A laboratory study of the effect of asymmetric-lattice collar shape and placement on scour depth and flow pattern around the bridge pier

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ABSTRACT

In this study, the effect of collar shape and its alignment on reducing scour depth in the front part of the structure, with the pier under clear water conditions, was investigated to determine changes in the flow pattern around the structure. The collars were examined in two asymmetrical shapes with dimensions of \((3 \times 4)\) and \((3 \times 6)\) at three levels of installation relative to the bed: bed level, 1 and 2 cm above the bed. The results revealed that the presence of the collar not only reduced the ultimate scouring depth but also delayed the formation of the scouring hole. This impact was observed to be greater as the size of the collar increased. In addition, reducing the alignment of the collars can lead to better performance of the collar and its efficiency in the cost of the design. Therefore, collars installed on the bed surface indicated good performance in controlling scour. On the other hand, once the flow characteristics around the bridge pier with and without collar were examined, it was determined that affecting the downstream flow reduces the strength of the vortices and changes the reciprocating behavior and the displacement of the vortices.

Key words: asymmetric collar, clear water, flow pattern, scour

HIGHLIGHTS

\begin{itemize}
  \item Investigate effect on different type of asymmetric-lattice collar shape in reducing local scour around the bridge pier in different flow conditions.
  \item Compare the position of collar on bridge pier in their performance.
  \item Check condition flow around the bridge pier with and without collar.
\end{itemize}

SYMBOLS

\begin{tabular}{ll}
\texttt{d_s} & Scour depth (m) \\
\texttt{y} & Flow depth (m) \\
\texttt{B} & Canal width (m) \\
\texttt{D} & Bridge pier diameter (m) \\
\texttt{d_{50}} & Bed sediments average diameter (m) \\
\texttt{V} & Flow velocity (m/s) \\
\texttt{V_c} & Critical velocity of the flow (m/s) \\
\texttt{g} & Acceleration due to gravity (m/s\textsuperscript{2}) \\
\texttt{\rho} & Volume unit mass (kg/m\textsuperscript{3}) \\
\texttt{\rho_s} & Sediments volume unit mass (kg/m\textsuperscript{3}) \\
\texttt{\vartheta} & Fluid kinematic viscosity (m\textsuperscript{2}/s) \\
\texttt{t} & Time (t) \\
\texttt{C_D} & Shape coefficient of the pier (-) \\
\texttt{\sigma_s} & Standard deviation of the sediment particles (-) \\
\texttt{B_C} & Large diameter of the collar (m) \\
\texttt{L_C} & Small diameter of the collar (m) \\
\texttt{t_C} & Thickness of the collar (m) \\
\texttt{Z_C} & Level of the collar (-) \\
\texttt{\varphi_C} & Shape of the collar (-) \\
\texttt{\alpha} & Netted collar (-)
\end{tabular}

