Larhyss Journal, ISSN 1112-3680, n°59, Sept 2024, pp.69-83

EFFECT OF PERFORATED COLLAR SHAPE AND OPENING PERCENTAGE ON SCOURING AROUND BRIDGE PIERS

BAGHERI A.[1,2], BORDBAR A.[2], HEIDARNEJAD M.[3*], MASJEDI A.R.[4]

[1] Department of Water Science Engineering, Khuzestan Science and Research Branch, Islamic Azad University, Ahvaz, Iran.

[2] Corresponding author: Department of Water Science Engineering, Ahvaz Branch, Islamic Azad University, Ahvaz, Iran

[3] Department of Water Science Engineering, Ahvaz Branch, Islamic Azad University, Ahvaz, Iran

[4] Department of Water Science Engineering, Ahvaz Branch, Islamic Azad University, Ahvaz, Iran

(*) mo_he3197@yahoo.com

Research Article – Available at http://larhyss.net/ojs/index.php/larhyss/index
Received April 10, 2024, Received in revised form August 25, 2024, Accepted September 2, 2024

ABSTRACT

Scouring is considered a major contributor to bridge failure across the world. The expansion of the scour hole can lead to instability of the bridge structure. Consequently, scour depth prediction is considered a common river engineering practice to take necessary controlling measures. Accordingly, this study investigated the impact of perforated collars of different shapes on scouring around bridge piers. It was found that the scour further decreased as the collar shape was changed from triangular to rectangular. By installing triangular, circular, square, and rectangular perforated collars with the same hole diameter (d/D) of 0.1, maximum scour depth respectively decreased by 35.2, 37.4, 38.4, and 50.9% in comparison with the collarless bridge pier. Installation of the triangular, circular, square, and rectangular perforated collars with a hole diameter (d/D) of 0.15 reduced scouring respectively by 27.7, 31.6, 33.4, and 45.8% compared to the collar-less pier. Scouring respectively decreased by 16.6, 22.3, 24.7, and 27.6% compared to the collar-less pier by installing the triangular, circular, square, and rectangular perforated collars with a constant hole diameter (d/D) of 0.2. Scouring increased by 29.7% on average at all velocities as the diameter of the collar hole (d/D) increased from 0.1 to 0.2. Furthermore, scouring increased with increasing velocity. Scouring was found to increase by 94.7% on average with a rise from 0.54 to 0.95 of the flow intensity (V/Vc).

Keywords: Bridge pier, Perforated collar, Scouring, Triangular collar, Rectangular collar, Square collar, Circular collar

INTRODUCTION

Scouring around bridge piers is a critical issue in civil engineering, as it can lead to structural instability and compromise the safety of bridges (Ghasemi and Heidernejad, 2023; Dalal and Deb, 2024). One of the key factors influencing scouring is the shape and opening percentage of perforated collars installed around bridge piers. Understanding the effects of these design parameters on scouring is essential for developing effective countermeasures to mitigate the risks associated with bridge pier scour (Melville and Sutherland, 1988).

The design, calculation, and construction of bridge piers are among the most important stages in bridge construction projects, especially when the bridge is intended to be constructed at the crossing of a river. In this case, the hydrological and hydrological data of the region should be considered and analysed by designers to select the lengths and number of openings and the minimum depth of piers. Scour-induced bridge failure is associated with huge economic and side damages. Numerous studies have been conducted on scouring. Due to the complexity and multiplicity of factors governing this phenomenon, no single solution has been proposed yet for calculating the scour depth (Mehta and Yadav, 2020). Different factors such as the waterway shape, flow characteristics, pier geometry, inclination angle concerning the flow direction, and sediment characteristics increase the complexity of scouring around bridge piers. It should be noted that the final scour depth around bridge piers is obtained by adding scour depths resulting from local scouring, general scouring, and narrowing of the channel breadth.

The water flow and sediment transport in rivers create a variety of shapes by the lithology and topography of each region due to the changes in the river bed and river banks. Despite their different geometric and hydraulic properties, the beds of most waterways and rivers are rarely straight but consist of many bends along their path (Achour et al., 2022 a,b,c). The transport of sedimentary materials in the river bed should be fully understood to estimate the scour depth at bridge piers (Adechina et al., 2018; Elahcene et al., 2015; Meddi, 2015). Bridge piers disrupt the normal flow of rivers and the resulting turbulent flow causes the erosion of sedimentary materials around the piers. The size of the scour hole at the bridge pier is mainly dependent on the geometry of the pier. Likewise, the type of river bed materials as well as hydraulic conditions of the flow such as floods and dunes may influence the scour depth (Zolghadr et al., 2023). Estimating the scour depth is one of the most common river engineering practices to take necessary controlling measures. Scouring around bridge piers has received much attention from researchers. Local scouring at bridge piers is considered a major contributor to bridge failures throughout the world potentially causing traumatic human consequences. Below, several studies on protective structures for controlling and reducing the scour depth at bridge piers are reviewed: The collar does not prevent the formation of horseshoe vortices but will play a significant role in scour reduction when located in a suitable place from the bed level (Dargahi 1990). Chiew (1992) found a 20% scour reduction with a collar diameter twice the diameter of the bridge pie. According to Zarrati and Azizi (2001) scouring will be further reduced by installing a collar at a lower level. They reported a depth of 0.1D (D:

