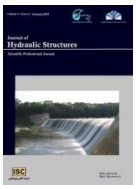
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Effect of Duration on Variations in Bed Topography and Water Surface Profile in a Meandering Channel

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Abstract

In this study, variations in water surface profile and bed topography along a meandering path were examined under different experiment durations. Although several studies have been conducted on sediment and scour in open channels, addressing temporal variations in meandering channels requires independent, merely experimental research. In this regard, a meandering laboratory flume consisting of two consecutive 180-degree bends was used in this study. The test was conducted under clear water conditions and in 6 different durations equal to 0.2, 0.4, 0.5, 0.6, 0.8, and 1 times the equilibrium time (240 minutes). Results indicated that at the downstream bend, lengthening the test time from 0.2 to 0.4, 0.5, 0.6, 0.8, and 1 times the equilibrium time added to the maximum scour by 70, 100, 115, 120, and 165%, and also increased the maximum sedimentation by 30, 25, 45, 45, and 45%, respectively. Moreover, with a comparison made between the average transversal water surface profile for 0, 120, and 240-minute duration tests, it was observed that when these transversal profiles were displaced from 45 degrees to 90, 135, and 180 degrees, the water surface at the inner bank was lowered by 2, 5, and 7% and that at the outer bank decreased by 2, 6, and 12%, respectively.

Keywords: Scour; Sediment Transport; Critical Velocity; Meandering River; Open Channel.

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1. Introduction

Meanders on river paths result in scouring and bed topography variations even in places where no hydraulic structures are installed [1]. Several researchers have so far carried out experiments on scour and sedimentation in meandering and curved channels; the following can be stated as instances:

Odgaard [2], Ervine et al. [3], Yen and Lee [4], Blanckaert and Graf [5], Spooner and Shiono [6], Blanckaert and Graf [7], Roca et al. [8], Kleinhans et al. [9], Wang et al. [10], Nicoll and Hickin [11], Barbhuiya and Talukdar [12], Uddin and Rahman [13], Xu and Bai [14], Termini [15], Mera et al. [16], Schuurman et al. [17], Liu et al. [18], Azarisamani et al. [19], and Moghaddassi et al. [20].

One of the factors influencing the maximum scour and sedimentation on meandering paths and bends in rivers is the effect of the scouring duration, as there are huge differences found in the time required to reach the equilibrium scour depth. Because there were time limitations on the tests, which took much longer than expected to conduct, most studies on bed topography variations were restricted to the equilibrium time. In the meantime, many researchers calculated and proposed definitions of the concept of equilibrium time under the presence of a bridge pier on a given river path. Chiew [21] selected a specific time as the equilibrium scour depth time in a channel hosting a pier, where, 8 hours into the experiment, the scour depth variations should be less than 1 mm. Vittal et al. [22] reduced the definition provided by Chiew [21] for the scour depth equilibrium time to 6 hours, and Kumar et al. [23] reduced it to 3 hours. In addition, Melville and Chiew [24] presented several equations for determining the scour depth's temporal variations at the front side of the bridge pier. They also put forth a formula for calculating the equilibrium time. According to the proposed equation, 50 to 80% of the scour occurs in a time interval equal to the initial 10% of the equilibrium time.

Despite the great number of studies carried out on equilibrium experiments in straight paths, there are a limited number of experimental studies on the effect of time on morphological variations in meandering and bent channels. So far, Hasegawa [25] in a 30-degree channel, Holzwarth [26] in a 70-degree channel, Whiting and Dietrich [27] in a 100-degree channel, and Termini [28] in a 110-degree channel have been conducted. Binns & da Silva [29-32] used their experimental results in a meandering channel with different curvature radii and different angles and proposed an equation for bed development time. Their experiments were carried out in a 21-meter-long and 7-meter-wide basin equipped with a water circulation system. Time was one of the parameters they studied, and they examined bed topography variations for different durations up to 108 minutes. Furthermore, their studies on 70-degree bends suggested that bed development in the initial stages of the tests occurred very rapidly. They observed that approximately 70 and 90% of the development happened when only 0.25 and 1.5 times the total bed development time had passed, respectively. Eventually, they determined the duration for bed development and generation of meandering channels using relevant formulation and experimental tests. Moreover, they predicted the development time for bed sedimentation in these channels with rigid walls under subcritical conditions [29-32].

Contrary to the few experimental studies available, many field studies of spatial and temporal variations in rivers were conducted, and a number of the most recent ones will be referred to here. Harrison et al. [33] studied morphological changes in a meandering river with a gravel bed in time. Their studies were carried out in an area named Robinson Reach in Merced River, California. Buehler et al. [34] considered spatial and temporal variations in a bifurcated river, the Taquari in Brazil, using the analyses on satellite images. Wang et al. [35] investigated bed variations in the Inner Mongolian in the Yellow River at different time spans. Bertalan et al. [36]

compared the spatial and temporal variations affecting the morphological changes of the Sajó River in Hungary in 8 different periods between 1952 and 2011. Saleem et al. [37] used field observations, topographic maps, digital elevation models, and multi-temporal remotely sensed data to study spatial and temporal changes of wall erosions in the Padma River, Bangladesh.

As it was observed, despite the great influence time had upon variations in bed topography in meandering channels, the number of studies conducted experimentally and exclusively in this regard is very small. Given that most studies conducted in this regard so far are limited to field studies by examining geographical data, an exclusive study about the influence of time on variations in bed topography in curved channels in the laboratory is deemed necessary. Therefore, the main aim of this study was to analyze the effect of time in a laboratory meander. Hence, the study is innovative in investigating variations in bed topography and water surface profiles in this meandering channel, which is composed of two 180-degree bends under clear water conditions. 240 minutes was considered as the duration of the tests [20]. In this study, first, the bed topography variations in a meandering channel were compared and examined with the aim of investigating the effect of temporal variations (at times equal to 0.2, 0.4, 0.5, 0.6, 0.8, and 1 times the equilibrium time). Then a comparison was made between the maximum scour and sedimentation as well as the area and volume of scour holes. Variations in bed longitudinal and transversal profiles were also compared at different points of time. In the end, the longitudinal and transversal water surface profiles were also presented at 0, 120, and 240 minutes, whose results were analyzed.

2. Materials and methods

As shown in Figure 1, the tests were performed in a curving channel with two successive mild bends. This channel was designed and constructed in the Hydraulics Structures Laboratory located in Bushehr, Iran. It consists of two straight ends at upstream and downstream sides, both of which are 8 meters long. Two 180-degree bends make the connection between them, both of which respectively have 3- and 4-meter-long inner and outer radii. The channel is 80 cm high and 100 cm wide. Silica sand with a diameter (d_{50}) averaged to 1.85 mm was selected for the channel bed to prevent dunes formation as recommended by Raudkivi and Ettema [38]. Its standard deviation was 1.2, and it covered the channel bed with a 30-cm thickness. As Oliveto and Hager [39] recommended, the water depth should be considered above 20 mm to prevent roughness effects. Considering the tests' conditions, the water depth was approximately 17 cm when running different tests. The discharge was considered constant and equal to 70 Lit/s throughout every test. Given the formula proposed by Neill [40], every test was run in a clear water condition for U/Uc=0.98, where U denotes the average flow velocity and Uc represents the threshold velocity. The use of laser bathymetry allowed the bed topography data collection. The data collection mesh grid all over the channel length was run at 1-cm distances at channel width (B) and at the determined angles in the channel. It should be noted that there is a bend upstream and another downstream in this meandering channel, and the origins of transverse coordinate, considered zero in this study, are the upstream outer bend and the downstream inner bend. Therefore, the value of 100 cm at channel width means the opposite of that, i.e., the upstream inner bend and the downstream outer bend, in every case.

