked collar width), hence the scour depth would be as function of the various following parameter:

$$d_s = f\left(B, W_p, d_f, U, d_{50}, \rho, \rho_s, U_c, \upsilon, t_d, A_t, g, H_w, H_{wh}\right) \tag{3}$$

$$f\left(\frac{B}{W_p}, \frac{d_s}{W_p}, \frac{U}{U_c}, \frac{\rho_s}{\rho}, \frac{d_f}{W_p}, \frac{d_{50}}{W_p}, \frac{\upsilon}{U.W_p}, \frac{H_w}{W_p}, \frac{H_{wh}}{W_p}, \frac{A_h}{A_t}, \frac{g d_f}{U^2}\right) = 0,$$

where B is channel width, W_p is width of pier, U_c critical velocity, H is the overall hook collar configuration, H_{wh} is hooked collar side wall height, H_w is the hooked collar width, ρ is fluid density, ρ_s is the sediment particles density, d_f is the depth of flow, U is the flow velocity, U_c is the critical velocity, d_{50} is mean sediment size, υ is kinematic viscosity of fluid, t_d is time duration A_t is the total area of hooked collar and pier, and d_s is the scour depth.

Given that $\rho, \rho_s, B, d_s, W_p, d_{50}$, and d_f are usually constant in all models, the parameters U/U_c, $\upsilon/U.W_p$, $g.d_f/U^2$ which are indicating flow intensity, viscosity force effects and inverse Froude number, respectively and are constant in this study which are equal to 0.89, 47723 and 0.26, respectively. Hence, their effect can be neglected and finally Eq. (4) may be simplified as:

$$\frac{d_s}{W_p} = \frac{H_w}{W_p} \cdot \frac{A_h}{A_t} \cdot \frac{H_{wh}}{W_p}, \tag{4}$$

$$r_{ds}\% = C_1 . C_{\frac{A_h}{A_t}} . C_{\frac{H_w}{W_p}} . C_{\frac{H_{wh}}{W_p}}, \tag{5}$$

where C_1 is constant value, C_{A_h/A_t} is function of A_h/A_t, C_{H_w/W_p} is function of H_w/W_p, C_{H_{wh}/W_p} is function of H_{wh}/W_p. Here, A_h is net area of the hooked collar, A_t is total area of the hooked collar and pier, $r_{ds}\%$ is percentage reduction in the
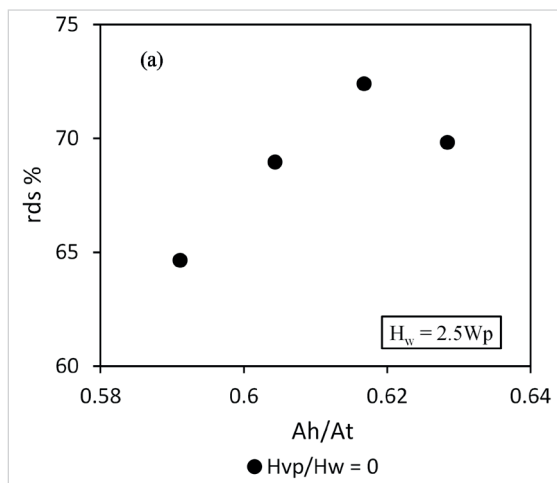
scour depth around the pier. Fig. 8(a, b) shows the non-dimensional parameters effect of A_h/A_t, H_{vp}/W_p and H_{wh}/W_p on percentage scour reduction of hooked collar.

Moreover, the Eqs. (6) to (8) are based on dimensional parameter $\frac{d_s}{Wp} = \frac{Hw}{Wp}$ and $\frac{H_{wh}}{Wp}$ for octagonal hooked collar by neglecting the constant parameters and dimensional analysis of above discussed parameter using experimental parameters. Hence, the following equations are derived for each parameter:
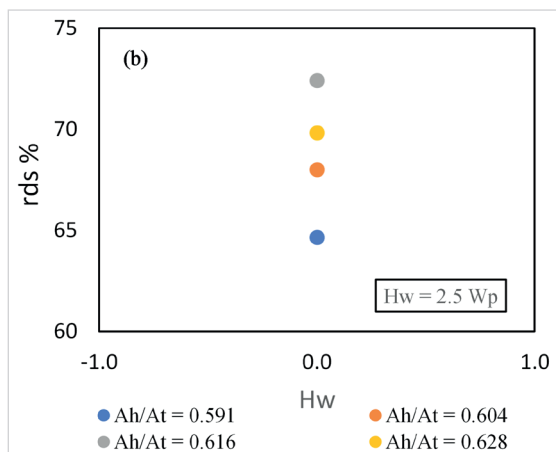
$$C_{\frac{Ah}{At}} = e^{x1\frac{Ah}{At}}, \tag{6}$$