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INTRODUCTION

The reduction of scouring is an inevitable affair for preventing the scour around hydraulic structures in the path of watercourses (Pandey et al. 2021). Local scouring is caused by structures in the path of water flow on an erodible bed. Built structures can apply additional erosive forces on the bed around the structure. As a result, sedimentation and erosion rates increase locally around these structures, leading to cavities around these barriers (Foti & Sabia 2011; MacBroom 2012). In this regard, the formation of scouring cavities around the piers and supports of the bridge, which takes place due to non-observance of hydraulic and river engineering issues in the designs, is one of the main causes of the destruction of bridges (Suib et al. 2006). Scour is one of the highly important problems for river as well as for piers of bridge. Bridges are the vital structure which must be designed to prevent failure against scour effect. Scour hole is deleterious effect on pier without warning for the failure of bridge (Darshan et al. 2020). In addition to undermining the bridge foundation and changing the shape and form of the bed, these cavities affect the life and ecosystem of the rivers (Singh et al. 2019). Therefore, controlling the conditions governing real systems is usually difficult, and measuring the governing parameters involves great complexity. Thus, studying this phenomenon is important from economic and environmental aspects (Ministry of Power 2012). It is, therefore, necessary to consider hydraulic criteria in design studies during bridge construction programs. Nowadays, with the advent of modern flow measuring devices such as ADV or PIV, studies have been conducted on the effect of bridge piers and support on the flow structure (Wang et al. 2008). The importance of these measurements is that we can investigate the effect of different causes on the flow structure around the piers and supports of bridges through the development of these studies. Ettema et al. (2017) showed that further research concerning the field in which water flows around the pier and bridge supports could be useful in estimating scour depth. Therefore, in the continuation of reviewing the present scouring experiments, the effect of parameters on the amount of scouring around the pier and the flow structure around it has been investigated. Placing the bridge pier in the flow path, the simple and uniform pattern that reaches the pier undergoes drastic and complex changes. Hence, the vertical current formed at the bridge’s pier is divided into ascending and descending sections. The surface wave formed on the surface of the water in front of the pier is caused by the movement of the rising current towards the surface of the water. The downflow on the surface of the sedimentary bed causes the formation of a scouring hole in the front of the bridge pier, which eventually creates a small scouring hole around it. Horseshoe vortex is a vortex-shaped system created by the rotation of a stream inside a hole. In addition, the separation of the approaching current from the sides of the bridge creates wake vortices behind the pier. The simultaneous effect of these two parameters increases the scouring rate and the potential for sediment transfer downwards. Protection effect of the collar on the bridge pier reduces the power of the downflow and the horseshoe vortices. Thus, the scouring rate is lower than the initial rate around the pier (Figure 1) (Guo et al. 2012). Muzzammil & Gangadhariah (2003) measured the strength, direction, and amplitude of horseshoe vortices around the pier. They concluded that during scouring, the amplitude of horseshoe vortices initially increases to a maximum and then takes a decreasing course afterward. When the collar is installed on the pier to protect against scouring, the downflow is deflected from the bed as soon as it hits the collar, and scouring is prevented (Khozeymeh Nezhad et al. 2012).

Hong et al. (2015) measured lines with the same velocity, the three-dimensional shape of velocities, and turbulence values by the Acoustic Doppler Velocimeter (ADV). They showed that the contractile flow around the abutment and the local turbulent structures near the downward part of the pier are important features of the flow field, which caused the maximum depth near the abutment. Most studies conducted on scouring have focused on the final depth of scouring and methods to reduce it (Zarrati et al. 2004; Ghorbani & Kells 2008; Heidarpour et al. 2010). On the other hand, the research studies on the turbulent and surface flow patterns (Dey & Nath 2010; Tafarojnoruz et al. 2010; Izadinia et al. 2013) have been conducted focusing only on a single cylindrical pier. Dargahi (1990) investigated the mechanism of scouring around the bridge pier and how the collar affects the performance of downflows and ultimately reducing the scour of the bridge pier. Dargahi (1990) used two circular and oval (asymmetrical) collars, and he chose the position of the collars from the bed \( y_0 = 0.25, 0.05, 0.015, 0.05 \). His experiments have been carried out in the conditions of \( d_{50} = 0.36 \text{ mm}, D = 0.15 \text{ m}, y = 0.2 \text{ m}, V = 0.26 \text{ m/s}, V/V_c = 0.85 \). He observed a decrease in scouring velocity in the case with collar and the greatest decrease in the depth of the hole in the oval (asymmetric) collar under the bed. On the other hand, the maximum reduction in the depth of the hole, in this case, was 50 and 70% upstream and downstream of the bridge pier, respectively. He was able to reduce the scouring depth up to 40% with a circular collar. Memar et al. (2020) investigated the level of collar installation from the sedimentary bed surface in reducing scour and the impact of the intensity of flow on this phenomenon. By reducing the flow intensity from 0.95 to 0/9(V/V_c), the maximum depth in the case with collars...
decreases by an average of 20 to 70%. He also found that installing the collar below the surface of the sediment bed compared to installing it 1 cm above the bed provides 5% protection of the scour hole. Pandey et al. (2020) investigated the effectiveness of a symmetrical collar on reducing scour holes around the pier of a cylindrical bridge. The results of their study showed that the performance of using the collar reduces the maximum scour around the pier compared to the case without the collar by about 60%.