bridge pier diameter) below the bed as the best location for installing collars. Their results suggested that the scour depth could be effectively reduced using collars of larger width positioned at lower levels. According to Shariati et al., (2011) and Masjedi and Gholamzadeh Mahmoudi (2011), scouring at the bridge piers at a 180◦ bend increased with increasing the collar diameter . Esmaili Varaki, Jafari, and Musapour (2012) found a significant impact of the placement level of the foundation on the scour depth. They also reported the more significant effect of the flow velocity on the temporal development of scouring around the inclined piers group in comparison with the flow depth. in the compound channel by 93% whereas scouring increased with increasing the collar thickness (Dargahi, 1990). the simultaneous use of the collar and hole on the bridge pier reduced the scour depth by about 80%. Hassanpour et al. (2013) investigated local scouring at a bridge pier of an airfoil-like cross-section with a collar. The maximum scour depth occurring at the airfoil-like pier was found to be 22% smaller compared to the corresponding value at its cylindrical counterpart. They also found the collar with a diameter twice the airfoil-like pier to reduce the scour depth by 80% as compared with the cylindrical pier. Other research investigated a riprap of a diameter triple to quadruple as large as that of the bridge pier to protect bridges against scouring and suggested a minimum riprap thickness of three times the average diameter of rocks (Mesabahi and Shamsaei, 2013). Ghasemifard et al. (2013) found the proper performance of sacrificing piers in controlling scouring around rectangular bridge piers. Azam and Ghomeshi (2013) investigated the effect of protective piles on scouring reduction around cylindrical bridge piers. They found the best location for the piles at an approximate distance of three times the diameter of the bridge pier. Jalili (2013) studied the manner the scouring at cubic and cylindrical bridge piers was affected by the perforated collar. Cubic and cylindrical bridge piers, a collar diameter, three placement levels for the cylindrical collar, and a placement level for the circular collar with three openings of 15, 30, and 40% were used for this purpose. It was found that collars with opening percentages of 30 and 40% showed the highest efficiency in scour reduction respectively around cubic and cylindrical bridge piers.

Ghasemi and Soltani-Gerdefaramarzi (2017) simulated bridge pier scouring using Flow-3D. They studied hydraulic parameters, including velocity, fluid depth, and Froude number. The maximum score depths at flow intensities of 5, 10, 19, and 30 lit/s were found to be 0, 3.1, 4.2, and 6.3 cm, respectively. Moreover, the largest scour was found to occur on the upstream side, while the downstream scour was lower (Ghasemi and Soltani-Gerdefaramarzi, 2017). Wang et al., (2019) studied the scour protection of cylindrical bridge piers equipped with collars in physical models. They utilized sedimentary particles with an average diameter of 0.324 mm. The tests were carried out at different depths and diameters in the presence and absence of collars. Collars were found to reduce scour; however, the protective effect declined as the collar height increased. Moreover, a rise in the collar diameter reduced scour. Namaee et al., (2019) experimentally evaluated bridge pier scouring under ice-covered conditions. The tests were performed at four circular pier diameters and sedimentary particle sizes of 0.48, 0.50, and 0.57 mm. The smaller piers were found to undergo lower scouring. Moreover, a rise in the diameter of sedimentary particles reduced the maximum scour depth. The vertical velocity was observed to experience a larger reduction under the ice cover. Raeisi and Ghomeshi (2021) explored how various asymmetric perforated collars could abate the local scouring at bridge piers under different flow conditions. According to their findings, the collar proved to be effective in both reducing the ultimate scour depth and decelerating the scouring. Valela et al. (2022) developed a modified collar model for bridge pier scour reduction. The model was intended to control scour-induced horseshoe vortices. They examined different collars at different levels and compared the results to a numerical model. Hamidifar, Shahabi-Haghighi, and Chiew (2021) studied the scour process at bridge piers in the presence of various floating substances. They found that collars reduced scour by up to 39% (compared to the scour in the absence of collars), and floating substances would reduce the collar contribution down to 25%. Although numerous studies have examined the use of collars as bridge protection structures, only non-perforated collars have been employed. Therefore, the present study seeks to experimentally explore the effects of perforated collars of different shapes and openings on scour control.

