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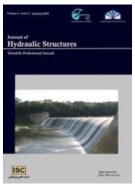

The influence of the submergence ratio of submerged vanes on the slope of the hole around the pier groups in a sharp bend

Neda Safaripour[1]
Mohammad Vaghefi[2]
Amin Mahmoudi[1]

Abstract

Bridges are metal or concrete structures, which make road connections across rivers when installed over river paths. When flooding or scouring occurs, several issues including bridge destruction and interruption of road connections arise. There are a variety of methods of protecting such structures, one of which is application submerged vanes. This research shows how two vanes with different submergence ratio affected decrease in local scour surrounding one pier and groups of piers installed in a 180-degree bend. The scour around pier groups either in a transverse position to the flow or with a longitudinal direction was analyzed. This finding suggested that applying vanes decreased the deepest scour around the piers in all the tests, and its maximum effect occurred in triad longitudinal pier groups. By raising the submergence ratio, bed scour depth at the outer bank reached its minimum size in longitudinal pier groups. In transverse pier groups, the first scour hole near the outer bank increased in depth in the presence of vanes. By using the vanes, the slope of the scour hole towards the inner bank grew larger than that towards the other bank. The maximum slope of the outer bank happened in the triad transverse pier group at an approximate value of 0.63. The most significant impact of submerged vanes on reducing the upstream slope was observed in a single pier with 75% submerged vanes and triad longitudinal piers with 25% submerged vanes, resulting in reductions of about 50 and 74% respectively compared to piers without vanes.

Keywords: Local scour; Pier Groups; Submerged Vanes; Topographical changes; 180-Degree Bend

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1. Introduction

Human beings have long been forced in some cases to construct bridge piers on natural paths of rivers in order to maintain road connections. Gradually, local scour due to horseshoe and

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[1] Department of Civil Engineering, Faculty of Engineering, Persian Gulf University, Bushehr, Iran.
[2] Department of Civil Engineering, Faculty of Engineering, Persian Gulf University, Bushehr, Iran, Email: Vaghefi@pgu.ac.ir **(Corresponding author)**

wake vortices occurring around bridge piers result in bridge destruction. Today, pier groups are widely employed in bridge designs. The flow pattern around pier groups is much more complicated than that of a single pier with a much wider local scour around them. Hydraulic engineers have always made efforts to increase bridge pier lifetime. A great number of strategies, for instance, stabilization of bed soil and reduction of flow velocity applied to bridge piers, have been suggested for scour reduction using protective hydraulic structures. Due to the significant impact of submerged vanes on erosion control and sediment transport changes, numerous researchers have attempted to investigate the influence of these hydraulic structures to mitigate local scour.

Voisin and Townsend [1] examined effective implementation of different parameters of submerged vanes in the bed scouring of a sharp and narrow bend. Their results illustrated that by raising the length of the vanes, scouring was transferred from thalwag to the outer bank and the overall channel bed scour decreased. The findings from Tan et al. [2] regarding the impact of a submerged vane on scouring in a straight channel indicate that the most effective vane height is approximately 2 to 3 times the height of the bed sediments. Ghorbani and Kells [3] conducted their experiments in a straight flume on the effective implementation of one and two submerged vanes in scour reduction at a single pier. As shown by the results of their work, the acting of the double vanes in decreasing scour was more favorable than that of the single vane. Bhuiyan et al. [4] examined their experiments on the scour pattern and meandering river flow pattern and the effective implementation of submerged vane installation in the outer bank scour. The results they obtained by experimenting showed that use of submerged vanes reduced outer bank scour and the scour was transported from the thalwag toward mid-channel.

Azizi et al. [5] carried out an experiment in a straight flume at the edge of different shapes of submerged vanes on reduction of bed topography alterations. The geometry of the vanes was assumed through the experiments in 4 different types, either rectangular or triple-blade, where the leading edge chamfered at 30, 45, and 60-degree angles in proportion to a vertical line. Barani and Shahrokhi Sardo [6] examined the influence of submerged vanes with different curved, flat, and angular shapes on the topography of the channel with two 90 and 180-degree bends. They discovered that the curved vanes were more effective in preventing scouring of the channel bank. Azizi et al. [7] conducted a numerical simulation of scour reduction at a single pier under the influence of submerged vanes in a straight flume. The results of modeling the flow pattern around the pier showed that by increasing the number of vanes from 2 and 4 to 6 and also increasing the angle from 20 to 30 degrees, better performance was achieved in reducing scour around the pier. Vaghefi et al. [8] installed a single bridge pier in a straight flume with two different types of piers, vertical and laterally inclined, and investigated the scour around each under different conditions. Dey et al. [9] performed their experimental research in a 180-degree bent flume so as to reduce bed scour under the influence of the angle of submerged rectangular vanes. Maatooq and Adhab [10] conducted their laboratory research by considering the role of installed submerged vanes on reduction of outer bank scour in a 180-degree channel. According to their research, when the ratio of the space of submerged vanes from the outer bank to the channel width was equal to 0.25, it demonstrated better performance than those at other distances. Laboratory and numerical research of Shabanlou et al. [11] regarding the reduction of a 180-degree bend scour influenced by submerged vanes by changing the Froude number and different parameters of submerged vanes showed that the outer bank scour was directly related to the height of the vanes from the primary bed level. In other words, raising the height of the vanes gave rise to the outer bank scour. Vaghefi et al. [12] studied topography of bed alterations due to placement of triad pier groups in two different directions of flow in different locations of a 180-

degree sharply bent. Biswas and Barbhuiya [13] found that by installing submerged vanes in a line on the outer bank of a 180-degree bend, the submerged vanes could decrease the scour depth of the outer bank by approximately 40%. Zarei et al. [14] studied the performance of various numbers, angles and lengths of vanes on topography of bed in a sharp 180-degree bend. By studying the flow pattern around triangular vanes connected to the outer bank in a rectangular flume, Bejestan et al. [15] demonstrated that submerged vanes tripled kinetic energy compared to a situation where no vanes where used. Safaripour et al. [16] studied scour reduction around pier groups under the implementation of submergence ratio of submerged double vanes in a sharp 180-degree bend. A variety of parameters, including number and different arrangements and directions of the pier group, and the submergence ratio of the submerged vanes were considered. In this research, the bed topography alterations along the bend and the downstream straight path, the scour temporal evolution of variations, the deepest scour, the highest sedimentary bar, the volume of the hole, the area of scour, and the rectangle surrounding the scour hole were investigated. Chooplou et al. [17] examined the different arrangements of double submerged vanes in scouring around a single pier located in a 180° sharp bend. Their findings indicated that positioning the vanes along the central axis of the channel led to an approximately 51% decrease in scour. Keshavarz et al. [18] investigated the effect of collar on reducing scouring of bridge piers. They examined nine different cross-sectional shapes of the pier protected with collar. Vaghefi et al. [19] altered the dimensions and number of submerged vanes to investigate scouring around a single bridge pier in a sharp 180-degree bend. They determined that submerged vanes exhibit positive results, leading to an approximated 30% decrease in scour depth around the bridge pier. Hamidi et al. [20] used a flow-3D numerical model approach to mitigate scour around a bridge pier using double submerged vanes. They found that increasing the height of the vanes above the initial bed led to a reduction in scouring. Safaripour et al. [21] investigated the flow pattern around single and twin pier groups affected by double submerged vanes. They discovered that the submerged vanes diverted the flow from the piers, with the highest velocity occurring near the vanes.

The results of prior research indicated that a combination of submerged vanes and piers in bent paths had rarely been addressed by researchers. This paper aimed to examine the role of submergence ratio of two vanes in scour decrease at one pier and at pier groups in 180-degree sharply bent channels. The pier groups have been installed in transverse or longitudinal directions. In this paper, lateral and longitudinal profiles along the channel, scour hole slopes surrounding the groups of piers, and the scour reduction at the piers were analyzed.

2. Material and methods

All of the tests were conducted in the laboratory of hydraulic structures at Persian Gulf University in Bushehr. A schematic of laboratory channel is shown in Fig. 1(a). The laboratory is equipped with a flow meter, a pump, and a bent flume. The U-shaped laboratory channel, as wide as 100 cm, is constructed with a relative curvature radius of 2 at the bend. The inlet tank is connected to the upstream side of the bend via a 6.5-meter-long straight end. The water flow is led out through an outlet tank located at the end of a 5.1-meter-long downstream end. The height is 70 cm throughout the channel, and 30 cm of this height is covered by d_{50}graded sediments and standard deviation (σ_g) equal to 1.5 mm and 1.14, respectively. According to the recommendation of Raudkivi and Ettema [22], the diameter of the sediment particles should be greater than 0.7, as suggested by Chiew and Melville [23] the geometric standard deviation should be less than 1.3. The shear Reynolds number (Re*) was determined to be 580, indicating turbulent flow, as it exceeded 250.

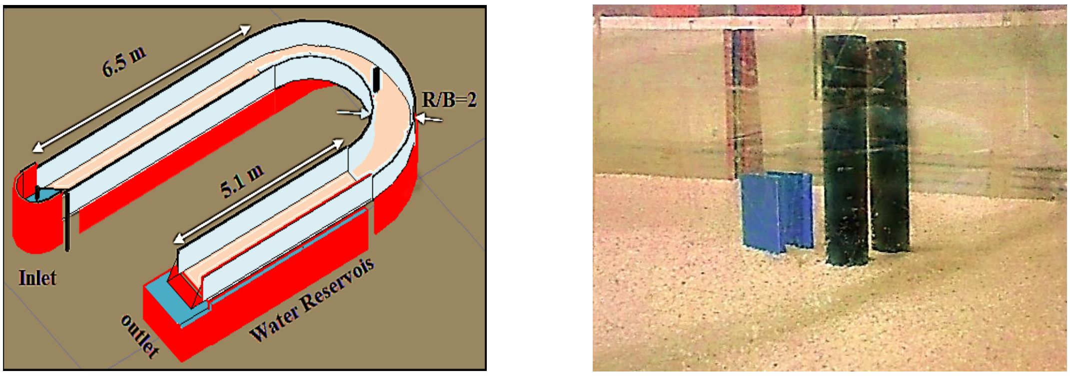


Figure 1. (a) Schematic view of laboratory channel , (b) Installation of piers and vanes

PVC pipes (where D=5 cm for Cylindrical Polyvinyl Chloride) were used to represent the piers. Rectangular Plexiglass vanes with a length of 7.5 cm (1.5 times the diameter of pier) and a thickness equal to 20% of the pier diameter were employed as submerged vanes with 25, 50, and 75% submergence ratios [16]. According to the research of Safaripour et al. [16], submerged vanes were placed upstream side of the piers at an angle of 25 degrees clockwise. Figure 1(b) illustrates a view of piers and vanes installed.

2.1. Description of the Experiments

Twenty experiments were conducted in a 180-degree sharply bent channel. The tests were carried out about one, two and three piers located in transverse or longitudinal directions, with and without the presence of vanes. The groups of piers were installed at a center-to-center space of 2 times the pier diameter from each other in the 90-degree position, located on the central line of the flume. The role of double vanes of varied submergence ratios in scour reduction at bridge pier groups was examined. The experiments were conducted for 25, 50, and 75% submergence ratios (13.5, 9, and 4.5 cm from the primary base level). Parallel arrangement of the vanes was assumed with 100% overlap at a 25-degree clockwise angle. The space between the vanes and the pier was determined to be 2.5 times the pier diameter. First, a 44-hour-long experiment was conducted with a 70-lit/sec discharge and an approximate depth of 18 cm on a single bridge pier in order to determine the te (where te= relative equilibrium time). The deepest scour was written at various intervals. After 9 hours into the experiment, the depth of scour reached 0.9 times the total scour depth; hence, 9 hours was selected as te. During the test, instabilities were observed in the slope of the hole. The slope of the hole was occasionally unstable because of the flow entering it, but the criterion for assessing the slope was complete drainage by the end of the tests. Subsequently, following drainage and throughout the measurements, the slope of the hole remained stable, as there was no flow present.

Experiment appellation denotes the pier properties in the first part and the vane properties in the second part. P represents the piers. The first symbol indicates the number of piers, and L and T denote that the group piers are in longitudinal and transverse direction, respectively. In the second part, S denotes the submerged vane, and the last number implies the submergence ratio. The variable parameters in the experiments are shown in Table 1.