In addition, their findings revealed that the effectiveness of the collar decreases as the level of crown placement on the bridge pier relative to the sedimentary bed surface increases. Bestawy et al. (2020) examined the performance of different shapes of circular (jagged) collars. The results showed that crowns have a significant effect on reducing scour by inhibiting the destructive downflows around the pier. They stated that the Sigma_Slot collar showed the most effective performance by reducing the amount of scouring the upstream and downstream by 59.3% and 52.8%, respectively. Pandey et al. (2018) The experimental results of time average velocity components measured around circular pier models during transient scour stage by using ADV are shown for flow pattern and turbulence. Conditions in a model of gravel bed stream with four circular pier models of diameter 6.6, 8.4, 11.5 and 13.5 cm were used for this study. Also, they investigated scour hole at 0° and 180° plane are shown, in that case study, at 0° 61% larger than that for smallest diameter pier model and 180° planes are also presented around each pier. Bakhshpuri & Yahyaei (2016) evaluated the performance of the collar in reducing the scour depth of the pier in cylindrical bridges. Circular and square-shaped collars with dimensions of one, two, and three times greater than the pier diameter were examined in a channel with dimensions of 6 meters in length and a width of 0.7 meters. Based on the above studies, it is inferred that installing the collar at lower levels and larger dimensions of the collar has the greatest effect on reducing the scour depth. Wang et al. (2019) river sand with a median particle size of 0.324 mm was selected and used as the sediment. According to their experimental results, it can be concluded that: the application of an anti-scour collar alleviates the local scour at the pier; and the protection decreases with an increase in the collar installation height, but increases with an increase in the collar external diameter and the protection range. Jalili & Ghomeshi (2014) investigated the effect of lattice collars on scouring the foundations of cubic and cylindrical bridges with side lengths and diameters equal to 4 cm. Experiments were conducted using 3 Froude Numbers of 0.19, 0.16, and 0.13 under clear water conditions. To simulate the collar, square Plexiglas plates with a side length of 3B and a circle with a diameter of 3 D were used. In this study, the performance of four simple collars, and 15, 30, and 40% lattice collars for scour hole changes were evaluated. At the Froude Number of 0.19 for the 30% lattice collar with cubic pier, the highest efficiency was 47% in reducing scouring. In contrast, for the cylindrical pier at the same Froude Number, the 40% lattice collar has the highest efficiency of 54% in reducing scouring compared with other lattice collars. Gogus & Dogan (2010) investigated the effect of collar installation level above the bed surface, level with the bed and below the bed on reducing scouring of bridge piers, based on the results of 97 experiments performed in a canal with 1.5 meters in width, 30 meters in length and 1 meter in height.

**Figure 1** | Flow pattern and scour hole around the bridge pier (a) Protected with collar, (b) Without collar (without scale).
and a slope of 0.001. Different collar sizes were examined at +1 and +2 levels above the bed surface and level with the bed and −1 and −2 below the bed. The results showed that increasing collar width below the bed surface reduces collar efficiency in resisting scouring by 30% compared to the control. Increasing the installation level leads to increased scouring holes. Since the fact that the shape of the bridge pier has an effect on the amount of scouring, and that the scour pattern is, based on scientific literature, definitely affected by the three-dimensional field of the flow pattern around the pier, thus, in this study, the scour hole and patterns of flow field have been investigated using different shapes of asymmetric lattice collars by placing them in different levels on the pier of a cylindrical bridge to control or reduce scouring. The role of collar affect on scour depth investigation in reducing scour’s hole around bridge pier that is the main purpose of the present manuscript. So, one of the objectives studied in this case would be position of collar above sediment’s bed, also the role of asymmetric-lattice collar shape examine how decrease scour around cylindrical pier. So far, the effect of asymmetric-lattice collar shape has not been tested simultaneously. The motivation for manuscript find the best collar shape to debilitate vortices, Also, performance of collar shape had examined for maximum scour depth around the bridge pier.

