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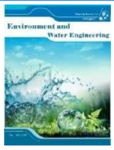

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Experimental investigation for the effect of the presence of bridge piers on the outer bank erosion of a river's bend

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ABSTRACT

The effect of the oblong-shaped bridge piers on the erosion of the outer bank has been experimentally investigated when it is present in the river bend. Two Oblong Piers are installed at two sections of the straight reach of a flume (before the bend), then at each 60 °, 90 °, 120 °, and 180 ° of the central angle inside the U-bend. The novelty of this work lies in experimentally investigating, under specified geometric and hydraulic conditions, how the presence of bridge pier, affects the morphological characteristics and the amount of erosion that occurs at the outer bank. The experiments are conducted under clear water conditions and a uniform grain size distribution of sand bed material. For all experiments undertaken, the flow intensity was fixed at V/Vc=0.98. The results show an appreciable increase in erosive length at the outer bank with the presence of a bridge as compared to that occurring with no bridge at the same flow condition. The percentage increase in erosion length with piers installation is: 49%, 55.4%, 77.5%, 55.4%, 20.5% and 61.75%, respectively. Furthermore, the results exhibit that the scour depth along the line of erosion generally decreases compared with the result with no bridge.

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1. Introduction

Outer banks in river bends are especially susceptible to scour and erosion due to bend effects (Russell and Vennell, 2019). Due to the erosion of the concave (outer) bank and the deposition of point bar deposits at the convex (inner) bank, curved river channels move laterally (Hickin et al.,1984). Stabilizing stream bank lines is of utmost importance in river management. It is undertaken primarily to reduce the lateral activity caused by river meandering, which occurs as a result of outer bank erosion in bend ways (Blanckaert and Graf, 1999). The outer-bank cell attains its maximum strength in the zone most susceptible to bed scour and bank erosion, confirming its morphological significance. The outer cell is generated primarily by reversed near-surface gradients in the streamwise velocity profile (Blanckaert et al., 2012; Wahyuningtyas et al., 2026; Agnihotri et al., 2022). It is most severe close to the outer bank in bends due to the higher velocities and deep bed scours caused by bend effects (Blanckaert and Graf, 1999; Moghavvemi et al., 2025).

In a channel bend, the highest erosion rates are found along the outer bank and just downstream of the bend apex (Minor et al., 2007). The greatest scour was observed experimentally along the outer bank near the bend exit (Jamieson et al.,2013). The bending experiment shows the core of maximum velocity, Vs, max = 1.5U (average velocity), was observed near the outer bank and in the lower portion of the flow depth (Blanckaert and Graf, 2001). The transverse fluctuations are more intense than the vertical ones. The most notable aspects detected in the experiment are the presence of an outer-bank cell of secondary circulation and the decrease in turbulent activity near the outer bank (Homayoonnezhad & Amirian, 2025, Ghaffar et al., 2024). The core of the highest velocity is located far below the water's surface, between the central zone and the outer-bank region.

Numerous studies on the outer bank exist, such as this conducted by Duarte, (2009) at this study, three tests were conducted in a 193° laboratory bend with varying outer-bank features; the results indicate that as outer-bank roughness increases, the outer-bank cell grows and expands additional results the outer-bank cell is smaller and weaker in trapezoidal channels than in rectangular channels. The study that presented by Konsoer, et al., (2016) was interested to investigate the relationship between outer bank roughness and near-bank flow parameters in two long meander loops. The study concluded that, flow structure and bed morphology in large elongate loops are comparable to those in small elongate loops but distinct from those in experimental elongate loops (Wanigasooriya, 2025; Fitriana, 2023). The experimental study had been conducted by Roca, et al., (2012) in 186°-flume, to investigate the efficacy of scouring reduction and bank protection at the outer bank of an open-channel bend using a horizontal footing. The reduction in scouring caused by the footing is the result of two phenomena: i) the development of a transverse bed slope is slowed, and (ii) the secondary flow's outward velocity redistribution is diminished. Blanckaert, et al., (2009) in their paper creates and evaluates a numerical model of river morphology for meandering bends with erodible cohesion banks. Using data from two flume tests and a natural river channel, the performance of the model is assessed. The model underestimates the scour depth in pools adjacent to the outer bank and, consequently, bank migration rates (Jam et al., 2025). Through adopting a numerical modeling, Dulal, et al., (2010) study focused on the application of the slump failure mechanism of free meandering, it considered a recent accomplishment in the modeling of outer meandering river bends. Similar to actual rivers, the results reveal bar formation and projection, channel formation, and migration towards the outer bends, which lengthen the flow route and increase its sinuosity over time. According to the field data extracted on the 35° simple Sand-bed meander bend, normal stresses on the outer bank are greatest near the water's surface, with the greatest values at the bend's apex (Anwar, 1986). Engel, F.L et al (2017) for their study, employs high-frequency flow velocity measurements to investigate the turbulence characteristics near the outer bank of an actively moving compound meander curve.

