



Effects of increasing the width of collar on reduction of scouring surrounding the rectangular piers in a 180-degree bend

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Abstract

Employment of protective structures is vital for reducing the effect of the local scour created surrounding the bridge piers. One of the most effective protective structures used for controlling and reducing scour surrounding the bridge piers is the collars. Hence, research on the mechanism of scouring surrounding the combination of pier and collar as well as the effect of collar on reduction of scouring surrounding the pier is of great significance. In this study, the effect of various collar width-to-pier width ratios on reduction of scouring parameters surrounding the rectangular piers has been investigated experimentally in various 180-degree sharp bend positions. The experiments were conducted under clear water and threshold of sediment motion in the upstream straight path. Results indicated that collars with collar width-to-pier width ratios equal to 3 to 4 perform the best at reducing the maximum depth of scouring in front of the nose of piers. Increasing the width of collar surrounding the piers reduces the maximum depth of scouring. Increasing the length of pier reduces the efficiency and effectiveness of the collar in delaying the scour process at the pier nose as well as the amount of the maximum scour reduction. The highest amount of scour depth reduction occurred in the vicinity of the pier and the collar at the 90-degree section with the collar installed with a ratio of collar width to pier width equal to 4 surrounding the piers with a ratio of length to width equal to 2 and 3 by approximately 75 and 70%, respectively.

Keywords Rectangular pier · Collar · Collar width-to-pier width ratio · Scour reduction · Ratio of pier length to width · 180-degree bend

Introduction

Every year, thousands of bridges all over the world are damaged or destroyed due to the scouring phenomenon taking place surrounding the bridge piers. Downflows and horseshoe vortices are among the important factors involved in scour generation surrounding the bridge piers. Protection of bridge piers against scour may prevent bridge destructions. A large number of researchers have considered various methods of protecting piers against scour. Using collars is one of such methods. A collar is a plate which is usually installed near the bed surrounding the pier. This protective plate is a flat surface with an insignificant thickness, which

is more effective than other protective structures in reducing the scour surrounding the piers. The collar installed surrounding the pier works as an obstacle against downflows and lessens the power of downflows when they collide with the pier. Therefore, the power of the horseshoe vortex also decreases and this prevents creation of scour cavities surrounding the pier.

There have been studies conducted on scour patterns surrounding the piers without any collars installed in the bend by (Sui et al. 2006; Masjedi et al. 2010a, b, c; Elsaedi et al. 2015; Ben Mohammad Khajeh et al. 2017; Maatooq and Mahmoud 2017; Vaghefi et al. 2017, 2018). Moreover, Sedighi et al. (2020) examined the scour surrounding the convergent and divergent circular piers in the bend and concluded that most scouring in convergent and divergent piers occurs surrounding the pier near the inner and outer banks, respectively. Asadollahi et al. (2021) numerically and experimentally compared the maximum depth of scouring and changes of bed topography surrounding the piers in the bend. They concluded that SSIIM could well simulate

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changes of bed topography and the maximum scouring depth location surrounding the piers. Solati et al. (2021), in the bend, investigated the effect of hydrographs' duration on scour surrounding the circular pier and indicated that by increasing the duration of hydrograph, the maximum depth of scouring and progress of sediments in the downstream straight path increased by 20 and 150%, respectively.

The application of collars on reduction of scouring surrounding the piers has been examined in a straight path and bend by researchers such as (Kumar et al. 1999; Zarrati et al. 2004; Zarrati et al. 2006; Garg et al. 2008; Mashahir et al. 2009; Moncada et al. 2009; Masjedi et al. 2010a, b; Izadnia and Heidarpour 2012; Karimae and Zarrati 2012; Tafarjnoruz et al. 2012; Salamatian et al. 2013; Jahangirzadeh and Akib 2015; Beg and Beg 2017; Chen et al. 2018; Memar et al. 2019; Wang et al. 2019). Furthermore, Karimae and Zarrati (2019) investigated the development of scour cavity surrounding the combination of a circular pier and a collar under steady and unsteady flow conditions in a straight channel and concluded that the major factor for collar efficiency in postponing scour development is the flow intensity parameter. Bestawy et al. (2020) studied the reduction of scouring surrounding the circular pier by a collar with various shapes and slots in a straight channel. They concluded that the collar is more effective in reducing scour surrounding the pier than the slot. Farooq et al. (2020) examined how an octagonal collar with various dimensions could play a role in reducing scour surrounding the octagonal pier in a straight channel and concluded that a collar with a width of 2.5 times the pier width reduces the scour cavity depth by 73.3% compared to the pier with no collar. Moghanloo et al. (2020a, b) investigated the effects of the thickness and the level of a collar on the scour and flow pattern surrounding the oblong pier in a 180-degree bend. They indicated that increasing the collar thickness increases scouring surrounding the pier and the greatest reduction in depth of scouring occurs surrounding the pier when the collar is placed near the initial bed level. In addition, increasing the thickness of collar leads to further deviation of streamlines toward the bed. Pandey et al. (2020), in a straight channel, examined the effect of elevation and diameter of a collar on reducing scour surrounding the circular pier and indicated that by increasing the collar diameter and the collar elevation relative to the initial bed level, scouring surrounding the pier decreases and increases, respectively. Also, the flow pattern in the 180-degree bend was examined by Abdi Choopoulou and Vaghefi (2019) surrounding the circular pier with a submerged plates, Akbari et al. (2021) surrounding the T-shaped spur dikes and Dehghan et al. (2021a) and Kesavarz et al. (2021) surrounding the rectangular piers with a collar.

Dehghan et al. (2021b) investigated the effects of ratio of length to width and the skewness angles of a rectangular

pier on scouring pattern and changes of bed topography in a 180-degree sharp bend. They concluded that a rectangular pier with a length-to-width ratio of 3 compared to other piers has the best performance in reducing scour in the bend. Moreover, the maximum depth of scouring surrounding the piers occurred by placing the rectangular piers in a 90-degree position. Skewed the pier more toward the inner bank increases the values of scouring parameters further than the outer bank.

Since the dimensions of the collar play an important role in reduction of scouring surrounding the piers, this paper also studied the effect of attaching collars with various collar width-to-pier width ratios to various length-to-width ratios of rectangular piers on scour reduction surrounding the piers installed at various 180-degree sharp bend positions. Furthermore, in a few cases investigated in this study, the scour parameters under discussion had been tested by the authors previously with a rectangular pier in the absence of any collars (Dehghan et al. 2021b). Hence, in a few of the experiments, a comparison was also made between presence and absence of collars surrounding the rectangular piers.

Materials and methods

Experiments were conducted in a bend channel with a rectangular section, a central curvature radius of 2 m, a height of 0.7 m and a width of 1 m (Dehghan et al. 2021b). The length of downstream and upstream paths connected to the bend is 5 and 6.5 m, respectively. The wall is made of glass so that the flow will be visible from various angles. According to the classification made by Leschziner and Rodi (1979), this channel, with a ratio of $R/B=2$, is in the category of sharp bend, where R represents the bend central curvature radius and B is the width of channel. With the aim of providing scouring conditions and covering the entire channel, sediments with an average diameter and a standard deviation, respectively, 1.5 mm and 1.14 and a thickness of 0.3 m were used. The scour experiments were conducted under threshold of sediment motion, $U/U_c=0.98$, where U is the average velocity of flow and U_c is the velocity of flow at the incipient motion of the particles. Therefore, a discharge of $0.07 \text{ m}^3/\text{s}$ and a water depth of approximately 0.18 m were selected.

Rectangular piers with a round nose and tail, a width of 0.05 m and ratios of length to width equal to 1 to 6 were made of PVC (Dehghan et al. 2021b). Collars with ratios of $W/b=1.5, 2, 2.5, 3, 4, 5$ were incorporated. W and b denote the width of collar and the width of pier, respectively. The collars were made of Plexiglass, with a constant thickness of 3 mm, and were installed at the initial bed level surrounding the rectangular piers (Moghanloo et al. 2020a). A combination of piers and collars was placed at the 60-, 90- and

120-degree positions of the bend. Figure 1 illustrates a view of this combination in the bend. L is the pier length. With the aim of determining the relative equilibrium time required for conducting each experiment, an experiment equilibrium time of 34 h was run for the rectangular pier placed at the position of 90 degree. Approximately 95% of the maximum scouring occurred during the initial 15 h into the experiment, which was in accordance with Melville and Chiew (1999). Hence, for conducting each experiment, 15 h was selected as the relative equilibrium time.

Results and discussion

Collars with various W/b were installed surrounding the rectangular piers with various L/b aligned with the flow at the 90-degree position of the bend at the initial bed level for scour reduction. As depicted in Fig. 2, attaching the collars with $W/b > 2$ to the piers splits the scour cavity created surrounding the pier without collars, one surrounding the pier and collar combination (the first scour cavity, FS) and the other at the downstream side of their location (the second scour cavity, SS). By attaching the collars with $W/b \leq 2$ to

the piers, the scour cavity is generated the same way as the cavity created surrounding the pier without collars, but in smaller dimensions.