MATERIALS AND METHODS

Laboratory facilities and experimental procedures
To conduct the scour experiments, a rectangular canal with a glass wall was used in the laboratory of physical and hydraulic models of the Faculty of Water & environmental Engineering of the Shahid Chamran University of Ahvaz. The length of the flume was 6 m, and its width and height were 0.72 and 0.6 m, respectively. The slope of the laboratory canal was adjustable, and it was set to a slope close to zero for the experiments. The canal contains an inlet pond at the beginning and the end. To measure the flow rate, a magnetic ultrasonic flow meter with an accuracy of 0.001 liters per second was used, which was installed at the beginning of the canal. The required water is pumped from the main tank to the canal using a pump, and a joint netted mesh is used to eliminate the turbulence of the inlet current. A sliding valve is designed to control and regulate the water level at the end of the canal, through which water can be returned to the tank, drained, and rotated in the system. Figure 2(a) and 2(b) shows an illustration of the flume and the laboratory equipment.

View of realistic image of laboratory flume

Dimensional analysis
The parameters affecting the scouring phenomenon around the pier of the bridge equipped with a collar are as follows:

\[ f_1(d_s, y, B, D, d_{50}, V, V_c, g, \theta, \rho, t, C_D, \sigma_B, B_C, L_C, t_C, Z_C, \phi_C, \alpha) = 0 \]
where $d_s$ is the scour depth, $y$ is the flow depth, $B$ is the canal width, $D$ is the bridge pier diameter, $d_{50}$ is the bed sediments average diameter, $V$ is the flow velocity, $V_c$ is the critical velocity of the flow. In addition, $g$ is the gravity acceleration, $\rho$ is the volume unit mass, $\rho_s$ is the sediments volume unit mass, $\theta$ is the fluid kinematic viscosity, $t$ is the time, $C_D$ is the shape coefficient of the pier, $\alpha$ is the standard deviation of the sediment particles. Moreover, $B_C$ is the large diameter of the collar, $L_C$ is the small diameter of the collar, $t_C$ is the thickness of the collar, $Z_C$ is the setting level of the collar from the bed surface, $\varphi_C$ is the shape of the collar, and $\alpha$ is the netted collar. By considering $y, g$ and $\rho$ as the iterative variables and applying Buckingham’s theory, Equation (1) was investigated after eliminating the fixed parameters of the experiment, based on the theory stated by Chow (1989) to ensure the turbulent flow in the canal. As a result, Equation (1) will be turned into Equation (2) as the following:

$$\frac{d_s}{D} = f_2\left( F_r, \alpha, \frac{Z_C}{D}, \frac{B_C}{D} \right)$$

Figure 2 | An illustration of laboratory equipment and canals.

To be able to apply the results of the experiments to a real model, it is necessary that the effects of different parameters on the scouring process be eliminated. In this way, the wall effect (blockage effect) and the effects of the flow depth (shallowness effect), the sediment particles size, and the viscosity will be eliminated. Therefore, to achieve the maximum scouring depth of the conditions of crystal water, the effects of dimensionless parameters mentioned in Table 1, studied by the previous researchers, should be applied in conducting experiments in this study. Considering the following cases, to determine the velocity of the movement threshold, different depths were measured by adjusting the maximum flow in the laboratory channel.
on the sediment bed without the presence of the pier so that the movement or non-movement of the bed sediments can be observed by using the unequipped eye. Then, its correctness was obtained from the diagram using Neill relation (1973): 
\[
V_c = 31.08K_u\theta_c^{1/2}y^{1/6}d_{50}^{1/3}
\]
where \( V_c \) is the critical velocity (m/s), \( y \) is the flow depth (m), \( d_{50} \) is the average particle size (m), \( K_u = 1 \) is the constant-coefficient, and \( \theta_c \) is the Shields parameter. Finally, \( V_c = 0.439\)m/s was calculated for the experiments.

