Collars for Scour Reduction Around Different Shapes of Bridge Piers in a 180° Sharp Bend

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Abstract

Collars play an effective role in reducing scour by preventing direct collisions of the flow with the piers. Furthermore, because most rivers meander, this study considered various shapes of bridge piers with collars at various locations along a 180° sharp bend and compared the findings with those of similar cases with no collars installed. The findings show that the aerodynamic shape of the pier and the collar as well as the location of these structures have significant effects on the amount of scouring. The maximum and minimum scour depths which are 2.58 and 0.8 times the pier diameter, occurred in bridge piers with collars at jou.round piers installed at 60° and elliptical piers at 120°, respectively. Moreover, another finding of this study was that use of collars played a significant role in reducing scouring. The greatest effect of the collar was found on the elliptical pier located at the 120° angle with the reduction of the scour depth by 75% and the scour hole volume by 95%.

Keywords 180° sharp bend · Bridge pier · Collar · Pier location · Pier shape · Scour

1 Introduction

Bridge pier scour is one of the most important factors involved in bridge destruction and has always been a problem considered by hydraulic engineers. The water flow' impact with a pier generates a horseshoe water vortex in front of and a wake vortex behind the pier. The horseshoe vortex plays the primary role in the scouring process. This flow pattern around the pier results in generation of sedimentary dunes downstream of the pier and a scour hole around the pier; if further deepened, the scour hole can entail bridge failure. Therefore, understanding the scour pattern around bridge piers is of utmost importance and engineers have always addressed this and methods of reducing the scour depth; a number of these studies are cited below.

Scour and flow pattern mechanisms at a group of semi-integral bridge piers in a straight path were investigated [1]. Scouring around a bridge pier mounted on top of a pile cap in a straight path was experimentally examined. A range of pile-cap-to-pier thickness ratios were tested considering various levels of the pile cap relative to the bed level [2]. The scouring phenomenon at circular-, upstream-, and downstream-facing round-nosed piers in a laboratory flume with a straight path was explored [3]. An experimental study on scouring around twin circular bridge piers placed in a straight water passage was conducted [4]. A senary pier group arranged in different regular, angled, and staggered configurations with various distances of piers from each other in a laboratory channel with a straight path were studied. Results indicate that using such arrangements would reduce the scour hole volume and depth by 27 and 22% respectively, compared with the single-pier case [5]. Scour around an oblong pier in a laboratory channel with a 180° bend was studied. It was found that the maximum scour depth occurred at the pier installed at 90° of the bend

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[6]. Experimental data studied and compared the results with the results of current relations and a relation for estimating the scour hole depth was proposed [7]. Scouring at twin circular piers aligned with a flow, twin piers at an angle to the flow, and triad piers perpendicular to the flow in a straight path were experimentally studied [8]. An inclined circular pier set up in a 180° sharp bend was experimentally examined [9]. Scouring around a group of bridge piers aligned with the flow in a straight path was experimentally studied [10]. Scouring at triad piers in a straight path was experimentally studied [11]. Scouring around a triad of circular bridge piers with piers installed in 2 positions with respect to the flow, perpendicular and streamwise, in a channel with a 180° bend was explored [12]. The flow pattern and scouring around 5 different pier forms in a straight channel were considered. It was found that the maximum scour depth occurred at the upstream side of the rectangular pier [13].

Engineers have always sought ways to reduce scour depth. Applying protective structures such as collars is one of the methods that has attracted several researchers. As previously mentioned, the flow is deflected toward the bed when it has an impact with the pier, and this leads to generation of a down-flow and weakening of the bed. Consequently, the longitudinal flows have the bed materials take a downstream direction and this in turn results in scouring. The collar is applied around the pier as a cover and causes a reduction in the power of down flows impacting it. In addition, the collar changes the direction of the down flows, leading to a less and weaker impact of the flow with the bed. Therefore, not only is the scour hole depth lowered, but the location of its development also further distances away from the pier. The following is a review of the literature on the effect of protective structures on the scour around piers.

Scour mitigation around a circular pier considering the influence of protective structures, collars, and slots in a laboratory channel with a straight path was explored [14]. The effect on scour control of collar level and dimensions, the angle of the pier, and the flow direction around rectangular bridge piers in a straight-path laboratory channel were studied [15]. Experiments to analyze the effect of multiple collars around a circular pier in a straight water passage were conducted [16]. The simultaneous effects of riprap, as well as independent and continuous collars, on scour reduction around twin circular piers placed in a straight channel were experimentally studied [17]. Collars and submerged vanes around rectangular bridge piers in a straight passage were experimentally compared and various protective structures in both single and multiple cases were addressed [18]. The effect of riprap and integration of riprap and collars on scour reduction around rectangular bridge piers in a straight passage were experimentally

studied [19]. Temporal variations in the depth of scour around an oblong pier installed at 60° of a 180° mild bend with and without the presence of a collar were investigated. Results indicate that widening the collar reduces the scour depth [20]. Scour at a single rectangular bridge pier with a collar in a 180° mild bend was studied. Four different widths of the collar were used at 4 different levels in those experiments [21]. The role of a slot in a circular pier in scour reduction in a channel with a straight path was examined [22]. The performance of a triad of vertical collars around a circular pier in a straight path was studied [23]. The performance of protective structures on scour around bridge piers over a linear path was examined. Results indicate that using collars, flow deflectors, and sacrificial piles upstream of piers reduced scour by approximately 90% [24]. The role of a subsidiary triangular pillar at the upstream side of a solitary circular bridge pier in scour reduction in a straight path was experimentally explored [25]. The effect on scour reduction of creating holes with various orientations in a pier on a straight path was studied [26]. The flow and scouring patterns around a circular bridge pier protected by a hooked collar in a straight path both experimentally and numerically were examined [27]. A submerged weir downstream of a circular bridge pier at various intervals in a laboratory channel with a straight path was installed and the scour mechanism with clear-water and live-bed conditions was studied [28]. Experiments to examine scouring around circular bridge piers with a collar in steady and unsteady flows in a straight path were conducted [29]. The function of a slot of various lengths regarding scour mitigation in a circular bridge pier in a straight path was examined. Results demonstrated that lengthening the slot reduced the depth of the scour hole [30]. The outcome of using submerged vanes of various lengths and angles for scour reduction at a circular bridge pier in a channel with a 180° sharp bend was investigated [31]. The role of collar thickness and level in scour reduction around an oblong pier located in a 180° bend in an experimental investigation were studied [32]. The role of a collar in reducing the temporal scour developed around a circular bridge pier was examined. In this study, various dimensions and levels of the collar were tested in clear-water conditions [33]. The effect of ice cover placed at the water's surface and submerged in water on scouring around a circular pier in a straight path was explored. The experiments were done on both smooth and rough surfaces. The results suggest that an ice cover around a pier increases scour under every condition. The results also indicate that increasing the flow velocity under submergence conditions leads to further scouring, causing greater scouring at every submergence level for the rough ice cover than for the smooth ice cover [34]. The effect of the ratio of length to width of an oblong pier, as well as the skew angle of the

pier, on scouring in a channel with a 180° bend were investigated [35]. The function of a flexible and permeable collar under clear-water conditions were considered. In that study, chains with 3 different diameters (5, 10, and 15 mm) were used to model the collar. The experiments were done for U/Uc = 0.73, 0.85, and 0.96. The findings suggest that increasing the diameter of the chain reduces the maximum scour depth [36]. The role of collars in causing variations in the maximum scour depth site downstream of bridge abutments and piers was explored. The abutment and collar tests were done under clear-water conditions, considering various lengths of abutment and a constant size and location of the collar. However, the pier and collar tests were done on a pier with a constant diameter and collars of various sizes at various levels [37]. A new type of ring-type collars and spiral threading at a circular pier in clear-water conditions was examined. In that study, the rings were tested at various distances and angles. Moreover, the spiral threading was analyzed at 4 different heights [38]. In an experimental study, the role of a collar base and a collar column in scour reduction around a monopile foundation under steady conditions were explored [39]. A new collar design to examine scour reduction around a circular bridge pier in an unbending path in an experimental and numerical study was applied. The outcome showed that that type of collar reduced the scour depth and volume downstream of the pier by approximately 69.7 and 75.7% respectively [40]. The performance of a collar and a suction system in isolation and in combination in a straight path were examined. The isolation experiments analyzed collars of various dimensions and the suction system at various levels. Then, combinations of the collar and the suction were investigated [41]. The performance of a collar with an asymmetrical shape in 2 forms and at 3 layers was studied. The results indicated that using a collar not only reduced the scour depth but delayed the scour hole formation. Also, that function was empowered with larger collar sizes. The lower levels of the collar also improved its effect against scouring [42].

