The effect of collar width ratio on the flow pattern around oblong pier in bend

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ABSTRACT

In this paper, the effect of collar width ratio on the flow pattern around an oblong pier in a 180-degree channel bend was experimentally studied. This channel has a rectangular cross section. It is 1 m in width and 0.7 m in height. The upstream and downstream paths are respectively 6.5 and 5 m long. The ratio of the bend’s central curvature radius to the channel width is 2; hence, it qualifies as a sharp bend. Experiments were carried out under clear water approach flow conditions. The results showed that the presence of collars around an oblong pier creates vortices in the opposite direction of the longitudinal flow, causes the distortion and disturbance of the streamlines toward the pier downstream, and decreases downstream strength in front of the pier nose. Furthermore, doubling the collar width results in 0.68 and 0.93 times the vorticity and the power of the secondary flow on the pier upstream, respectively. It also reduced the maximum values of the Reynolds stresses perpendicular to the \textit{x}-plane in \textit{x} direction and perpendicular to the \textit{z}-plane in \textit{y} direction by respectively 45 and 60%, and increased the Reynolds stress perpendicular to the \textit{z}-plane in \textit{x} direction by 25%.

Key words: 180-degree bend, collar, flow pattern, oblong pier, Reynolds stress, streamlines

HIGHLIGHTS

- Experiments were carried under clear water conditions.
- An increase in the collar width by two times has increased the vortices by 0.93 times.
- Doubling the collar width has increased the Reynolds stress on \textit{zx} by 25%.
- The maximum vertical velocity has decreased by about 15% by doubling the collar width.
- Increasing the collar width around the pier increases the maximum turbulence kinetic energy values by 50%.

INTRODUCTION

Rivers with a straight path can rarely be found in nature since most rivers follow a sinusoidal path. The river bends have always been considered by hydraulic engineers due to the presence of a flow pattern known as the spiral flow. The complexity of the flow pattern increases with the placement of a bridge pier in the bend (Moghanloo \textit{et al.} 2020). Due to variations of velocity along the flow depth, a pressure gradient is generated upstream of the pier from top to bottom and leads to formation of a downflow in front of the pier. The downflow acts as a vertical jet, causing scouring around the pier after encountering the river bed (Zarrati \textit{et al.} 2004). One of the major reasons for the bridge destruction is the occurrence of scour around the bridge piers. Therefore, protection of bridges against scouring is deemed necessary. The scour around bridge piers can be reduced by using collars. The collars are flat plates of low thickness that are installed around the pier. The collars prevent the direct collision of the downflow with the river bed and reduce the flow velocity. As a result, the scour at pier decreases.

Despite a very large number of research carried out so far, the flow pattern around the bridge pier has not yet been fully understood due to its complexity. The flow pattern in the straight channel was studied by researchers such as (Kirkil & Constantinescu 2010; Kumar \textit{et al.} 2012; Das \textit{et al.} 2013a, 2013b) around the single pier and (Ataie-Ashtiani & Aslani-Kordkandi 2012, 2013; Das & Mazumdar 2015; Beheshti & Ataie-Ashtiani 2016) around the group of piers. Also, Gautam \textit{et al.} (2019) investigated the flow characteristics around single and complex piers with the pile-cap in different Reynolds numbers. The results showed that in a straight channel the flow around the single pier is more complicated than that of the complex piers. Also, downstream of the pier, the...
intensity of vortices is reduced by placing the pile-cap around the pier. Vijayasree et al. (2019) studied the flow and scour pattern around the piers with different shapes in different discharges in a straight channel and showed that the greatest reduction in flow velocity occurred near the bed around rectangular, oblong and trapezoidal piers. With an increase in the velocity and discharge of flow, the scouring depth in front of all piers increases. Vijayasree et al. (2020) investigated the flow pattern around the oblong and circular piers. They concluded that in a straight channel the turbulence of flow around the circular pier is greater than that of the oblong pier, which under the same flow conditions causes more scouring around the circular pier. Furthermore, research works like (Tang & Knight 2014; Vaghefi et al. 2014, 2016; Dey et al. 2017; Abdi Chooplou et al. 2018) in a 180-degree bend have investigated this phenomenon. Moghanloo et al. (2020) investigated experimentally the flow pattern around the combination of oblong pier and collar with different thicknesses in a 180-degree sharp bend. The results showed that increasing the thickness of the collar placed at the level 0.4 times the pier width above the initial bed level significantly reduces the kinetic energy at the pier upstream and increases the orientation of the streamlines toward the bed, thus deepening the scour hole. Keshavarz et al. (2021) studied and compared the flow pattern around rectangular and oblong piers accompanied by a collar placed in a 180-degree sharp bend. They installed the collar at a level equal to 0.4 times the pier width below the initial bed and with a thickness equal to 0.12 times the pier width. They indicated that the Reynolds stresses around the oblong pier and collar combination had lower values than those around the rectangular pier and collar combination.

