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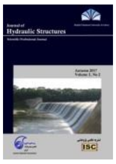

Experimental Study of the Effect of Base-level fall at the Beginning of the Bend on Reduction of Scour around a Rectangular Bridge Pier Located in the 180 Degree Sharp Bend

Mohammad Vaghefi[1]
Mohammad Moghanloo[2]
Danesh Dehghan[2]
Arsalan Keshavarz[2]

Abstract

Base-level fall in river beds occurs due to varying natural or unnatural causes. Base-level fall causes the change in the behavior of flow at the location of drop in base-level. In such situations, most of scour occur at the foot of the slope, and slope wall retreats in the upstream direction. This phenomenon widens the wall of the river bank, thus leading to its destruction. The amount of bed topography variations and scour around a rectangular bridge pier with an oblong nose located in the 90 degree angle of a 180 degree sharp bend was studied in this work by generating base-level fall at the beginning of the 180 degree sharp bend, and it was compared with a case without a base-level fall. The results indicated that in the case of base-level fall at the upstream side of the bridge pier, increase in flow depth, as well as reduction in velocity at the area around the pier, is observed, and the maximum depth of scour hole and the volume of scour hole around the pier respectively reduce by 73 and 97% in comparison with those in the case where no base-level fall occurs.

Keywords: 180 degree sharp bend, base-level fall, scour, bridge pier, topography.

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1. Introduction

As in all the other natural phenomena, rivers tend to preserve their sustainability system. Hence, any geometric or hydraulic change in rivers entails a dynamic response from the river in order to restore equilibrium. Such a response is at times too widespread and uncontrollable. Base-level drop and bed erosion in rivers result in an abrupt change in bed slope and generation of knickpoints, all leading to base-level fall. In geomorphology, knickpoints are a part of rivers

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[1] Civil Engineering Department, Persian Gulf University, Bushehr, Iran. vaghefi@pgu.ac.ir (**Corresponding author**)
[2] Civil Engineering Department, Persian Gulf University, Bushehr, Iran.

or channels, causing discontinuities on the slope and bed level of channels, and they occur vertically or inclined on channel bed.

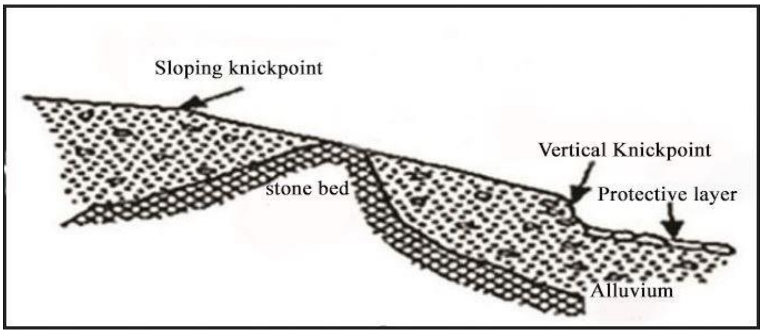


Figure 1. Inclined and vertical knickpoints (Julien, 2002)

Knickpoints make river beds unstable. River system confronts bed degradation and erosion at the upstream, and sedimentation at the downstream sides of the knickpoint. This process means expansion and migration of the knickpoint, damage to surrounding structures and lands, and bed topography variations. Several studies have been conducted on bed level variations before, a summary of which is presented in the following:

Brush and Wolman (1960) carried out an experimental study of the behavior of a drop in a bed constituted of non-cohesive material. The generated knickpoints in these experiments retreated from base-level fall. Consequently, the slope at the upstream side of the drop sharpened, while the downstream slope reduced. Transported sediments settled in the form of dunes at the downstream side of base-level fall. Holland and Pickup (1976) studied the knickpoint transport at the layered and cohesive sedimentary bed by creating a base-level fall in a laboratory flume. The results indicated that placing a thin sand layer through cohesive layers reduces the retreat velocity of the knickpoint in upstream direction. Begin et al (1980) examined knickpoint transport in upstream direction by making a base-level fall in a 15-meter-long laboratory flume with a 1% slope. The results revealed that under constant discharge, the velocity of knickpoint transport upstream is reduced in time. May et al. (1989) experimentally analyzed knickpoint erosion under the influence of hydrodynamics and geology factors. Results showed that knickpoint erosion depends on factors including knickpoint geometry, water velocity, and the pressure developed at the downstream side of the knickpoint, so that the occurrence of base-level fall as well as water velocity and pressure drop can help control bed erosion at the downstream side of the knickpoint to a great extent. Garcia and Parker (1993) conducted an experimental study of water jump resulting from a turbid flow by creating base-level fall in a channel. The results indicated that varying the level in a turbid flow (converting a supercritical flow into a subcritical flow due to water jump) leads to a great decrease in bed shear stress at the downstream side of the water jump. Migeon et al. (2011) studied the effect of changing the slope on turbid flows existing in nature by using field data. Their results demonstrated that the hydraulic jump caused by slope reduction leads to a drop in velocity of the turbid flow and in bed shear stress; thus the sediments of turbid flow in this zone suddenly settle. Turmel and Locat (2012) created a base-level fall in a laboratory flume in order to examine factors influencing the knickpoint displacement towards upstream under turbid flow conditions. The results suggested that upstream movement of knickpoint in a turbid flow occurs as a result of two erosive factors of turbid flow and the process of sedimentary material slippage at the upstream side of the base-level fall area. Cantelli and Muto (2014) conducted an experimental study on the effect of an abrupt drop at the base-level of the river on formation of knickpoints migrating upstream. The drop caused numerous staircase knickpoints on the bed of the channel, all of which retreated in upstream direction, and a hydraulic jump occurred on every stair. The results indicated that an abrupt change in base-level led to conversion of the supercritical flow into a subcritical flow at the downstream side of the slope, thus reducing bed shear stress of the flow at the downstream side of the slope. Grimaud et al (2016) experimentally examined the profile of river and knickpoint, and concluded that for a constant rate of base-level fall, knickpoints of similar forms occur. Retreat velocity, the front slope angle, and the hole depth at the downstream side of the knickpoint highly depend upon the structure of bed material. Also, time intervals between knickpoint formations depend on bed thickness and rate of base-level drop. Meandering rivers are the most common type of rivers in plan. However, a comprehensive study is yet required to be conducted on base-level variations in a bend.