$$C_{\frac{Hw}{Wp}} = e^{x2\frac{H_w}{Wp}}, \tag{7}$$

$$C_{\frac{Hwh}{Wp}} = e^{x3\frac{H_{wh}}{Wp}}. \tag{8}$$

In these equations, C is a constant value and $x1$, $x2$ and $x3$ are coefficient determined by the IBM SPSS Nonlinear Regression Analysis, which gives the following values for coefficient by using the experimental data for octagonal hooked collar:

$$C = 0.68, \quad x1 = 2.56, \quad x2 = -1.42, \quad x3 = 0.98. \tag{9}$$

The final Eq. (10) to predict the reduction of the scour depth around an octagonal pier using an octagonal hooked collar, as follows:

$$\gamma_{ds}\% = Ce^{x1\frac{Ah}{At}} e^{x3\frac{H_w}{Wp}} e^{x3\frac{H_{wh}}{Wp}}. \tag{10}$$

Fig. 9 demonstrates the relation of measured and predicted values of scour depth reduction around the octagonal hooked collar fitted at octagonal pier. It is noticeable that the measured values have a satisfactory agreement with the predicted values.

3.5 Volume of scour hole

It is of utmost importance to determine a relation between maximum scour depth and volume of scour hole. Therefore, firstly detail results of maximum scour depth are analyzed. The variation of maximum scour depth of unprotected pier U_p, collared pier C_p, and hooked collar with different combinations of hooked collar width and side wall height are shown in Fig. 10. The results indicate that a significant reduction in final scour depth is observed by applying protection around octagonal bridge pier. Interestingly, this reduction is more prominent for the case when pier protected with hooked collar compared to protected collared pier. Furthermore, the percentage scour reduction for the case of collared pier is 45.7 % compared to unprotected pier. Similarly, it is observed that the
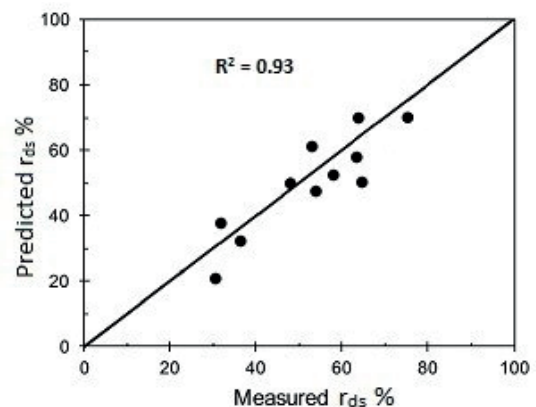

(a)

(b)

Fig. 8 Effect of non-dimensional parameters of a hooked collar on percentage reduction (a) A_h/A_t (b) H_w

Fig. 9 Comparison of measured and predicted values for an octagonal hooked collar
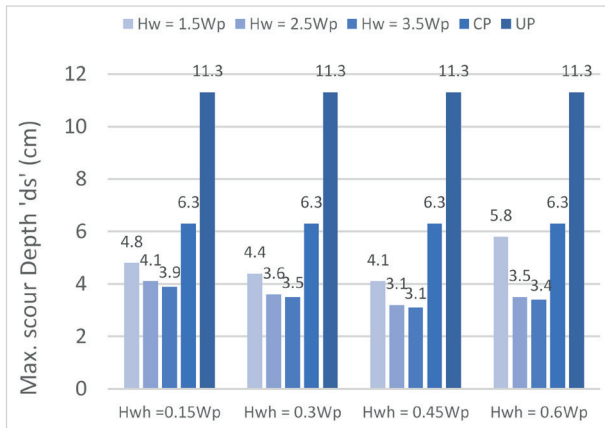
Fig. 10 Comparison of maximum scour depth for protected and unprotected pier

percentage reduction of maximum scour depth is 73.3 % and 26.7 % compared to unprotected pier and protected collared pier, respectively.

Secondly, the scour hole volume V_s, which is indicative of the extent of soil support loss to the pier base, is computed for each experimental run from the scour contour map by applying Simpson's 3/8th rule. The V_s is noticed to increase for the scenario when hooked collar width for all side wall heights around the octagonal pier is smallest to the scenario when hooked collar width against all sidewall height around the octagonal pier is largest. However, for the best combination of H_w and H_{wh} the value of V_s is observed to be the minimum at 0.0013 m³. This value indicates an 92.9 % decrease in V_s for a decrease of 73.3 % in maximum scour depth d_s. Table 3 presents the geometric parameters of scour for pier with and without modification applied around octagonal pier.

