Applied Water Science (2024) 14:194
https://doi.org/10.1007/s13201-024-02257-5

ORIGINAL ARTICLE

The influence of collar parameters on local scour mechanism around the circular pier at the bend

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Received: 26 May 2023 / Accepted: 28 July 2024 / Published online: 12 August 2024

Abstract
Analysis of bridge failures due to scouring has been extensively studied by different researchers in recent years and as a result various methods of controlling local scour cavity have been given. Since most of the research in this field has been done on straight paths and also the complexity of the flow pattern in bends, studying the scouring pattern around the bridge piers located in the bends has become a necessity. Therefore, one of the main objectives of this study is to investigate the scouring around the circular piers which are protected by collars at the river bends. The performance of the collar significantly depends on its level around the pier, which has been studied in this study. The results showed that the optimal performance of this structure, in positions 60°, 90° and 120° at the level of 0.2 pier width under the bed with 3 mm thickness (0.06 of pier width) by approximately 68, 63 and 70% of the maximum pier scour depth was reduced compared with collarless pier, respectively. By analyzing the results of this research, it was observed that the optimum level range of collar around the pier at various bend angles is the initial bed level up to 0.4 times the pier width at the bottom of the incipient level of the bed. Moreover, getting closer to the plate placement level toward the initial bed elevation enhances the collar's function in decreasing scouring.

Keywords Bridge piers · River bend · Erosion · Scour cavity · Sediment · Collar

Abbreviations

List of symbols

As	Area of the main scour hole
B	Channel width (m)
b	Width of pier (cm)
ds	Scour depth
dsmax	Maximum scour depth
d_{50}	The average diameter of sediment particles (mm)
hsmax	Maximum sedimentary height
L	Collar length (cm)
Lc	Level of collar (cm)
Ls	Length of the rectangle environing the scour hole
P	Pier without collar
R	Central radius of the bend (m)
Sd	The slope of the downstream wall of scour hole
Si	The slope of the scour hole that's near the inner bank
So	The slope of the scour hole that's near the outer bank
Sr	Scour reduction (%)
Su	The slope of the upstream wall of scour hole
t	The time of the experiment
tc	Thickness of collar (mm)
te	Equilibrium time
U	Flow velocity (cm/s)
U_C	Flow velocity under incipient motion conditions (cm/s)
Vs	Volume of the main scour hole
W	Collar width
Ws	Width of the rectangle environing the scour hole
y	Upstream flow depth (cm)
Z	Distance from the bed (cm)
θ	Angles from the beginning to the end of the bend (deg)
θ_P	Location of the pier in the bend (deg)
α	Location of ds_{max} or hs_{max} (deg)

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Introduction

The most common pattern of the rivers in the plan is a meandering form (Dehghan et al. 2021a). The main characteristic of flows in bended rivers is secondary currents. Because of the interaction of the secondary current with longitudinal velocity profile, a specific flow called the spiral flow is created. Locating the bridge piers in the river's bend affects the flow created in the bend and changes the flow characteristics. In addition, the flow structure is changed due to locating the pier in the current path and leads to the formation of down-flows at the upstream of the pier by hitting the pier and the horseshoe vortex and wake vortex around the pier. Presence of helical flows in meandering rivers in addition to down flows and semi-horseshoe vortices around the bridge piers exacerbates the scouring and therefore increases the possibility of failure of the bridges within the bends. This study utilized the adjoint collar structure in order to improve the pier strength against down flows, helical flows and semi-horseshoe vortices. When the scour hole is formed around the pier, horseshoe and wake vortices are intensified and play an important role in increasing the volume of the local scour hole gradually with sediments transported downstream. Given the flow pattern formed around the pier, the adjoint collar structure was used to prevent the impact of the down flows with the bed and reduce the scouring around the pier. The flow structure around the circular pier has been presented in research of Kumar et al. (1999). Various methods have been presented by researchers to control and reduce scouring around bridge piers, among which riprap, sacrificial piers, slot creation in piers, submerged vanes, upstream spur dike installation, modification of the shape of the pier and collar installation can be pointed out (Beg and Beg 2013). The aforementioned methods are generally in the form of measures to increase the resistance of the bed materials or change the flow pattern to reduce the power of erosion factors. Each of these methods has its own problems. For example, one of the obvious problems of the riprap method is that during high-intensity floods, these stones are easily moved in downstream direction, which causes stones to hit downstream structures and destroy them as a result. Among the disadvantages of sacrificial piers, the implementation of additional piers can also be mentioned. In addition to being uneconomical, these also increase the blockage of the flow and, as a result, destroy the river banks. Among the obvious problems of creating a slot in the pier, the slot is blocked by floating debris, thus the reduction in the effective cross-sectional area of the pier in terms of its stability. For this reason, this method is not recommended when the strength and stability of the pier is of great importance. The existence of submerged vanes upstream of the pier could be considered as an indirect protection method, which in shallow rivers will have the possibility of colliding with the bottom of the vessels. In addition, these plates are weak in terms of strength. One of the disadvantages of a bridge pier with an irregular geometric shape, in addition to design problems, is the difficulty of its formatting and execution. By examining the disadvantages of the above methods, it can be stated that the collar method, in addition to being easier to implement, will bring better performance in reducing scour depth, increasing the bearing capacity of the pier, having no possible risks to aquatic life and vessels, etc. Many researchers have used laboratory and numerical methods in the past to assess the scouring around bridge piers, some of which have focused on straight paths such as Kirkil and Constantinescu (2010), investigated the scour mechanism around the rectangular bridge pier, perpendicular to the flow direction. The findings showed that one of the main factors in the formation of scour hole is horseshoe vortices that are formed upstream of the pier. Najafzadeh and Barani (2014) investigated the local scour around a pier embedded in cohesive soils in a laboratory channel. The piece of research explored the effect of parameters such as flow velocity, flow depth, initial moisture content, clay percentage and undrained shear strength in each experiment on scour depth. The results showed that the eventual scour depth decreased with the increase in undrained shear strength of unsaturated soils, while it increased with the increase in the Froude number. Moreover, for a constant Froude number, the eventual scouring depth increased with the decrease in clay percentage and soil moisture percentage. Das and Mazumdar (2015), reported the results of an experimental activity on the turbulent flow pattern around the two circular piers with 7 cm diameter and with distance of 3.46 pier width located along the longitudinal flow and with distance of 3 times of the pier width in the transverse direction, outside each other. The results showed that the depth of the deepest scour cavity around the pier groups was around 44% higher than the one pier. Horseshoe vortex formed around the eccentric rear pier with more power, which increased the scour hole in this area. Imamzadehei et al. (2016), investigated the scour reduction around the circular pier using armed soil by Geotextile coating in a different layer with a circular and oval coating pattern. The results indicated that by using geotextile with an appropriate cover around the pier, the scour location is moved to downstream and the scour depth is decreased. The amount of scour cavity also decreased after increasing the geotextile layers. Also, the oval coating pattern had a better efficiency compared to the circular one. Karimi et al. (2017), studied on the scour mechanism around an inclined circular pier with angles of deviation of 0°, 5°, 10° and 15° to the downstream direction along a straight path with different discharges 12, 14, 16, and 18 lit/s. The depth of the scour hole was also greatly reduced by tilting the piers. Also, more scour reduction was observed at different flow rates with angle of 15°. Chen et al. (2018), by installing the hooked-collar (single and double) around the circular pier, studied the flow and scour patterns in both experimentally and numerically. They pointed out that hooked-collar with a width of 1.25 and a height of 0.25 times the pier width. Installing of double hooked-collars at the bed level and 0.25 times the width of the pier under the bed level had the greatest effect on reducing scour. Both laboratory and numerical experiments showed that the maximum down-flow, along with the reduction in horseshoe vortex strength for hook-collar experiments, was significantly reduced compared to without collar experiments. Liu et al. (2019), conducted a numerical simulation to investigate the effect of inclined angle on flow characteristics around the parallel inclined piers at low Reynolds number. The angle of inclination of the piers from the vertical axis toward a downstream in the range of 0 to 60 degrees was considered. The results showed that the longitudinal currents are strongly influenced by the angle of inclination of the piers. Vortex currents near the piers were are significantly reduced by increasing the angle of inclination. For inclination angle less than 30°, the recirculation area with return flow at downstream of two piers were created and by increasing the angle of pier inclination, the vortices flow area at downstream of the piers were considerably reduced. Ghodsi et al. (2021) addressed the effect of various geometrical parameters on the maximum scour around a complex bridge pier under clear water conditions. They concluded that altering the pier geometry significantly influenced the maximum scour depth, so that by reducing the longitudinal extension of the pile cap from the column, an increase was observed in the maximum scour depth. Further, increasing the number of piles along the flow decreased the maximum scour depth. Najafzadeh and Oliveto (2021) predicted the scour rate around a pier group using four powerful artificial intelligence techniques. A wide range of experimental studies covering different arrangements of pile groups, non-sticky bed materials and clear water conditions were considered in their study to achieve reliable regression-based equations using artificial intelligence models. The results indicated that among the famous artificial intelligence techniques, multivariate adaptive regression spline (MARS), Evolutionary polynomial regression (EPR), gene-expression programming (GEP) and model tree (MT), respectively, enjoyed high accuracy in evaluating the scour depth. Mashahir et al. (2024) investigated the effect of single and double collars around the circular pier on the reduction of scouring around the pier under live bed conditions. A circular pier with a diameter of 0.04 m and a collar with diameter of 3 times the pier width were placed on the streambed level and double collars were installed, one on the initial level of the bed and one on a lower elevation. The results showed that the minimum and maximum scour depths fluctuated due to the movement of sediments during the experiment. By installing two collars, the average and maximum scour depths decreased by about 53% and 35%, respectively, in the highest flow intensity mode. The collar had a better performance in scour reduction in lower flow intensities. Najafzadeh and Sheikhpour (2024) examined the local scour depth around a group of piles exposed to regularwaves based on classification concepts and evolutionary algorithms. The study used four symbolic models of artificial intelligence to predict the ratio of local scour depth to pier diameter (S/D). The obtained results indicated that the regression equation provided by the MARS (multivariate adaptive regression spline) model performed better with the correlation coefficient [R] = 0.9297, the root mean square error [RMSE] = 0.3489, and the scatter index [SI] = 0.2765) in comparison with the other artificial intelligence models. Occasionally, given the topographic circumstances of drainage basins as well as the changeability of the river path in time and its tendency to create geometric cutoffs, the river is developed as bends with a central angle of above 90°. In the meantime, construction of road connections and vital pathways deems it necessary to build bridges over meandering paths. In fact, under some conditions occurring in drainage basins, bridge construction over bended rivers becomes indispensable. Since meandering paths have complex flow conditions compared to straight paths, there is a greater risk of scouring and bed and bank topography variations than that for straight paths and therefore the bridges are more prone to damage. Hence, investigation into flow and scour patterns around bridge piers situated within bends and recommendation of methods, such as collar installation around the pier, with the aim of reducing scour around bridge piers is among the appealing topics that matter to researchers and hydraulic engineers. Instances of bridge pier construction over meandering paths include the Mond bridge over the Mond river located in Bushehr, Iran, the István Türr Bridge located in a 180° bend over the Danube in Baja, Hungary, multiple bridges, including the Marscchallbrucke bridge, the Crown Prince Bridge, and the Moltke bridge, over the meandering river of Spree in Berlin, and the Michael J. E. Sheflin Bridge in Ottawa, Canada over the Rideau river. According to this issue, a lot of research has been done in open-channel bends such as, Barbhuiya and Talukdar (2010), in a rectangular channel with a 90° bend by 16 m long with a width and depth of 80 cm, three-dimensional pattern of turbulent flow and the resulting scour were experimentally investigated. The results showed that the flow lines tend to the concave bank at beginning of the bend and to the convex bank at the bend exit. The deepest scour cavity occurred at the 30° angle, azimuthal section near the outer wall with amount of nearly 0.17 times of the channel width. Unlike that, the largest sedimentary stack formed near the convex bank with a maximum height of 0.07 of times the channel width. The Intensity of turbulence flow increased close to the bed and also greatest down-flows close to the concave wall was 0.20 times the mean of longitudinal flow. Uddin and Rahman (2012), worked on the flow behavior and the process of bend eroding in the Jamuna River located in Bangladesh. This investigation revealed that the current velocity near walls is 1.1 to 1.3 times greater than the section averaged velocity. Also, the main reason of sediment transfer from the concave wall toward the convex wall or sedimentary stacks is secondary flows. Vaghefi et al. (2015), conducted their studies on deviation of streamlines and secondary current intensity on bed shear stress variations in a curved flume. By investigating the streamlines in the cross sections was observed that the maximum velocity was seen at the bend entrance near the convex wall and at the bend exit near the concave wall. The maximum secondary current intensity was observed in the upstream moiety of bend at the 60° and 80° cross sections. The maximum bed shear stress around the bend entrance happened close to the convex wall. Dey et al. (2017), studied experimentally on the protection of side wall erosion by using the placement of submerged plates in different positions of the 180° curved channel close to the concave wall. The submerged plates were fixed vertically with flow attack angle of 10°, 15°, 20°, 30°, and 40° by distance of 75 cm from each other. They found that in the without submerged vane test, the most bank erosion occurred between 120° and 140° angles. By installing the vane at angle of 15°, the greatest reduction in scouring was observed in this area. Vaghefi et al. (2018), examined the scouring around the three circular piers in the both vertical direction and toward the flow by clear-water condition with a 5 cm width and 15 cm distance from each other at angles of 60°, 90°, and 120° of bend at rate of 70-L per second. The results showed that the most critical state of local scouring occurred by establishing a pier at the direction perpendicular to the flow and at angle of 90 degrees. Also, in two positions of the piers at 60°, the largest area of scour cavity was created around piers and sand bars at the downstream side of the piers. The highest sand bar formed in the piers perpendicular to flow test at 90° angle with distance of 20% of the flume width from the convex wall at 156° position of the bend. Solati et al. (2020), experimentally investigated the topographic changes of the river bed under unsteady flow conditions in a 180° curved flume. In the study, the effect of flood hydrograph peak time on bed variations around the pier under the flood conditions with one or two consecutive peaks was evaluated. The main finding of the study indicated that in hydrographs with two different peaks and the same duration time, the scour depth is almost equal. In single-peaked analysis by changing hydrograph duration from 25 to 100 min, besides an increase in the maximum depth by 20%, the progression of sediments along the downstream straight path also increased by 150%. In single-peaked hydrographs, the bed topographic changes were almost negligible at the last 20 min of the experiment, but in double-peaked hydrographs, the scour hole depth continued to increase until the end of the experiment. Moghanloo et al. (2020a), experimentally investigated the effect of the thickness of the collar at level of 2 cm above the bed surface around the rectangular pier with the ratio of the collar width to the pier width equal to $W/b = 4$ on the flow pattern in the bend. They concluded that by increasing the collar thickness by a factor of 4, the collar edge caused flow obstruction and the longitudinal flows tended toward the bed by hitting the edge of the collar. The down-flows resulting from this collision intensified the downward flows and increased the maximum depth near the pier by 30% in relation to the lower thickness. Further, with the thickened collar, the maximum velocity near the bed was closer to the pier, and, at the flow surface in both thicknesses, the maximum velocity path was the same. Dehghan et al. (2021a) investigated the effect of the collar width around the rectangular pier on the flow pattern in the bend. In this research, the ratio of the collar width (W) to the pier width (b) was considered $W/b = 2$, 4. The experimental results showed that the presence of the collar around the pier caused the creation of eddy currents against the direction of the longitudinal flow, and doubling the width of the collar not only reduced the strength of the down-flows but also caused more deviation of the streamlines to the downstream side. Near the bed level, these streamlines were inclined toward downstream and the inner bank, and these flow pattern changes caused a decrease in the maximum power of the secondary flow by about 10% compared to the smaller width of the collar, and the maximum value of the vorticity flow also decreased by approximately 30%. Dehghan et al. (2021b) conducted their research on the efficacy of deviation and ratio of length to pier width on scouring around the pier located at angles of 60°, 90° and 120° of a 180° sharp curved channel. This research found that an optimal range for length of a rectangular pier in a sharp curved channel to reduce the amount of scour cavity depth near the pier was between 3 and 5 times the pier width. By increasing the deviation angle of the piers toward the inner and outer banks, the depth and volume of the scour hole increased significantly. Keshavarz et al. (2021) studied the influence of the shape of the pier along with collar on the flow pattern in the state of installation in the bend. In this research, two different shapes, one rectangular shape and another rectangular shape with a round nose (oblong) were used at the position of 90° in the 180° sharp bend. The results showed that in the presence of a rectangular pier with a collar, the deviation of the streamlines toward the outer bank and also the reverse flow upstream of the pier was more than those for the oblong pier with collar. In addition, by installing the pier with a round nose, the maximum power of the secondary flow decreased by about 35% compared to that for the rectangular one. The values of shear stress in the case of the oblong pier were also lower than those for the rectangular pier. The installation of the rectangular pier with the collar caused the creation of a region with significant turbulence kinetic energy near the inner bank in the position of installation at an angle of 90 degrees in the bend. Keshavarz et al. (2022) investigated the effect of the pier shape on the amount of scouring and also changes inbed topography in different positions of a 180° sharp bend. The results of this research indicated that piers with small width and sharp noses had less scouring depth, and on the contrary, the maximum scouring depth pertained to piers with wider widths and sharp edges. In addition, the highest depth of the scour hole near the rectangular pier with a sharp edges was 4.22 times the width of the pier at the position of 90°, and the lowest of this value was observed around the jou.sharp pier with the value of 2.12 times the pier width at the position of 120° of the bend. By locating a collar around rectangular round-nosed piers, Dehghan et al. (2023), investigated the effect of collar width changes on scouring parameters and bed topography changes in different positions of a 180° sharp bend. The results of this research showed that collars with a width of 3 to 4 times of the pier width had a better performance in reducing the maximum scour depth upstream of the pier. Increasing the collar width reduced scouring near the pier and increasing the length of the pier reduced the performance of the collar in protecting the pier from scouring, and also the time of occurrence of the maximum scouring depth was significantly reduced. The maximum amount of reduction in the highest scour depth by installing collar with a width of 4 times the pier width around the piers with a length of 2 and 3 times the width of the pier occurred by about 75 and 70%, respectively, compared to the pier without a collar. Keshavarz et al. (2024) conducted an experimental study on the effect of the pier shape along with the collar on the scour pattern. Considering a constant geometry and level of collar installation, bed topography variations on piers of 9 different shapes along a 180° sharp bend were experimented. The results showed that the elliptical-shaped pier located at the 120° position of the bend performed the best by 75% reduction in the maximum scour depth and 95% reduction in the scour depth volume. Since meandering rivers are the most common rivers in the plan and being more usage of the circular pier compared to other shapes and also in order to present a method to decrease the amount of scouring around the bridge pier, which is one of the important research topics of the modern day, the present study has attempted to experimentally assess the amount of scouring around curricular piers placed on a 180° sharp bend with the help of an attachment structure, collar. It should be noted that a similar study on the effect of these parameters on rectangular bridge piers has previously been conducted in 2020 by the researchers of the present study. In this paper, the achievements of this research are compared with the results of experiments carried out by Moghanloo et al. (2020b) that examined the experiments around the Oblong pier with a protective plate at two levels above the initial bed level, two levels under the initial bed level, and also at the initial bed level in four thicknesses such as 3, 6, 9, and 12 mm at 60°, 90° and 120° of a 180° sharp bend. The results showed that the lowest scouring rate occurs at the position of 120 angle of 180° sharp bends. Besides as the level of the collar gets closer to the initial bed surface from the negative side (under the initial bed level) and by reducing the thickness of the collar, the amount of local scour decreases significantly. Therefore, according to these results, as well as increasing usage of the circular cross section in the construction of bridge piers, in the present research, the circular bridge piers and also the level of 1 cm under the bed level have been investigated.

