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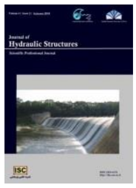

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Construction of Meandering Channel and Its Application in Investigation of Bed Topography around Hydraulic Structures

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Abstract

Considering river behavior analysis, numerous researchers worldwide have so far attempted to construct experimental channels. This piece of research discussed the construction of a channel with two bends and its application. Beginning from the upstream side, the channel respectively consisted of an 8-meter-long straight path, two consecutive 180-degree bends, and another 8-meter-long straight path downstream. In addition to presenting the stages of design and construction of this channel, this study provided some instances, where different hydraulic structures, including a T-shaped spur dike, a gate, sharp-edged and wide-edged spillways, submerged vanes, and a bridge pier, were implemented in meandering paths. A comparison of the results from the use of different hydraulic structures in this meandering channel showed that these structures had different effects on bed topography variations. For instance, under similar flow conditions, the maximum scour depth increased in the sharp-edged spillway experiment by approximately 40% compared to that in the wide-edged spillway experiment. In addition, the maximum scour around the T-shaped spur dike located in the external bend was 2.7 times greater than that with the case it was placed at the upstream internal bend. Reviewing the results of two cases of using submerged vanes in front of a single pier located at an angle of 180 degrees in the meandering channel, as compared to the case of a single pier without the use of vanes shows that the maximum scour depth around the bridge pier was reduced by approximately 10% when utilizing submerged vanes in conjunction with the single pier. Furthermore, by positioning three submerged vanes at the intersection of the two bends, the maximum depth of the scour hole was observed to occur at an angle of 358 degrees, located at a distance equivalent to 5% of the channel width from the outer wall, corresponding to 0.185 times the channel width. By repositioning the T-shaped spur dike to a 180-degree angle from the outer bend to the inner bend, an increase of nearly 35% was observed in the maximum scour within the bend.

Keywords: Flume Experiments; Scour; Spur Dike; Submerged Vanes; Bridge Piers

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1. Introduction

Predicting river behavior, particularly at bends, is of great importance as rivers mostly have meandering paths in nature, Akbari and Vaghefi [1]. It is highly complicated to use field studies and mathematical computations to study river processes. Nevertheless, physical modeling can be used as a complementary method for simulating complicated processes, Peakall and Ashworth [2]. However, developing such models is often highly costly and sometimes impossible. While constructing experimental and research channels under specific conditions helps researchers study river behavior, this method has made possible many research studies conducted on laboratory channels. After inspections made on the quality and conditions of different research channels and considerations of the importance that meandering rivers have, this study has involved the design and construction of a meandering channel to make different experimental studies feasible for studying the behavior of river structures present in it.

A review of the research conducted around river engineering topics refers to the particular importance of studying the flow behavior in bends in different experimental channels with varied materials, dimensions, and shapes worldwide. Instances of hydraulic channels incorporated by researchers at different research institutes all over the world have been introduced as follows:

Researchers such as Raudkivi and Ettema [3], Chiew and Melville [4], Chiew [5], Shakibaeinia et al. [6], Nazari-Giglou et al. [7], Vaghefi et al. [8], Wang et al. [9], Yagci et al. [10], Chavan and Kumar [11], and Zou et al. [12] utilized straight channels to carry out their experiments.

Since flow and sediment patterns in meandering river paths are more complicated than those in straight paths, river meanders and bends have received less attention from researchers. A number of these research works are mentioned here:

Tarbiat Modares University in Tehran has a collection of different experimental channels, an instance of which is a steel channel with glass walls and a 90-degree bend. Ghodsian and Vaghefi [13] and Vaghefi et al. [14,15] may be stated as instances of research studies conducted in this university. In China, Wang et al. [16] used a channel with six meandering bends. A concrete hydraulic experimental channel with a 90-degree bend was constructed in the hydraulics laboratory of Urmia University by Abdolahpour et al. [17]. Dugue et al. [18] presented their studies on a single-bend channel with PVC walls in Switzerland. The University of Minnesota in the U.S. hosts several experimental channels for researchers, and Khosronejad et al. [19] conducted some experiments in a straight channel in St. Anthony Falls Laboratory. Various channels have been used by researchers in India, among which Moharana and Khatua [20] conducted in a sinuous channel may be referred to. Termini [21] presented his research in a meandering channel having sinuous curves with an angle of 110 degrees at the University of Palermo in Italy. Queen’s University in Canada has different research departments in river and coastal engineering. Meandering channels made of PVC have been used by numerous researchers, including Binns and da Silva [22]. Mera et al. [23] built a river model with construction and building materials at the University of A Coruña to study the Mero River in Cambre, Spain. Pagliara et al. [24] utilized a channel comprised of three bends for their studies. Liu et al. [25] conducted their research at Sichuan University in China on a meandering concrete channel with sinuous bends. Akhtari and Seyedashraf [26] used a channel with a 60-degree bend. In Bushehr, Persian Gulf University has a steel channel with glass walls and a 180-degree sharp bend designed and constructed by Vaghefi and Akbari [27]. Moqanlu et al. [28], Keshavarz et al. [29], Solati et al. [30], Vaghefi et al. [31], Keshavarz et al. [32], Sedighi et al. [33], and Akbari et al. [34] conducted a thorough examination of their respective findings within this 180-degree sharp bend. Park and Ahn [35] used a double-bend, S-shaped meandering channel with a length of 16.5 meters, a width of 1 meter, and a height of 60 centimeters in South Korea to carry out their experiments. This channel consisted of two 150-degree bends connected via a 1-meter-long straight path. Serajian et al. [36] presented their experimental studies in a 90-degree bend channel in Ahvaz.

According to surveys on the experimental channels available in different universities and research institutes, it has been observed that channels with a straight path or with a single bend have been constructed in most laboratories. These few meandering channels under investigation are also mostly straight channels that have been changed from straight into meandering using construction materials to study the behavior of meandering rivers. Therefore, this study aimed to present a method of constructing a meandering channel comprised of two 180-degree bends. Experimental channels in a meandering shape with a steel structure and glass walls have less often been considered and constructed. Among the many prominent features of this channel are its being 1 meter wide and long and having consecutive 180-degree bends Moghaddassi et al. [37,38].

Patel and Kumar [39] employed a glass flume measuring 17.2 meters in length, 1 meter in width, and 0.72 meters in depth for their investigative study. Within the scope of their research, they examined various configurations of spur dikes, specifically T-shaped, L-shaped, and rectangular designs. Additionally, Pradhan et al. [40] utilized a T-shaped spur dike in their research to analyze alterations in the topography of the bed.