Since the collars play an important role in reducing scour around the bridge pier, quantitative studies have been conducted on the flow pattern around the collar structure. Therefore, in this research, the flow pattern around an oblong pier located at 90 degrees along with installation of the collar around it with different ratios of collar width to pier width has been investigated. Given the long duration of the flow pattern experiment, only the parameter of the collar width to pier width ratio, an influential parameter in the flow pattern and consequently scouring, was investigated.

MATERIALS AND METHODS

Experiments were conducted in a rectangular channel with a 180-degree bend as shown in Figure 1(a). The width and height of the channel were 1 m and 0.7 m, respectively. The curvature radius of the channel bend was 2 m with \( R_C/B = 2 \), and according to Leschziner & Rodi (1979), it qualifies as a sharp bend. \( R_C \) is the central radius of the bend and \( B \) is the channel width. Sediment particles with a mean diameter of 1.5 mm and a standard deviation of 1.14 were used as the bed material and covered the total length of channel with a thickness of 0.3 m. The discharge and Flow depth at the end of the upstream straight path \( (y_o) \) were 0.07 m\(^3\)/s and 0.178 m for all the experiments, respectively. Following the criterion suggested by Chiew & Melville (1987) and Melville & Sutherland (1988), an oblong pier, made of PVC, with width and length of 0.05 and 0.2 m \( (L/b = 4, \ L \) is the pier length and \( b \) is the pier width) was used, respectively. Two experiments (hereafter named as PC2 and PC4) were carried out with the installation of collars having ratios of \( W/b = 2 \) (PC2) and \( W/b = 4 \) (PC4) around the pier. \( W \) is the width of the collar. The collars, made of Plexiglas, with a thickness of 3 mm were placed on the bed with the top level equal to the sediment bed level. The pier and collar were placed at the 90 degrees section of the bend.

Initially, the scouring experiments were carried out under threshold conditions; \( U/U_C \approx 0.98 \). \( U \) is the average flow velocity and \( U_C \) represents the flow velocity at the threshold motion of particles. To create the maximum local scour around the pier and collar combination as well as the most bed topography changes in the bend, the \( U/U_C \) ratio was selected near one, equal to 0.98. This experiment was conducted for about 15 hrs, during which the equilibrium state was achieved. The bed topography was recorded with a digital point gauge after the water was drained out. The bed was then stabilized by spraying an adhesive over the scour hole. Water was again allowed to flow into the channel and 3D velocity components were obtained by using an Acoustic Doppler Velocimeter. Velocity measurements were taken at different heights from the channel bed (Figure 2(a)). At each section, velocity components were recorded at 5 levels above the original bed level, 4 levels in the scour hole, and 33 points at 3 cm intervals at width (Figure 2(b)). \( X \) and \( Y \) represent respectively the longitudinal and transverse axes and \( Z \) is level of measurement.

