Flow field around side-by-side piers with and without a scour hole

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The present study provides the experimental results of the flow pattern around two-circular piers positioned in side-by-side arrangement. The experiments were performed for two bed configurations (with and without a scour hole). Velocities were measured by an Acoustic Doppler Velocimeter (ADV). Flat bed and scour hole were frozen by synthetic glue to facilitate the performance of the experiments. The contours and distributions of the time-averaged velocity components, turbulence intensities, turbulence kinetic energy, and Reynolds stresses at different horizontal and vertical planes are presented. Streamlines and velocity vectors obtained from time-averaged velocity fields are used to show further flow features. Bed shear stresses at specific points around the piers are given. The results of power-spectra analysis are presented inside and outside the scour hole. It is shown that the horseshoe vortex is elongated further to the downstream of the gap between the two piers. The flow between the two piers is accelerated into the scour hole so that it influences the vertical and transverse deflections of the flow around and especially between the two piers. The maximum downflow was inside the scour hole near the base of the pier. Between the two piers, the magnitude of downflow and vertical turbulence intensity as well as turbulence kinetic energy are greater than that at the outer sides of the two piers. Bed shear stress has substantially large values between the two piers, as much as two times in comparison to the other sides of the piers. The presence of scour hole changes the behavior of vortex shedding considerably. The present detailed measurements can also be used for the verification of numerical models.

1. Introduction

Local scour around piers is the main cause of destruction of many bridges inside rivers. An estimate of the maximum possible scour around a bridge pier is necessary for its safe design [1]. A large number of studies have been conducted to predict the scour depth in the base of piers [2–4]. These studies have been performed primarily by means of laboratory-flume experiments, including the use of dimensionless equations finally resulting in some semi-empirical equations for the maximum scour depth. A long-standing concern is the tendency of most of these equations to over-predict the maximum scour depth for field or even for laboratory conditions [5–7]. A lack of understanding of the flow structures around the bridge pier and its interaction with the bed sediment seem to be at least partly responsible for this problem. Therefore, a comprehensive understanding of the turbulent flow structure can provide more insight into the scouring process and aid to predict scour depth precisely [1,8].

For a better understanding of the flow field and turbulent flow around piers, many researchers have focused on the flow field around piers and cylinders with and without a scour hole [7,9–12,8,13–15]. Most of these studies have been confined to only single piers and provide detailed information around single piers. However, due to geotechnical and economical reasons, bridge designs often lead to complex piers or pier groups [16,17], in which case the direct application of the results derived from single piers may be problematic [18]. There are a large number of studies around pier groups and complex piers that focused on the prediction of the maximum scour depth [6,16,17] and the effect of the pile spacing on the scour depth [19,20]. Despite a large number of the investigations (as mentioned earlier) around single piers, a comprehensive understanding around pile groups and complex piers in both bed configurations is still deficient because most of the investigations around pile groups have been confined to the near-wake region on flat plates (beds) [21–24] and the effects of the flow characteristics on the bed sediments and vice versa have not been investigated. To our knowledge, there are no detailed measurements around complex piers, except Beheshti and Ataie-Ashtiani [25], providing detailed description of flow field around a complex pier. However, their study does not provide better...
understanding of flow field around piles situated under a pile cap and inside the scour hole.

At the present study, flow field around one of the simplest arrangements of the pile groups, i.e. side-by-side arrangement, is investigated. Whereas the characteristics of the flow in the near-entrance region around side-by-side piles have been well investigated (as mentioned earlier for pile groups), there is no detailed measurements around these structures to investigate flow field inside the scour hole and between the two piles. Fig. 1 shows a sketch of the flow pattern and local scour around side-by-side piles in the scoured-bed case. Scour is initiated at, or close to the nose of the cylinders as well as around the piles, especially between the two piles. The scour hole of each pier grows in depth and in volume and then overlap each other at the region between the two piles. This situation shows the interference of horseshoe vortices at this area. Due to decrease in flow area between the two piles, a contracted flow is formed. Behind the piles, the wake-vortex structures change, depending on the pier spacing [21]. The downflow and surface roller formed in the front of the piles are similar to those in single piles.

The primary objective of the present study is to provide a better understanding of the three dimensional (3-D) flow around two side-by-side piles. In addition, this study addresses how the horseshoe flow and corresponding turbulence characteristics change between the two piles and how the two piles affect the flow structure and its intensity in comparison with single-pier case. The single-pier case carried out by authors in order to have a comparative study in the same experimental conditions as for the two side-by-side piles. Furthermore, this study provides an investigation on the vortex shedding and other vortical structures from the viewpoint of the power-spectra analysis. The experimental data of this study can be used as a useful data bank not only to promote the related studies of the flow structure and scour depth around multi-cylinder arrangements, but also to validate the complex flow fields obtained by numerical simulations. In this study, the contours and distributions of the time-averaged velocity components, turbulence intensities, turbulence kinetic energy, and Reynolds stresses at different horizontal and vertical planes are presented. Streamlines and velocity vectors obtained from the time-averaged velocity fields are used to show further flow features. Calculation of bed shear stress around the pier is presented. The results of the power-spectra analysis are also presented inside and outside the scour hole.