The current study experimentally addresses a method of preventing destruction of downstream structures, and retreating erosion. In this method, the amount of local scour around a rectangular bridge pier with an oblong nose located in the 90 degree position is examined by dropping base level at the beginning of a 180 degree sharp bend and creating a base-level fall. Bed topography variations, material displacement at the beginning of the bend and the sideway banks, and the difference in the maximum scour, dimensions, and the volume of scour hole were studied.

2. Materials and Methods

Experiments were carried out in a bended channel with a 180 degree bend. Figure (2) depicts the channel. This rectangular channel is 1 meter wide and 70 cm high at the section. The straight upstream- and downstream-directed paths are respectively 6.5, and 5 meters long. The central curvature radius of the bend is 2 meters. With a ratio of R/B=2, according to classification proposed by Leschziner & Rodi (1979), this channel falls into the category of sharp bends, where R denotes the central radius of the bend, and B the channel width. Considering the research efforts by Chiew & Melville (1987), the standard deviation of sediment particles must be less than 1.3 in order to preserve the effect of non-uniformity of particles on scour. Also, according to experiments conducted by Raudkivi & Ettema (1983) aiming at prevention of ripple formation upstream, the average diameter of the particles must not be smaller than 0.7 mm. Hence, particles with an average diameter of 1.5 mm and standard deviation of 1.14 were employed in this laboratory. All the experiments were conducted under inception motion conditions with a ratio of flow velocity to critical velocity (U/U_c) equal to 0.97.According to Oliveto & Hager (2002), in order to prevent roughness effects, the water depth must exceed 20 mm; therefore, a discharge capacity of 70 liters per second and a depth of 18 cm were selected for conducting the experiments.

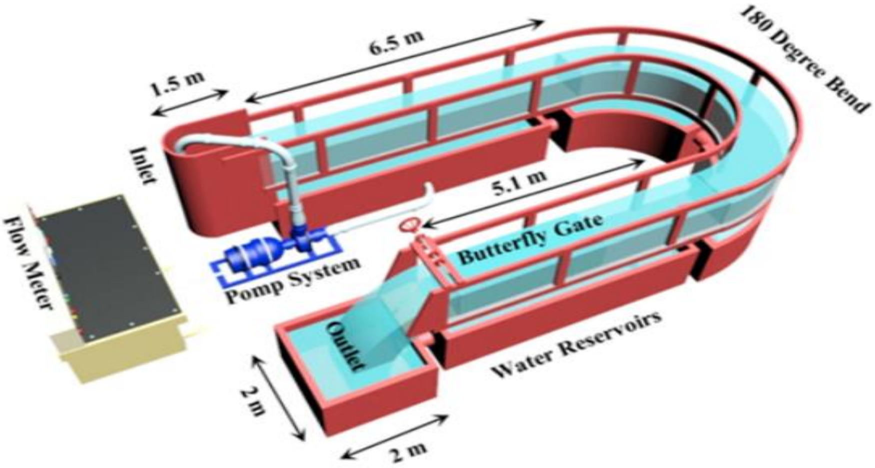


Figure 2. Laboratory flume employed by Vaghefi et al (2016)

As suggested by Chiew & Melville (1987), pier diameter must not exceed 10% of channel width, so that the effect of walls on local scour around the pier will fade. Additionally, as recommended by Melvill & Sutherland (1988), the length of the rectangular pier must be at least 3 times its width. Therefore, a 20 cm long, and 5 cm wide pier (L/b=4) was used for the experiments, where L denotes length and b is the pier width. The pier is made of PVC, and cut by CNC. Prior to the experiments, the whole bed was cleared by a metal plate connected to a cart moving on the rail, so that the upstream straight channel was covered by 30 cm of material, and the bed from the beginning of the bend to the end of the downstream straight path was covered by 20 cm of material. Then, the pump was turned on, and water was slowly let into the channel. As water level rose, when the sediments were evidently wet, and in a period of about 40 minutes, the motor rotation was gradually increased up to 70 liters per second. Also, at the end of the experiment, when the pump was turned off, and after 2 hours of full drainage, bed topography was collected by using ±1 mm laser meter. Figure (3) illustrates base-level drop at the beginning of the bend. Such a drop encompasses the beginning of the bend to the end of the downstream straight path. Base-level drop was achieved with a 20 degree angle (slope of 36%) in proportion to horizon, and a 30-meter-long sloped.

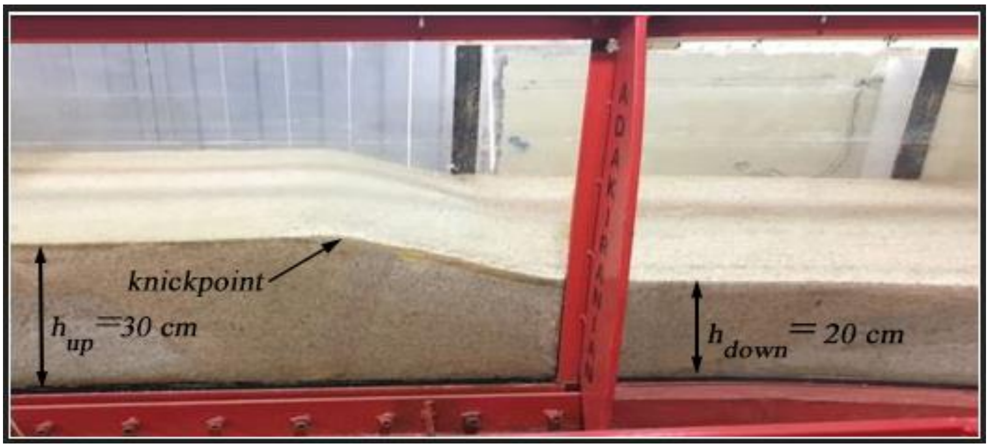


Figure 3. Base-level fall from the beginning of the bend to the end of the downstream straight path