The cited studies well indicate that application of different methods of scouring control, such as using collars, reduces scouring. Most of these studies were conducted on straight paths, whereas the greater complexity of the flow pattern in bends makes scouring control even more important. In addition, earlier research was conducted on the effect of different collar parameters, such as dimensions, thickness and elevation, and also investigated integration of collars with other methods. However, another important parameter which can have a substantial effect on the performance of collars, particularly in bends, is the collar's shape, which is a function of the pier's shape and has rarely been explored comprehensively.

How the shape of a bridge pier installed in a 180° bend in bed topography caused alterations in the bend and the local scour hole variations was experimentally studied in [43]. 9 different pier shapes at various angles of the 180° bend are used to examine the total bed topography and parameters such as the maximum scour depth and sedimentary height, the scour hole volume, and the shape coefficients (Ks's) of the piers.

This work repeated every previous experiment conducted in [43] by creating the collar protective structure connected to the pier in the same positions as in that study, and variations in various scour and bed topography parameters are measured. This study aimed to analyze the effect on the amount of scour of using a collar and pier as a combined structure with various shapes and installed at varied locations in a 180° sharp bend. Among the other aims of this work was examining the collar's performance on scour reduction around the piers compared with an unprotected pier.

2 Materials and Methods

The tests in the current study were run in a curved channel composed of a 180° bend. That channel is shown in Fig. 1. The rectangular section of the channel was 1 m wide and 70 cm high, and the lengths of the upstream and downstream straight channel parts were 6.5 and 5 m respectively. The central curvature radius of the bend was 2 m. In that channel, R/B = 2, where R is the central curvature radius, and B is the channel width. In addition, the study used particles with d_{50} = 1.5 mm with a standard deviation of 1.14 ($\sigma_g = (d_{84}/d_{16})^{0.5}$ = 1.14). Every experiment was done under incipient motion conditions at the upstream straight path of the bend with U/U_c = 0.98, where U is the mean flow velocity, and U_c is the critical velocity. The flow rate was 70 L per second, and the flow depth read at the end of the upstream straight path was approximately 18 cm. The Froude and Reynolds numbers were calculated as 0.3 and approximately 50,000 respectively.

The following shapes were used with the collar for doing the tests: oblong, circular, rectangular, sharpnose, octagonal, hexagonal, elliptical, Joukowsky sharpnose (jou.sharp), and Joukowsky roundnose (jou.round). Moreover, the results of experiments conducted in [43] with no collars installed were incorporated to compare them with the results of piers reinforced by collars. Piers with a width and length of 5 and 20 cm respectively (L/D = 4, where L is length and D is pier width) were used in the experiments. Also, to find the scouring results of using a collar, collars 4 times as wide as the pier (Dc/D = 4, where Dc is the collar width) were used. Additionally, it was found that a collar 0.12 D thick at 0.4 D under the initial bed level had the

Fig. 1 **a** Laboratory channel used in the experiments, **b** The device collecting the temporal variation of the scour hole depth

best performance [32]. Hence, in this study, that same thickness and depth of collar were used.

The collar width was 20 cm. The joukowsky pier was placed in the streamwise direction both on the sharp nose (jou.sharp) and on the round nose (jou.round).Thus, the experiments used 9 different shapes of the pier with a collar at 3 different positions (i.e., the 60°, 90°, and 120° angles). The results of 27 tests previously conducted [43], were incorporated to compare them with the cases with collars installed. Table 1 shows the shapes of the piers and collars and their dimensions. Before beginning the tests, a test was carried out for determining the relative equilibrium time. In this test, an overall equilibrium test was conducted in 34 h. Then it was determined in this test that 95% of the maximum scour depth occurred in the initial 15 h of the test and therefore this duration was selected as the relative equilibrium time [43, 44].

3 Results and Discussion

Table 2 shows the results of experiments conducted on 9 different shapes of the bridge pier with a collar. The results of those tests were compared with those of collar-free tests [43] and the percentage of change in each parameter due to the use of the collar was calculated.

In Table 2, dsmax is the maximum scour depth, hsmax is the maximum sedimentation height, b is the distance from the inner bank, V is the scour hole volume, Lms is the length of sediment movement downstream, and θ is the distance from the beginning of the bend in degrees. Table 2 shows that the maximum scour depth in most cases where a collar was used occurred downstream of the piers, because incorporating a collar caused much energy loss and deviation in downflow streams after their impact with the collar. Therefore, in most collar experiments, the maximum scour depth occurred downstream of the piers under the influence of horseshoe vortices. However, according to the

results, in most experiments without collars, the maximum scour depth occurred by the upstream nose. That is due to the impact of the flow with that nose and the generation of downflow streams with a great amount of power. Hence, collars not only reduce the size of the scour hole at the piers but also change where the maximum scour hole depth occurs. Table 2 shows that the maximum and minimum scour depths in cases with collars occurred at jou.round piers installed at 60° (Fig. 2a) and elliptical piers installed at 120° respectively, at values of 2.58 D and 0.8 D respectively. The shape of the jou.round pier was asymmetric, and it confronted the flow with its round nose, which might be the reason for the high amount of scour around that pier.

The sediments collected around the piers were transported to the downstream side by the flow, generating sedimentary piles. The highest sedimentary piles occurred downstream of the circular pier installed at 60° near the inner bank at 115° at a value of 2.22 D (Fig. 2b).
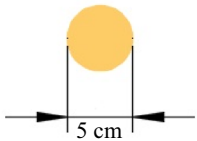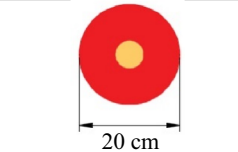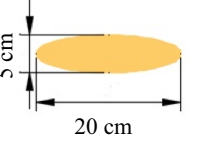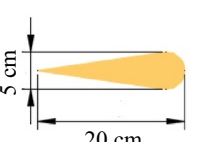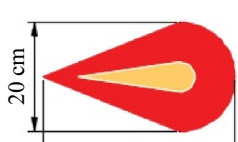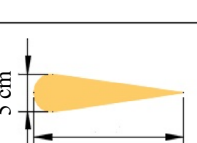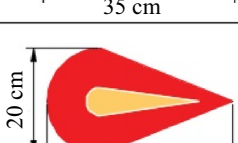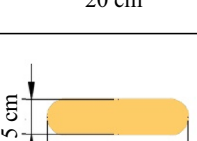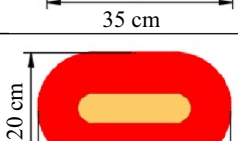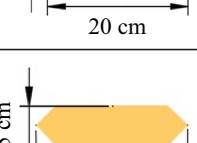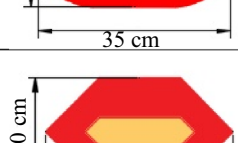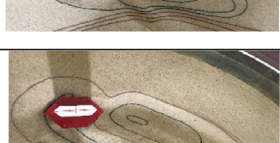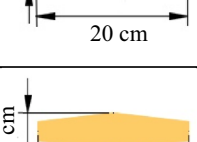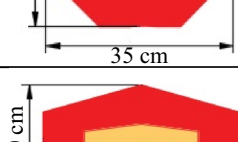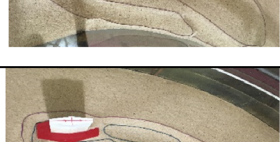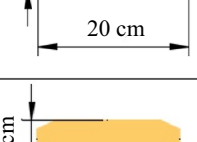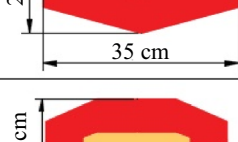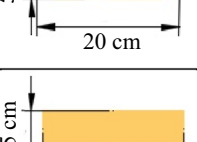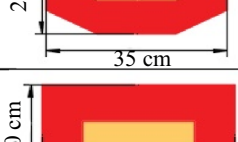
Regarding the sediments' downstream reach, as shown in the table, the materials around the oblong pier installed at 60° had the maximum reach for up to 80.2 D of movement (Fig. 2c), and the sediments around the hexagonal pier installed at 120° had the minimum reach for up to 21.D of movement (Fig. 2d).

The greatest volume of the hole occurred in the case of a rectangular pier installed at 90° at a value of 152.8 D^3. Due to its wide nose and the sharpness of the nose edges, that pier demonstrated a greater resistance against the flow and created a hole with a significant volume (Fig. 3a). In contrast, the minimum scour volume was created around the elliptical pier installed at 120° at a value of 3.5 D^3. Due to its aerodynamic nose, that pier created less flow separation, and with its less deviation in the flow (Fig. 3b), generated a hole with a small volume.