MATERIAL AND METHODS

Properties of the test flume

A test flume belonging to the Azad University of Ahvaz was utilized to perform the experiments in this study. The straight plexiglass-made inlet and outlet channels of the test flume were 4.5 and 2.5 m long respectively. The channels were rectangular in cross-section. Both the inlet and outlet featured metallic bottom and plexiglass walls of thicknesses of 3 mm and 10 mm respectively. The straight inlet allowed for a uniform flow to develop, with its length and wall material minimizing the effect on the flow of the wall roughness. The test flume measured 50 cm wide by 60 cm high and was installed 70 cm above the ground. The fixed-bed flume was secured at a perfectly horizontal configuration (Fig.1). The sediment bed had no slope and a length of 3 m, in the middle of which the pier was located. A sluice gate mounted past the water reservoir was employed for adjusting the discharge. Likewise, a 90-degree v-notch weir was utilized for discharge measurement. To evaluate the effects of perforated collars of different shapes and hole diameters, perforated collars with four different shapes and three hole diameters were constructed (Fig. 2).

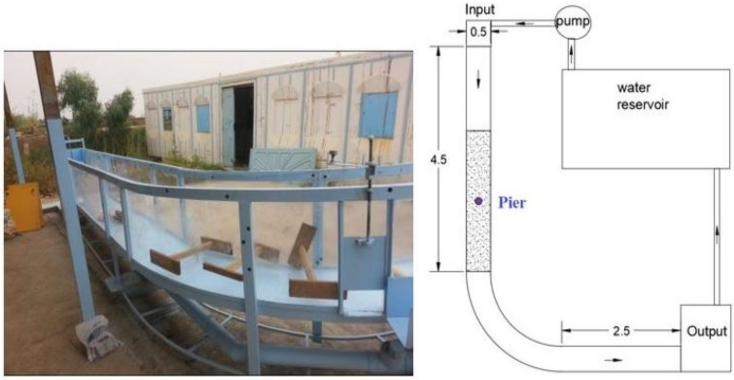

Figure 1: Schematic of the laboratory flume

Figure 2: The Perforated collar and the bridge pier

A bridge pier diameter of 5 cm was considered and a height of 20 cm was to prevent its submersion.

Bed sediments. Various proposals have been given for determining the suitable size of the sediments. According to Dongol (1993) (La: length of support perpendicular to the flow direction, d50: average diameter of sedimentary particles) should be greater than 25 to avoid the effect of sediment size on the scour depth and bed formation. Based on their results, the more uniform the riprap particle size, the larger the scour extent. For a uniform particle size distribution, should be less than 1.3 where σg represents the standard deviation of sediments (Melville, 1997). Raudkivi (1988), to preclude the creation of ripples, the average particle diameter should be larger than 0.7 mm. As a result, they used sedimentary sand with an average particle diameter of 1.37 mm a geometric standard deviation (σg) of 1.13, and a density of 2.65.

Dimensional analysis

For the experimental study of a phenomenon, the relationships of factors affecting that phenomenon should be examined. This reveals the significant role of dimensionless numbers in interpreting the experimental results and establishing relationships between the factors involved in the phenomenon under study. Factors associated with the geometry of the channel: channel breadth (B) and the longitudinal slope of the flume (S), Hydraulic conditions of the flow: the upstream flow velocity (V), the depth of the flow (y), and the acceleration of gravity (g) Particle characteristics: the average diameter of sedimentary particles (d50), sediment density (s), the scour depth of sediments (ds) Fluid properties: the fluid density (ρ) and dynamic viscosity (μ) The parameters influencing scouring are represented as:

$$F(S0, B, R, \delta, L, S, h, N, v, vc, y, g, d, D, d50, \rho, ds, \rho s, \mu) = 0 \quad (1)$$

According to dimensional analysis based on the Buckingham π theorem,

$$\frac{ds}{D} = f\left(S_0, \frac{B}{Y}, \frac{R}{Y}, \delta, N, \frac{L}{Y}, \frac{d}{D}, \frac{h}{Y}, \frac{d_{50}}{Y}, \frac{\rho_S}{\rho}, \frac{d_S}{Y}, \frac{\mu}{\rho v y}, \frac{v^2}{gy}\right) \quad (2)$$