Figures 3, 4 and 5 provide the values of the volume, the area, and the maximum depth of scouring cavities created surrounding the combination of piers and collars and their comparison with the case of a pier without collars, respectively. In this figures, V , A and d_{sm} , respectively, represent the volume, the area and the maximum depth of scouring cavity created surrounding the combination of pier and collar, and y is the average depth of flow at the bend entrance. By attaching the collars with $W/b > 2$ to the piers, the second scour cavity parameters were developed downstream of the combination. By attaching the collars to the piers, it may be observed that increasing the width of collar decreases the values of the volume, the area and the maximum depth of first scour cavity in comparison with attaching the collar of $W/b = 1.5$. However, increasing the width of collar causes an increase in these values at the second scour cavity in comparison with attaching the collar of $W/b = 2.5$ to the pier. Furthermore, the values of the volume, the area and the maximum depth of first scour cavity are greater than those of the second scour cavity by attaching the collars with W/b

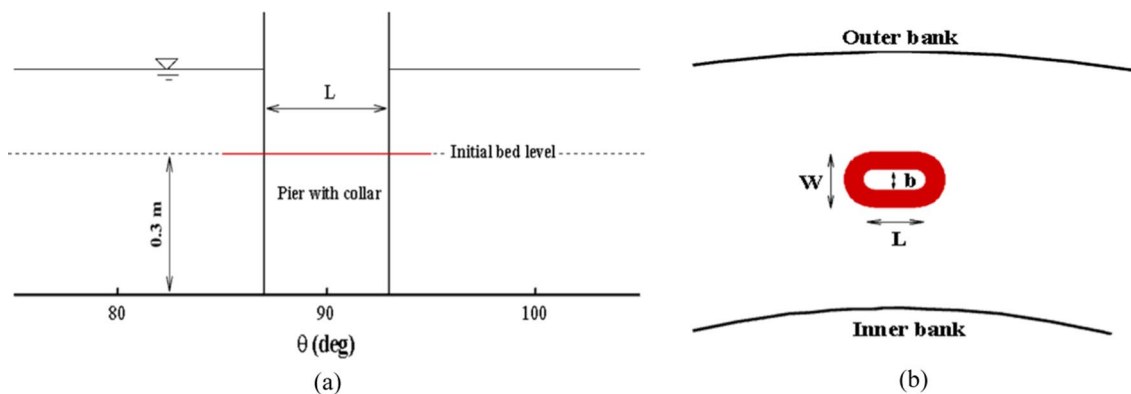


Fig. 1 a Lateral and b plan views of a combination of pier and collar in the bend

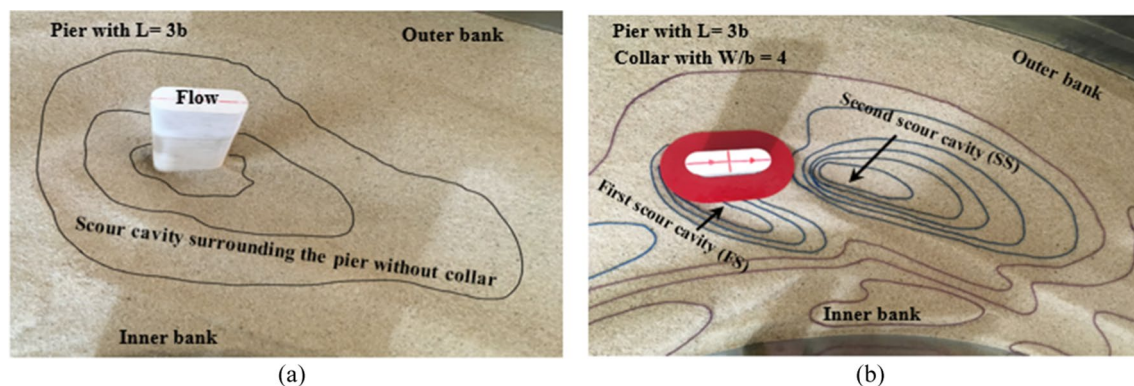


Fig. 2 The scour cavity created surrounding the pier a without and b with a collar

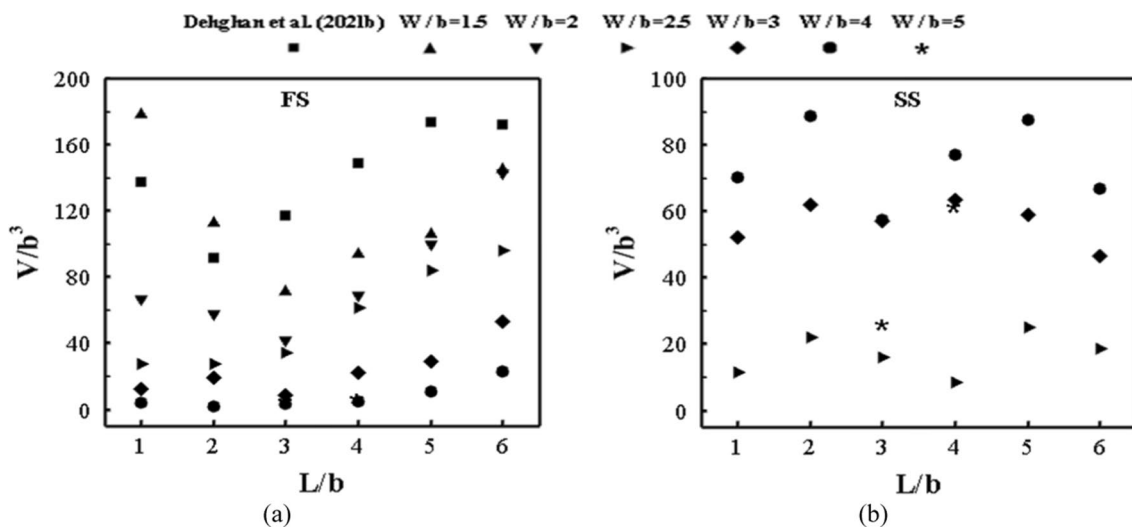


Fig. 3 Values of the volume of scouring cavities created surrounding the rectangular piers and collars combination

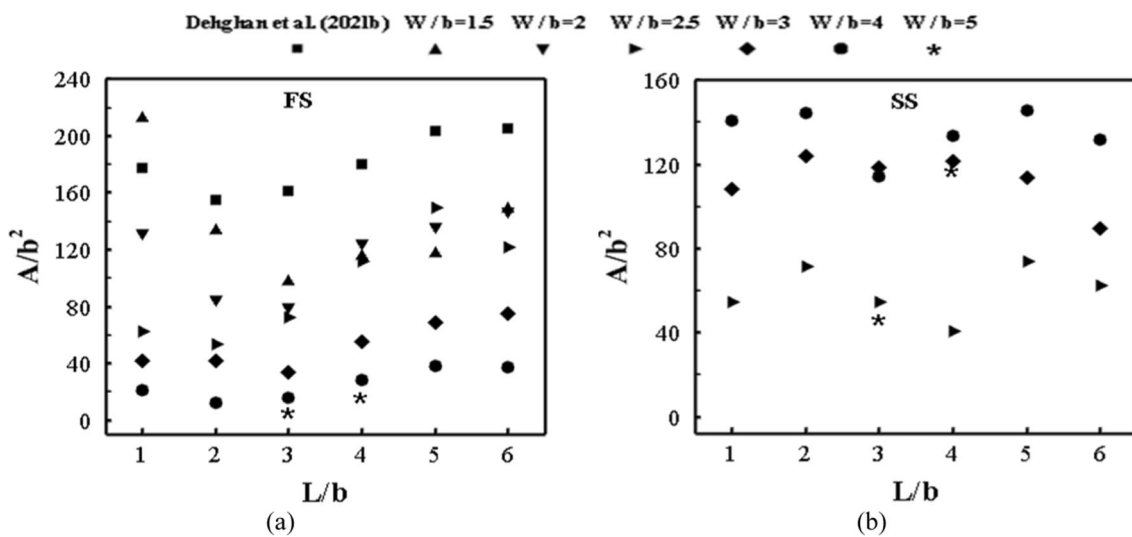


Fig. 4 Values of the area of scouring cavities created surrounding the rectangular piers and collars combination

≤ 2.5 to the piers, and increasing the width of collar would make the values of the volume, the area and the maximum depth of second scour cavity greater than those of the first scour cavity. The length of pier also has a direct effect on the values of the volume, the area and the maximum depth of first and second scour cavities so that increasing the length of pier would increase these values.

According to Fig. 3a, the minimum and maximum volumes of first scour cavity occur surrounding the piers by attaching the collars of $W/b=4$ and 1.5 , respectively. The maximum first scour cavity volume was measured surrounding the pier of $L=1b$ by attaching the collar of $W/b=1.5$, and the minimum surrounding the pier of $L=2b$ by attaching the collar of $W/b=4$ at, respectively, $178.4b^3$ and $1.6b^3$. In

Fig. 3b, the minimum and maximum volumes of the second scour cavity occurred by attaching the collars of respective $W/b=2.5$ and 4 to the piers of $L=4b$ and $2b$ at respective values of $8.6b^3$ and $88.8b^3$. Attaching the collar of $W/b=5$ to the piers of $L=3b$ and $4b$ significantly reduced the first scour cavity volume in comparison with the other collars. Furthermore, it reduced the second scour cavity volume by, respectively, 60 and 30% in comparison with attaching the collar of $W/b=4$ to these piers. Attaching the collar of $W/b=1.5$ to the piers of $L=1b$ and $2b$, respectively, increased the scour cavity volume surrounding the pier and collar combination in comparison with the case of a pier with no collars installed by approximately 30 and 25% . By attaching the collar of $W/b=4$ to the piers, in contrast to other collars, the

