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ORIGINAL ARTICLE

Evaluation of angled splitters as scour countermeasure at circular piers

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Angled splitter;
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Velocity distribution;
Bed configurations

Abstract Scour around bridge piers is local phenomenon may cause complete failure for the hydraulic structure. This study explored experimentally using splitter plates at specific angles installed upstream single circular bridge pier to improve the nearby flow field and minimize the local scour. Ninety runs were carried out considering 9 splitter models. Four splitter lengths and 3 vertex angles were used. The splitter lengths were between 0 and 1.5 times of pier diameter, each was tested for 3 vertex angles ranged between 0° and 30°. The tests were done under 9 different hydraulic conditions including 3 discharges of 75, 100, and 125 l/s and 3 tailwater depths of 12.5, 15, and 17.5 cm. The turbulent flow conditions were investigated by plotting velocity profiles at different sections. The bed configurations under clear water conditions were presented. The results of pier without splitter were used as reference. The study outcome that the local scour depth was decreased by the increase of splitter length and vertex angle. The near-bed flow velocity and the corresponding Froude No. downstream of the pier was minimized for 1.5D splitter length at 30° vertex angle and the minimum scour geometry was located. The effectiveness of splitters were remarkable by the decrease of flow discharge and increase of tailwater depth provided that the discontinuity of scour hole length in case of multi-circular piers. Regression analysis was employed to develop empirical formula for the estimation of maximum scour depth around circular pier with splitter.

1. Introduction

Scouring around bridge piers and abutments is an important challenging issue in hydraulic engineering. Besides overloading collision, and lack of maintenance, localized scour is the common reason for bridge failures. Scouring at the bridge piers may be defined as local lowering in the bed level around the

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Nomenclature

B	Flume width [m]	X	The total distance measured from the apron toe [m]
b	The distance measured from the left wall to a given location along the flume width [m]	x_1	The distance measured from apron toe to a given location along the flume [m]
D	Pier diameter [cm]	y	Tailwater depth [cm]
ds	Scour depth [cm]	y_m	Specific point water depth [cm]
$ds_{max.}$	Maximum scour depth [cm]	ds/y	Relative scour depth [-]
d_{50}	Median particle diameter [mm]	$ds_{max.}/y$	Relative maximum scour depth [-]
F_r	Froude No. [-]	L/D	Relative length of the splitter plate [-]
g	Gravitational acceleration [m/s^2]	θ	Splitter plate angle [degree]
L	Length of the Splitter plate [cm]	ρ	Density of water [Kg/m^3]
Q	Flow discharge [l/s]	μ	Dynamic viscosity of water [Kg/m.s]
S_o	Bed Slope [-]	σ	Surface Tension [N/m]
V_m	Mean Velocity [m/s]		

pier, Chiew [1]. Many studies were presented to control the scour based on the geometrical changes in pier shape. Elsebaie [2] experimentally studied the local scour around circular bridge pier in sand soil to examine the maximum scour depth in addition the flow pattern in longitudinal and transverse directions. The study proved that maximum scour depth was directly proportional to flow discharge. Moussa [3] Applied 1-D and 2-D numerical models to simulate the local scour around Aswan and El-Minia bridge piers. The study concluded that the sharp-nosed piers gave the minimum local scour at normal flow conditions. EL-Alfy et al., [4] experimentally explored the effect of bridge pier shape as a local scour countermeasure. The results showed that the semi-conical piers improved the reduction percentage of scour depth. Dahe and Kharode [5] used HEC-RAS software to investigate the impact of various geometries of bridge piers on local scour. The results proved that the minimum and maximum scour depths were recorded at sharped nose, and squared shaped piers, respectively. Researches were done to define the influence of pier angle of inclination on the local scour under different flow conditions; [6–9]. Many studies have tried to protect the bridge piers from local scour by implementing countermeasure mechanisms to reduce the strength of down flow and horseshoe vortex. The applied techniques to protect the bridge pier against local scour are generally classified into bed armoring and flow-altering countermeasures. Bed armoring countermeasures are barrier withstanding the shear stress around the bridge pier. The most common armoring material was the riprap stones placed around bridge piers [10–12]. Gabions and Concrete blocks were also used; [13–16].