Flow velocity was measured with a Vectrino device with three-receiver tentacles. The three-dimensional flow velocity was measured by using an ultrasonic sent by a transmitter and then receiving a reflection wave from the flow with at least three transceivers. Two probes, down-looking and side-looking, were used to measure the flow velocity (Figure 2(c)). In most parts of the network, harvesting was performed by a down-looking probe that
measures the flow velocity in all three directions at a point 5 cm below the probe. The side-looking probe was used in the areas near the flow surface, the bed level and the banks. This device is capable of measurement within a velocity range of 0 to 7 m/s. In this study, the measured velocities fell within a range of 0 to 1 m/s, which enjoyed an acceptable accuracy considering the stated correlation coefficients. A frequency of 25 Hz and duration of 60 s were used in these experiments, and at sensitive points, the duration was set to 120 s (Akbari et al. 2021). The device can record up to 1,500 data of flow velocity per minute in three directions. The quality of the velocity signals was investigated using two parameters: Signal-to-Noise Ratio (SNR) and correlation coefficient. The SNR amounts for the mean and instantaneous velocity measurements shall be greater than 5 and 15 dB, respectively. The correlation coefficient evaluates the rate of disturbance in velocity signals by calculating the rate of change between consecutive readings of the instantaneous velocity. The average correlation of 71% is suitable for high-quality data. In these experiments, the appropriate ranges for SNR and correlation coefficient were 10 dB and 70%, respectively.

RESULTS AND DISCUSSIONS
Since the flow pattern experiments were performed under balanced bed conditions, first, the bed topography changes in the bend caused by the installation of collars with W/b ratios of 2 (PC2) and 4 (PC4) around the oblong pier at the bend vertex have been provided. Figure 1(b) and 1(c) shows the bed topography of the scour pattern after the relative equilibrium time. The sedimentation area adjacent to the inner bank and scour holes around the pier has been determined. The maximum scour depth is one of the most effective components of a scour hole. The maximum scour depth in Experiment PC2 was measured to be 13.5 cm and equal to 0.75 times the flow depth at the pier nose. In Experiment PC4, according to Figure 1(c), due to the larger collar
dimensions, two scour holes have occurred around the pier. The maximum scour depths in the first and second scour holes were measured to be 5.2 and 9.3 cm, respectively, equal to 0.28 and 0.51 times the flow depth along the collar and 7 times the pier width at the pier downstream. In both experiments, sedimentation began adjacent to the inner bank at 30 degrees and continued to 150 degrees. Also, the maximum sedimentations for Experiments PC2 and PC4 were 6 and 7.6 cm, equal to 0.33 and 0.42 times the flow depth at 115 and 136 degrees, respectively.

Streamlines

Figure 3 shows samples of the streamlines at positive and negative levels at the plan section in Experiments PC2 and PC4 at the pier and collar position at 90 degrees. Zoomed of the streamlines around the pier is also given to better illustrate the flow pattern. In these figures, in some areas at positive levels, the streamlines have not been plotted due to the formation of sedimentary stacks and zero velocity. The streamlines crossing through the collar at positive levels and crossing beneath the collar at negative levels are evidently illustrated in figures. According to Figure 3(a), since the collars have been installed at the initial bed level in both experiments, the only factor affecting the flow near the surface is the placement of the oblong pier at 90 degrees of the bend. Therefore, in both experiments, the streamlines near the flow surface in the first half of the bend orient toward the outer bank. Also, at 1 cm below the flow surface (95% of the flow depth from the bed level), at about 26 times the pier width at the pier upstream for both experiments, return flows are observed followed the deviation of the streamlines toward the outer bank. The reason for this is the collision of the flow with the oblong pier, the return to the pier upstream and collision with the mainstream. Also, this deviation causes higher deviation of the streamlines from about 80% of the channel width from the inner bank to the outer bank in the second half of the bend. These return flows are not observed at lower levels. In Experiment PC4, at the distance of 7 times the pier width at the pier downstream, a wave of flow has been formed at the water surface affected by the upward flow generated from the collar, and streamlines are deviated more toward the outer bank than those in Experiment PC2. According to
Figure 3(b) and considering the presence of collars at the bed level, as the collar width increases, the tendency of the streamlines toward the inner bank increases in Experiment PC4 after the pier. This causes the formation of a sedimentary stack near the inner bank so that the maximum sedimentation rate in Experiment PC4 occurs at