Experimental setup

This study was performed in a curved flume at the Persian Gulf University in Bushehr. Figure 1 shows a schematic illustration of the desired channel. The flume has a 180° curved path with a central radius (R) equal to 2 m and a width (B) of 1 m with ratio of $R/B = 2$ which is considered

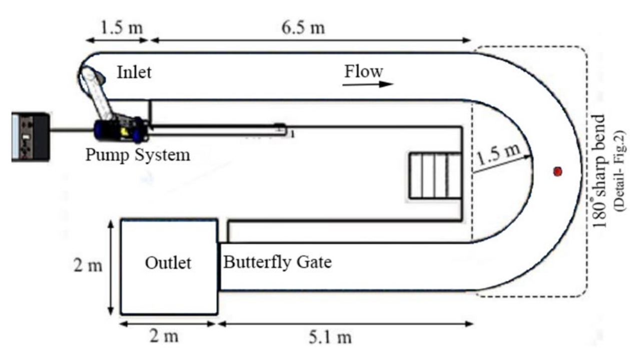


Fig. 1 Schematic view of the experimental setup

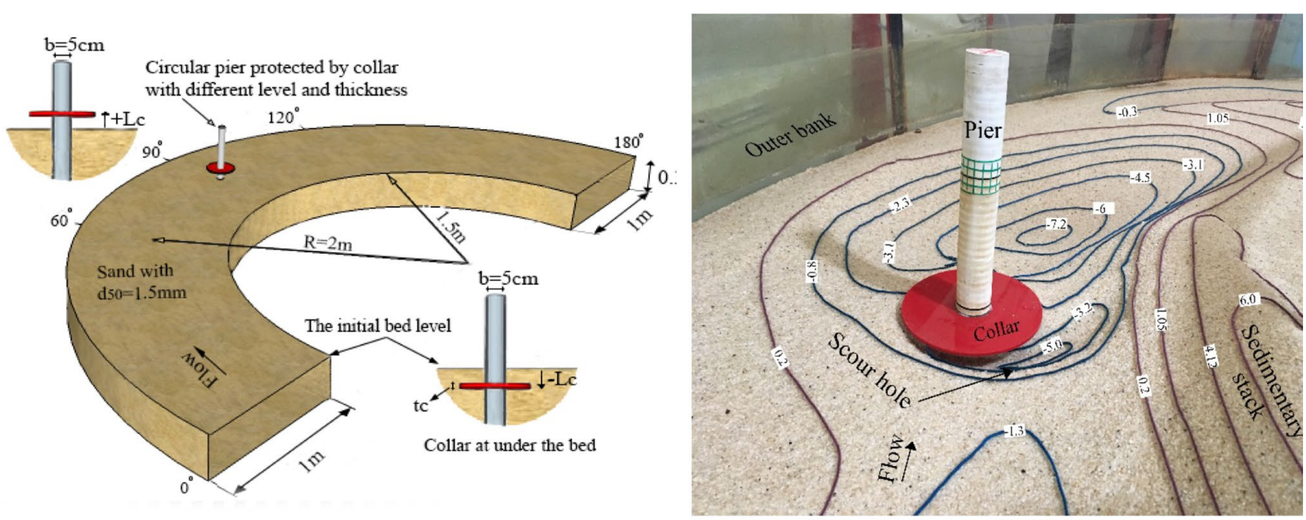
as one of the sharp curved channels (Leschziner and Rodi 1979). The glass wall of the flume is 70 cm and held by steel frames.