Observations from the field indicate that turbulence structure is associated with curvature-induced effects via the increasing advection of high momentum fluid toward the outer bank. These data validate this fundamental mechanism for bank erosion. This analysis provided the foundation for a conceptual model of the structure of the outer bank turbulence for this meander bend. The experimental data of bed scour and three-dimensional flow patterns around a spur dike located at various sections in a 90° channel under clear water and steady flow conditions demonstrate a correlation between the maximum depth of scouring and the Froude numbers, lengths, and locations of the spur dike in the bend (Ghodsian, M. et al., 2008; Khan et al., 2024). Maatooq and Adhab, (2017) examine an experimentation plan to determine the performance of a vane in a 180° bend flume by utilizing various distances from the outer bend to the width of the flume. Based on the application of selected standards to the results, it was determined which distance of submerged vanes from the outer bank improves performance. Kalamizadeh, et al., (2021) installed permeable triangular vanes (PTVs) comprised of six-pillar elements to assess scour and sediment deposition in a 180° flume bend. The results demonstrated that permeable triangular vanes with an effective length to flume width ratio of 0.20 reduced the maximum scour hole and shifted the scour from the outer bank to the nose of the vanes. Bahrami and Bejestan (2016) examined the effects of varying the distance between triangular vanes on patterns of scouring deposition. Flume with a gentle 90-degree bend and triangular vanes under varying hydraulic conditions. With multiple vanes in place, the thalweg was observed to be shifted toward the flume halfway from the outer bank; consequently, it has been determined that triangular vanes function optimally when they are separated by 5 le (where, le, represents the vane's effective length from tip to the outer bank) or less.

Regarding studies related to spur dike, Vaghefi and Abdi, (2021) have been evaluated the effectiveness of a T-shaped spur dike in reducing scour around bridges installed with a 90-degree pier in a 180-degree sharp bend. According to the results, the construction of the T-shaped spur dike on the outer bank significantly reduced bridge pier scour. A laboratory work was conducted to measure the local scour which is formed around single circular pier fixed at each 30° of the bend while adopting three different diameters. The results show that the maximum depth of scour and the maximum extents (length and width) of scour hole, and maximum modification factor due to bend have occurred when the pier is located at sector 90o of the bend (Maatooq and Mahmoud, 2018; Noor et al., 2022).

Bridges built across a river bend and supported by more than one pier has been experimentally studied regarding the shape and nature of erosion and deposition. For this purpose, a U-shaped laboratory channel was used with two oblong piers installed at different locations. The first one was at the mid-section of the upstream straight reach, whereas in the second site within the bend, the piers have been installed at sections of central angles 0°, 30°, 60°, 90°, 120°, 150°, 170°, and 180°, from the beginning to the end of the bend segment respectively. The studies were conducted under clear water and threshold flow conditions. The results show that the higher and lower values of local scour around the pier positioned close to the outer bank, are 1.803 and 0.623 times the pier width when the bridge was installed at an angle of 90° and 30° respectively (Abdulwahd and Maatooq, 2023; Shah et al., 2024).

Through a brief presentation of what previous studies have targeted, especially when there are bridge piers within a river bend, it is noted that, despite the importance of piers in a bend of river, the effect of bridge to erosion at the outer bank has received less attention.

Accordingly, the novelty of this study is its focus on the effect of the presence of bridge piers installed in a specific section within the curved reach of the river on the nature, extent, and magnitude of the erosion that will occur on the outer bank of the bend. This will be represented in the current study by using a model consisting of two oblong bridge piers of a specific diameter, installed at specific sections within a sharp bed of a laboratory flume with a sandy bottom uniform sand gradation.

2. Materials and Methods

2.1 Laboratory U-shaped flume

To complete the current study, a laboratory U-shaped flume was used. This flume was located in the Hydraulic Laboratory of the College of Civil Engineering at the University of Technology-Iraq. The lengths of the straights that comprise the upstream and downstream segments of the flume were 1.66 and 2 meters, respectively. The bend reach is represented by the curved segment at 180° working section that joins these two reaches. The radius of curvature of the curved section is 0.375 m at the inner bank, 0.675 m at the middle of the flume, and 0.975 m at the outer bank to replicate a bend in rivers and canals. Water was extracted from a sump tank and pumped into the flume by a centrifugal pump with a capacity flow rate of 280 liters per minute (4.67 liters per second); this pump was powered by a rotameter-type flow meter, which also served as a discharge measurement device. A manually controlled valve provided the desired discharge.