As the streamwise extent of scour reduced with ds, the scour hole volume, V_s, is appeared to reduce with the depth of scour. The specific nature of this relation between V_s and ds is establish by fitting an equation to the data, as demonstrated in Fig. 11.

The volume of scour is observed to reduce quadratically with scour depth, following the equation $V_s = 1.4\,d_s^{\,2}$, where V_s and ds are in cubic meters and centimeters, respectively. This relation has a similar form to the one suggested by Ebrahimi et al. [35], i.e., $V_s = 2.2\,d_s^{\,2}$, where scour depth and volume are in cubic centimeters and meters, respectively, for scour at a sharp nose pier in the presence of debris. This equation may be helpful for the planning of the post flood remedial activities [e.g, 36], where just most often maximum depth of scour is initially analyzed.
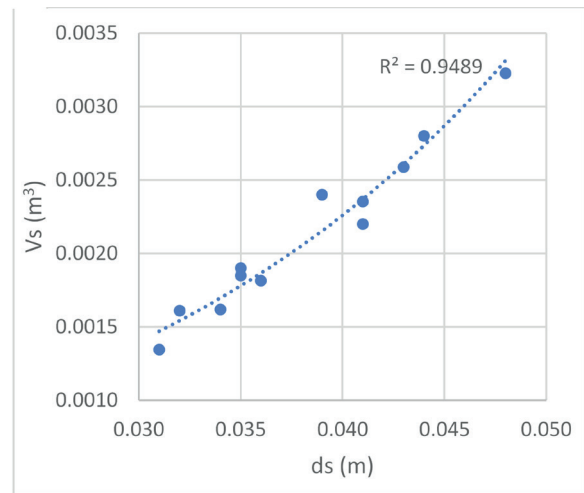

Fig. 11 Volume of scour hole calculated around protected hooked collar bridge pier. Dash curve is a quadratic curve ($V_s = 1.4\,d_s^{\,2}$) fitted over the data

Table 3 Scour geometric parameters for unprotected and protected pier around octagonal pier

Run	Pier shape	Modification	Pier width W_p (cm)	Mean Sediment size d_{50} (mm)	Max. scour depth d_s (cm)	Percent Scour depth reduction E_{ds} (%)	Volume of scour hole V_s (m³)	Percent Scour volume reduction E_{vs} (%)
0	O	-	6	0.88	0.116	-	0.0188	0.0
0'	O	Co	6	0.88	0.063	45.7	0.0056	70.5
1	O	H	6	0.88	0.048	58.6	0.0032	82.9
2	O	H	6	0.88	0.041	64.7	0.0022	88.3
3	O	H	6	0.88	0.039	66.4	0.0024	87.3
4	O	H	6	0.88	0.044	62.1	0.0028	85.1
5	O	H	6	0.88	0.036	69.0	0.0018	90.4
6	O	H	6	0.88	0.035	69.8	0.0019	90.2
7	O	H	6	0.88	0.041	64.7	0.0024	87.5
8	O	H	6	0.88	0.032	73.3	0.0013	92.9
9	O	H	6	0.88	0.031	73.3	0.0013	92.9
10	O	H	6	0.88	0.043	62.9	0.0026	86.3
11	O	H	6	0.88	0.035	69.8	0.0019	89.9
12	O	H	6	0.88	0.034	70.7	0.0016	91.4

4 Scour maps of unprotected and protected pier

The contour maps of bed elevations at the equilibrium state of scour for unprotected, protected collar and best performing protected hooked collar (run 8) are shown in Figs. 12(a–c) for a given discharge of 0.048 m³/s. It is observed that for pier without any modification scour is maximum at the upstream front edges and also more prominent compared to the protected collared pier, whilst the scour at the upstream side edges in protected collared pier is larger both in depth and extent compared to the protected hooked collar pier (run 8). Furthermore, for the protected hooked collar pier (run 8), the scour is significantly reduced at the upstream, with little scour on the pier front.

Moreover, comparing across the pier with and without modification the deepest scour observed close to the leading edges of the pier in all cases i.e., at L_2-L_3, whereas it is deepest at the upstream two side corners for the unprotected pier. This indicates that the scour for the unprotected pier is relatively more influenced by streaming around the pier, whilst for the other two protected piers scour is mostly driven at the leading edge may be due to the presence of the horseshoe vortex which are in fact, weakest for the hooked collar pier.