According to Raudkivi and Ettema (1983) aiming at prevention of ripple formation, the median diameter of the particles should be no smaller than 0.7 mm. For this purpose, the 30 cm of the channel height was filled with sediments with a median diameter of 1.5 mm with a standard deviation of 1.14 along the channel. The water flow was adjusted by using a flowmeter type ultrasonic placed on the inlet flow pipe and adjusted at 70 L per second. A butterfly gate placed at the end of the downstream path was used to adjust the current. The researches were conducted at motion threshold conditions with ratio of average approaching flow velocity in upstream path of the channel to critical flow velocity (U/Uc) equal to 0.98. This way the flow depth (y) is 18 cm, which is in accordance with Oliveto and Hager's (2002) study. Chiew and Melville (1987) state that in order to prevent scouring around the pier due to the impact of the walls, the diameter of the pier must be less than 10% of the width of the channel. Given that the channel has a width of 1m, the diameter of the circular pier diameter is 5 cm. In this experiment, approximately 95% of main scour depth by using a depth gage device observed in the first 15 h of the test, accordance with Melville and Chiew's (1999) study. For this reason, the equilibrium time to carry out the main experiments was set at 15 h (Vaghefi et al. 2017). Once the experiments time was determined, the collarless pier was placed at three positions of bend and the scouring process around the pier with circular cross-sectional area and bed topographic changes along the bend were measured by using a laser distance meter with a ± 1 mm precision. This measuring device which was installed on an aluminum linear rail and was moved along the channel in both cross and longitudinal sections, sends out a pulse of laser light on the bed topography. The time it takes for the beam to get there and back determines the distance measurement. By considering the initial level of the bed as zero level, the amount of scour depth or the sedimentation height was calculated. In order to control and reduce the amount of scour around the circular pier, the collar attachment structure according to Fig. 2a was installed around the pier with different thicknesses and levels. Figure 2b shows the displacement of bed sediments around the protected pier by plate. In this figure, blue and red lines indicate scouring and sedimentation levels, respectively. The material of pier and collar are fabricated out of PVC and Plexiglas, respectively. Pier is surrounded by a collar with a width (w) of 4 times bigger than the pier width which has been introduced as an optimum ratio according to Dehghan et al. (2023) and also placed at 6 levels (Lc) and 4 various thicknesses (tc).

Research limitations

This study was conducted in an advanced hydraulic laboratory but nonetheless, these results must be interpreted with caution and a number of limitations should be borne in mind.

1. The wall of the channel was made of glass and was completely smooth and rigid.
2. The bed was covered with sediments which had uniform grain size and its surface was completely smoothed at the beginning of the tests.
3. A constant flow rate was considered during the experiments.



(a) (b)

Fig. 2 Schematic view of **a** the bend and protected pier **b** bed level changes

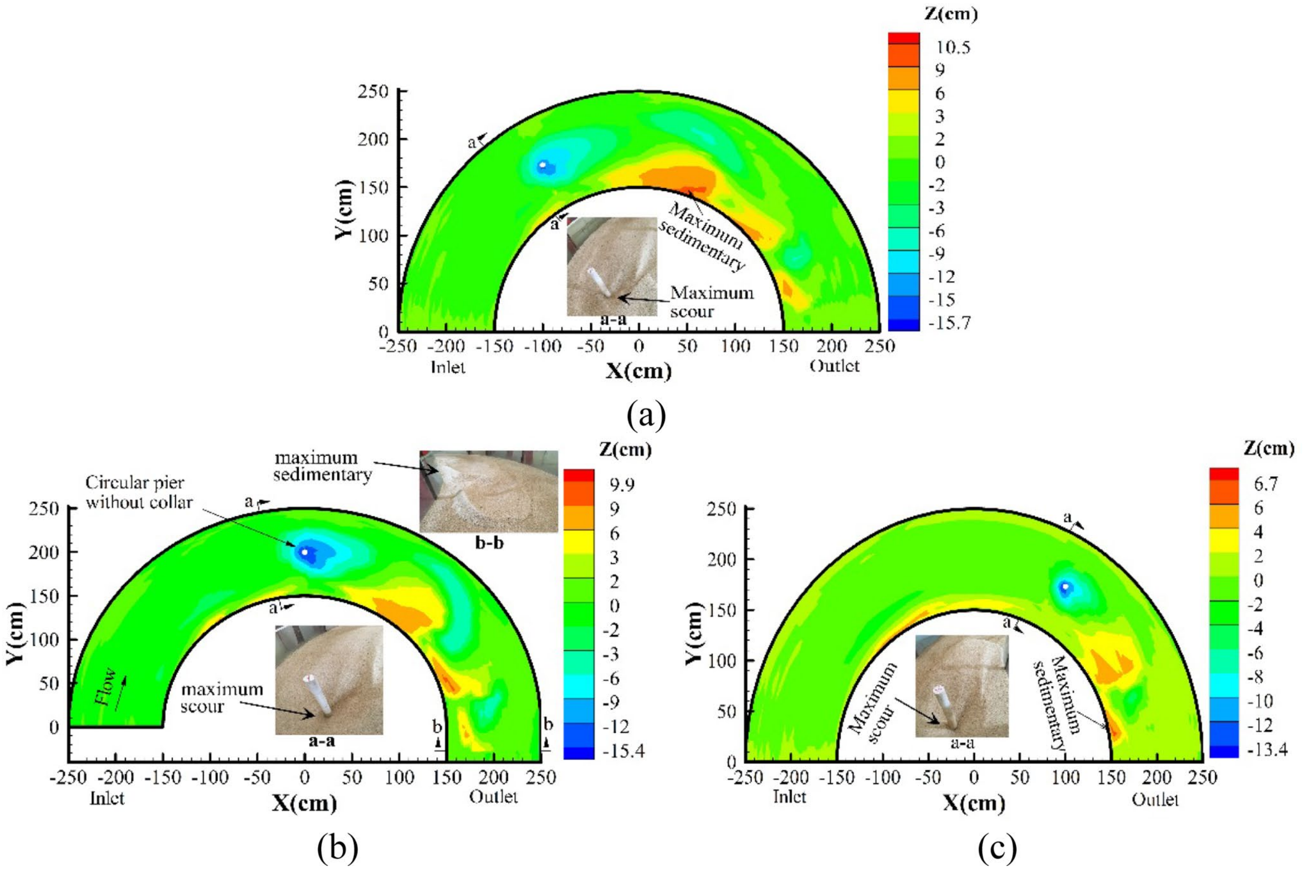


Fig. 3 Topographic changes in bed with collarless pier tests located at **a** 90° **b** 60° **c** 120°

Results and discussion

Figure 3 illustrates the bed topography changes at the bed of experiments carried out on circular pier without applying the collar at 60°, 90°, and 120°, for the purposes of comparison. As shown in Fig. 3a, by placing the pier at 60°, the maximum pier scour cavity depth is approximately three times the pier diameter (3.14b), and the sedimentary stack did not enter the downstream straight path. By comparing the bed topographic changes created in this case and located the pier at 90° (Fig. 3b), it is observed that at 90° the displaced sediments as a result of scouring enter the straight downstream path at a 5b rate. And also by transferring the pier to 90° angle the maximum scouring depth dropped by 2% compared to 60° angle. By locating the pier at 120°, as depicted in Fig. 3c, the scouring hole around the pier is smaller than when it is placed at 60° and 90°, it also has the lowest depth of scour.

By comparing the variations of bed topography due to deployment of collarless circular pier in different positions of bend with unprotected rectangular pier (Moghanloo et al. 2020b) was demonstrated that the depth of the scour cavity around the circular pier is on average of 10% less than the rectangular pier. Moreover, by placing the circular pier, the dimensions of the scouring hole have decreased in comparison with a rectangular pier and less sedimentation are formed in the first part of the bend. In addition to investigating the effect of the shape of the pier on scouring according to the results of Moghanloo et al. (2020b), with the level of the collar being closer to the bed surface from the negative side, which had a better performance in scour reduction, this study also included the level of −0.2b in the examined levels of collar with acceptable results. Moreover, this study also used a collar with a thickness of 3 mm due to its better performance in reducing scouring at 60° and 120° angles. All tests performed and measurement parameters can be found in Table 1. In this table ds-max and hs-max express the maximum depth of scour hole and the maximum height of sedimentation along the channel, respectively. Besides, their position is expressed by ∝ (degree). The location of the pier is indicated by θp (degree) and the amount of scour reduction compared to the pier without collar is shown by Sr (%). By comparing the results of the experiments related to the establishment of the circular pier protected by the collar at 90° position can be seen that placing the 3 mm and 6 mm thickness of collars in the range of the initial bed

Table 1 Comparison of present study results with Moghanloo et al. (2020b)

Test No.	Collar		θ_p(deg)	Present study					Moghanloo et al. (2020b)				
	Lc (cm)	tc (mm)		dsmax		Sr %	hsmax		dsmax		Sr %	hsmax	
				dsmax/*y*	∝(deg)		hsmax/*y*	∝(deg)	dsmax/*y*	∝(deg)		hsmax/*y*	∝(deg)
1	–	–	90	0.86	89	–	0.55	165	0.92	87	–	0.47	135
2	0.0b	3	90	0.28	91	67.5	0.49	138	0.29	89	68.5	0.45	140
3	0.2b	3	90	0.36	89	58	0.46	58	0.62	87	33	0.43	140
4	0.4b	3	90	0.53	89	38	0.42	57	0.66	87	28.3	0.51	65
5	−0.2b	3	90	0.32	93	63	0.45	135	–	–	–	–	–
6	−0.4b	3	90	0.33	93	62	0.51	145	0.32	86	56	0.43	60
7	−0.8b	3	90	0.50	87	42	0.51	145	0.69	87	25	0.51	110
8	0.0b	6	90	0.34	89	60	0.49	140	0.46	89	50	0.48	50
9	0.2b	6	90	0.51	89	41	0.40	120	0.51	87	44.6	0.49	140
10	0.4b	6	90	0.57	89	34	0.49	80	0.64	87	30.4	0.50	75
11	−0.2b	6	90	0.32	93	63	0.51	60	–	–	–	–	–
12	−0.4b	6	90	0.43	95	50	0.54	140	0.27	86	70.6	0.41	80
13	−0.8b	6	90	0.52	87	40	0.50	140	0.53	86	42.4	0.46	55
14	0.0b	9	90	0.36	87	58	0.48	70	0.48	87	47.8	0.49	75
15	0.2b	9	90	0.54	89	37	0.45	130	0.71	87	22.8	0.41	135
16	0.4b	9	90	0.56	89	35	0.36	55	0.70	87	24	0.48	75
17	−0.2b	9	90	0.32	87	63	0.42	135	–	–	–	–	–
18	−0.4b	9	90	0.45	95	48	0.42	135	0.36	89	61	0.41	135
19	−0.8b	9	90	0.47	87	45	0.46	132	0.48	84	48	0.48	60
20	0.0b	12	90	0.41	88	52	0.46	135	0.59	87	35.8	0.46	80
21	0.2b	12	90	0.54	89	37	0.46	130	0.76	87	18	0.49	60
22	0.4b	12	90	0.59	89	31	0.42	125	0.73	87	21	0.42	84
23	−0.2b	12	90	0.37	87	57	0.45	145	–	–	–	–	–
24	−0.4b	12	90	0.29	93	66	0.42	135	0.39	85	57.6	0.38	87
25	−0.8b	12	90	0.42	90	51	0.50	135	0.57	87	38	0.44	65
26	–	–	60	0.87	60	–	0.58	110	0.94	57	–	0.51	125
27	0.0b	3	60	0.28	61	68	0.57	125	0.33*	61*	65*	0.49*	155*
28	0.2b	3	60	0.31	65	65	0.52	115	0.41*	57*	56.4*	0.59*	157*
29	0.4b	3	60	0.46	59	47	0.51	59	0.45*	57*	52*	0.49*	150*
30	0.2b-	3	60	0.28	63	68	0.57	125	–	–	–	–	–
31	−0.4b	3	60	0.34	63	61	0.62	120	0.33*	59*	65*	0.57*	125*
32	−0.8b	3	60	0.42	63	52	0.56	113	0.56*	56*	40.4*	0.51*	115*
33	–	–	120	0.74	119	–	0.37	170	0.86	117	–	0.47	60
34	0.0b	3	120	0.23	125	70	0.52	180	0.13*	117*	85*	0.51*	70*
35	0.2b	3	120	0.26	123	65	0.45	175	0.23*	119*	72.7*	0.46*	60*
36	0.4b	3	120	0.44	123	41	0.42	145	0.24*	119*	72*	0.46*	60*
37	−0.2b	3	120	0.22	123	70	0.38	50	–	–	–	–	–
38	−0.4b	3	120	0.32	123	57	0.36	70	0.23*	123*	73*	0.44*	75*
39	−0.8b	3	120	0.48	126	35	0.47	70	0.43*	115*	50*	0.46*	60*