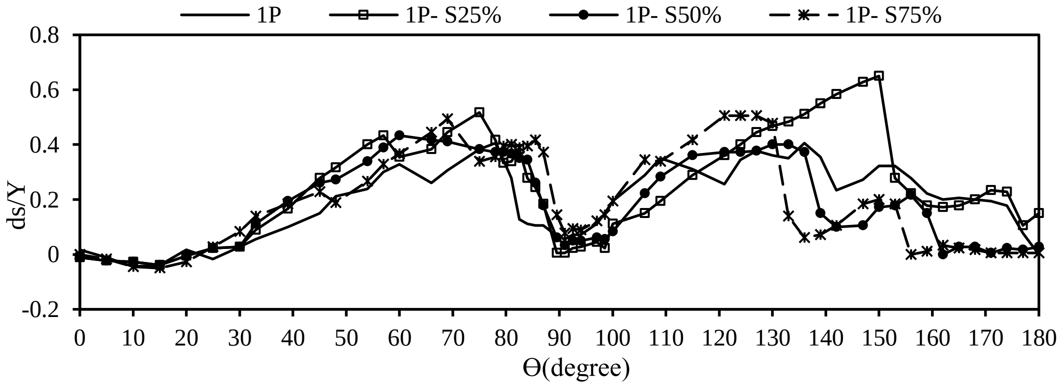
Table 1. Variable parameters in the experiments

Row	The number of piers	submergence ratio of the vanes	placement of piers in two different directions of flow
1	1P, 2P, 3P	25%, 50% , 75%	Longitudinal or Transverse

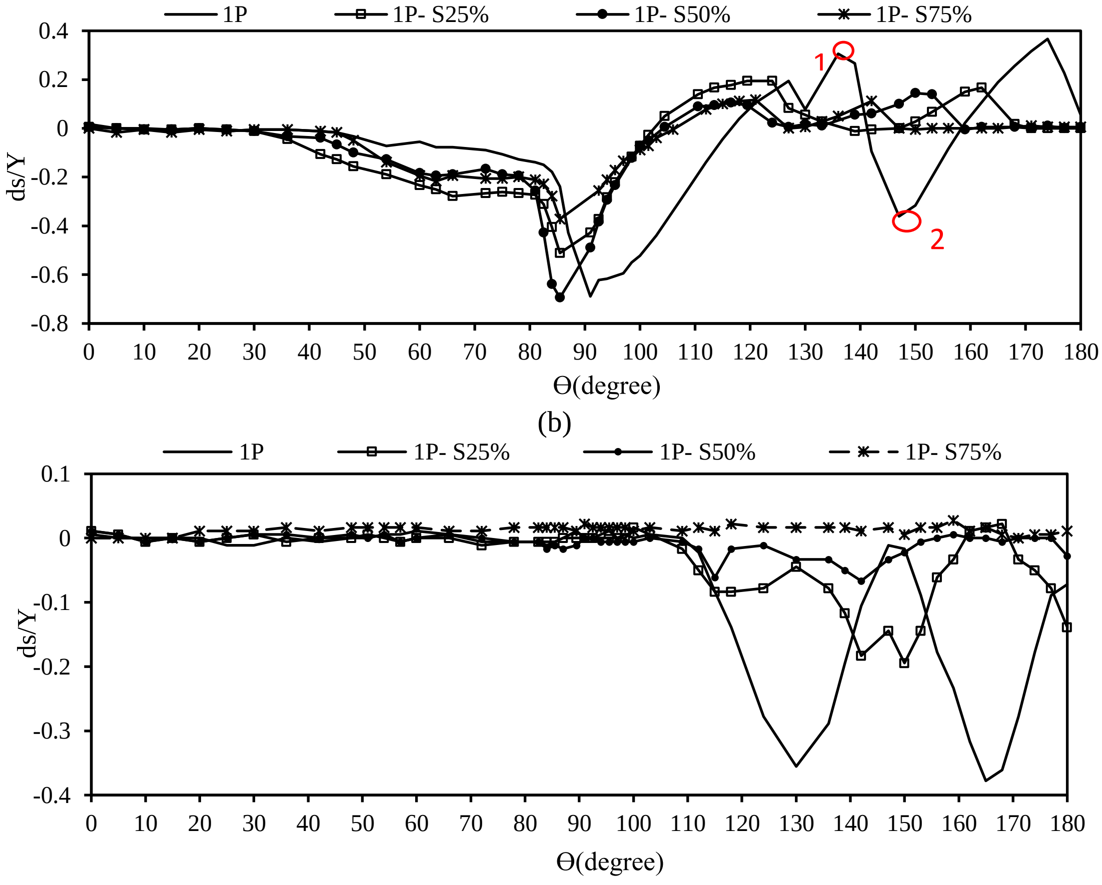
3. Results

Instances of a few longitudinal profiles along the channel are shown in Fig. 2 for investigating the implementation of the vanes present at the upstream region of a single pier. Figure 2(a) illustrates the longitudinal profile near the inner bank in single pier and tests using vanes. According to this figure, sediment piles have been created in proximity of the inner bank from the beginning to the end of the bend. The height of these piles has been reduced to approximately the same amount as the primary bed level at the center of the bend near the inner bank. According to Fig. 2(a), pile formation at a single bridge pier has an ascending trend through the first half of the bend, increasing after installation of the submerged vanes. Upon reaching the channel center, no piles are developed there. The highest sedimentary bar increased in single pier experiments accompanied by vanes from the 90 to 180–degree positions of the bend. For instance, 1P- S25% had a maximum sedimentation height almost equal to 0.65Y among the experiments.

As is observed in Fig. 2(b) by reducing the submergence ratio in the experiments including vanes, the scour increases at the upstream side of the vanes from the 0 to 90–degree positions of the bend in mid-channel. Sediments in this area oriented towards the inner bank considering the streams inside the bend, the result of which was the increased height of sediment pile in proximity of the inner bank, as is illustrated in Fig. 2(a). As shown in Fig. 2(b), after placement of the submerged vanes, the deepest scour happened at the site of the vanes. A study of the longitudinal profile in mid-channel suggested that the scour about the pier declined when using submerged vanes. It may be concluded that the vanes were capable of reducing wake vortices created at the downstream region of the pier. As is indicated in Fig. 2(b), the flow velocity increased with reduction of water height over pile (Zone 1) in P experiment, which resulted in creation of vortex and scour; therefore, the second scour hole (Zone 2) occurred. In the experiments using vanes, the pile was developed at its downstream side within the approximate distance of 100 to 125 degree angles. Thereafter, topography variations of bed get to the lowest value.



(a)



(b)

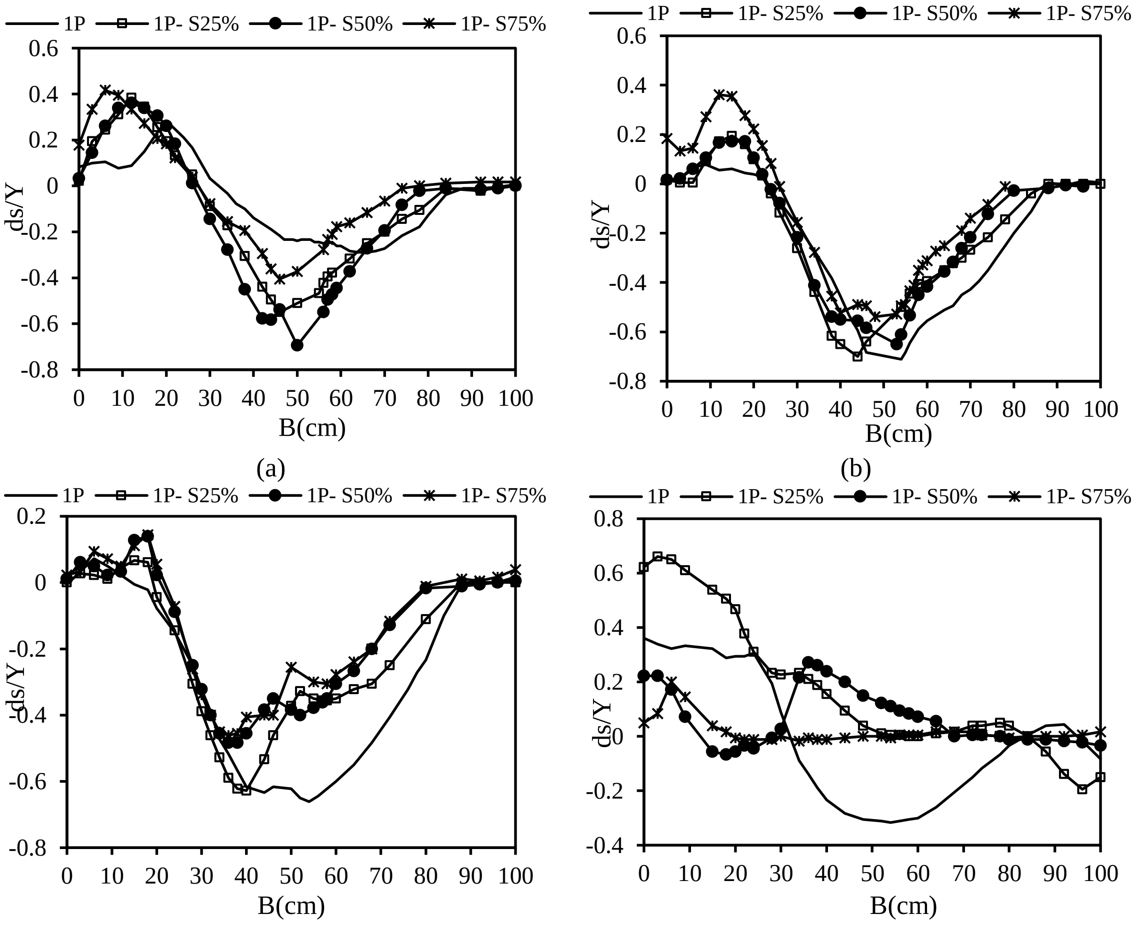
(c)

Figure 2. A sample of a longitudinal section at a distance equal to (a) 5, (b) 50, and (c) 95% of the channel width from the inner bank in the single bridge pier experiments with and without submerged vanes

It is obvious in Fig. 2(b), 1P- S75% conditions provided an acceptable performance with the most significant reduction in scour along the channel in comparison to the pier without any vanes. At the downstream region of the piers, after the pier site, the lateral flows inside the bend dragged the sediments from the outer bank towards mid-channel, the event which is verified in Fig. 2(b) and Fig. 2(c). Two consecutive scour holes of almost the same depth happened at approximate spaces of 90 and 110D from the beginning of the bend close to the outer bank in the single pier experiment in Fig. 2(c), and sediments at this area approached mid-channel and created two consecutive piles. It may be observed in Fig. 2(c) in the single pier tests containing two vanes that the longitudinal profile variations at the outer bank decreased when the submergence ratio increased. For instance, it may be stated about 1P- S75% experiment that bed topography at the outer bank underwent almost no significant variations. In 1P- S25%, the scour depth close to the outer bank increased at a space of approximately 40D from 90° position of the bend, and the sediments of this area were driven towards mid-channel.

Figure 3 presents a sample of a few lateral profiles at specific intervals in order to examine bed variations in single pier experiments with submerged vanes. The lateral profile of the single bridge pier in Fig. 3(a) indicates that the scour occurs at a space of approximately 30 to 80% of

B (where B= channel width) away from the inner wall. It may thus be concluded that the flow oriented towards mid-channel. With installation of the vanes in this position as well as reduction of the submergence ratio, the local scour increased.



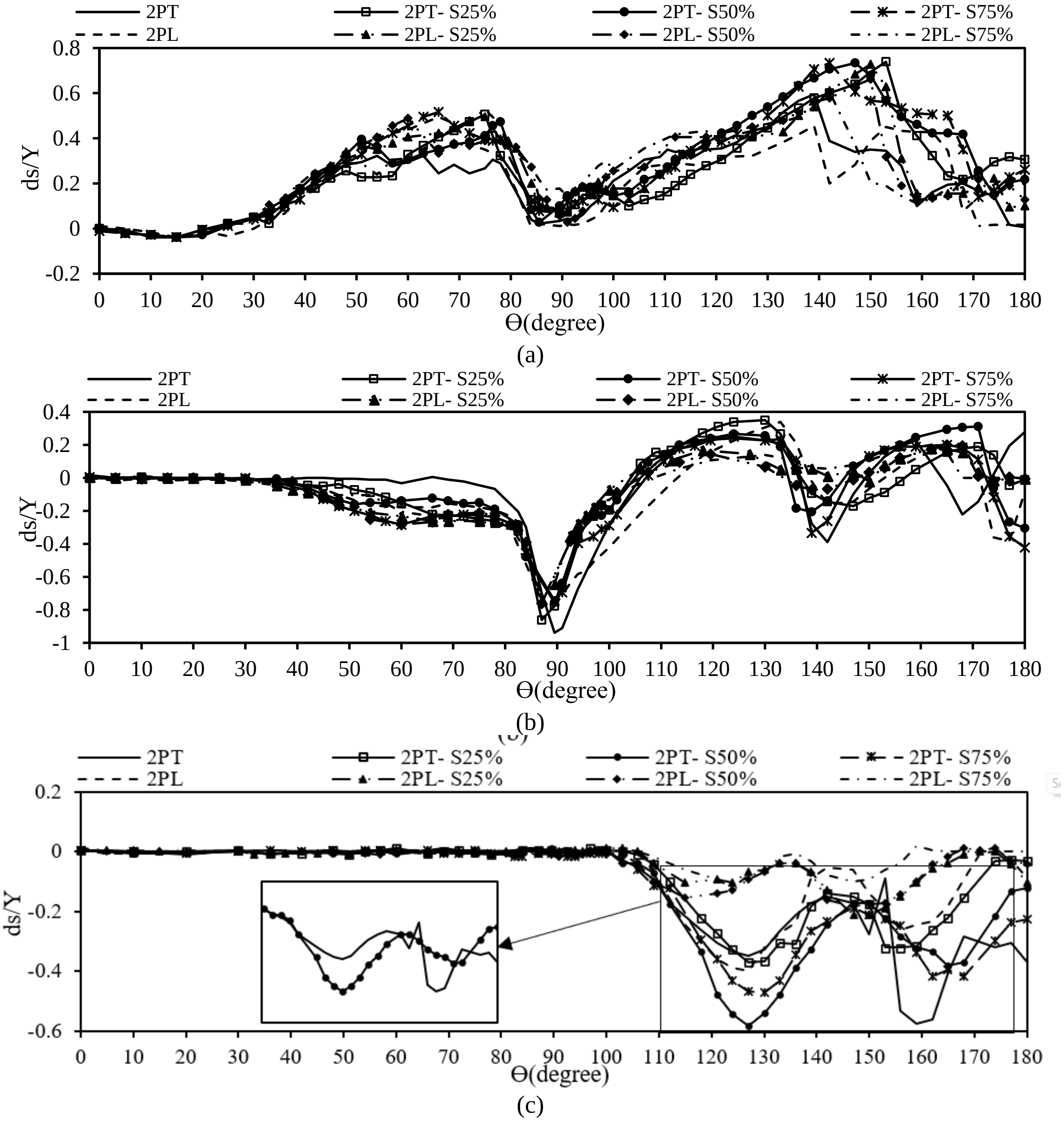
(a) (b)