To measure the depth of the erosion, a point gauge and laser instrument are used. The flume bed is covered by sand with an average particle size of d_{50}=0.305 mm and is used as a representative particle size for sediment, and the degree of uniformity of the particle size distribution is measured. σg= 1.278. This value is smaller than 1.3, which was used as a measure of sediment uniformity.

The bridge's oblong piers were 3 cm wide, 9 cm long and equally distributed from the flume sides, with a spacing of 20 cm between the centers and the walls. All studies under clear water condition with a 0.98 intensity (v/vc). The oblong piers were positioned in the mid-section and the end of an upstream straight line, 60^o, 90^o, 120^o and 180^o as sketched in Fig. 1.

2.2 Experiments

For all of the experiments prior to beginning any run, the sediments at the flume's bed were re-plowed and levelled with scrapers using some water. The tail gate of the flume was closed to fill the flume gradually with the required depth of water. At this point, the pump was turned on with the required discharge, and the tail gate was set to obtain the experiment's depth and intensity requirements. The pumps continue to turn on for 6 hours, after which the pumps stop, at this moment raise the gates to maintain the morphological of the channel unaltered, and then start the process of draining water from the bottom of the channel through small holes for a full day, and then the depths are measured using the laser device and the Point gauge with precision ±1mm. The depth, length, and angle of start of the erosion to the canal's outer bank were measured, and the results were compared to trials conducted without bridge for the same intensity and discharge.

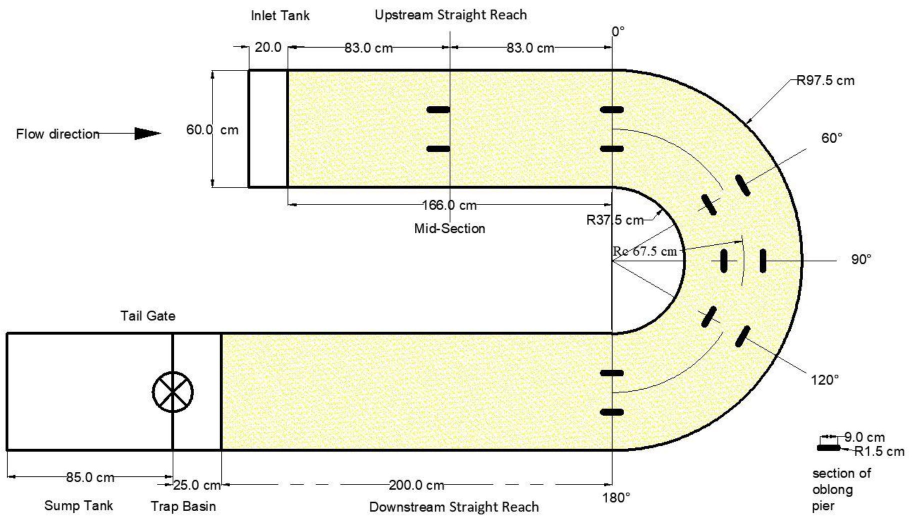


Fig. 1 Plan sketch of the flume

3. Results and Discussion

To investigate the influence of multi-oblong piers on the outer bank erosion under clear water conditions, a discharge of 280 L/min, 0.98 flow intensity, and 3.5 cm water depth were experimentally conducted. The locations of bridge piers installation have been identified, one at the upstream straight reach and the others within the U-shaped bend as depicted in Fig. 1.

3.1. Basic run without presence the piers

It worth notably that, one experiment run has been conducted without presence the piers to be use the resulting data as a base for comparison.

When water reaches the bend, it is forced centrifugally, which cause an increase in the outer bank's height and a drop in the inner bank's height. This causes water to migrate towards the outer bank at the surface, while water at the bottom moves towards the inner bank with transporting sediment that eroded from the outer bank. This is illustrated in Fig. 2(a) where it is observed during the first hour of the experiment that the accumulation of sediment on the inner bank of the bend with the appearance of dunes on the inner bank with the progression of time. As illustrated in Fig. 2(b) these dunes travel downward and towards the inner bank. At equilibrium the erosion has stopped at angle 126^o, which represents the commencement of the erosion of the outer bank, as illustrated in Figure 2d. Fig. 2(e) shows the longitudinal section of the outer bank at the end of experiment. It is obvious that a dramatic drop in the depth of the scour has occurred between angles 126^o and 132^o, with a depth of 4.6 cm. Generally, the depths of scour are fluctuated due to the formation of dunes but its trend is gradually increases towards the bend's end recording a maximum depth of 7.2 cm at angle 174^o.