*Values are in conditions that thickness of collar is 6 mm

level (Lc = 0.0b = 0) to 2 cm under the bed (Lc = − 0.4b), the protective plate efficiency compared to positive elevation increased by an average of 60 percent and the maximum scour cavity decreased compared to the collarless pier. Based on the results presented in this table, when the collar was in positive levels, the location of maximum pier scouring holes were at nose of the pier but at negative levels, except for collar placement at Lc = − 4 cm, the scour hole was mostly located at sides or its downstream. In 60° and 120° angles it can be seen that the collar has functioned better in decreasing the amount of scouring at the initial and lower bed levels in comparison with when it was placed at higher bed levels. Moghanloo et al. (2020a) explored the flow pattern around the bridge pier protected by a collar and observed that installation of the collar at a higher level than the initial level further directed the flow layers toward the bed. This meant an increase in the down flow and hence exacerbation of scouring around the pier. However, with the collar placed at the level near the bed and at a negative level, the scouring onset upstream of the pier was significantly delayed owing to the impact of the down flow with the upper surface of the collar. Further, when the collar was installed deeper at a negative level (lower than the suggested value in this study), the down flows caused further scouring in the region around the pier from the very beginning of the test by moving the sediments around the pier. For example, in the experiment on placing the circular pier with the collar at 60°, it was seen that after setting the plate at bed level up to 0.4b under the bed level, the maximum scouring depth would decrease about 65% on average but at positive elevations this decrease was less. By comparing the obtained results with that of Moghanloo et al 2020b on rectangular piers, it can be concluded that the amount of scouring around collarless circular piers in different positions around the bend is less than that found in rectangular piers with the same placement position. Also placing the collar around the circular piers at 90° indicated the formation of scouring holes with a lower maximum scouring depth in comparison with rectangular piers.

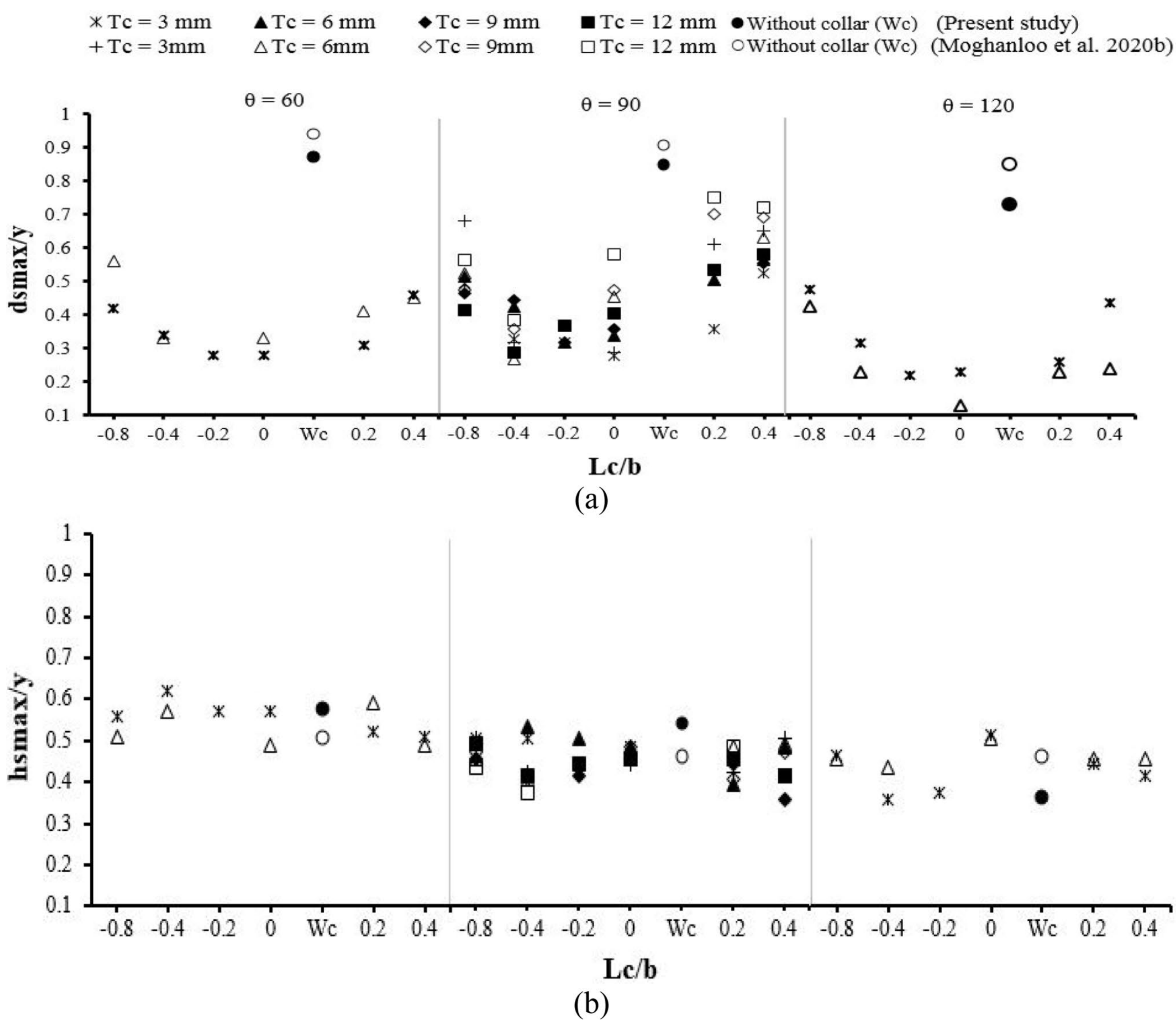


Fig. 4 Influence of thickness and level of collar on **a** maximum local scour depth **b** maximum height of sedimentation along the 180° sharp bend

Some of the results presented in Table 1 are also illustrated in Fig. 4 for better comparison. Figure 4a vividly shows how the circular pier undergoes less local scouring than the rectangular pier for different positions of the 180° sharp bend in case of a pier without collar. With the adjunct collar around the pier, this amount of scouring significantly decreased around both piers, this trend which can be observed with the less thick collar at the initial bed level and 0.2b lower than that. At the 90° position for collar at initial and above bed level, the performance of the collar is significantly affected by increased thickness. Almost for every case of protected circular piers at this position, the local scour is less than that of the rectangular pier. Unlike this position and regardless of the collar thickness difference around both piers, the protected rectangular pier at the 120° position undergoes less scouring for all the levels of the collar. The contrary is observed at the 60° position, where the protected circular pier has a better performance than the protected rectangular pier. Figure 4b illustrates the maximum sedimentation height under the influence of the thickness and level of the collar around both piers located at the 60°, 90° and 120° positions. According to this figure, prior to applying the collar around the piers at the 90° position, the maximum sedimentation height for the circular pier at the 90° position is approximately 0.1y greater than that of the rectangular pier, and with implementation of the piers at the 60° position, this value increases for both piers by about 0.04y. Unlike the two upstream positions, at the 120° position, the maximum sedimentation height associated with the rectangular pier without a collar was greater than the circular pier and it occurred in the first half of the bend as shown in Table 1. At this position, with the placement of the collar at different levels around the rectangular pier, the maximum sedimentation height is greater than that for the circular pier unlike the 60° position. The comparison of this research and the research done by Dehghan et al. (2023) indicated that with the establishment of the pier along with the collar at the position of 90 degrees, the maximum scour depth range in this article and Dehghan et al. (2023) occurred about 0.28y–0.59y and 0.22y–1.02y, respectively. Further, the maximum sedimentation height ranged about 0.36y–0.54y and 0.27y–0.57y, respectively.

Figure 5 indicates the impact of the collar thickness on topographic changes found around the circular pier placed