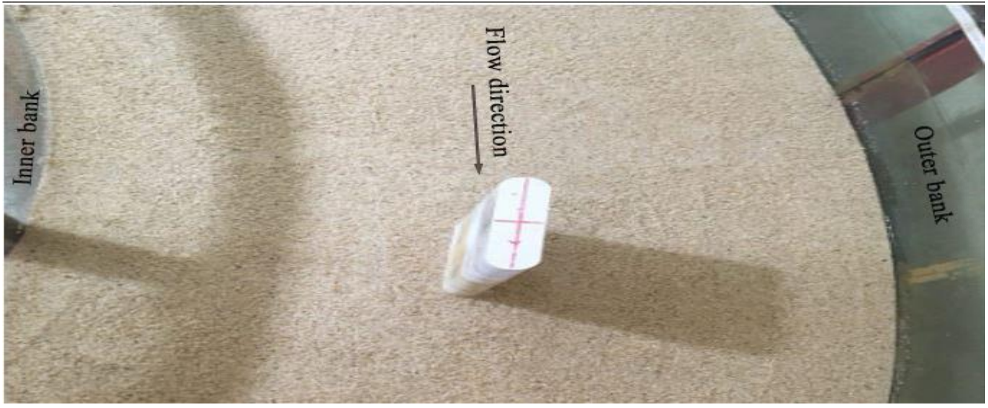


Figure 4. A view of the rectangular pier with an oblong nose, located in the 90 degree position in the 180 degree sharp bend

In the first stage, a 34-hour-long equilibrium time test was carried out on the oblong-nosed rectangular pier located in the 90 degree bend without changing the base level in order to determine the relative equilibrium time for conducting the experiments. In the equilibrium time test, increase in the maximum scour depth (d_s) was continuously measured in time. Measurement lasted until 4 hours of consecutive intervals did not reveal any perceptible change in the maximum scour depth. As is observed in Figure (5), approximately 95% of the maximum scour occurred in the first 15 hours of the experiment, which is in agreement with the results of Melville & Chiew (1999). Therefore, 15 hours was selected as the relative equilibrium time for conducting each experiment.

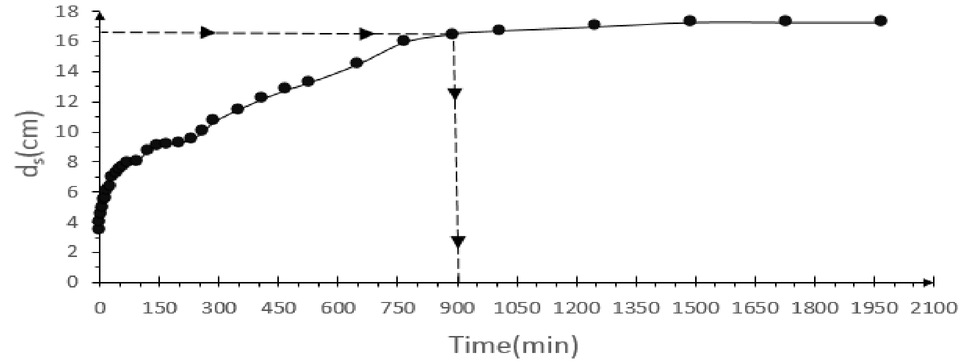


Figure 5. Variations of the maximum scour depth in time in the test on equilibrium time

Three tests were run in order to conduct the experiments and study the effect of base-level fall on reduction of scour around the rectangular bridge pier, and bed topography variations. First, a test was conducted in order to investigate bed topography variations in the bed without creating base-level fall, and with a bend empty of pier along the flow. This aimed to help identify the behavior of the bend when there are no base-level changes or existing hydraulic structures, under the influence of hydraulic conditions. The second test was run in order to examine bed topography variations in the bend by placing the rectangular bridge pier with an oblong nose in the 90 degree position of the bend without creating base-level fall.

This experiment aimed at studying the effect of placing the pier in this position on bed topography variations and amount of scour in comparison with the experiment on the bend without a pier. The third test was conducted with the aim of examining the effect of drop on bed topography of the bend and scour around the rectangular bridge pier. The results are addressed in the following section.

3. Results and Discussion

After determination of the relative equilibrium time, the experiment was conducted in an empty bend without a pier in order to provide a better understanding of flow behavior and bed topography variations in the bend. Bed topography after equilibrium time is presented in Figure (6). As is evident in the figure, bed topography in the bend is accompanied by sedimentation at the inner bank as well as erosion at the outer bank, due to formation of helical flows.

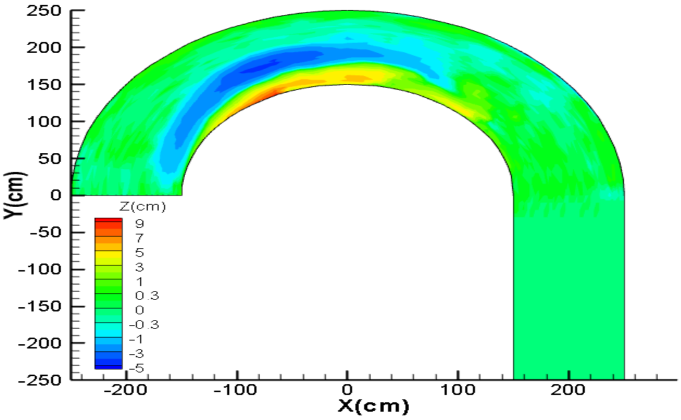
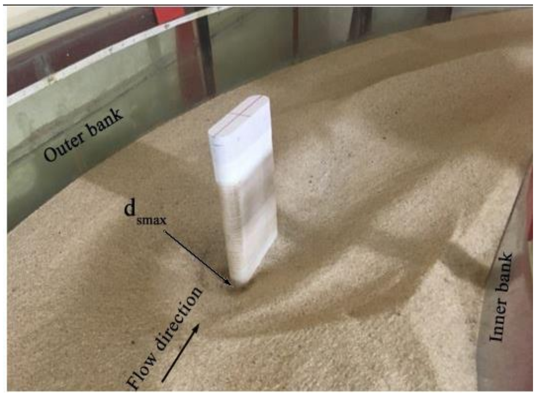
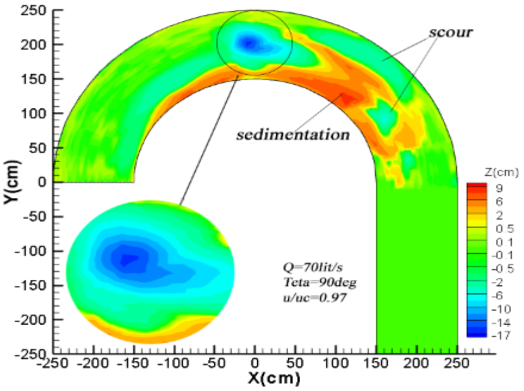