Based on those results, it might be stated that in most piers, the depth and volume of the scour cavity, as well as the length of sediment reach downstream, were reduced

Table 1 Shapes of piers and collars with their dimensions

No	Pier name	Pier without collar	Pire with collar	
1	Circular	5 cm	20 cm	
2	elliptical	5 cm / 20 cm	20 cm / 35 cm	
3	Jou.sharp	5 cm / 20 cm	20 cm / 35 cm	
4	Jou.round	5 cm / 20 cm	20 cm / 35 cm	
5	Oblong	5 cm / 20 cm	20 cm / 35 cm	
6	Sharpnose	5 cm / 20 cm	20 cm / 35 cm	
7	Hexagonal	5 cm / 20 cm	20 cm / 35 cm	
8	Octagonal	5 cm / 20 cm	20 cm / 35 cm	
9	rectangular	5 cm / 20 cm	20 cm / 35 cm	

Table 2 Results of the experiments

Pier's shape	Position		Scour				Sedimentation				V/D³	Change (%)	Lms/D	Change (%)
			Dsmax/D	At θ	b/B	Change (%)	Hsmax/D	At θ	b/B	Change (%)				
Circular	60°	Without collar [43]	3.14	60°	0.48	− 39.5	2.1	110°	0.01	5.7	141.6	− 47.2	77.5	− 2.7
		With collar	1.9	70°	0.48		2.22	115°	0.01		74.7		75.4	
Elliptical	60°	Without collar [43]	3.64	57°	0.5	− 34.1	1.98	115°	0.01	− 6.1	175.1	− 44.3	71.9	− 25.3
		With collar	2.4	72°	0.48		1.86	115°	0.01		97.6		53.7	
Jou.sharp	60°	Without collar [43]	2.44	63°	0.53	− 4.1	2.06	115°	0.01	− 1	86.4	10.5	59.3	26
		With collar	2.34	70°	0.45		2.04	120°	0.01		95.5		74.7	
Jou.round	60°	Without collar [43]	3.5	57°	0.53	− 26.3	2.1	110°	0.01	− 18.1	171.2	− 32.9	70.5	− 10.9
		With collar	2.58	70°	0.48		1.72	120°	0.01		114.9		62.8	
Oblong	60°	Without collar [43]	3.4	57°	0.5	− 30.6	1.84	125°	0.01	10.9	175.8	− 29.9	69.8	14.9
		With collar	2.36	70°	0.45		2.04	125°	0.01		123.2		80.2	
Sharpnose	60°	Without collar [43]	2.82	57°	0.5	− 12.8	1.78	115°	0.01	− 7.9	91.2	44.1	52.3	20.1
		With collar	2.46	72°	0.43		1.64	115°	0.23		131.4		62.8	
Hexagonal	60°	Without collar [43]	3.38	57°	0.53	− 32.5	2.3	115°	0.01	− 26.1	159.8	− 18.3	77.5	− 23.5
		With collar	2.28	72°	0.5		1.7	120°	0.25		130.6		59.3	
Octagonal	60°	Without collar [43]	2.88	57°	0.53	− 21.5	1.98	115°	0.01	− 6.1	121.3	− 8.3	50.2	57
		With collar	2.26	70°	0.48		1.86	120°	0.2		111.2		78.8	
Rectangular	60°	Without collar [43]	4.18	57°	0.48	− 51.2	2.16	140°	0.1	− 19.4	236.6	− 48.7	93.7	− 33
		With collar	2.04	70°	0.48		1.74	110°	0.01		121.3		62.8	

Pier's shape	Position		Scour				Sedimentation				V/D³	Change (%)	Lms/D	Change (%)
			dsmax D	At θ	b/B	Change (%)	hsmax D	At θ	b/B	Change (%)				
Circular	90°	Without collar [43]	3.08	90°	0.48	− 35.7	1.98	165°	0.13	− 1	137.7	− 31.8	68.2	− 13
		With collar	1.98	100°	0.53		1.96	140°	0.01		93.9		59.3	
Elliptical	90°	Without collar [43]	3.54	87°	0.53	− 33.9	1.52	132°	0.18	11.8	126.5	− 44.9	48.8	− 9.8
		With collar	2.34	100°	0.45		1.7	60°	0.01		69.7		44	

Table 2 (continued)

Pier's shape	Position		Scour			Change (%)	Sedimentation			Change (%)	V/D³	Change (%)	Lms/D	Change (%)
			dsmax/D	At θ	b/B		hsmax/D	At θ	b/B					
Jou.sharp	90°	Without collar [43]	2.44	87°	0.53	− 25.4	1.66	133°	0.03	− 18.1	64.5	− 18	52.3	− 9.4
		With collar	1.82	100°	0.5		1.36	135°	0.03		52.9		47.4	
Jou.round	90°	Without collar [43]	3.68	87°	0.5	− 49.5	1.88	160°	0.13	− 40.4	149.9	− 69.8	76.8	− 50
		With collar	1.86	98°	0.45		1.12	50°	0.01		45.3		38.4	
Oblong	90°	Without collar [43]	3.32	87°	0.5	− 42.2	1.7	135°	0.18	-14.1	148.6	-67.8	53.4	-15
		With collar	1.92	100°	0.48		1.46	80°	0.03		47.9		45.4	
Sharpnose	90°	Without collar [43]	3.6	87°	0.5	− 33.3	1.56	130°	0.15	− 19.2	133.7	− 46	45.4	− 26.2
		With collar	2.4	87°	0.5		1.26	55°	0.01		72.2		33.5	
Hexagonal	90°	Without collar [43]	4.12	87°	0.53	− 64.6	1.86	123°	0.23	− 15.1	180.2	− 78.7	48.1	− 30.4
		With collar	1.46	91°	0.38		1.58	70°	0.05		38.4		33.5	
Octagonal	90°	Without collar [43]	3.56	87°	0.53	− 41	1.56	128°	0.01	6.4	134.5	− 27.7	56.5	− 25.8
		With collar	2.1	102°	0.48		1.66	135°	0.15		97.2		41.9	
Rectangular	90°	Without collar [43]	4.22	87°	0.48	− 40.8	1.9	135°	0.18	− 8.4	211.7	− 27.8	60	8
		With collar	2.5	103°	0.5		1.74	145°	0.2		152.8		64.8	
Circular	120°	Without collar [43]	2.68	119°	0.5	− 41.8	1.34	170°	0.05	− 10.4	64.6	− 62.7	34.9	− 10
		With collar	1.56	127°	0.43		1.2	45°	0.01		24.1		31.4	
Elliptical	120°	Without collar [43]	3.22	117°	0.5	− 75.2	1.6	60°	0.01	− 3.75	74.1	− 95.3	32.8	− 68
		With collar	0.8	121°	0.48		1.54	60°	0.01		3.5		10.5	
Jou.sharp	120°	Without collar [43]	2.12	123°	0.53	− 33	1.38	80°	0.03	− 4.3	30.6	− 46.1	31.4	− 29
		With collar	1.42	128°	0.53		1.32	70°	0.03		16.5		22.3	
Jou.round	120°	Without collar [43]	3.12	117°	0.53	− 57.1	1.62	65°	0.01	1.2	80.1	− 80.1	34.2	− 40.9
		With collar	1.34	125°	0.48		1.64	70°	0.01		15.9		20.2	
Oblong	120°	Without collar [43]	3.08	117°	0.48	− 56.5	1.7	60°	0.01	− 7.1	82.5	− 84.7	36.3	− 42.4
		With collar	1.34	128°	0.48		1.58	70°	0.03		12.6		20.9	

Table 2 (continued)

Pier's shape	Position		Scour				Sedimentation				V/D³	Change (%)	Lms/D	Change (%)
			dsmax/D	At		Change (%)	hsmax/D	At		Change (%)				
				θ	b/B			θ	b/B					
Sharpnose	120°	Without collar [43]	3.12	117°	0.5	− 64.1	1.5	50°	0.01	2.7	83.1	− 87.5	34.9	− 50.1
		With collar	1.12	127°	0.45		1.54	57°	0.01		10.4		17.4	
Hexagonal	120°	Without collar [43]	3.54	117°	0.5	− 69.5	1.62	60°	0.01	− 8.6	103.1	− 91.9	33.5	− 93.7
		With collar	1.08	119°	0.48		1.48	70°	0.01		8.34		2.1	
Octagonal	120°	Without collar [43]	3.24	117°	0.53	− 66.7	1.78	73°	0.01	− 6.7	87.1	− 90.8	37	− 62.2
		With collar	1.08	121°	0.48		1.66	70°	0.03		8		14	
Rectangular	120°	Without collar [43]	3.7	117°	0.48	− 47	1.72	174°	0.18	− 4.7	118.2	− 50.3	55.9	− 37.6
		With collar	1.96	125°	0.35		1.64	55°	0.01		58.8		34.9	

because the piers were installed closer to the ending sections of the bend. That, might be attributed to higher vorticity and shear stress at the first half of the bend at the interval of 40° to 60° [45].