2. Experimental setup and procedure

All experiments were conducted in a channel at the Hydraulics Laboratory in the Department of Civil Engineering at Sharif University of Technology, Tehran, Iran. The Channel was 15 m long, 1.26 m wide, and 0.9 m deep as shown in Fig. 2. A false floor at an elevation of 0.35 m from the channel bottom was made and a 2 m long and 1.26 m wide recess was placed at a distance of about 10 m from the entrance of the channel. Two piles were placed in the sediment recess and then the recess was filled with uniform sand of median size, $d_{50}$, 0.71 mm. The sand does not ripple according to the ASCE [26] and it had specific gravity, $S_s$, 2.45 and geometric standard deviation, $\sigma_g$, 1.20. Finally the bed was leveled carefully. The nylon-made piles had diameters, $D$, of 9.1 cm and the distance between the centers of the two piles was equal to 27.3 cm (3D) as shown in Fig. 3. Ataie-Ashtiani and Beheshti [6] showed that for two piles with the centerline gap of 3D, the maximum scour depth increases by 20%. Elliott and Baker [27] suggested $G/D = 7$ as a limit for pier independency where $G$ is the center-to-center distance of the piles. Experiments were conducted in two stages: at the first stage, to facilitate performance of the experiments on a flat bed, the top layer of the recess was frozen by spraying synthetic glue. The synthetic glue mixed with water (1:3 by volume) was sprayed uniformly over the bed. After 72 h, the synthetic glue was set and the bed was stabilized. This glue has not any undesirable effects on the sediment. The uniform sand having the same size used at test section was glued over the false floor to simulate the turbulent flow over a rough planar sand bed. Then a flow with a water discharge of 134 L/s, an approaching flow depth ($h$) of 32.5 cm (by operating the tailgate), and mean approaching velocity ($U_0$) of 33 cm/s was run using a pump. Before the pump
3-D down-looking probe of the ADV was unable to measure the Nikora and Goring [31], Song and Chiew [32], and Ge et al. [33]. The ADV has little flow-field interference as the measurement samples were positioned about 5 cm away from the probes. Having used the stationary analysis, the sampling durations were varied from 120 to 250 s in order to achieve a statistically time-independent average velocity. Ge et al. [33] adopted the smaller time duration equal to 120 s. Buffin-Béland and Roy [36] by determining standard errors of turbulence statistics obtained from velocity measurements in fluvial turbulent boundary layers show that, for most turbulence statistics, the optimal record length (minimum sampling effort to achieve low standard errors) ranges between 60 and 90 s.

The measurements in these experiments were taken in the Cartesian coordinate system (X, Y, Z) with time-averaged velocity components \( (u, v, w) \) whose corresponding fluctuations are \( (u', v', w') \). The origin of the Cartesian coordinate system, as shown in Fig. 3, was centered at the base of the pier that measurements were carried out around it in the flat-bed case. The measurements were only carried out at the one side of the centerline \( (Y ≤ 13.65 \text{ cm}) \) as shown in Fig. 3 and therefore the results are presented just at one side of the centerline. The measurements were carried out at 5 vertical sections in both bed conditions at the longitudinal and transverse directions of the channel. The longitudinal sections were located at \( Y = 0 \text{ cm} \) and \( Y = 13.65 \text{ cm} \) and the transverse sections were located at \( X = -4.7, 0 \) and
10 cm respectively [Fig. 3]. In addition, the measurements were performed at a large number of points for the two horizontal planes one near the initial bed (Z = 1 cm for the flat-bed case and Z = 0.5 cm for the scoured-bed case) and another almost in the middle of the water depth i.e. Z = 17.5 cm. A total of 2350 point-velocity measurements were made around piers in the flat-bed case and about 3550 in the scoured-bed case. By comparing the horizontal planes with each other, the effect of the bed configurations on the flow is specified. Also, the planes Z = 17.5 cm show the flow behavior at the area far from the initial bed and scour hole for comparison. All data were processed using the public domain software WinADV [37] to obtain the time mean and RMS (root mean square) values from the entire velocity record. The measurements were filtered using this software to eliminate points having a correlation coefficient less than 0.70 and SNR (Signal-to-Noise Ratio) less than 15. Furthermore, data obtained from ADV was filtered using the spike removal algorithm after Wahl [38]. Fig. 5 shows examples of raw, filtered and despiked data obtained using the WINADV. The experimental uncertainties were estimated at 99% confidence level using the method provided by Kline [39].