The flume had a longitudinal slope of zero, and the central curve angle was constant in the tests. Therefore, they could be neglected. Furthermore, since the materials and their sizes, fluid type, and flow depth would remain unchanged in the tests, the $\frac{d_s}{Y}$ ratio and $\frac{\rho_s}{\rho}$ could be neglected. As a result, the division of $\frac{L}{Y}$ by $\frac{B}{Y}$ and $\frac{R}{Y}$ by $\frac{B}{Y}$ gives:

$$f\left(\frac{R}{B}, \frac{L}{B}, \frac{L}{D}, \frac{h}{Y}, \frac{ds}{Y}, N, \frac{v}{vc}, \frac{d}{D}, Re, Fr\right) = \frac{ds}{D} \quad (3)$$

The $\frac{R}{B}$ ratio and $\frac{L}{B}$ were constant in the flume. Thus, they could be neglected. Furthermore, since the flume flow was turbulent, the Reynolds number was ignored. As a result,

$$\frac{ds}{D} = f\left(N, \frac{d}{D}, \frac{v}{vc}\right) \quad (4)$$

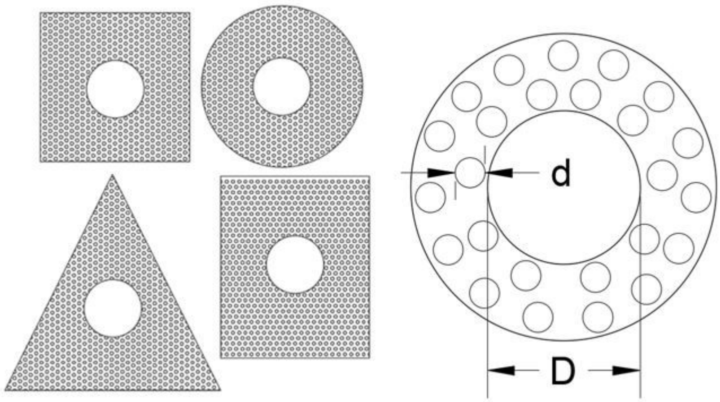

Figure 3: The schematic view of the aerodynamic perforated collar

The collar thickness is 5 mm and the placement height is zero relative to the ground level.

The experimental variables include:

1. The hole diameter (d/D): 0.1, 0.15 and 0.2
2. The collar shape (N): square, rectangular, circular, and triangular
3. Flow intensity (V/Vc): 0.54, 0.65, 0.76, 0.86 and 0.95

A total of 65 experiments including 5 control tests were performed as listed in Table 1.

It should be noted that all the flume shapes had the same area.

The ratio of the diameter of the orifice to that of the pier was taken into account in the test. The collars were deployed on the bottom of the bed and did not affect on the adjacent flow. A test was carried out under normal conditions in the absence of the pier, and Vc was found once the bed began scouring due to the increased flow velocity.

Bed material thickness

According to Chiew and Melville (1987), the maximum scouring is equal to 2.4D, which is equivalent to 120 mm in this study. For the sake of enhanced accuracy of the experimental results, a bed thickness of 200 mm was made use of in this study.

Duration of experiments

The duration of experiments was selected according to Ettema (1980), which is the duration of less than 1 mm increase in the scour depth in one hour. Fig4. depicts the variation with time of scouring at the control cylindrical pier. As seen, the scour depth sharply changes initially and then leveled off. Due to major scouring in the first 3h period, a constant duration of 3 h was considered in all experiments.

As can be seen, the scour depths of 3.5, 4.02, and 4.090 occurred in 1, 2, and 3 hours, respectively, suggesting a scouring rate below 1 mm/h.

According to the above criteria and calculated critical velocity considering a flow depth of 16 cm and a flow rate of 9 L/s, a flow intensity (V/Vc) of 0.95 was employed in the experiments.

As maximum scour happened at the peak velocity, V/Vc was assumed to be below 0.95 to determine the test time.

Table 1: Experimental variables

Number of experiments	Hole diameter (d/D)	Collar shape (N)	Flow intensity (V/Vc)	Control
65	0.1, 0.15, 0.2	square, rectangular, circular, and triangular	0.54, 0.65, 0.76, 0.86 and 0.95	5

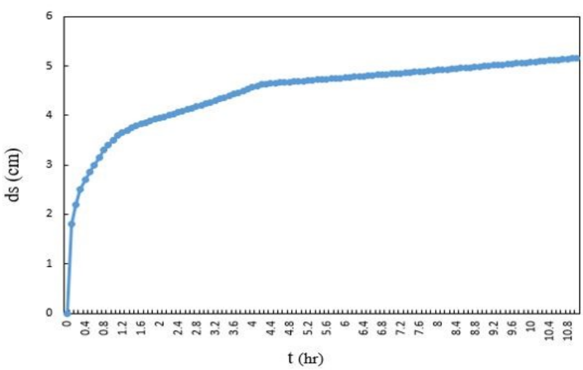

Figure 4: The temporal development of scouring

Surveying tool for the scour profiles

To survey the scour profile, a laser distance measure with an accuracy of 1 mm equipped two spirit levels. The distance measure was secured on a metal plate that could slide over a frame which allowed it to move in the direction of the flow as well as transversely. The frame was graduated at every 5 cm along its length and width and located nearly 69.5 cm above the flume bed.