This study presented a comprehensive examination of the technical and lesser-known aspects pertaining to the construction and installation of meandering channels, which are certainly of significant interest to river engineers. In the following, the stages of constructing a meandering channel will be addressed from the onset to the end , and instances of its applications will be presented. Additionally, it illustrated examples of the application of various river structures, such as bridge piers and spur dikes, … and compared their performance in relation to scouring and sedimentation across different channels. This article presented an analysis of technical and less commonly discussed aspects pertaining to the construction, installation, and operation of meandering channels, which would be of significant interest to professionals in the field of river engineering. The discussion included a comparative evaluation of various structures, such as bridge piers and spur dikes, in relation to their functionality in different channel contexts, particularly concerning scouring and sedimentation processes.

2. Process of Meandering Channel Construction and Implementation

This section first introduces the meandering channel properties and then addresses the stages of its construction and setup.

2.1 Meandering Channel Properties

Beginning with the upstream side, this meandering channel is comprised of an 8-meter-long straight path, two consecutive 180-degree bends, and another 8-meter-long straight path downstream. The bends have an outer curvature radius of 4 meters, and considering the 1-meter-wide channel, their relative curvature radius is 3.5. The bed is made of steel, and the channel has 0.8-meter-high walls made of shatter-proof security glass with a thickness of 10 millimeters. A reservoir with a length of 2 meters, a width of approximately 1 meter, a height of 85 centimeters, and a volume of 1700 liters is implemented at the channel entrance on five pillars. To adjust the flow depth in the channel, a butterfly gate is used at the end of the straight downstream path

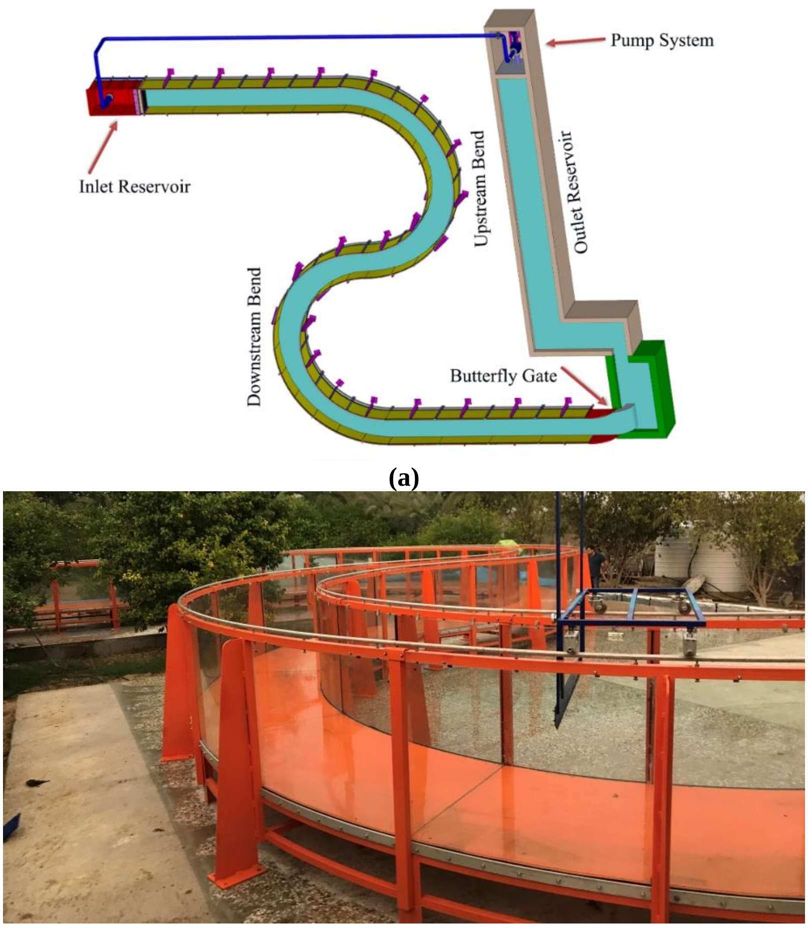
Moghaddassi et al. [37].

The outlet reservoir is made of concrete and is 15 meters long, which transfers water to the inlet reservoir with the pump set up at its end. Figure 1 illustrates a 3D model along with the construction of the real model.

2.2 Meandering Channel Construction Stages

2.2.1 Designing and Preparing the Ground

Prevention of potential ground subsidence under the influence of the applied loads requires implementing a proper and reinforced substructure. A concrete substructure with a thickness of 20 cm and a mosaic pavement was used to reinforce the present bed. In order to determine the control points and install the channel at the precise location, a Leica Total Station camera was used.



(a)

(b)

Figure 1. A 3D view of the channel: a) a schematic view and b) a real picture in the laboratory

2.2.2 Structural Design

Solid work and Sap2000 software programs helped design the structure. The channel's main structure consists of 20 parts with a length of 2 meters, a width of 1 meter, and a height of 80 centimeters, and each 2-meter-long part is located on five pillars. The required steel for constructing every part of the channel was considered to be ST37 with a yield strength of 2400 kg/cm^2. The loads from different sections, including the glass, the water, and the filler materials made of Sicilian Sand, are considered in the model. Since the internal stress of the structural members is insignificant, the deformations and the maximum deflection of the members are the decisive factors in this analysis. The inlet reservoir and the outlet butterfly gate of the channel have been designed considering a flow rate of 100 L/s.

2.2.3 Designing Pump and Water Supply System

Supply of water to the meandering channel is made possible using Pumpiran 150-200. In this pump, the circle number (n) is 1450, the transferable discharge (Q) is 330 m^3/hr, the head (H) is 9 m, and the power (P) is 15 kw. Due to flow drop on the water transmission pathway, this system allows a transferable discharge up to 100 L/s. Considering the type of electropump employed and the pipes available on the market, an 8-inch-long pipe is used at the inlet suction and a 6-inch-long pipe at the outlet discharge. Considering the discharge pipe harnessed at the structural wall around the channel and the shock proof implemented at the pump outlet, the vibration transfer is controlled through the flow pipe in this channel.

An ultrasonic flowmeter, Altek (Type: TFM3100-F1), is used to determine the flow rate with an accuracy of ±1%. Transducers of this type of flowmeter can be installed in different methods: N, W, Z, or V. The best place to install the flowmeter transducers is a point on the pipeline which is at the maximum distance from the pump inlet, the valve, or any obstacle generating a turbulent flow. In this channel, the transducers are 4 meters away from the pump's outlet area. The minimum upstream distance of the transducers must be five times the pipe's diameter (80 cm), and it is predicted to be 12 meters in this case. Different arrangements of the transducers were tested and controlled. Given the diameter of the discharge pipe, the best choice in this project is the V-method installation. The performance of the ultrasonic flowmeter was evaluated and verified using two different flowmeters. Figure 2 illustrates how the pump, the piping system, and the flowmeter are installed in this channel.