Figure 3 | Samples of streamlines plotted at positive and negative levels at the plan section in Experiments PC2 and PC4. (a) 95% of flow depth from the bed level; (b) 5% of flow depth from the bed level; (c) 50% of flow depth in the scour hole below the bed level.
136 degrees and that in Experiment PC2 at 115 degrees. Due to sedimentation on the inner bank at the second half of the bend, the deviation of the streamlines toward the outer bank in Experiment PC4 is greater. In both experiments and at this level, it is observed that the flows after the sedimentary stacks near the inner bank are slightly deviated toward the inner bank, which is due to the flow drop from the sedimentary stack. Due to the presence of sediments around the scour hole at negative levels, there are no streamlines at any points. Since the collar has been installed at the bed level around the oblong pier, in Experiment PC2, the flow can penetrate beneath the collar and cause a scour hole around the oblong pier. In Figure 3(c), the flow into the scour hole is directed from the outer bank to the inner bank. Therefore, this flow causes the sediments to leave the scour hole and move toward the inner bank. At the level of 50% of the flow depth in the scour hole below the initial bed level in Experiment PC2, the streamlines return to the upstream sections after penetration below the collar and collision with the pier nose. Collision with the plunging flows leads to accumulation and turbulence of the streamlines at the pier upstream, and also the deviation of the flow toward the inner bank. On the other hand, with an increase in the collar width, as shown in the zoomed figure, the flow has somehow penetrated the collar. This flow caused a small scouring hole near the collar edge, ranging from 33 to 42% of the inner bank around the pier and the collar.

The streamlines in a 50% longitudinal section of the channel width from the inner bank have been shown in Figure 4(a). $\theta$ is position of the velocity harvest along the bend. In both experiments, the flow after collision with the pier, causes a return and a downstream flow at the pier upstream. These changes have occurred at the middle levels to the flow surface, and the flow continues in downstream direction after passing the pier parallel to the mainstream. In Experiment PC2, after penetration beneath the collar and collision with the pier, the flow is transmitted into the scour hole in the form of downflows and causes scouring at the pier nose. An up flow is also observed along the pier due to wake flows. In Experiment PC4, after collision with the collar, the flow is transmitted downstream and falls into the second scour hole, and at the end of the bend and under the influence of topography changes in the lateral sections, the flow near the bed is directed upward. In Figure 4(b)–4(d), samples of the streamlines in different transverse sections has been plotted for the region around the oblong pier in Experiments PC2 and PC4. The main secondary flow is observed along the channel due to the reduction in the effect of the longitudinal pressure gradient and the dominance of the centrifugal force on the field as a rotary cell.

Figure 4(b) indicates that in the Experiment PC2, two clockwise vortex have been formed alongside the pier nose, one near the inner bank at mid-depth, and the other approximately at the mid-channel width near the bed level. The vortex formed near the bed level causes the formation of a scour hole in front of the pier nose. While, due to the larger collar width in Experiment PC4, the formed clockwise vortex did not fully penetrate the collar. Also, due to the collision between the flows generated by the vortex and the collar, these flows deviate toward the pier downstream side. Figure 4(c) indicates that the pier nose causes the flow to be separated. These isolated flows create clockwise vortices around the pier due to collisions with the pier. As in Experiment PC2, these clockwise vortices penetrate beneath the collar and cause scouring around the pier. Near the inner bank, as a result of the collision of the flows with the collar and the bed level, a small counterclockwise vortex has been formed beneath the collar near the pier. However, in Experiment PC4, in addition to deviating vortices toward the pier downstream side, the collar prevents their penetration beneath. Also, the pier in both experiments transformed the secondary flow of the main channel into two secondary flows. According to Figure 4(d), as the flow progresses downstream, the secondary flows on both sides of the pier collide in front of the pier tail. In Experiment PC4, at the collision point of flows, downflows have been formed, and they extend to the downstream side due to collision with the collar and cause scouring downstream. Also, in Experiment PC2, the wake and up flow is more noticeable at the collision point of the flows and causes higher scouring.