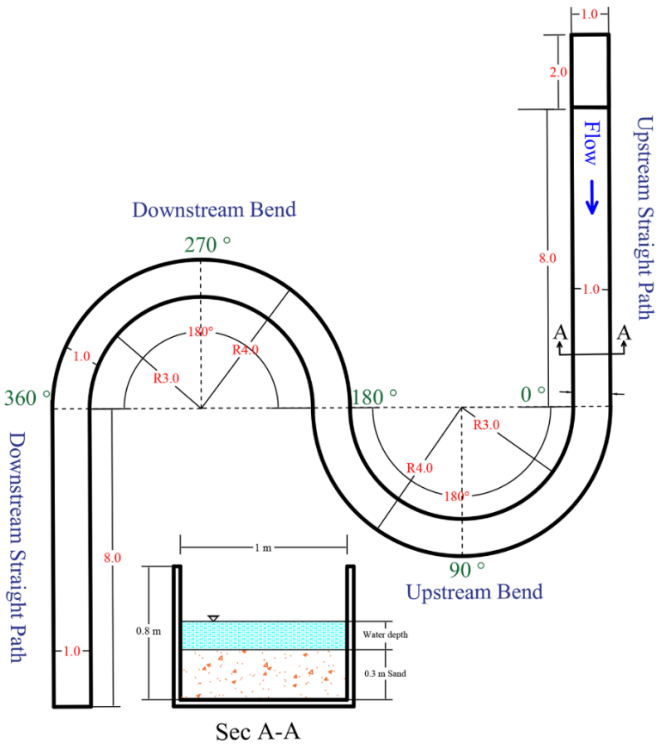


Figure 1. Schematic view of the meandering channel's plan and cross section as employed in this study.

According to the criterion provided by Chiew [21], the equilibrium time for running the tests was obtained to be equal to 240 minutes, in which 90% of scour depth occurred at this time. Therefore, to examine the effect of time on variations in bed topography and water surface profiles, the tests were run for durations of 48, 96, 120, 144, 196, and 240 minutes, equal to 0.2, 0.4, 0.5, 0.6, 0.8, and 1 times the equilibrium time (t_e). The scour equilibrium time graph is illustrated in Figure 2. This figure is associated with the equilibrium time test with the bridge pier in a 180-degree bend; it is selected to be comparable and referable to research by Chiew [21], which is conducted on the equilibrium time with the presence of a bridge pier. When conducting this test, it was observed that bed topography variations were trivial after 4 hours, and the equilibrium was established. To make the results obtained from this study also comparable to the scour results related to the case where a bridge pier was present, the selected time intended for performing these tests, where no piers are installed, is also 4 hours.

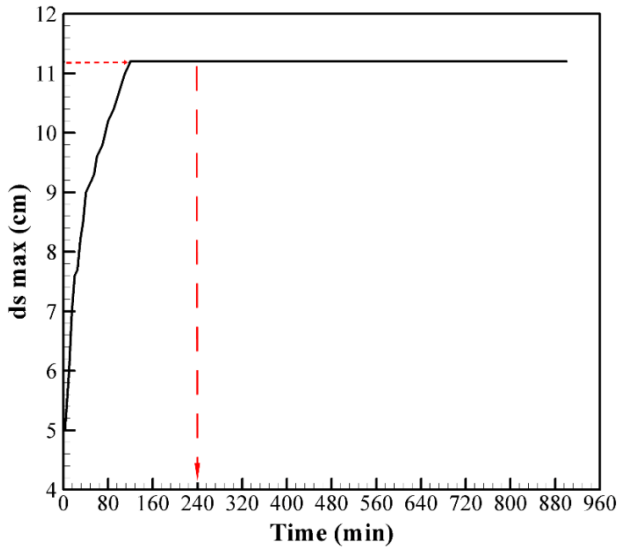


Figure 2. The variations in scour depth versus equilibrium time for 15 hours duration.

3. Results and discussion

Flow pattern complexity in meandering channels is due to not only its turbulence and three-dimensional nature but also variations in topography and water surface level; this study addressed both of these parameters under the effect of temporal variations.

3.1. Scouring and sediment patterns in the meandering channel under the influence of temporal variations

3.1.1. Bed topography variations

Figure 3 illustrates bed topography variations in tests with durations equal to 0.2, 0.4, 0.5, 0.6, 0.8, and 1 times the equilibrium time (t/t_e=0.2, 0.4, 0.5, 0.6, 0.8, and 1) in the meandering channel. A comparison between Figures 3-a and 3-b (t/t_e= 0.2 and 0.4) indicates that the upstream bend secondary flow [41] did not yet have enough strength to create any changes in bed topography in this bend. In contrast, partial changes in bed topography are found in the upstream bend's lower half in Figures 3-c to 3-e for t/t_e=0.5 to 0.8 by increasing the duration. In the end, the maximum variations in the upstream bend occur in the 240-minute test (t/t_e=1) in Figure 3-f; however, in every figure, the maximum topography changes take place in the second bend. Therefore, the maximum scour depth and sedimentation in every case provided in this study have been nondimensionalized using the equilibrium time.

As visibly observed in Figure 3-a, the greatest bed topography variations occurred approximately between 180 and 270 degrees in the downstream bend. The maximum dimensionless values of scour depth and sedimentation height at separate values of 0.38 at 183 degrees and 0.69 at 215 degrees occurred at a distance of 5%B from the inner bend. The scour holes also occurred within the ranges of 180 to 190 degrees (at a distance of 5%B from the inner bend), 200 to 210 degrees, and 240 to 270 degrees (at mid-channel).

It is observed in Figure 3-b that the maximum dimensionless scour and sedimentation respectively occurred at values equal to 0.65 at 185 degrees and 0.90 at 225 degrees. Increasing the test time from t/t_e=0.2 to 0.4 added to the maximum values of scour depth and sedimentation

height by respectively 70 and 30%. In addition, a scour hole developed within the range of 180 to 200 degrees at the inner bank under the influence of the channel geometry at the junction between the two bends. Under the influence of the helical flows [42] in the first half of the downstream bend, the sediments were separated from 20%B away from the vicinity of the outer bank and moved towards the inner bank. Considering this figure, two scour holes were developed at the mid-channel section within the ranges of 205 to 230 and 240 to 310 degrees. Further, in the bend's downstream sections, given the flow orientation towards the outer bank, the scour hole was extended towards the outer bank, and the fourth scour hole developed from 340 to 360 degrees.

There are trivial bed topography changes observed in the second half of the upstream bend in Figure 3-c, within the range of 170 to 180 degrees near the outer bank; hence, the maximum dimensionless scour depth was found at the value of 0.54 at 180 degrees, whereas the downstream bend's bed topography changes were observable from the beginning to the end of the bend. In this case, the maximum dimensionless scour depth occurred at 187 degrees at the value of 0.77, and the maximum dimensionless sedimentation height also happened at 230 degrees at the value of 0.87.

In Figure 3-d, as in Figure 3-c, there are no significant changes noticed in the first half of the upstream bend, but further bed topography variations are found in the second half at the outer bank from 170 to 180 degrees. The maximum dimensionless value of the scour depth in this bend occurred at 180 degrees at the value of 0.64, and the maximum dimensionless sedimentation height also occurred at 45 degrees at the value of 0.05. The trend described for this sedimentation and scour experimentally refers to the correspondence between the results obtained from this study and the studies conducted by other researchers, including Xu and Bai [14] and Moghaddassi et al. [20]. Unlike the changes in bed topography in the first bend, those in the second bend were created from the beginning to the end of the bend, where the maximum dimensionless value of scour depth was noticed at the 187-degree angle at the value of 0.82. Moreover, in this case, the maximum dimensionless sedimentation height was observed at 230 degrees at the value of 0.99.

Changes in the bed topography in the first and second halves of the upstream bend in Figure 3-e are similar to those in Figures 3-c and 3-d. In this case, the most bed topography variations were found between 180 and 270 degrees at the downstream bend. This is because the secondary flow strength [43] in this region reached the maximum value, and the helical flow (given the interaction between secondary and longitudinal flows) had the highest effect in the bend. In this case, the maximum dimensionless scour and sedimentation respectively occurred at 188 and 235 degrees at the values of 0.84 and 1. Figures 3-d and 3-e comparison shows no significant changes observed in the highest values of scouring and sedimentation at the downstream bend after increasing t/t_e from 0.6 to 0.8, and they only showed a 5% increase.

