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Experimental investigation of local scour under two oblong piers of a bridge crossing a sharp bend river

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Abstract: 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. As for the pier close to the inner bank, the deepest local scour was 1.786 times of the pier width when the bridge was installed at 60° of the bend, while the least one was 0.516 times of the pier width when the bridge was located in the 180° sector. It is worth noting that the presence of piers within sector 150 is less affected by local scour than in the other sections.

Keywords: intensity of flow, local scour, oblong pier, sharp bend

INTRODUCTION

Bridges support nearly all transportation modes, and no transportation system is complete without them (Kothyari and Kumar, 2010). In 1973, the Federal Highway Administration (FHWA) assessed 383 bridge failures caused by extreme floods across the country and found that 75% of the failures involved abutment damage and 25% pier damage (Richardson and Davis, 2001). In 1985, 73 bridges were destroyed by floods in West Virginia, Virginia, and Pennsylvania. During the spring floods of 1987, 17 bridges in New York and New England either sustained scour damage or were totally destroyed. In the United States as of April 2002, there were 20,353 scouring sensitive bridges and 26,149 scouring critical bridges (Richardson, 2002). According to statistics and information acquired in certain nations, scouring is the leading cause of bridge destruction (Heidarnejad, Bajestan and Masjedi, 2010). Scour around the pier reduces the retention length and makes the foundation base exposed to currents. This leads to the pier collapse and the inevitable failure of the bridge (Oveici, Tayari and Jalalkamali, 2020). Local scour is defined as a reduction in bed level in the vicinity of an obstruction resulting from the flow effect of the obstruction (Chiew and Melville, 1987). The mechanism of local scour occurs due to the collision with water. The bridge pier creates local scouring in the bed near the position of the pier, which is related to flow separation phenomena and vortex formation around the bridge pier. This phenomenon, which is one of the leading causes of a bridge failure, is characterised by a horseshoe-shaped vortex in front of a pier and diverse flow patterns created around it (Solati, Vaghefi and Behroozi, 2020). Natural rivers seldom run in straight lines, on the contrary, they frequently have bends, and meandering or braided courses (Moghaddassi *et al.*, 2021). The sediment movement in the meandering stream includes morphologic elements, such as a pool caused by erosion and a point bar when depositions occur (Maatooq and Hameed, 2019). The forecast of scour depth surrounding bridge piers is important for hydraulic engineers (Muhsen and Khassaf, 2022).