To conduct the experiments, a cylindrical wooden pier with a diameter of 40 mm and a height of 50 cm was used to prevent the pier from sinking. To ensure the installation of the collar at the desired height from the bed surface, the pier was calibrated using a laser cutting machine with an accuracy of 1 mm. By examining the scour on the collars, Dargahi found that the large thickness of the collar creates a barrier to the flow and increases the scouring (Dargahi 1990). Therefore, the collars were prepared in Plexiglas plates with a thickness of 2 mm and were attached to the pier using silicone glue. Considering the results of many studies conducted in simple collars, Singh et al. (2009) proposed that the collars symmetric with 1.5\( D \), 2\( D \), 2.5\( D \), 3\( D \) could be used for the cylindrical piers. Therefore, asymmetric collars with protrusions three times larger than the pier diameter towards the downstream of the canal, which have the greatest effect on the scour reduction, were experimented with. Thus, to investigate the effect of the asymmetric netted collar in this study, all collars were prepared from elliptical plates with (3 \times 4) and (3 \times 6) dimensions in three percent of 15, 30, and 40% netted openings, in two models of 4 and 6 times larger than pier diameter in the longitudinal direction to weaken the downward currents around the pier (Figure 3). In the current study, the experiments were conducted for three different heights: on the surface of the sediment bed \( Z_c = 0 \), 1 cm above the bed \( Z_c = 0.25D \), and 2 cm above the bed \( Z_c = 0.5D \) and exposed to three different flow rates including 35, 30 and 25 liters per second, and Froud numbers \( (F_r = V/\sqrt{gy}) \) equal with 0.37, 0.32 and 0.26, respectively.

At a distance of 2 meters from the beginning of the canal, a box equal to the width of the canal with a length of about 2 meters and a height of 15 cm was considered. The box was filled with a uniform sediment sample with an average diameter of 0.73 mm so that after filling, it became parallel with the channel bed level. On the other hand, to achieve the depth of scouring equilibrium around the bridge pier, it is necessary to perform the experiments over a relatively long time so that changes in scour depth are insignificant over time, and the slope of the scour time development diagram is inclined towards zero (Cardoso & Bettess 1999). To determine the equilibrium time of the experiments, a 24-hour experiment with a relative speed \( V/V_c = 0.94 \) was performed. During the experiments, changes in the sediment bed surface were controlled. Equilibrium time (8 hours) was obtained based on the measurements according to the initial level and scouring cavity formation. Then, at the beginning of each experiment, first, the canal will be filled at a low-flow rate; this is to prevent erosion caused by the laminar flow at the beginning of the experiment. The rate of the water flow will be increased slowly to reach the desired flow rate. The experiments were performed at a constant current depth of 0.12 m, and after the end of the experiment, water slowly flows out of the canal. Finally, the maximum scouring depth and the sedimentation pattern created around the bridge pier were collected using a laser meter.

Furthermore, to the shape and the geometric dimensions of the scour cavity do not change during the velocity data collection, a very thin layer was sprayed on the bed using the cement and rock powder, which was combined with a 1:3 aspect ratio

| Table 1 | Conditions of the conducted experiments |
|---------|----------------------------------------|
| Suggested by | Melville & Chiew (1999) | Melville & Sutherland (1998) | Dey et al. (1995) | Breusers & Raudkivi (1991) | Melville & Chiew (1999) |
| **Scope of dimensionless parameter theory** | \( V/V_c = 0.3 - 1 \) | \( y/D \geq 2.6 \) | \( \sigma_\rho < 1.4 \) | \( D/d_{50} < 120 \) | \( D/B \leq 0.1 \) |
| **Impact** | Obsverance of the maximum shear stress in the conditions of crystal water | Elimination of the effect of flow depth on the positional scouring | Elimination of the effect of non-uniformity of the bed sediments | Elimination of the effect of sediment size on the positional scouring | Elimination of the wall effect on the positional scouring |
| **Evaluated in the current study** | 0.94-0.81-0.67 | 3 | 1.22 | 54.8 | 0.05 |
for the bed to be stabilized. Velocity data were collected using an ADV velocity meter at 200 Hz (Figure 4(a)). To study the flow pattern, it is necessary to measure and collect data around the pier; therefore, a specific network was considered around it according to Figure 4(b). Furthermore, three-dimensional velocity components were removed from the initial sediment bed of the canal at depths of 5, 6, 8, and 10 cm. At each point, more than 500 continuous speeds were recorded in three dimensions using a device. In general, more than one million three-dimensional components of the velocity were recorded in the experiments at this stage. Moreover, the average of the continuous velocities at each point was also calculated. Thus, in each of the desired points, three velocity components in three different dimensions were calculated and used to study the flow pattern.