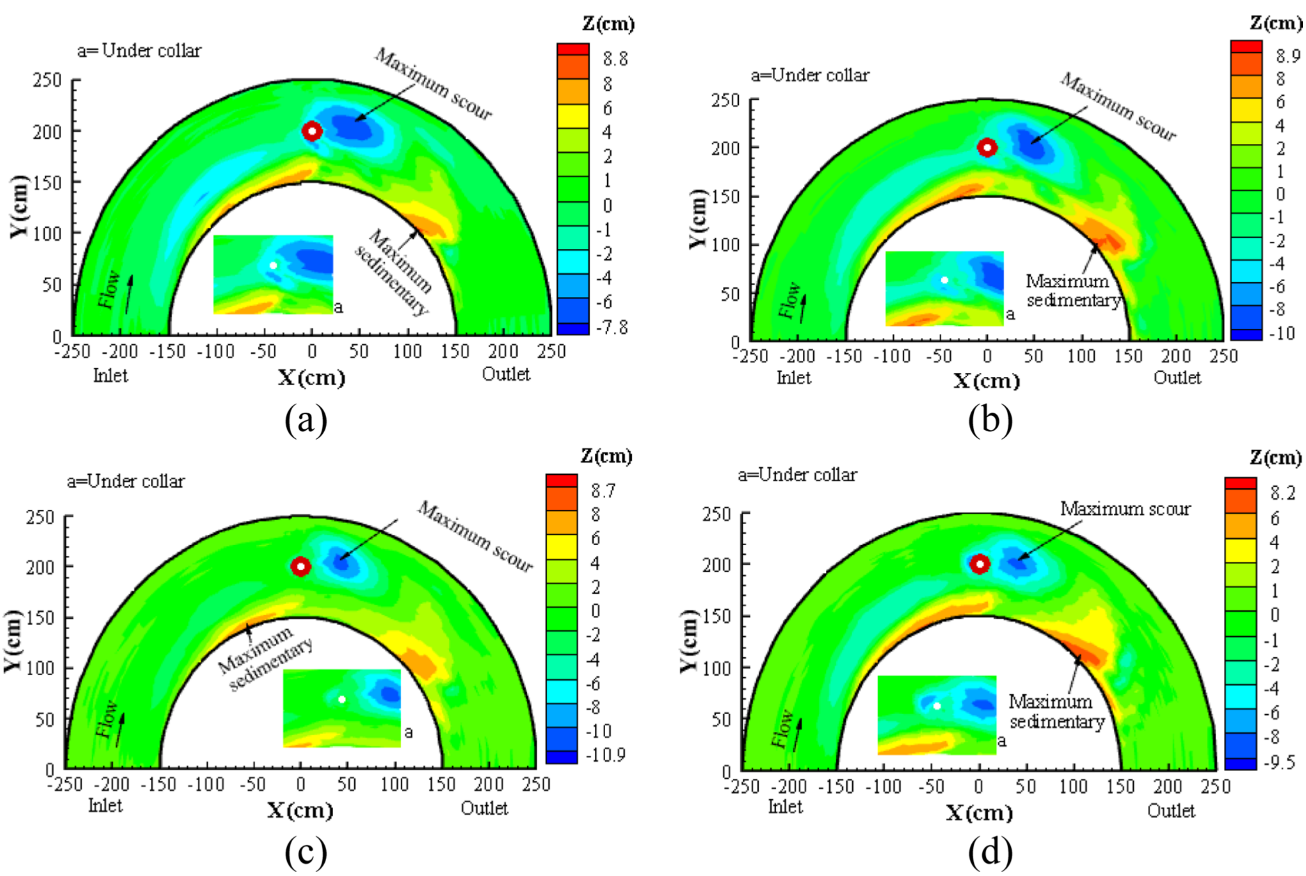


Fig. 5 Variations of bed topography due to locating the protective plate around the circular pier at incipient level of bed with thicknesses of **a** 3 mm, **b** 6 mm, **c** 9 mm and **d** 12 mm

at 90° from the bend. As shown in Fig. 5a, by installing a 3 mm plate around the pier, the depth of the scouring hole was observed 1.56b at distance of about 10b from the pier tail toward the downstream. According to Fig. 5b, by doubling the thickness of the collar the scouring hole, at first half of the bend moves toward the circular pier and connects to the scouring hole around it. In addition, the function of the collar in decreasing the deepest pier scouring hole has reduced by 8% in comparison with the case that has 3 mm thickness. By tripling collar thickness in Fig. 5c, unlike 3 and 6 mm thickness of collar in addition to reducing the scouring area and sedimentation shaped in upstream moiety of bend, the position of the maximum

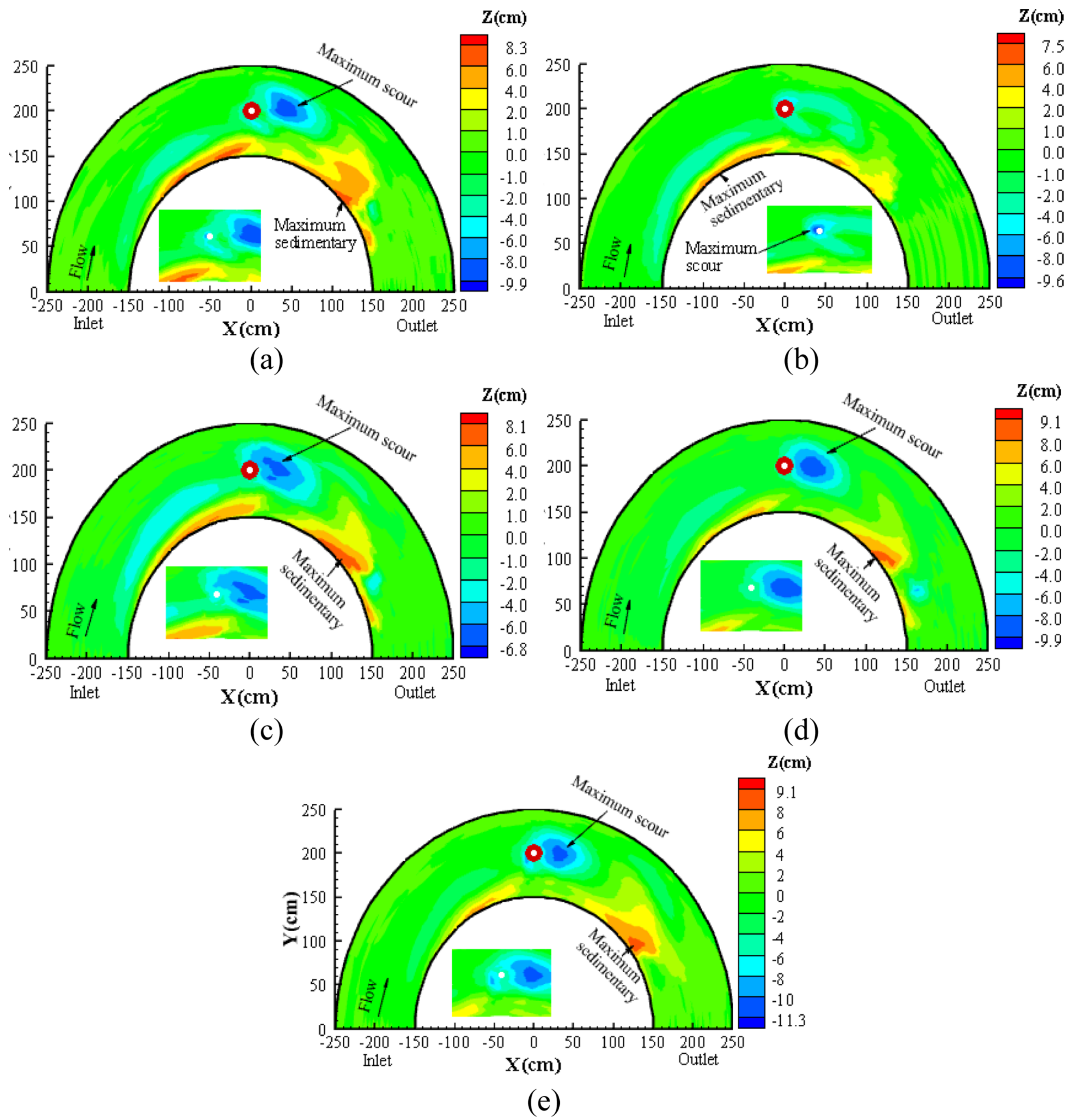


Fig. 6 Variations of bed topography with 3 mm thickness of collar at levels, **a** Lc = +1 cm, **b** Lc = +2 cm, **c** Lc = −1 cm, **d** Lc = −2 cm and **e** Lc = −4 cm and located at 90°

sedimentation height was also found in the first half of the bend and its height was 1.74b.

In a magnified version of Fig. 5d, it is observable that the deepest pier scouring hole has increased in comparison with other thickness, amounting to 1.47b. Similar to the study done by Moghanloo et al. (2020b), the present study has shown that increasing the thickness of the protective plate leads to an increase in the maximum depth of pier scour. Also unlike rectangular piers, circular piers have sedimentary stacks that are less dispersed and their position does not necessarily change as the protective plate thickness increases.

In Fig. 6a, the deepest scouring hole is increased in contrast to the plate placement at initial bed elevation. By locating the protective plate at an elevation of 2 cm and approaching the flow surface according to Fig. 6b, the ability of the plate in preventing the scour near the circular pier is reduced by about 30% against to installing the protective plate at the initial bed elevation. Figure 6c relates to the collar located at Lc = − 1 cm. Attaching the protective plate at negative level decreases scouring greater compared to a positive level. A comparison of Fig. 6b, c indicates that the maximum scour depth near the pier (pier nose), as also illustrated in the magnified figure, is a greater value with installation of the collar at the level of Lc = + 2 cm than that with the collar at the level of Lc = − 1 cm. However, the opposite has taken place downstream and the bed topography in case of Lc = + 2 cm has undergone fewer changes. It is seen in Fig. 6d, e that by attaching the collar at level of 2 and 4 cm under the incipient level of bed, in the upstream moiety of bend the scouring and sedimentation range is less than the level of − 1 cm (Lc = − 1 cm). As can be seen in the magnification of the protective plate at Lc = − 4 cm, with establishment of collar at this level, by accordance with Table 1, the deepest scouring hole close to pier is 0.5y and increased by about 50% in relative to the level of − 2 cm which is a considerable amount. In investigating the effect of collar levels around the rectangular pier (Moghanloo et al. 2020b), the results show that in collar establishment levels except Lc = − 2 cm, the location of the deepest scouring appeared at the pier nose but in circular pier at all levels except Lc = + 2 cm, the position of the deepest scour cavity is at the downstream of the pier. It should be noted that, the results of studies conducted by Moghanloo et al. (2020b) indicated that setting the collar under the incipient level of the bed and moving it closer to the incipient bed level leads to less scouring in compared to other levels. Hence, in this study locating the plate at the level of − 1 cm provided satisfactory results in reducing the pier scour compared to other levels.

The characteristics of scour hole formed around the protected and unprotected circular pier, placed at various bend locations are given in Table 2 for the purpose of comparing them with each other and with a rectangular pier. As it is evident, locating a 3 mm protective plate on the incipient level of bed around a circular pier placed at 90° reduces the length of the rectangle surrounding the scour cavity (Ls) in comparison with a collarless pier, and this dimension increases when the collar is placed at positive levels. On both levels, increasing the thickness of the protective plate increases the length of the rectangle environing the scour cavity. When the pier is located at 60° and 120° angles, placing the plate around the circular pier reduces the length of the rectangle environing the scour cavity in comparison with collarless piers. In the collarless piers, the length and width of the rectangle environing the scour cavity (Ws) of the rectangular pier relative to the circular pier is larger at different situations of the bend. Connecting the protective plate to pier at 90°, the length and width of the rectangle environing the scour cavity in the circular pier in comparison with a rectangular pier, respectively decreases and increases. As it is evident, by setting the protective plate at the incipient level of bed and lower than it around the circular piers the slope of the upstream wall of the scour cavity (Su) has decreased compared to collarless piers. In both piers, the maximum slope of the Su is found when the collar is placed at positive levels. Based on the table, in comparison with other levels, when the protective plate is located at negative levels, the Su related to the circular pier has increased. The minimum of the downstream wall of the scouring cavity's slope (Sd) in both piers is formed with installing the protective plate above the incipient level of bed. The highest amount of the slope of the scour cavity wall near the convex bank (Si) in the circular pier is found when the plate placed at the elevations of − 2 cm and − 4 cm. The slope of the scouring cavity's wall close to the concave bank (So) in both piers, at situation of 90° from the curved is increased when the collar gets away from the initial bed level. Overall, the Su, Si, and So of circular piers are less than that found in rectangular piers and the Sd of the scouring hole is higher.

Based on Table 1, placing the protective plate around the piers decreases the scour cavity depths but walls of that due to the vortices have moved toward the sides and leading to increase the dimensions of the rectangle surrounding the scour cavity. As the thickness of the protective plate increases, the volume of the scour cavity around the circular pile which located in the 90° position has increased too. The minimum volume of the scour cavity in circular pier which located at 90° angle is formed with protective plate at Lc = + 2 cm level while the same thing happens at Lc = − 2 cm level in the case of rectangular piers. When the pier located at 60° and 120° angles, the minimum volume of the scour cavity surrounding the circular pier is, respectively, found at the levels of + 2 cm and − 2 cm.