Furthermore, comparing the results obtained from the tests involving a pier and a collar and the results of collar-free tests [43] indicated that using a collar in all 3 positions—60°, 90°, and 120°—in most piers reduced the scour depth, the sedimentary height, the scour hole volume, and the sediment reach length. The maximum effect of the collar on the maximum depth of the holes occurred with the piers installed at 120°. For instance, the maximum reduction in scour hole volume and depth among all the experiments occurred in the case of an elliptical pier installed at 120°, where using a collar decreased the scour cavity depth and volume by approximately 75 and 95% respectively. The minimum decrease in the maximum scour hole depth occurred in cases of jou.sharp and sharpnose piers installed at 60° by 4.1 and 12.8% respectively. Those piers had less resistance against the flow and created less flow separation as a result of having a sharp nose. Hence, the scour depths of those piers were relatively lower, and the use of the collar did not significantly affect those depths. Even using the collar on the sides of those 2 piers at 60° increased the contact surface between the pier and the flow, augmenting the scour hole volume. Consequently, unlike the other experiments, using the collar in cases of jou.sharp and

sharpnose piers installed at 60° increased the scour hole volumes by 10.5 and 44.1% respectively.

The greatest change in the sedimentary height occurred when a collar was used on the jou.round pier installed at 90°, where the maximum sedimentary height decreased by 40.4% in comparison with the case of no collars installed. Further, that sedimentary pile was transported from 160° at a distance of 13% of the channel width from the inner bank to 50° near the inner bank. That happened due to a reduction in the power of downflow streams and a change in the amount of flow deviation toward the inner bank because of using the collar.

Alterations in the power of the vortices due to the collar made the sediment reach length downstream undergo significant changes. The maximum reduction occurred with the hexagonal pier installed at 120°, where using the collar reduced the length of the sediment reach by 93.7%. Few of those experiments resulted in an increase in the length of sediment reach due to the use of the collar. For instance, the length of the sediment reach around the octagonal pier installed at 60° in the case with a collar was 57% greater than that in the case without collars, whereas incorporation of the collar had little effect on the length of sediment reach around the circular pier installed at 60° and created the minimum variation by causing only 2.7% reduction.

One of the parameters affecting the performance of different pier shapes is their Ks. The Ks is the ratio of the
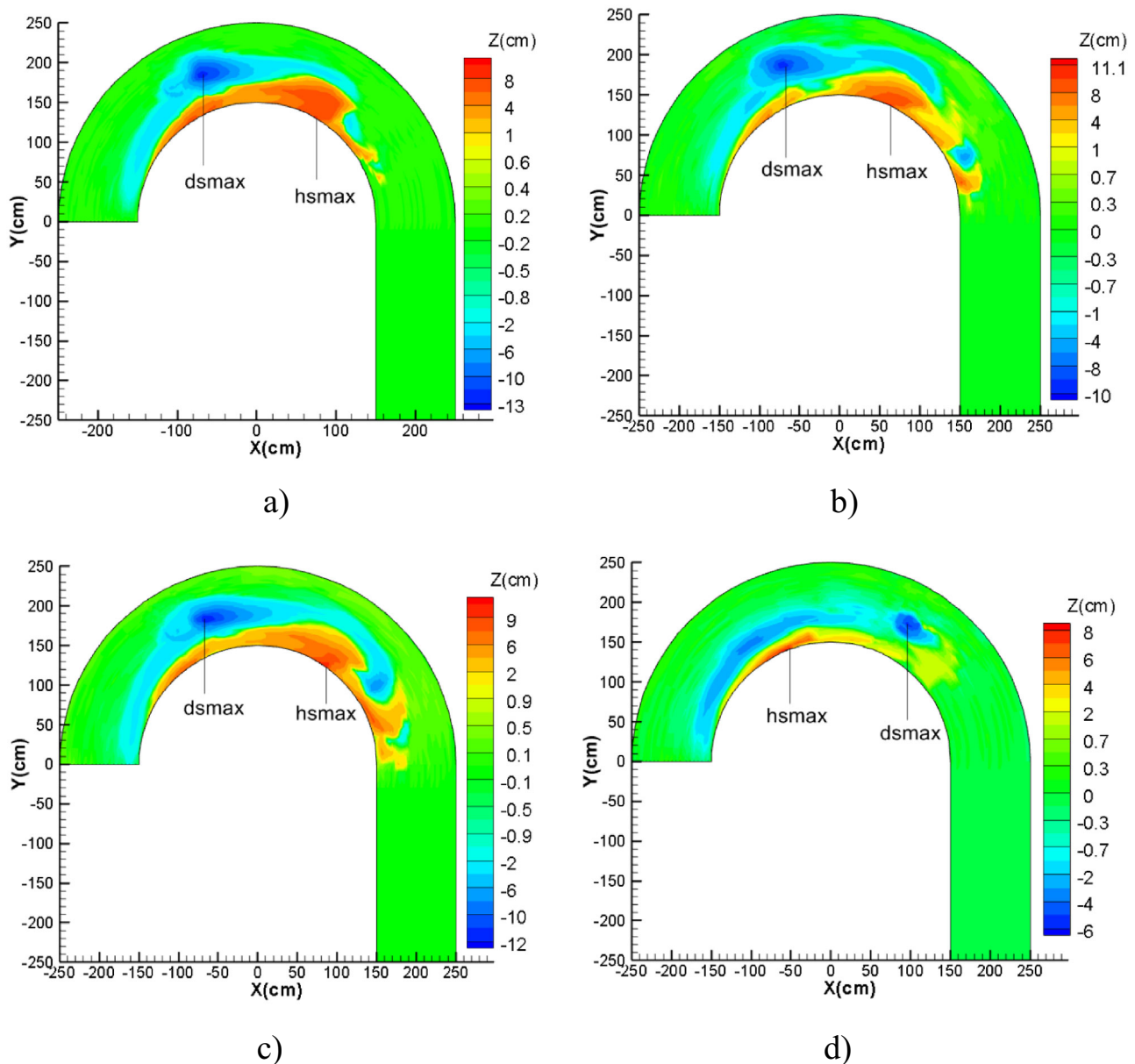
Fig. 2 Bed topography around **a** jou.round, **b** circular, and **c** oblong piers installed at 60°, and **d** a hexagonal pier installed at 120°

maximum scour depth of each individual pier to the maximum scour depth at the circular pier in the same location.

Table 3 shows the values of Ks for every pier with a collar, along with comparisons with the case of no collars installed [43] and the percentage of change in that parameter as a result of using the collar.

It can be seen that when a collar was used, in most cases with the piers implemented closer to the end of the bend, the values of the Ks had a falling trend. For instance, the Ks at 60° was equal to or greater than 1 for every pier, whereas it was less than 1 for every pier except the circular and rectangular piers. It might be observed that for the oblong pier, for example, in the case of an installed collar, the Ks

values at 60°, 90°, and 120° were 1.2, 1, and 0.9 respectively. Therefore, it might be stated that for piers with a collar, the location of the piers had a substantial effect on the values of the Ks. The reason might be that in the case of using a collar, closer to the end of the bend, the downstream straight reach affected the scour mechanism, resulting in the decrease in the value of the Ks. The maximum value of the Ks among the piers using collars at 60° occurred in the case of the jou.round pier at 1.4, and the Ks among the piers installed at 90° and 120° was 1.3 for the rectangular pier.