RESULTS AND DISCUSSION

To investigate the effect of the presence of the collar on the scour of the pier of the cylindrical bridge, the experiments were divided into two categories as follows.

The first category, the experiments without collars (control experiments)

The experiments in this section are carried out according to Figure 2 to observe the effects of vortical currents around the bridge pier and to determine the scour maximum depth to be compared with the results of the experiments in the presence of the collar. In this case, the scour started from the front of the pier with the formation of a downflow and symmetrically
according to the axis of the pier. As the scour cavity deepens and the horseshoe vortices become stronger, sediment is washed from the front and around sides of the pier and accumulates in the form of a stack behind the pier. Moreover, as the scour cavity expands and creates a low-pressure area behind the pier, wake vortices are formed transporting sediments that have been carried by the flow downstream. In this regard, the scour cavity became wider by increasing the flow intensity, and the maximum scour depth increased. Table 2 and Figure 5 show the changes in the scour dimensionless depth and the pattern of erosion and sedimentation without the presence of a collar in the 8-hour experiment.

The second category, experiments in the presence of the collar

By installing the collar around the pier, at first, the scour was created due to the presence of the wake vortices downstream of the pier. In this case, unlike the pier-without-collar state, the horseshoe vortex was not observed from the beginning, and over time, grooves were formed on both sides of the pier at the edges of the collar. These grooves gradually expanded upstream and downstream, and their depth increased as well. The results of the experiments are presented in Table 3 at the setting level of $ZC = 0$, $ZC = 0.25D$ and $ZC = 0.5D$.

Comparison of the results of the experiments of the asymmetric netting collars

In all experiments performed in the presence of the collar, the rate of scouring cavity formation was reduced compared to the control experiment according to Table 3 and based on the relationship $\%R = ((d_1 - d_2)/d_1) \times 100$ as the percentage of scouring reduction. According to the results, it can be said that the $(3 \times 6)$ asymmetric collars were more effective in reducing scour than $(3 \times 4)$ collars (Figure 6). Investigation of the flow mechanism around the pier shows that the wake vortices are activated downstream of the bridge’s pier along with low-pressure centers for the sedimentation of the sedimentary deposits. Therefore, it seems that $(3 \times 6)$ collars prevent some of these vortices from working, while in the $(3 \times 4)$ collars; these vortices can be

### Table 2 | Dimensionless scouring depth changes around the pier without the collar (control experiment)

| Froude Number | $F_f = 0.37$ | $F_f = 0.32$ | $F_f = 0.26$ |
|---------------|-------------|-------------|-------------|
| $(d_1/D)$     | 1.62        | 1.47        | 1.2         |
Table 3 | Percentage of scour reduction in the presence of netting asymmetric collar

| Type of collar | Percentage of scour reduction (%R) | Percentage of scour reduction (%R) | Percentage of scour reduction (%R) |
|----------------|-----------------------------------|-----------------------------------|-----------------------------------|
|                | Z(MM)                             | 0.25D                             | 0.26                              |
| 3×4            | %15 On the bed Surface            | 47 57 54                          | 0.25D                             |
|                | %30                               | 41 55 54                          | 44 44 47                          |
|                | %40                               | 41 45 54                          | 35 35 33                          |
| 3×6            | %15                               | 56 66 72                          | 55 59 58                          |
|                | %30                               | 47 66 68                          | 46 57 56                          |
|                | %40                               | 46 47 56                          | 43 40 39                          |

Figure 5 | (a) Erosion and sedimentation pattern around the bridge pier (Froud Numbers of 0.26 and 0.37), (b) An illustration of the flows around the pier by injecting the dye material (Froud Number of 0.32).

Figure 6 | The efficiency of the scour reduction in the presence of collar in the Froud Number of 0.37.
more active, thus increasing the performance of the asymmetric collar. The installation of the collar no only leads to the reduction of the maximum scouring depth in front of the bridge pier but also reduces the height of the deposited sediments.