A concrete reservoir with a width of 1 meter, a height of 2 meters, and a length of 15 meters is constructed along the channel to tighten the path of water transmission from the outlet section and pump water to the channel inlet. Construction of this basin includes excavating the site, implementing a concrete slab for the wall and the bed, isolating and waterproofing, implementing the tiles and ceramic, installing a trash capture filter at a distance of 1 meter from the pump inlet, and implementing a concrete slab on the flow path. Figure 3 shows the construction of the outlet reservoir and the water transmission system.

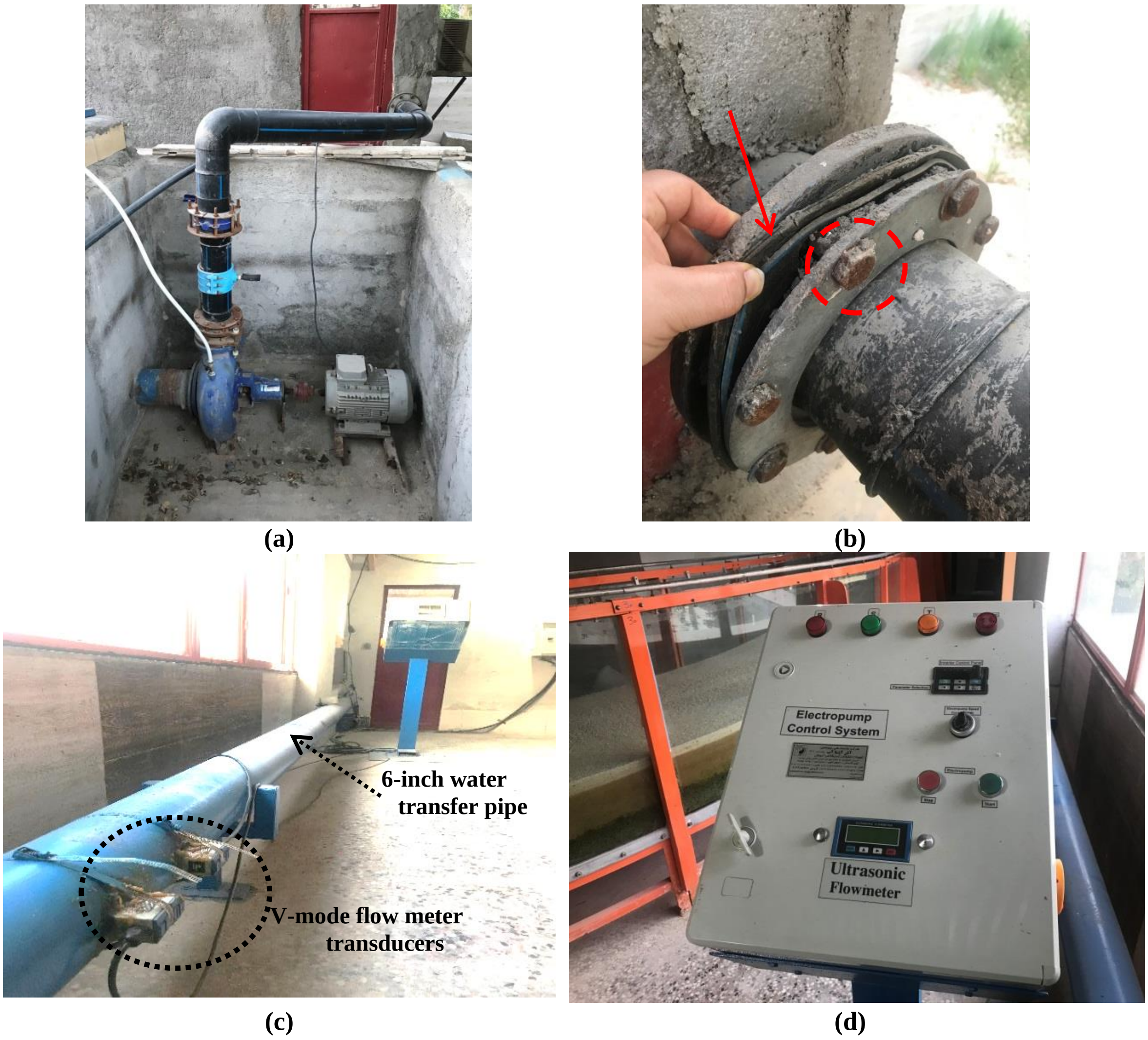


Figure 2. Installation of the pump and the flowmeter: (a) the installed pump, (b) 1- the waterproof rubber O-ring sealing gasket, and 2- bolts and nuts, (c) the flowmeter transducers in V-mode, and (d) the flowmeter control box

2.2.4 Installation of Channel Modules

A 2-meter-long module of the channel structure was first constructed. Then stencils were supplied for making and installing the glass. After testing and verifying the proper and precise connection between the parts, the other parts of the structure and glass were built and assembled in the workshop. After designing and constructing the first module, the other channel modules were built and assembled according to the working drawings. After assembling different modules according to the working drawings and visiting the first module, the installation and the initial test of the glass were done.

(a) (b) (c) (d) (e) (f)

Figure 3. Construction of the outlet reservoir and the water transmission system: (a) site excavation, (b) concrete wall implementation, (c) walls and bed waterproofing, (d) bed and body tiling, (e) trash capture filter implementation, and (f) the final concrete cover on the reservoir

Figure 4 illustrates the construction of a part of the structure, the inlet reservoir, the outlet gate, and the initial assembly of the channel in the workshop. After the initial assembly of the whole structure according to the drawings, different channel modules were assembled and moved to the paint workshop. After painting, the modules were prepared to be loaded for implementation at the project site. Figure 5 shows the stages of painting the channel modules.

Figure 4. Construction of the structure and assembly of the first channel in Azar Ashena Ab Co

(a)

(b)

Figure 5. Stages of painting the channel modules: (a) sanding and removing the rust from the parts and (b) painting

After transferring the modules to the site, the stages of installation and assembly of the channel, including implementation of the 2-meter-long modules and glass, were done according to the working drawings. The heat-resistant sealing paste was used to waterproof the modules. As a waterproofing test, the channel was exposed to a hydrostatic pressure of water for a height of 0.8 meters for 24 hours.

Engine and gear, which could be transported both electrically and manually, were used to adjust the gate, and they were able to move the gate with the precision degree of 1 millimeter. Figure 6 illustrates the different parts of the outlet butterfly gate.