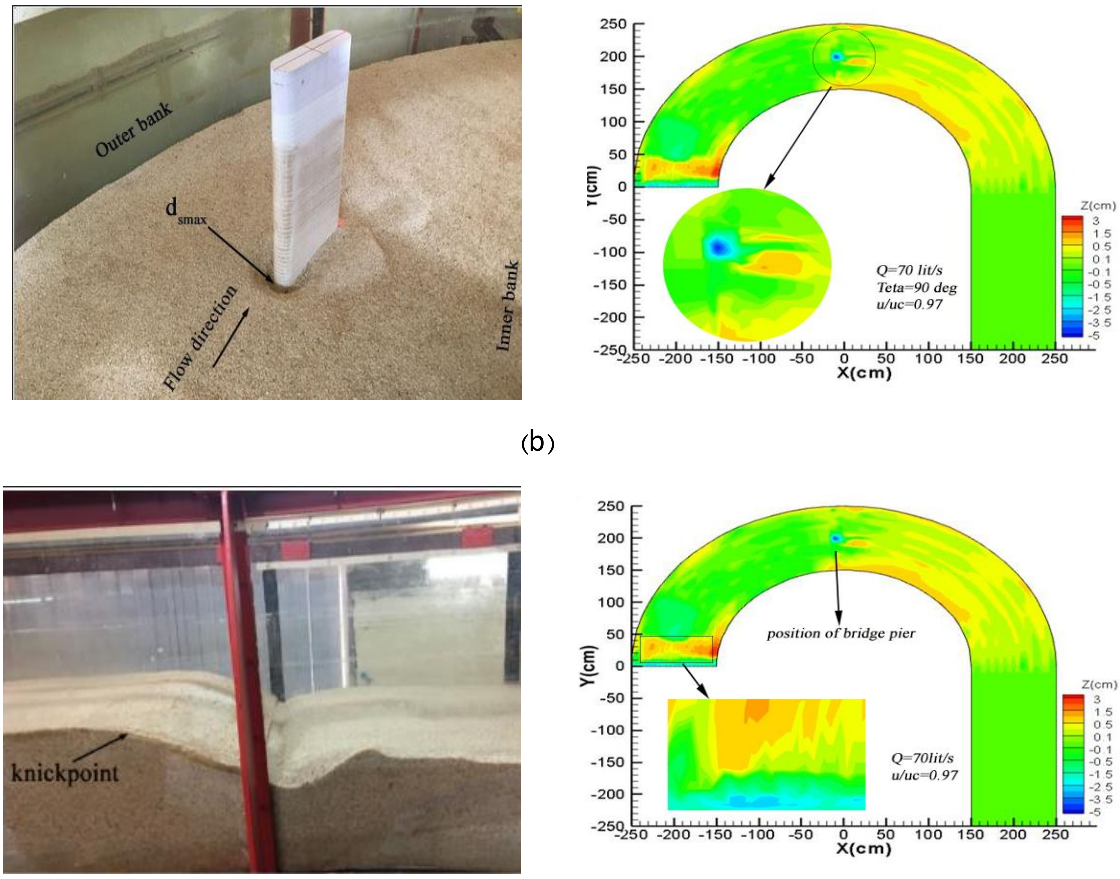
Figure 6. Bed topography variations in the case of empty bend (without a pier)

As noted in Figure (6), sedimentation in the vicinity of the inner wall began at the 35 degree and lasted until the 145 degree angle. The maximum sedimentation has occurred for 8.7 cm (equivalent to 0.087 times the channel width) in the 65 degree position. Further, the scour began at the 35 degree angle and lasted until the 95 degree angle, as is observed in the figure. The maximum scour also occurred for 4.2 cm (equivalent to 0.042 times the channel width) at the 65 degree angle. Results refer to the maximum degree of helical flow strengths at the 60 to 70 degree interval of the bend. Then, a better understanding of the effect of base-level fall in the presence of the pier on bed topography of the bend is achieved by conducting the following experiments and comparing their topographies with the experiment on the bend without a pier.





(a)