Furthermore, comparing the Ks's calculated in cases of the piers with a collar and those calculated by collar-free

Fig. 3 Hole created around **a** the rectangular pier installed at 90°, and **b** the elliptical pier installed at 120°

Table 3 Values of the shape coefficients of the piers

		Circular	Elliptical	Jou.sharp	Jou.round	Oblong	Sharpnose	Hexagonal	Octagonal	Rectangular
θ = 60°	Without collar [43]	1	1.2	0.8	1.1	1.1	0.9	1.1	0.9	1.3
	With collar	1	1.3	1.2	1.4	1.2	1.3	1.2	1.2	1.1
	Change (%)	–	8.3	50	27.3	9.1	44.4	9.1	33.3	− 15.4
θ = 90°	Without collar [43]	1	1.1	0.8	1.2	1.1	1.2	1.3	1.2	1.4
	With collar	1	1.2	0.9	0.9	1	1.2	0.7	1.1	1.3
	Change (%)	–	9.1	12.5	− 25	− 9.1	–	− 46.2	− 8.3	− 7.1
θ = 120°	Without collar [43]	1	1.2	0.8	1.2	1.1	1.2	1.3	1.2	1.4
	With collar	1	0.5	0.9	0.9	0.9	0.7	0.7	0.7	1.3
	Change (%)	–	− 58.3	12.5	− 25	− 18.2	− 41.7	− 46.2	− 41.7	− 7.1

[43] indicates that with the piers installed at 60°, the use of the collar in most piers increased the Ks, and the maximum increase among all the piers occurred in case of installing the jou.sharp pier at that position. With that pier shape, using the collar increased the Ks by 50%; however, when the pier locations approached the end of the bend, that trend changed. Installation of the piers at 120° reduced the values of the Ks in most cases due to the use of the collar, and the maximum reduction was approximately 58% for the elliptical pier installed at that angle. Moreover, among the piers installed at 90°, both a decrease and an increase in the Ks values as a result of using the collar were observed. Only for the sharpnose pier at 90° did incorporating the collar have no effect on the Ks, and whether or not the collar was installed, the Ks was 1.2. When the flow approached the end of the bend and the downstream straight path, the power of the vortices decreased due to the impacts of the flow with the bend walls. In other words, the

second half of the bend played the role of flow dissipator and this results in the occurrence of scouring with a lower depth. This could also influence the values of the shape coefficient and therefore the use of collars at the beginning of the bend could increase ks and decrease the coefficient at the end of the bend.

Scour hole wall slopes were also measured. Table 4 shows the scour hole wall sloping in 4 directions for piers with collars, along with the percentage of change in each compared to the case of no collars installed [43]. In Table 4 I.S and O.S denote the slope of holes toward the inner bank and outer banks respectively, and U.S. and D.S refer to the slope of holes in upstream and downstream directions respectively. The sharpnose pier caused less flow diversion toward the banks because of its sharp nose; hence, it created holes with extreme slopes at the lateral walls. As is evident, the maximum slope toward the inner bank among the piers with a collar was 0.59 and occurred with the

Table 4 Slopes of the scour hole walls

No	Pier's shape		θ = 60°				θ = 90°				θ = 120°			
			I.S	O.S	U.S	D.S	I.S	O.S	U.S	D.S	I.S	O.S	U.S	D.S
1	Circular	Without collar [43]	0.52	0.5	0.64	0.15	0.57	0.43	0.64	0.18	0.54	0.47	0.78	0.22
		With collar	0.4	0.28	0.14	0.03	0.34	0.24	0.14	0.15	0.42	0.24	0.12	0.23
		Change (%)	− 23.1	− 44	− 78.1	− 80	− 40.4	− 44.2	− 78.1	− 16.7	− 22.2	− 48.9	− 84.6	4.5
2	Elliptical	Without collar [43]	0.45	0.55	0.57	0.12	0.46	0.59	0.59	0.23	0.48	0.53	0.65	0.47
		With collar	0.5	0.36	0.13	0.14	0.33	0.41	0.16	0.22	0.15	0.08	0.02	0.09
		Change (%)	11.1	− 34.5	− 77.2	16.7	− 28.3	− 30.5	− 72.9	− 4.3	− 68.8	− 84.9	− 96.9	− 80.9
3	Jou.sharp	Without collar [43]	0.5	0.59	0.29	0.08	0.48	0.55	0.64	0.12	0.45	0.51	0.25	0.27
		With collar	0.41	0.35	0.16	0.06	0.47	0.35	0.09	0.12	0.29	0.44	0.09	0.17
		Change (%)	− 18	− 40.7	− 44.8	− 25	− 2.1	− 36.4	− 85.9	0	− 35.6	− 13.7	− 64	− 37
4	Jou.round	Without collar [43]	0.42	0.42	0.5	0.07	0.45	0.53	0.57	0.22	0.42	0.47	0.54	0.39
		With collar	0.41	0.39	0.18	0.12	0.54	0.45	0.11	0.16	0.28	0.48	0.1	0.17
		Change (%)	− 2.4	− 7.1	− 64	71.4	20	− 15.1	− 80.7	− 27.3	− 33.3	2.1	− 81.5	− 56.4
5	Oblong	Without collar [43]	0.45	0.57	0.63	0.11	0.45	0.47	0.58	0.2	0.45	0.44	0.52	0.35
		With collar	0.45	0.39	0.15	0.08	0.47	0.38	0.09	0.14	0.35	0.56	0.08	0.14
		Change (%)	0	− 31.6	− 76.2	− 27.3	4.4	− 19.1	− 84.5	− 30	− 22.2	27.3	− 84.6	− 60
6	Sharpnose	Without collar [43]	0.42	0.58	0.67	0.07	0.51	0.61	0.63	0.24	0.46	0.48	0.63	0.37
		With collar	0.59	0.43	0.13	0.12	0.33	0.56	0.65	0.14	0.34	0.21	0.05	0.12
		Change (%)	40.5	− 25.9	− 80.6	71.4	− 35.3	− 8.2	3.2	− 41.7	− 26.1	− 56.3	− 92.1	− 67.6
7	Hexagonal	Without collar [43]	0.39	0.44	0.62	0.14	0.54	0.54	0.65	0.29	0.45	0.57	0.62	0.38
		With collar	0.52	0.37	0.12	0.11	0.37	0.18	0.17	0.06	0.21	0.27	0.13	0.12
		Change (%)	33.3	− 15.9	− 80.6	− 21.4	− 31.5	− 66.7	− 73.8	− 79.3	− 53.3	− 52.6	− 79	− 68.4
8	Octagonal	Without collar [43]	0.36	0.59	0.49	0.08	0.43	0.6	0.63	0.23	0.46	0.5	0.54	0.38
		With collar	0.57	0.4	0.12	0.09	0.43	0.43	0.1	0.17	0.22	0.22	0.11	0.08
		Change (%)	58.3	− 32.2	− 75.5	12.5	0	− 28.3	− 84.1	− 26.1	− 52.2	− 56	− 79.6	− 78.9
9	Rectangular	Without collar [43]	0.48	0.63	0.59	0.18	0.56	0.53	0.59	0.29	0.46	0.51	0.63	0.35

Table 4 (continued)

No	Pier's shape		θ = 60°				θ = 90°				θ = 120°			
			I.S	O.S	U.S	D.S	I.S	O.S	U.S	D.S	I.S	O.S	U.S	D.S
		With collar	0.29	0.42	0.1	0.07	0.43	0.39	0.06	0.16	0.38	0.39	0.16	0.15
		Change (%)	−39.6	−33.3	−83.1	−61.1	−23.2	−26.4	−89.8	−44.8	−17.4	−23.5	−74.6	−57.1

sharpnose pier installed at 60°. The most significant slope toward the outer bank was 0.56 and occurred with the sharpnose pier installed at 90°.

The sharpnose pier installed at 90° caused weaker downflow streams due to its narrow nose, resulting in a scour hole having less upstream reach and creating a maximum slope of 0.65 at the upstream wall of the hole. The most significant slope of the downstream hole wall was 0.23 and occurred with the circular pier installed at 120°. That suggests that, considering the smaller cross-section of the circular pier compared with other piers, the created hole around it was skewed downstream less than that around the other piers.

Note that for most holes in cases of applied collars, the slope toward the inner bank exceeded those in other directions, which was a result of a sedimentary pile development in the vicinity of the inner bank; that increased the hole wall slope in the direction of the inner bank.