(c) (d)

Figure 3. A sample of cross section at a distance equal to (a) 2.5 times the pier diameter towards upstream from the bridge pier location, (b) the center of the pier, (c) 2 times the pier diameter towards downstream from the bridge pier location, and (d) 42 times the pier diameter towards downstream from the bridge pier location in the single bridge pier experiments with and without submerged vanes

As shown in Fig. 3(b), the deepest scour at the location of the pier decreases in experiments containing vanes. For instance, the deepest scour at the location of the pier in 1P- S75% decreased by almost 25% compared to 1P experiment. The slope of the hole is sharper at the inner bank than that at the outer bank at this section. As is observed, increase in submergence ratio reduced the depth of scour at the cross section. Given the fact that the flow was directed by the vanes towards the inner wall, reduction of the submergence ratio increased scour at the inner bank in comparison with a pier in the absence of vanes at this section. The scour at the inner bank in 1P- S75% did not change in comparison to that in a single pier, and the scour at the outer bank decreased by an average of 44% compared to the experiment without vanes. In experiments accompanied by vanes, the highest sedimentation bar increased, where raising the submergence ratio made further evident such an increase in height of the sediment pile. As it appears in Fig. 3(c), with installation of the vanes in the experiments, bed alterations at a space of 40% of B from the inner bank are the same in every experiment. After that distance, scour decreased by 54% on the average in tests with vanes compared to pier without any vanes. Therefore, it can be concluded that the scour volume decreased with installation of the vanes. The implementation of vanes having an effect on scour depth reduction is observable for 50 and 75% submergence ratios in this figure. According to Fig. 3(d), in the single pier experiment, the amount of scour created at mid-channel is approximately 10D on both sides with the maximum depth of around 0.3Y. Placement of vanes reduced bed scour in comparison to the tests without any vanes, and bed topography variations in 1P- S75% approximately reached the minimum. With reduction of the submergence ratio, the sediment pile was created near the inner bank. The highest pile at this section occurred in 1P- S25% with an approximate value of 0.65Y.

Figure 4 illustrates instances of a few longitudinal profiles at specified intervals in twin pier group experiments. A review of Fig. 4(a) reveals that in the first half of the channel, there are more sediment piles in 2PL than in 2PT since 2PL pier group is longitudinal, and the front pier plays the protective role. Upstream-directed recursive flows in this pier group transported the sediments in this area towards the inner wall of flume. As also indicated in Fig. 4(a), by using the submerged vanes in 2PT, the highest pile at the first half of the flume increased by approximately 1.6 times, and that in the second half increased by approximately 1.3 times in comparison to 2PT test. By using submerged vanes in 2PL pier group, the height of sediment bar barely changed in the first half of the bend; however, it increased by approximately 1.6 times that without vanes at the downstream region of the piers. The maximum sedimentation height at this section in experiments containing vanes was almost equal in both pier groups. As shown in Fig. 4(b), scour is observed in every experiment with vanes at the upstream region of the vanes. In the second half of the bend, there were more sediment piles in 2PT than 2PL because the piers were placed across the channel, which caused an increase in local scour around them, Therefore, the sediments shifted from the proximity of the piers and vanes created a pile in close of the inner bank. The transverse station of the piers to the flow added to the sedimentation height. The sedimentation height also increased in every experiment containing vanes with an approximate value of 0.7Y at a distance of 35D from the center of the channel. In experiments involving longitudinal piers with vanes, the scour pattern was the same for all three submergence ratios of the vanes. Scour depth reached the downstream side of the piers at a mild slope of 0.17 in 2PL, and 0.32 in experiments using vanes. Profile variations at the outer bank are indicated in Fig. 4(c). In this figure, the vanes installed in 2PL experiment reduced bed topography alterations to a minimum. By using the vanes in 2PT experiment, the depth of the first scour hole dropped, while that of the second scour hole climbed on the graph. The deepest scour at this section happened at spaces of 26 and 50D from the center of the channel in 2PT- S50% and 2PT experiments, respectively.



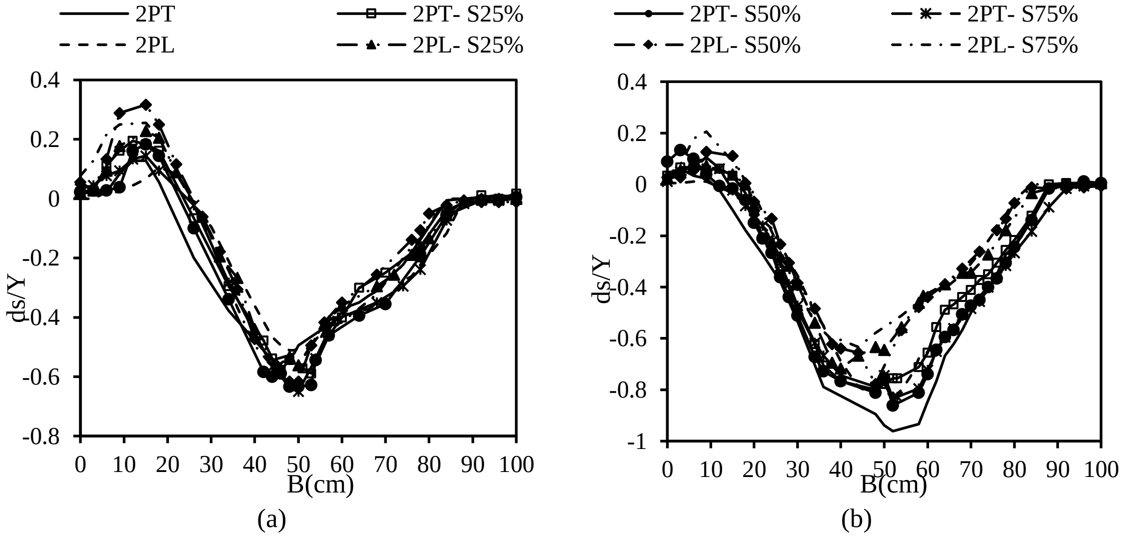
(a)

(b)

(c)

Figure 4. A sample of a longitudinal section at a distance equal to (a) 5, (b) 50, and (c) 95% of the channel width from the inner bank in twin pier groups experiments with and without submerged vanes

Figure 5 illustrates instances of a few lateral profiles in twin pier groups experiments accompanied by double submerged vanes. As shown in Fig. 5(a), in 2PL experiments using the vanes, the scour throughout the width of the section decreased, and the sedimentation height increased up to a space of 20% of B from the inner wall. In 2PT experiments, for every submergence ratio of the vanes, the inner bank scour was reduced, and the outer bank scour reduction happened only in 2PT- S25%. In 2PT- S50% and 2PT- S75% experiments, the lateral profile of the outer bank did not change in comparison to the piers without vanes. In Fig. 5(b), application of double vanes in 2PT has an acceptable performance in reducing scour in this section. 2PT- S25% experiment reduced scour in channel width by approximately 16% on the average. Installation of the vanes in 2PL experiment did not change the bed lateral profile up to a space of 40% of B from the inner wall, compared to the piers without using vanes; however, after this point, the bed lateral profile decreased by 50% on the average. According to Fig. 5(b), it can be seen that in both groups of piers, changing the submergence ratio leads to almost equal profile variations, i.e. the same performance is observed for every submergence ratio of the vanes. As can be seen in this profile of Fig .5(b), the deepest scour in 2PL- S75% and 2PT-S25% experiments respectively decreased by approximately 30 and 20% in comparison with the test with no vanes. Figure 5(c) illustrates the area behind the piers, where the vanes reduced scour at the outer wall by directing the flow towards the inner wall. In 2PL experiment, at a distance of 60% of B from the inner wall, an average of 50% reduction in scour occurred in comparison with the test using only piers. Considering this profile in 2PT experiments, the depth of scour of the outer and inner banks with the presence of vanes underwent little change; however, the scour depth at a distance of 20% of mid-channel decreased by approximately 28% in comparison to the piers without using vanes. Alterations in the profiles of inner and outer banks in 2PT experiments accompanied by vanes almost complied with those of piers without the vanes. According to Fig. 5(d), sediment pile developed in the twin pier groups near the inner bank, the value of which took a descending trend approaching towards the outer wall. The smallest bed topography alterations occurred in 2PL- S75% experiment. As shown in Figs. 5(c) and 5(d), the lower depth of scouring at the outer bank in 2PL experiments with vanes compared to that in 2PT experiments with vanes indicates the lower volume of scour and the smaller width scour of the rectangle circumscribing the hole in the group of longitudinal piers compared to the group of transverse piers.



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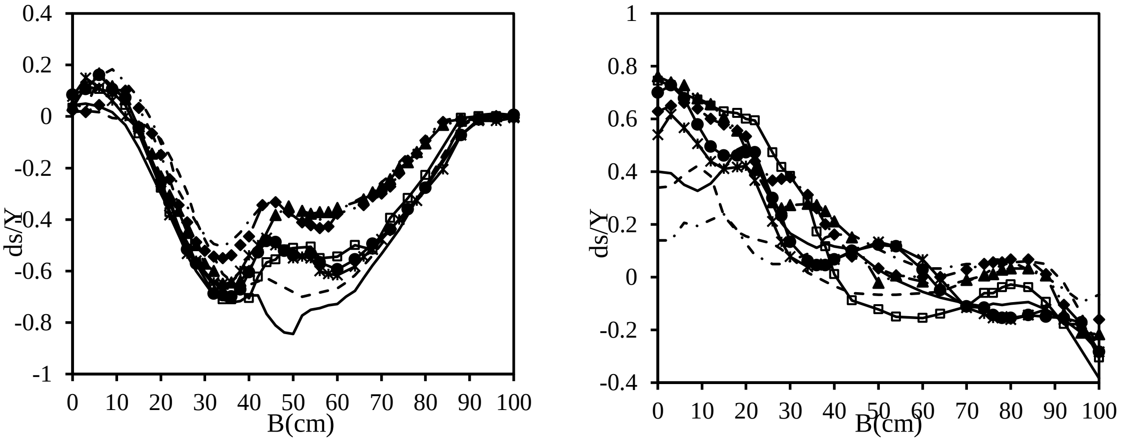
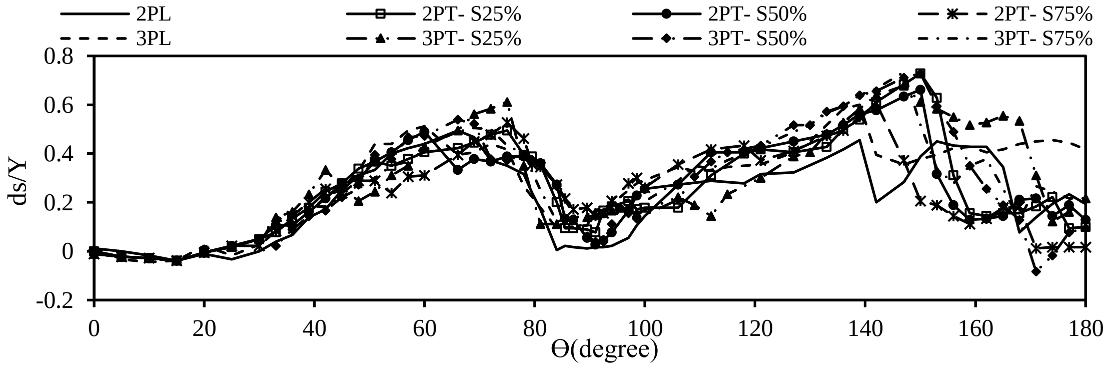


(c) (d)

Figure 5. A sample of cross section at a distance equal to (a) 2.5 times the pier diameter towards upstream from the bridge piers location, (b) the center of the piers, (c) 2 times the pier diameter towards downstream from the bridge piers location, and (d) 42 times the pier diameter towards downstream from the bridge piers location in twin pier groups experiments with and without submerged vanes

Figure 6 examines bed alterations along the channel in experiments on longitudinal piers. As shown in the longitudinal profile near the inner bank in Fig. 6(a), the highest pile in the first half of the flume was approximately equal in both pier groups; however, in the second half of the flume, the highest sedimentation bar in 3PL experiment was approximately 1.3 times that in 2PL. As is observed in longitudinal profile variations in 2PL experiment, reduction in the height of the pile occurred at approximately 140 and 170-degree angles. With placement of the vanes in 2PL and 3PL experiments, the height of the pile at the inner bank along the channel increased in comparison with the piers with no vanes. By reducing the submergence ratio of the vanes, the sediment pile in the second half of the bend increased in twin pier group experiments with vanes, and decreased in triad pier group experiments with vanes. The maximum sediment pile was developed at a space of approximately 40D from the center of the flume in 3PL- S75%, 3PL-S50%, and 2PL- S25% experiments.