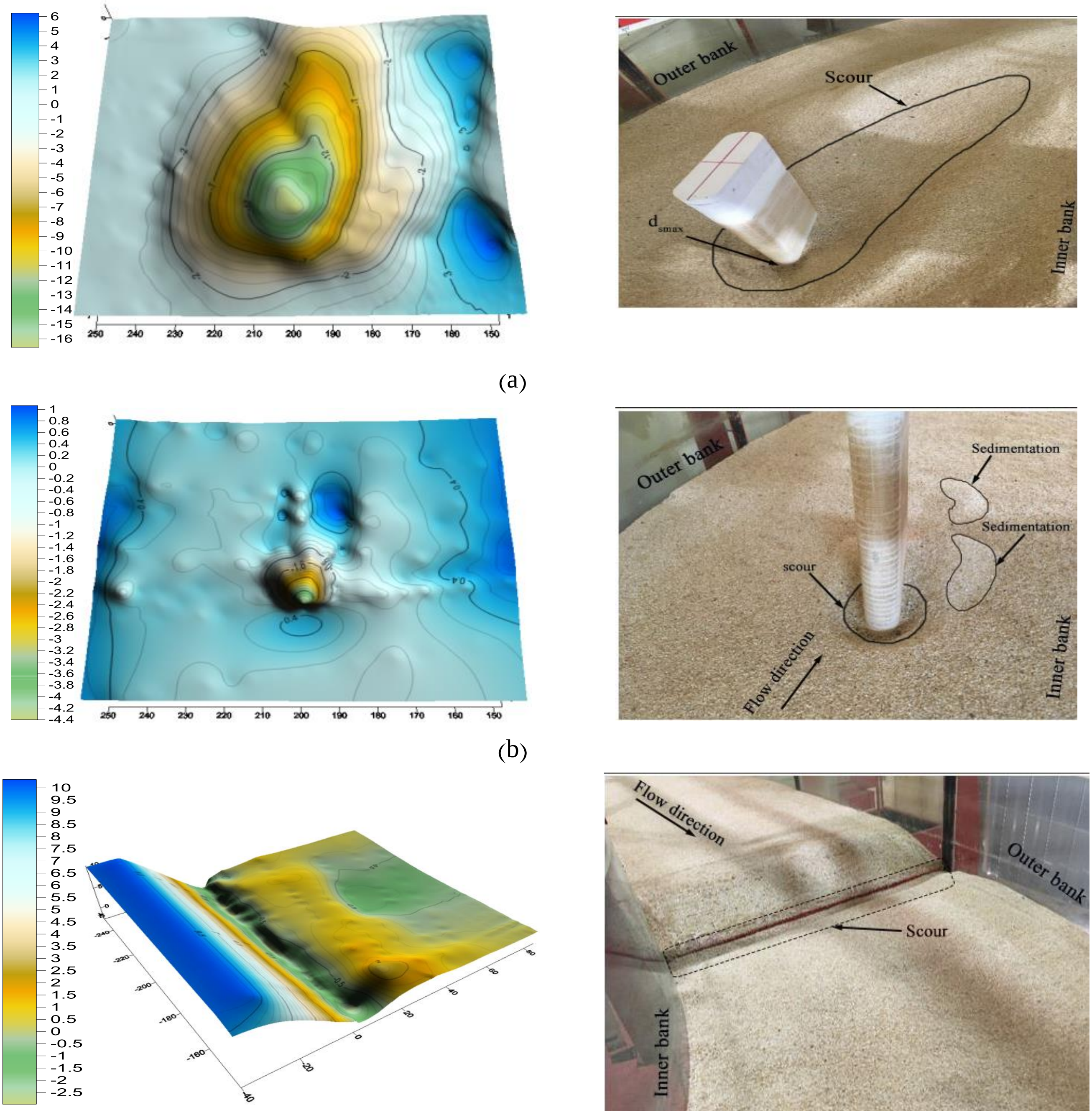
(c)

Figure 7. bed topography variations of the experiment on the oblong-nosed rectangular pier in the 90 degree position of the bend a) without base-level drop, b) with base-level drop, and c) for the hole created at the beginning of the bend due to water crossing the inclined surface

As is seen in Figures 7-a, and 7-b, the maximum scour at the pier nose (the 87 degree angle) occurred in both experiments. This maximum scour depth in the case of no base-level fall was equal to 3.3 times the pier width, and it was equal to 0.9 times the pier width in the case of base-level fall. Comparison reveals a 73% reduction in the maximum scour depth due to base-level drop. This could be due to the fact that, according to continuity equation, with base-level drop and raise in water depth, the velocity of water reduces upon entering the bend, thus reducing the strength of horseshoe vortices generated as a result of the collision of water with the pier and helical flows. This has led to a significant reduction in the maximum depth and width of scour hole, and decrease in sediments advancing towards the downstream side of the pier in the case of base-level drop. It should be noted that at the onset of the experiment at the beginning of the bend, a hole with the maximum depth of 0.6 times the pier width is created due to water crossing an inclined surface with formation of falling submerged flows (Figure 7-c).

Figure (8) shows scour holes created around the pier in the experiments with and without base-level drop, as well as the hole created at the beginning of the bend as a result of the falling submerged flow crossing the inclined surface. Surfer software was employed for the sake of more precise calculations in measuring the volume of the hole, and drawing the figures. As presented in Figures 8-a and 8-b, the volume of the hole created around the pier in the case of no base-level drop and in the case of base-level drop, is respectively around 28750 and 750 cm^3, equal to 230 and 6 times the third power of the pier width. Also, according to Figure 8-c, due to falling submerged flow crossing the knick point and the inclined surface, a wide hole of $3500cm^3$, equal to 28 times the third power of the pier width, is formed at the beginning of the bend.

Figure (9) presents an instance of cross sections along the bend. Figure 9-a presents sedimentation in the vicinity of the inner bank in the case of empty bend (without a pier), and the case without base-level fall. This sedimentation may be due to the effect of the onset of the bend and change in flow conditions under the influence of the sharp bend. Also, in the case of base-level fall, because the base-level fall created at the beginning of the bend extended all through the channel width, the width of the created hole in this area occupied 100% of the channel width, forming a wide hole. Figure 9-b depicts a transverse profile of the channel at a distance equal to 17 times the pier depth in the upstream direction (the 65 degree position). As is observed, in the cases of the bend without a pier, and no base-level fall, sedimentation in the vicinity of the inner bank is respectively 1.65 and 1.15 times the pier depth, the fact which is due to the effect of the secondary flows, their interaction with longitudinal flows, and formation of helical flows in the bend. The maximum scour in this section occurs in the case of the bend without a pier. This scour is 0.84 times the pier width, and occurs at a distance of 0.4 times the channel width from the inner bank. Also, the bed in this section undergoes little change in the case of base-level fall. Figure 9-c, the cross section is at a distance of 3 times the pier width towards the upstream side of the pier. This section undergoes the maximum sedimentation in the case of empty bend. Such sedimentation occurs at a distance of 0.05 times the channel width from the inner bank, at a height of 0.38 times the pier width. The maximum scour in this section occurs in the case of no base-level fall at a distance of 0.52 times the channel width from the inner bank at a depth of 2.68 times the pier width. This scour is a result of proximity to the pier, and presence of horseshoe vortices. This section also undergoes little change in the case of base-level fall. As provided in Figure 9-d, the scour hole, created at the pier nose, has occupied 60% of channel width in the case of no base-level fall. However, after creating a base-level fall, the created hole has occupied only 8% of channel width. Then it can be stated that base-level fall has led to 87% decrease in the width of scour hole. The maximum scour depth in the cases with and without a base-level drop is respectively 16.6 and 4.5 cm, equal to 3.32 and 0.9 times the pier width, i.e. a 73% reduction in the maximum scour depth due to base-level drop. The maximum sedimentation of this section occurs for the empty bend, equal to the pier width at a distance of 0.05 times the channel width from the inner bank.