The majority of research have focused on scouring at a bridge pier in a straight channel, but a local scour at a bend is of enormous importance, and numerous studies have been conducted to date. Eghbalnik, Vaghefi and Golbaharhaghigh (2019) investigated the temporal variation of scour depths and bed topography in the presence of six vertical and inclined cylindrical piers positioned in a 180-degree bend flume. The piers were placed at a 60-degree bend in the flume, and the maximum scour depth changed with time, moving from the inner bank to the centre of the flume and then to the outer bank. Asadollahi, Vaghhefi and Tabibnejad Motlagh (2021) used the Sediment Simulation In Intakes with Multi-block option (SSIIM) model to evaluate flow and scour patterns when a 180-degree bend was constructed with no pier, a single cylinder pier, and triple piers, respectively. Sedighi, Vaghefi and Ahmadi (2020) examined the effects of an inclined pair of piers on the bed topography in a sloping river bend under three separate conditions: clear water, incipient motion, and a movable bed at 60°, 90°, and 120° of the bend. For a pair of V-shaped piers, the scouring was greater on the pier closer to the bends beyond the border. Chooplou and Vaghefi (2019) studied variations in shear stress along a bend, particularly around a bridge pier, when submerged vanes were implemented upstream of the bridge pier. As the flow enters the bend, the secondary flow strength has two maximum values: one at the bend apex and another at the bend end. Vaghefi *et al.* (2018) evaluated scouring around piers perpendicular to flow (PPF) and piers toward the flow (PTF) by putting a set of three cylindrical piers at 60°, 90°, and 120° of the bend. The PPF test, which included a pier positioned at 90° of the bend, showed the largest depth of scouring. Vaghefi *et al.* (2017) were able to measure the amount of bed topography changes and scour around a rectangular bridge pier with an oblong nose, by creating a base-level fall at the start of the 180-degree sharp bend. Ben Mohammad Khajeh, Vaghefi and Mahmoudi (2017) examined the depth and location of scour around an inclined cylindrical bridge pier at the apex of a severe 180-degree bend and compared the results to those obtained for a vertical pier. The largest and smallest scour depths were generated adjacent to the pier's outside and inner banks, respectively. Emami, Salamatian and Ghodsian (2008) studied scour in both a straight and U-shape channel with a central angle of 180°. To study local scour, a pier was placed in a straight channel as well as at 30° and 60° in the bend. In a straight channel, the scour depth was shallowest, however it increased when the pier was at an angle. The bends scour is close to the outer wall of the channel, while the point bar is close to the inner wall. One ogival model pier was utilised for the experiment in a laboratory flume with a 180-degree curve. The scouring depth was the largest at 60°, and it increased with the Froude number (Masjedi, Zeraat and Hydarnejad, 2011). Rasaei, Nazari and Eslamian (2020) created a physical hydraulic model with a converging curve at an angle of 90°. Under conditions of clear water, a cylindrical pier was positioned at angles of 0°, 30°, 45°, 60°, and 75°, and local scour was measured. Additionally, the SSIIM-2 numerical model was used to simulate the scour pattern, and the results were compared to those obtained experimentally. The largest scour depth and volume occurred at an angle of 75° in the second segment of the curve. Maatooq and Mahmoud (2017) examined the local scour at the equilibrium state, which was centred on a single rectangular pier fixed in the middle of the section at every 30 degrees of the 180-degree arc. When the pier was located in a sector that is 90° from the curve, the maximum depth and extent of scouring occurred.

Through the foregoing, we find that the previous studies of local scour around a bridge pier when it is located within the sharp bend of a river have focused on a single circular pier positioned on the longitudinal central axis of the bend. From that, the idea adopted for the current study is to investigate experimentally whether the shape, depth, and extension of the local scour would occur when a bridge rests on two "oblong" piers installed at specific sections within the sharp bend of a river.

The aim of the current study is approach reality, and it is expected that the outputs obtained through laboratory experiments will provide additional knowledge in this field. Previous study indicated that one pier was employed in the majority of situations, with only a few studies focusing on double and triple piers. Furthermore, because circular piers were the most commonly utilised in earlier research, it was important to investigate the multi-oblong pier types that are widely employed in bridge construction. The aim of this study was to determin the optimal location of multi-oblong pier bridges and investigating the state of local scour around piers at various locations before and within the river sharp bend sections. In addition, the determining of the depth of scouring around piers in any section within the bend is recommended.

MATERIALS AND METHODS

A LABORATORY U-SHAPED FLUME

A U-shaped laboratory flume that was used to conduct the tests (Fig. 1). This flume was designed using AutoCAD and consisted of 1.66 and 2 m in length upstream and downstream straight reaches respectively. It was located at the hydraulic laboratory of the civil engineering department, the University of Technology-Iraq, and used for the experimental programme of the present study. The working portion that joined these two reaches was at an angle of 180° and had a radius of curvature 0.375 m at the inner bank, 0.675 m in the centreline of the flume, and 0.975 m at the outer bank. The width of the flume for all straight and bend segments was 0.6 m to confirm that Rc/B = 1.125 < 3, as recommended by (Leschziner and Rodi, 1979). There, Rc is the radius at the centreline of the bend and B is the width of the bend. A centrifugal pump capacity was 280 $dm^3 \cdot min^{-1}$ (4.67 $dm^3 \cdot s^{-1}$), powered by a rotameter-type flow meter that also acted as a discharge measurement device. It was used to deliver water from a sump tank to the flume. The desired discharge was selected by a manually controlled valve.