The flow-altering countermeasures significantly decrease the downflow intensity and the horseshoe vortex. Controlling the scour around bridge pier using slots were widely used; [17–19]. The studies detailed that the slots reduced the scour dimensions which were influenced by slots size, shape, height and position. Moncada-M et al., [20] investigated the scour depth around circular pier by using collar with rectangular slots. The results presented that the scour depth was decreased by installing the collar on the bed level and the slot near the bed. Also, the scour depth was inversely proportional to collar diameter and slot length. Elnikhely [21] found that the perforated pile with 45°hole angle and hole diameter equal to 0.43 times of the pile diameter showed good performance to reduce the scour depth. Equation (1) was expressed to predict the scour depth as follows:

$$\frac{d_s}{D} = 0.36\,F_t - 0.24\frac{d_2}{D} - 0.0024\theta_r - 0.0022\alpha_r - 0.198\frac{y_t}{D} + 0.181 \quad (1)$$

In which, d_s = maximum scour depth, D = pile diameter, F_t = tail Froude Number, d_2 = diameter of hole of perforated sacrificial pile, y_t = tailwater depth, θ_r = oblique angle of the hole in the horizontal plan, α_r = oblique angle of hole of perforated sacrificial pile in the horizontal plan.

Bestawy et al., [22] experimentally explored the efficiency of various types of circular collars and pier slots in scour reduction. The study emphasized that the collars significantly reduce scour depth compared to slots. Also, developed empirical equation to estimate the scour depth as shown in Eq. (2).

$$\frac{y_s}{b} = 2\,k_1\,k_2\,k_3\,k_4\left(\frac{h}{b}\right)^{0.35} F_r^{\,0.43} \quad (2)$$

In which, y_s = scour depth, b = flow depth, k_1 = correction for pier shape (k_1 = 1 for circular pier), k_2 = correction of attack angle of approach flow (k_2 = 1 for direct approach flow), k_3 = correction for bed form (k_3 = 1.1for clear-water scour), k_4 = correction for armoring (k_4 = 1 for sand bed material), h = pier width, F_r: Froude No.

Singh et al., [23] studied the performance of various flow-altering techniques. The study concluded that the combination between permeable sheet piles and riprap reduced the scour depth up to 91%. Also, using vanes with collar plates around bridge pier effectively decreased the scour geometry compared to unprotected pier. Gerdefaramarzi et al., [24] experimentally utilized water jet injection through the pier body to reduce the scour upstream and downstream circular bridge pier. The outcomes concluded that the jets technique was remarkable for minimum flow depth, maximum flow rate of the jets, and 90° angle between jets. In addition, increasing the number of jets has a positive impact on decreasing the scour. Gris [25] examined the effect of using sheath fixed to pile surface to decrease the local scour. The study inferred that the sheath effectively controlled the scour with unnoticed impact on the waterway. Heidarpour et al., [26] experimentally studied the assessment of circular collars in decreasing scour around combination of two and three piers with various sizes and spacing. The outcomes revealed that the rear piers were affected by collar installation than the front piers. Wang et al., [27] set up physical model to study the influence of anti-scour collars on scour around circular bridge piers. The results proved that the scour depth was decreased by the increase of collar diameter.

Focusing on splitter plate technique, Wu et al., [28] used splitter plates with various lengths ranging between one to twice times of the pier diameter to reduce the scour geometry. It was revealed that the splitter length equal to 1.33 times of pier diameter reduced the scour hole in terms of length and width. Also, increasing the plate height decreased the scour area. Equation (3) was deduced to predict the maximum scour depth.

$$\frac{ds_{max.}}{ds} = 1.71\left(\frac{L}{D}\right)^{-0.6}\left(\frac{h}{H}\right)^{0.6} \quad (3)$$

In which, $ds_{max.}$ = maximum scour depth with splitter plate (mm), d_s = maximum scour depth without splitter plate (mm), L = splitter plate length (mm), D = pier diameter (mm), h = splitter plate height (mm), H = flow depth (mm).