As illustrated in Figure 3-f, in the second half of the bend, given the secondary flow's direction towards the outer bank, the maximum scour occurred near the outer bank from 170 to 180 degrees, as in the foregoing occasions. Further, the maximum dimensionless scour was equal to 0.86 and occurred at 180 degrees. A comparative examination of all the cases depicted in Figure 3 shows that only in the test with the equilibrium time ($t/t_e=1$) did the scour hole occur significantly and completely within the range of 170 to 180 degrees in the first bend, whereas the scouring happened only partially in other cases. Examination of the second bend's bed topography changes indicates that in this case, as in the previous ones, the highest variations were observed between 200 and 300 degrees. Therefore, the highest level of sour and sedimentation respectively occurred at 185 and 235 degrees at the values of 13.2 and 10.9 cm

(these values represent the basis for nondimensionalization of the maximum scour and sedimentation at other times). A comparison between Figures 3-e and 3-f at the downstream bend suggests that increasing t/t_e=0.8 to 1 added to the maximum value of scour depth by 20%, while the height of sedimentation remained constant.

A review of Figure 3 is indicative that both maximum values of scour and sedimentation occurred 5%B away from the inner bank in the downstream bend. The maximum scour and sedimentation took place within 180 to 190 and 215 to 235-degree locations. These results also comply with the findings in Termini [44] in a curving channel having successive bends about the generation of the maximum scour depth at the second bend's inner bank. Another important note regarding Figure 3 is that the bed deformation rapidly unfolded in the initial stages of each test. Then, when time passed, and the bed equilibrium conditions were approached, it gradually slowed down. The same trend was also observed in Eghbalnik et al. [45] investigations in a sharp bend which was 180 degrees, and those of Binns and da Silva [29] in a meandering channel with central angles of 20, 45, 70, and 95 degrees.

Figure 4 depicts changes in bed topography within the upstream bend's ending sections and the downstream bend's beginning sections at different times. In this figure, areas A, B, and C represent sedimentation, scour, and unchanged points. As shown in this figure, increasing time increased the height of the sedimentary stacks developed in the downstream inner bend, and its maximum values occurred at different angles. In addition, the trend of variations in sedimentation and scour was the same in every case. For every duration, the maximum scour occurred near the upstream outer bend at 180 degrees and in the downstream inner bend within the range of 183 to 188 degrees. It was observed that increasing the time relocated the maximum sedimentation at the second inner bend between 215 and 225 degrees. The trend presented in Figure 4 for different cases corresponds to the descriptions provided in Figure 3, which are also in line with the results presented by Moghaddassi et al. [20].

3.1.2 Maximum scour and sedimentation values

Table 1 shows the growth in the maximum values of scour and sedimentation and the growth in the volume of the output sediments from upstream and downstream bends with temporal variations. In this table, T is the test time, d_{smax} denotes the maximum scour hole depth, V represents the scour hole volume along the bend, A is the scour hole area along the bend, H_{smax} indicates the maximum sedimentation height, Θ represents the maximum scour and sedimentation location, and V' is the volume of output sediments from upstream and downstream bends [46].

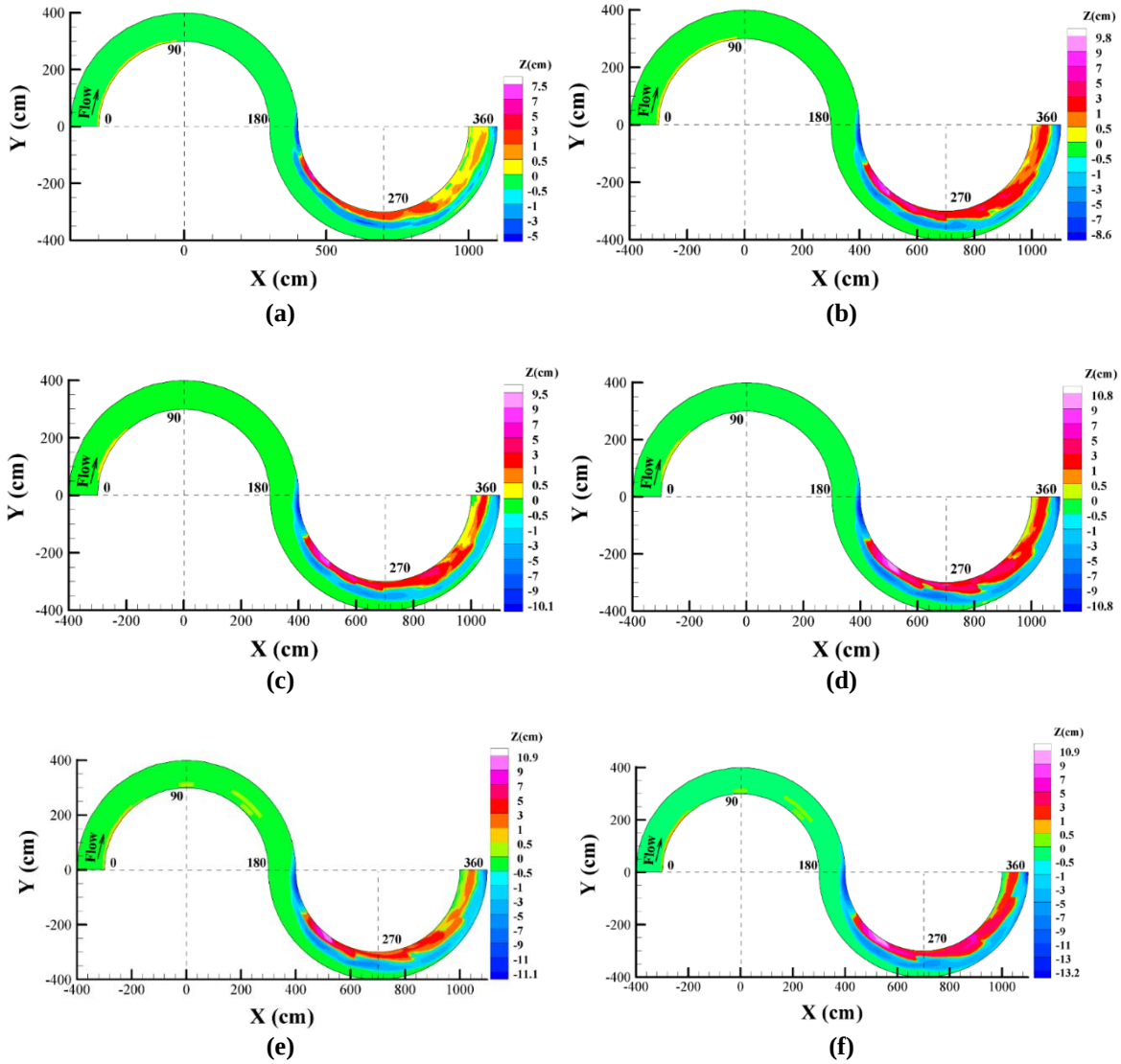


Figure 3. Bed topography changes of the meandering channel with t/t_e= a) 0.2, b) 0.4, c) 0.5, d) 0.6, e) 0.8, and f) 1.