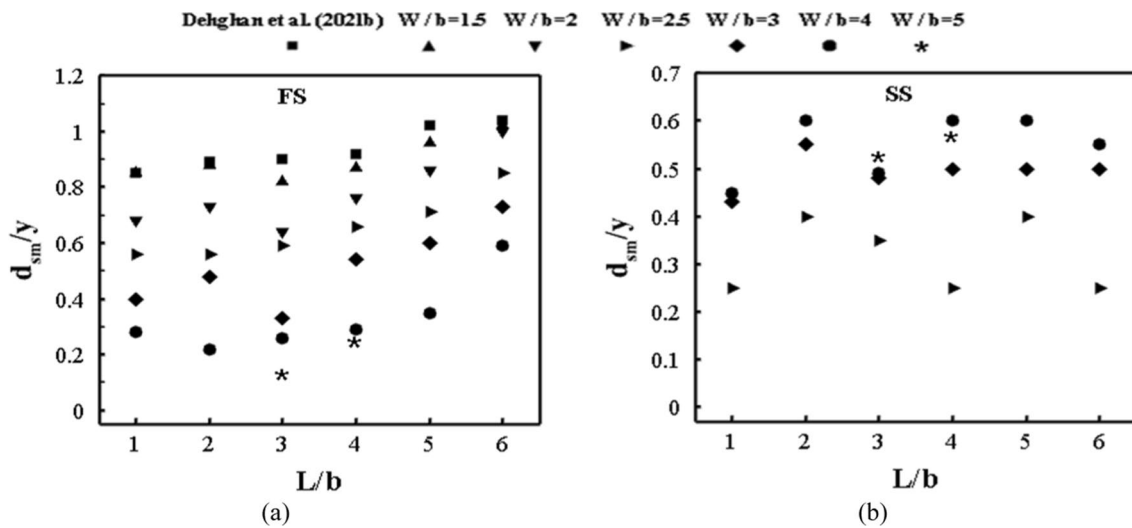


Fig. 5 Values of the maximum depth of scouring cavities created surrounding the rectangular piers and collars combination

scour cavity volume created surrounding the piers similarly reduced. Increasing the length of pier lessened the amount of scour cavity volume reduction surrounding the pier.

In Fig. 4a, the maximum first scour cavity area was measured surrounding the combination of the pier of $L=1b$ and the collar of $W/b=1.5$ at a value of $212.4b^2$, and its minimum surrounding the combination of the pier of $L=2b$ and the collar of $W/b=4$ at a value of $12b^2$. In Fig. 4b, the minimum and maximum areas of the second scour cavity occurred at respective values of $40.7b^2$ and $145.8b^2$ at the downstream of the combination of piers of $L=4b$ and $5b$, and collars of $W/b=2.5$ and 4 , respectively. By attaching the collars of $W/b=1.5$ and 2.5 , respectively, to the piers of $L=1b$ and $5b$, and attaching the collars of $W/b=3$ and 4 to the pier of $L=2b$, the total areas of the first and second scour cavities increased compared to the pier without collars. When collars with smaller widths are installed surrounding the piers, they result in a greater reduction of the total areas of the first and second scour cavities surrounding the combination of pier and collar compared to the pier without collars. The highest amount of reduction of area and volume of the scouring cavity occurred surrounding the combination of pier and collar compared to the pier without collars when the collar of $W/b=2$ was installed surrounding the pier of $L=3b$ by, respectively, 50 and 65%.

According to Fig. 5, the maximum depth of scouring created in the first scour cavity by attaching the collar of $W/b=1.5$ to the pier of $L=6b$ equals $1.02y$, and that in the second scour cavity by attaching the collar of $W/b=4$ to the piers of $L=2b, 4b$ and $5b$ is $0.6y$ for all the three cases. The minimum depth of first scour cavity occurred surrounding the combination of the pier of $L=2b$ and the collar of $W/b=4$ at a value of $0.22y$, and that of the second scour cavity occurred by attaching the collar of $W/b=2.5$ to the

piers of $L=1b, 4b$ and $6b$ at a value of $0.25y$ for all the three cases. Attaching the collar of $W/b=5$ to the piers of $L=3b$ and $4b$ almost prevented the creation of a scour cavity surrounding the pier. Values of the area and the maximum depth of scouring created surrounding the pier of $L=3b$ and the collar of $W/b=5$ were, respectively, $0.1b^2$ and $0.1y$ and reduced the area and the maximum depth of scouring by approximately 90 and 85%, respectively, in comparison with the pier having the collar of $W/b=1.5$. By attaching the collars with greater widths to the pier of $L=6b$, the greater length of this pier compared to others caused the maximum depth of the first scour cavity to be greater than that of the second scour cavity. Attaching the collars to the piers reduced the maximum depth of scouring cavity in front of the nose of piers in every case. Therefore, increasing the width of collar increased the reduction of maximum depth of scouring in comparison with the case of a pier without collars, and increasing the length of pier reduced this value. The highest amount of reduction in the maximum depth of scouring occurred by attaching the collar of $W/b=4$ to the piers of $L=2b, 3b$ and $4b$ by, respectively, 75, 70 and 70%. Furthermore, the lowest amount occurred by attaching the collars to the pier of $L=6b$ due to the great length of the pier and hence the reduction in the efficiency of the collar.

It is noteworthy that the highest amount of reduction in the volume, the area, and the maximum depth of scouring cavity in comparison with the case of a pier without collars occurred when collars with various W/b were installed surrounding the pier of $L=3b$. Consequently, to reducing the scouring parameters surrounding the pier and collar combination, the pier of $L=3b$ had a better performance compared to the pier without collars than other piers installed at the 90-degree position did, which corresponds with the results obtained by Dehghan et al. (2021b), reporting the

appropriate performance of the pier of $L=3b$ in a 180-degree sharp bend.

The maximum depth of scouring cavity surrounding the pier and collar combination located at the 90-degree position of the 180-degree sharp bend is affected by the length of pier and the width of collar. Equation (1) was calculated to estimate the maximum depth of scouring cavity surrounding the pier and collar combination.

$$\frac{d_{sm}}{y}(\text{Cal}) = 0.0538 \frac{L}{b} - 0.2305 \frac{W}{b} + 1.0468, \quad R^2 = 0.91 \quad (1)$$

Besides, Fig. 6 illustrates the comparison between the experimental data and the values obtained from Eq. (1).

Figure 7 shows a sample of the effects of increasing the width of collar surrounding the pier of $L=4b$ on changes of bed topography at the pier downstream. In Fig. 7a, by attaching the collar of $W/b=1.5$ to the pier, the scouring cavity is formed surrounding the pier. By increasing the width of collar according to Fig. 7b, the scouring cavity at the pier downstream is inclined toward the outer bank, so that in Fig. 7c, attaching the collar of $W/b=2.5$ to the pier causes the transfer of the scour cavity surrounding the pier to the downstream of the pier and creation of a second scour cavity at the downstream of the combination of pier and collar and almost in the center of the channel width. Also, the scouring cavity surrounding the pier is more inclined toward the outer bank. As can be seen in Fig. 7d, by attaching the collar of $W/b=3$ to the pier, a second scour cavity with larger dimensions than the previous figures is created at the downstream of the combination of pier and collar and has caused the first scour cavity to incline toward the inner bank. In Fig. 7e, as the width of collar increases surrounding the pier, the first scour cavity is formed along the length of pier inclined toward the inner bank, so that in Fig. 7f, this increase in the width of collar has caused about 90% of the scouring cavity to be transferred to the downstream of the

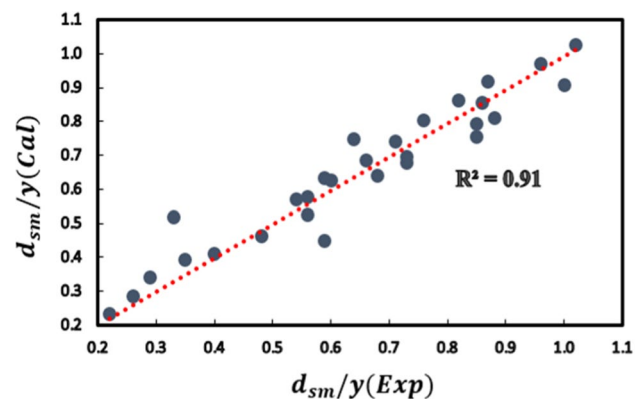


Fig. 6 Comparison between the experimental data and the values obtained from Eq. (1)

pier and collar combination compared to Fig. 7a. As shown in the figures, the scouring cavity created surrounding the pier has been transferred to the downstream of the pier and collar combination due to the increase in the width of collar surrounding the pier. This matter by transferring the scour cavity surrounding the pier to the channel center prevents the destruction of downstream banks. Furthermore, increasing the width of collar surrounding the pier has caused more transfer of sediments from the scour cavities to the downstream of bend along the inner bank.