The uncertainties for the velocities and turbulence intensities were 1% and 2.5% respectively. The uncertainties in the streamwise direction (u) [Fig. 8(a) and (b)] indicates the values of u increase between the two piers. This increase becomes visible in the form of expansion in the high-velocity region as well as the magnitude of u. Since the wake is a recirculating zone that does not contribute to the net transport of fluid in the downstream direction, the flow in the region adjacent to the wake tends to accelerate in order to transport the extra fluid [1].

The presence of scour hole accelerates the flow towards the hole by decreasing the friction effects as bed falls down from its initial level and by increasing the area for the flow passage. These effects in combination with nearly jet-like flow between the two piers form the feature of the flow. Owing to the passage of the great portion of the flow in the area close to the hole, the maximum u at the upper level in the scoured-bed case becomes smaller than

3. Results and discussions

3.1. Flow fields at horizontal planes

In this section, the experimental results for both bed configurations (flat bed and equilibrium scour hole) are presented. Figs. 6 and 7 show the streamlines and velocity vectors for flat- and scoured-bed configurations. In these figures, the magnitude and direction of the velocity vectors are ($u^+ = \sqrt{\frac{u^2}{\langle u^2 \rangle}}$ and $v^+ = \sqrt{\frac{v^2}{\langle v^2 \rangle}}$) respectively. In order to avoid congested vectors, some of the measured points were omitted from the plots. As seen in Fig. 6, a boundary layer upstream of the pier is separated due to adverse pressure gradient induced by the pier(s) [7]. The point of the boundary layer separation at both sides of the pier shifts further to downstream close to bed. It confirms the results of the Dargahi [9], Unger and Hager [40], and Krikil et al. [15] for single pier. This phenomenon results in smaller wake in comparison to the upper level. This situation is attributed to the effect of bed roughness on turbulence increase near the bed. The turbulent boundary layer resistance on the sides of the piers delays separation to downstream face of the piers. The distance that the separated shear layers from the pier sides reach each other, is shorter close to the bed in comparison with that at the upper level [Fig. 6]. A comparison between velocity vectors and streamlines for flat-bed [Fig. 6] and scoured-bed cases [Fig. 7] indicates that the extension of the wake region in the scoured-bed case is smaller and more asymmetrical than that in the flat-bed case. This difference is related to the geometrical conditions of the scour hole and the corresponding flow pattern. Furthermore, due to presence of the scour hole, the interaction of the separated shear layers with each other become weaker and consequently the magnitudes of the reverse vectors decrease in the wake of the pier. The vectors and streamline plots obtained from the average velocity in Figs. 6 and 7 show that the wake vortices being formed downstream of each pier do not interfere with each other. The flow visualizations made by Zdravkovich [21] and Akilli et al. [22] for free surface and mid depth at this pier spacing also show independency in the wake vortices.

To present further details of the flow pattern and the difference between the flow features in both bed configurations, the contours of the mean-velocity components and kinetic energy are shown at two horizontal planes. The investigation of mean-velocity in the streamwise direction (u) [Fig. 8(a) and (b)] indicates that the values of u increase between the two piers. This increase becomes visible in the form of expansion in the high-velocity region as well as the magnitude of u. Since the wake is a recirculating zone that does not contribute to the net transport of fluid in the downstream direction, the flow in the region adjacent to the wake tends to accelerate in order to transport the extra fluid [1].

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Fig. 5. Example of (a): raw (unfiltered) and filtered time series; (b): raw data and spike-removed data.
Fig. 6. Velocity vectors and streamlines at two horizontal planes in the flat-bed case.

Fig. 7. Velocity vectors and streamlines at two horizontal planes in the scoured-bed case.
that in the flat-bed case. Transverse deflections are presented by contours of the $v$ component in Fig. 8(c) and (d). As shown in Fig. 8(c) and (d), when the equilibrium scour hole is achieved, the flow deflection towards the outside of the piers decreases near the initial bed, due to the passage of a certain amount of the flow through it. The presence of the nearly jet-like flow between the two piers partly restricts the flow deviation at this area compared to that outside of the piers in the flat-bed case; however, this difference becomes negligible as the scour hole is formed. At the upper level and pier upstream, due to the high-momentum flow, the values of the transverse velocity are greater than that at the level close to the bed. The intensity of the transverse deflection at the downstream of the pier is inversely related to the size of the wake region. Fig. 9 shows the contours of the vertical component ($w$) in the scoured-bed case. According to this figure, a downflow is formed upstream of the pier as the flow reaches the pier. Near the initial-bed level, the downflow is seen in a wider area at the sides and upstream of the pier. The maximum values of negative $w$ (intense downflow) are found upstream of the pier. These values are stronger than those at the upper level which is related to the effect of the scour hole that accelerates towards its inside. In the wake of the pier, an upward flow is observed and hence to satisfy the continuity of the flow, the flow at the sides of both pier and wake region is directed towards the bed. Between the two piers, the downflow is stronger than that at the outer sides of the piers. In comparison to flat-bed case (whose contours of $w$ component not shown herein), the presence of the scour hole increases the downflow and upflow in both quantity and the region involved.