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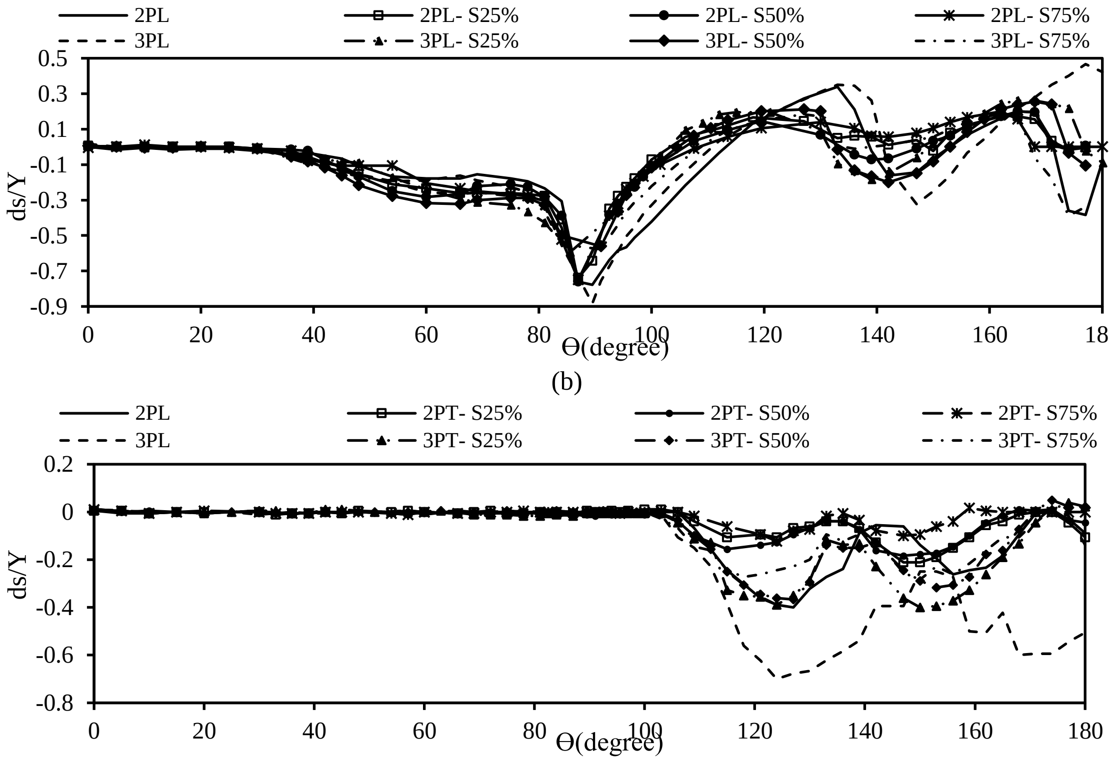


(b)

(c)

Figure 6. A sample of a longitudinal section at a distance equal to (a) 5, (b) 50, and (c) 95% of the channel width from the inner bank in experiments on longitudinal piers with and without submerged vanes

As is observed in Fig. 6(b), the longitudinal profile variations in mid-channel almost have the same pattern in both 2PL and 3PL experiments. Almost no alterations occurred in bed from the beginning of the bend to approximately 40-degree angle in every experiment. From approximately 40 to 80-degree angles, the bed underwent scour with a mild slope, the event which is due to down flow streams oriented towards bed. Then the scour slope increased at a distance of 80 to 90 degrees, which is due to local scour at the location of the vanes and the piers. After the 90-degree angle, sediment stemming from the vicinity of the piers and the vanes was developed at their downstream side and resulted in scour depth reduction. At a distance of about 30% of the end of the channel in experiments with vanes, two consecutive piles were developed in the same position with very little difference in height. By using the vanes in both pier groups, the height of the piles decreased in comparison with the piers without using vanes, and reductions in the height of the first pile in 2PL and 3PL tests were approximately 55 and 44% respectively compared to that in the test without any vanes. The second sediment pile in 3PL experiments with the presence of vanes decreased by approximately 50% in comparison with the piers without any vanes; however, in 2PL experiments, the pile height was the same whether with or without vanes. In this profile, reduction in deepest scour in both pier groups is approximately 29% in 3PL tests and 3.5% in 2PL in comparison with the piers-only tests. The second hole was formed at the downstream side, with its maximum depth occurring in 3PL experiments. As illustrated in Fig. 6(c), from the beginning of the channel to approximately 100-degree angle, no bed topography variations are observed. Thereafter, due to the flow turbulence present after the pier, and due to orientation of the flow, the bed underwent scour. Sediments transported from the outer bank were led towards mid-channel by lateral flows. Increasing the number of piers from 2 to 3 increased scour at the outer bank. By using the vanes and increase in their submergence ratio, the scour decreased. Two scour holes were developed in both pier groups without upstream submerged vanes, where the deepest scour of the first hole in 3PL experiment was almost 1.75 times that in 2PL. With installation of the vanes, maximum depth at the outer bank decreased in both pier groups, where the ratio of deepest scour in triad pier groups to twin pier groups was approximately 4.3 times.

With the groups of piers installed in longitudinal direction and the protective role of the upstream pier, a different scour pattern happened in comparison to that in a single pier. A comparison was made between twin and triad longitudinal pier groups in order to examine the variations resulting from these pier groups and the effect of raising the number of bridge piers on topography of bed. To this end, an instance of the lateral profile is depicted in Fig. 7. The lateral profile in Fig. 7(a) at the upstream region of the front pier illustrates that the maximum scour depth in 3PL experiment is approximately 1.5 times that in 2PL. In 3PL experiments accompanied by vanes, the scour decreased throughout the cross section. Therefore, the scour at the inner bank barely changed in comparison to the piers with no submerged vanes applied, and that at 60% of B from the outer wall in 3PL- S75% decreased by averagely 45% compared to 3PL experiment. In 2PL experiments with vanes, the scour increased at an approximate distance between 30 and 50% of B from the inner wall, and decreased by about 20% at the outer bank in comparison with that in 2PL experiment. The sediment pile at 10% of B from the inner wall in 2PL experiments with vanes was approximately 2.5 times that in 2PL experiment. As shown in Fig. 7(b), by using the vanes in the pier groups tests, the bed did not change at 35% of B from the inner wall in comparison with the experiment without any vanes installed. According to this figure, the vanes have reduced scour at the outer bank in both pier groups by approximately 30% in comparison to the piers without using vanes. A review of bed topography alterations at the inner bank reveals that in twin pier group experiments, increasing the submergence ratio raised the sediment level in comparison with the piers with no vanes applied. In 3PL experiments, the vanes have not had any effect on changing the sedimentary height. In Fig. 7(c), with reduction of scour in the second half of the channel width, it might be deduced that the flow velocity in proximity of the outer bank has decreased. The scour depth decreases more in experiments with vanes in the twin pier groups than in the triad pier groups. The bed lateral profile is almost the same from mid-channel line to the outer bank for every submergence ratio in 2PL experiments accompanied by vanes. It may be observed in Fig. 7(d) that increasing the number of piers from 2 to 3 in the longitudinal pier groups, the distance of 70% of B from the outer wall has undergone scour. Installation of vanes revealed an acceptable performance in reducing scour in this area. In experiments containing vanes in both pier groups, a slope of bed profile variations increased, when the submergence ratio reduced. For example, 2PL- S25% has the highest pile in near the inner bank, and the deepest scour near the outer bank among the twin pier groups. By reducing the submergence ratio in both piers groups, the sedimentation height near the inner bank and the deepest scour of outer bank increased in comparison with the experiment without any vanes.

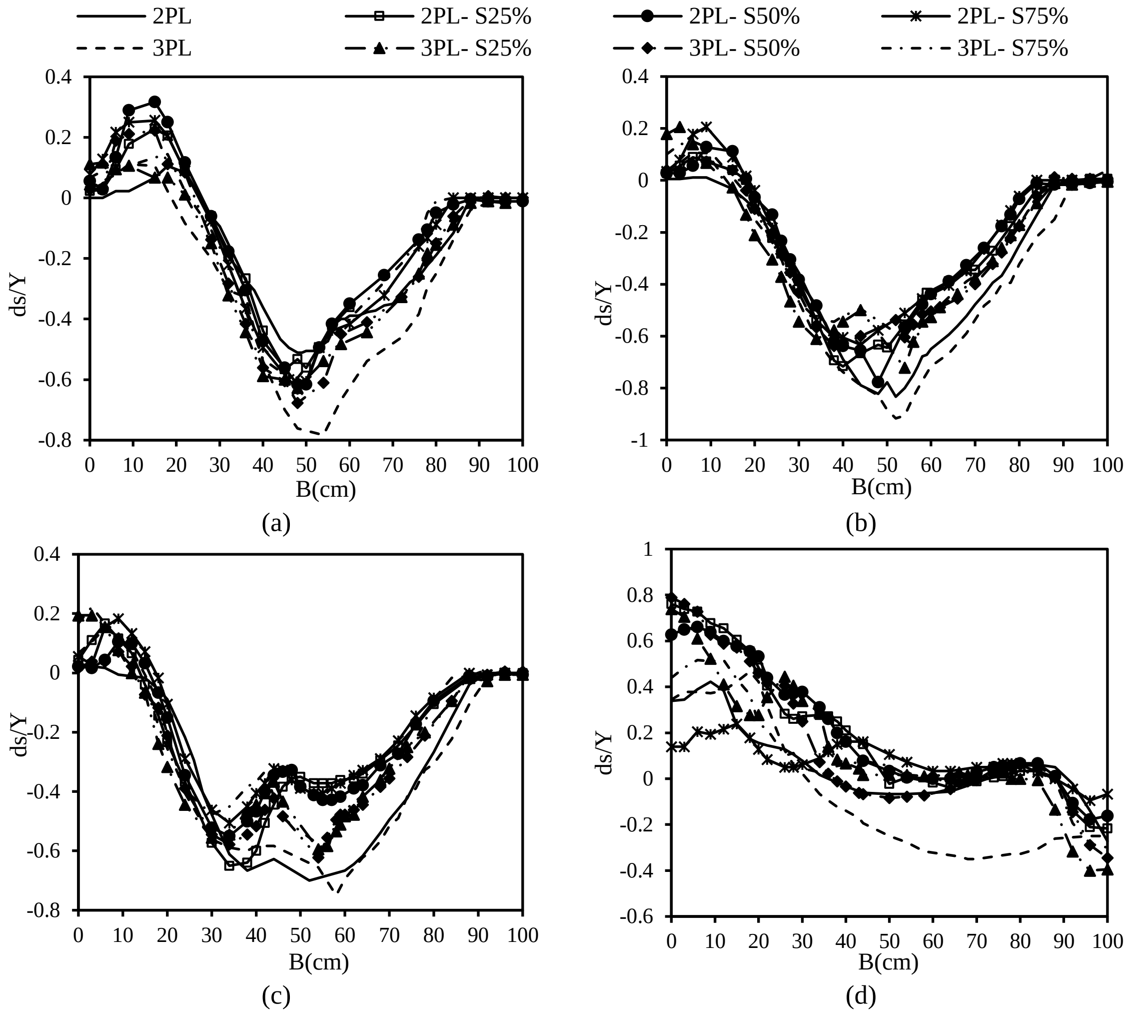
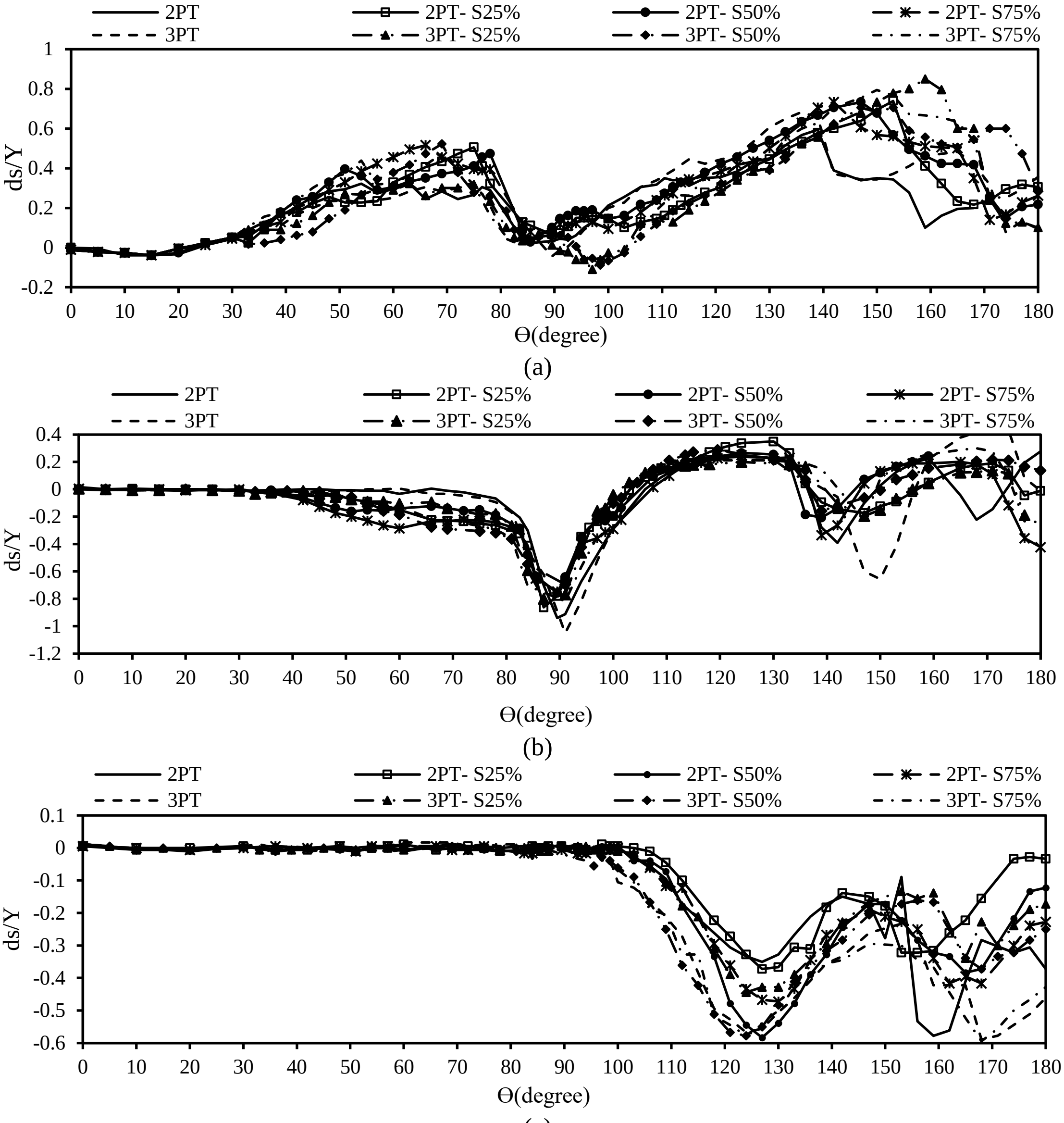