Dey et al., [29] proved that splitter plate attached to circular pile decreased the scour depth by 61.6%. Khaple et al., [30] explored experimentally the impact of splitter plate length and thickness on the scour hole around circular pile. The study showed that the scour depth was minimized for splitter plate length equal to twice time the pier diameter while the splitter plate thickness gave insignificant influence. In addition, developing an equation for calculating scour depth as shown below.

$$\frac{d_{s.c}}{b} = C_{sp}\left(\frac{L_p}{b}\right)^{-0.22}\left(\frac{d_{50}}{b}\right)^{0.13} \quad (4)$$

In which, $d_{s.c}$ = computed scour depth, C_{sp} = coefficient of splitter plate = 1.88, b = pier diameter, L_p = splitter plate length, d_{50} = median sediment size.

Mehta and Yadav [31] simulated numerically the effect of dual bridges on the scour depth by implementing HEC-RAS software tool. The studied location was the Sardar Bridge on Tapi River. They concluded that the new constructed bridge should be located on the upstream the existed bridge. Ardiclioglu et al., [32] proved that the presence of bridges affected the hydraulic regime of the rivers and induced the backwater effect. Sato [33] investigated numerically the influence of multiple piers with 3D geometries on the water levels, the riverbed fluctuations and the local scour. The study used the Kintaikyo Bridge in Japan as a case study. The outcomes inferred that the piers with foundations gave smaller scour region compared to the piers without foundations. Azamathulla et al., [34] deduced that the performance of Genetic Programming (GP) was more efficient than the artificial neural networks (ANNs) in predicting bridge scour depth. Karkheiran et al., [35] proposed two hybrid models, Artificial Veural Networks (ANN) combined to Adaptive Particle Swarm Optimization (APSO) and Genetic Algorithms (GA) to predict the local scour depth at bridge piers. The results showed that (ANN-GA) showed better fitness compared to (ANN-APSO). The bridges may be constructed over single or multi-circular piers. Fig. 1(a) showed the bridge with single circular pier constructed on the Rayah Tawfiki canal in Egypt. Diwedar and Ashour [36] presented bathymetric survey for this location and declared the existence of local scour hole around the single circular pier located at Km 0.500. Fig. 1(b) showed the Pai-Furn Bridge in the Da-Ja River, Taiwan to present another type of bridges constructed over multi-circular piers, Wei et al., [37].

From the previous survey, most of researches and techniques involved in controlling the local scour around the bridge pier were focused on applying different geometries of piers and abutments, using collars at different levels, using piers with slots in different shapes and dimensions, using riprap around the pier. There are few researches were conducted to study splitter plates as new technique for local scour countermeasure. The innovativeness in the current research study is to explore the efficiency of using different lengths of single or double plates forming different vertex of triangular shape to mitigate the scour in terms of reduction the geometry of the developed scour hole around single circular bridge pier under clear water conditions. Also, the turbulent flow characteristics is identified by analyzing the vertical velocity distribution at different cross sections with and without splitter plates. In addition, the influence of Froude No. on the local scour is also presented.

2. Experimental methodology and procedure

The experimental program was executed in 23.0 m long, 1.4 m wide, and 0.6 m deep recirculating rectangular flume with horizontal bed that installed at hydraulic laboratory at Hydraulics Research Institute (HRI), National Water Research Center (NWRC), Egypt. The flume bed was made of concrete. Side walls were made of bricks covered by mortar to avoid leakage. A tailgate was fixed at the flume end to adjust the water level. A head tank was responsible for feeding the flume with water. Centrifugal pump with total discharge of 150 l/s pumped water from sump to a reservoir; then the flow was conveyed through flume channel. The flume inlet consisted of masonry basin of 3.8 m long, 1.7 m wide and 2.5 m deep. The circular pier was made of steel pipe and installed at 1.0 m downstream of the fixed bed area, as shown in Fig. 2.