Another point is that the sediments do not exist up to a considerable distance downstream of sedimentary hills. In this regard, the lack of formation of the sedimentary hills around the pier in the collar installation position is one of the advantages of the collar installation. This is because the improper distribution of sediments and the presence of sedimentary hills would result in a flow blockage between the bridge piers, which in itself causes a kind of scour, especially scouring due to the contraction scour. During the installation of the \((3 \times 4)\) collar, the same pattern of erosion and sedimentation occurred similar to that of \((3 \times 6)\) collar. On the other hand, while lesser reducing the depth of the scouring cavity, the installation of the collar has also reduced the height of the sediments deposited downstream. Figure 7 also shows the longitudinal profile of the sediments around the pier in the conditions with and without the collar in the Froud number of 0.37.

The effect of collar installation level from the bed on the amount of scour around it

The installation level of the collar has a significant effect on reducing scour around the bridge pier. As the installation level of the collar decreases about the bed, the performance of the collar increases. In all three distances of the collar installation on

![Figure 7](image-url)
the pier, the scour cavity development was reduced compared to the control experiments. By placing the collar on the surface of the bed and preventing the formation of horseshoe currents under the collar, and increasing the time required for the development of the scouring cavity from the sides of the collar to the beneath, the maximum depth, longitudinal and transverse development of scouring cavity showed a significant reduction compared to the control state. At this level, by increasing the collar opening percentage, the maximum scour depth increased as well.

On the other hand, by increasing the collar distance from the bed, the power of horseshoe currents under the collar increases, and as a result, the scour will increase. According to Figure 8, by reducing the distance of each one of the collars from the sedimentary bed, it will remain no space for the vortical currents to be expanded under the collar. Thus the maximum depth will decrease. The (3 x 6) collar model 15% will show the best performance on the bed surface, with a 72% reduction in the scour rate at the Froud number of 0.26. On the other hand, the (3 x 4) collar model 40% indicated the lowest performance regarding the scour control at the distance of 0.5D and with the same Froud number. Equation (3) shows the regression relationship between the two parameters of dimensionless scour depth and the change in the collar setting installation level, indicating a high correlation coefficient ($R^2$).

$$d_s/D = 0.25(Zc/D)^2 + 0.8(Zc/D) + 0.5 \rightarrow R^2 = 0.998$$  (3)

According to Figure 8 and Equation (3), as the distance of the dimensionless parameter of the collar installation level would increase from the sedimentary bed, the scour reduction percentage (\%R) decreases in the presence of the collar. The percentage of scouring reduction is determined using the results of control experiments and based on the maximum scour depth in the presence of the obtained collar. If the installation level increases again, this so-called parameter has little effect on the scour depth. Figure 9 shows the collar model scour pattern of 40% at the Froud number of 0.26 for the two levels of installation on the bridge pier.

**The third category, flow speedometer experiments around the bridge pier**

**Checking the profile of the velocity components at the maximum scouring point (without collar)**

To become familiar with the velocity distribution at the maximum scouring point, in the without collar state or in the control experiment, three-dimensional velocity components were measured at different depths from the water surface to near the scour cavity floor. In this series of experiments regarding the velocity, the velocity profile has been considered in the depth direction and for the Froud Number of 0.32. Figure 10 shows the longitudinal, transverse, and depth velocity profile. According to this Figure, the maximum speed belongs to the transverse velocity, which is about 30 cm/s, although this velocity decreases during its way towards the bottom, reaching 28 cm/s. In terms of the depth velocity, it can be said that a downward current is formed from the water surface to a depth of about 3 cm, and its velocity is gradually reduced. When the velocity reaches zero amount, its direction changes, and an upward current is formed. This vortex, which is known as the horseshoe vortex, exerts a lifting force on sediment particles and the transverse and longitudinal velocities leading to the transition of the sediment particles raised from the bed.