Figure 7. A sample of cross section at a distance equal to (a) 2.5 times the pier diameter towards upstream from the bridge piers location, (b) the center of the piers, (c) 2 times the pier diameter towards downstream from the bridge piers location, and (d) 42 times the pier diameter towards downstream from the bridge piers location in experiments on longitudinal piers with and without submerged vanes

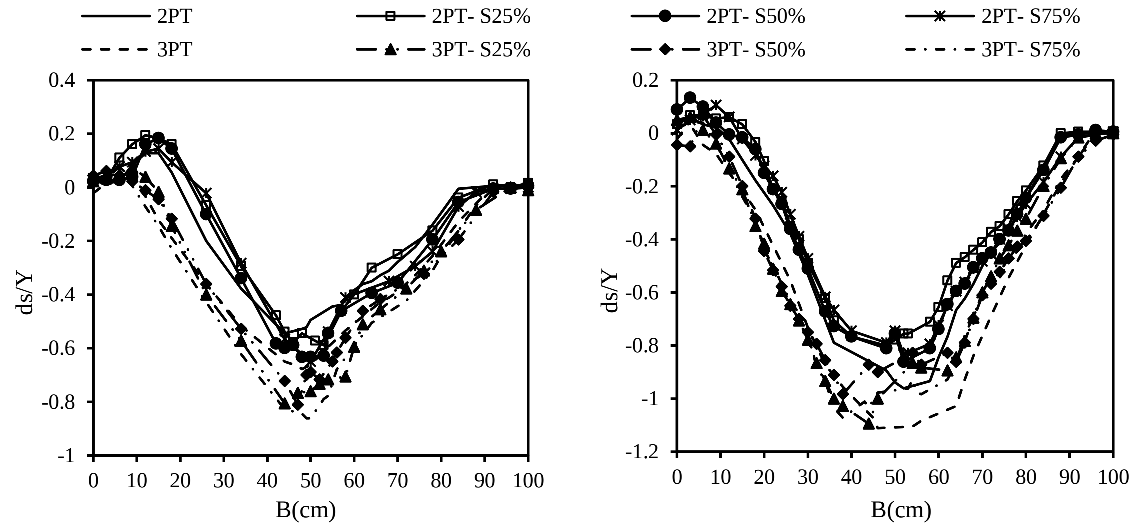
Figure 8 provides an instance of longitudinal profiles in the transverse pier groups. According to Fig. 8(a), the height of sediment bar along the bend increased by using vanes in both pier groups. Increasing the number of piers heightened the sediment pile. In the second half of the flume, the highest pile was created in 3PT- S25% experiment at a space of approximately 48D from the center of the channel in downstream route with a height of around 1.2 times that in 3PT experiment. The height of pile in the second half of the flume was approximately 1.6 times that in the first half in tests with pier groups placed transverse to the flow.



(c)

Figure 8. A sample of a longitudinal section at a distance equal to (a) 5, (b) 50, and (c) 95% of the channel width from the inner bank in experiments with pier groups transverse to the flow with and without submerged vanes

Figure 8(b) depicts the longitudinal profile in mid-channel. In 2PT and 3PT experiments, bed alterations from the beginning of the channel up to approximately 80-degree angle (equal to 55D from the beginning of the bend) were insignificant. The scour began almost from the 40-degree angle after installation of the vanes in these experiments. Increasing the number of piers from 2 to 3 in the transverse pier groups increased the highest scour in the vicinity of the piers by approximately 1.2 times. With submerged vanes utilized in twin transverse piers, the scour decreased compared to the piers with no submerged vanes installed when increasing the submergence ratio. Submerged vanes decreased the deepest scour by approximately 20% in 2PT, and 33% in 3PT experiments in comparison to the piers without any vanes, the event observed in 2PT- S75% and 3PT- S50% respectively according to this figure. The second hole was formed at a space of approximately 30D from the center of the bend in downstream direction, where its maximum depth in 3PT was almost 1.7 times that in 2PT. Reduction in the second scour hole depth by vanes in comparison with the piers with no vanes was observed in 3PT experiment more prominently than in 2PT. In 2PT experiment accompanied by vanes, the second scour hole decreased with the submergence ratio of the vanes reduced in comparison to 2PT experiment, and the second scour reduction was about 55% in 2PT- S25%. The second hole depth in every 3PT experiment with vanes was reduced by averagely 70% in comparison with the test with no vanes applied. In this profile, the maximum height of the pile at the end of the bend was about 0.4Y, the fact observed in 3PT experiment. According to Fig. 8(c), with transverse placement of the piers to the flow, the bed at the outer bank underwent scour with a maximum depth of approximately 0.6Y. In every experiment, two consecutive scour holes were formed in almost the same positions near the outer bank. In 2PT experiments using vanes, the depth of the first hole was heightened, where its maximum value in 2PT- S50% was approximately 1.7 times that in 2PT experiment. Submerged vanes reduced scour in 3PT experiments in the vicinity of the outer bank in comparison with the piers with no vanes due to reduction of the submergence ratio. Therefore, bed topography alterations in 3PT- S75% and 3PT experiments were almost the same, and the outer bank scour in 3PT- S75% was deeper than that in 3PT- S25%.Figure 9 compares instances of a few lateral profiles at the pier groups transverse to the flow.



(a)

(b)

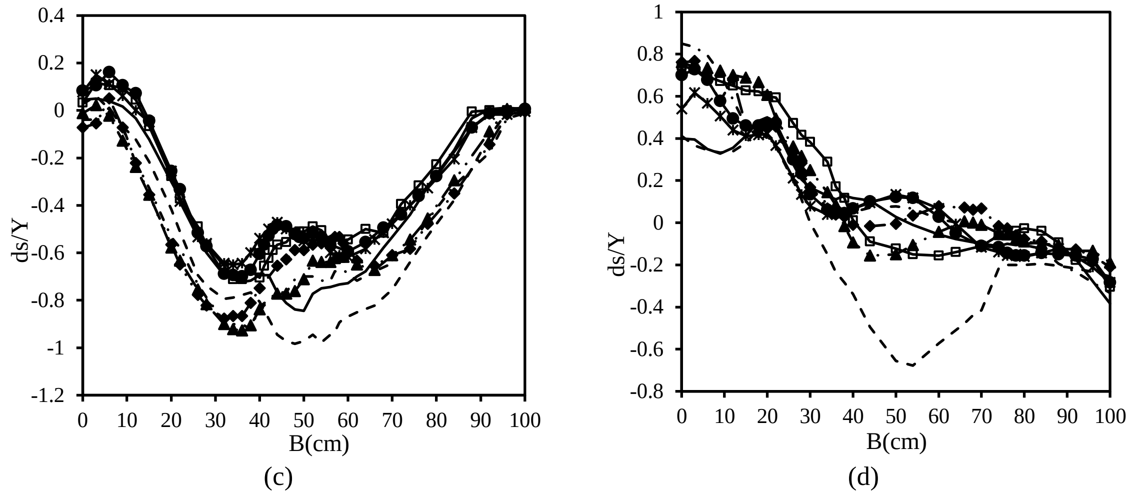
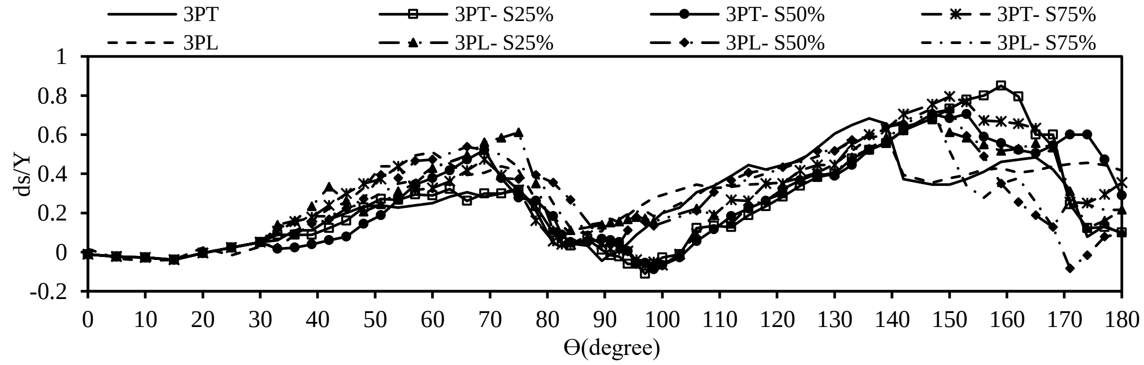