The movable bed area has 0.3 m deep and 4 m long started 17.5 m downstream of the flume inlet. The filled material was sand layer of median particle diameter of d_{50} = 0.432 mm.

2.1. Experimental program

The model test program was designed to study the influence of the selected independent variables: flow discharge, Q; tailwater depth, y; length of splitter plate, L; angle of a splitter, θ; for each case of the tested nine runs as presented in Table 1. The tests were carried out in two phases. The first phase, a pier without splitters was used as standard case, where the generated scour was used in comparison, see Fig. 3 Case (A). The second phase, a pier with splitter plate was used. Three splitter lengths of ratio $\frac{L}{D}$ = 0.5, 1.0, and 1.5 were tested with three splitter plates vertex angles; θ = 0°, 15°, and 30°. Each case was examined under nine hydraulic conditions considering three flow discharges, Q = 75, 100, and 125 l/s, and three flow depths y = 12.5, 15.0, and 17.5 cm. The water level of the flow passed through the flume was adjusted using point gauge of accuracy ± 0.1 mm. An ultrasonic flowmeter was installed on the feeding pipe to measure the flow rate with a reading accuracy of ± 1.0%. The main flow velocity; V was measured with an accuracy of ± 0.2% using Electromagnetic Current-meter type EMS (manufactured by Delft Hydraulics).

Eighty-One experimental runs with total number of nine different piers attached to splitter models were implemented

Fig. 1 Photographs for bridges with circular piers: (a) single circular pier; (b) multi-circular piers.

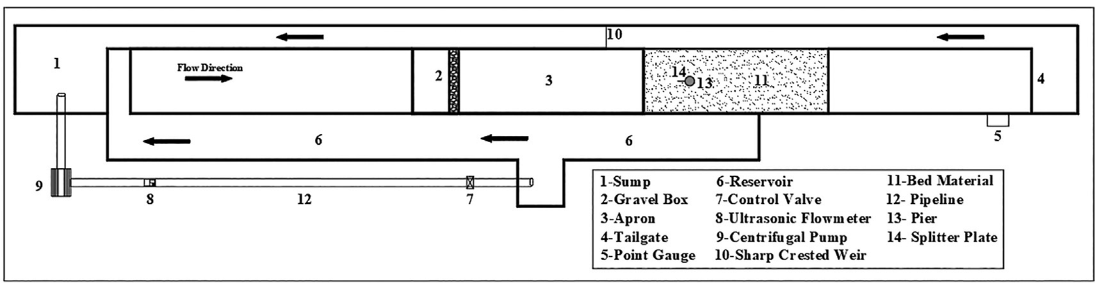

Fig. 2 Definition sketch for the used flume.

Table 1 The experimental test program.

Case No.	L (cm)	θ (degree)	Q (l/s)	y (cm)
A	–	–	75, 100, 125	12.5, 15.0, 17.5
B	0.5D	0	75, 100, 125	12.5, 15.0, 17.5
C	0.5D	15		
D	0.5D	30		
E	1.0D	0	75, 100, 125	12.5, 15.0, 17.5
F	1.0D	15		
G	1.0D	30		
H	1.5D	0	75, 100, 125	12.5, 15.0, 17.5
I	1.5D	15		
J	1.5D	30		

Where; L = splitter plate length (cm), θ = splitter plate angle (degree), Q = flow discharge (l/s), y = tailwater depth (cm).

out of them, nine tests using pier without splitter plates; Figs. 3 and 4.

2.2. Justifications of parameters assumptions

The current experimental work has some parameter assumptions as preliminary estimates obtained after a few trial tests as;