(a) (b)

Figure 6. Different outlet gate sections: (a) the gate manual control and (b) the butterfly gate

Using a ¾-inch PVC pipe to prevent the turbulent flow from entering the channel and calm it, a system was designed and implemented as shown in Fig. 7; this set well converted the turbulent inlet flow of the reservoir into a uniform and steady flow in the channel.

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

Figure 7. How turbulence is controlled and the flow is calmed: (a) installing PVC pipes to control the flow, (b) the flow inlet before turbulence control, (c) the turbulent inlet flow, and (d) the uniform outlet flow through the channel entrance path

2.2.5 Design and Construction of Protective Structures

Structural walls and ceilings were implemented around the channel to protect the channel structure under different weather conditions such as wind and rain, to eliminate the external variables' effect on experimental results, and to provide appropriate moisture and temperature for laboratory conditions.

2.2.6 Implementation of Bed

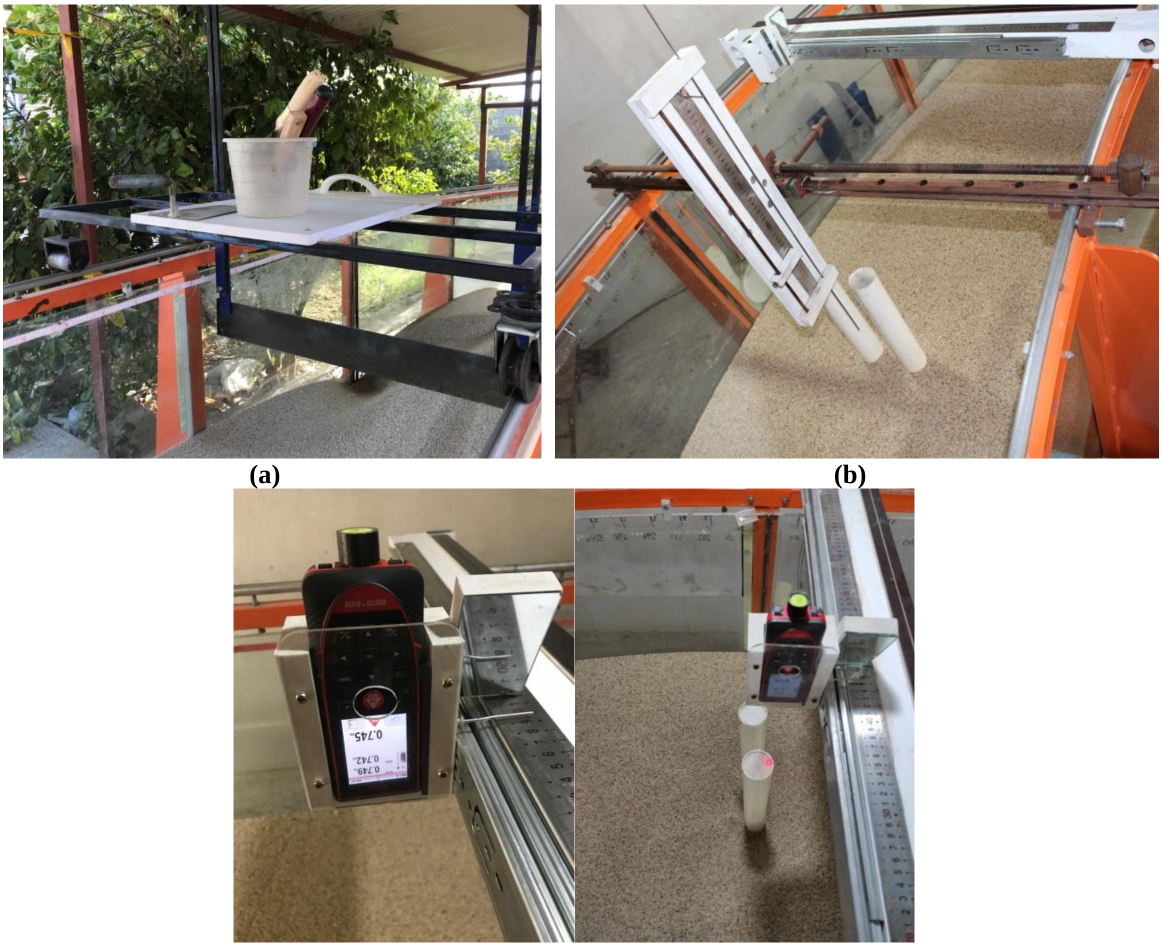
This channel will host various experiments under both rigid and mobile bed conditions (as shown in Fig. 8). Fig. 8-a depicts the rigid bed, and Fig. 8-b shows the mobile bed filled with Sicilian fine materials. To prevent materials outpour, galvanized sheets function as sloped surfaces at the beginning and the end of the channel's straight paths, as shown in Fig. 8-b.

(a) (b)

Figure 8. Channel bed: (a) the rigid bed and (b) the mobile bed along with the galvanized sheets at the beginning and the end of the channel for preventing materials outpour

2.2.7 Designing Other Measuring Devices Related to the Channel and Preparing It to Begin the Tests

To conduct different experiments with respect to scour in this channel, a flattener device was designed and incorporated for leveling the bed, as shown in Fig. 9-a. A 12 gauge galvanized wire was attached to the channel structure throughout the path to allow the bed flattener device to move on it with the help of rollers. Figure 9-b illustrates the device designed for measuring the maximum scour depth during the tests. Figure 9-c shows the bed profiler device for measuring sediment variations and bed scour. Precise point determination will be needed for conducting experiments in the bend. Therefore, as shown in Fig. 10, bend gradation was done using the Total Station camera with a precision of 0.1 mm.



(a) (b)

(c)

Figure 9. Pieces of equipment used for mobile bed experiments: (a) the bed flattener device, (b) the scour depth measurement device, and (c) the bed profiler used for measuring sediment variations and bed scour

Given the high flow velocity on the straight path following the downstream bend outlet, part of the downstream straight region was made rigid using bricks. To prevent the entrance of particles to the output reservoir, a region was predicted as the sediment intake basin at the end of the straight path (Fig. 11). Application of this method could be useful, particularly at channels with a small length with the possibility of particles entering the pump suction area.

Figure 10. Bend gradation using the Leica Total Station camera

Figure 11. Creating a sediment intake basin at the end of the downstream straight path to prevent sediment from entering the outlet reservoir

3. Applications of Hydraulic Structures in the Meandering Channel

As previously explained, it is possible to carry out different experiments regarding river engineering and different relevant hydraulic structures in this laboratory. Submerged vanes, T-shaped spur dikes, bridge piers Dehghan et al. [41], gates, and spillways Parsaie et al. [42] are instances of such structures that were introduced and analyzed in this study.