Figure 7 indicates the effect of the thickness and level of the collar around circular and rectangular piers on the value of area and volume of the local scour hole at the 90° position

Table 2 Characteristics of scouring holes formed around circular piers with and without collars (present study) and in rectangular piers (Moghanloo et al. 2020b)

Test No.	Collar		θ_p(deg)	Ws/b		Ls/b		As/b^2		Vs/b^3		Su		Sd		Si		So	
	Lc(cm)	tc (mm)		Circular	Rectangular	Circular	Rectangular	Circular	Rectangular	Circular	Rectangular	Circular	Rectangular	Circular	Rectangular	Circular	Rectangular	Circular	Rectangular
1	–	–	90	11	12	17.5	17.5	176.2	175.2	137.7	148.6	0.53	0.58	0.18	0.18	0.47	0.47	0.47	0.38
2	0.0b	3	90	10	9	16.1	20.2	147.8	133.3	61.1	67.7	0.11	0.31	0.16	0.14	0.19	0.53	0.24	0.21
3	0.2b	3	90	10.5	8	19.5	21.6	148.6	167.8	72.2	86.2	0.14	0.49	0.16	0.07	0.27	0.31	0.30	0.34
4	0.4b	3	90	7.5	7.5	19.5	25.1	77.3	128.9	17.5	62.7	0.50	0.53	0.08	0.08	0.32	0.35	0.47	0.46
5	−0.2b	3	90	8	–	14.7	–	126.6	–	49	–	0.11	–	0.12	–	0.29	–	0.17	–
6	−0.4b	3	90	9.5	6	16.1	18.2	156.2	115	85.7	41.6	0.16	0.11	0.21	0.15	0.37	0.46	0.27	0.46
7	−0.8b	3	90	10.5	10.5	17.5	20.9	194.8	170.9	132.7	96.9	0.17	0.25	0.25	0.12	0.35	0.51	0.32	0.30
8	0.0b	6	90	10	6.5	20.2	21.6	178.3	142.6	95.1	60.8	0.13	0.09	0.16	0.19	0.27	0.30	0.33	0.29
9	0.2b	6	90	10.5	7.5	19.5	21.6	154.7	135.3	63.1	61.2	0.48	0.38	0.07	0.06	0.24	0.26	0.27	0.28
10	0.4b	6	90	7.5	7.5	16.5	25.1	121.5	134	34.8	71.9	0.56	0.52	0.11	0.08	0.45	0.54	0.39	0.46
11	−0.2b	6	90	9.5	–	19.5	–	180	–	105.9	–	0.15	–	0.18	–	0.33	–	0.37	–
12	-0.4b	6	90	10	6.5	16.1	17.5	168.7	120.2	93.9	47.7	0.16	0.12	0.21	0.15	0.33	0.35	0.27	0.35
13	-0.8b	6	90	11	8	17.5	19.5	163.7	153.5	108.5	92.3	0.17	0.12	0.22	0.25	0.29	0.49	0.39	0.38
14	0.0b	9	90	10	6.5	20.2	25.1	173.5	135.6	104.5	58.1	0.14	0.35	0.18	0.05	0.37	0.24	0.37	0.35
15	0.2b	9	90	10.5	9	20.2	22.3	138.6	166.3	45.4	82	0.68	0.58	0.08	0.10	0.22	0.42	0.27	0.37
16	0.4b	9	90	7.5	9	16.1	21.6	92.1	155	23.9	81.2	0.54	0.41	0.10	0.09	0.30	0.45	0.34	0.45
17	-0.2b	9	90	9.5	–	16.8	–	154.7	–	73.2	–	0.14	–	0.16	–	0.31	–	0.31	–
18	−0.4b	9	90	8.5	6	16.8	21.6	127.2	132.9	64.3	55.4	0.19	0.12	0.16	0.14	0.41	0.37	0.36	0.42
19	−0.8b	9	90	9.5	7.5	14	19.5	144.1	134.7	93	70.7	0.22	0.10	0.33	0.21	0.45	0.36	0.61	0.32
20	0.0b	12	90	9	7.5	16.8	23	146.2	133.1	68.6	58.1	0.14	0.47	0.20	0.16	0.35	0.43	0.28	0.41
21	0.2b	12	90	10.5	8.5	19.5	21.6	149.3	155.6	61.8	76.6	0.52	0.64	0.08	0.10	0.26	0.56	0.29	0.44
22	0.4b	12	90	9	8	16.1	25	121.9	137.1	40.3	69	0.58	0.61	0.11	0.10	0.29	0.44	0.46	0.42
23	−0.2b	12	90	10	–	16.8	–	170	–	86.6	–	0.11	–	0.23	–	0.27	–	0.27	–
24	−0.4b	12	90	8	7	16.8	21.6	134.3	133.6	66.9	54.5	0.15	0.09	0.20	0.11	0.47	0.27	0.28	0.41
25	−0.8b	12	90	9.5	8	13.3	19.5	131.2	152.1	76.9	84.7	0.20	0.32	0.28	0.09	0.39	0.39	0.28	0.39
26	–	–	60	11	11.5	20.9	30	194.8	244.1	141.6	177.9	0.77	0.59	0.15	0.11	0.48	0.41	0.48	0.52
27	0.0b	3	60	9.5	9.5	31.4	42	199.7	228.2	77.5	111.8	0.10	0.21	0.08	0.09	0.30	0.37	0.27	0.30
28	0.2b	3	60	8.5	8	21.6	45.4	132.7	231.5	60.8	95.4	0.18	0.11	0.10	0.07	0.28	0.42	0.41	0.36
29	0.4b	3	60	8	7	31.4	31.4	141	183.5	33.4	85.3	0.12	0.10	0.05	0.09	0.26	0.37	0.33	0.34
30	−0.2b	3	60	8.5	–	31.4	–	168.5	–	85	–	0.09	–	0.11	–	0.45	–	0.32	–
31	−0.4b	3	60	8	8.5	24.4	35	160.1	235.4	84.5	123.5	0.17	0.18	0.10	0.09	0.39	0.47	0.39	0.37
32	−0.8b	3	60	8.5	8.5	19.5	25	158.8	222.2	85.9	141.8	0.22	0.16	0.12	0.16	0.50	0.69	0.27	0.34
33	–	–	120	9	11	10.5	10.5	100.2	125.4	64.6	82.5	0.26	0.42	0.24	0.37	0.48	0.63	0.48	0.47
34	0.0b	3	120	9	2.5	15.4	5.6	103.3	17.9	49.8	4.1	0.15	0.15	0.18	0.22	0.33	0.50	0.26	0.33

Table 2 (continued)

Test No.	Collar Lc(cm)	tc (mm)	θ_p(deg)	$^{Ws}/_{b}$ Circular	Rectangular	$^{Ls}/_{b}$ Circular	Rectangular	$^{As}/_{b^2}$ Circular	Rectangular	$^{Vs}/_{b^3}$ Circular	Rectangular	Su Circular	Rectangular	Sd Circular	Rectangular	Si Circular	Rectangular	So Circular	Rectangular
35	0.2b	3	120	9	2.5	14.7	14	100.6	29.4	57	5.6	0.22	0.20	0.24	0.20	0.43	0.43	0.34	0.38
36	0.4b	3	120	8.5	2.5	12.6	13.3	105.2	29.2	54	5.4	0.21	0.21	0.26	0.14	0.33	0.29	0.37	0.24
37	−0.2b	3	120	8	–	11.2	–	82	–	33.5	–	0.19	–	0.19	–	0.24	–	0.31	–
38	−0.4b	3	120	8.5	4.5	12.6	9.8	90.1	49.7	40.7	12.7	0.18	9.8	0.23	0.30	0.28	0.27	0.32	0.56
39	−0.8b	3	120	9.5	8.5	9.1	11.2	149.4	84.2	73.1	35.1	0.24	11.2	0.54	0.10	0.37	0.24	0.27	0.26

of the bend. As shown in Fig. 7a in case of the unprotected pier, the local scour hole area is greater in the circular pier than that in the rectangular pier. When the collar is placed at a level above the initial bed level, this area is greater in the rectangular pier than the circular pier and it also increases when the collar is thickened. At the level of 0.8b lower than the initial bed level, the scour hole area increases with a decrease in the collar thickness in both piers, so that the value for the circular pier increases by about 1.5 times when the collar thickness is increased by a quarter. Figure 7b depicts variations in the scour hole volume with respect to the change in the thickness and the level of the collar. Unlike area, the maximum volume of the scour hole prior to application of the collar occurred around the rectangular pier, which is indicative of increase in the scour hole depth around this pier. The local scour hole volume with the collar of different thicknesses applied at the initial bed level is greater around the circular pier than the rectangular pier, while increasing the collar level (above the base level), unlike the negative level (0.4b lower than the base level), increased the scour hole volume around the rectangular pier. In general, the area of the scouring hole in this research was measured to be about 77.3b^2–194.3b^2, which was found by Dehghan et al. (2023) to be approximately 12–212.4b^2 when placing the pier with collar at a position of 90°. In addition, the volume of the scour hole in this study and the research by Dehghan et al. (2023) is about 17.5–132.7b^3 and 1.6–178.4b^3, respectively.

Figure 8 illustrates the wall slopes of the scour holes around rectangular and circular piers in four different directions. As shown in Fig. 8a, the upstream wall slope of the scour hole (Su) is greater in the unprotected rectangular pier than the circular pier without a collar. For collar of medium thicknesses (6 and 9 mm), the wall slope resulting from using a rectangular pier decreased unlike thicknesses of 3 and 12 mm compared to the circular pier. It can be observed that the upstream wall slope is slightly greater than the other three slopes of the scour hole, which can be due to presence of upward flows near the wall surface, increasing the stagnation of the sediments and preventing their rapid removal. Figure 8b indicates how the downstream wall slope of the scour hole (Sd) in both piers is much smaller than the upstream wall slope, the prominent reason of which is the reduced power of down flows at the downstream side of the piers. This wall slope in the case of an unprotected pier is almost unchanged for both cross sections and it can also be stated that this slope was greater for every level of the collar around the circular pier than the rectangular pier. As shown in Fig. 8c, d, the scour hole wall slope in the inner bank direction (Si) and that in the outer bank direction (So) is greater in the rectangular pier than the circular pier for almost every level of the collar. The greatest Si occurred with application of the pier with a thickness of 12 mm at the