A sample of the transverse sections near the nose of combination of pier and various collars installed at the 90-degree position of the bend is depicted in Fig. 8. Z denotes the distance from the initial bed level. In all of the figures, sedimentation is evident near the inner bank due to the effect of the secondary flow in the bend, and increasing the width of collar increases the height of maximum sedimentation. Increasing the width of collar inclines the maximum scouring depth location at width of channel toward the inner bank and reduces the maximum scouring depth. However, increasing the length of pier entails an increase in the scour cavity width and inclines the location of the maximum scouring depth toward the channel center. Increasing the width of collar decreases the scour cavity width surrounding the pier and collar combination compared to the scour cavity created surrounding the pier without collars. Moreover, bed topography in the vicinity of the outer bank is located at its initial level. In Fig. 8a, the amount of reduction in the scour cavity width when the collar of $W/b=4$ is installed surrounding the pier of $L=1b$ is greater than that with the collar of $W/b=1.5$ installed in comparison with other collars due to the greater width of the collar. According to Fig. 8b, increasing the length of pier leads to an increase in the amount of reduction in the scour cavity width. Attaching the collar of $W/b=4$ to the pier of $L=1b$ and $2b$, respectively, reduced the scour cavity width by 40 and 70% in comparison with the collar of $W/b=1.5$. By attaching the collar of $W/b=5$ to the pier of $L=3b$ in Fig. 8c, the changes of bed topography from a distance of $0.15B$ of the inner bank to the outer bank are insignificant, and in front of the nose of pier, the collar prevents creation of a cavity. With smaller widths of the collar, a scour cavity is created in front of the nose of pier, where the scour cavity width decreases by increasing the width of collar. The effect of collars with $W/b > 2.5$ on reduction of the scour cavity width is greater than that of the collars with $W/b < 2.5$ in comparison with the scour cavity width created surrounding the pier without collars. When the collar width is doubled, tripled and quadrupled, the width of the scour cavity decreases by approximately 30, 60 and 80%, respectively, in comparison with the case of a pier without collars, and it orients toward the inner bank. According to Fig. 8d, by attaching the collar of $W/b=5$ to the pier of $L=4b$ in comparison with the previous figure, a scour cavity occurs

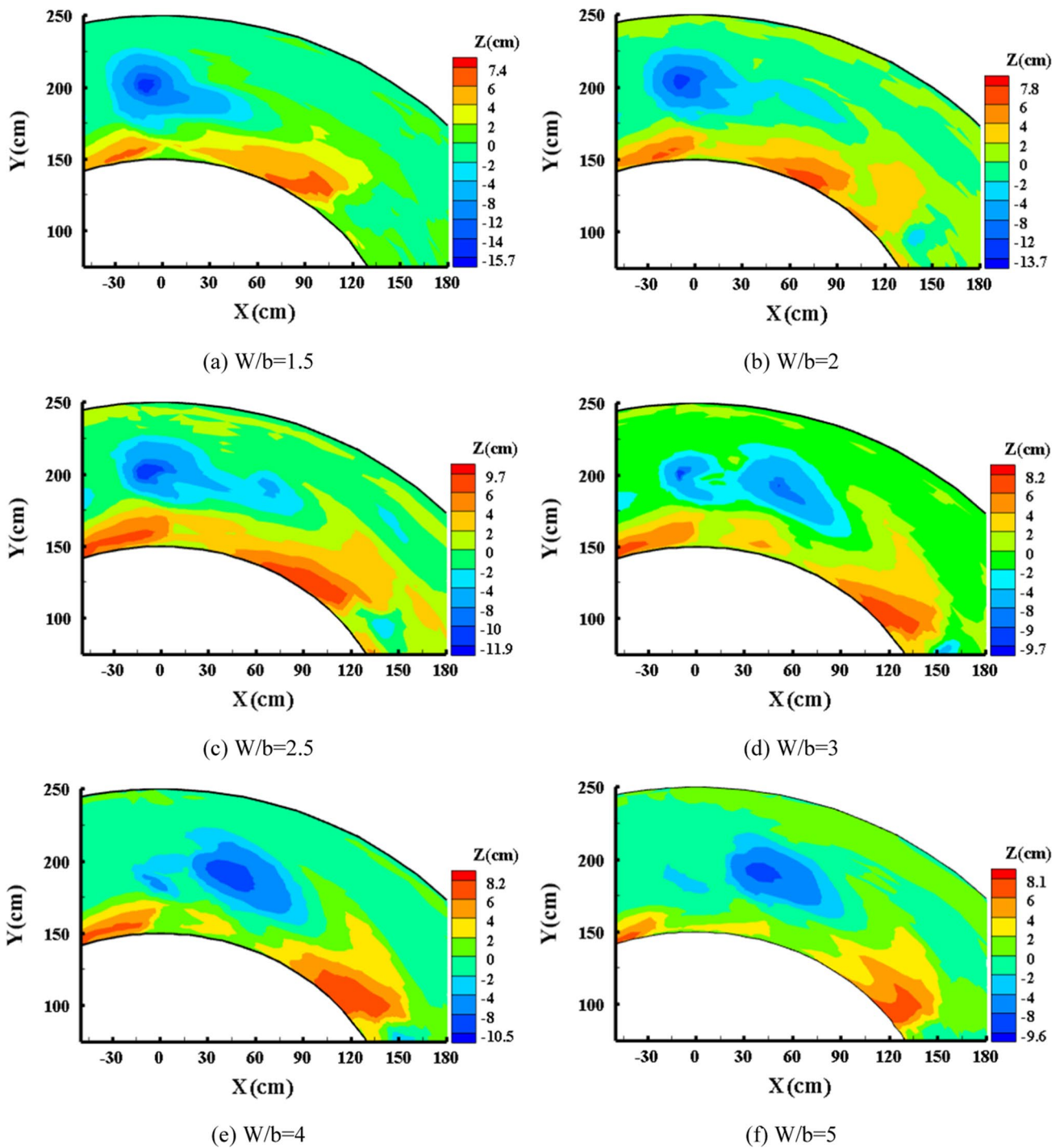


Fig. 7 The effects of increasing the width of collar on the changes of bed topography surrounding the pier of $L=4b$

before the nose of pier with a width of $0.1B$ due to pier length increase. Triple and quadruple collar widths reduce the scour cavity width by approximately 40 and 60%, respectively, compared to the pier without collars, and incline the scour cavities further toward the inner bank in comparison with the previous figure. The maximum scouring depth location by attaching the collar of $W/b=4$ to the piers of

$L=3b$ and $4b$ approaches the inner bank by approximately 15 and 20%, respectively, in comparison with the location of maximum scouring depth in the case of pier without collars. By attaching the collars to the pier of $L=5b$, according to Fig. 8e compared to previous figures, the scour cavity is created before the nose of the combination of pier and collar in every case. This is because increasing the length of

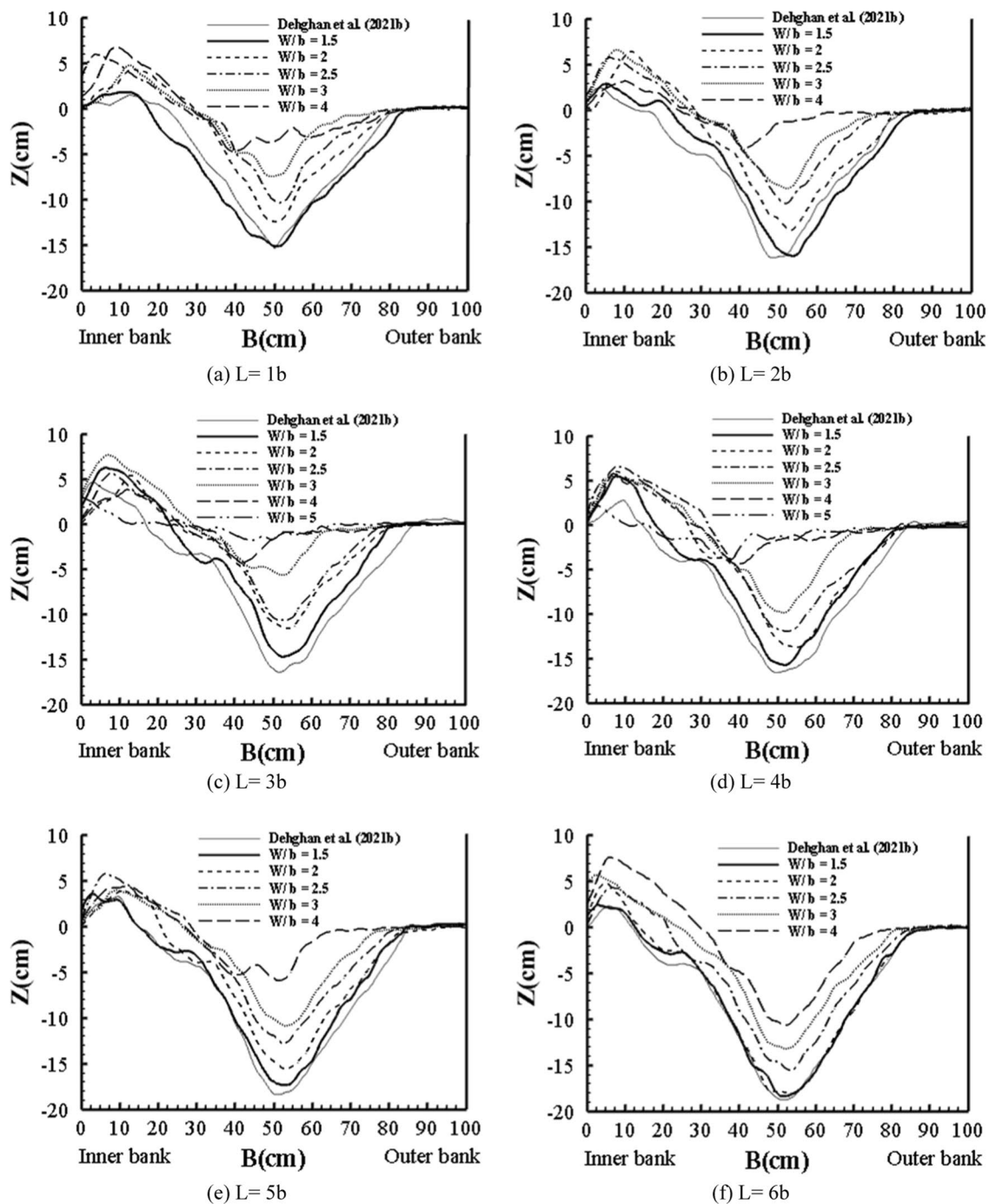


Fig. 8 Sample of the transverse sections near the nose of combination of pier and collar installed at the 90-degree position

pier increases the width of scouring cavity in front of the nose of pier. Therefore, by attaching the collars to the pier of $L=6b$ in Fig. 8f, because of the great length of the pier, scour cavities of a greater depth and width than the other piers are created in front of the nose of pier. By attaching the collar of $W/b=1.5$ to the pier of $L=6b$, little change occurs in the scour cavity width in comparison with the case of a pier without collars, and the scour cavity width in both

cases is equal to $0.625B$. It is noteworthy that by increasing the width of collar surrounding the piers of $L=5b$ and $6b$, the location of maximum depth of scouring occurs in front of the nose of pier in every case due to the great length of the pier and penetration of the flow beneath the collar. By attaching the collar of $W/b=1.5$ to the piers of $L=1b$ and $5b$, the scour cavity width surrounding the combination of pier and collar increases by approximately 15 and 5%,

respectively, in comparison with the case of a pier without collars. The reduction of the scour cavity width is important in that the scour cavity will not reach the banks and destroy them. The amount of reduction in the scour cavity width is almost the same by attaching the collars of $W/b = 3$ and 4 to the piers of $L = 3b$ and $4b$, respectively; i.e., in order to reduce the scour cavity width by 60% surrounding the piers of $L = 3b$ and $4b$, collars of $W/b = 3$ and 4 must be used, respectively. The greatest reduction in the scour cavity width surrounding the piers occurred by 78% by attaching the collar of $W/b = 4$ to the pier of $L = 3b$.