SETUP AND PROCEDURE

The flume bed was covered with horizontal level of homogenous sand to a depth of 12 cm, with a median particle size d_{50} = 0.305 mm, and the degree of uniformity of the particle size distribution σ_g = 1.278. This value was smaller than 1.3, which was used as a measure of sand particle uniformity (Chiew and Melville, 1987).

Two oblong piers (12 × 3 cm, length × width, respectively), equally spaced at 20 cm from the flume sides having the span in between, were installed to simulate the ratio of a bridge crossing pier length to its width (L/b = 4). The rectangular pier length had to be at least three times its width, as recommended by (Melville and Sutherland, 1988). Most of the runs were conducted at flow intensity less than one, v/v_c = 0.98, which was the basic flow pattern for maintaining a clear water condition with a water

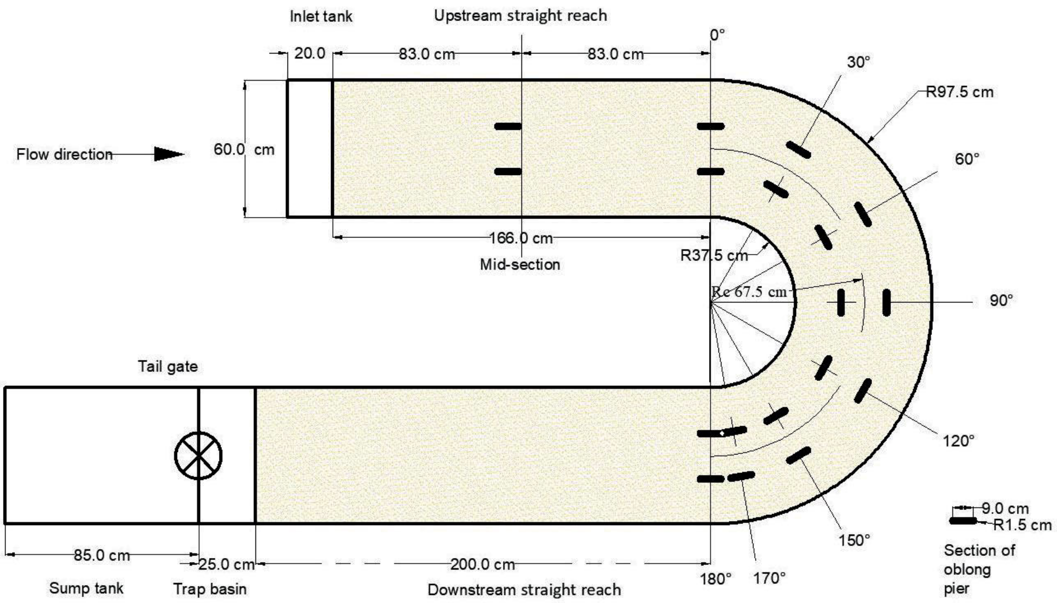

Fig. 1. Sketch of the flume; source: own elaboration using AutoCAD

depth 3.5 cm with approach velocity v = 0.222 m·s^{-1} and subcritical flow that Froud number Fr = 0.378. The critical velocity was calculated by using formula published by (Melville, 1997):

$$v_{*c} = 0.0115 + 0.0125(d_{50})^{1.4} \tag{1}$$

where: v_{*c} = the critical bed shear velocity (m·s^{-1}), d_{50} = median particle size (mm).

$$\frac{v_c}{v_{*c}} = 5.75 \log\left(5.53 \frac{y}{d_{50}}\right) \tag{2}$$

where: y = depth of water.