![Figure 8](image_url)  
**Figure 8** | Changes in the dimensionless depth of the scour with changing the distance from the sedimentary bed (a) (3 x 4) collar, (b) (3 x 6) collar.
Investigation of the flow pattern in the vertical profiles around the cylindrical pier

In both experiments, the flow moved down near the water surface after colliding with the obstacle. Then the flow is diverted toward the main waterway near the bed after colliding with the floor. Near the bed, the velocity is fluctuating less than in a collarless profile. The resulting vortex and downstream currents are the main causes of scouring around the pier. Since the wake zone does not help transfer fluid downstream, the current in its adjacent area moves rapidly, transferring excess fluid (Ahmed & Rajaratnam 1998). However, what is clear is that the presence of the collar has caused the spatial displacement of this parameter. In the presence of the collar, the created boundary layer flow could have performed better by delaying the separation of the flow from the collar surface in comparison with the created vortical currents. In the current study, an experiment was performed to determine the three-dimensional components and draw the flow pattern around the optimal collar installed on the bed surface. As shown in Figure 11, the horseshoe vortex indicated the least contact with the surrounding bed.

Figure 9 | The pattern of $(3 \times 6)$ collar scouring model of 40% in the installation level of (a) $Z_C = 0.5D$, (b) $Z_C = 0.25D$.

Figure 10 | Velocity profile at the maximum point of the scour depth: (a) longitudinal, (b) transverse & (c) deep.
Figure 11 | The field of flow around the pier of a cylindrical bridge (a) with collar, (b) without collar.

Figure 12 | Field of the flow around the pier of the bridge (a) with collar, (b) without collar.
of the obstacle, delaying the scour for a longer time. Of course, the horseshoe vortex washes the sediments around the collar. It penetrates beneath it, causing scour to happen, which this obtained scouring was delayed compared with the collarless state. Furthermore, the intensity of horseshoe vortices in the optimal collar experiment has decreased compared to the control experiment. The flow pattern in the profiles shows that the presence of a downward current and the intensity of the formed horseshoe vortex is reduced in the front part of the bridge pier compared with the control experiment if the collar is used, causing more bed protection.

In Figure 11(a), it is observed that during the passing of the current along the path of the laboratory canal, the opposite longitudinal pressure occurs near the pier after the passing of the gradient flow due to the collision of the current with the obstacle, which is located vertically in the path of the flow. This may cause the current to be separated from the pier and the particles to accelerate in areas where the pressure increases after the separation points of the wake return current. According to Figure 11(b), the use of the collar leads the return flow area to be kept away from the laboratory pier; by doing so, the collar creates the conditions for protecting the bed. The flow around the pier of the cylindrical bridge with a circular cross-section may create a uniform pattern of the vertex downstream. The end vertices cause the lifting force on the cylinder to fluctuate in the direction perpendicular to the movement of the flow lines, leading to the displacement of the sediment particles of the bed and moving them downstream. On the other hand, as the currents pass through the pier, they are joined together again, creating uniform flow conditions in the canal. It is also observed that by moving away from the surface of the sedimentary bed near the canal sidewalls, the velocity of the flow layers approaches the velocity of the free-surface flow.

CONCLUSIONS
In the present study, the performance of two collar models, including \((3 \times 4)\) and \((3 \times 6)\) collars, was investigated to reduce positional scour around the bridge pier. The results showed that increasing the dimensions of the collars leads to the improvement of its performance. In the case of collar installation, the sediments around the pier have a uniform distribution. The difference between the deepest and highest points of the bed is reduced to more than 50\% of the case without a collar. On the other hand, by increasing the Froud Number and the installation level of the collar based on the amount of scouring, the scour increases in the areas around the pier.

The collars installed at a distance of 2 cm above the bed showed less efficiency regarding the scour control. The \((3 \times 6)\) collar model of 15\% with installation at a distance of 2 cm and the Froud Number of 0.37 indicated the highest efficiency with a 44\% reduction. In contrast, a \((3 \times 4)\) collar with installation at a distance of 2 cm indicated the lowest scour control efficiency, which is related to the 40\% model with a scour rate reduction of 26\%.

By examining the velocities around the collar, it can be said that the flow of the boundary layer created around the collars causes more sublation of the vortical currents, resulting in a smaller cavity around the pier. The experimented collars reduced the volume of the scour by affecting the boundary layer flow by delaying the separation of the flow. The current study also indicated the effects of a downstream flow and the resulting vortices in a bridge pier with a circular cross-section on the onset and development of the scour around it.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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