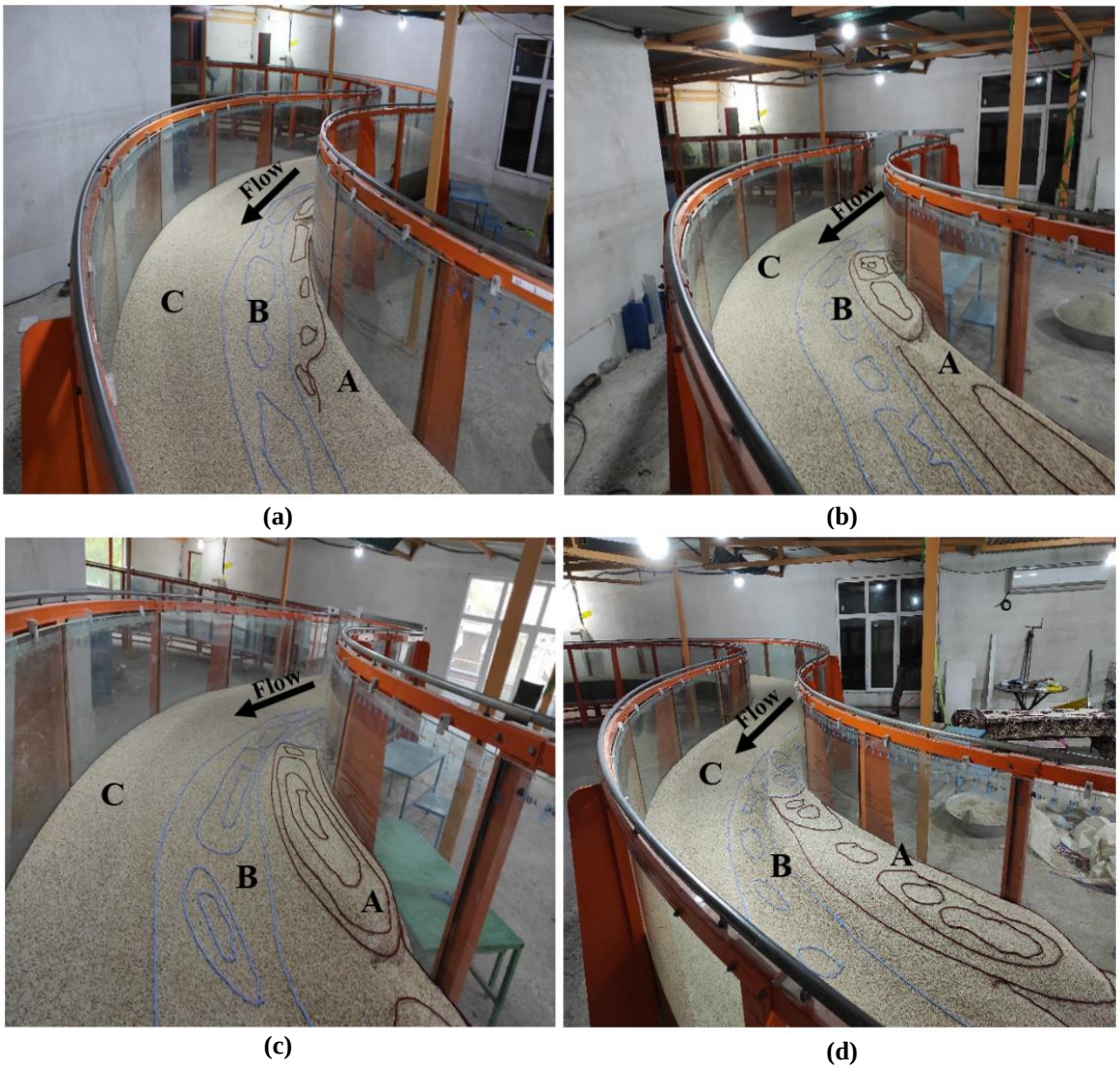


Figure 4. Examples of bed topography changes at the ending sections of the first bend and the beginning sections of the second bend in the laboratory channel with t/t_e= a) 0.2, b) 0.5, c) 0.8, and d) 1.

Table 1. Variations in the maximum values of scour and sedimentation and the scour hole area and volume in different tests.

Bend Location	T (min)	Sedimentation					Scouring			
		H_{smax} (cm)	H_{smax}	Θ (deg)	V (cm^3)	A (cm^2)	d_{smax} (cm)	d_{smax}	Θ (deg)	V' (cm^3)
Upstream Bend	48	0.2	0.02	70	-	-	-4.1	-0.31	180	-578
	96	0.3	0.03	75	-	-	-6.1	-0.46	180	-620
	120	0.5	0.05	45	-	-	-7.1	-0.54	180	-960
	144	0.5	0.05	45	-	-	-8.5	-0.64	180	-1568
	196	0.8	0.07	40	-	-	-7.7	-0.58	180	-1852
	240	0.8	0.07	45	-765	145	-11.4	-0.86	180	-2692
Downstream Bend	48	7.5	0.69	215	-6508	2012	-5.0	-0.38	183	-38800
	96	9.8	0.90	225	-41756	10173	-8.6	-0.65	185	-82414
	120	9.5	0.87	230	-43943	11328	-10.1	-0.77	187	-86987
	144	10.8	0.99	230	-69411	14872	-10.8	-0.82	187	-110476
	196	10.9	1.00	235	-70407	14962	-11.1	-0.84	188	-111046
	240	10.9	1.00	235	-116099	23671	-13.2	-1.00	185	-148682

As observed in this table, bed topography was dependent on temporal variations of the tests. It experienced significant variations so that increasing t/t_e from 0.2 to 0.4, 0.5, 0.6, 0.8, and 1 at the upstream bend raised the maximum scour depth value by 50, 75, 110, 90, and 180%, and also added to the maximum sedimentation height by 50, 150, 150, 300, and 300%, respectively. The volume of the output sediments from this bend increased by 10, 65, 170, 220, and 365% under the effect of this much increase in time. In addition, the maximum downstream bend's scour depth rose by respectively 70, 100, 115, 120, and 165%, and the sedimentation height also increased by 30, 25, 45, 45, and 45%. Further, the amount of the yielding sediments from the bend soared by 115, 125, 185, 185, and 285%. Besides, the scouring hole's volume and area in this bend increased by factors of 6.5, 6.8, 10.5, 10.8, and 17.8, and 5, 5.5, 7.4, 7.4, and 11.8, respectively.

Throughout all these tests, in the first bend, the maximum depth of scour was observed in the proximity of the outer bend at 180 degrees (the junction between the two bends). These results are completely in line with the qualitative results of Binns [31]. The maximum scour hole also occurred at the downstream bend at the junction between the two bends within the range of 185 to 190 degrees. Moreover, a scour hole was also generated near the outer bank between 320 and 360 degrees, while the maximum sedimentation height in both bends occurred near the inner bank. The maximum sedimentation height happened in a very trivial amount within the range of 10 to 70 degrees in the upstream bend and 216 to 235 degrees in the downstream bend.

3.1.3 Variations in transverse bed profile

Figure 5 illustrates variations in transverse bed profiles at 45, 90, 135, and 180 degrees in the upstream bend. Based on this figure, it could be observed that variations were highly trivial at the upstream bend, and partial sedimentation was observed within the range of the inner bank only at the equilibrium time. As shown in this figure, at the 180-degree location in the upstream bend, increasing t/t_e from 0.2 to 0.4, 0.5, 0.6, 0.8, and 1 increased the maximum scour depth by 50, 75, 110, 90, and 180%.

Figure 6 depicts changes in transverse bed profiles in the downstream bend at 225, 270, 315, and, 360 degrees. It can be observed in Figure 6-a that the secondary flows led to the sediments'

detachment from the outer bank and mid-channel, which resulted in scour hole development from 30 to 60%B away from the outer bank; however, bed topography variations were insignificant in the rest of the channel width. It can be observed in the figure that increasing t/t_e from 0.2 to 0.4, 0.5, 0.6, 0.8, and 1 added to the maximum scour depth by 230, 255, 255, 280, and 280%. Furthermore, the maximum sedimentation height increased by respectively 115, 100, 100, 95, and 80%.

The sediments gradually distanced from the inner bank in Figure 6-b, given the flow direction towards mid-channel at 270 degrees. The observation is that the maximum value of sedimentation happened from 10 to 20%B away from the inner bank (similar to the trend presented in Figure 3). The maximum dimensionless sedimentation height, in this case, occurred in the 144-minute test (t/t_e=0.6) at the value of 0.52. In contrast, the maximum dimensionless scour depth was observed in the 240-minute test (t/t_e=1) at the value of 0.43 at mid-channel.

As depicted in Figure 6-c, in the downstream half of the bend at 315 degrees, the sediments were slowly taken away from the inner bank and developed towards mid-channel. With the flow redirected towards mid-channel and then in the outer bank direction, a scour hole was generated within the range of mid-channel to the outer bank. At the 315-degree cross section, the maximum dimensionless scour hole and sedimentation height in the test for t/t_e=1 occurred at the respective values of 0.36 and 0.39.