A comparison of the hole wall slopes in cases of piers with collars and piers without collars [43] showed that in most piers, the slopes of the hole walls decreased due to the use of the collar. For instance, the slopes of all of the following decreased as a result of using the collar: the slope of the hole walls in the outer bank direction and those in the upstream direction with the piers installed at 60°, the slope of the hole in the outer bank direction with the piers installed at 90°, and the slope of the holes toward the inner bank and those in upstream direction with the piers installed at 120°. As shown in Table 2, using the collar on most piers entailed a decrease in the hole depth and the sedimentary height, which in turn reduced the slope of the hole walls. Note that in Table 4, the maximum reduction in the slope of the holes as a result of using the collar in every 4 directions happened with the elliptical pier implemented at 120°. When the collar was applied, the hole slopes in the inner and outer bank directions decreased by 68.8 and 84.9% respectively, and those directed upstream and downstream of the pier decreased by 96.9 and 80.9% respectively, relative to the cases of no collars installed. That occurred because the maximum effect of the collar in reducing scour hole depth and volume happened with the

elliptical pier set up at the 120° angle of the bend. According to Table 4, some instances of increase in the slope of the hole walls due to the use of the collar were also observed. For instance, the slope of the hole downstream wall around the sharpnose pier installed at 60° increased by 71.4% due to the collar; that is the maximum increase value in any slope among all the piers. That might be attributed to a rise in the scour hole volume at that pier due to using the collar, which is also mentioned in the Table 2 descriptions. In addition, in some cases, the use of the collar did not affect the values of the wall slopes. Those cases include the hole wall slope downstream of the jou.sharp pier installed at 90°, the slope toward the inner bank around the oblong pier installed at 60°, and the slope toward the inner bank around the octagonal pier installed at 90°, which were 0.12, 0.45, and 0.43 respectively with or without the collar, and use of the collar had no effect on their values.

Measurements of the maximum scour depth were collected at various time intervals while conducting the experiments; the results are shown in Fig. 4. There, ds is the scour depth.

Observations indicated that with the beginning of the experiments and the impact of the flow with the piers, the scour was generated near the upstream nose of the piers. On the other hand, when the scour depth reached the collar level (2 cm lower than the bed level), the scouring speed decreased in that area, and a hole at an approximate distance of 7 times the pier width was gradually formed downstream of the pier. Also, in most experiments, the maximum scour depth occurred downstream of the piers at the test completion time. Figure 4a shows that with the piers installed at 60°, at approximately the first 20% of the experiment duration, the maximum scour depth was observed at the oblong pier, at 20 to 40% intervals at the jou.sharp pier. At the ending 60% of the duration, the maximum depth occurred at the jou.round pier. On the other hand, in the first 50% of the duration, the elliptical pier had the minimum scour depth, yet after one-third of the duration, the slope of the curve on the elliptical pier increased, and a dramatic increase occurred in the scour
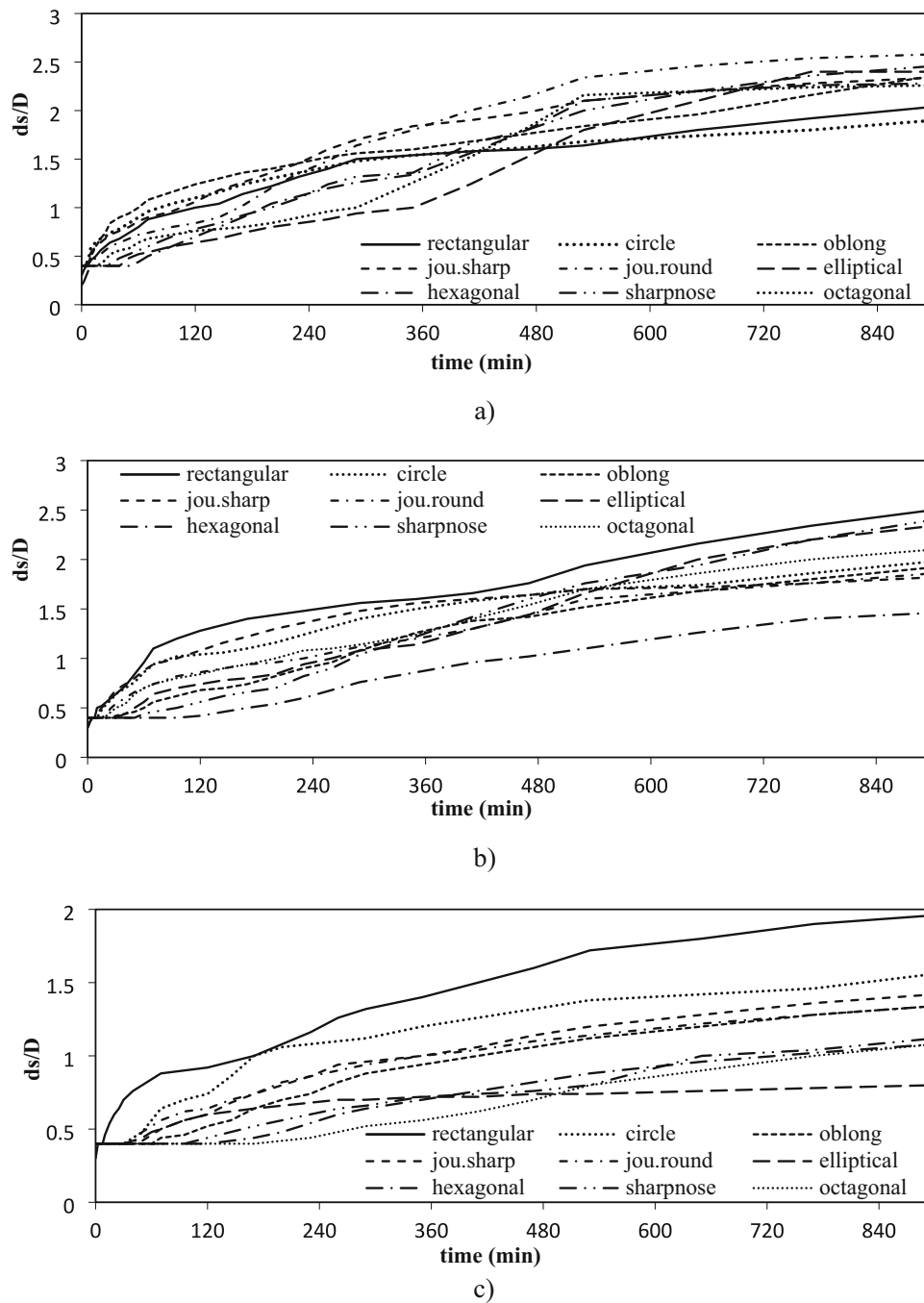
Fig. 4 Temporal evolution of the maximum scour depth nondimensionalized with the pier width with piers installed at **a** 60°, **b** 90°, and **c** 120°

depth around that pier. In the second 50% of the duration, the circular pier had the minimum scour.

As shown in Fig. 4b and c, the rectangular pier caused the greatest scour depth throughout the experiment, given the geometry of its nose.

According to Fig. 4b, the hexagonal pier had the least scour depth throughout the experiments. However, as shown in Fig. 4c, with piers installed at 120°, over the first 50% of the experiments, the octagonal pier had the least

scour depth, but around the middle of the experiment duration, the slope of the curve on that pier increased. The elliptical pier caused the least scour depth in the second half of the experiment's duration. It is evident from the graph on the elliptical pier that the slope of the curve is very mild, which might be attributed to the high aerodynamics of that pier and its installation at 120°.