3.2. Turbulence fields at horizontal planes

The contours of turbulence kinetic energy ($K$) are presented in Fig. 10. A core of higher magnitude of $K$ is found in the wake of the pier due to the formation and shedding of very strong rollers, while the values of $K$ are negligible upstream of the pier. In the flat-bed case, the peak values of turbulence kinetic energy at the upper level are almost 1.5 times of those at the lower level, while in the scoured-bed case this behavior is completely altered and the peak values of $K$ shift from the upper level to the lower one near the scour hole.

3.3. Flow fields at vertical planes

In this section, the flow fields are presented at the vertical planes in both longitudinal and transverse directions. As the main difference between the flow fields at single and a side-by-side piers arrangement is in the flow through the gap between the two piers, the vertical distribution of the longitudinal velocity are presented in Fig. 11 at the plane of symmetry ($Y = 13.65$ cm) in both bed configurations. In this figure, the values of vertical distance and velocity have been normalized by $h$ and $U_0$ respectively. In the flat-bed case [Fig. 11(a) and (b)], at the far upstream of the gap ($X/D = -7.69$) as the flow approaches the two piers, the longitudinal velocity decreases due to the general effect of two piers as obstacle. Then at the closer distance to the gap ($X/D \geq -2.2$), due to the flow contraction, the velocity increases and reaches its maximum value ($1.25 U_0$) at $X/D = 0$. At this area the velocity profile is not logarithmic profile. In the downstream of the gap, the flow maintains its high velocity up to 1.5D from the origin. As mentioned earlier, the wake region also decreases the area for the flow passage like as the two piers and causes the high velocity. In the region $X/D \geq 1.5$, the velocity decreases as the distance from the gap increases. In the scoured-bed condition [Fig. 11(c) and (d)], far upstream of the gap and at the upper part of the initial bed, flow velocity decreases until it reaches the $X/D = -1.1$. As seen, this point is closer to gap than that is in the flat-bed condition due to the presence of the scour hole. While near the gap, the effect of flow contraction of the two piers on the velocity values is more than the diminishing effect of the scour hole on them and consequently the velocity increases but slightly less than that is in the flat-bed condition. Inside the scour hole, the flow velocity linearly decreases until it reaches the value of zero as the distance
Fig. 10. Contours of turbulence kinetic energy at two horizontal planes, (a): in the flat-bed case; (b): in the scour-bed case.

Fig. 11. Vertical distribution of longitudinal velocity at the plane of symmetry \( (Y = 13.65 \text{ cm}) \) in the: flat-bed condition (a, b) and scour-bed condition (c, d).

from the hole bottom decreases then the reverse flow is found. The maximum reverse flow is found near the middle of the scour hole. At the downstream of the gap and inside the scour hole, contrary to the plane \( Y = 0 \text{ cm} \) (not shown here), reverse flow is not seen and the flow velocity decreases to the zero near the scour-hole bottom.

Velocity profiles \((w)\) and streamline plot at the upstream of the pier in the flat-bed case are presented in Fig. 12. The pier induces separation in the upstream flow along the bed surface, resulting in transversely rolling vortices, which is called horseshoe vortex system [41]. At the upstream of the pier, there is a downward and reverse flow which is directed upward near the bed. It is an evidence of a horseshoe vortex at the base of the pier [Fig. 12(a) and (b)]. Furthermore, the investigation of streamline plot (Fig. 12(c)) confirms that there is a horseshoe vortex at the small region near the bed just upstream of the pier which according to the Dargahi [9] and Ahmed and Rajaratnam [1], the point located at the end of this region is the primary flow separation point. Horseshoe vortices emanating from the upstream base of the cylinder convect downstream exterior to the shear layer, magnifying the mixing process and add extra turbulence around the base of the pier. Due to this additional turbulence, the wake region downstream of the cylinder is small at the elevation near the bed in addition to the effect of bed roughness on turbulence growth as explained earlier.