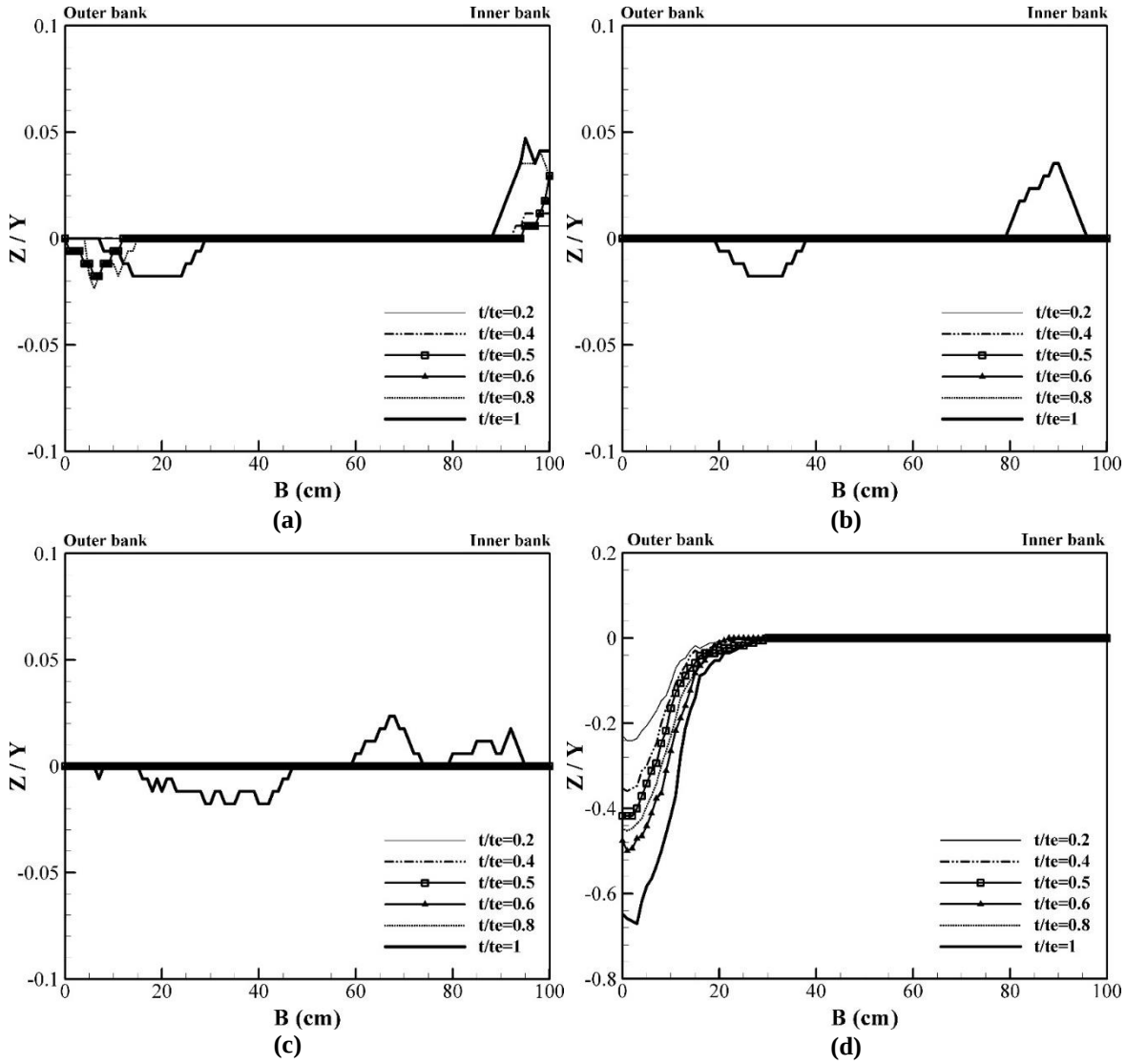


Figure 5. Examples of changes in the transverse bed profiles in the meandering channel for different durations at a) 45, b) 90, c) 135, and d) 180-degree locations.

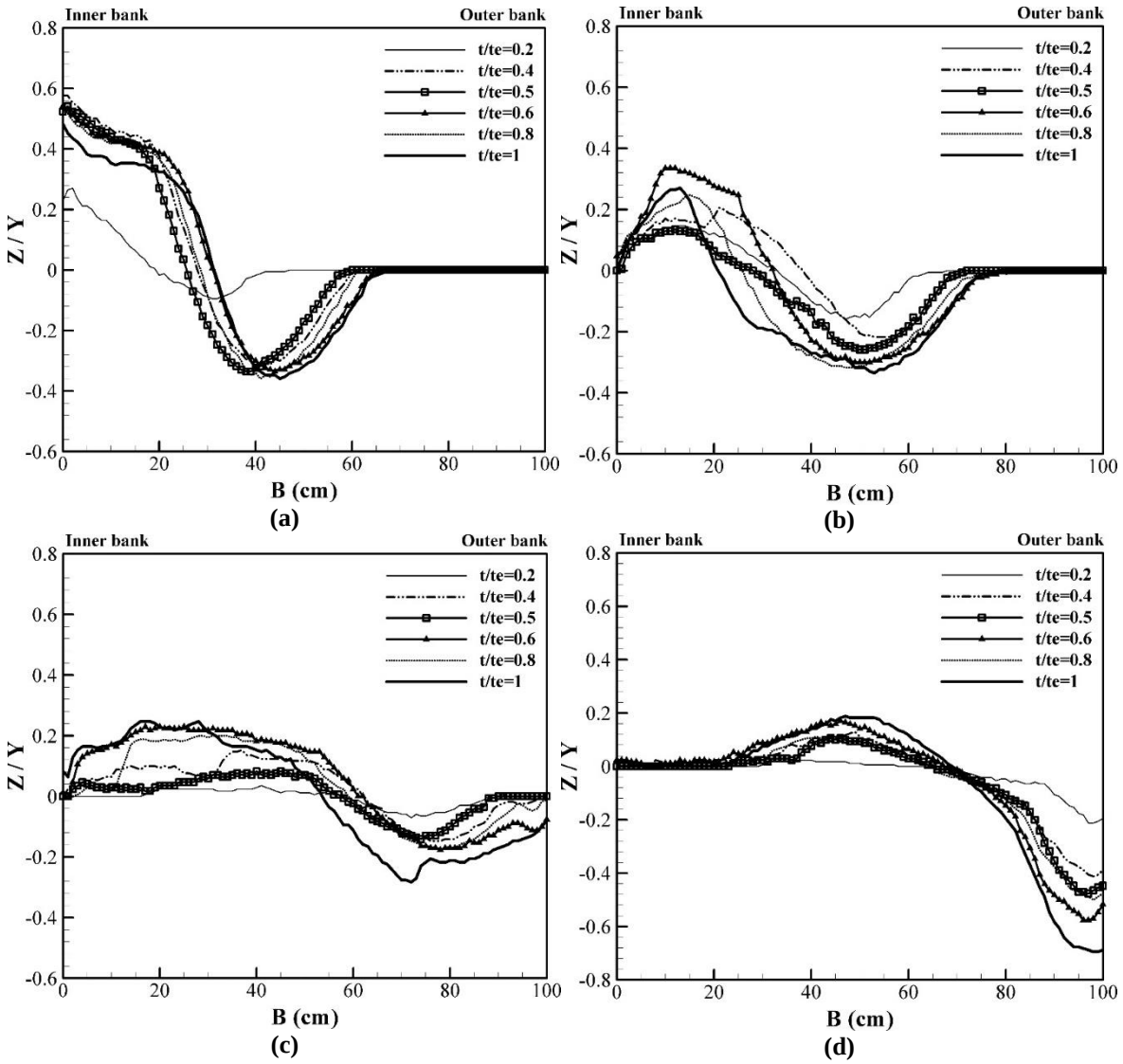


Figure 6. Examples of changes in the transverse bed profiles in the meandering channel for different durations at a) 225, b) 270, c) 315, and d) 360-degrees locations.

According to Figure 6-d, it can be observed that in every case in this figure, closer to the end of the bend, which was affected by the downstream straight path, bed topography variations decreased at mid-channel. The maximum dimensionless sedimentation height was observed at the value of 0.29 in the test with t/t_e=1, where the diversion of the flow towards the outer bank resulted in the generation of a scour hole within the range of 70 to 100 %B from the inner bank. The maximum dimensionless scour hole also occurred in the test performed in the equilibrium time at the value of 0.89, and it increased by respectively 95, 125, 170, 135, and 230% by increasing the test time.