Figure 5 depicts Instances of longitudinal sections crossing the channel center with piers installed at 60°, 90°,
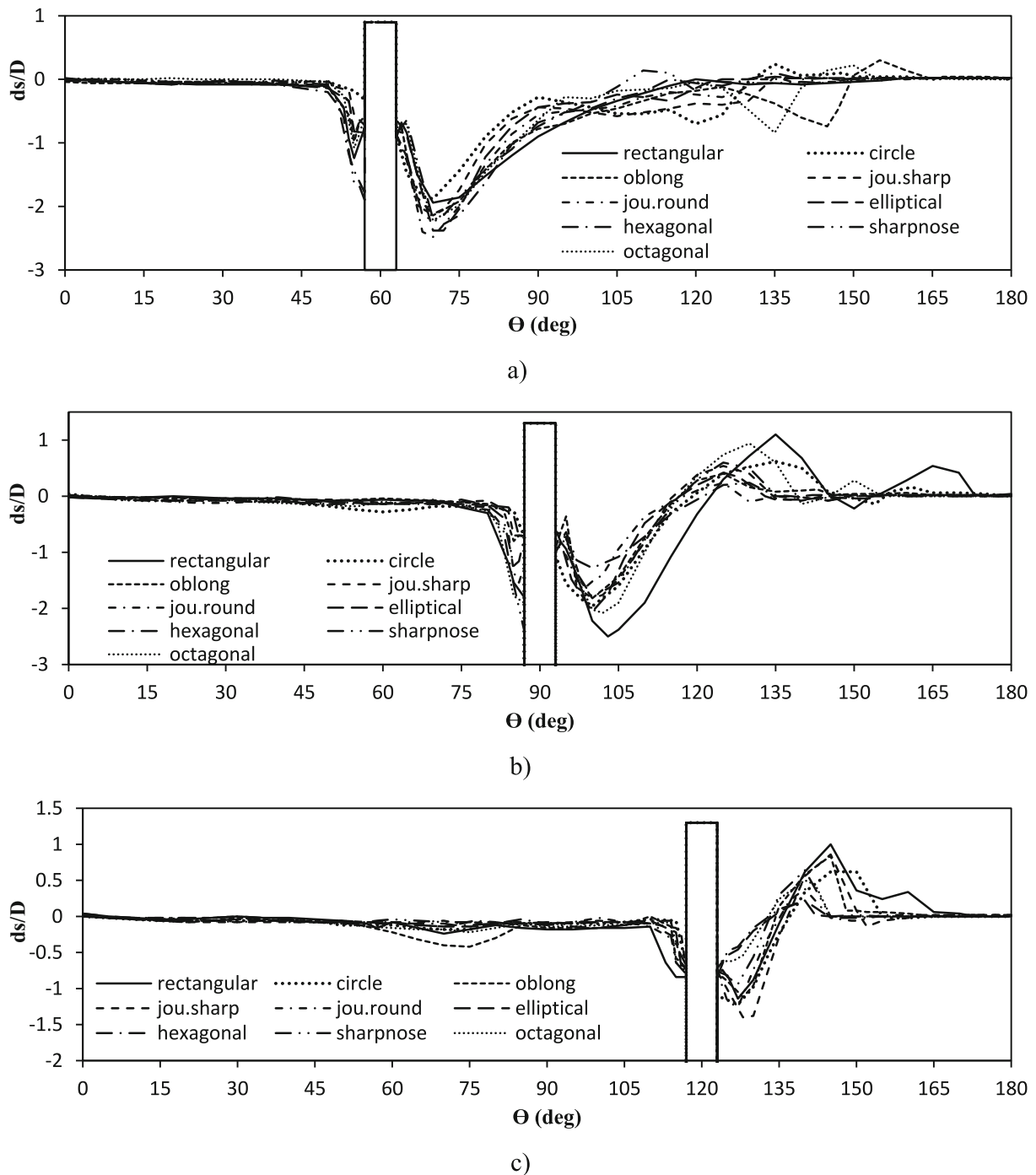
Fig. 5 Longitudinal sections crossing the channel center with installation of the piers with a collar at **a** 60°, **b** 90°, and **c** 120°

and 120°. As shown in Fig. 5a, scour hole of a relatively small depth was created near the upstream nose of the piers. As was also pointed out in the descriptions of Table 2, the holes' depths near the piers' upstream noses were low because the collars around the piers reduced the power of downflow streams, preventing the deepening of the holes. However, at a distance of approximately 7 times the pier width downstream, the main holes were generated

without the collar's effect and under the influence of horseshoe vortices. Whereas, according to the results of collar-free tests [43], when collars were not used, the maximum scour depth of most piers occurred near the upstream nose under the influence of vortices generated due to the impact of the flow with the pier, which created deep holes at the upstream side of the piers. It might therefore be concluded that using the collar not only
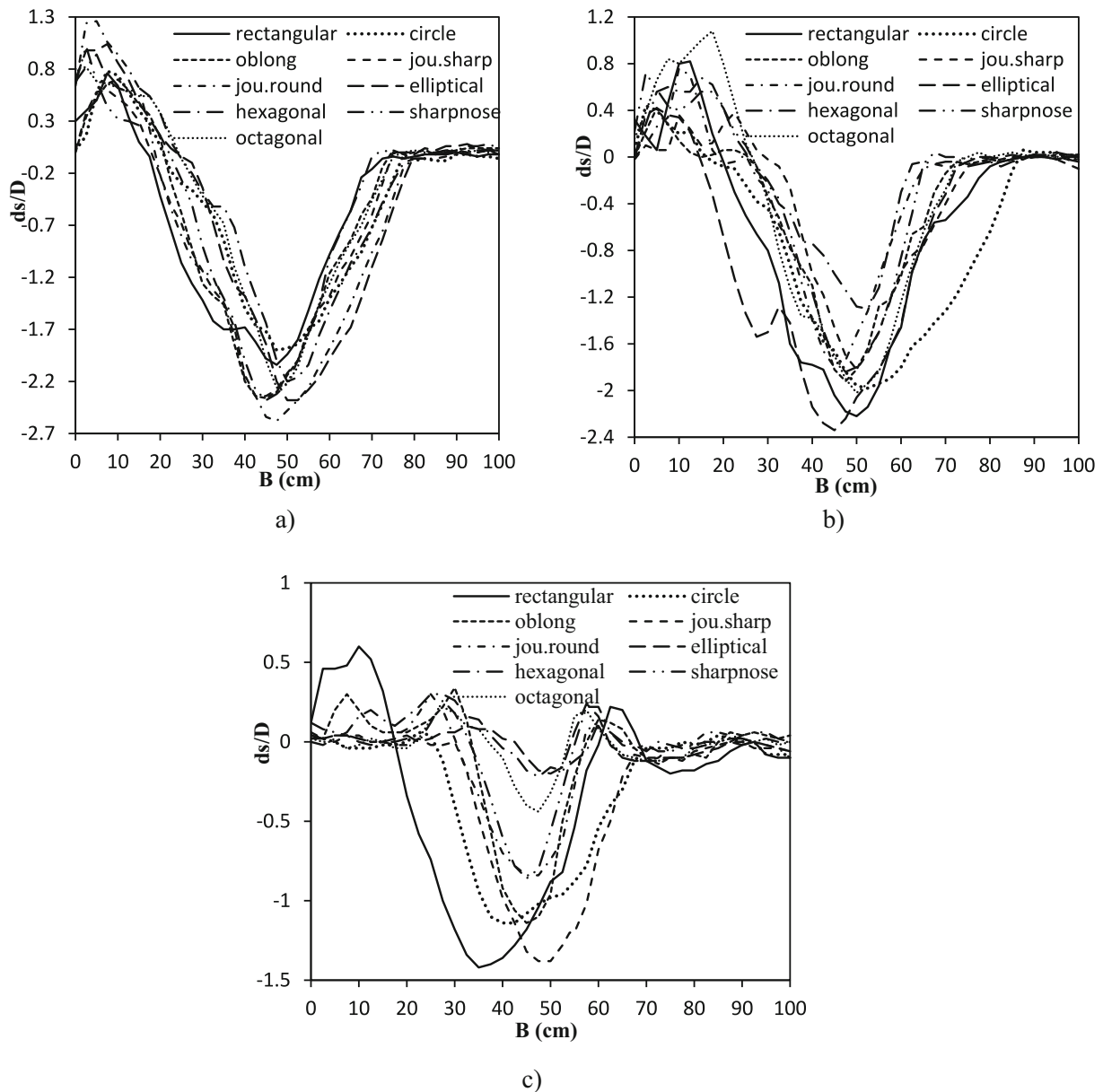
Fig. 6 Cross-sections at a distance of 7 times the pier width at the downstream side of the piers with the piers installed at **a** 60°, **b** 90°, and **c** 120°

decreased the hole depth, but also caused the main hole to form farther away from the sensitive points around the pier. Every time the piers were installed closer to the end of the bend, the skewness of the main holes in the downstream direction lessened. That was due to the direct impact of the flow coming from the upstream straight reach with the piers installed at 60°, creating longer holes in the downstream direction. As shown in Fig. 5a, the materials collected from the holes accumulated downstream created sedimentary piles. For instance, the materials around the oblong pier reached approximately 155° at the center of the channel. Then, the secondary scour holes were generated because of water dropping on those piles. Further, with