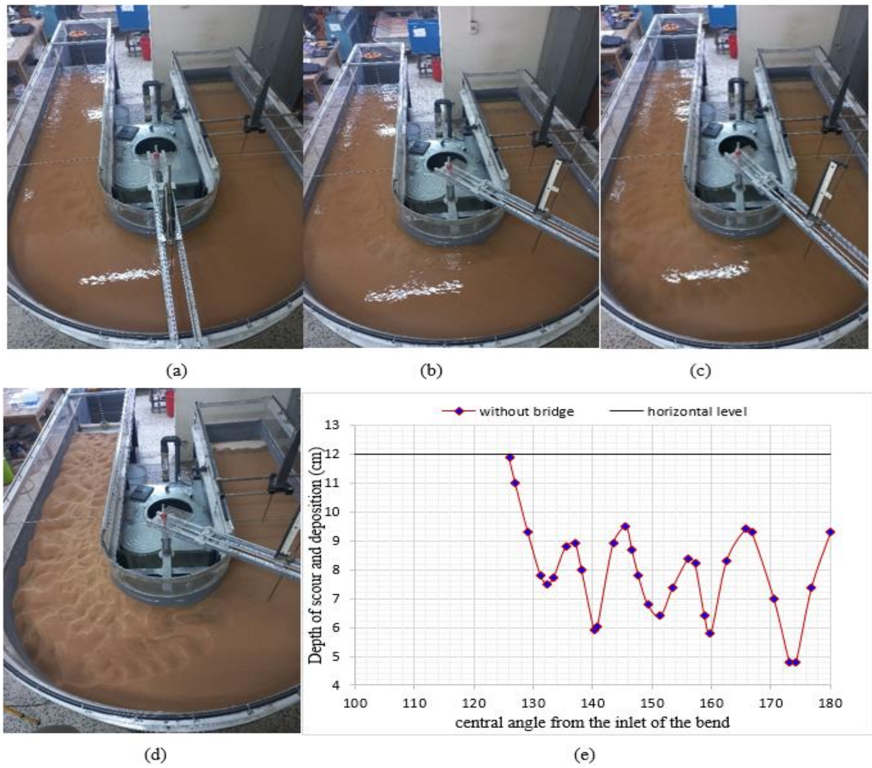


Fig. 2 Without bridge where Q=280, V/Vc=0.98. (a) at 1 hour after run, (b) at 3 hours after run, (c) at 4 hours after run, (d) at 6 hours after run (e) Longitudinal profile of bed along the outer bank without bridge after 6 hours

3.2. Piers installation before bend

Fig.3(a) show the morphological change when the bridge piers are installed at the mid-section of the upstream straight section of the flume, and the Fig.3(b) shows the length of the region exposed to erosion along the outer bank rises by 49.5%, with erosion start at an angle of 95^o, whereas the beginning of erosion was recorded at an angle 126^o for the run without presence of piers. For this run case, the erosion depths are also fluctuated along the outer bank, with the greatest depth value of 6.4 cm at angle 136^o.

This recorded scour depth is less than the highest value that recorded for run without piers, which was 7.2 cm at angle 174^o. It indicates that erosion has been reduced, but the length of the region exposed to erosion along the outer bank is increased. The existence of piers at the mid-section of the upstream is creating more turbulence, which inducing to more erosion near the outer bank when the flow inters the bend, increasing the shear stress at the outer bank, so the length of erosion increases accordingly.