Fig. 13 shows the streamlines and velocity vectors at longitudinal vertical planes at \( Y = 0 \text{ cm} \) plane. In this figure, the magnitude and direction of velocity vectors are \((u^2 + w^2)^{1/2}\) and \(\arctan(w/u)\) respectively. Downstream of the pier, reverse flow is observed which expands as the distance from the bed increases. This region is distinguished with a semi-linear boundary in Fig. 13(a) beyond which the flow resumes its main direction. In the scour-bed case and at the upstream of the piers [Fig. 13(b)], the separation of the approaching flow occurs just beneath the edge of the scour hole forming a reverse flow inside the scour hole. The vertical component \((w)\) (according to the velocity profile not shown herein) is negligible at the distant upstream, but subsequently grows considerably and reaches significant negative (downward) values equal to 0.83\(U_0\) near the base of the pier. This value is greater than of 0.7\(U_0\) found for the present single-pier study (conducted for comparison). It seems that the expansion in the scour hole, due to presence of the two piers, makes flow accelerate more towards the scour hole than of the single-pier-made scour hole. The maximum magnitude of \(w\) found for the two side-by-side piers is also greater than of 0.6\(U_0\) reported by Graf and Istriarto [11] and Dey and Raikar [8] for single-pier cases.

Horseshoe vortex is considered as one of the major players in the development of the scour hole. In agreement with the findings of Kirkil et al. [14,15], there is a horseshoe vortex with two legs (one large and another small leg) in the scour hole upstream of the piers. However, the size of horseshoe vortex in the present study is larger than that of the mentioned studies due to the larger scour hole. A reverse and upward flow are seen downstream of the pier extending by moving away from the bed [Fig. 13(c)]. The oblique line distinguishing the reverse and main (streamwise) flow shows the place where shear layers separated from the sides of the piers (except for near the free surface [15]) reach each other.
In Fig. 14 streamlines and velocity vectors at $Y-Z$ planes (transverse sections) are shown at the three sections presenting flow features at the upstream, downstream and sides of the pier. In these figures, the magnitude and direction of the velocity vectors are $(v^2 + w^2)^{0.5}$ and $\arctan(w/v)$ respectively. Fig. 14(a) shows a downflow at the leading edge of the pier(s) and a transverse flow at the sides of the downflow due to the inverse pressure gradient induced by the piers. Fig. 14(b) shows a transverse deflection occurs at both sides of the pier slightly weaker (especially between the two piers) than that in the former section ($X = -4.7$ cm). It is remarkable that at the two sections $X = -4.7$ and 0 cm, a small converging of the flow to the pier near the bed from outer side along with the upper divergent flow create a vortex whose axis is parallel to the main flow direction (seen better in the streamline plots), while in the region between the two piers such a vortex is not visible. In the section $X = 10$ cm, near the bed, the flow from the sides rushes strongly to the plane $Y = 0$ cm then is turned upward and moves away from the bed. As the upward flow approaches the free surface, in agreement with the findings of Kirkil et al. [15], it starts moving away from the plane $Y = 0$ cm to its two sides to ensure continuity. It seems that at the outer sides of the piers the divergent flow is stronger than that of in between the two piers. Similar to the former two sections, a vortex is formed at the outer sides of the piers but slightly at upper height.

The horseshoe vortex is part of a system of turbulence structures that in combination with a downflow, a flow acceleration around the flanks of the pier and large-scale wake rollers are the erosive factors of the bed sediments in single-pier cases, however besides these mechanisms, in side-by-side arrangements some alterations occur in the flow structures which are interference of vortex shedding from each pier, interference of horseshoe vortices, and velocity increase between the two piers.

At the horizontal planes shown previously, the existence of the high-velocity flow between the two piers was found from Fig. 8(a), but there was no interference between the wake vortices of the piers (according to the average velocity obtained from the ADV) as the streamlines and velocity vectors reveal in Figs. 6 and 7. However, it does not mean that the vortices shedding downstream...
of each pier have not any interactions with each other. The investigation of turbulence kinetic energy distribution (normalized by $U_0^2$) in the vertical plane $Y = 13.65 \text{ cm}$ downstream of the gap (as shown in Fig. 15) confirms that how these interactions affect the values of turbulence in this region. According to this figure, after $X/D = 1.65$, in both bed configurations, the values of $K$ begin to increase considerably as the flow moves away from the piers. In the single-pier case, as the flow moves away from the pier, the values of $K$ decrease and reach the approach-flow condition. Akilli et al. [22] observed the interaction between the vortices from the Reynolds stress contour for $G/D = 2$.

To identify the interference of the horseshoe vortices formed at the front and sides of each pier, there is a need to investigate the scour-hole topography and corresponding flow pattern at the vertical planes. As mentioned earlier, the maximum scour depth located between the piers in the region $-90° \leq \phi \leq -45°$ was measured as 17.5 cm (0.54 h) which $\phi$ is the polar angle measured from plane $Y = 0 \text{ cm}$ upstream of the pier in counter-clockwise direction. According to Fig. 4, the topography of the equilibrium scour hole between the two piers substantiates that there exists an overlap between the holes in this area. Also, the maximum depth of scour hole is about 15% greater than that in the single-pier case. These situations are related to the strong contracted flow and interference of horseshoe vortices at the region between the two piers.