In this section, all experiments were performed under incipient motion conditions with a discharge of 70 liters per second and a water depth of 17 cm at the inlet of the upstream bend (except for experiments with a spillway). In addition, the duration of 4 hours was considered as the equilibrium time for all experiments. The channel bed was filled with uniform silica with a thickness of 30 cm. The average particle diameter (d_{50}) was equal to 1.85 mm and its standard deviation was equal to 1.2.

3.1 Effect of Submerged Vanes

Using submerged vanes is one of the methods which gain the researchers' attention to reduce bridge pier scour or protect the outer wall of bends against erosion. Figure 12 illustrates submerged vanes placed at the outer bend of a meandering channel.

Figure 12. Application of submerged vanes at the outer bend of a meandering channel

As can be seen in this figure, submerged vanes are thin rectangular structures created due to having a streamwise angle, and a high-pressure and low-pressure region on both sides. Moreover, these structures cause secondary vortices, change the flow pattern in the riverbed and, as a result, change sediment transport and scour. For this reason, it is highly important to study the bed topography variations around them. Figure 13 shows these changes in the meandering channel under the presence of these three vanes. These vanes are made of Plexiglas with a thickness of 1 cm and a width of 7.5 cm. They are spaced 7.5 cm apart at a 25-degree angle, so that they are located at the 180-degree angle of the first external bend, with the center of the vanes being 10 cm away from the edge of the external bend. The water height over the vanes is 8 cm and their submergence ratio is 50%.

As shown in Fig. 13, with the submerged vanes placed at the junction between the two bends, a scour hole is developed at a distance of 5% of channel width from the end of the upstream bend outer wall and the beginning of the downstream bend inner wall. This maximum value in the upstream bend was 17.6 cm, which occurred at the 178.5-degree angle, while changes in other parts of the first bend were too small. These trivial changes in the upstream bend were also reported with no hydraulic structures in this channel Moghaddassi et al. [38]. In the downstream bend, sedimentary piles were observed near the inner wall of the downstream bend from the 290-degree angle onward, extended toward the mid-channel. The maximum sedimentation along the path was 11.9 cm in the downstream bend and at a distance of 60% of the channel width within the range of 355 to 358 degrees. In addition, two maximum scour holes were observed near the inner and outer walls in this bend. According to the figure, it can be seen that the first hole is skewed from the 210-degree angle to the mid-channel and is drawn to the outer bank up to the 300-degree angle. In this case, the maximum scour hole depth was equal to 18.5 cm at the 358-degree angle and at a distance of 5% of the channel width from the outer wall. Another scour hole with a depth of 17.9 cm was also observed at the 182-degree angle at a distance of 5% of the channel width from the inner wall of the downstream bend.

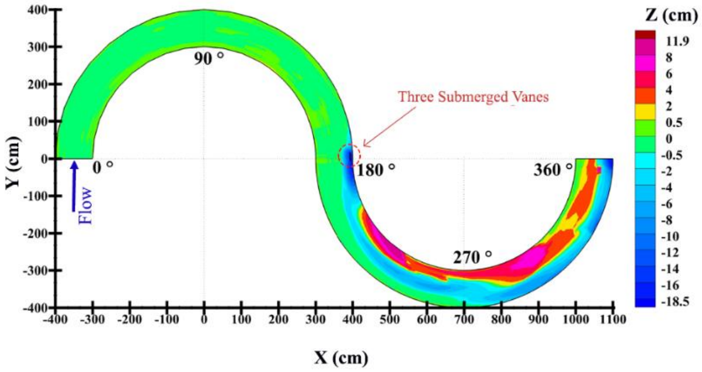


Figure 13. Bed topography variations in the meandering channel equipped with submerged vanes

Upon analysis of the two scenarios involving the application of submerged vanes in front of a single pier positioned at an angle of 180 degrees within the meandering channel, compared to a single pier without such vanes, it was observed that the maximum scour depth around the bridge pier, when utilizing the submerged vanes in conjunction with the single pier, was approximately reduced by 10%.

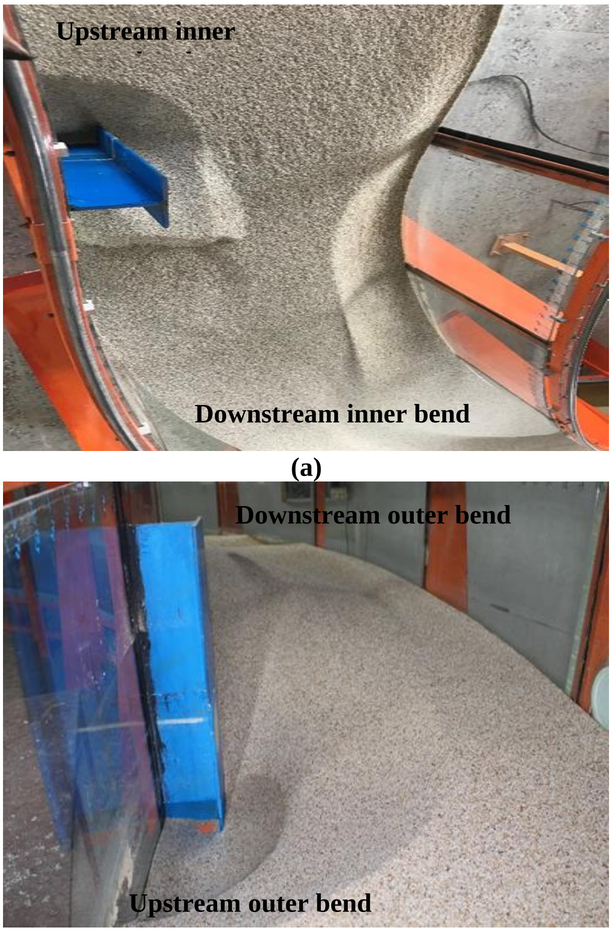
In alignment with the findings presented in this study, Odgaard and Wang [43] similarly demonstrated that submerged vanes serve effectively in safeguarding riverbanks against erosion and enhancing drainage efficiency at culverts and bridge crossings. Furthermore, the research conducted by Ouyang et al. [44] indicated that the sediment management capacity within a complex arrangement of three submerged vanes positioned in a sequential manner decreased as the spacing between the vanes is reduced.

In their study, Safaripour et al. [45] examined the impact of submerged vanes immersion ratios on the scour hole slope surrounding pier groups situated within a sharp bend channel. The findings of this research indicated that submerged vanes had the most influence in the reduction of the upstream slope, particularly in scenarios involving a single pier, when the vanes were submerged by 75% in conjunction with triad longitudinal piers featuring a 25% immersion, where a reduction of about 50% and 74% in scour slope was observed, respectively, in comparison to piers that were not equipped with vanes.