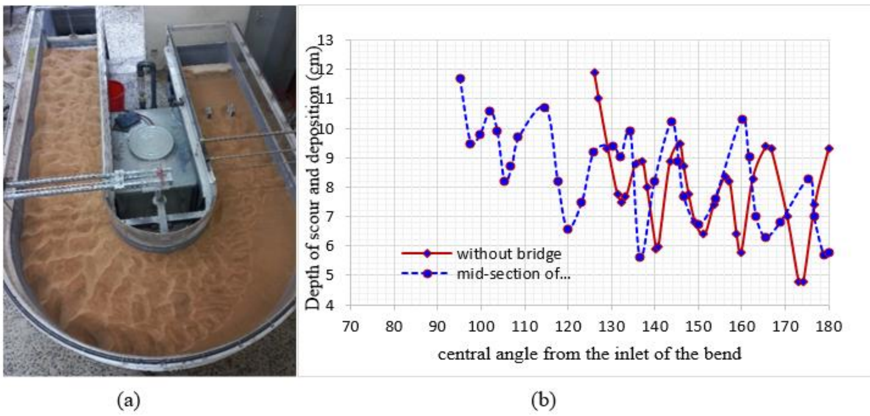
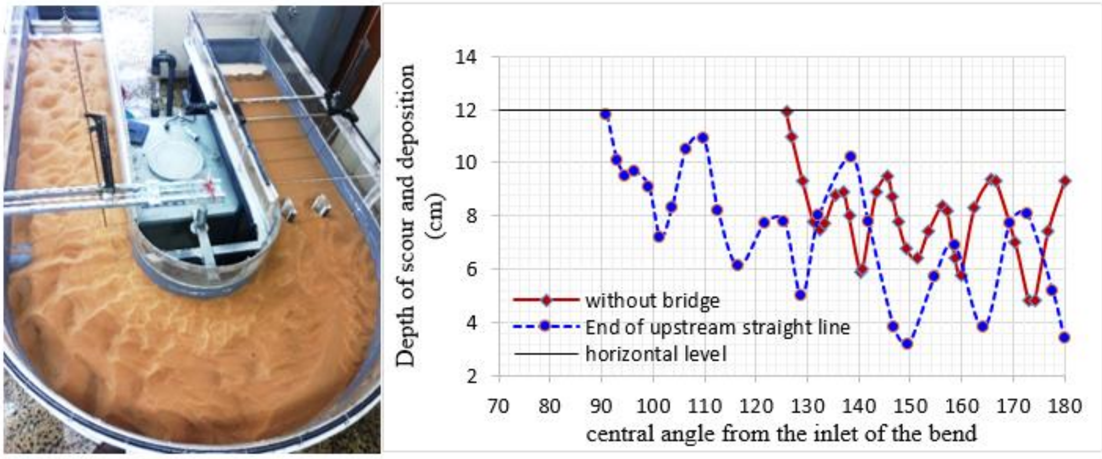


Fig. 3 Bridge at mid-section where Q=280, V/Vc=0.98. (a) photo of bridge after 6 hours, (b) Longitudinal profile of bed along the outer bank after 6 hour

3.3. Piers installation at the front of bend

The outer bank can be divided into two sections. A first section is from the beginning (front) of the bend, where the bridge piers are installed, up to the 70° angle, where small ripples and not appreciable depths of erosion can be observed due to slight disturbances generated by the piers adjacent to the outer bank. As for the second section, the influence of the centrifugal forces and the movement of the vortices that causes erosion will be predominant where the length of the region exposed to erosion along the outer bank increases by 55.4%, with erosion recorded at an angle of 91° as shown in Fig.4(a) and (b). In contrast, the beginning of erosion was recorded at an angle of 126° in the case of bridge absence. Also, the depth of erosion fluctuates along the erosion region, with the highest depth 8.2 cm occur at angle 149.7°, compared to what happened in the absence of a bridge, the highest scour value of 7.2 cm was recorded at angle 174°. That indicates the depth and length of erosion are increased, due to the wide area exposed to flow disturbance and the effect of secondary currents when the bridge located at the front of the bend (at the end of the upstream reach).

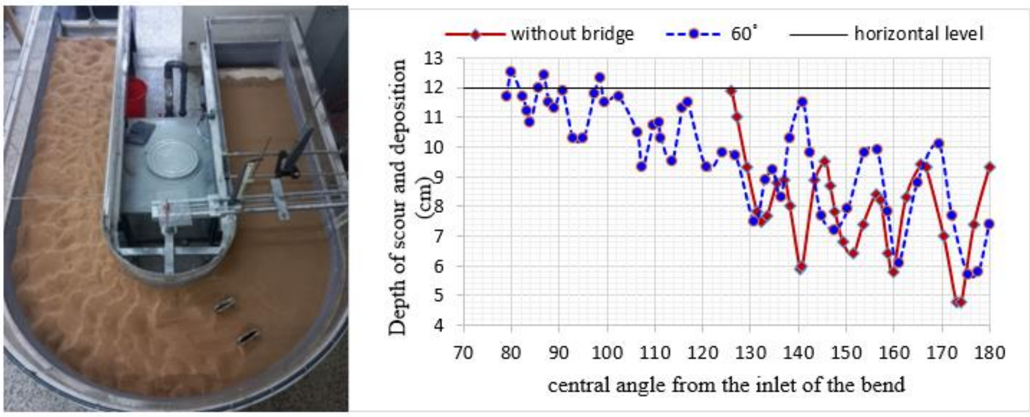


(a) (b)