**Velocities and dispersion**

Figure 5(a) indicates the return flows at the pier upstream side near the flow surface at 50% of channel width. In both experiments, the tangential velocity is increasing at the pier upstream until mid-depth from the bed level and the flow collides with the pier nose at the same velocity and is then deviated. In Experiment PC2, due to the small size of the collar dimensions and the bed topography, the tangential velocity in the scour hole is increasing and the return flow is observed below the collar near the bed. This occurs as a result of the collision of the flow with the pier and its return toward upstream. However, in Experiment PC4, the tangential velocity has decreased beneath the collar; whereas, it increases after the collar and inside the second scour hole. In both experiments, with progression of the flow along the bend toward the downstream side of the pier, the tangential velocity
increases from the proximity of the collar to the flow surface so that the tangential velocity values at the positive levels in both experiments are approximately identical at 1.2 times the pier length toward the pier downstream. Such a difference in the increase and decrease of tangential velocity in the pier placement range is a consequence of the difference in the width of the collar, which causes a difference in the values of this tangential velocity. Figure 5(b) shows the positive direction of radial velocity toward the outer bank and the negative radial velocity toward the inner bank. It is observed at the pier upstream that the radial velocity for both experiments at the negative levels and near the bed level occurs toward the inner bank. Approaching the flow surface, the radial velocity is shifted toward the outer bank. This change in direction in the radial velocity creates a secondary flow through the channel width. However, at the pier downstream at the levels close to the flow surface, the radial velocity is directed toward the inner bank. Moreover, variations and irregularities of the radial velocity are reduced away

**Figure 4** | Samples of the streamlines in longitudinal and transverse sections of the bend. (a) 50% of the channel width from the inner bank; (b) 86 degrees (nose of pier); (c) 90 degrees; (d) 94 degrees (tail of pier).
Figure 5 | Samples of distribution of the (a) tangential, (b) radial and (c) vertical velocities at the longitudinal section.
from the pier region in downstream direction, but radial velocity values and its changes at the upstream side and at the pier area are higher than those at the pier downstream. The radial velocity value in Experiment PC4 below the collar is negative. The highest positive radial velocity in both experiments occurred at a level of 45% of the flow depth from the bed level in front of the pier nose. In Experiments PC2 and PC4, the highest negative radial velocity was detected in the scour hole around the pier and the second scour hole near the materials, respectively (the levels of −60 and −40% of the flow depth from the bed level, respectively). In Figure 5(c), the performance of the collar with W/b ratio of 4 is clearly observed compared to the collar with W/b ratio of 2. Although the downflow in Experiment PC2 has the greatest velocity in front of the pier nose, the vertical velocity in the same position in Experiment PC4 is very small. This implies the greater impact of collar dimensions on downflows and zero penetration of the flows underneath the collar at the pier nose. The maximum vertical velocity values for Experiments PC2 and PC4 are −14 and −11.8 cm/s, respectively. In Experiment PC2, the vertical velocity at the pier upstream is directed downward, and the negative vertical velocity is increasing at negative levels (within the scour hole) as the flow approaches the pier. This causes scouring at the pier nose. Whereas, the vertical velocity at the pier downstream is upward, and consequently the wake flows occur after the pier. By doubling the W/b ratio at the pier upstream, the vertical velocity has decreased sharply. Also, the vertical velocity at the downstream side of the pier is downward. These downflows incline toward the second scour hole after collision with the collar. With progression from the negative levels toward the flow surface in both experiments along the bend, the vertical velocity decreases.