The position of the plate was adjusted such that it laid over the centerline of the flow, namely where the peak of the velocity profile was assumed to occur. The plate was then moved along the flume and the laser meter readings were recorded at the reading stations spaced at 5 cm intervals prior to- and subsequent to the scouring. The height of the scour profile at a given station was then calculated using Eq. 5.

$$Z = -\left(\frac{Z_s}{10}\right) + \left(\frac{Z_0}{10}\right) \qquad (5)$$

where Z denotes the height of the scour profile at a given station in cm, Zs represents the laser measure reading after the scouring in mm, and Z0 stands for the initial reading of the laser measure in mm before the scouring. Values greater- and smaller than zero of Z reflect uplift and trough in the bed respectively.

RESULTS

The effect of flow velocity (Froude number), collar shape, and hole diameter on scouring around the bridge piers was examined. In Fig 5. images of scour around the piers with triangular, square, and circular perforated collars are shown. The findings are discussed in the three following subsections:

1. The effect on the scouring of the collar shape
2. The effect on the scouring of the hole diameter
3. The effect on the scouring of the flow rate and flow velocity

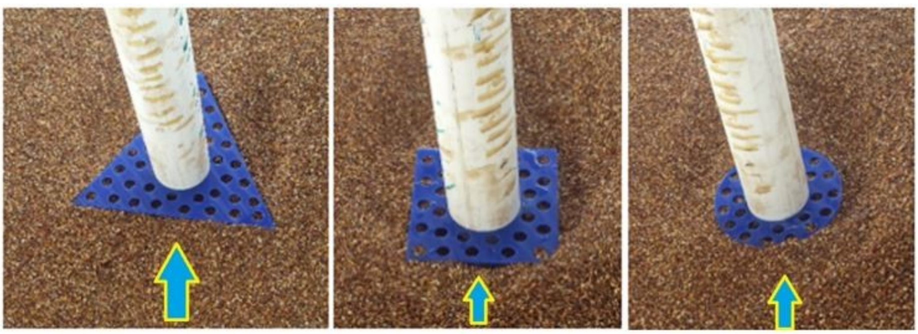

Figure 5: Images of scouring around the bridge piers

The effect on the scouring of the collar shape

The experimental data were analyzed and the results thereof are illustrated in the following diagrams. The effect on the scouring of the collar shape is investigated in this section.

According to Figs. 6 to 9, scouring decreases by installing the perforated collar on the bridge pier. As seen, scouring decreases further as the collar shape changes from triangular to rectangular. By installing the triangular, circular, square, and rectangular perforated collars with a hole diameter (d/D) of 0.1, scouring respectively decreases by 35.2, 37.4, 38.4, and 50.9% as compared to the collar-less pier. The installation of the triangular, circular, square, and rectangular perforated collars with a hole diameter (d/D) of 0.15 respectively reduces scouring by 27.7, 31.6, 33.4, and 45.8% in comparison with the collar-less pier. By installing the triangular, circular, square, and rectangular perforated collars with a hole diameter (d/D) of 0.2, scouring respectively reduced by 16.6, 22.3, 24.7, and 27.6% relative to the collar-less pier. In Fig. 6. the impact of collar shape on scouring with a hole diameter (d/D) of 0.1 is visually represented.

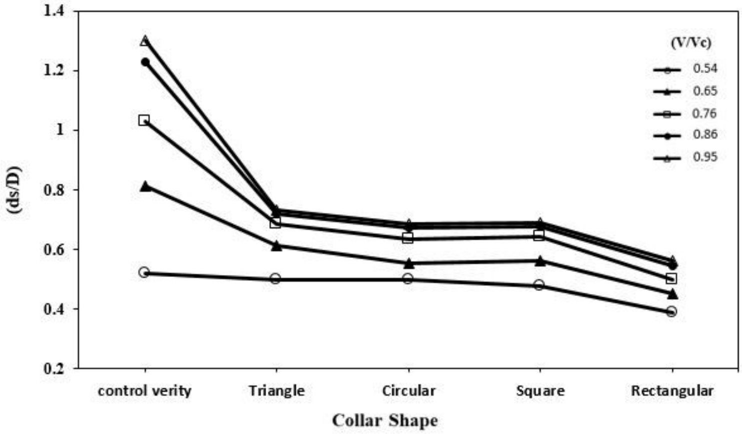

Figure 6: The effect on the scouring of the collar shape with a hole diameter (d/D) of 0.1