The transverse scour hole’s profiles and corresponding flow features are shown in Fig. 16(a)–(c). The horseshoe vortices formed upstream of each pier stretch as they fold around the piers because of the lateral pressure gradients. Fig. 16(a) shows the horseshoe vortex in the front of the pier at the transverse section $X = -4.7 \text{ cm}$. The horseshoe vortices at the two sides of the piers’ front are alike. As shown in Fig. 16(b) (section $X = 0 \text{ cm}$), between the two piers, the downward flow and horseshoe vortex is stronger than that in the outer sides of the piers. In contrast to the former two sections, at $X = 10 \text{ cm}$ [Fig. 16(c)] the flow from the sides converges (except for the area near the free surface) into the plane $Y = 0 \text{ cm}$ then is pushed upward in the wake of the pier. Coincident with the upward flow at the wake region, a downward flow takes place at the sides of this region for satisfying the continuity. Downstream of the pier and near the free surface, the combination of upward and downward flow make a vortical flow at this region. Fig. 16(a)–(c) shows the attenuation stages of the horseshoe vortex from upstream side of the piers to the downstream side of them. Contrary to the outer sides of the piers where the horseshoe vortex dissipates in the $X = 10 \text{ cm}$ section, a leg of the horseshoe vortex is observed between the two piers. It seems that strong downflow and interference between the horseshoe vortices formed around each pier as well as contracted flow make this vortical structure preserve its coherence between the piers even up to $X = 10 \text{ cm}$.

### 3.4. Turbulence fields at vertical planes

The contours of the turbulence intensities in the scoured-bed case at the transverse sections $X = -4.7$ and $0 \text{ cm}$ are presented in Fig. 17. The symbols of $u^+$, $v^+$ and $w^+$ refer to the magnitudes of
turbulence intensities in the longitudinal, transverse and vertical directions respectively. Within the scour hole, there exists a core of higher magnitude of turbulence intensities at both sides of the pier as a result of the flow separation which occurs at the edge of scour hole as reported by Dey and Raikar [8] at a single pier. Having a careful look at the Figs. 16 and 17, shows that the core of higher magnitude of turbulence intensities is coincident with the core of horseshoe vortex. As seen, the distributions of $u^+$ and $v^+$...
are almost similar as well as their magnitudes are equal at both sides of the piers. By contrast, the values of $u^+$ at outer sides of the piers differ from those in between the two piers and stronger magnitudes of $u^+$ are observed between the two piers. The further scouring between the two piers, besides the strong contracted flow, can be partly attributed to the stronger magnitudes of $u^+$ associated with the interferences of the horseshoe vortices because the high levels of the turbulent intensities can result in sediment motion, even if the mean shear stresses would be below the critical values [42]. Fig. 18 shows contours of turbulence kinetic energy ($K$) at $X = -4.7, 0$ cm and $Y = 0$ cm sections. The behavior of $K$ is also similar to those of turbulence intensities ($u^+$, $v^+$ and $w^+$) and a core of high-value of $K$ is seen inside the scour hole. Fig. 18(a) shows, similar to $w^+$, stronger magnitudes of $K$ is observed between the two piers whose positions are nearer to the pier base than those at the outer sides of the piers. According to Fig. 18(b), the magnitudes of $K$ behind the pier, in the wake of the pier, are considerably greater than those in front of the pier due to the formation and shedding of very strong rollers at this region. Fig. 19 shows the contour of Reynolds stress $\overline{u'w'}$ at $Y = 0$ cm at the upstream and downstream of the pier. This figure like the other turbulence characteristics (turbulence intensities), shows the higher level of $u'w'$ inside the scour hole associated with the horseshoe vortex. In the wake of the pier, the core of higher magnitude extends in part over the wake region outside of the scour hole.

### 3.5. Bed shear stresses

Bed shear stresses were estimated by the extrapolation of Reynolds stresses to the bed in the flat-bed case. At this method, the (local) bed shear stresses are determined by

$$\tau_b = \left( \tau_X^2 + \tau_Y^2 \right)^{0.5} \big|_{\text{at bed}}$$

where $\tau_X = -\rho(\overline{u'v'} + \overline{u'w'})$ and $\tau_Y = -\rho(\overline{v'u'} + \overline{v'w'})$ and $\rho$ = mass density of water. This method was used by Dey and Barbhuiya [43] around a vertical-wall abutment, Dey and Raikar [8] around circular and square piers, and Beheshti and Ataie-Ashtiani [25] around a complex pier.

The estimation was made on $X = 0$ cm and $Y = 0$ cm planes.