In the figures on the transverse sections, B represents the width of the section. Figure 6(a) shows the tangential velocity. In the figure, at the intervals of 10 to 20 and 80 to 90% of the channel width from the inner bank, according to topography of the bed, the variation of the velocity longitudinal component (tangential velocity) at the collection levels is identical for both experiments so that at both intervals, the tangential velocity is increasing up to 5 and 45% of the flow depth from the bed level, but after that, the variations in tangential velocity to the flow surface are almost constant. According to the figure, in Experiment PC2, the return flow has occurred from 50 to 60% of the channel width from the inner bank near the flow surface, while in Experiment PC4, the return flow has occurred with a lower value. In Experiment PC4, at a distance of 40% of the channel width from the inner bank, it is observed that the tangential velocity has penetrated beneath the collar, and the tangential velocity has decreased with the progress toward the outer bank so that the collar has directed the tangential velocity toward downstream from 60% of the channel width from the inner bank to the outer bank according to the topography of the bed. However, in the region around the pier and collar in Experiment PC2 up to 45% of the flow depth from the bed level, the tangential velocity is positive and increasing. Also, in Experiment PC2, at negative levels close to the bed level, the tangential velocity penetrates beneath the collar, and its value is positive; the tangential velocity becomes negative (return flow) with progression into the scour hole (the level of −60% of the flow depth from the bed level) (area A). This is due to the collision of the mainstream to the pier and its return to the upstream side of the pier. The transverse velocity component (radial velocity) has been shown in Figure 6(b). As can be seen, in both experiments, the radial velocity has been negative at the levels close to the bed surface and the negative level (inside the scour hole around the pier), and it becomes positive by approaching the flow surface. This negative value of radial velocity on the channel bed leads to the movement of the outflow sediment from the scour hole toward the inner bank. This means that the flow near and below the bed is directed toward the inner bank and that near the flow surface is directed toward the outer bank. This suggests the presence of a vortex in this position. This vortex is actually the main vortex of the secondary flow. In Experiment PC4, the tangential velocity has penetrated beneath the collar at the distances of 40 and 42% of the channel width from the inner bank, and the highest tangential velocity values have occurred at these distances. Whereas, from approximately 48% of the channel width from the inner bank to the outer bank affected by the collar, the flow is deviated toward the outer bank. In Experiment PC2, a small clockwise vortex is observed at 10% of the channel width from the inner bank at the level of 45% of the flow depth from the bed level (area B). Also, in area C, a clockwise vortex has been formed at 44% of the channel width from the inner bank, which causes scouring in front of the pier nose. The vertical velocity in Figure 6(c) at the levels near the flow surface and at 80 to 100% of the channel width from the internal bank is insignificant in both experiments. In Experiment PC4, the vertical velocity has decreased and approaches zero away from the inner bank up to 80% of the channel width from the inner bank at positive levels. As it has previously been stated, the reason for this sharp decrease in vertical velocity at this transverse section is the presence of the collar at the bed...
level at this section so that it has completely neutralized the impact of the vertical flows on the bed at this section. However, in Experiment PC2, due to the small size of the collar, the highest negative vertical velocity (downflow) has occurred at this section in front of the pier nose. In the figure, in Experiment PC2, in the range of 20 to 42% of the channel width from the inner bank within the scour hole, the vertical velocity has a positive value, and after this interval up to 70% of the channel width from the inner bank, it is negative. This change in the direction of vertical velocity causes irregularity and turbulence of the flow at 42% of the channel width from the inner bank at −40% of the flow depth from the bed level (area D). Also, the vertical velocity in this experiment decreases by moving from negative levels toward the flow surface.

**Turbulence fields**

In identifying the hydrodynamic of the flows in the bend, determining the secondary flow power of the transverse sections along the bend and around the hydraulic structures can play a significant role in identifying flow variations. In this study, the measure provided by Shukry (1950) was used to evaluate the secondary flow power.
Shukry has introduced the following criterion (Equation (1)) for calculating the secondary flow power by conducting studies on the flow in the river bend, while describing the secondary flow mechanism.

\[
S_{xy} = \frac{K_{lateral}}{K_T}
\]  

(1)

Where, \(K_{lateral}\) is the kinetic energy of lateral flow and \(K_T\) is the kinetic energy of the main flow. Figure 7(a) has presented the diagram of the secondary flow power for both Experiments PC2 and PC4. When the flow enters the bend, the secondary flow power increases in both experiments up to 60 degrees. In the Experiment PC4, this ascending trend continues up to the top of the diagram at the pier upstream (in front of the pier nose). Whereas, in Experiment PC2, the secondary flow power continues its ascending trend until the peak of the diagram after a 5% reduction at 80 degrees (the starting point of the scour hole at the pier upstream). As can be seen, the maximum secondary flow intensity in Experiment PC2 occurs at 86 degrees equal to 17.5%. In Experiment PC4, this maximum was measured at the upstream and downstream sides of the pier at 80 and 103 degrees positions, respectively equal to 16.30 and 14%. According to the diagram, it can be stated that the collar with a \(W/b\) ratio of 4 transfers the location of the maximum power of the secondary flow from the pier region to the upstream section compared to the collar with \(W/b\) ratio of 2. In the range of 80 to 100 degrees, the percentage of reduction in the secondary flow intensity increases by doubling the \(W/b\) ratio. Hence, the scour hole volume created at the pier area is lower with respect to the bed topography in Experiment PC4 than that in Experiment PC2. After the pier range in Experiment PC2, the intensity of the secondary flow has greatly decreased. Whereas, in Experiment PC4, the secondary flow power inside the hole increases due to the presence of a second scour hole, and then greatly decreases. In both experiments, this descending trend of the secondary flow power continues up to