1. The pier material was steel; where its dimensions were not affected by water. The pier diameter was selected to be 4 in. because smaller diameters showed unnoticed impact on the bed configuration.
2. The pier was fixed 1.0 m downstream the bed material area to include any disturbance in bed material upstream the pier.
3. The tested splitter plate vertex angles were ranged between 0° and 30°, where for greater vertex angles; the splitter plate base was greater than the pier diameter for the scenario where $\frac{L}{D} = 1.5$; also, the used splitter plate length ratios $\frac{L}{D}$ were ranged between 0 and 1.5, to avoid small vertex angles where the influence of splitter angle was unremarkable compared to pier with single splitter.
4. The used bed material was selected to be of median grain size d_{50} = 0.423 mm to simulate the majority of bed area in the Nile River, Egypt.
5. The selected range of flow discharges Q were between 75 l/s and 125 l/s, and the tailwater depths y were between 12.5 cm and 17.5 cm, as displayed in Table 1. This was reasoned by the complete removal of bed material for Q and y, more than 125 l/s, and 12.5 cm, respectively. On the contrary, unremarkable movement of bed material and for Q and y, less than 75 l/s, and 17.5 cm, respectively.
6. Six hours were selected as an equilibrium time for all runs, where the quasi-equilibrium state was reached, and no appreciable changes in the scour hole geometry were observed around the used pier.

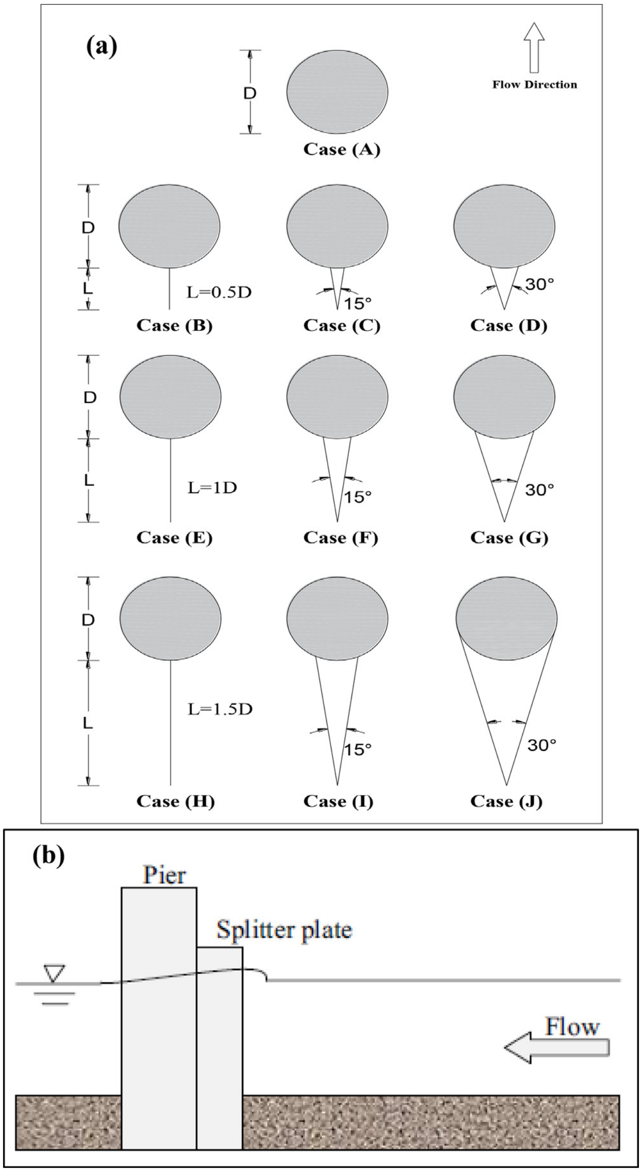

Fig. 3 The tested splitter plates: (a) plan view; (b) elevation.

2.3. Experimental procedures

After fixing the pier at its desired position on the movable bed area and the flume was filled with bed material and precisely levelled at its place in the model using levelling device; the tailgate was closed; and the downstream feeding gradually began until the water depth became higher than the operating water depth for a certain scenario. Simultaneously, the main pump was switched on until the required flow discharge was reached. The tailgate was tilted gradually to achieve the required flow depth, and consequently, the six hours run duration was begun. By the end of the six hours, the velocity measurements were recorded and then the pump was switched off, and the flume was drained gradually to stabilize the bed sand. The geometry of hole in terms of length, width, and depth were reported using levelling device at various locations according to the designed mesh, each 0.10 m in longitudinal and transverse directions. All previous steps were repeated for each run.