5 Conclusions

This experimental investigation intended at assessing the most effective provision of octagonal hooked collar around octagonal pier in terms of decreasing scour depth and also the potential of hooked collar provision to reducing the erosive power of flow acting on the riverbed in comparison with unprotected and protect collared pier. The main conclusions drawn from this work are as follows.

1. By increasing sidewall height after 0.45 W_p results in greater scour hole. Likewise, increasing the hooked collar width afterwards 2.5 W_p is not effective and economical because the reduction in scour depth is not observed.

2. It is concluded that octagonal hooked collar having width of 2.5 W_p and side wall height of 0.45 W_p performs best in protecting pier against local scour. As compared to octagonal pier without any modification, the scour reduction percentage for the best hooked collar provision around octagonal pier is 73.3 %.

3. We recommended an optimized hooked collar as the most effective and efficient pier modification countermeasure around octagonal cross-sectional pier.

4. Since the main goal of the experiments is to support the planning of bridge piers against local scouring, therefore, the current reduced scale experiments may apply to prototype scale.
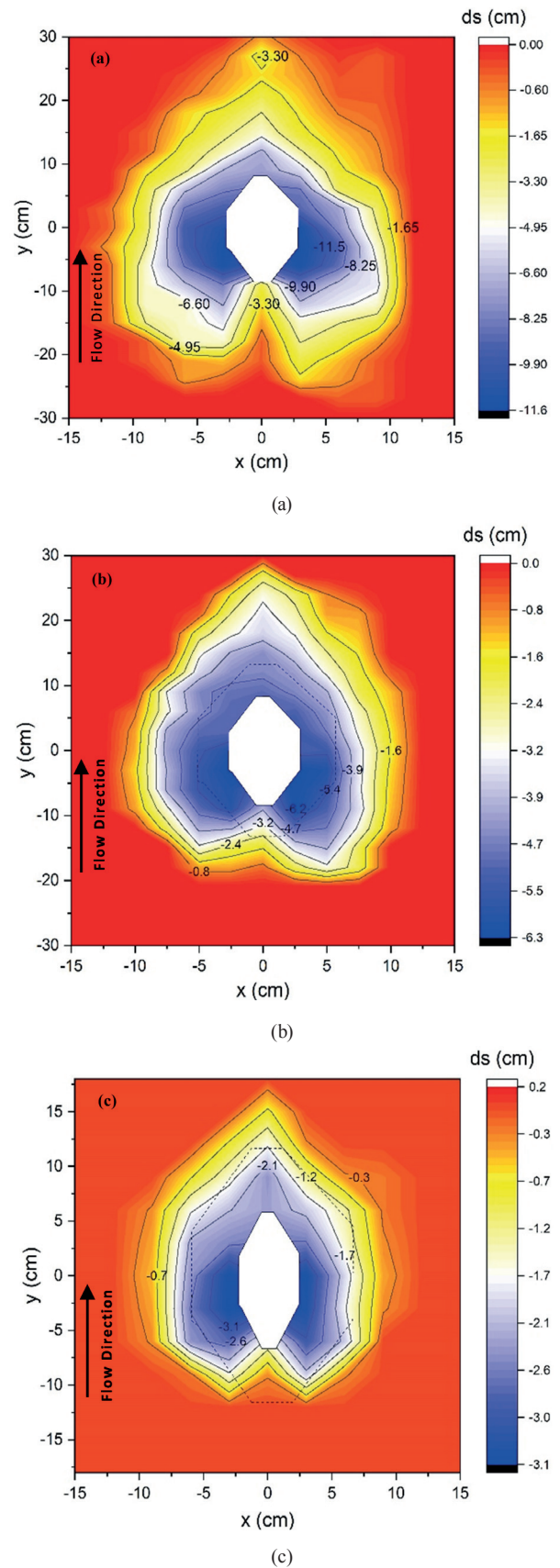

(a)

(b)

(c)

Fig. 12 Equilibrium scour hole profile around unprotected and protected pier (a) unprotected octagonal pier (b) collared pier and (c) hooked collar at bed level with 0.45W_p side walls height and 2.5W_p hooked collar width

5. Considering the obtained experimental data, a new equation is proposed for predicting the hooked collar provision on the percent scour reduction.

6. The scour hole volume increased quadratically with maximum scour depth measured after 24 hours. The developed equation would be useful in determining the exact volume of material required to fill the scour holes in post flood remedial field works in which only maximum scour depth is measured.

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