Figure 9 shows the longitudinal sections in the center of channel width surrounding the combination of pier and various collars. θ in this figure denotes the angle from the bend entrance in the channel. In Fig. 9a, by attaching various collars to the pier of $L = 1b$ from the beginning to the angle of 75 degree of the bend, changes of bed topography are insignificant. Increasing the width of collar decreases the length and depth of the scour cavity created surrounding the pier and increases the length and depth of the scour cavity created at the downstream of pier. By attaching the collars to the pier, sedimentary stack is created from the 120- to the 140-degree angles. Thereafter to the end of the bend, bed topography remains the same as its initial level in every case except in the cases of a pier installed without collars and a pier with a collar of $W/b = 1.5$ because the downflow falling from the sedimentary stack onto the initial bed level creates a cavity at that region. In Fig. 9b, increasing the width of collar surrounding the pier of $L = 2b$ increases the length and depth of the scour cavity created at the downstream of pier in comparison with the previous figure. By attaching the collar of $W/b = 2$ to the pier after the second scour cavity, there are no sedimentary stacks accumulated at this longitudinal section to the end of the bend. In other cases, sedimentary stacks are created from the 120- to the 140-degree angles of the bend, and increasing the width of collar decreases the length of these stacks. A scour cavity is generated at the downstream of the pier without collars at the 135- to 150-degree angles approximately, but attaching the collars to the pier prevents this scour cavity, and the bed topography undergoes no changes to the bend end. In Fig. 9c, where the pier of $L = 3b$ is installed, increasing the width of collar decreases the length and height of the sedimentary stack at the pier downstream compared to the pier without collars. Furthermore, by attaching the collars to the pier, the sediments discharged from the scour cavities are accumulated at the approximate interval of 120 to 135 degrees of the bend. In front of the nose of pier, increasing the width of collar leads to a reduction of the scour cavity length at the upstream side of the pier, whereas with creation of the second scour cavity in front of the tail of pier, the scour cavity length increases by increasing the width of collar. In Fig. 9d, by attaching the collars of $W/b = 1.5, 2,$

2.5 and 3 to the pier of $L = 4b$, a scour cavity is generated in front of the nose of pier, where the depth and length of scour cavity at the upstream of the pier nose are reduced by increasing the width of collar. By attaching the collars of $W/b = 4$ and 5 to the pier, a scour cavity is created at the pier downstream, and increasing the width of collar increases the depth and length of scour cavity. Furthermore, by attaching the collar of $W/b = 3$ to the pier, the scour cavities depth created in front of the nose of pier and the pier downstream remains almost the same and equal to $0.5y$. According to Fig. 9e, the scour cavity depth created at the upstream of pier nose of $L = 5b$ when collars of $W/b = 1.5$ to 3 are installed surrounding the pier is greater in comparison with the scour cavity depth created at the pier downstream, while attaching the collar of $W/b = 4$ results in the reverse. By attaching the collars of $W/b = 2$ to 4 to the pier, the sediments discharged from the scour cavities are accumulated at the interval of $24.4b$ to $48.8b$ toward the piers downstream. Increasing the width of collar decreases the length of the sedimentary stack generated at the pier downstream. Furthermore, by attaching the collar of $W/b = 1.5$ to the pier, the sedimentary stack is formed as high as $0.12y$ at a distance of $17.3b$ to $38.4b$ toward the pier downstream. In Fig. 9f, by attaching the collars to the pier of $L = 6b$, the scour cavity depth in front of the nose of pier is greater than the depth of that created at the pier downstream in every case. Increasing the length of pier in comparison with the two previous figures inclines the sedimentary stacks toward the pier downstream up to an approximate distance of $55.8b$. The maximum sedimentation height, equal to $0.27y$, occurs by attaching the collar of $W/b = 2.5$ to the pier at $29.2b$ toward the pier downstream almost equal to the maximum sedimentation height in the case of a pier without collars. As evident in bed longitudinal profile figures, by attaching the collars to the pier and increasing the width of collar, the depth and length of the scour cavity created at the pier upstream decrease; however, the depth and length of the scour cavity created at the pier downstream increase by increasing the width of collar.

Regarding the attaching the collars with various W/b to the piers, the sediment reach toward the straight path at the pier downstream and the height of maximum sedimentation non-dimensionalized with the average depth of flow at the bend entrance are presented in Fig. 10. In this figure, L_D and h_{sm} represent the distance of sediment progress toward the straight path at the pier downstream and the height of maximum sedimentation, respectively. Attaching the collars to the piers reduces sediment progress toward the straight path at the pier downstream compared to the pier without collars. In Fig. 10a, the maximum sediment progress occurs by attaching the collar of $W/b = 1.5$ to the pier of $L = 1b$, equal to $64.8b$, toward the pier downstream; i.e., the sediments reach up to $2b$ from the end of the bend in the downstream straight path. Further, by attaching the collar of $W/b = 2$ to

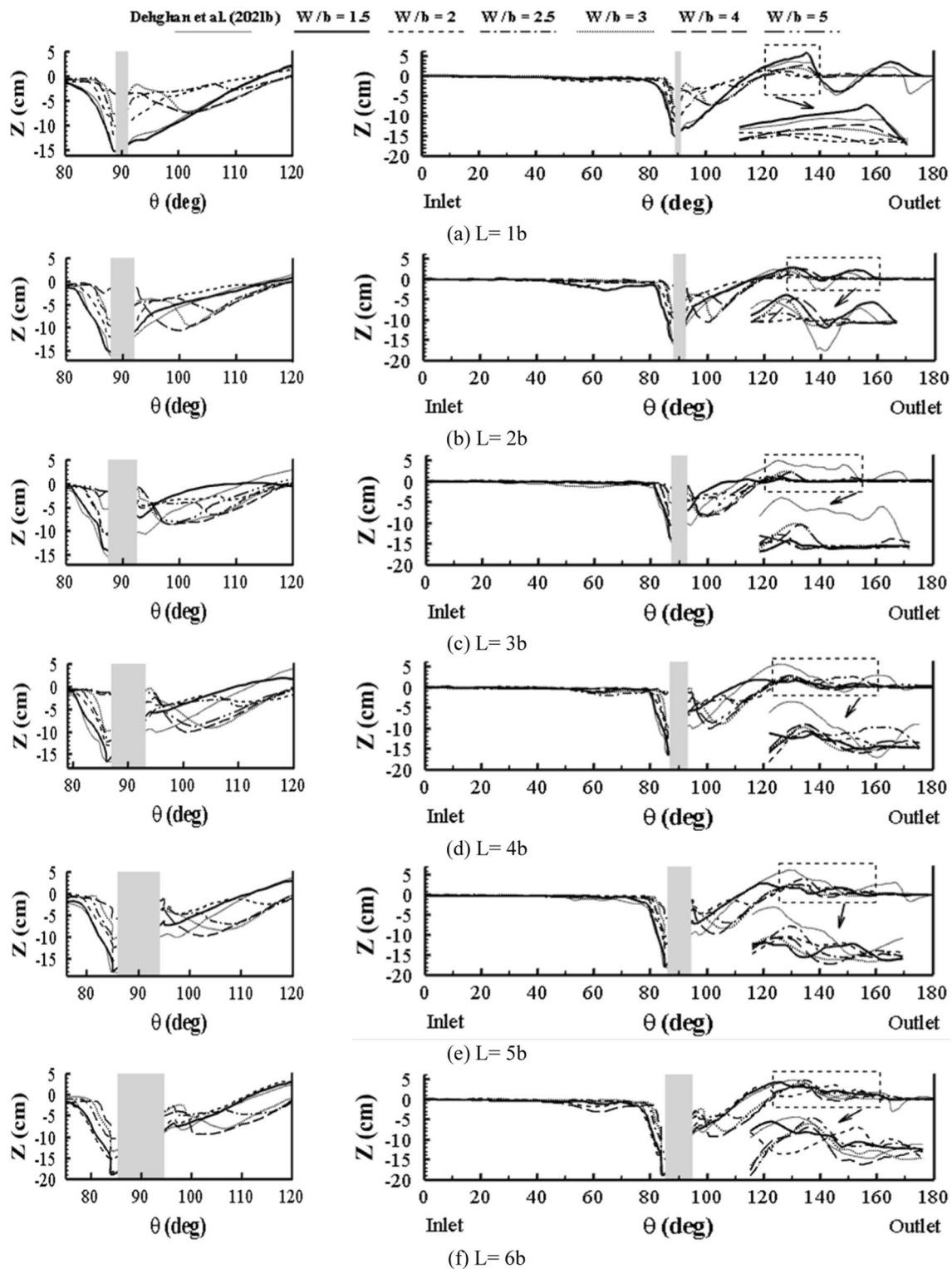


Fig. 9 Longitudinal sections in the center of channel width surrounding the combination of pier and various collars

the pier of $L = 3b$, the minimum sediment progress, equal to $33.5b$, occurs toward the pier downstream. Increasing the width of collar surrounding the piers of $L = 1b$ and $2b$ increases the sediment progress toward the pier downstream.