(a)

(b)

(c)

Figure 8. Scour holes created a) around the bridge pier in the case of no base-level drop, b) around the bridge pier in the case of base-level drop, and c) at the beginning of the bend in the case of base-level drop

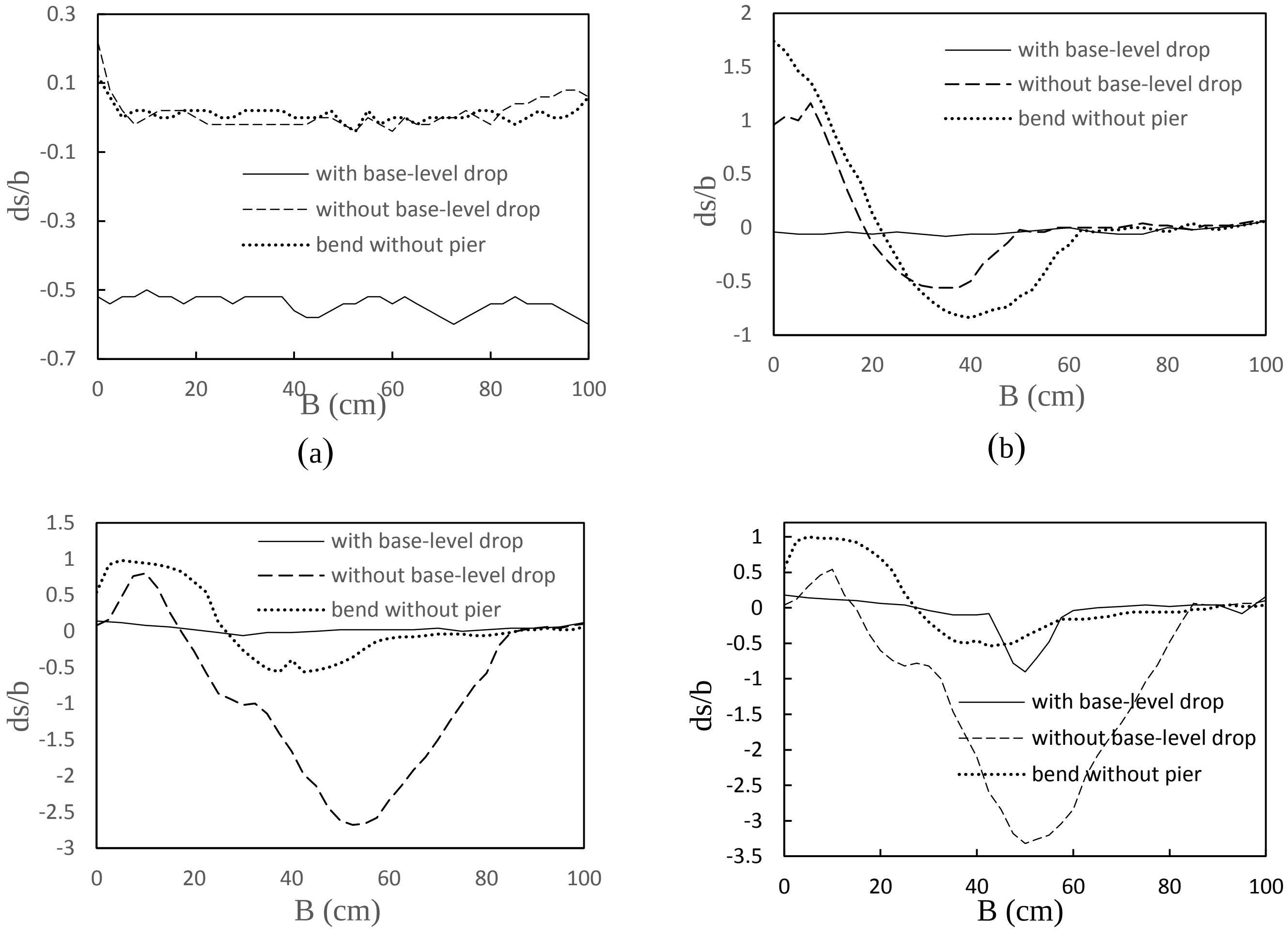
As is evident in Figure 9-e, sediments transported from the pier nose by horseshoe vortices pile up at a distance of 3 times the pier width at the downstream side with a height of 0.16 times the pier width in the case of base-level drop. However, in the case of no base-level drop, in the same situation, the scour hole lasts at a depth equal to 2.22 times the pier width. The maximum sedimentation at this section in the case of an empty bend has occurred 1.06 times the pier depth at a distance of 0.05 times the channel width from the inner bank. At a distance of 17 times the pier width downstream, at the 115 degree section, as in Figure 9-f, in the case of no base-level drop, sedimentation piles are formed at intervals equal to 0.1 and 0.6 times the channel width from the inner bank with a height of 1.28 and 0.86 times the pier width. Also, presence of secondary flows leads to creation of the secondary scour hole as deep as 0.66 times the pier width at a distance of 0.22 times the channel width from the outer bank. Under the empty bend conditions, the sediment pile is formed with a height of 0.6 times the pier width at a distance of 0.025 times the channel width from the inner bank, and the scour hole occurs as deep as 0.28 times the pier width at a distance of 0.3 times the channel width from the inner bank.

Table (1) presents the size of the scour hole nondimensionalized with the third power of the pier diameter, and the width of scour hole nondimensionalized with the channel width. According to this table, due to the base-level drop, the size and maximum width of the scour hole have reduced by respectively 97 and 87% in comparison to the case of no base-level drop.