Critical bed shear velocity (v_{*c} = 0.01387 m·s^{-1}) and critical velocity (v_c = 0.223 m·s^{-1}) were used in the current investigation. The bridge was installed to cross the mid-section, and then on the centreline of the bridge, oblong piers were installed within the bend at the central angles of 0°, 30°, 60°, 90°, 120°, 150°, 170°, and 180° as shown in Figure 1. The topography of the bed along the transverse section between the outer and inner banks, passing through the nose of the two piers, were measured using a point gauge and a laser distomat device. When a multi-oblong pier bridge was present in the flume, measurements were taken around the piers by taking the centre angle, every 1 or 2° and the transverse distance every 2 cm to investigate local scour depth longitudinally, transversely, deposition of sediment behind the piers, and their extensions. The remaining length of the bend readings were made every 10° centrally and 2 cm transversely.

The base experiment was conducted where a bridge model at the mid-section of the upstream flume with the same flow conditions was used for comparison. During this research, the discharge of 280 dm^3·min^{-1} and the maximum intensity of 0.98 was applied to all sections. The duration for all experiments was 6 h adopted based on the recommendations of previous studies with similar flow conditions through which the scour approached to the equilibrium state (Heidarnejad, Bajestan and Masjedi, 2010; Masjedi, Zeraat and Hydarnejad, 2011; Wang *et al.*, 2016; Rasaei, Nazari and Eslamian, 2020). The depths of the bed at end of each run were determined using a point gauge and a laser instrument which were used by many researchers (Vaghefi *et al.*, 2017; Chooplou and Vaghefi, 2019; Rasaei, Nazari and Eslamian, 2020; Moghaddassi *et al.*, 2021; Sedighi, Vaghefi and Ahmadi, 2021). It was verified that the depth of the bed surface on a randomly set of points could be measured using a laser instrument and a point gauge, with a correlation coefficient of 0.98, as shown in Table S1.

RESULTS AND DISCUSSION

GENERAL INFORMATION

First, a test on piers with a straight line was undertaken in order to evaluate the outcomes of local scour in which piers were at a curve with those of piers at a straight line. In every test, the scouring was caused by a downward flow at the pier front, which created and developed scour there. A stronger horseshoe vortex was created as the scour in front of the pier increased depth. Sediments on upstream, downstream, and left sides of the pier were then raised by the wake vortex and exposed to the main current (Ben Mohammad Khajeh, Vaghefi and Mahmoudi, 2017). The piers were situated at nine sections of the flume under a flow rate of 280 dm^3·min^{-1} and an intensity of 0.98 as shown in (Fig. 1).

With the above flow conditions, it is possible to explain and discuss the state of the curved river bed at the site of the bridge and beyond downstream at the end of each run, as listed below.

A BRIDGE AT A MID-SECTION OF THE UPSTREAM STRAIGHT REACH

Once a bridge is installed at the mid-section of the upstream straight reach, at the beginning of experiments, especially in the first half hour of the flow, the local erosion is very high. Then, it decreases gradually because the strength of the erosive action at the bed decreases as the scour continues until it finally reaches the equilibrium. The material that has been eroded from a scour hole is deposited by the action of a horseshoe and weak vortices at the downstream end of the pier at a level higher than the adjacent bed. It is in agreement with the results indicated by Carmo (2005), Wang *et al.* (2016), Asadollahi, Vaghefi and Akbari (2020), Ben Mohammad Khajeh, Vaghefi and Mahmoudi (2017), Vaghefi *et al.* (2017), Vaghefi *et al.* (2018), Eghbalnik, Vaghefi and Golbaharhaghighi (2019), Oveici, Tayari and Jalalkamali (2020), Solati, Vaghefi and Behroozi (2020), Sedighi, Vaghefi and Ahmadi (2021), and Keshavarz, Vaghefi and Ahmadi (2022). It appears that both piers have the same depth of local scour (3.14 cm), in addition to the approximate symmetry of the longitudinal and transverse profiles of the bed according to Emami, Salamatian and Ghodsian (2008). They show that the scour hole and pointed bar are symmetric around the middle line of the channel. As shown in Fig. S1, the percent of local scour depth that occurs at the apex of piers can be estimated at 1.05 times of the pier width.