By attaching the collars to the piers of $L = 3b$ and $4b$, the maximum sediment progress values occur by attaching the collars of $W/b = 3$ and 4 to the piers at, respectively, $45.4b$ and $52.3b$ toward the piers downstream. The maximum

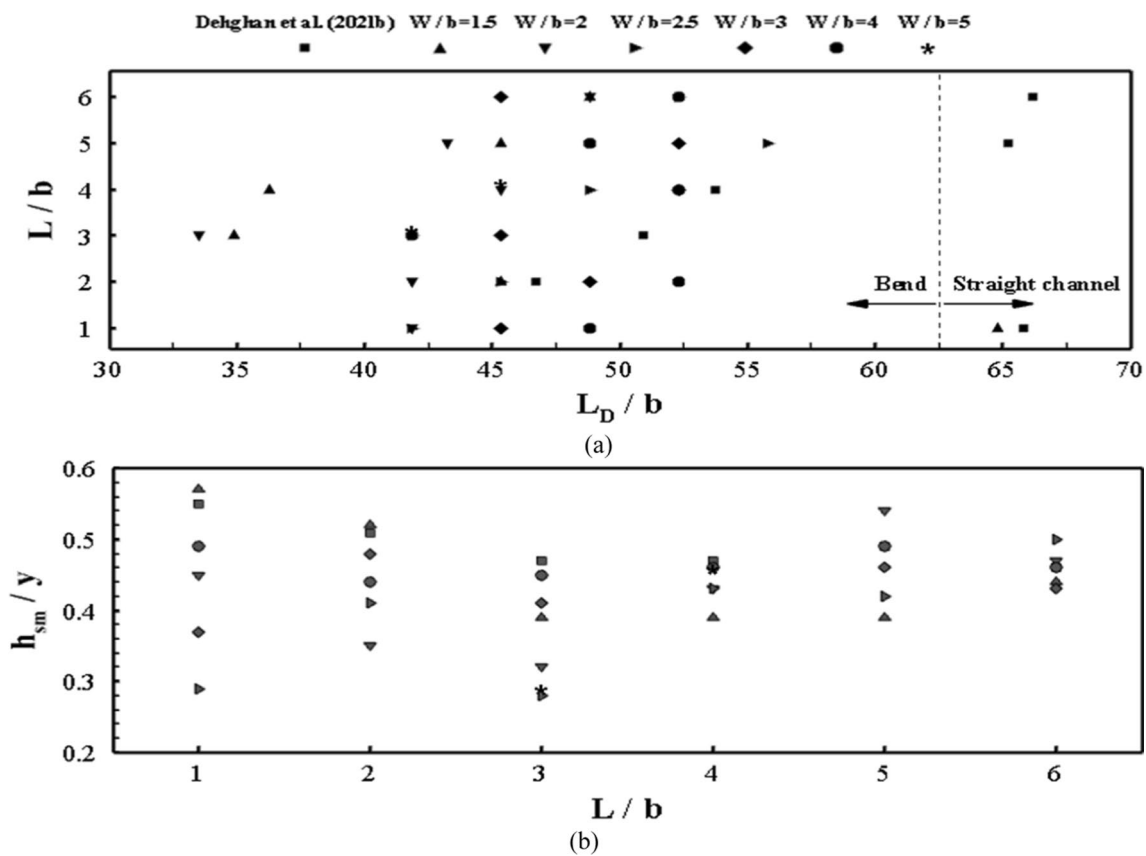


Fig. 10 **a** Sediment progress toward the downstream straight path and **b** the maximum sedimentation height when various collars are installed surrounding the piers

sediment progress values surrounding the piers of $L=5b$ and $6b$ and the attached collar of $W/b=2.5$ to the piers occur at, respectively, $55.8b$ and $52.3b$ toward the piers downstream. Increasing the length of pier entails further sediment progress toward the downstream of the pier and collar combination; however, increasing the width of collar causes a reduction in sediment progress toward the downstream straight path. Additionally, the minimum progress toward the pier downstream occurs by attaching the collars to the pier of $L=3b$. The maximum sedimentation height decreases in comparison with the case of a pier without collars only when the collars are installed surrounding the pier of $L=3b$; however, by attaching the collars with smaller widths to the other piers, the maximum sedimentation height increases in comparison with the case of a pier without collars. According to Fig. 10b, the maximum sedimentation height, $0.57y$, occurs by attaching the collar of $W/b=1.5$ to the pier of $L=1b$, and the minimum sedimentation height, $0.51y$, takes place when the collars of $W/b=2.5$ and 5 are installed surrounding the pier of $L=3b$. By attaching the collars to the piers of $L=3b$, $4b$ and $5b$, the maximum sedimentation height increases when the collar width is increased. Moreover, increasing the length of pier increases the maximum sedimentation

height. By attaching the collars of $W/b=1.5$ and 2.5 to the piers, increasing the pier length, respectively, decreases and increases the maximum sedimentation height. By attaching the collars of $W/b=2.5$ and 3 to the pier of $L=6b$, the maximum and the minimum sedimentation heights, respectively, equal to $0.5y$ and $0.43y$, occur at the pier downstream. The maximum sedimentation height increases by attaching the collars to the pier of $L=5b$ in comparison with the case of a pier of $L=4b$ and the increased pier length. In general, attaching the collars to the piers entails reduction of the maximum sedimentation height so that a simultaneous increase in the width of collar and the pier length decreases the reduction of these values.

Kumar et al. (1999) and Zarrati et al. (2004) considered collars with various W/b ratios surrounding the rectangular piers in a straight channel and concluded that the collar of $W/b=3$ performed better than collars with other ratios in reducing the maximum scouring depth in front of the nose of pier in comparison with the case of a pier without collars. According to the results obtained from the present work on the ratio of collar width to pier width in the bend channel, it may be stated that in a 180-degree sharp bend, collars with the collar width-to-pier width ratios equal to 3 to 4 have the

best performance in reducing the maximum depth of scouring in front of the nose of pier, and the area and volume of scour cavity surrounding the piers. Therefore, incorporation of the collar of $W/b=3$ for piers with smaller L/b ratios and the collar of $W/b=4$ for the piers with greater L/b is more appropriate and economic for reducing the maximum scouring depth and the volume and area of the scour cavity. The effect of the collar of $W/b=4$ installed surrounding the piers on scour parameters including the area, the depth and the volume of the scour cavities at the positions of 60 and 120 degree of the bend was investigated.

The parameters measured in this stage and their comparisons with the case of a pier without collars are presented in Table 1. In this table, θ_p is where the combination of pier and collar is situated along the bend. According to the table, attaching the collar to the piers and increasing the length of pier at the 60-degree position increase the maximum first scour cavity depth, whereas at the 120-degree position up to the pier of $L=5b$, increasing the length of pier results in

an initial reduction and then an increase in the maximum first scour cavity depth. Furthermore, increasing the length of pier at the 60-degree position up to the pier of $L=3b$ first increases and then decreases the maximum second scour cavity depth. However, at the 120-degree position, increasing the length of pier almost reduces the maximum second scour cavity depth. The maximum depths of the first and the second scour cavities, equal to $0.46y$ and $0.63y$, at the 60-degree angle were, respectively, measured surrounding the piers of $L=6b$ and $3b$, and those, equal to $0.22y$ and $0.44y$, at the 120-degree angle were, respectively, measured surrounding the piers of $L=6b$ and $4b$. At the 60-degree position, increasing the length of pier until the pier of $L=4b$ first reduces the area and volume of the first scour cavity and then increases them. Further, increasing the length of pier, except for the pier of $L=1b$, increases the area and volume of the first scour cavity at the 120-degree position. The increase in the length of pier at the 120-degree position decreases the second scour cavity volume, while the increase

Table 1 Experimental data surrounding the combination of piers and collar of $W/b=4$ installed at the 60- and 120-degree positions