The shear stress amplification $\tau_b/\tau_{bc}$ is used for better understanding of the bed shear stress situation where $\tau_b$ and $\tau_{bc}$ are the local bed shear stress and the critical bed shear stress.
in the approach flow (calculated using $u_o^+$) respectively [1,8,25]. The shear stress amplification greater than 1 is representative of the condition of scour initiation and $t_s/t_{bc}$ smaller than $-1$ also indicates of the condition of scour initiation but with bed shear stress in a direction opposite to the main flow (negative $x$-direction). The values of $t_s/t_{bc}$ between the $-1$ and 1 indicate the condition prior to the initiation of scour. It is pertinent to mention that a scale of $t_s/t_{bc}$ would be meaningful from the point of view of the scouring initiation.

In Fig. 20, the shear stress amplification $t_s/t_{bc}$ is shown on $X = 0$ cm and $Y = 0$ cm planes. In this figure, the area between the two horizontal lines ($t_s/t_{bc} = -1$ and 1) shows the condition prior to the initiation of scour. According to Fig. 20, the value of $t_s/t_{bc}$ is close to 1 upstream of the pier indicating near the threshold condition for sediment motion. The shear stress decreases as the pier is approached. The value of shear stress at $X/D = 0.65$ is equal to zero which according to the Dargahi [9] and Ahmed and Rajaratnam [1] this point is in correspondence with the primary flow separation point upstream of the pier as seen in Fig. 12. This point is closer to pier than the distance 0.83D reported by Dargahi [9]. In the region $X/D = 0.65$ the sign (direction) of the shear stress changes indicating the reserve flow associated with horseshoe vortex. The maximum shear stress amplification (having a negative value) occurs near the leading face of the pier equal to 2.63. This is comparable with the findings of Ahmed and Rajaratnam [1] being about 2.75–3.25.

Downstream of the pier, $t_s/t_{bc}$ is less than $-1$ up to $X/D = 3.2$ beyond which bed shear stress is between the two lines. Both sides of the pier (plane $X/D = 0$), show conditions near and greater than the threshold shear stress but at the area between the two piers, appreciable value larger than the critical stress indicating the strong potential of scour at this region. A quick glance at the scour-hole map showing deeper depth of the scour hole between the two piers confirms the higher level of bed shear stress at this area.

3.6. Power spectrum analysis

Power spectrum analysis of the instantaneous-velocity measurements at different points in the wake of the piers as well as inside the scour hole was conducted in order to find the dominant vortex-shedding frequency of the large scale coherent structures. Power spectrum at each point was calculated using Fast Fourier Transformation (FFT) of auto-covariance function of velocity time-series data. The power spectra for velocity components are presented in Fig. 21 downstream of the pier at different points for both bed conditions. In this figure, the resultant power spectra $S(f) = (S_v(f)^2 + S_u(f)^2 + S_w(f)^2)\frac{0.5}{(cm^2/s)}$ have been calculated where $S_v(f)$, $S_u(f)$, and $S_w(f)$ are power spectra for streamwise, transverse, and vertical velocity components respectively.

The power associated with the peak frequency for the power spectrum distribution indicates the strength of vorticity of wake vortices formed by the cylinder. In turn, the strength of wake vorticity expresses the capacity the of wake vortices to entrain and move bed sediment from the flanks and rear of each cylinder [13]. According to Fig. 21, for the flat-bed case, the maximum values of $S(f)$ at both horizontal levels are found at the same frequency of 0.781 Hz which in terms of the Strouhal number, $St = fD/U_o$; is approximately 0.22 where $f$ is the vortex-shedding frequency. This value of Strouhal number is comparable with the findings of Kamemoto [44] ($=2.2$), Sumner et al. [24] ($=2.1$) and Bearman and Wadcock [45] ($=2$) for both conditions of low and high Reynolds number indicating that the vortex shedding behavior in term of the Strouhal numbers are independent of the Reynolds numbers. For vortex-shedding frequencies equal to 0.781 Hz, the sampling time ($120–250$ s) corresponded to between 94 and 195 vortex-shedding periods.

As seen in Fig. 21, the strength of vortices in the upper level is greater than that near the bed and there is no evidence of biased or bistable flow pattern (vortex shedding with two dominant frequencies behind the piers) in agreement with the findings of Sumner et al. [24] for flat bed. Contrary to the flat-bed case, the power spectra in the scoured-bed case become weak and there are several dominant frequencies (Strouhal numbers) with considerable decrease. This situation indicates that when the equilibrium scour hole is achieved, the capacity of wake vortices to entrain and move bed sediment from the flanks and rear of each cylinder considerably decreases. As seen in the power spectra figures, the high strength of wake vortices is found downstream of the gap (inner area) rather than the outer side of the two piers.