Fig. 4 Bridge at the end of the upstream straight section, Q=280, V/Vc=0.98 (a) after 6 hours, (b) Longitudinal profile of bed along the outer bank after 6 hours

3.4. Piers installation at 60° inside the bend

It should be noticed that when the bridge located at the 60° of sharp bend flume, Figs.5 (a) and (b) the length of the region exposed to erosion along the outer bank rises significantly by 77.5%, as the start of the erosion had started at the angle 79°. That is because of the intensity of the spiral flow increases at section 0° to 60° of the bend, and then progressively decreases for the remainder of the bend [19]. Also, the erosion depth fluctuates along the erosion region, with the same trend of erosion recorded when there is no bridge except for the angle 140° which observed a reduction in scouring by about 95 %.

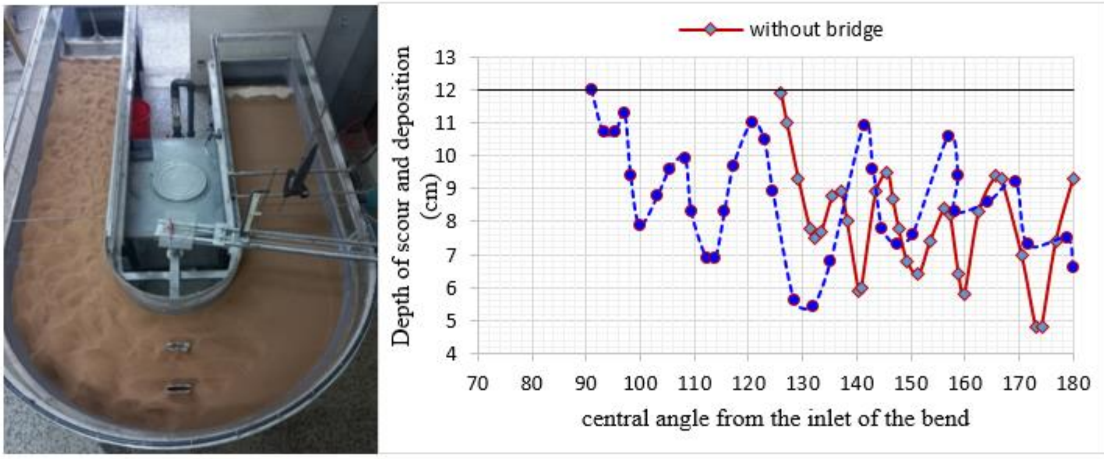


(a) (b)

Fig. 5 Bridge at 60°, Q=280, V/Vc=0.98 (a) photo after 6 hour, (b) Longitudinal profile of bed along the outer bank after 6 hour

3.5. Piers installation at 90° inside the bend

The length of the region affected by erosion along the outer bank rises by 55.4% when the bridge installed at the 90° of the bend, as shown in Figs.6 (a) and (b), where the erosion starting at an angle of 91°. However, the erosion along the outer bank when the bridge located at the apex of bend, appears through the results as well as the experimental observation less than these resulted when the bridge installed at 60°. This result can be attributable to the lateral kinetic energy at 60° become greater compared with this occurs when the piers are installed at the apex of the bend. The same conclusion has been observed by Asadollahi, et al., (2020). A noteworthy, the erosion depth alters along the erosion region, with the max value of 6.6 cm at an angle of 130°, then decreasing gradually towards the end of the bend at 180°.

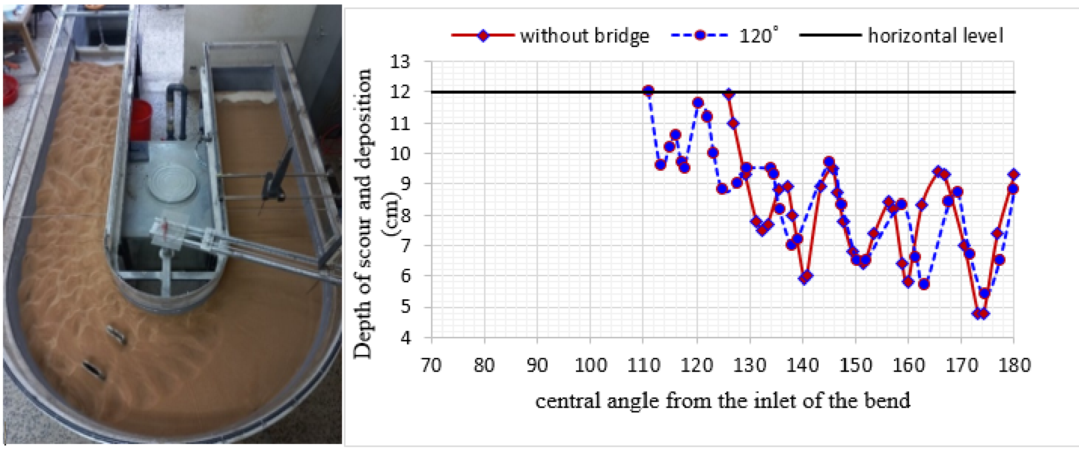


(a) (b)