A BRIDGE AT THE 0° SECTOR OF THE BEND

An increase in the depth of the local scour at the inner pier was observed when taking into consideration that the centreline of the bridge was installed at the end of the upstream portion of a straight reach. At the same time, this section was considered to belong to the bend reach, and represented the first section of it at a zero-axial angle. Then, a reduction in the depth of the local scours occurred at the outer pier. Lateral flows from the outer bank to the inner bank were required to maintain flow continuity because longitudinal acceleration increased around the inner bend and decreased significantly at the outer bend, causing an increase in local scour around the pier near the inner side and decreased around the pier near the outer bank (Vaghefi, Akbari and Fiouz, 2016). According to Fig. S2, the depth of scour relative to pier width (d_s/b) were 1.163 and 0.926, respectively, and the local scour depth measured was 3.49 cm and 2.78 cm for the inner and outer piers respectively.

A BRIDGE AT THE 30° SECTOR OF THE BEND

When the bridge is installed across the 30° axial section of the sharp bend reach, it can be noticed a large rise in the local scour depth and volume of erosion related to the inner pier and a relatively significant decrease in the scour depth at the apex of the outer pier. These results depend on maximum velocity redirected towards the inner wall at the action of the centrifugal force which is more effective beyond the 0° cross-section (Vaghefi, Akbari and Fiouz, 2016). As shown in Figure S3, the local scour depth is 4.12 cm and 1.87 cm and correspond to 1.37 and 0.62 times of pier width for the inner and outer piers, respectively. Based on this finding the scour at the apex of the inner pier has been increased when it is installed at 30° section instead of the 0° section, whereas the reverse situation occurs for the outer pier, referring to the values of d_s/b.

A BRIDGE AT THE 60° SECTOR OF THE BEND

The scour around piers when the bridge is installed across a 60° sector is characterised by a larger increase in the local scour depth and volume of scour holes at both the inner and the outer piers. The largest scour is observed at the inner pier because of the increase in the velocity which causes increase in shear stress around the inner pier. The results obtained by Emami, Salamatian and Ghodsian, 2008, include the highest local scour at the 60° sector. The local scour depth is 5.36 cm and 2.54 cm corresponding to 1.79 and 0.85 times pier width for the inner and outer piers, respectively, as shown in (Fig. S4).

A BRIDGE AT THE 90° SECTOR OF THE BEND

It should be noticed that local scour to the inner pier was less severe when the bridge was at an angle of 90° than when it was at an angle of 60° and accumulated sediment was observed behind the piers. In the case of flow around the bend, sediments accumulated on the inner bank due to centrifugal forces and the difference in water height between the outer bank and the inner bank of the flume. This caused the movement of eddies from the outside to the inside at the bed of flume and the movement of sediments from the outer bank. Thereby, it increased the amount of sediment feeding from the outer bank (Raudkivi and Ettema, 1983) which led to less scour around the inner pier compared with the amount that occurred around the same pier when the bridge was installed at previous sections where the value was 3.44 cm. Moreover, the maximum velocity remained near the outer bank within the second half of the way to the end of the route (due to the rise in secondary flow strength) (Vaghefi, Akbari and Fiouz, 2016). This led to the action of secondary current to increase the equilibrium local scour around the outer pier up to 5.41 cm contrary to the case recorded in the previous sections for the same pier. Fig. S5b explains that the area between the piers is susceptible to erosion due to an increase in local scour between both piers. The relative scours to the width of the pier are 1.15 and 1.80 for the inner and outer piers, respectively, as illustrated in Fig. S5a, c and d.