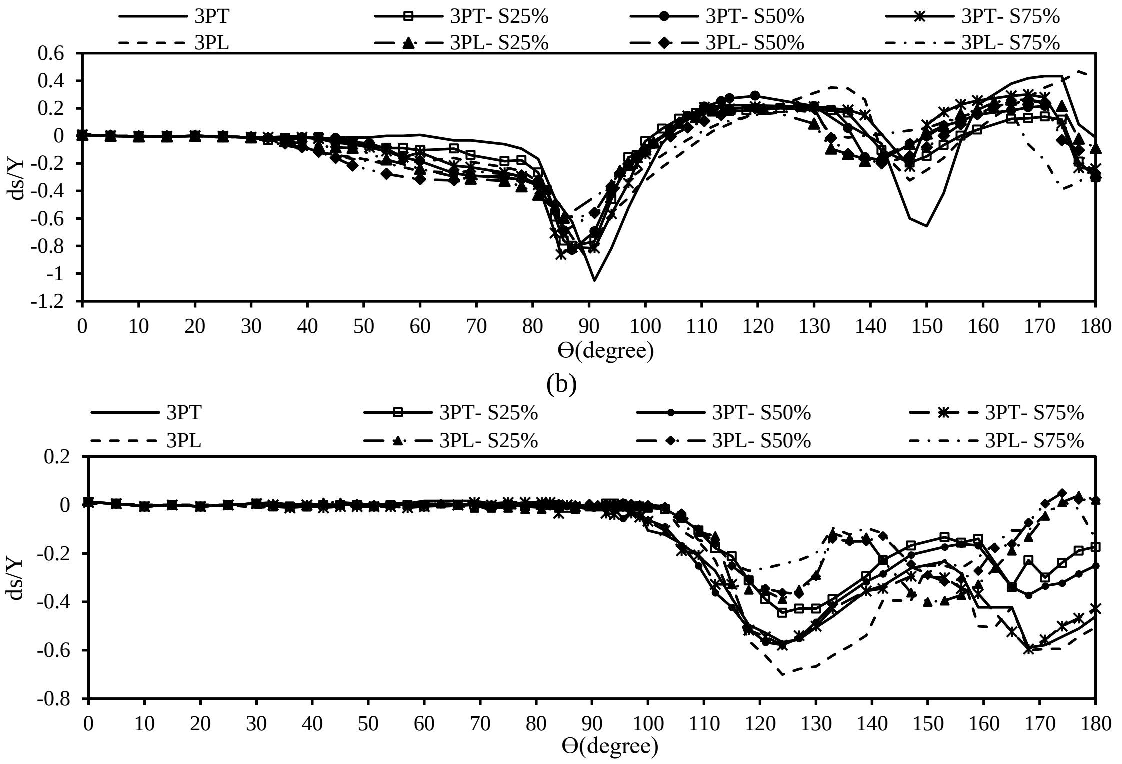
Figure 9. A sample of cross section at a distance equal to (a) 2.5 times the pier diameter towards upstream from the bridge piers location, (b) the center of the piers, (c) 2 times the pier diameter towards downstream from the bridge piers location, and (d) 42 times the pier diameter towards downstream from the bridge piers location in experiments with pier groups transverse to the flow with and without submerged vanes

As shown in Fig. 9(a), the scour depth at the location of the vanes increases at this section by averagely 32% in 3PT compared to 2PT experiment. This result was also 32% in 3PT experiments with vanes in comparison to 2PT experiments with vanes. With installation of vanes, the scour depth at this section was deeper than that in the case with no vanes installed. It may be concluded that the intervention of the vortices at the vanes with horseshoe vortices at the piers was intensified and led to sediment withdrawal from the upstream side of the piers. The bed topography alterations were the minimum in 2PT- S25% experiment in comparison to other experiments. As Fig. 9(b) illustrates, the scour depths in 3PT are averagely 1.5 times those in 2PT experiment. The scour hole slope at the inner bank was almost equal in 2PT and 3PT experiments accompanied by vanes. The submerged vanes in 3PT experiment reduced the scour about the groups of piers, and raised the scour at the inner bank. For instance, in 3PT- S50% experiment, the scour around the piers was reduced by averagely 20%, and that at the outer bank by averagely 15% in comparison with the piers with no vanes used. In 2PT experiment with vanes, the scour throughout the cross section decreased in comparison with the experiment with no vanes applied. 2PT- S50% and 2PT- S75% lateral profiles were almost the same at this section, and the scour profile in 2PT- S25% experiment was similar to those aforementioned experiments up to 50% of B from the inner wall. 2PT- S25% experiment presented an acceptable performance with 20% reduction in depth of scour at the second half of the channel width in comparison to other submergence ratios. In this pier group, the scour depths at the inner bank were almost equal for every submergence ratio. According to Fig. 9(c), bed topography alterations up to 40% of B from the inner wall are almost similar in both 2PT and piers experiments accompanied by submerged vanes. Then from this point to the proximity of the outer bank, installation of the vanes reduced scour in comparison with the piers with no vanes applied. In 2PT experiments containing vanes, the scour depths were decreased by averagely 35% in comparison to 2PT experiment. In 3PT tests, with application of submerged vanes, an increase occurred in scour depth up to 40% of B from the inner wall in comparison with the groups of piers with no vanes. Then the scour decreased after this point, where the highest reduction happened in the middle of the flume width. For instance, 3PT- S50% experiment had the most influence with approximately 37% reduction in depth of scour around the pier groups in comparison with the piers without using vanes amongst all 3PT experiments. As shown in Fig. 9(d), the patterns of bed topography alterations in every experiment in either presence or absence of vanes in twin transverse pier groups are almost similar at this section, and the slope of these variations is approximately 0.11. By raising the number of bridge piers from 2 to 3, scour was created in mid-channel, where its maximum depth occurred at the center of the channel at an approximate value of 0.7 times the flow depth at the channel's entrance section. Application of the vanes reduced scour at cross section compared to tests of absent vanes, and a sediment pile was created up to almost 40% of B from the inner wall.

Figure 10 provides a comparison between three piers placed in two different directions to flow with submerged vanes in order to examine longitudinal profile variations. Figure 10(a) illustrates the longitudinal profile close to the inner bank. In this profile, the highest pile along the channel occurred in experiments with vanes. In a comparison between the piles in 3PT and 3PL experiments, two major differences were observed in profile variations in these pier groups. In the first half of the bend, the highest pile in 3PL experiment was about 1.5 times that in 3PT experiment. With progress of sediments towards the outlet of the bend, it could be observed that the amount of sediments accumulated near the inner bank was higher in 3PT experiment than in 3PL test. By using the submerged vanes in 3PT experiments, the sedimentation height was reduced by averagely 37% in comparison with the piers-only test from approximately the location of the piers to 32D in downstream direction. Thereafter, the height of the piles in piers with vanes increased in comparison to the pier groups without using vanes. In 3PT experiments accompanied by vanes, up to approximately 160-degree angle, the sedimentation height was ascending, and the maximum sediment pile occurred in 3PT- S25%. In 3PL experiments, in either presence or absence of vanes, the longitudinal profiles were almost the same up to approximately 140-degree angle. Thereafter, the maximum sediment pile occurred in experiments with vanes for every submergence ratio of vanes with a value equal to approximately 0.7Y. With transverse installation of the piers to the flow as well as the presence of vanes in experiments, the sediment pile increased in comparison to the pier groups with no submerged vanes so that the maximum pile in experiments accompanied by vanes for transverse piers was about 1.2 times that for longitudinal piers.



(a)



(b)

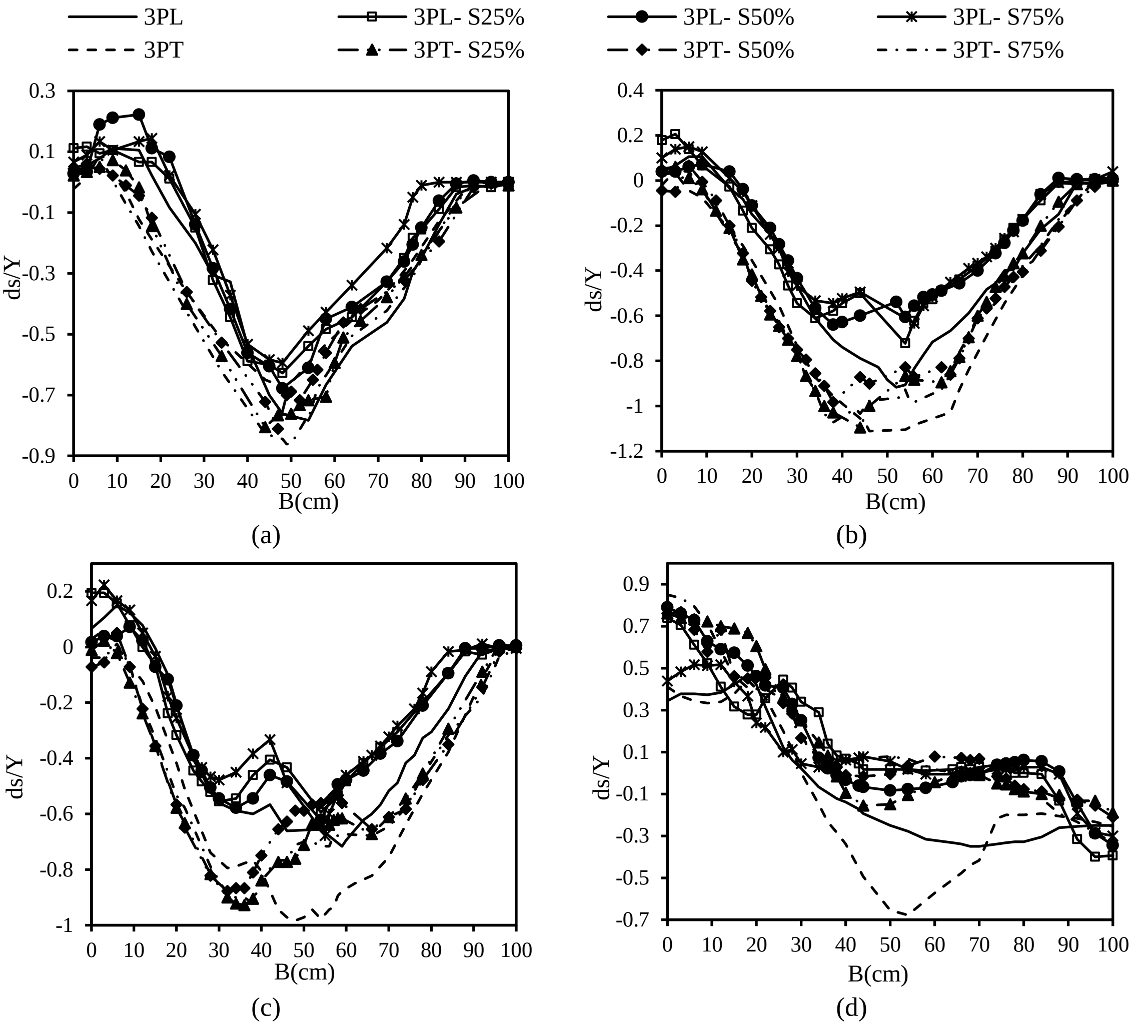
(c)

Figure 10. A sample of a longitudinal section at a distance equal to (a) 5, (b) 50, and (c) 95% of the channel width from the inner bank in triad pier groups experiments with and without submerged vanes

As shown in Fig. 10(b), with installation of the vanes in these pier groups, the deepest scour in 3PT tests reduced by averagely 22% and that in 3PL experiments by approximately 29% compared to the piers with no vanes used. When the triad piers were placed transverse to the flow, the scour hole slopes at the upstream and downstream regions of the piers in these experiments, as compared to each other, were almost equal, averagely 0.52 and 0.44 respectively. With longitudinal direction of the piers, the scour at the piers location decreased in proportion to that with transverse direction of the piers; however, its domain at the upstream region of the pier groups was extended to a distance of approximately 38D. The slope of scour around the piers in 3PL experiment extended at the downstream region of the piers with a slope of 0.25. The highest sediment pile at this section was created in 3PL and 3PT tests at a space of approximately 59D from the 90-degree position towards downstream. The second scour hole in 3PT and 3PL tests happened downstream at a distance of approximately 40D from the location of the piers. The deepest scour at transverse piers grew deeper by approximately 2 times that at longitudinal piers. By using vanes, the depth of the second scour hole declined by approximately 70% in 3PT experiments, and 50% in 3PL experiments for 50 and 25% submergence ratios in comparison to the pier groups with no vanes. In 3PL- S75% experiment, there was absolutely no trace of a second scour hole in mid-channel. According to Fig. 10(c), scour occurred at the outer bank at the downstream side of the piers in every experiment on triad pier groups. Two scour holes were observed in these experiments, and they occurred at almost the same point in 3PL and 3PT experiments. The deepest scouring of the first hole in 3PL was approximately 1.2 times that in 3PT, and the depths of the second hole were almost equal in both pier groups. Topography alterations at the outer bank corresponded in 3PT and 3PT- S75% experiments, but in 3PT- S25%, scour depths decreased by averagely 40% compared to 3PT experiment. In 3PL experiments accompanied by submerged vanes, the depth of scour reduced in comparison to 3PL experiment due to the rise in the submergence ratio of the vanes. The minimum bed alterations happened in 3PL- S75% test with about 65% reduction of the deepest scour of the hole in comparison to the test of absent vanes.