Table 1. The volume of the scour hole nondimensionalized with the third power of the pier diameter, and the width of the scour hole nondimensionalized with the channel width

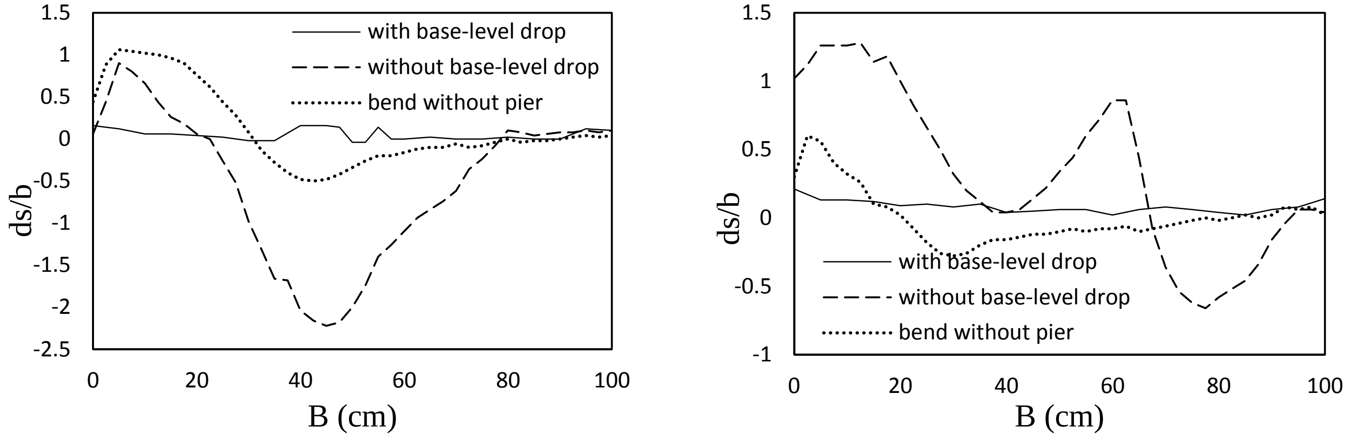
Scour hole position	Around the pier in the experiment with no base-level drop	Around the pier in the experiment with the base-level drop	Percentage of reduction
Ratio of hole volume to the third power of pier diameter	230	6	97
Ratio of hole width to channel width	0.6	0.08	87
Ratio of the maximum scour depth to pier width	3.32	0.9	73

Figure (10) illustrates an instance of bed longitudinal profiles at different distances from the inner bank. As can be seen in Figure 10-a, in the case of base-level drop, the sediments are carried from the base of the slope and piled up to the 30 degree section of the bend. Whereas, in the cases of no base-level drop and empty bend, sedimentation occurs from the 30 to 165 degree sections of the bend, in the vicinity of the inner bank. Its maximum height respectively occurs at distances of 1.5 times the pier width in the 135 degree angle, and 1.46 times the pier width in the 65 degree angle of the bend. As in Figure 10-b, in the case of base-level drop, the scour hole with a depth of 0.4 times the pier width is created at the beginning of the bend due to falling submerged flows crossing the knickpoint. In cases of no base-level drop and empty bend, the scour occurs from the 30 to 70 degree sections. In the case of an empty bend, the sediments carried with the maximum height of 0.48 times the pier width pile up in the 100 degree section. Whereas, in the case of no base-level drop, the presence of the pier results in occurrence of scour with a depth of 0.86 times the pier width in the 85 degree section. Sediments carried through this scour have piled up to the 140 degree section of the bend with the maximum height of 1.6 times the pier width. According to Figure 10-c, it is evident that bed properties up to the 75 degree section of the bend are the same under both conditions of with and without base-level drop in the longitudinal profile of the center of the channel. In the case of no base-level drop, the scour hole is formed from the 75 to 110 degree sections of the bend. The maximum depth of this scour is 3.32 times the pier width in the 87 degree section of the bend (the pier nose). The sediments washed at the pier nose are piled up from the 115 to 145 degree sections of the bend. The maximum height of sedimentation is equal to 1.24 times the pier width in the 125 degree section of the bend. However, in the case of base-level drop, the scour hole is formed from the 85 to 95 degree sections of the bend. Also, the maximum depth of this scour occurs in the 87 degree section of the bend (the pier nose), as large as 0.9 times the pier width. In the case of empty bend, the maximum scour depth of 0.66 times the pier width occurred in the 75 degree section of the bend. As is evident in Figure 10-e, in the case of no base-level drop, after the main scour hole, a secondary scour hole is formed at the distance between the 110 and 145 degree angles due to water falling from sediment piles.



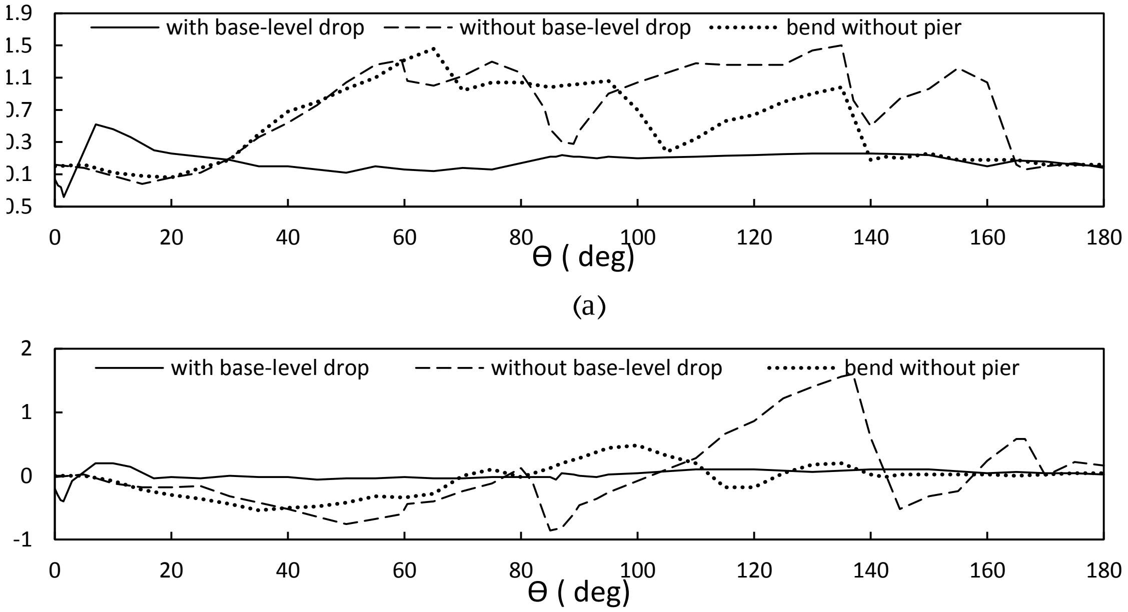
(a) (b)