2.4. Dimensional analysis

The effective variables governing the scour depth around a bridge pier outfitted with the splitter plates were as follows:

$$f(B, L, D, y, \theta, g, \rho, \rho_s, S_o, d_{50}, Q, V, \mu, \sigma, x, ds_{max.}) = 0 \qquad (5)$$

Where, B is the flume width, L is the length of the splitter plate, D is the pier diameter, y is the flow depth, θ is the splitter plate vertex angle, g is the gravity acceleration, ρ is the water density, ρ_s is the soil particle density, S_o is the flume bed slope, d_{50} is the median grain size, Q is the flow discharge, V is the mean flow velocity, μ is the dynamic water viscosity, σ is the surface tension, x is the total distance of the scour hole, and $ds_{max.}$ is the maximum scour depth.

In this study, B, y, x, S_o, ρ, d_{50}, and ρ_s were kept constants throughout the experimental work. Therefore, they can be neglected from Eq. (5). The equilibrium time for scour geometry was fixed for all experimental runs. Using the π-theorem and applying the properties of dimensional analysis, it yields;

$$f\left(\frac{L}{D}, \theta, \frac{V}{\sqrt{gy}}, \frac{\rho Q}{B\mu}, \frac{\rho V^2 B}{\sigma}, \frac{d_{smax.}}{y}\right) = 0 \qquad (6)$$

Where; $\frac{V}{\sqrt{gy}}$ is the Froude number, F_r; and $\frac{\rho Q}{B\mu}$ is the Reynolds number, R_e; and $\frac{\rho V^2 B}{\sigma}$ is the Weber number, substitute in Eq. (6);

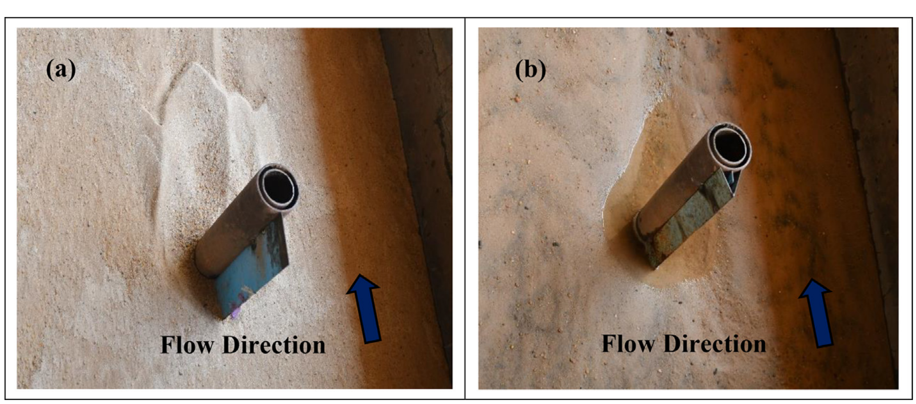

Fig. 4 Photographs for the tested splitter plates: (a) L = 1.0D, θ = 0°; (b) L = 0.5D, θ = 30°.

$$f\left(\frac{L}{D}, \theta, F_r, R_e, W_e, \frac{ds_{max.}}{y}\right) = 0 \quad (7)$$

The effect of viscosity and surface tension are assumed of secondary importance since the flow is mainly gravitational in open channels; therefore, the effect of Reynolds and Weber numbers, R_e and W_e may be neglected. Hence, Eq. (7) may be written as:

$$\frac{ds_{max.}}{y} = f\left(\frac{L}{D}, \theta, F_r\right) \quad (8)$$

3. Results and discussions

The analysis of the experimental work were focused on the velocity distribution and the bed configurations associated to installation of circular bridge pier with and without splitter plates. In addition, the statistical determination of the constants proposed by the dimensional analysis for the maximum scour depth equation was explored.