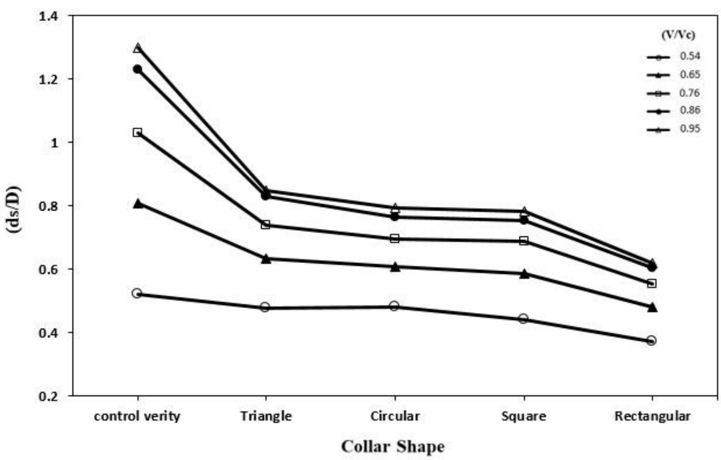

Figure 7: The effect on the scouring of the collar shape with a hole diameter (d/D) of 0.15

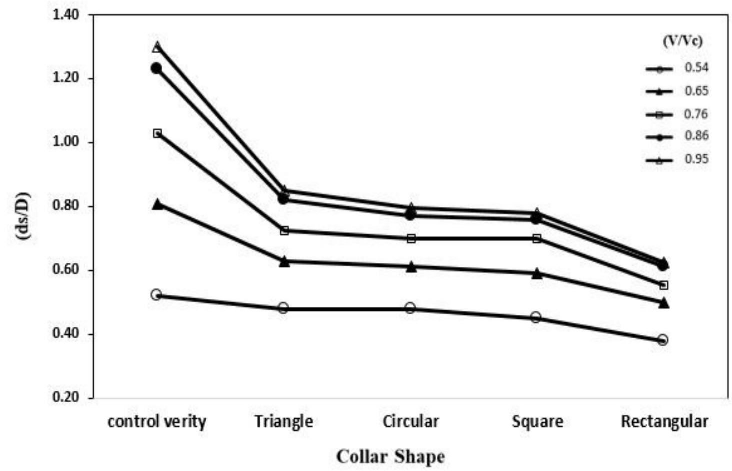

Figure 8: The effect on the scouring of the collar shape with a hole diameter (d/D) of 0.2

The effect on the scouring of the hole diameter of perforated collar

The results of the analysis of the experimental data are depicted in the following diagrams. This section is devoted to the effect on scouring of the perforated collar hole diameter.

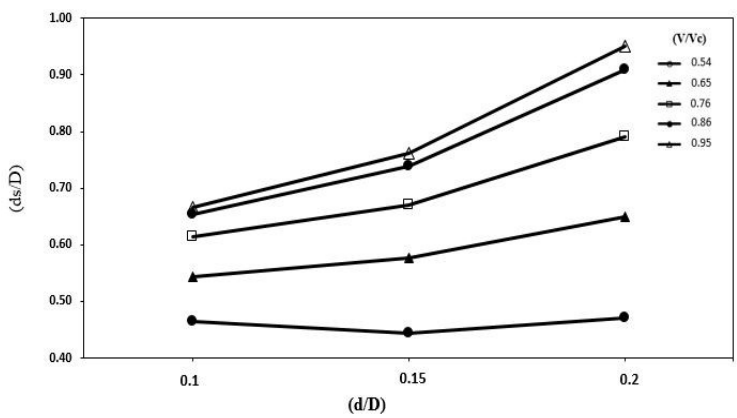

Figure 9: The effect on the scouring of the perforated collar hole diameter

As seen in Fig 9, scouring increases with increasing the diameter of perforated collar holes. As the hole diameter increases from 0.1 to 0.2, scouring increases by 29.7% on average at all velocities. Scouring also increases with increasing velocity. The effect on scouring of the flow intensity .The effect on scouring of the flow intensity is discussed in this section.