An analysis of the research findings of Chooplou et al. [46] indicated that when the pier was oriented at a 90-degree angle within a sharp 90-degree bend, the maximum scour reduction occurred with the implementation of submerged vanes positioned at a distance of 2.5 times the pier diameter from the centerline of the pier, as well as at distances of 1 and 1.5 times the pier diameter. This arrangement resulted in a 30% and 25% decrease in local scour around the bridge pier.

3.2 Effect of T-shaped Spur Dike

Numerous researchers have shown interest in studying the behavior of rivers while using spur dikes to protect the walls against erosion, Bora and Kalita [47]. Since T-shaped spur dikes have the least amount of scour and the best performance in protecting river walls against erosion among spur dikes of different geometries Vaghefi et al. [15], Akbari et al. [34], this type of spur dike was selected to be used in this study. Figure 14 illustrates an instance of the bed variations in the meandering channel while using a T-shaped spur dike at the 180-degree angle of the upstream inner and outer bends. These impermeable spur dikes are made of Plexiglas with a thickness of 1 cm and a wing and web length of 15 cm under non-submerged conditions. These dimensions were selected based on the recommendations of Ghodsian and Vaghefi [13].

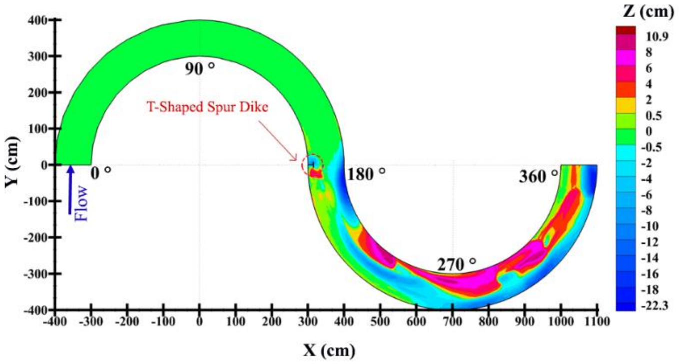


(b)

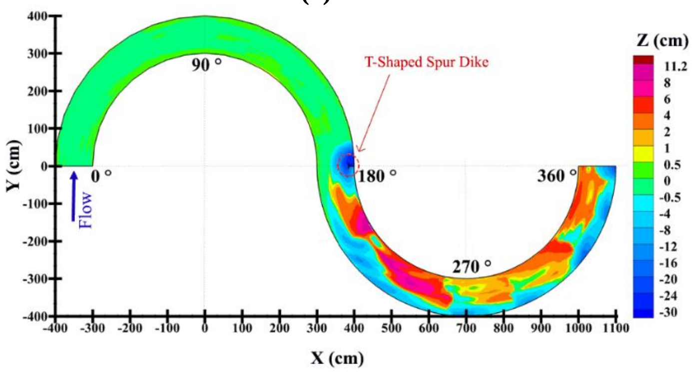
Figure 14. Bed variations with the T-shaped spur dike installed at the 180-degree angle: (a) the upstream inner bend and (b) the upstream outer bend

Figure 15 shows the effect of the T-shaped spur dike installed perpendicular to the inner and outer walls of the upstream bend on bed topography variations of the meandering channel. According to Fig. 15-a, it can be seen that the maximum scour depth, equal to 22.3 cm, at a distance of 5% of the channel width from the outer bank of the downstream bend occurs within the 353-degree angle. The maximum scour around the spur dike, equal to 11.1 cm, was also observed at the 179-degree angle near the inner wall of the upstream bend. The maximum sedimentation height in this case, equal to 10.9 cm, occurred within the range of 233 to 236 degrees of the inner wall of the downstream bend.

The findings from the research conducted by Ghodsian and Vaghefi [13] regarding the impact of T-shaped spur dikes in a 90-degree channel bend on alterations in bed topography indicated that the extent of scouring occurring upstream of the spur dike was significantly greater than that experienced downstream. This observation was confirmed by the results of the current study.



(a)



(b)

Figure 15. Bed topography variations of the meandering channel bed with the installation of a T-shaped spur dike at the 180-degree angle: (a) the upstream inner bend and (b) the upstream outer bend

This is because the duration of the experiments was initially predicted to be 4 hours, but in the case of the spur dike installed at the outer wall (Fig. 15-b), the maximum scour around the web and wing of the spur dike was skewed toward upstream after 2.5 hours into the experiment. According to this figure, it is observed that the maximum scour depth, equal to 30 cm, occurs at a distance of 10% of the channel width from the outer bank of the upstream bend at the 179-degree angle. The maximum scour depth in the downstream bend, equal to 21.5 cm, occurred at a distance of 10 to 20% of the channel width from the inner bank of this bend and at the 181-degree angle. The maximum sedimentation height, equal to 11.2 cm, was reported at the 212-degree angle and close to the inner wall of the downstream bend.

Comparison of these two figures indicates that the maximum scour near the spur dike, with the spur dike located in the external bend, is 2.7 times greater than its position in the upstream internal bend. By repositioning the T-shaped spur dike to a 180-degree angle from the outer bend to the inner bend, an increase of nearly 35% was observed in the maximum scour within the bend.

In the study conducted by Tripathi, Pandey [48], an in-depth examination was performed regarding the local scour phenomena surrounding T-shaped spur dikes positioned at various locations along the external bend of a meandering channel. Their tests were executed within a meander characterized by a rectangular cross section, featuring two successive bends arranged in reverse order, each measuring sharp 180 degrees with a relative radius of 1. The channel width was also set at 1.0 units with the central radius of both bends equal to 1.0 meters, specifically designed for this purpose. Notably, both the bottom and walls of the rectangular channel were constructed using impermeable cement material. A bed sediment layer with a thickness of 0.25 meters, exhibiting a mean particle diameter of 2 millimeters and a standard deviation of 1.8 millimeters, was uniformly distributed throughout the channel. The spur dike was constructed from a perspex sheet with a thickness of 10 millimeters and a height of 200 millimeters, positioned perpendicular to the curve of the flume bend. The length of the spur dike wing was typically considered to be 20% of the channel's width (200 millimeters); however, for the purposes of this study, this ratio was adjusted to 15% of the channel's width (150 millimeters). The findings of this research indicated that the extent of local scour surrounding the spur dike was positively correlated with both the Froude number and the positions along the meandering pathway from the entrance to the bends. Furthermore, the transition stage (curvy region) exhibited a clear and stable configuration when assessed at an angle of 30 degrees. Conversely, as the spur dike was positioned nearer to the conclusion of the initial bend, the transition stage became sharper or more unstable.