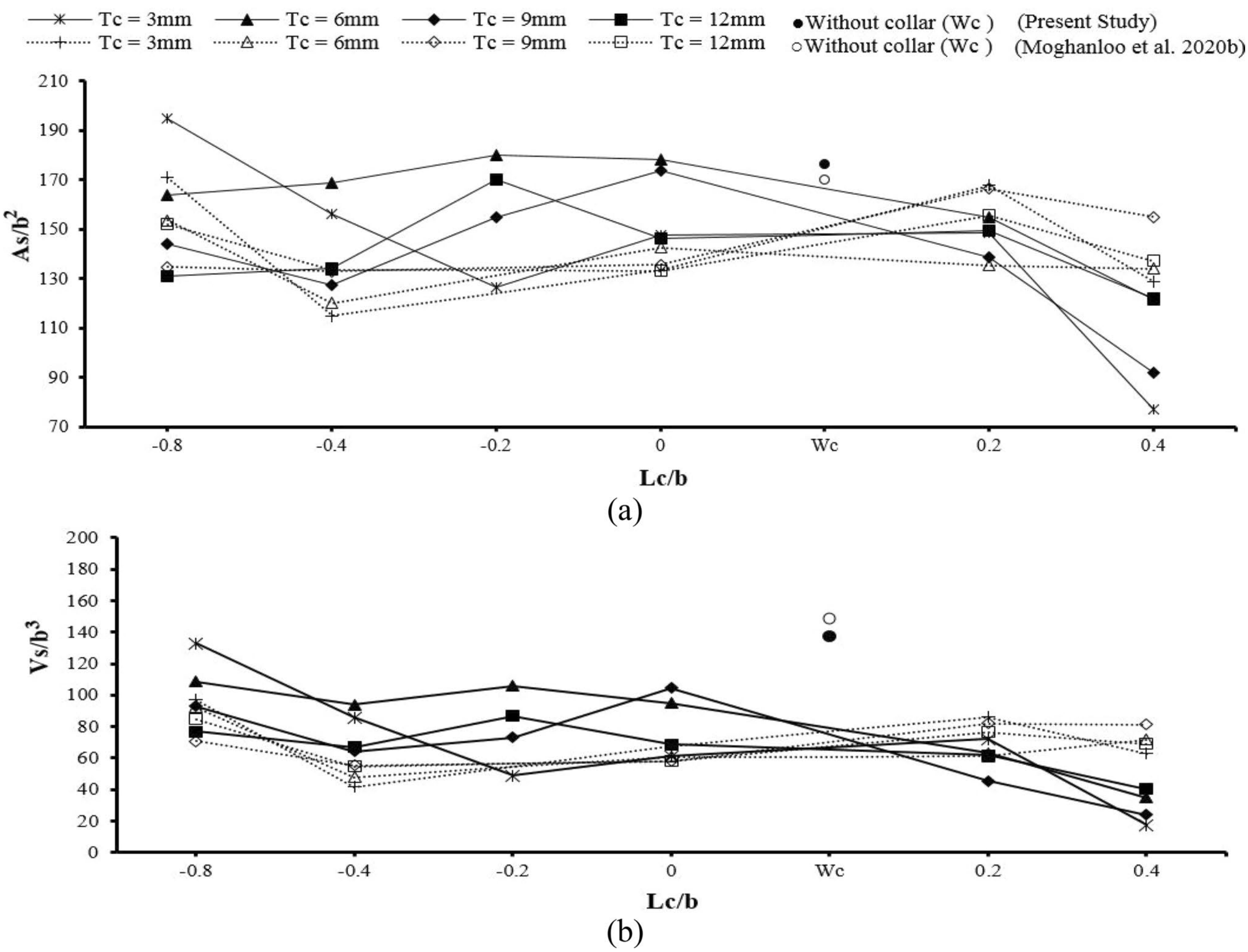


Fig. 7 Changes caused by the collar with different thickness and levels on **a** area of rectangle environing the local scour cavity **b** volume of the scour hole around the pier at 90° angle

level of 0.2b higher than the initial bad level around the rectangular pier and 0.4b lower than the initial bad level around the circular pier. Among the slopes investigated around the mentioned piers, the slope in the outer bank direction (So) has the greatest correlation.

Figure 9 depicts the topographic changes that occur on the bed when the collar is placed at different elevations with circular pier placed at 60°. According to Fig. 9a, with installing 3 mm plate at the incipient level only decreases the depth of the deepest pier scour cavity by 68%. Figure 9b, c depicts by setting the protective plate above the incipient level of bed in addition to reducing sedimentation near the convex bank, its location is also changed and transferred to the upstream moiety of curved. Moving the plate to under the incipient level of bed in Fig. 9d, the scope of sedimentation as well as the situation of the scour cavity downstream of the pile has the same characteristics as when the plate is placed at the incipient level of bed. Figures 9e, f indicate that establishing the protective plate at these levels the position of the downstream scour cavity changes and becomes closer to the pier. Additionally, the deepest pier scour cavity in this level shows a 50% increase in comparison with collar at Lc = − 1 cm elevation, as shown in Table 1. By disregarding the impact of collar thickness and comparing rectangular piers (Moghanloo et al. 2020b) with circular pier placed at 60°, it can be seen that the scope of sedimentation in circular piers and the scouring hole formed along the bend in such piers is lower than that of rectangular ones hence leading to a decrease in the amount of the maximum scouring hole depth. The changes of the scouring hole near the pier in this research locating the pier along with the collar at the position of 60° were about 0.28y–0.46y, which is almost the same as the range presented by Dehghan et al. (2023). Furthermore, in this situation, the maximum area and volume of scour hole were, respectively, about 1.76 and 2 times the values obtained in the work conducted by Dehghan et al. (2023).

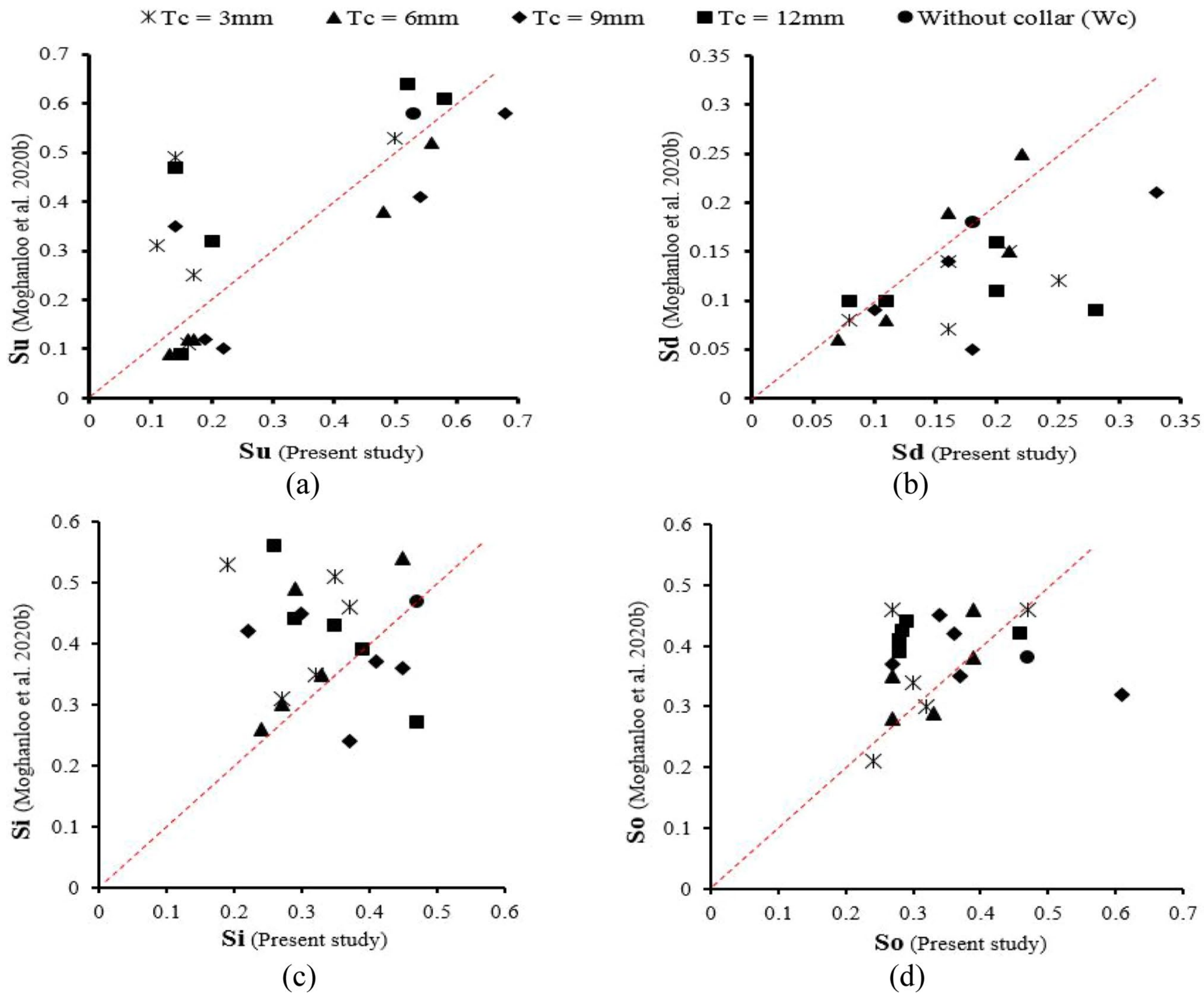


Fig. 8 Comparison of slope of the scour cavity walls. **a** Upstream wall of the hole **b** downstream wall **c** near the convex bank **d** close to the concave bank for pier at 90° angle

Figure 10 indicates the impact of a 3 mm collar level on the variations of bed topography around the circular pier in 120° position. By locating the protected pier at this position in the first part of the curved, the trend of bed topographic changes was observed same as the pier without the collar according to Fig. 3c. In Fig. 10a, the depth of the deepest pier scour cavity is reduced by about 70% in relative to collarless test. Additionally, this figure depicts a scour cavity with a depth of 1.8b located after pier. According to Fig. 10b, setting the protective plate at Lc = + 1 cm elevation the deepest scour cavity depths at the downstream increases and its dimensions in comparison with the protective plate at incipient level of bed are reduced. In Fig. 10c related to Lc = + 2 cm, the maximum depth of the downstream scour cavity is 2b and the upstream wall of this cavity has moved toward the pier location in comparison with elevations of protective plate at incipient level of bed and Lc = + 1 cm. In Fig. 10d, e which unlike the incipient surface of bed and positive levels the maximum sedimentation height of the entire bend according to Table 1 is formed in the upstream moiety of bend. The deepest scour cavity formed around the pier when the plate is located at 0.2b under the incipient level of bed (Lc = – 1 cm) is reduced by about 70% which indicates the highest amount of decrease in relation to other placement levels. The magnified image of Fig. 10f, indicates that by moving the plate away from the bed (in the negative level), the position of the downstream scour cavity changes and becomes closer to the pier, and as a result, it increases the dimensions of the pier scouring. By comparing Fig. 10 and locating the rectangular pier with collar at 120° angle (Moghanloo et al. 2020b), it can