3.1.4 Variations in longitudinal bed profiles

Instances of longitudinal bed profiles at distances of 10, 50, and 90%B away from the inner bank are depicted for different occasions in Figure 7. In Figure 7-a, given the flow direction towards the outer bank in the downstream half of the upstream bend, the greatest scour hole occurred from 180 to 200 degrees. The figure indicates that sedimentation happened 10%B away from the inner bank in the second bend from 220 degrees to the exit of the second bend; its high intensity took place in the upstream half of the bend, and its maximum value was observed between 240 and 260 degrees.

It can be observed in Figure 7-b that bed topography variations were trivial from the mid-channel section to the beginning of the downstream bend (210 degrees). In the downstream half of the bend, the flow was slowly deviated from the inner bank and oriented towards mid-channel and then in the direction of the outer bank. As shown in this figure, sedimentation was observed within the range of 220 to 270 degrees. These sediments increased the flow velocity at mid-channel upon an alteration in the bed level.

As also illustrated in Figure 7-c, changes in bed topography at the outer bank from the beginning to the 300-degree angle were insignificant. Considering the flow orientation towards the outer bank, the maximum bed topography variations happened from 300 to 360 degrees. Here, the maximum dimensionless scour hole depth occurred in the test run with the equilibrium time for 0.75. In this range, increasing t/t_e from 0.2 to 0.4, 0.5, 0.6, 0.8, and 1 raised the highest scour depth by separately 2.7, 3.3, 4.5, 3.5, and 5.5 times.

3.2 Water surface profiles in the meandering channel under the influence of temporal variations

3.2.1 Variations in transverse water surface profiles

Figure 8 illustrates instances of transversal variations in the water surface profile from the entrance to the exit of the first bend for 0, 120, and 240 minutes to investigate water surface variations in the meander. As this figure depicts, water surface inclination along the channel width in these figures refers to the bent path in the channel.

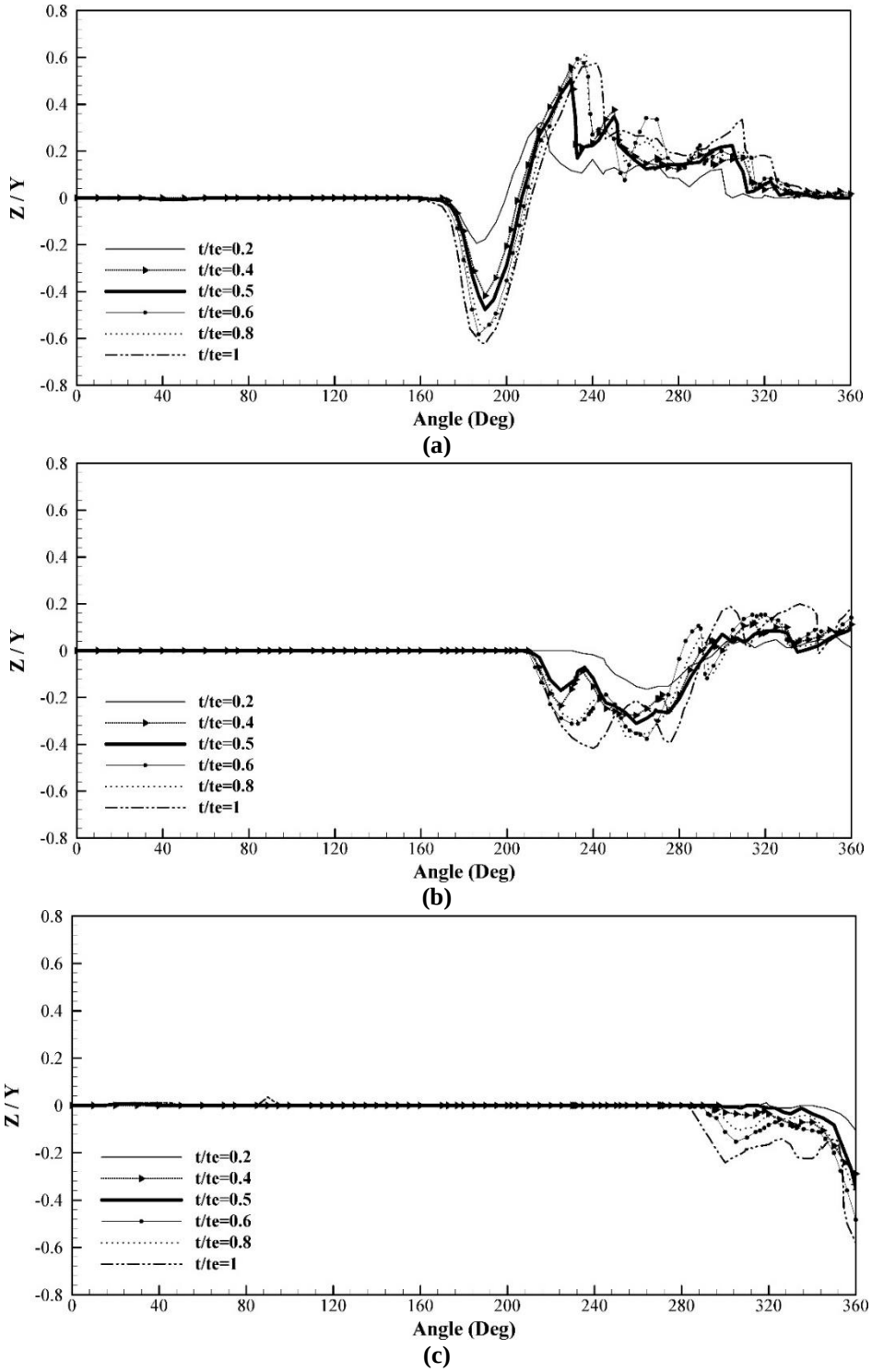


Figure 7. Examples of changes in the meandering channel's longitudinal bed profiles for different timespans at distances of a) 10%B away from the upstream outer bend and the downstream inner bend, and b) 50% B, and c) 90%B away from the upstream inner bend and the downstream outer bend.

It can be observed in Figure 8-a that the average water surface level at the inner bank decreased by 10% compared to that at the outer bank in the light of the flow direction towards the inner bank in the upstream half of the bend. This water level decrease at the inner bank indicates the velocity increase in this region compared to the outer bank. The lateral slope observed in these figures, resulting in water surface increase at the outer bank and its decrease at the inner bank, is due to the presence of the centrifugal force at the meander [47]. As depicted in Figure 8-b at 90 degrees, the same trend illustrated in Figure 8-a is dominant here, except that the water surface difference decreased to 5%. A comparison between the two figures indicates that the average water surface level at different times remained constant at 90 degrees compared to that at 45 degrees. In addition, it can be observed in both figures that the water surface level at the outer bank underwent trivial variations every time.

By considering Figure 8-c and comparing it with Figure 8-b, it can be observed that the trend of water level reduction remained unchanged with the progress of the flow along the bend so that the average water surface level at 135 degrees decreased by 2 and 5% at the inner bank and the outer bank, respectively, compared to that at 90 degrees.

It can be observed in Figure 8-d that the flow was influenced by the downstream bend near the end of the bend; hence, the water surface levels at the inner and outer banks show a slight difference. Furthermore, given the descriptions presented in Figure 3 and due to flow orientation towards the outer bank at the upstream bend, the water surface level at the outer bank was only slightly lower than that at the inner bank. As previously explained, since sedimentation occurred in the first half of the upstream bend at the inner bank, the increase in the height of these sediments increased the water surface level when the test time was increased.