3.3 Effect of Bridge Pier

Bridge piers represent one of the most practical and important structures utilized in rivers, the failure of which causes many casualties and financial losses annually. Figure 16 shows an example of bed topography variations at the site of a single cylindrical pier in the laboratory. A PVC pipe with a diameter of 6 cm was used to represent the pier ,based on the recommendation of Chiew and Melville [4], which was placed at the 180-degree angle.

Figure 16. Installation of a cylindrical bridge pier in a laboratory channel and bed variations near it

Bed topography variations along the whole meandering path and around this pier are presented in Fig. 17. According to this figure, the maximum scour depth around the bridge pier is reported to equal to 10.8 cm, while the maximum sedimentation height, equal to 11.1 cm, occurs at a distance of 5% of the channel width from the inner bank of the downstream bend within the range of 235 to 245 degrees. The maximum scour depth in the channel also occurred affected by the bend geometry at 5% of the channel width from the outer bank of the downstream bend and at the 348-degree angle equal to 16.1 cm (1.49 times the maximum scour around the pier). Different parameters (change of position, geometry, angle, flow conditions, etc.) in relation to bridge pier and bridge pier influence on bed topography variations have their effects, which have received less discussion regarding meandering channels.

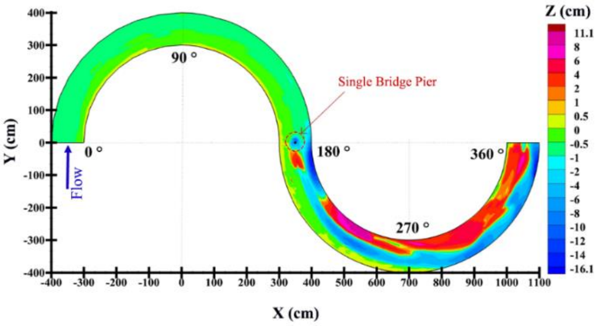


Figure 17. Bed topography variations of the meandering channel with the installation of a cylindrical bridge pier.

Upon examination of the findings presented by Moghaddassi et al. [49] concerning a meandering channel, it became evident that in the downstream bend, from the inception to the midpoint of the bend, there was a discernible trend of increasing maximum scour at the pier, which paralleled the observations made in the upstream bend. However, commencing from the angle of 315 degrees, a diminishing trend was noted. Specifically, there was a significant reduction of approximately 90% in the maximum scour at the pier as the angle was changed from 270 degrees to 315 degrees.

Asadollahi et al. [50] conducted a numerical and experimental analysis of the flow dynamics and scour patterns surrounding both individual and grouped bridge piers within a sharp 180-degree bend. The findings from their research revealed that the maximal scour depth and sedimentation height associated with the bend with a single pier were found to be 3.4 and 1.8 times the pier diameter, respectively. Furthermore, a comparative assessment of the current study's outcomes indicated that, for a U/UC ratio of 0.98 and the positioning of the single pier at 90 degrees of the mild bend, the maximum scour approximately equated to 2.1 times the pier diameter.

The study conducted by Sedighi et al. [51] on a single bend channel featuring a sharp 180-degree bend indicated that, in scenarios without a pier, the highest level of scour was observed from angles ranging from 40° to 80°, specifically at a location 20% of the channel width from the inner bank. Conversely, in the present research, due to the relatively mild 180° bend, no significant alterations were detected during the same timeframe in this region. Instead, the most pronounced scouring was identified at the end of the 180° bend at the junction with the downstream section.

According to the results presented by Sedighi et al. [51], Keshavarz et al. and Dehghan et al. [52], it was observed that within a sharp 180-degree bend, the maximum sediment height at the pier location exceeded that recorded at 90 and 120 degrees for all pier shapes. Conversely, in the current study, focusing on a mild 180-degree bend, it was determined that for a single pier positioned at an angle of 135 degrees, the maximum sedimentation surpassed that at 90 degrees, which in turn exceeded that at 45 degrees. Notably, within the mild bend under consideration, variations in pier position throughout the bend indicated that the maximum sedimentation observed in the latter half of the bend was greater than that in the initial half.

3.4 Effect of Gate

Figure 18 illustrates the gate in the meandering channel. The effect of parameters on bed variations can be analyzed by altering the water depth beneath the gate and the positioning at different points in the meandering channel.

In this figure, the gate is placed at the 176-degrees angle and the upstream bend, so that it is 3.5 cm away from the channel bed material at the onset of the test. Bed topography variations with the installation of the gate in the meandering channel are shown in Fig. 19. In this case, under the presence of the gate in the channel, the maximum scour depth occurred at the gate site after 1.5 hours into the experiment. This figure shows that the maximum scour depth, equal to 30 cm, occurs within the range of 10% of the channel width from the outer wall of the upstream bend at the 178-degree angle, and continues up to 5% of the inner wall of the downstream bend at the 181-degree angle. The maximum sedimentation height was equal to 18.2 cm at the 232-degree angle at mid-channel and at the 247-degree angle at a distance of 20% of the channel width from the outer wall of the downstream bend. This was the highest amount of sedimentation observed under the influence of the structures used in this study.

Figure 18. Installing a gate at the meandering path

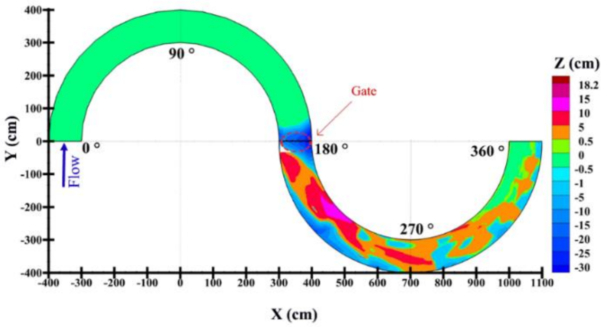


Figure 19. Bed topography variations of the meandering channel with the installation of the gate

3.5 Effect of Wide-Edged Spillway

Figure 20 illustrates the installation of a wide-edged spillway at the junction of two meandering channel bends. This spillway is 16 cm wide and installed at a 180-degree angle. The discharge in this test is 30 liters per second and the water depth in the direct upstream direction is 16 cm. The depth changes were such that the water depth was 16 cm at the upstream bend entrance, 15.5 cm at the end of the upstream bend before the spillway, 6 cm at the beginning of the spillway edge, and 4 cm at the spillway outlet. Test duration was 4 hours, as in other tests.