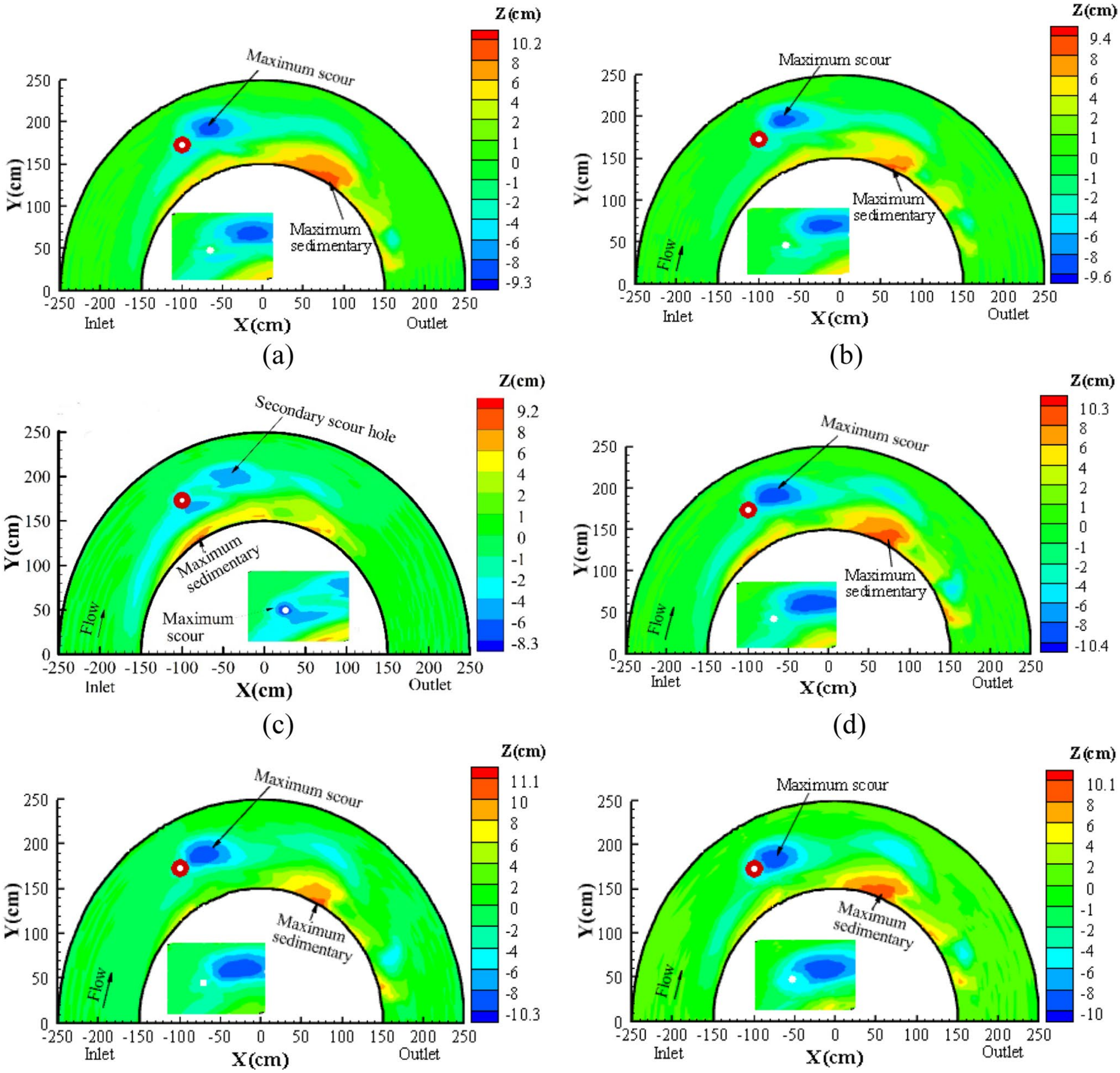
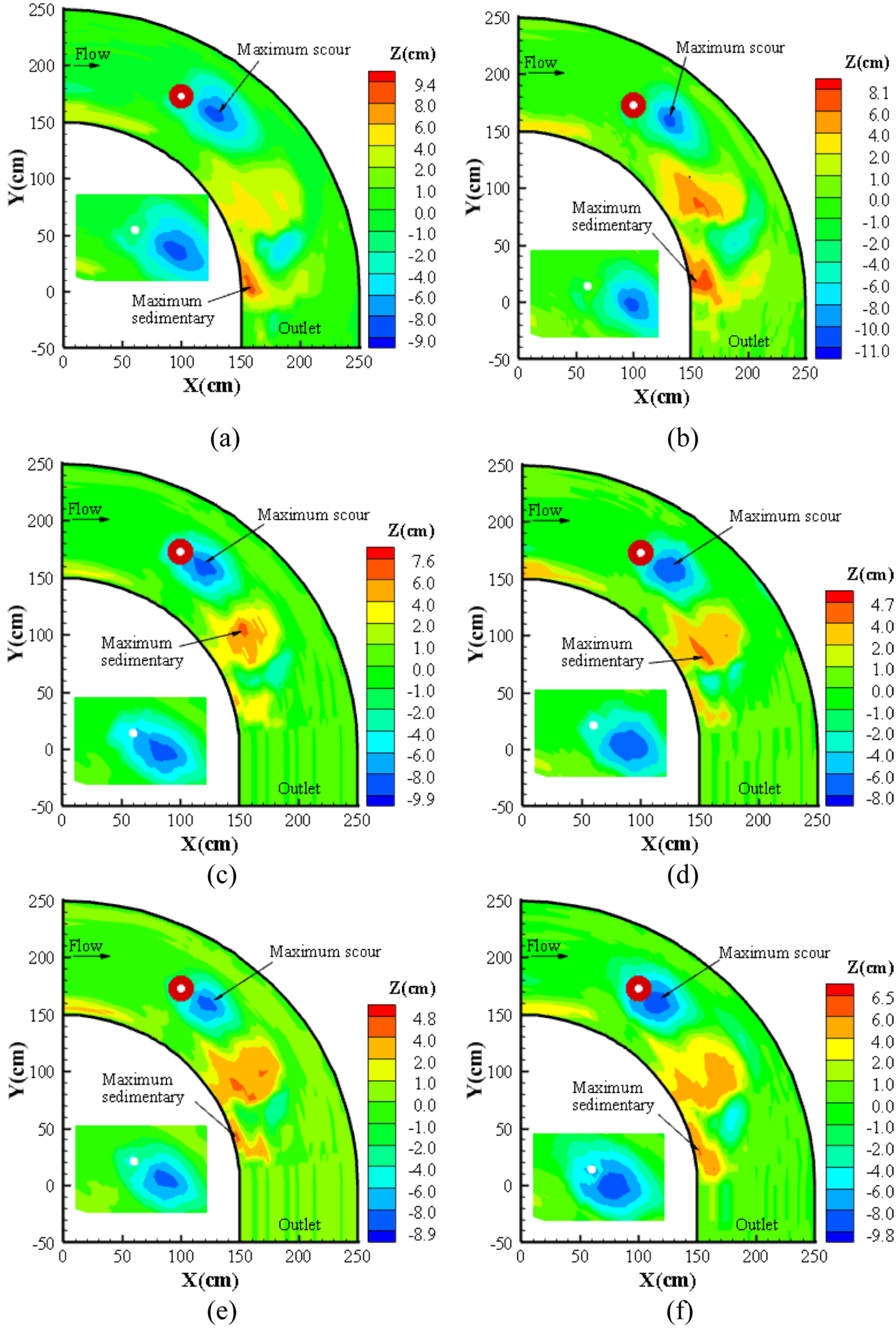


Fig. 9 Variations of bed topography with 3 mm collar placed at level of **a** initial bed surface, **b** Lc = +1 cm, **c** Lc = +2 cm, **d** Lc = −1 cm, **e** Lc = −2 cm and **f** Lc = −4 cm in location of 60°

be seen that in the case of circular pier with collars, sediments are formed in the downstream moiety of bend and based on Table 1, the pier scour depth increases relative to the rectangular pier. By locating the pier with collar in the 120° of bend, this study found the depth of scour hole in the range of 0.22y–0.48y, which had been previously reported to be about 0.07y–0.22y by Dehghan et al. (2023). This is due to the change in the position of the piers in this research from the middle of the bend to the second half of the bend and also the effect of the straight path downstream of the bend on the flow performance.

Conclusions

The set of experiments of this study was first performed to investigate i) the variations of bed topography with the establishment of a circular pier in three locations of 180° bend, ii) the effect of collar on the bed's topography and iii) the development of pier scour cavity. Also, the achievements of this research were compared with the results of a rectangular pier. In general, connecting the protective plate at the levels near the incipient level of the bed weakens the down-flows and horseshoe vortex, which


Flow
Maximum scour
Maximum sedimentary
Outlet
Z(cm)
9.4 8.0 6.0 4.0 2.0 1.0 0.0 -1.0 -2.0 -4.0 -6.0 -8.0 -9.0
Y(cm)
X(cm)
(a)
Flow
Maximum scour
Maximum sedimentary
Outlet
Z(cm)
8.1 6.0 4.0 2.0 1.0 0.0 -1.0 -2.0 -4.0 -6.0 -8.0 -10.0 -11.0
Y(cm)
X(cm)
(b)
Flow
Maximum scour
Maximum sedimentary
Outlet
Z(cm)
7.6 6.0 4.0 2.0 1.0 0.0 -1.0 -2.0 -4.0 -6.0 -8.0 -9.9
Y(cm)
X(cm)
(c)
Flow
Maximum scour
Maximum sedimentary
Outlet
Z(cm)
4.7 4.0 2.0 1.0 0.0 -1.0 -2.0 -4.0 -6.0 -8.0
Y(cm)
X(cm)
(d)
Flow
Maximum scour
Maximum sedimentary
Outlet
Z(cm)
4.8 4.0 2.0 1.0 0.0 -1.0 -2.0 -4.0 -6.0 -8.0 -8.9
Y(cm)
X(cm)
(e)
Flow
Maximum scour
Maximum sedimentary
Outlet
Z(cm)
6.5 6.0 4.0 2.0 1.0 0.0 -1.0 -2.0 -4.0 -6.0 -8.0 -9.8
Y(cm)
X(cm)
(f)

◂**Fig. 10** Variations of bed topography with 3 mm collar placed at level of **a** initial bed surface, **b** Lc = +1 cm, **c** Lc = +2 cm, **d** Lc = −1 cm, **e** Lc = −2 cm and **f** Lc = −4 cm in location of 120°

causes a reduction in pier scour. The following results were obtained from the presented study by considering the limitations presented in the research limitations section:

1. By installing the collar with 3 mm and 6 mm thicknesses in the range of initial bed level up to 0.4 times the pier diameter under the incipient level of the bed around circular piers at 90° locations, can help increase the functionality of the collar in comparison with other levels and hence lead to an approximately 60% decrease in the maximum scouring hole depth of circular piers.
2. By distancing the collar from the incipient level of the bed around the circular pier and placing it at 0.4 times the pier diameter above the incipient level of the bed, in order to decrease the depth of the scour cavity in comparison with the incipient level of the bed, the functionality of collar decreases by 30%.
3. The maximum scouring hole depth when the collar is located at above the initial bed level is created on nose of the pier but at under the initial bed levels except at 0.8 times the pier diameter under the incipient level of the bed, the maximum scouring hole depth has mainly occurred on the sides or downstream of the pier.
4. When the collar with 3 mm thickness is located at 1 cm under the incipient level of the bed at 60° and 120° angles, respectively, the maximum pier scour cavity decreases by 68% and 70% compared to collarless piers.
5. Analysis of the results for positions of 60, 90 and 120 degrees indicated that the optimal levels for installing the collar were, respectively −0.2b, 0b and −0.2b.

A comparison of the obtained results from this study with the research done around the rectangular piers, it can be seen that at 90°, the circular pier with and without collar had less scour than the rectangular pier. Also at 60° and 120° positions in the collarless piers, the scour cavity depths related to the circular pier are less than the rectangular pier.

Author contributions All authors contributed to the study conception, preparation material, performing laboratory tests, collecting data, data analysis, review and design. All authors read and approved the final manuscript.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Consent to participate The authors have read the final manuscript, have approved the submission to the journal and have accepted full responsibilities pertaining to the manuscript's delivery and contents.

Consent to publish The authors agree to publish this manuscript upon acceptance.

Ethical approval This paper has neither been published nor been under review for publication elsewhere.

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