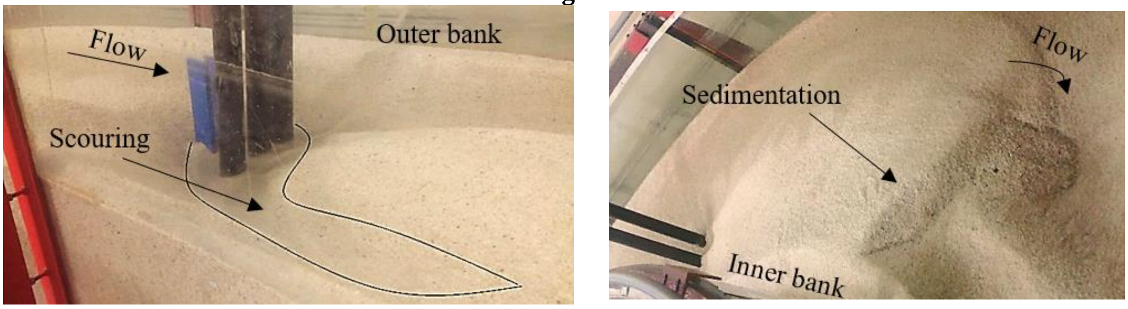
Figure 11 illustrates instances of a few lateral profiles in tests on triad pier groups in longitudinal and transverse directions at specific intervals. As it can be noticed in Fig. 11(a), after placement of the vanes in 3PL experiments, the scour decreased throughout the cross section in comparison with the experiment of absent vanes. In 3PT experiments with vanes, the scour occurred only at the 20% distance in the middle of the cross section. 3PL- S75% and 3PT-S75% experiments respectively had the minimum and the maximum scours amongst all the experiments in this cross section. As shown in the lateral profile in Fig. 11(b), the effect of installing vanes was acceptable in both pier groups, and the scour decreased throughout the cross section. With presence of vanes in these experiments, reduction of scour at the outer bank in proportion to the opposite bank was evident. The maximum bed scour happened in 3PT, while the minimum happened in 3PL- S75%. Hence, the largest volume of scour holes took place in 3PT experiments. After changing the submergence ratio in both group of piers in tests with vanes, the scour pattern almost remained the same. The decrease in the deepest scour of 3PT-S50% to 3PT was approximately 18%, and that of 3PL- S75% to 3PL was around 23%. As depicted in Fig. 11(c), the maximum scour occurred up to 40% of B from the inner wall in 3PT tests accompanied by vanes. Thereafter, the scour decreased up to the proximity of the outer bank in 3PT experiments with vanes in comparison to the 3PT experiment. According to Fig. 11(c), the submerged vanes has an acceptable performance in reducing scour depth, with the most significant reduction behind the piers occurring in 3PT- S50% experiment. Close to the outer bank, approximately the last 30% of B, changing the submergence ratio caused no changes in bed profile in 3PT experiments; however, in 3PL experiments, the acceptable effect of vanes on scour reduction was observed in comparison with the pier groups with no vanes. For example, 3PL- S75% had the lowest bed topography alterations in both pier group experiments. According to Fig. 11(d), the scour depths increased by placing the piers transverse to the water flow, and the scour at this section was evident in 3PT experiment. This figure is also indicative of the fact that the submerged vanes reduce the scour depth, yet increase the sediment pile created at the inner bank.

Figure 12 depicts instances of the bed in the experiments. These images specify the location of sediment accumulation and scour around the piers. Given the fact that the bend used in the research was sharp, the inlet flow into the bend had a significant effect on bed topography, and made for generation of lateral flows inside the bend and creation of piles at the inner bank. With placement of the vanes in a clockwise angle, the flow was directed toward the inner wall, and resulted in scour after the location of piers and close to the inner bank, the fact which is also shown in Fig. 12(a). Sediments stemming from the scour hole formed around the piers were moved in downstream direction and toward the inner bank by lateral flows inside the bend and caused formation of a pile in this region. Figure 12(b) is illustrative of this fact.



(a) (b) (c) (d)

Figure 11. A sample of cross section at a distance equal to (a) 2.5 times the pier diameter towards upstream from the bridge piers location, (b) the center of the piers, (c) 2 times the pier diameter towards downstream from the bridge piers location, and (d) 42 times the pier diameter towards downstream from the bridge piers location in triad pier groups experiments with and without submerged vanes



(a) (b)

Figure 12. (a) An instance of the water flow redirected towards the inner bank, and the scour at this area in 3PT- S75%, and (b) an instance of sediments redirected towards the inner bank in 2PT

Figure 13 illustrates the scour hole slopes about the piers. In this figure, the slopes towards the inner bank, the outer bank, and the downstream side are denoted by m_i, m_o, and m_d respectively. Moreover, the upstream slope is denoted by m_u. It may be explained that m_u is a slope against m_d slope, calculated from the vicinity of the piers towards the upstream side of them.

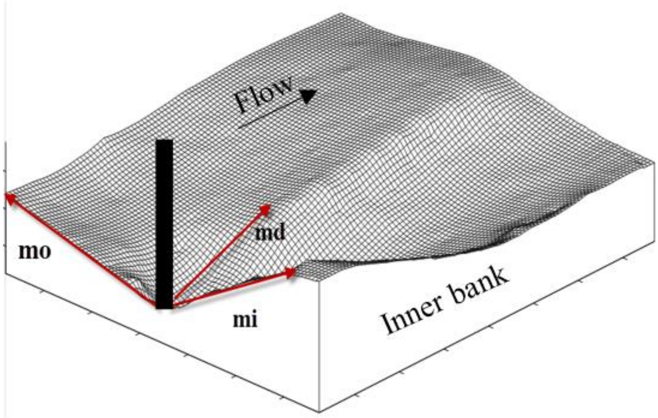


Figure 13. The scour hole slopes around the piers

Figure 14 is provided to examine the slopes of the generated scour.

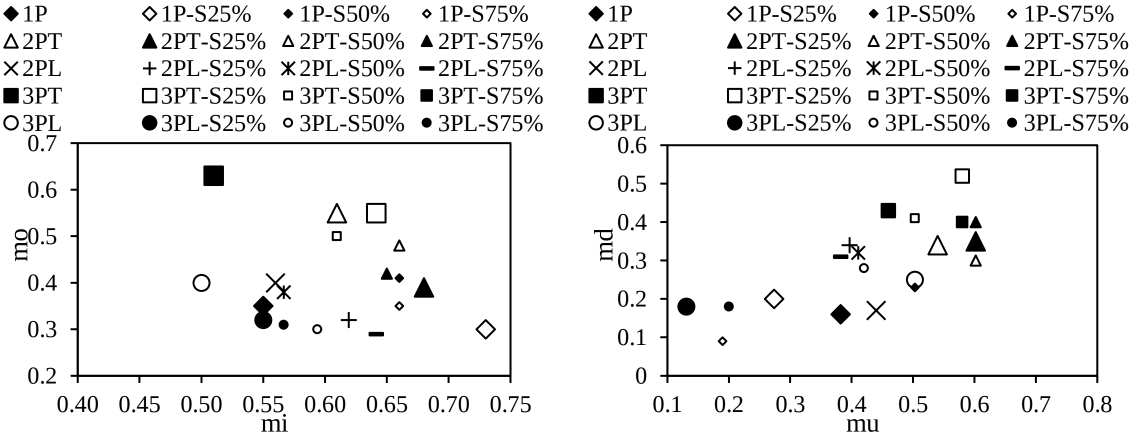
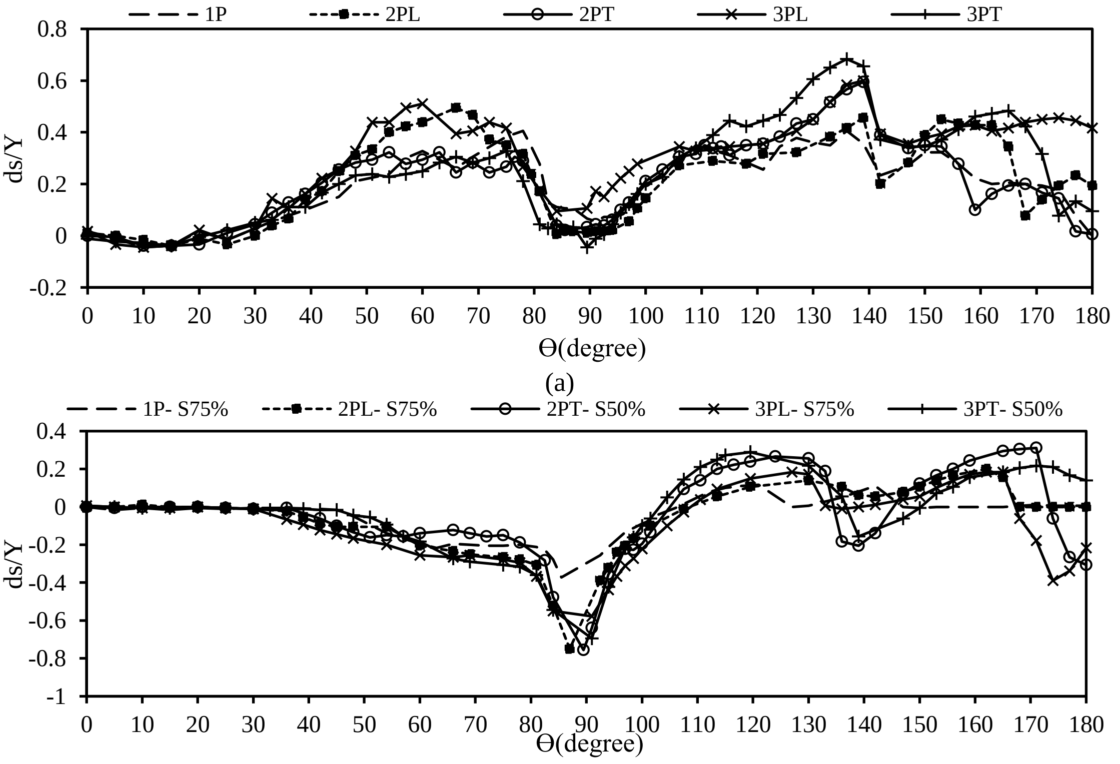


Figure 14. A comparison of scour hole slopes in the vicinity of the piers at (a) the cross section and (b) the longitudinal section of the channel

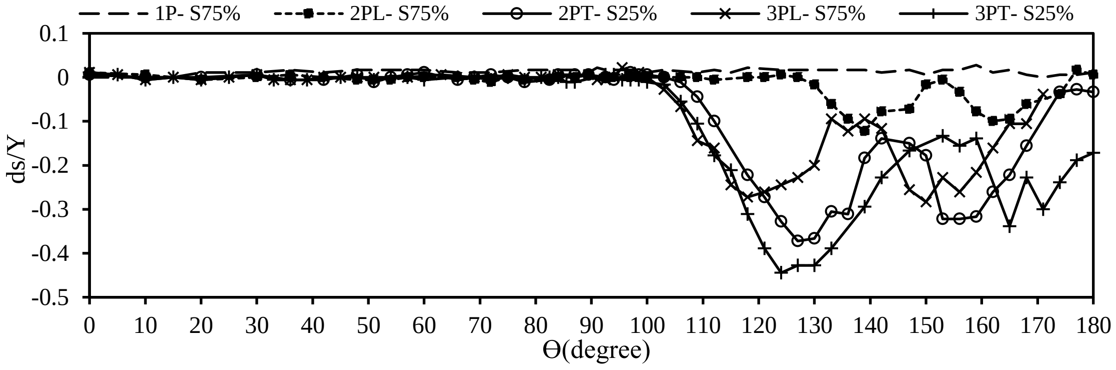
As shown in Fig. 14(a), the slope of scour at the inner bank (the mark) increases by using submerged vanes. The minimum slope of the inner bank, approximately 0.5, occurred in 3PT and 3PL experiments, and the maximum, approximately 0.73, occurred in 1P- S25%. The slope at the inner bank was approximately between 0.5 and 0.65 in most experiments. In other words, the inner bank underwent scour in an approximate horizontal angle of 26 to 33 degrees. The slope at the outer bank remained almost the same after changing the submergence ratio in 3PT and 3PL experiments using vanes. The slope at the outer bank was increased by reducing the submergence ratio in 2PT experiments using vanes. The minimum and the maximum scour hole slopes respectively happened in 2PL- S75% and 3PT. With transverse installation of the piers to flow, slopes of the outer and inner banks increased in comparison with those of longitudinal installation of the piers to flow. The vanes in twin and triad groups of piers reduced the slope of the scour at the outer bank. According to Fig. 14(a), by using the two vanes in the piers, the scour slope at the inner bank was greater than that at the opposite bank. As Fig. 14(b) revealed by using the vanes in 2PL and 3PL experiments, the slope of the upstream hole decreased, while that in 2PT and 3PT experiments increased in comparison with the piers without using vanes. The maximum upstream slope among all the experiments occurred in 2PT- S25%, 2PT- S50% and 2PT- S75%. The slope downstream remained almost the same after changing the submergence ratio in 2PT experiments using vanes. In 1P experiments, the minimum slope downstream occurred for 75% submergence, and the maximum slope downstream in 3PT experiments occurred for 25% submergence. In Fig. 14(b), 1P- S75% experiment has the mildest slope upstream and downstream amongst all the experiments. In transverse and longitudinal twin and triad pier groups, the submerged vanes increased m_u and m_d slopes.