A BRIDGE AT THE 120° SECTOR OF THE BEND

Whenever the bridge is located at this sector, the local scour just upstream of the piers increases, and its trend is towards the outer bank, while the deposition depends on the condition of the inner bank. It is important to note that the local scour at the outer pier is slightly higher than at the inner pier. As can be seen in (Fig. S6), where d_s/b is 1.05 for the inner pier and 1.61 for the outer pier, the value is 3.16 and 4.84 cm respectively. Because of the pier's presence and the deposition at the inner bank, the flow velocity corresponding with the centrifugal action near the outer bank increased, creating a scour hole that extends along the outer bank from sector 105° up to 180° at end of the bend. The flow at the pier site is pushed toward the outer bank by the pier geometry. As a result, the scour hole surrounding the pier widens towards it as the flow shifts to the outer bank (Solati, Vaghefi and Behroozi, 2021).

A BRIDGE AT THE 150° SECTOR OF THE BEND

As it seems obvious when the bridge crosses the 150° sector of the sharp bend, the local scour at the inner pier appears low in comparison to all other previous locations for the same pier within the bend. It results from the decrease in flow velocity, as the secondary flow gradually weakens and the core vortex weakens (Vaghefi, Akbari and Fiouz, 2016). Figure S7b shows that the rate of erosion increases towards the outer bank. The local scour depths are 1.96 cm and 3.30 cm at the inner and outer piers respectively to get a dimensionless local scour ratio at the apex of each pier (d_s/b) of 0.65 and 1.1 for inner and outer piers respectively as depicted in Fig. S7c and d.

BRIDGE AT SECTOR 170° OF THE BEND

A significant local scour is recorded when the bridge is situated at the sector above 170° than the previous one. On the other hand, the slope of the frontal scour face becomes steeper. The same is true for the lateral section. The local scour depths at the inner and outer piers are 2.64 cm and 4.52 cm, respectively, and the d_s/b are 0.88 and 1.50, as shown in Fig. S8. The local scour depth is larger at the outer pier and smaller at the inner pier, which is attributed to the secondary current carrying sediment particles from the outer bank towards the inner one.

A BRIDGE AT THE 180° SECTOR OF THE BEND

At the end of bend, where the sediment accumulation increases towards the inner bank and the erosion continues adjacent to the outer bank, the local scour depth is reduced around the inner pier and increased at the pier near the outer bank, as in Fig. S9c and d. At the same time, appreciable deposition has been found behind the outer pier. The inner and outer piers have local scour depths of 1.55 and 4.43 cm, and represent 0.52 and 1.48 times of pier width, respectively. The reduction in scouring around the inner pier can be attributed to the continuation of deposition along the inner bank within the bend and it increases towards the end of the bend. Therefore, it is logical that is shows less erosion around the pier that lies on the path. In the case of the external pier, the hydrodynamic effect is exactly opposite. The external pier is located next and close to the erosion path, and it continues to increase along the outer bank of the curvature. This is attributed to an increase in erosion around the external pier of the bridge.

SUMMARY

A U-shaped canal was used to study the local scour around piers when constructing a multi-oblong piers bridge, with nine flume locations. They were set at the mid upstream section within sectors of 0°, 30°, 60°, 90°, 120°, 150°, 170° and 180°. Conditions were the following: discharge of 280 dm^3·min^{-1}, 0.98 intensity, 3.5 cm of water depth, subcritical flow in a steady state, horizontal level bed flume with 12 cm of sediment thickness, the median particle size of 0.305 mm, degree of uniformity of the particle size distribution of 1.278, and duration of each experiment of 6 h.

Before starting each experiment, the surface of the canal was levelled by adding a small amount of water and using a scraper to level the bed surface. After that, water was gradually added until the required depth was reached. It was followed by pumping with the required discharge and water depth control by the channel tailgate. At the end, water was gradually drained from the flume's bottom during 24 h to avoid any morphology deformation. A laser device was used to measure the depths inside the flume while a point gauge was used to measure the topography close to the edges. Laser measurements were validated by calibration with the point gauge. To increase the measurement accuracy, a 2 cm transverse interval was applied between each reading and a 1–2° angle at the pier in the bend segment.