(c) (d)



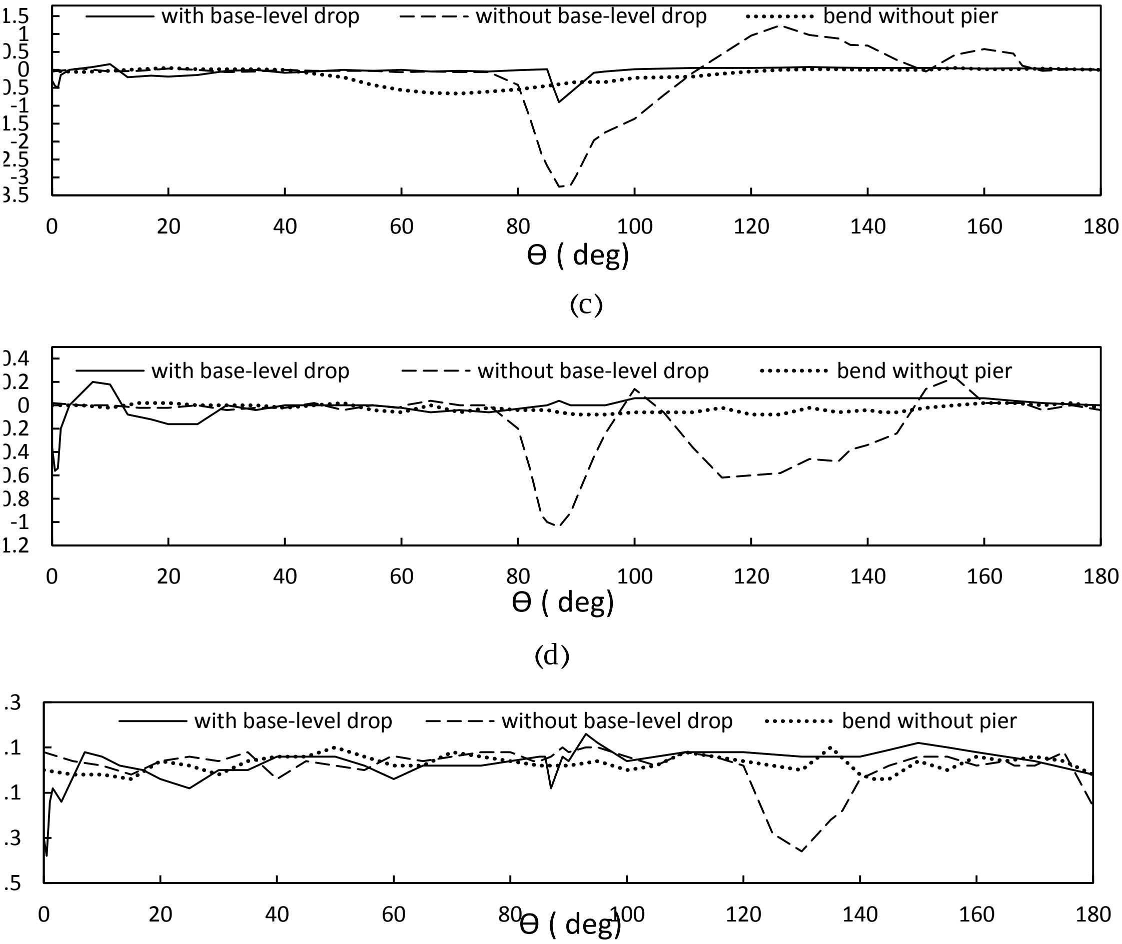
(e) (f)

Figure 9. cross sections of a) the beginning of the bend, b) 17 times the pier width at the upstream side of the pier (65 degrees), c) 3 times the pier width at the upstream side of the pier (85 degrees), d) the pier nose, e) 3 times the pier width at the downstream side of the pier (95 degrees), and f) 17 times the pier width at the downstream side of the pier (115 degrees)



(a)

(b)



(c)

(d)

(e)

Figure 10. longitudinal sections at distances of a) 5, b) 25, c) 50, d) 75, and e) 95% of the channel width from the inner bank

The maximum depth of the secondary scour hole, equal to 0.6 times the pier width, occurred in the 115 degree section. In the case of base-level drop at the beginning of the bend, a scour hole is created with the maximum depth of 0.56 times the pier width. In addition, the sediment pile with a height of 0.2 times the pier width is formed in the 7 degree section of the bend. In the case of empty bend, the bed variations along the bend are insignificant. According to Figure 10-d, in the case of no base-level drop, a scour hole with the maximum depth of 0.36 times the pier width is created in the 130 degree section of the bend, in the vicinity of the outer bank, under the influence of the secondary flows, and their interaction with the longitudinal flow and formation of a helical flow. In the case of base-level drop at the beginning of the bend, a scour hole has occurred with a depth of 0.38 times the pier width, and bed variations after this scour hole are insignificant to the end of the bend. Also, there have been few changes in the case of empty bend.

4. Conclusion

This paper addressed the effect of base-level fall on scour around a rectangular bridge pier located in the 90 degree angle of a 180 degree sharp bend. The most important findings are as follows:

The maximum scour occurred for 16.6 cm, equal to 3.32 times the pier width at the pier nose after installation of the pier in the intended position. However, with the position of the pier, after applying base-level fall, the maximum scour depth occurred for 4.5 cm, equal to 0.9 times the pier width, the fact which indicates a 73% reduction in the scour hole around the pier. In both cases, the maximum scour depth occurred at the nose of the pier. After creating a base-level drop, the volume of scour hole around the pier reduced by 97%, and a wide scour hole with a size of 28 times the third power of the pier width, and the maximum depth of 0.6 times the pier width formed at the downstream side of the slope.

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