	Piers	θ_p deg	Scour cavity	L/b						
				1	2	3	4	5	6	
dsm/y	Without collar Dehghan et al. (2021b)	60	FS	0.87	0.88	0.89	0.92	0.95	0.76	
		120	FS	0.74	0.72	0.82	0.85	0.93	0.91	
	With collar (This study)	60	FS	0.28	0.33	0.37	0.35	0.4	0.46	
			SS	0.51	0.63	0.63	0.61	0.62	0.6	
		120	FS	0.16	0.07	0.08	0.14	0.13	0.22	
			SS	0.5	0.36	0.4	0.44	0.34	0.25	
	Reduction (%)	60	FS	68	62	58	62	57	40	
		120	FS	78	90	90	83	85	75	
	V/b3	Without collar Dehghan et al. (2021b)	60	FS	141.3	132.8	147.3	175.5	209	201.3
			120	FS	64.6	47.7	67.8	82	98.4	99.3
With collar (This study)		60	FS	19.4	17.6	12.3	9.4	15.1	41.4	
			SS	87.2	125.1	126.7	110.2	114.2	118.1	
		120	FS	14	0.1	0.1	1.3	1	1.5	
			SS	67.2	10.8	12.8	21.6	7.1	3	
Reduction (%)		60	FS	25	-15	6	32	38	21	
		120	FS	-26	77	81	72	92	95	
A/b2		Without collar Dehghan et al. (2021b)	60	FS	194	211.7	221.5	235.2	254.4	290
			120	FS	99.6	80.6	97.2	118	158.3	132.5
	With collar (This study)	60	FS	99.4	67.3	56.3	46	55	113	
			SS	179.4	198.4	185.8	170.4	173.7	215.1	
		120	FS	30.4	3	5	15	22	11	
			SS	149.8	34.9	36.4	59.8	25	15	
	Reduction (%)	60	FS	-43	-25	-9	8	10	-13	
		120	FS	-80	52	57	36	70	80	
	hsm/y	Without collar Dehghan et al. (2021b)	60		0.58	0.57	0.53	0.51	0.62	0.65
			120		0.37	0.31	0.36	0.4	0.38	0.4
With collar (This study)		60		0.57	0.54	0.55	0.49	0.53	0.51	
		120		0.52	0.19	0.25	0.26	0.22	0.17	

in the length of pier at the 60-degree position increases the second scour cavity volume. At the 60-degree position, by attaching the collar to the pier of $L = 6b$, the maximum area and volume of the first scour cavity occur at respective values of $113b^2$ and $41.4b^3$, and those of the second scour cavity surrounding the pier of $L = 3b$ and $6b$ occur at respective values of $215.1b^2$ and $126.7b^3$. Moreover, the maximum values of these parameters occur surrounding the combination of pier and collar of $L = 1b$ for the first scour cavity at, respectively, $30.4b^2$ and $14b^3$, and for the second scour cavity at, respectively, $149.8b^2$ and $67.2b^3$. The values of the volume, the area and the maximum depth of the scour cavities surrounding and downstream of the combination of piers and collar at the 60-degree position are greater than those at the 120-degree position due to installing the piers at the first half of the bend under the direct influence of the upstream straight path. Attaching the collar to the piers at the second half of the bend entails a greater reduction of the maximum scouring depth in front of the nose of pier, and the area and volume of the scour cavities created surrounding the combination of pier and collar compared to the pier without collars because of the direct influence of the downstream straight path on flow conditions in this half compared to the first half of the bend. At the 120-degree position, increasing the length of pier increases the reduction of the maximum scouring depth compared to the pier without collars, while, at the 60-degree position, increasing the length of pier reduces this amount. The maximum and minimum reductions in the maximum scour cavity depth compared to the pier without collars were measured at the 60-degree position with the collar installed surrounding the piers of $L = 1b$ and $6b$ by approximately 68 and 40%, respectively. In addition, at the 120-degree position, the maximum and minimum values, respectively, occurred surrounding the piers of $L = 3b$ and $6b$ by approximately 90 and 75% in comparison with the pier with no collars. Attaching the collar to some piers resulted in an increase in the area and volume of the scour cavities created surrounding the combination of pier and collar in comparison with the area and volume of the scour cavity created surrounding the pier without collars in both positions, which is demonstrated in the table with a minus. The greatest reduction in the area and volume of the scour cavities at the 60-degree position occurred with the collar installed surrounding the pier of $L = 5b$ compared to the pier without collars by approximately 10 and 38%, respectively, and that at the 120-degree position surrounding the piers of $L = 5b$ and $6b$ by approximately 80 and 92%, respectively. Additionally, by attaching the collar to the piers at the 60-degree position, except for the piers of $L = 4b$ and $5b$, the scour cavities area surrounding the combination of pier and collar increased compared to the pier without collars because of installations in the first half of the bend, where the greatest increase, about 43%, was

measured surrounding the combination of pier and collar of $L = 1b$. The maximum sedimentation height also decreased in both positions by attaching the collar to the pier compared to the pier without collars.

Figure 11 illustrates the longitudinal sections in the center of channel width surrounding the piers and collar combination installed at the positions of 60 and 120 degree of the bend. As indicated in Fig. 11a, the first scour cavity surrounding the piers begins from $7.6b$ toward the piers upstream and continues to $2.8b$ toward the piers downstream. The second scour cavity is also created at the interval of $3.5b$ to $33.5b$ toward the piers downstream. Since the piers are installed in the first half of the bend, with an increase in the length of pier, the length of the scour cavities created surrounding the pier increases. The greatest length of the second scour cavity, equal to $32.1b$, occurs by attaching the collar to the pier of $L = 1b$. From $35b$ at the pier downstream to the end of the bend, except for the pier of $L = 1b$, there are sedimentary stacks and scour cavities generated for every pier. At the end of the bend, and from the beginning to approximately 45 degrees, there are no significant alterations observed in bed topography. According to Fig. 11b, when the piers are installed with the collar of $W/b = 4$ at the 120-degree position, the scour cavity with the maximum scouring depth equal to $0.21y$ for the pier of $L = 2b$ is created at the longitudinal profile of the channel center at the interval of 40 to 115 degrees of the bend for every pier except that of $L = 1b$. Creation of such cavities in this region is due to presence of the secondary flows in the bend. Before this interval and also at the end of the bend, except for the pier of $L = 1b$ where sediments progressed in the downstream straight path, changes of bed topography are very few in every pier and the bed is still almost at the initial level. Attaching of the collar to the piers and presence in the second half of the bend under the influence of the downstream straight path prevented generation of a deep and voluminous scour cavity surrounding the piers and collar combination. Increasing the length of pier decreased the second scour cavity length. The greatest length of the second scour cavity occurred by attaching the collar to the pier of $L = 1b$ at $11.7b$. The length of the first and second scour cavities at the 60-degree position is greater than that at the 120-degree position.

Figure 12 illustrates a sample of transverse sections near the nose of the piers and the location of the second scour cavity maximum depth at the downstream of piers and collar combination installed at the 60- and 120-degree positions. According to Fig. 12a, increasing the length of pier increases the width of the scour cavities in front of the piers at the 60-degree position. The maximum scour cavity width occurs by attaching the collar to the pier of $L = 6b$ at $0.4B$, and the minimum occurs by attaching the collar to the pier of $L = 4b$ at $0.25B$, whereas the length of pier increase at

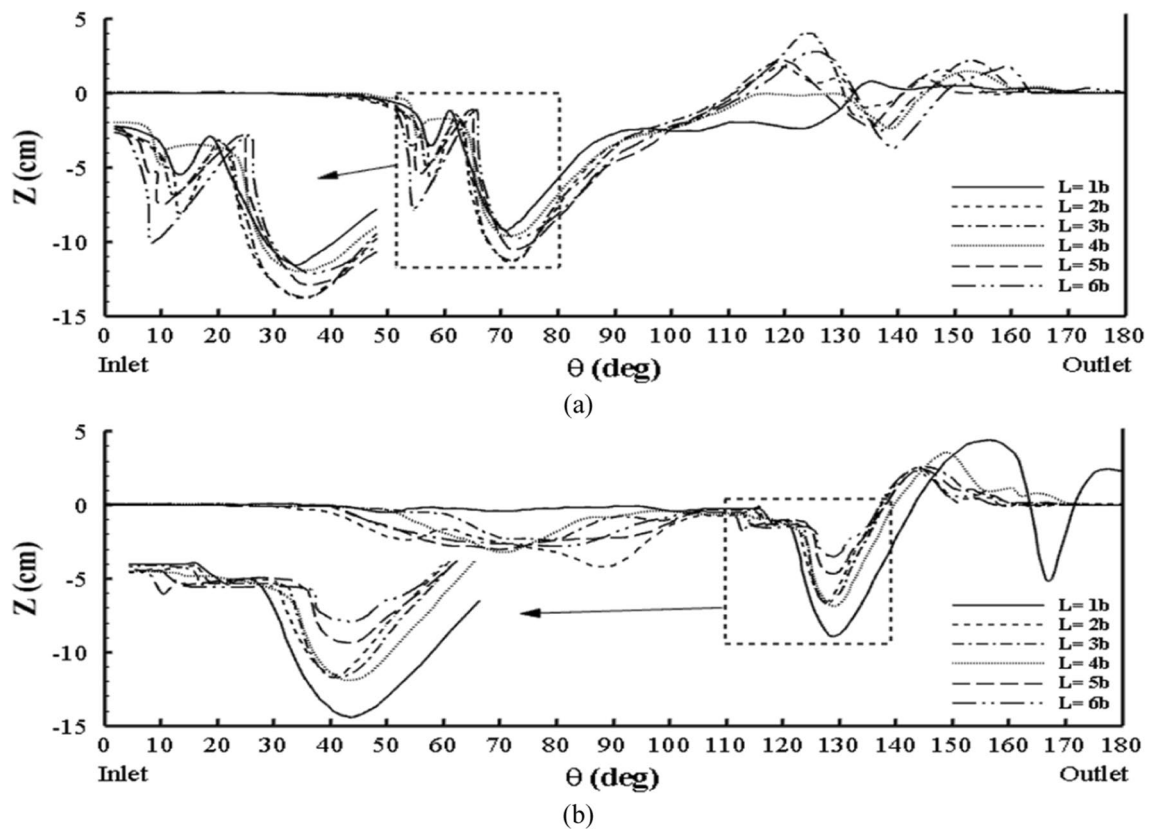


Fig. 11 Longitudinal sections in the center of channel width surrounding the combination of piers and collar installed at **a** 60- and **b** 120-degree positions of the bend