Figure 2 illustrates the relationship between the local scour depths at the two piers near their respective outer and inner edges relative to the scour depth in front of them when they are in the mid-section of the upstream reach (straight reach equal to pier width). Where the pier was close to the inner bank of the bend, the local scour depths increased up to angle 60°, where the deepest value of the local scour was recorded (1.786 times local scour depth where pier was in mid-section of upstream reach). Then it gradually descended to the angle 150°, where the lowest depth was recorded 0.653 times of local scour depth in the mid-section of upstream after that section increased slightly at 170°. At the end of the curve, it lowers again, recording the lowest value of 0.516.

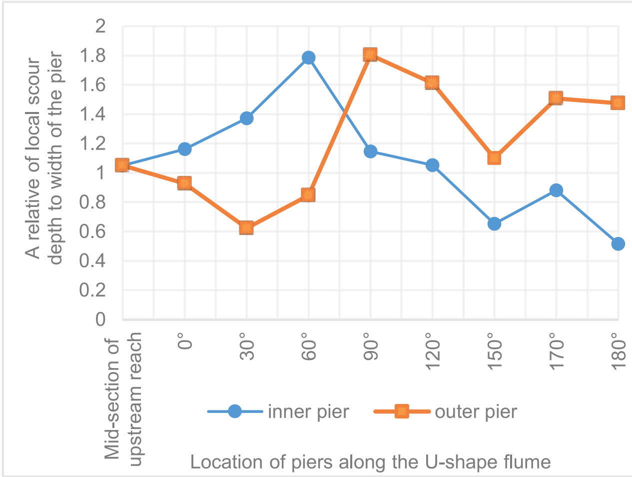

Fig. 2. Relationship between local scour depths at the two piers near the outer and inner edges relative to the scour depth at the mid-section of the upstream reach; source: own study

As for the piers close to the outer edge, it is noted that the depth of scour decreases along such progressions towards the curve end, where it records the lowest value of relative scour at 0.623 at 30° angle. Then, it gradually increases at 60°, and sharply increases at 90°, where the largest value of relative scour has been 1.803. The value of the slope gradually drops until it reaches 150°, where it records the lowest value of relative scour of 1.1. After that, the value of the slope climbs to 170°, recording 1.5 relative scour, and continues to be around the same value until the curve ends.

CONCLUSIONS

This study included an investigation of the local scour depths around the multi-oblong piers of bridges built in the various positions at river sharp bend zones under clear water and threshold conditions. Such conditions must be considered during designing in order to avoid bridge piers being distorted.

The local scour depth at multi-oblong pier bridge situated in river bend areas varies from pier to pier depending on the distance from the bank and the location within the curve. Moreover, the local scour at piers is symmetrical in the straight reach with local scour equal to the width of the pier. At the first bend, the behaviour of local scour depth around piers is similar to straight reaches and approximately equal in value. Nonetheless, there is a slight increase in scour at the inner pier. After the first section within the bend, the scour depth around at the pier close to the inner bank increases compared to the pier close to the outer bank. This effect persists until the 60° sector, where the largest effect is observed 1.79 times of pier width.

When the bridge is set at 90° and 120° sectors, the maximum increase in the local scour around the pier close to outer bank has been observed. It is 1.8 and 1.61 times pier width, respectively, whereas a significant decrease in scour is noted around the pier close to the inner bank. This is due to the stronger impact of the secondary current restricted at these two sectors. Noteworthy, the findings of the local scouring around the piers for various pier locations demonstrate that 150° section is the optimal section for bridge building due to a significant decrease in scour values for both the inner and outer piers.

It is proposed that countermeasures be used to avoid erosion around the pier at the inner bank at the first section of the curve, specifically at the 60° sector. In the case of piers close to the outer bank in the second half of the curve, specifically in 90° and 120° sectors, countermeasures must be used to avoid erosion.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at https://www.jwld.pl/files/Supplementary_material_Abdulwahd.pdf

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