Fig. 6 Bridge at 90°, Q=280, V/Vc=0.98 (a) photo after 6 hours, (b) Longitudinal profile of bed along the outer bank after 6 hour

3.6 Piers installation at 120° inside the bend

When the piers are installed at the 120° of the bend, it is observed that there is a great match in the scour results with the case without a bridge at angle 145° and beyond. As for the length of the part exposed to erosion, it began at angle 110°, with an increase of 20.5% compared to the length of erosion that the bank was exposed to in the absence of the bridge, as depicted in Figs.7 (a) and (b). This convergence of results with the no-bridge case can be attributed to the diminishing effect of the horseshow vortex and being parallel with the velocity vector after the first half of the bend, which leads to a reduction in the effect of turbulence and eddies resulting from the secondary current, that causes a decrease in the movement of sediment particles from the outer bank.



(a) (b)

Fig. 7 Bridge at 120°, Q=280, V/Vc=0.98 (a) photo after 6 hours, (b) Longitudinal profile of bed along the outer bank after 6 hour

3.7 Piers installation at 180° inside the bend

According to Fig. 8 (a) and (b), when the bridge is placed at the 180° (at the end of bend), the length of the zone along the outer bank that is significantly more vulnerable to erosion increases by 61.75% when compared to the case of no-bridge, where erosion recorded to begin at an angle of 87.5°. Furthermore, the depth of the erosion tends to increase up to the angle of 135° to about 6.6 cm, and decreases thereafter until the end of the bend.

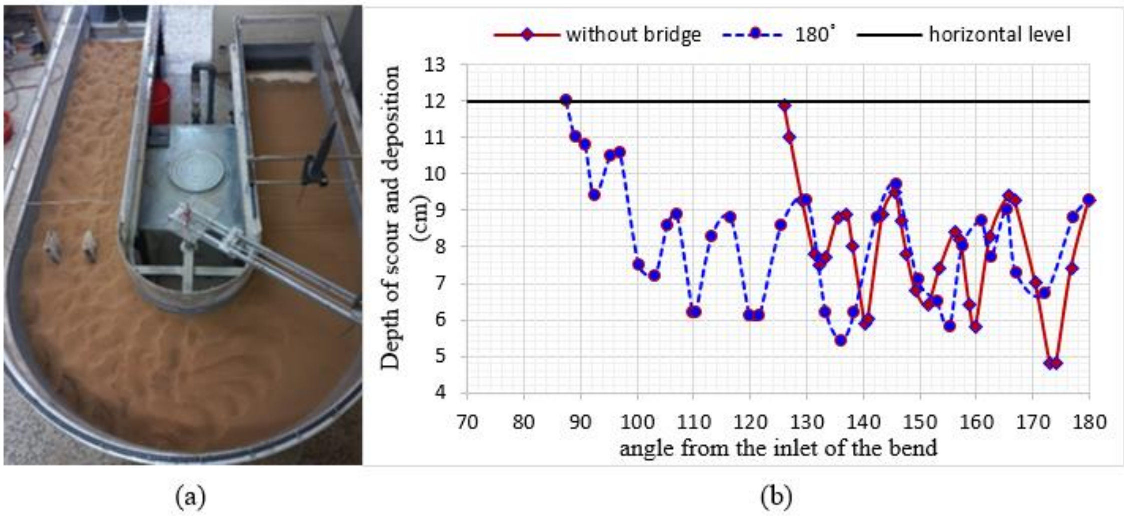


Fig. 8 bridge at 180^o, Q=280, V/Vc=0.98 (a) photo after 6 hours, (b) Longitudinal profile of bed along the outer bank after 6 hour

4. Discussion

In curved channels, flow tends to generate secondary current, leading to a complex and dynamic movement. Due to centrifugal forces, the flow typically rapidity up along the outer edge of the curve and decelerates down along the inner edge. As a result, sediments tend to be deposited on the inner bank, while the outer bank experiences higher pressure and flow velocity, which enhances the probability of erosion. In the case of no presence the piers, the secondary current's turbulence and movement continue within the second half of the bend, causing an increase in the erosion towards the bend's outer bank, where erosion is adjacent to the outer bank at 180o, then it rushes towards the front of the bend and along the outer bank, as shown in Fig. 2(c).