installed circular, octagonal, and oblong piers, the secondary scour holes were generated at 120°, 135°, and 145° respectively. Figure 5b and Fig. 5c suggest that a secondary scour hole was not created at midchannel. At the downstream area of the piers set up at 90°, the scour hole was extended up to approximately 110°, and the maximum scour hole reach occurred with the installation of the rectangular pier. After the scour hole, the sedimentary pile was created at the interval from 125° to 140°, and very few variations occurred between 145° and 180°. As evident in Fig. 5c, there were fewer bed variations, including the scour around the pier and sedimentation downstream, than in Fig. 5a and b. Scour holes were extended only to
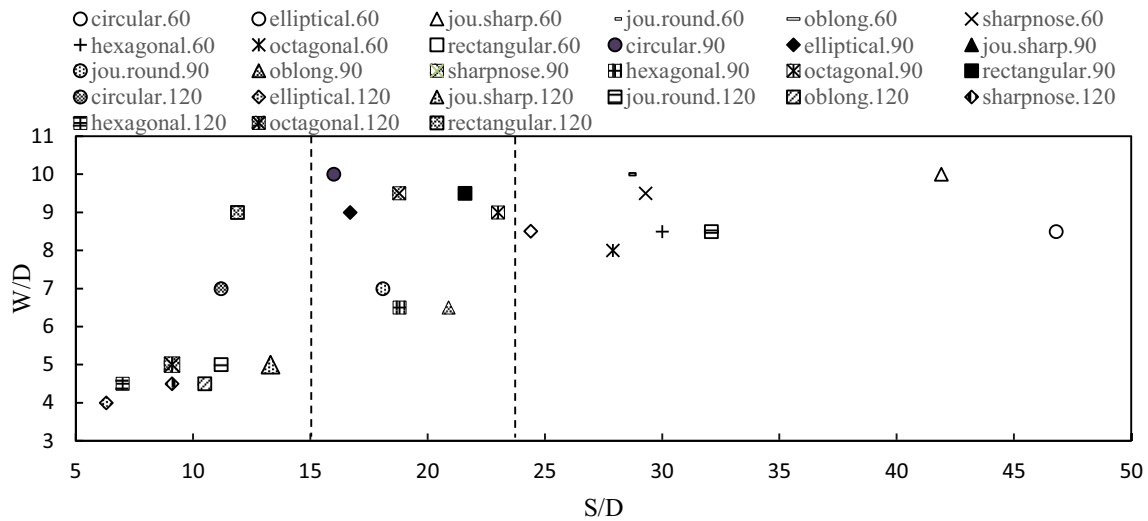
Fig. 7 Nondimensionalized dimensions of the rectangle circumscribed over the scour holes around the piers with a collar
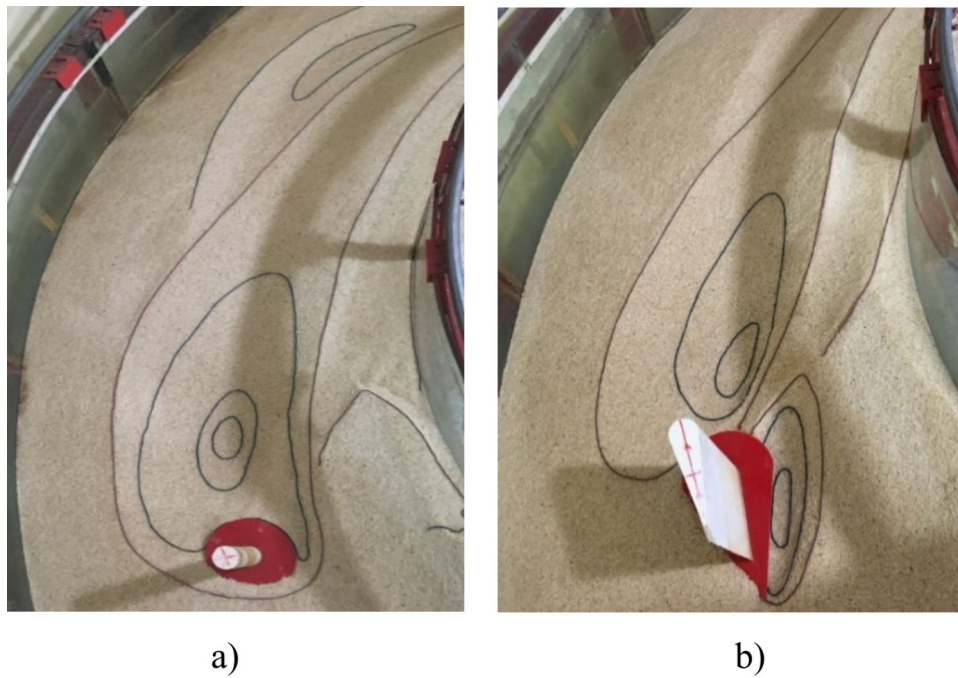

a)   b)

Fig. 8 Scour holes around **a** the circular pier with collar installed at 60°, and **b** the jou.sharp pier with collar installed at 60°

approximately 130°, and a low sedimentary pile was generated around 145°. Furthermore, from 150° to the end of the bend, there were very few alterations in bed level at midchannel. That might be attributed to the direct effect of the downstream straight part and the loss in the strength of vortices and the secondary flows in the second half.

Figure 6 shows an instance of cross-sections for all 3 installations of the piers. As mentioned in the descriptions of Table 2, the maximum scour depth in most cases of the piers with the collar occurred downstream of the piers. Hence, Fig. 6 shows cross-sections at a distance of 10°,

which is equivalent to 7 times the pier width downstream of the piers.

Sedimentation at the inner bank under the influence of helical flows might be observed in that figure. The closer the piers were to the end of the bend, the lower the sedimentary heights. In addition, in all 3 cross-sections, at a distance of approximately 80% of the channel width from the inner and outer banks, very few alterations occurred in the bed. Figure 6a shows the maximum sedimentary height occurring with the jou.round pier installed, which occurred at a distance of 5% of the channel width away from the

inner bank at a value of 1.26 D. Moreover, the maximum scour depth at midchannel happened with the jou.round pier implemented at a value of 2.58 D. In Fig. 6b, the hole developed around the elliptical pier had the greatest skew toward the inner bank and was extended to a distance of 20% of the channel width from the inner bank. That pier also created the highest scour depth at midchannel at a value of 2.34 D.

On the other hand, the hole around the circular pier had the greatest skew toward the outer bank and was extended to a distance of 20% of the channel width from the outer bank. As shown in Fig. 6c, the sedimentary height and the maximum scour depth decreased compared to that of the piers installed at 60° and 90°. Given the specific geometry of its nose, the rectangular pier created the highest sedimentary pile equal to 0.6 D 10% of the channel width away from the inner bank and the highest scour depth equal to 1.42 D 35% of the channel width away from the inner bank.

Figure 7 shows the circumscribed rectangle around the scour holes in all 3 positions. The longitudinal and lateral axes of that graph denote the maximum length of the hole (S) and the maximum width of the scour hole (W) respectively, nondimensionalized using the pier width. As shown in Fig. 7, the area of the hole around the elliptical pier installed at 120° with a length equal to 6.3 and a width of 4 times the pier width was the smallest area of the circumscribed rectangle. On the other hand, the hole at the circular pier installed at 60°, with a length of 46.8 times the pier width, was the longest (Fig. 8a), and the hole around the jou.sharp pier installed at 60°, with a length of 41.9 and a width of 10 times the pier width, had the greatest area of the circumscribed rectangle (Fig. 8b). Among the piers installed at 90°, the hole created around the circular pier, with a width of 10 times the pier width, was regarded as the widest hole. Attention to Fig. 7 reveals that the points related to the location of the piers at each angle are situated near each other in a region; from the beginning to a distance of 15 units on the longitudinal axis lie the points related to the piers installed at 120°, from a distance of 15 units to approximately 24 units lie the points related to the piers installed at 90°, and from a distance of 24 units to the end of the longitudinal axis lie the points related to the piers installed at 60°. Those regions are highlighted with a dashed line. That indicates that the implementation of the piers in the first half of the bend created longer holes, and with the piers set up closer to the end of the bend, the length of the scour holes decreased.

4 Conclusion

Applying collars is considered one of the most effective methods of controlling scouring around bridge piers. This study tested 9 differing shapes of piers with collars in three different positions of a 180° bend and compared the results with those of tests with no collars employed. The findings were indicative that use of collars played a significant role in mitigating scouring. For instance, the highest effect of a collar was observed on the elliptical pier positioned at the 120° angle, with a 75% decrease in the maximum scour depth and a 95% decrease in the scour hole volume. Furthermore, the use of collars made the maximum scour depth form away from the sensitive points around the pier, which can substantially reduce the risk of bridge failure. Moreover, another finding of this study was the aerodynamic shape of the pier and the collar as well as the location of these structures were highly affected the amount of scouring; the greater the aerodynamic shape of the piers and the closer their location to the end of the bend were, the less scouring would occur. For example, the jou.round pier located at the 60°angle of the bend generated a hole as deep as 2.58 times the pier width due to its low aerodynamic shape, its location in the first half of the bend, the presence of a powerful helical flow and the high strength of the vortices, whereas the elliptical pier located at the 120° angle created a hole with the maximum depth of 0.8 times the pier width due to its aerodynamic geometry against the flow, its position in the second half of the bend and the lower effect of the helical flow.

Data Availability All data generated or analysed during this study are included in this published article.

Declarations

Conflict of Interest The authors have no relevant financial or non-financial interests to disclose.

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

Consent to Participate The authors declare their consent to participate in this work.

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