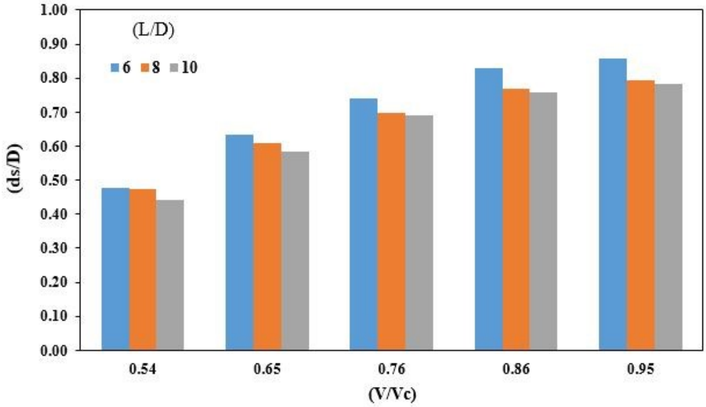

Figure 10: The effect on scouring of the flow intensity

As can be seen in Fig. 10. as the flow intensity (V/Vc) increases from 0.54 to 0.95, scouring increases by 94.7% on average.

CONCLUSION

The effect of perforated collars of different shapes was investigated on scouring at bridge piers. According to the findings of this study, a decrease in scouring due to the reduction and displacement of eddy currents. Collars of different shapes and hole diameters had different impacts on the scour reduction. The results are summarized as follows:

1. As per the results obtained, the change of collar shape from triangular to rectangular resulted in a further decrease of scouring. By installing the triangular, circular, square, and rectangular perforated collars with a hole diameter (d/D) of 0.1, scouring respectively decreased by 35.2, 37.4, 38.4, and 50.9% compared to the collar-less pier. The installation of the triangular, circular, square, and rectangular perforated collars with a hole diameter (d/D) of 0.15 decreased scouring respectively by 27.7, 31.6, 33.4, and 45.8% compared to the collar-less pier. By installing the triangular, circular, square, and rectangular perforated collars with a hole diameter (d/D) of 0.2, scouring respectively decreased by 16.6, 22.3, 24.7, and 27.6% concerning the collar-less pier.
2. An increase from 0.1 to 0.2 of the collar hole diameter (d/D) resulted in a scouring rise of 29.7% on average at all velocities.
3. An increase from 0.54 to 0.95 of the flow intensity (V/Vc) led to an increase in scouring by 94.7% on average.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper

REFERENCES

ACHOUR B., AMARA L., MEHTA D. (2022 a). Control of the hydraulic jump by a thin-crested sill in a rectangular channel, new experimental considerations Larhyss Journal, No 50, pp. 31-48.

ACHOUR B., AMARA L., MEHTA D., BALAGANESAN P. (2022 b). Compactness of Hydraulic Jump Rectangular Stilling Basins Using a Broad-Crested Sill, Larhyss Journal, No 51, pp. 31-41.

ACHOUR B., AMARA L., MEHTA D. (2022 c). New theoretical considerations on the gradually varied flow in a triangular channel, Larhyss Journal, No 50, pp. 7-29.

ADECHINA A.R.M.A, KELOME C.N., HOUNKPE J.B. (2018). Hydrodynamic sedimentary of the middle delta of the Ouémé River in the context of the current floods, Larhyss Journal, No 33, pp. 93-110. (In French)

AZAM N., GHOMESHI M. (2013). Influence of sacrificial piles on scouring reduction of cylindrical bridge piers, Journal of Water and Soil Science, Vol. 33, Issue 3, pp. 134-123.

CHIEW Y. M. (1992). Scour protection at bridge Piers. Journal of hydraulic engineering, Vol. 118, Issue 9, pp. 1260-1269.

CHIEW Y. M., MELVILLE B. W. (1987). Local scour around bridge Piers, Journal of hydraulic research, Vol. 25, Issue 1, pp. 15-26.

DALAL B., DEB S. (2024). An experimental study on the variation of scour depth for different pier shapes using a tilting flume, Larhyss Journal, No 57, pp. 209-239.

DARGAHI B. (1990). Controlling mechanism of local scouring, Journal of hydraulic engineering, Vol. 116, Issue 10, pp. 1197-1214.

DONGOL D. (1993). Local Scour at Bridge Abutments. PhD Thesis, Civil Engineering, The University of Auckland, New Zealand.

ELAHCENE O., REMINI B., TERFOUS A., GHENAIM A. (2015). Evolution of the concentrations and the sediment discharge according to the liquid flows in the watershed of the wadi Bellah Tipaza, Larhyss Journal, No 21, pp. 169-180.

ESMAILI VARAKI M., JAFARI M., MUSAPOUR, S. (2012). Experimental study of the effect of foundation placement level on the maximum scour of inclined piers group, Paper presented at the 9th International Congress of Civil Engineering, Isfahan, Iran.