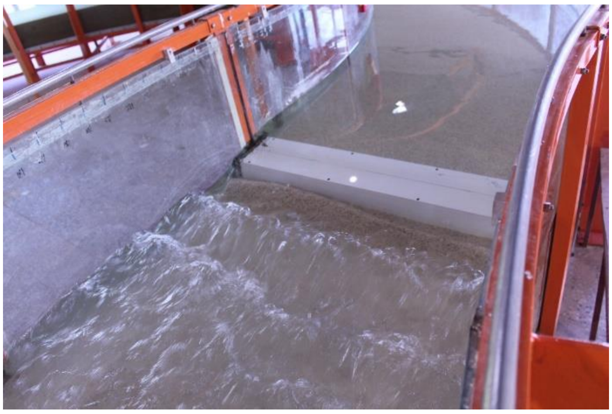


Figure 20 Installation of the wide-edged spillway in the meandering channel

Figure 21 indicates bed topography variations along the meandering channel in the presence of the wide-edged spillway. The maximum scour depth at the upstream bend, equal to 3 cm, occurred near the outer wall at the 174-degree angle, while that at the downstream bend, equal to 10.2 cm, occurred at the 194-degree angle near the outer wall. The maximum sedimentation height, equal to 5.4 cm, happened at a distance of 5% of the channel width from the inner wall of the downstream bend at the 200-degree angle. As can be seen in this figure, from the 230-degree angle of the downstream bend to the end of the bend, there are no significant changes in bed topography.

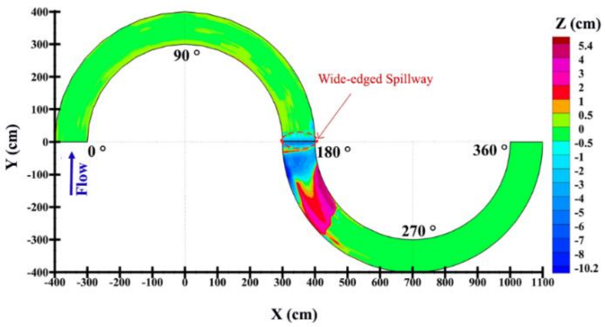


Figure 21. Bed topography variations of the meandering channel with the wide-edged spillway installed

3.6 Effect of Sharp-Edged Spillway

Figure 22 depicts the installation of a sharp-edged spillway with a thickness of 16 mm (0.1 times the width of the wide-edged spillway) at the junction of the two bends. In this case, as in the previous case, the discharge is 30 liters per second and the water height over the spillway is 5 cm.

Figure 23 shows bed topography variations around the sharp-edged spillway with other parts of the channel for comparison. As can be seen, the maximum scour depth, equal to 14.3 cm, occurred in the channel at the 226-degree angle and at the outer wall of the downstream bend, while this maximum value occurred around the spillway at the 181-degree angle with a height of 12.2 cm. The maximum sedimentation height began at a distance of 10 to 20% of the channel width from the inner wall of the downstream bend and reached a height of 5.4 cm towards the outer wall at the 224-degree angle.

Figure 22. Installation of the sharp-edged spillway in the meandering channel

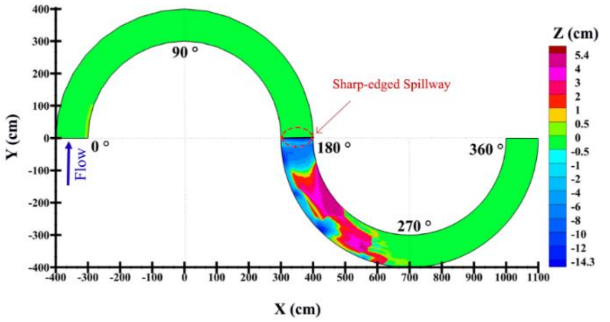


Figure 23. Bed topography variations of the meandering channel with the sharp-edged spillway

Comparison of Fig.21 and Fig.23 indicated that if this sharp-edged spillway is used with a ratio of 0.1 times the width of the wide-edged spillway, the maximum sedimentation height along the path remains constant. With both spillways, under the influence of bend geometry, the maximum scour depth took place near the outer bank of the downstream bend. Furthermore, implementing a sharp edge Spillway instead of a wide edge at the junction of the two bends resulted in a maximum scour increase of approximately 40%.

As mentioned above, these are merely examples presented here on the use of these structures in a meandering channel. In fact, for more extensive and practical research, the combination of these structures can be used to study the flow status and changes in bed topography in a meandering channel to examine the interaction effect of these structures.

4. Conclusions

Considering the importance of investigating meandering rivers' behavior, a meandering, double-bent channel was designed and constructed. This channel comprises a straight path upstream, two consecutive 180-degree bends, and another straight path downstream. The circular flow system is developed by the pump and the side reservoir attached along the channel, and a semi-automatic system controls this flow. Further, a butterfly gate implemented at the channel outlet is responsible for adjusting the flow properties. In addition to the stages of designing and constructing this channel, this study presented instances of performance of different hydraulic structures, including a T-shaped spur dike, a gate, a sharp-edged and a wide-edged spillway, a bridge pier, and submerged vanes installed in the channel, and their effect on meandering paths. All these experiments were performed under incipient motion conditions. A summary of the most important results is as follows:

- Installation of submerged vanes created two maximum scour holes near the inner and outer walls of the downstream bend. These maximum values were 17.9 and 18.5 cm occurring at 182 and 358-degree angles, respectively.
- The maximum scour around the T-shaped spur dike in the external bend was 2.7 times greater than that around this spur dike in the internal bend.
- The maximum scour in the channel, with the cylindrical pier placed in it, was equal to 16.1 cm, which was 1.49 times the maximum amount of scour around the pier itself.
- The highest amount of sediment bars observed in the channel, equal to 18.2 cm, was associated with the condition in which the gate was implemented.

- In the sharp-edged spillway experiment, the maximum scour depth increased by approximately 40% compared to the wide-edged spillway experiment.
- As witnessed here, the different hydraulic structures will have different effects on river bed topography variations. Predicting the behavior of rivers under the influence of different structures using experimental results will help reduce the damage caused by implementing those structures in reality.

Statements and Declarations

The authors declare that they have no conflict of interest.

Competing Interests

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Authors' contributions

N.M: flume construction, preparation of material, performing laboratory tests, collecting data, preparing graphical illustrations, and the first draft of the manuscript. M.V: flume designer, Methodology, collecting data, data analysis and editing of manuscript. All authors reviewed the manuscript.

Data Availability

The data presented in this study are available on request from the corresponding author.

Consent for Publication

All the authors have read and agreed to the submitted version of the manuscript.

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