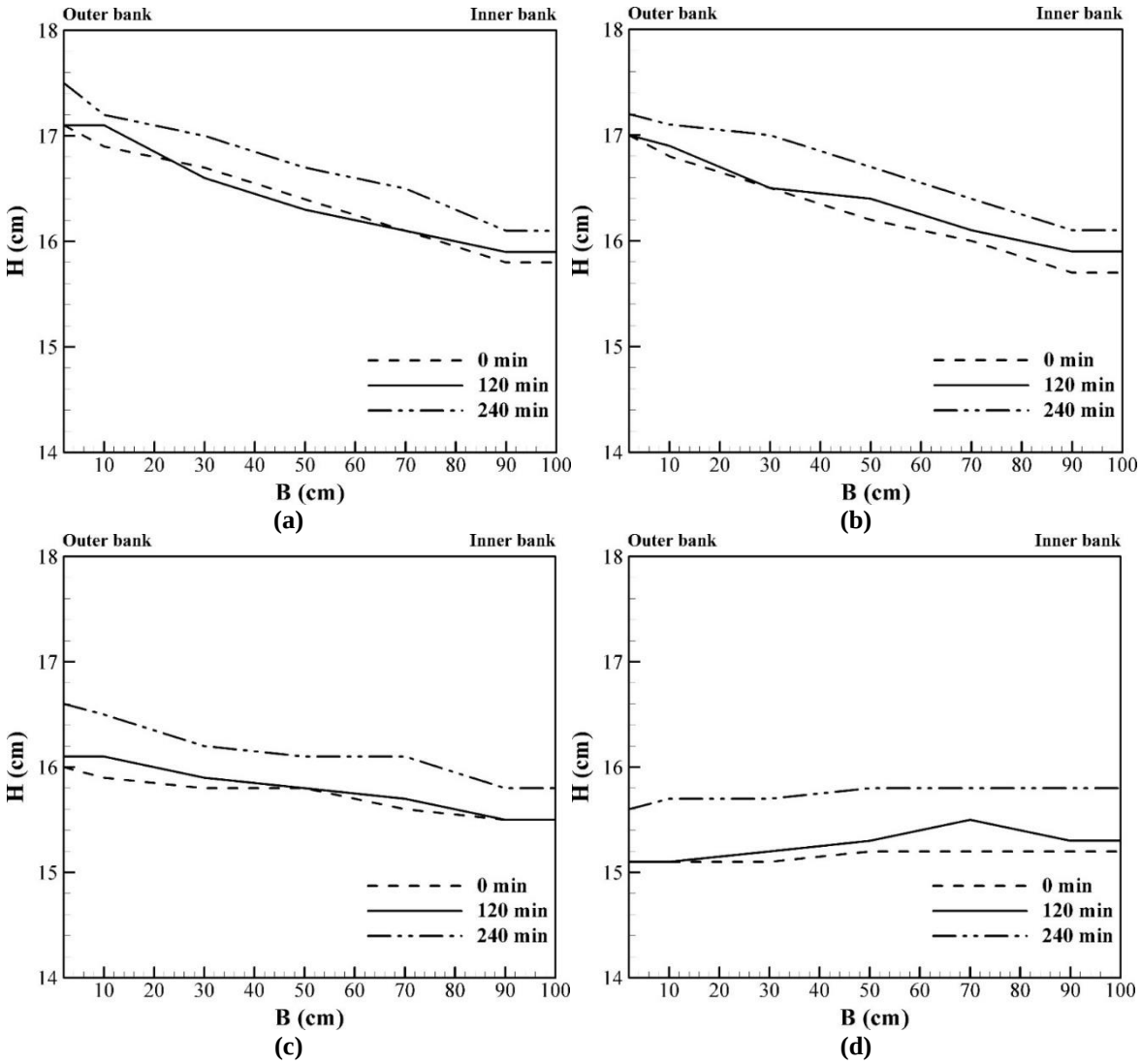


Figure 8. Examples of changes in the transverse water surface profile in the meandering channel for 0, 120, and 240 minutes at a) 45, b) 90, c) 135, and d) 180-degree locations.

A comparison between Figures 8-a to 8-d indicates that the maximum water surface level occurred in the test run for 240 minutes. Hence, by looking at the differences between the average water surface level at the upstream bend for 0, 120, and 240 minutes, it is concluded that the change in the position of the transversal profile from 45 to 90, 135, and 180 degrees decreased the water surface level at the inner bank by 2, 5, and 7% and reduced that at the outer bank by 2, 6, and 12%, respectively.

Figure 9 depicts transverse water surface profile variations in the downstream bend at 225, 270, 315, and 360 degrees. It can be observed in Figures 9-a and 9-b that given the flow orientation towards the inner bank in the first half of the bend, the average water surface level at the inner bank decreased by 5% compared to that at the outer bank. A comparison of these two figures indicates that with an increase in the test time from 0 to 120 minutes, the water surface level at the outer bank remained constant, while increasing the test time to 240 minutes increased

the water surface level by 5%.

As shown in Figure 9-c for the 315-degree angle in the second half of the bend, the average water level at the outer bank remained unchanged after the transversal profile positional change from 270 to 315 degrees. Given the descriptions presented in Figure 3, the flow orientation changed from the inner bank towards mid-channel and the outer bank. Hence, the average water surface level at the inner bank decreased by 10% compared to that at the outer bank.

As observed in Figure 9-d, closer to the end of the bend, the flow was influenced by the channel ending straight path, and the variability between the water surface level at inner and outer banks was decreased. Figures 9-a to 9-d comparison shows that, as in the upstream bend, the maximum water surface level in this bend occurred in the test run for 240 minutes as well.

A comparison between the average water surface level at 0, 120, and 240 minutes was indicative that changing the position of the transversal profile from 45 to 90, 135, and 180 degrees increased the water surface level at the inner bank by 3, 8, and 7% and that at the outer bank by 2, 2, and 8%, respectively. Figures 8 and 9 comparison illustrates that the water surface level for all durations was lower at the downstream bend than that at the upstream bend, which entailed the flow velocity increase at the downstream bend.

3.2.2 Variations in longitudinal water surface profiles

Figure 10 depicts variations in the longitudinal water surface profiles at gaps of 10, 50, and 90%B away from the first outer bend and the second inner bend at 0, 120, and 240 minutes into the test. According to this figure, the greater number of bed topography changes at the second bend and the insignificant number of bed topography variations at the upstream bend (according to Figure 3) can be attributed to water level decrease and velocity increase at the downstream bend.