ETTEMA R. (1980). Scour at bridge piers. PhD Thesis, Civil Engineering, The University of Auckland, New Zealand.

GHASEMI M., SOLTANI-GERDEFARAMARZI S. (2017). The Scour Bridge Simulation around a Cylindrical Pier Using FLOW-3D? Journal of hydraulic engineering, Vol. 1, Issue 2, pp. 46-54.

GHASEMI ASL M., HEIDARNEJAD M. (2023). A numerical study of the maximum scour depth around inclined bridge piers and comparison with an experimental model, Larhyss Journal, No 56, pp. 55-75.

GHASEMIFARD M., HAYDARPOUR M., SEDAGH M. (2013). Local scour control of rectangular bridge piers in the presence of sacrificial piers, Paper presented at the National Conference on Civil and Sustainable Development in Risk Reduction of Natural Disasters, Mashhad, Khavaran Higher Education Institution.

HAMIDIFAR H., SHAHABI-HAGHIGHI S.M.B., CHIEW Y. M. (2021). Collar performance in bridge pier scour with debris accumulation, International journal of sediment research, Vol. 37, Issue 3, pp. 328-334.

HASSANPOUR N., HOSSEINZADEH DELIR A., ARONAGHI H. (2013). Local scouring around airfoil-shaped bridge piers, Journal of Environmental Health Science and Engineering, Vol. 23, Issue 3, pp. 234 – 221.

JALILI A. (2013). The effect of perforated collar on the scouring of bridge piers, MSc, Shahid Chamran University of Ahvaz, Iran.

MASJEDI A., GHOLAMZADEH MAHMOUDI M. (2011). Experimental study of the effect of the collar in scouring control around cylindrical bridge piers 180° bend of the river, Journal of Agriculture and Natural Resources Abbreviation, Vol. 38, Issue, pp. 27-55.

MEDDI M. (2015). Contribution to the study of solid transport in northern Algeria, Larhyss Journal, No 24, pp. 315-336. (In French)

MEHTA D. J., and YADAF S. M. (2020). Analysis of scour depth in the case of parallel bridges using HEC-RAS. Water Supply, Vol. 20, Issue 8, pp. 3419-3432.

MELVILLE B. W. (1997). Pier and abutment scour: Integrated approach, Journal of hydraulic engineering, Vol. 132, Issue 2, pp. 125-136.

MELVILLE B. W., and SUTHERLAND A.J. (1988). "Design Method for Local Scour at Bridge Piers, Journal of Hydraulic Engineering, Vol. 114, Issue 10, pp. 1210-1226.

MESABAHI M., SHAMSAEI A. (2013). Comparison of the criteria for the selection of riprap for the protection of bridge piers. Paper presented at the Paper presented at the International Conference on Civil Engineering, Architecture and Sustainable Urban Development, Tabriz, Iran.

NAMAEE M. R., SUI J., WU P. (2019). Experimental Study of Local Scour around Side-by-Side Bridge Piers under Ice-Covered Flow Conditions, In The Fluvial Processes and Forms-Dynamics, Delineation and Conservation, 23 p.

RAEISI N., GHOMESHI M. (2021). A laboratory study of the effect of asymmetric-lattice collar shape and placement on scour depth and flow pattern around the bridge pier. Water Supply, Vol. 22, Issue 1, pp. 734–748.

RAUDKIVI A. J. (1988). The roughness height under waves, Journal of hydraulic research, Vol. 26, Issue, pp. 569-584.

SHARIATI H., KHODASHENAS S., ESMAEILI K. (2011). Experimental study of the effect of collar and hole on local scouring at bridge piers, Journal of Civil Engineering and Construction Technology, Vol. 23, Issue 1, pp. 85-96.

VALELA C., RENNIE C. D., NISTOR I. (2022). Improved bridge pier collar for reducing scour, International journal of sediment research, Vol. 37, Issue 1, pp. 37-46.

WANG S., WEI K., SHEN Z., XIANG Q. (2019). Experimental Investigation of Local Scour Protection for Cylindrical Bridge Piers Using Anti-Scour Collars. Water, Vol. 11, Issue 7, pp. 1515.

ZARRATI A. R., AZIZI M. (2001). Scouring control around bridge piers. Journal of Faculty of Engineering, Vol. 35, Issue 1, pp. 21-33.

ZOLGHADR M., ZOMORODIAN S. M. A., FATHI A., TRIPATHI R. P., JAFARI N., MEHTA D., SIHAG P., AZAMATHULLA H.M. (2023). Experimental study on the optimum installation depth and dimensions of roughening elements on abutment as scour countermeasures, Fluids, Vol. 8, Issue 6, pp. 1-14.