When bridge piers are installed at the mid-section of the upstream straight reach of the flume, the scour depth is less than the highest value that recorded for run without piers, which was 7.2 cm at angle 174^o. This result indicates that erosion has been reduced to being about 6.4 cm at approximately 136^o of the bend, but the length of the region exposed to erosion along the outer bank is increased. The existence of piers at the mid-section of the upstream is creating more turbulence, which inducing to more erosion near the outer bank when the flow inters the bend, increasing the shear stress at the outer bank, so the length of erosion increases accordingly.

Whereas, when the piers located at the end of upstream straight section the erosion was recorded to begin at angle 91^o compared to what happened in the absence of a bridge where the beginning of erosion was recorded at an angle of 126^o. Also, the depth of erosion fluctuates along the erosion region, with the highest depth 8.2 cm occur at angle 149^o. That indicates the depth and length of erosion are increased, due to the wide area exposed to flow disturbance and the effect of secondary currents when the bridge located at the front of the bend.

The increase in the length of the region exposed to erosion along the outer bank where the bridge piers at 60^o because of the intensity of the spiral flow increases at section 0^o to 60^o of the bend, and then progressively decreases for the remainder of the bend (Emami, et al., 2008).

When the piers are present at the 90^o of the bend, it causes less erosion compared to that measured when it is present at 60^o, this result can be attributable to the lateral kinetic energy at 60^o become greater compared with this occurs when the piers are installed at the apex of the bend. The same conclusion has been observed by Asadollahi, et al., (2020).

When comparing the presence of piers in 120^o with the case without piers, it is noted that convergence of results with the no-bridge case can be attributed to the diminishing effect of the horseshow vortex and being parallel with the velocity vector after the first half of the bend, which leads to a reduction in the effect of turbulence and eddies resulting from the secondary current, that causes a decrease in the movement of sediment particles from the outer bank.

5. Conclusion

Through experiment observation, it is clear that the process of erosion and sediment accumulation begins on the inner bank and gradually turns towards the outer bank and toward downstream, so that the process of erosion and dune formation begins at the end of the outer bank, that is, at the angle of 180^o, and erosive process moves towards the front of the bend, but it remains within the second half and does not entering to the part of first half of the bend.

Where bridge piers installed at a middle, at the end of the upstream straight section, at the 60^o, 90^o,120^o and 180^o into the bend section, the exposed length to erosion is increased by 49%, 55.4%, 77.5%, 55.4%, 20.5% and 61.75% respectively compared with the case of no-bridge.

The percent variation in the maximum scouring depth along the outer bank when the bridge located at the above mentioned six locations are respectively, -11%, +14, -11%, -8%, -7% and -11% as compared with no-bridge. It is noted that the increase in the maximum amount of erosion occurred only when the bridge piers were implemented at the section representing the beginning of the river bend.

For all experiments, the maximum scour depth was 2.4, 2.13, 2.73, 2.4, 2.2, and 2.2 times the pier width for the six selected locations respectively.

The results indicate that the presence of bridge piers within the river's bend results in an increase in the length exposed to erosion on the outer bank, but at the same time, it reduces the depth of erosion. Therefore, the presence of bridge supports has only a benefit in terms of reducing the depth of erosion on the bank, which is the same effect performed by the spur-dike structures

It is recommended to both the decision maker and the designer that the worst location for installing bridge piers is at the 60º angle, as this increases the length of the part subject to erosion, in addition to the increased depth of erosion. Accordingly, it is recommended to avoid installing bridge at this section of the bend. On the other hand, the best section for construction within the bend at the 120º angle, as the presence of the bridge at this angle has a positive impact on the nature and depth of erosion on the outer bank, both in terms of preventing a longer part of the outer bank to subject to erosion and reducing the depth of erosion, reaching the depth of scour along the bank that is, generally, lower than the depth recorded without piers.

Statements and declarations data availability

The data used in this research are provided in the text of the article.

Conflicts of interest

The authors of this paper declared no conflict of interest regarding the authorship or publication of this paper.

Author contribution

Maatooq: Methodology, Research Management, Supervisor, Review of writing and Editing; Abdulwahd: Investigation, conduting experimental works, evaluation the data,Writing the draft.

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