the 120-degree position causes a reduction in the width of the scour cavities to some extent. Furthermore, scour cavities with depths smaller than $0.11y$ are created surrounding the pier at this position. The maximum scour cavity widths, equal to $0.1B$ and $0.05B$, respectively, occur by attaching the collar to the piers of $L=6b$ and $1b$. By attaching the collar to the piers at the 60-degree position, the scour cavity penetrates beneath the collar due to its presence at the first half of the bend, and increasing the length of pier adds to this penetration and further inclines the cavity toward the center of the channel. However, attaching the collar to the piers at the 120-degree position prevents creation of a cavity in front of the nose of pier and beneath the collar. Therefore, a scour cavity is created at the edge near the inner bank of the collar. In Fig. 12b, the location of the second scour cavities maximum depth at the 60-degree position is almost at $8.4b$ toward the piers downstream. The highest and the lowest second scour cavity widths at the 60-degree position were, respectively, measured surrounding the combination of the piers and the collar of $L=2b$ and $5b$ at $0.525B$ and $0.45B$. At the 120-degree position, the location of the second scour cavities maximum depth approaches the proximity of the combination of the pier and the collar by approximately $1.5b$ in comparison with the 60-degree position. The maximum

and minimum widths of the second scour cavity, $0.475B$ and $0.175B$, at the 120-degree position occur by attaching the collar to the piers of respective $L=1b$ and $6b$. In both positions, increasing the length of pier reduces the second scour cavity width. The location of the maximum scouring depth in both positions is inclined toward the inner bank when the length of pier is increased. In addition, the created sedimentation heights in the proximity of the inner bank increase when the length of pier increases. Depending on the location of the combination of the piers and the collar along the bend, the second scour cavity is oriented toward the outer bank at the 60-degree position, and toward the inner bank at the 120-degree position.

Figure 13 illustrates the height of maximum sedimentation and the sediment progress toward the downstream of the combination of piers and collar. By attaching the collar of $W/b=4$ to the piers, the amount of reduction in the height of maximum sedimentation compared to the pier without collar is greater at the 120-degree position than the 60-degree position due to fewer changes of bed topography at the 120-degree position. It may be observed that when the piers and the collar of $W/b=4$ are installed at the 120-degree position, increasing the length of pier reduces the height of maximum sedimentation and the value of L_D . The height of

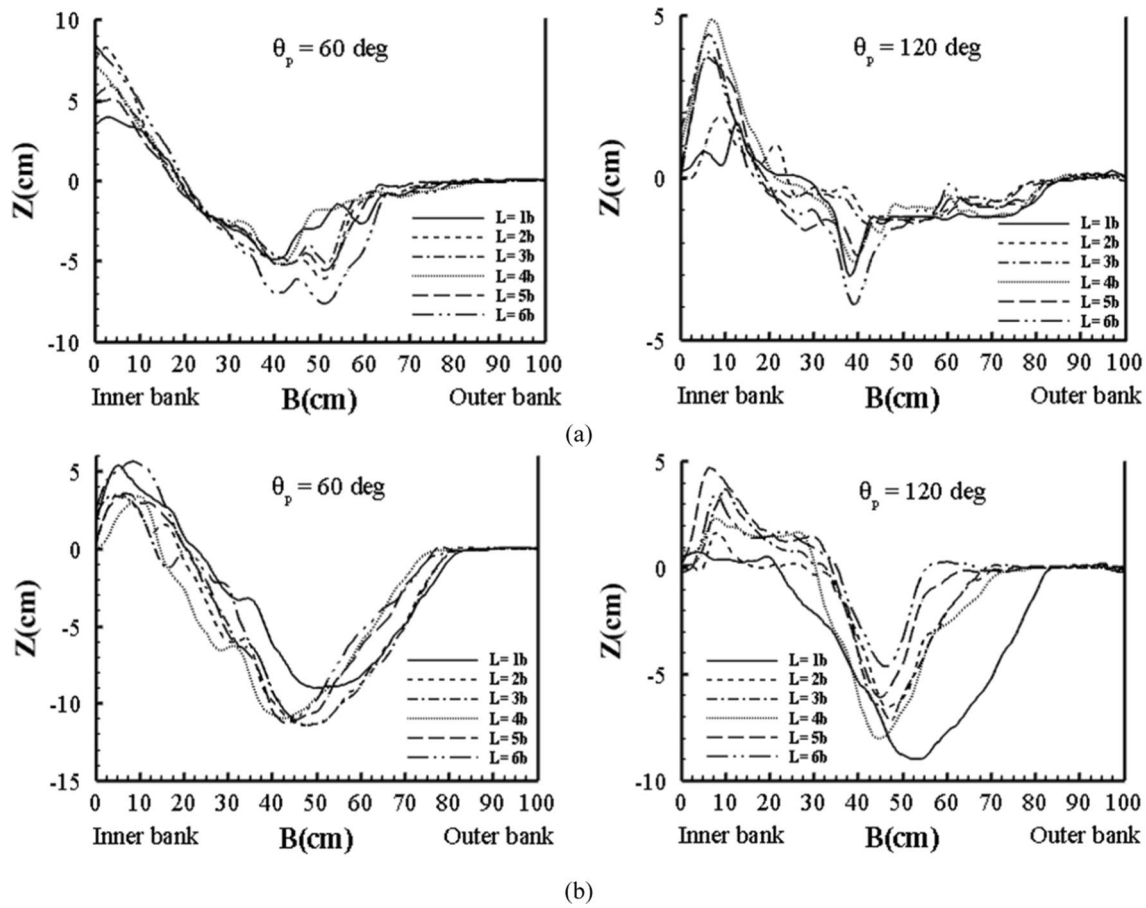
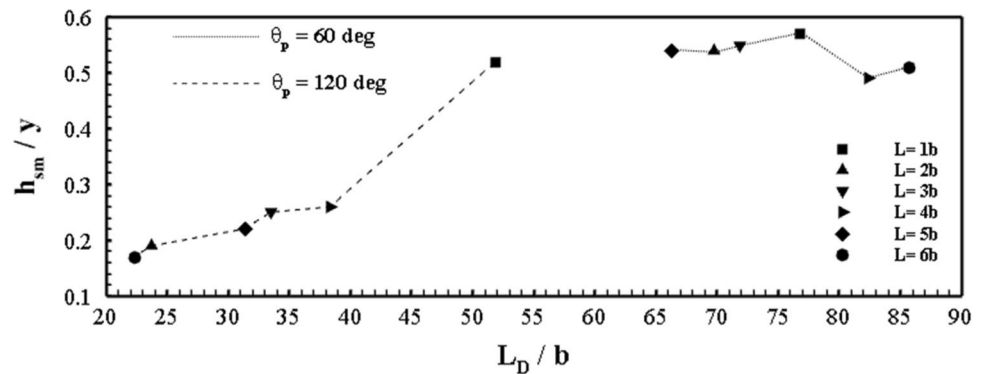


Fig. 12 A sample of transverse sections surrounding the piers and collar combination **a** near the piers nose and **b** at the location of the second scour cavity maximum depth

Fig. 13 The height of maximum sedimentation against the length of sediment progress toward the downstream of piers and collar installed at the 60- and 120-degree positions



maximum sedimentation, equal to $0.52y$, occurs at the downstream of pier of $L = 1b$, and the minimum, equal to $0.17y$, at the downstream of pier of $L = 6b$. Moreover, the maximum and minimum values of L_D occur surrounding these piers at, respectively, $51.9b$ and $22.3b$. By attaching the collar of $W/b = 4$ to the piers at the 60-degree position, increasing the length of pier decreases the height of maximum sedimentation. The maximum and the minimum sedimentation

heights, equal to $0.57y$ and $0.49y$, are, respectively, created at the downstream of piers of $L = 1b$ and $4b$. Further, installation of the piers of $L = 5b$ and $6b$ at this position entails the maximum and the minimum values of L_D , respectively, equal to $66.3b$ and $85.7b$. As it may be observed in the figure, the values of the height of maximum sedimentation and L_D are greater when the piers are installed at the 60-degree position, where the upstream straight path has a

direct influence on the first half of the bend, than those of the 120-degree position.

Conclusions

In this study, the effect of collars with various collar width-to-pier width ratios on the reduction of scouring parameters surrounding the rectangular piers has been investigated experimentally in various positions of the 180-degree sharp bend, and its comparison with the case of a pier without collars. Results indicated that increasing the width of collar surrounding the piers reduces the maximum scouring depth, and the area and volume of the scour cavity surrounding the piers. Increasing the length of pier has a negative influence on the efficiency and performance of the collar in delaying the scour process at the nose of pier and also reducing the maximum scouring depth.

In the sharp bend of 180 degree, collars with collar width-to-pier width ratios equal to 3 to 4 have the best performance in reducing the maximum scouring depth in front of the nose of pier, and the area and volume of the scour cavity surrounding the piers. The greatest scour depth reduction at the 90-degree position occurs by attaching the collar with the collar width-to-pier width ratio equal to 4 to the piers with the ratio of length to width equal to 2 and 3 by approximately 75 and 70%, respectively. By attaching the collar with the collar width-to-pier width ratio equal to 4 to the piers at various positions, the amount of reduction in the maximum scouring depth surrounding the piers at the 120-degree position is greater than that at the 90-degree position, and both are greater than that at the 60-degree position. The performance of the collars in reducing the scour cavity parameters in comparison with the case of a pier without collars is better when they are installed surrounding the pier with $L/b = 3$ than the performance of those installed surrounding other piers.

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