Figure 7 | The variations of (a) the power of the secondary flow, (b) vorticity and (c) the maximum turbulence kinetic energy in the 180 degrees bend in Experiments PC2 and PC4.
approximately 140 degrees. Along the rest of the bend, the variation of the secondary flow power is affected by the bed topography as well as the downstream straight path.

Another important and theoretical criterion which is used to determine the effect of the secondary flow along bended paths is vorticity. By definition the net counterclockwise rotation rate of a cell around the perpendicular axis is called rotation and is expressed as Equation (2) (Das et al. 2013b):

$$W_o = \frac{1}{2} \left( \frac{\partial w}{\partial z} - \frac{\partial w}{\partial r} \right)$$

Here, $W_o$ is the rotation rate at the transverse section along the longitudinal direction of the flow and $v$ and $w$ represent the components of mean radial and vertical velocities, respectively. The value of $W_o$ is calculated for all cells at each section and is then averaged, and the result has been presented in the form of a diagram in Figure 7(b). The positive value of vorticity indicates the counterclockwise rotation and its negative value indicates the clockwise rotation. Vorticity values in both experiments are greatly similar. The maximum vorticity was measured at 86 degrees in Experiment PC2 and at both positions of 86 and 103 degrees in Experiment PC4 (the maximum vorticity value for both positions was approximately the same). The ratio of the maximum vorticity in Experiment PC2 to that in Experiment PC4 is 1.8. This value indicates that in Experiment PC2, due to the presence of more vortices at the middle transverse sections, the maximum vorticity value is greater than that in Experiment PC4. According to the figure, it is observed that the value of vorticity has been increasing to reach the peak of the diagram in both experiments from the beginning of the bend, except at the 65-degree transverse section. The vorticity value at the 96-degree transverse section in both experiments is sharply reduced, which is due to the simultaneous presence of clockwise and counterclockwise vortices. Then the ascending trend continues to the 103 degrees section in Experiment PC4 and 110 degrees in Experiment PC2. Then both diagrams are mildly decreasing to the end of the bend. Finally, the vorticity value has increased at the end of the bend at approximately 160 degrees in Experiment PC2, but the vorticity value in Experiment PC4 is constant.

To calculate the kinetic energy per mass resulting from fluctuations in velocity or turbulence ($TKE$), the following relation has been employed (Das et al. 2013b).

$$TKE = \frac{1}{2} \left( u'^2 + v'^2 + w'^2 \right)$$

$u'$, $v'$ and $w'$ respectively denote the fluctuating velocity components in longitudinal, transverse and vertical directions. The calculated turbulence kinetic energy values per mass along the bend have been illustrated in Figure 7(c). It may be observed that the maximum turbulence kinetic energy value in both experiments occurs in the first half of the bend at the 60-degree angle; hence, the measurements were made under equilibrium bed conditions. At the end of the bend, due to higher sedimentation near the inner bank and the created constriction, the turbulence kinetic energy values per mass are increasing in Experiment PC4, while such values decrease in Experiment PC2. Further, the minimum kinetic energy value in Experiments PC2 and PC4 occurs at the 86-degree position due to presence of a scour hole and an increase in the cross section at this point. With the collar width increased, the maximum and minimum turbulence kinetic energy values around the pier have increased by approximately 50 and 55%, respectively.