To evaluate the overall results of the lowest amount of bed scour in each group of piers, bed topography variations of the experiment in longitudinal and cross sections are shown in Figs. 15 and 16, and images of scouring around these experiments is depicted in Fig. 17 . Fig. 15 shows the smallest bed topography variation in each of the pier groups compared to other experiments in longitudinal sections. It can be seen in Fig. 15(a) that the smallest bed topography variations occurred at a space of 5% of B from the inner wall in each group of piers in tests without vanes. The lowest and highest sedimentary piles developed in these experiments occurred in respectively single pier and triad transverse pier groups.



(a)

(b)



(c)

Figure 15. The smallest bed topography variation at a distance equal to (a) 5, (b) 50, and (c) 95% of the channel width from the inner bank in each of the pier groups compared to other experiments in longitudinal sections.

Figure 15(b) indicates that in the longitudinal section of the central axis of the channel, the minimum scouring happened in experiments with piers accompanied by vanes. The smallest longitudinal changes also happened in the one pier test with 75% submerged vanes compared to other tests, which also included the lowest scour volume. It can also be observed in Fig. 15(c) that bed topography variations of the outer bank in the one pier test with 75% submerged vanes were almost negligible. Then, the least variation occurred in the longitudinal piers experiments with 75% submerged vanes and in the group of transverse piers experiments with 25% submerged vanes.

Figure 16 suggests the smallest variation in bed topography in each experiment in each of the pier groups at cross sections. Images of the lowest bed scour in these experiments are presented in Figure 18 as examples. According to Fig. 16(a), it is observed that at a space of 2.5D from the pier towards upstream, the minimum scour occurred in tests without vanes except in the group of triad longitudinal piers where placement of 75% submerged vanes declined scour depth. According to Fig. 16, the least variation occurred at the site of the pier and its downstream sections in the group of longitudinal piers and the single piers in experiments with 75% submerged vanes, while in the group of transverse piers, the optimum submergence percentage differed for each section. In Figs. 16 (b) and 16 (c), the scour width in the 3PT- S50% experiment was larger than that in the other experiments. According to Figs. 16 (b) and 17 (d), the deepest scour in this experiment happened around the pier placed close to the inner bank.

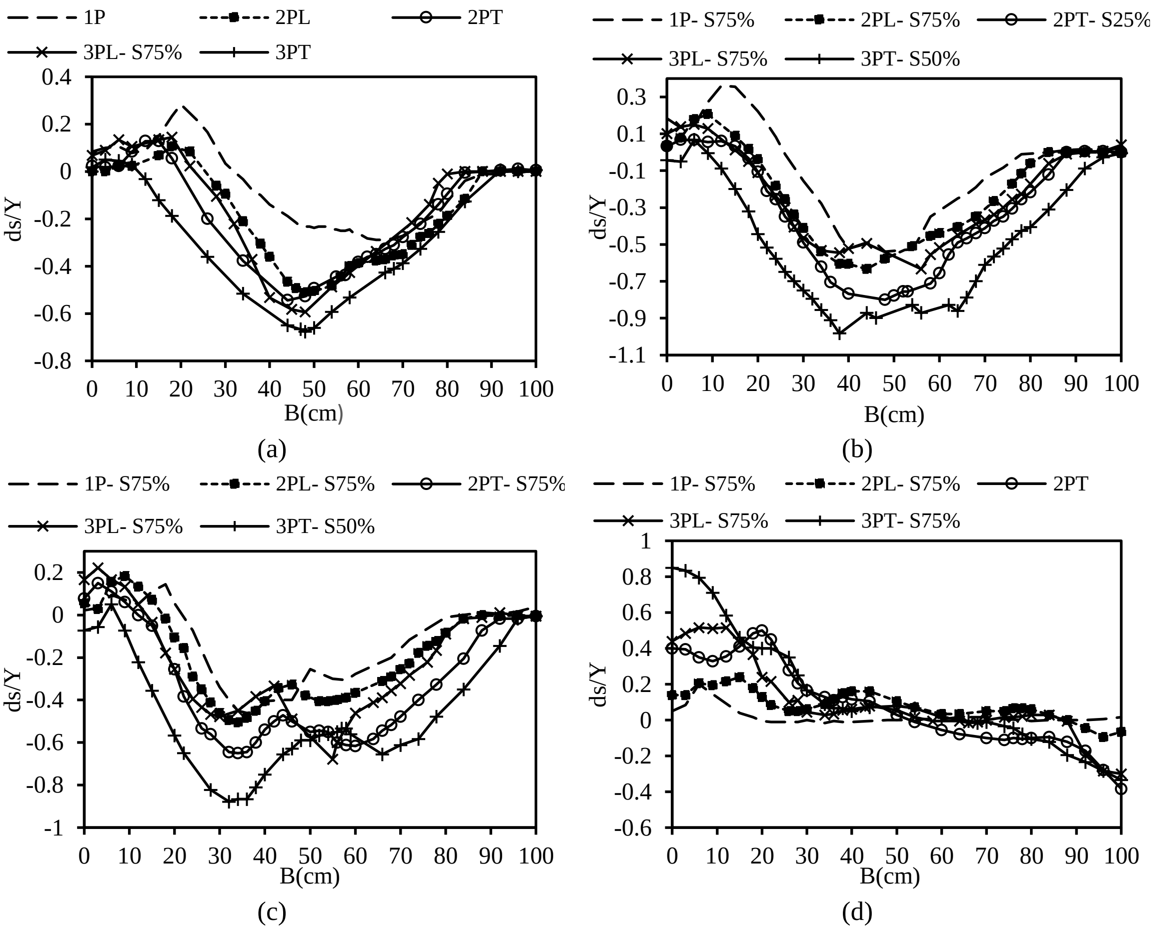
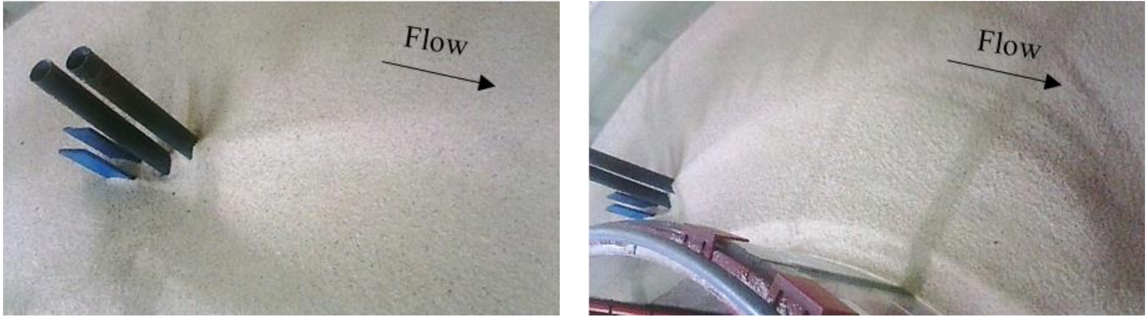
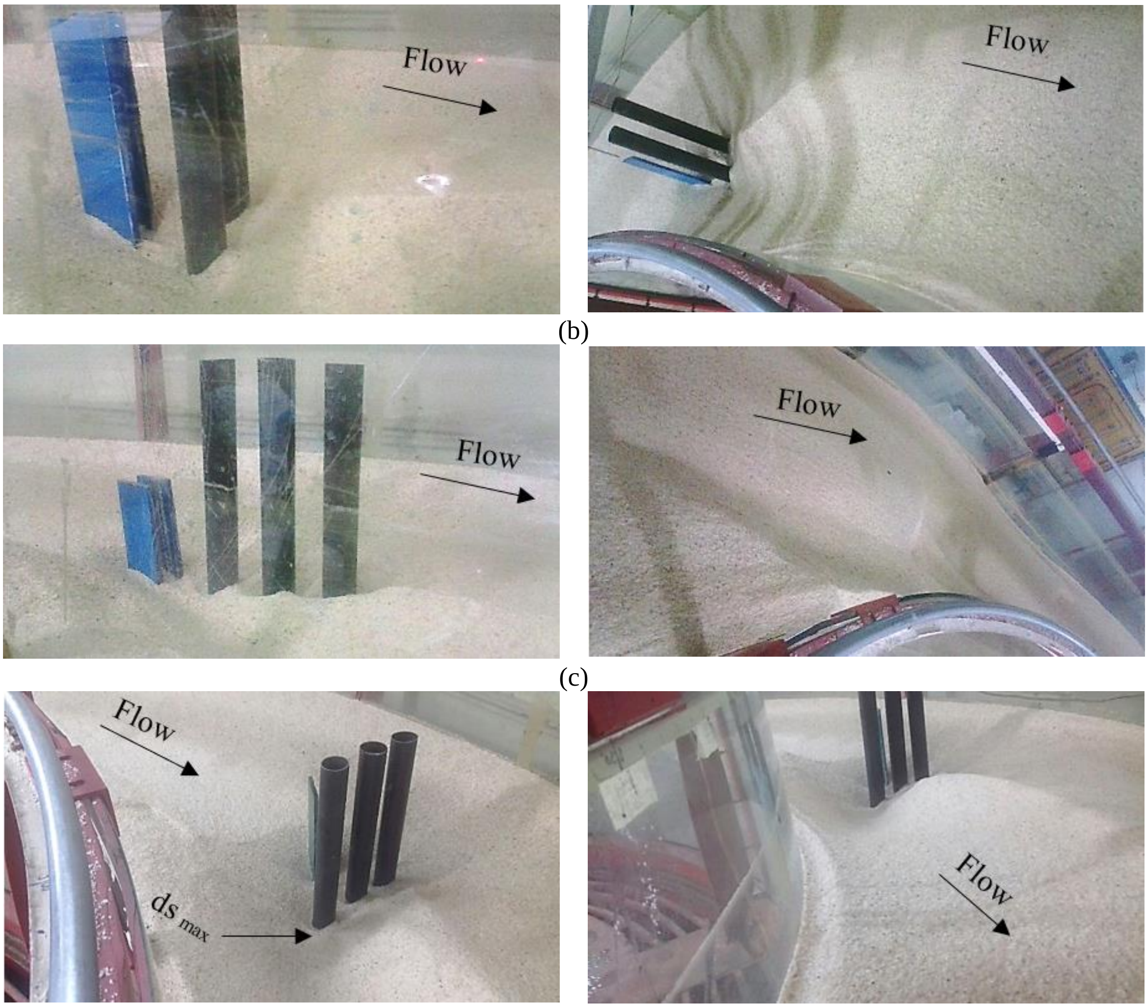


Figure 16. The smallest bed topography variation at a distance equal to (a) 2.5 times the pier diameter towards upstream from the bridge piers location, (b) the center of the piers, (c) 2 times the pier diameter towards downstream from the bridge piers location, and (d) 42 times the pier diameter towards downstream from the bridge piers location in each of the pier groups compared to other experiments in cross sections



(a)



(b)

(c)

(d)

Figure 17. A sample of the smallest bed topography variation around the piers and along the downstream straight path in each of the pier groups compared to other experiments (a) 2PL- S75%, (b) 2PT- S25%, (c) 3PL- S75%, and (d) 3PT- S50%

4. Conclusion

The following results have been obtained from the effect of the use of submerged vanes with different submergence ratios on the bed topography around the pier groups.

In the one pier experiments with double vanes, the scour at the outer bank reduced by increasing the submergence ratio. In the one pier test accompanied by 75% vanes, the scour depths at the pier (the cross-sections at the angle of 90 degree) decreased by approximately 35% in comparison with the experiment of nonexistent submerged vanes.

In experiments of twin piers with vanes, reducing the submergence ratio increased the sedimentation height in proximity of the inner bank in comparison with the pier groups without using vanes, and it increased even more with placement of the piers as transverse to the water flow. The maximum height occurred in the transverse pier groups with vanes for every submergence ratio, and in the longitudinal pier groups with 25% submerged vanes, it was observed with a height of approximately 0.7Y at a distance of around 35D from the center of the bend.

In longitudinal twin and triad pier groups, increasing the number of piers raised the scour at the outer bank in comparison to the test of absent vanes.

In transverse pier groups, the significant reduction of the deepest scour was observed to occur along mid-channel in the twin pier experiments with 75% submerged vanes, and in the triad pier experiment with 50% submerged vanes, by approximately 20 and 33% respectively.

After installation of the vanes, the slope of the scour hole at the inner bank grew sharper than that at the outer bank. The slope of the inner bank underwent scour with an approximate horizontal angle of 26-33 degrees.

In the single pier test with 75% submerged vanes, the upstream and downstream slopes decreased by around 50 and 43%, respectively, compared to the test without vanes. Vanes with 25% submergence ratio had the most significant effect on reducing the upstream slope by about 70% in the triad longitudinal piers compared to the piers without vanes.

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