The results obtained for flat-bed case (not shown) show an increase in the strength of wake vortices as they moves further from the gap ($X = 0$ cm) in the line of symmetry ($Y = 13.65$ cm). This situation indicates the interaction between the vortices shedding from each pier and as presented in Fig. 15, the increase in the values of turbulence kinetic energy in the plane of symmetry is related to this situation.

Some spectra analysis of the measured velocity time series were carried out around the pier situated at the other side of the plane of symmetry in order to demonstrate what kind of vortex shedding occurs downstream of the two piers. Some power spectra and their counterparts are presented in Fig. 22 at the other side of the plane of symmetry. As seen in Fig. 22, dominant frequency occurs at a same value and the behavior of the power spectra is similar to each other indicating that the form of vortex shedding is out of phase (anti-phase) whereby vortices were formed and shed in a symmetric manner. However, the vortices shedding from each pier have interaction with each other as they move away from the piers. Comparison with the results of power spectra for the single-pier case at the level $Z = 17.5$ cm (not shown) shows a decrease in the maximum strength of vortices in the side-by-side arrangement. The power spectra analysis also shows that the strengths of the vortices downstream of the gap were found to decay at a greater rate than those adjacent to the outer flow (outer side of the two piers) consistent with the results of Kolar et al. [46].

The power spectra analysis was also carried out inside the scour hole as presented in Fig. 23. From this figure, the oscillation frequency of the horseshoe vortex (the periodic motion of the horseshoe vortex) is close to the shedding frequency of the wake vortices. This is in agreement with the findings of Dargahi [7,9] in both flat- and scoured-bed cases. In the present study, the values of these frequencies are close to 0.4 Hz ($St = 0.11$). This figure also shows that inside the scour hole the strength of vortices are lower than those outside the scour hole.

4. Summary and conclusions

The effects of two piers in side-by-side arrangement on the flow field were investigated using the instantaneous velocities measured by an ADV. Streamlines and vectors obtained from the velocity fields, the contours and distributions of the time-averaged velocity components, turbulence intensities, Reynolds stresses at different horizontal and vertical planes were presented around the piers with and without a scour hole. Furthermore, the bed shear stress has been estimated at some points around the piers. Here, the main conclusions derived from this study are presented.

The streamwise velocity ($u$) increases between the two piers which changes the behavior of vertical and transverse deflections at this area in comparison with the outer sides of the piers. The maximum depth of scour hole was about 15% greater than that in the single-pier case. In addition, the extension of scour hole at the upstream side of the piers is more than that in the single-pier case. The contours of the scour hole substantiate that
there exists considerable overlap between the two piers’ scour holes indicating the interference in the horseshoe vortices formed around each pier. Furthermore, the investigation of the vectors and streamlines at three transverse sections shows that the leg of the horseshoe-vortex systems is elongated further downstream of the gap. A rush of accelerated flow into the scour hole strengthens the contracted and downward flow between the two piers. In comparison with the single-pier case, the larger horseshoe vortex and stronger downflow (maximum value of 0.83U₀) are found at the upstream of the piers. Between the two piers, the magnitudes of vertical turbulence intensity (w⁺) as well as turbulence kinetic energy are greater than those at the outer sides of the piers. The estimation of the bed shear stresses in the flat-bed case shows considerable values between the two piers, twice as large as that at the other sides of the piers. Between the two piers, the scour depth was deeper than that at the other side of the piers. The flow pattern including the contracted flow and interference between the horseshoe vortices plays an important role in the beginning and formation of the greater scour depth between the two piers. A core of high magnitude of turbulence kinetic energy is concentrated in the wake region which as the scour hole is developed this core moves towards the scour hole at this area. The results show that...
there are high levels of turbulence intensity, turbulence kinetic energy and Reynolds stresses inside the scour hole due to flow separation.

The presence of the scour hole changes the behavior of vortex shedding considerably and contrary to the flat-bed case, the power spectra in the scoured-bed case become weak and there are several dominant frequencies (Strouhal numbers) with considerable decrease. The high strength of wake vortices is found downstream of the gap (inner area) rather than the outer side of the two piers. The oscillation frequency of horseshoe vortex (periodic motion of horseshoe vortex) is close to shedding frequency of wake vortices. The strength of the vortices and the values of turbulence kinetic energy increase at the plane of symmetry ($Y = 13.65$ cm) with moving away from the $X = 0$ cm in the streamwise direction indicating an interaction between the vortices.

The presence of the fully developed scour hole alters both of the flow structure and the intensity of the vortical structures such as the horseshoe vortices, especially between the two piers compared to flat-bed case. Some of the flow features presented in this study are exclusively related to the side-by-side arrangement different from those formed around single-pier cases, so for a better prediction of the scour depth around side-by-side piers, the effects of these flow features on maximum scour depth should be considered in the semi-empirical equations.

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References