Reynolds stresses for a height equal to 5% of the flow depth from the initial bed level may be calculated as follows (Das et al. 2013b):

$$\tau_{yx} = -\rho u' v'$$

$$\tau_{zx} = -\rho u' w'$$

$$\tau_{zy} = -\rho v' w'$$

Here, $\tau_{yx}$ is the Reynolds stress perpendicular to the y-plane in x direction, $\tau_{zx}$ is the Reynolds stress perpendicular to the z-plane in x direction, and $\tau_{zy}$ is the Reynolds stress perpendicular to the z-plane in y direction and $\rho$ is the water density. Figure 8 illustrates the maximum Reynolds stresses. According to Figure 8(a), $\tau_{yx}$ values in the first half of the bend follow an approximately similar trend in both experiments. With an increase in the collar
width, $\tau_{yx}$ has decreased around the pier and at the end of the second half of the bend. However, at a distance from the 105 to 135 degrees angle, the Reynolds stress has increased in Experiment PC4 due to a higher sedimentation near the inner bank. The maximum $\tau_{yx}$ values in Experiments PC4 and PC2 have occurred at the 94 and 98-degree angles, respectively. Increasing the collar width has resulted in an approximately 45% reduction in the maximum $\tau_{yx}$ value around the pier. In Figure 8(b), with an increase in the collar width in reverse $\tau_{yx}$, the $\tau_{zx}$ value increases around the pier and the second half of the bend. The maximum $\tau_{zx}$ value in both experiments has occurred in the first half of the bend at a distance of approximately 21 times the pier width toward the pier upstream. A double collar width has increased the maximum $\tau_{zx}$ value at the pier upstream and around it by approximately 15 and 25%, respectively. A significant difference is also observed in $\tau_{zx}$ value in the second half of the bend through the experiments. According to Figure 8(c), $\tau_{zy}$ values in the first half of the bend have decreased in Experiment PC4 compared to PC2, while these values have increased in the second half. The maximum $\tau_{zy}$ value has decreased around the pier by approximately 60% with an increase in the collar width. Presence of a scour hole at the pier downstream in Experiment PC4 has increased $\tau_{yx}$ and $\tau_{zy}$ values by respectively 2.7 and 1.5 times compared to those in Experiment PC2 in this position. Furthermore, between the 150 and 160-degree angles in the bend, the Reynolds stresses have increased due to bed topography changes in this area in Experiment PC2.

**CONCLUSIONS**

This paper has studied the flow pattern around the oblong pier with installation of the collar at different ratios of the collar width to the pier width ($W/b = 2, 4$), located at 90 degrees from the 180 degrees bend. The presence of collars around the oblong pier causes generation of vortices in the opposite direction of the longitudinal flow, further deviations of the streamlines toward the pier downstream, and a decrease in the downflow power in front of the pier nose so that increasing the collar width adds to the deviation of the streamlines near the bed level toward the inner bank and the downstream side of the pier. By installing the collar with $W/b = 4$
(Experiment PC4), more sedimentation has accumulated along the inner bank compared with installation of the collar with \( W/b = 2 \) around the oblong pier (Experiment PC2). Also, doubling the collar width has decreased the width of the scour hole around the combination of pier and collar by 85%.

The maximum tangential and radial velocities have increased by 15 and 10%, respectively after doubling the ratio of the collar width to pier width. Whereas, the maximum vertical velocity has decreased by about 15%, which indicates the effect of increasing the collar width on decreasing the downflows and the consequent reduction of the scour around the pier.

The maximum secondary flow power was observed by installing the collar with \( W/b = 2 \) around the oblong pier (Experiment PC2) at 86 degrees of the bend equal to 17.5%. By doubling the collar width around the oblong pier, the maximum position of the secondary flow was shifted 4 times the pier width toward the pier upstream. Also, the maximum power of the secondary flow has decreased by about 10%. The maximum value of vorticity was reduced by 30% after increasing the collar width, and for both experiments, it was observed at 86 degrees of the bend.

Doubling the collar width has reduced the maximum values of the Reynolds stresses on \( yx \) and \( zy \) coordinates by respectively 45 and 60%, and increased the Reynolds stress on \( zx \) by 25%.

With an increase in the collar width around the pier, the maximum and minimum turbulence kinetic energy values have increased by approximately 50 and 55%, respectively.

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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