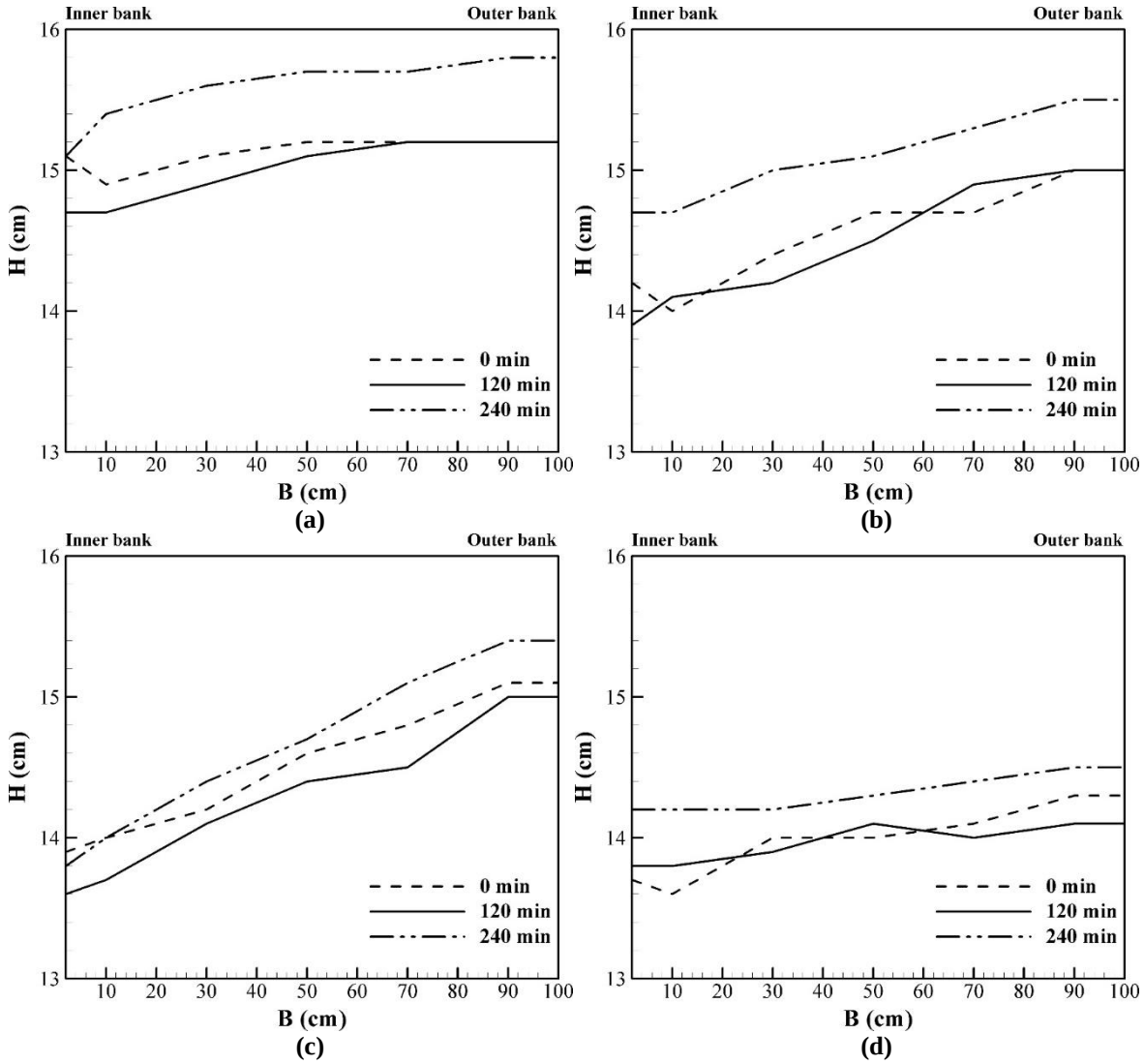


Figure 9. Examples of changes in the transverse water surface profile in the meandering channel for 0, 120, and 240 minutes at a) 225, b) 270, c) 315, and d) 360-degree locations.

A comparison between Figures 10-a to 10-c demonstrates that the water surface level at the upstream bend was maximum at the outer bank and minimum at the inner bank for all of these durations. Considering the direction of the flow towards the inner bank in the upstream half of the bend, at the 0-degree location, the water surface level at the inner bank decreased by 5% compared to that at the outer bank.

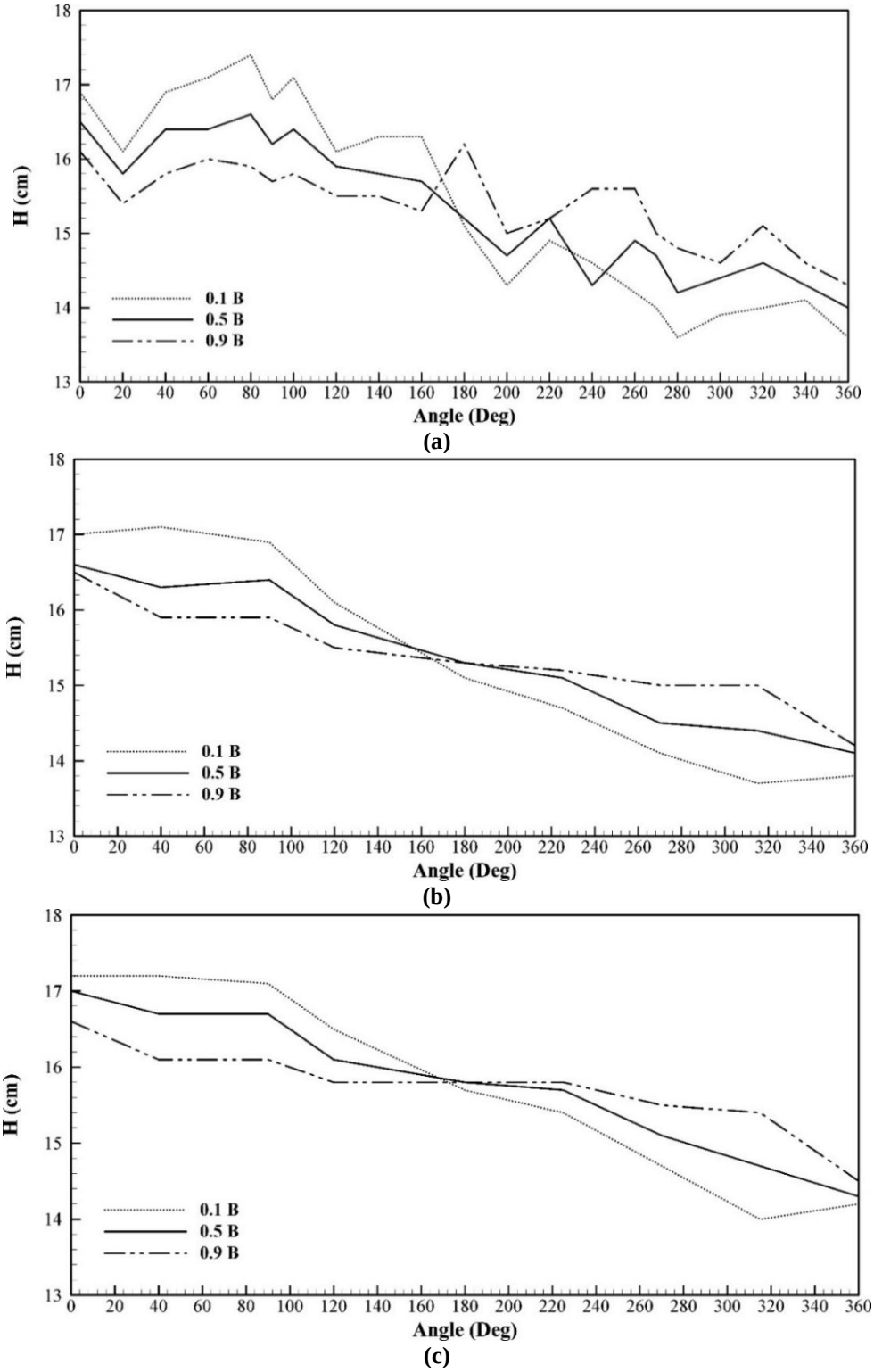


Figure 10. Examples of changes in the water surface longitudinal profile at different distances in the meandering channel for a) 0, b) 120, and c) 240 minutes.

Averaging the water surface level at the beginning of the upstream bend (the 0-degree location) and that at the end of the downstream bend (the 360-degree location) for every longitudinal distance shows an approximately 15% decrease in the average water surface level. This can be attributed to flow diversion from the first outer bend towards the second inner bend, which causes an increase in the flow velocity and a decrease in the water depth. In addition, the sediment's motion towards the inner bend causes channel constriction in this region, which is itself a reason for water depth decrease over sedimentary stacks and velocity increase.

4. Conclusions

To investigate the effect of temporal variations on scour and sedimentation in the meandering path, this paper examined the variations in bed topography and water surface profile under the influence of this parameter experimentally in a meander. The findings were compared at t/t_e=0.2, 0.4, 0.5, 0.6, 0.8, and 1. The following is a summary of the findings:

- Only in the test with the equilibrium time (t/t_e=1) did the scour hole visibly and completely develop within the range of 170 to 180 degrees at the upstream bend, while in other cases, the scouring occurred partially at the upstream bend.
- At the upstream bend, because of the increase in t/t_e from 0.2 to 0.4, 0.5, 0.6, 0.8, and 1, the maximum scour increased by 50, 75, 110, 90, and 180%, and also the maximum sedimentation rose by 50, 150, 150, 300, and 300%, respectively.
- At the downstream bend, with an increase in the test time, the maximum scour was augmented by 70, 100, 115, 120, and 165%, and the maximum sedimentation increased by 30, 25, 45, 45, and 45%.
- With an increase in the test time at the downstream bend, the scour hole volume increased by 6.5, 6.8, 10.5, 10.8, and 17.8 times and its areas developed by 5, 5.5, 7.4, and 11.8 times, respectively. In addition, the volume of the output sediments also increased by respectively 115, 125, 185, and 285%.
- In every test, the maximum scour depth happened at the junction between the two bends within the range of 185 to 190 degrees. Moreover, the second scour hole also developed within the range of 320 to 360 degrees near the outer bank.
- In the first half of the downstream bend, the flow was directed towards the inner bank; therefore, the maximum sedimentation height in every test occurred within the range of 215 to 235 degrees in the proximity of the inner bank.
- At the upstream bend, a comparison between the average water surface levels for 0, 120, and 240 minutes indicated that when the transversal profile was relocated from 45 to 90, 135, and 180 degrees, the water surface level at the inner bank decreased by 2, 5, and 7% and that at the outer bank decreased by 2, 6, and 12%, respectively.
- In every test run for different durations, the average water surface level decreased by approximately 15% within the range of the upstream bend entrance to the downstream bend exit for different longitudinal distances.

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