3.1. Velocity distribution at upstream and downstream the pier

To study the effect of the pier with an angled splitter on the velocity distribution; the flow velocity was measured on the centerline along 2 m at 7 locations. For the first 1 m upstream the pier location, the velocity was measured at 2 cross sections 0.5 m apart. The downstream part along 1 m started from pier location, the flow velocity was measured every 0.2 m. For each measuring location, the flow velocity was rcorded at 9 water depths; started at 0.1 and ended at 0.9 of the operating tailwater depths; y.

3.1.1. Effect of splitter length on the velocity distribution

Fig. 5 was presented to explore the influence of splitter plate length on the velocity distribution at the designed cross section. The installed pier has constant $\theta = 30°$ with different splitter tested lengths (L = 0.5, 1.0 and 1.5 times of pier diameter). The tested hydraulic conditions were remained constants of Q = 125 l/s and y = 12.5 cm where the maximum flow condition was predicted. It was noticed that the section where X = 1.2 m was most affected by pier installation where it was the first section at the downstream, and the flow disturbance was significant. As the flow moved towards the tailgate, the turbulence was decreased and uniform flow condition was formed. Focusing on the velocity distribution along the centerline, the figure showed the splitter length has not remarkable difference between the upstream and downstream of the pier considering the first half of the flow depth (i.e. the measured points started from the water surface to the mid-flow depth at 0.5y). Emphasizing the near bed velocity which presented the focal component in the generated scour, the figure demonstrated that the velocity at 0.9y was decreased by the increase of the splitter length specifically at the first cross section downstream the bridge pier. Also, the splitter influence tended to vanish as the distance from the bridge pier increased towards the tailgate. Focusing on the splitter length, the figure demonstrated that the maximum measured velocity was decreased by 9.4%, 11.7%, and 14.2% for$\frac{L}{D} = 0.5$, 1, and 1.5, respectively compared to the referenced case for the pier without splitter, $\frac{L}{D} = 0$. Consequently, it was concluded that the splitter length significantly improve the flow characteristics in terms of velocity distribution.

3.1.2. Effect of splitter angle on the velocity distribution

Fig. 6 showed the influence of splitter angle on the velocity distribution at different cross sections upstream and downstream the bridge pier located similar to the presented in Fig. 5. The figure was plotted under constant hydraulic condition of Q = 125 l/s, and y = 12.5 cm. The used splitter length was equal to 1.5D. The velocity distribution associated to the case of pier without splitter was also given to be used in comparison. The figure explored that the splitter installation at any given angle decreased the velocity at the monitored locations along the flow direction. Also, it was noticed that the velocity was decreased by the increase of the splitter angle, where the most of turbulences due to pier installation were scattered. The figure demonstrated that the maximum measured velocity was decreased by 7.3%, 10.1%, and 14.2% for $\theta = 0°$, 15°, and 30°, respectively compared to the basic case without splitter. Therefore, it was concluded that the splitter angle $\theta = 30°$ proved remarkable improvement regarding the velocity distribution compared to the tested splitters angles.

3.2. Effect of tested bridge pier model on the Froude number

3.2.1. Effect of splitter length on the Froude number

To explore the relation between the Froude No., and the produced maximum relative scour depths (ds_{max}/y) taking into account the tested splitter lengths, Fig. 7 was plotted. The figure considered different flow discharges, Q = 75, 100, and 125 l/s, under constant tailwater depth and splitter angle y = 12.5 cm, and $\theta = 30°$, respectively. The Froude No. was recorded corresponding to the maximum velocity located 20 cm downstream the installed pier. Similar trends was noticed, where the ds_{max}/y was found in direct relation to the F_r affected by the measured velocity regardless the splitter length which emphasized the findings of Fig. 5. Also, the figure demonstrated that the longer splitter length produced lower Froude No. consequently, the ds_{max}/y decreased. The findings proved the superiority of splitter of L = 1.5D in controlling the maximum local scour depth.

3.2.2. Effect of splitter angle on the Froude number

The effect of splitter angle on the Froude No. and the developed maximum relative scour depths (ds_{max}/y) was introduced in Fig. 8. The figure was plotted under different flow discharges, Q = 75, 100, and 125 l/s and fixed splitter length and tailwater depth of L = 1.5D and y = 12.5 cm, respectively. Similar to Fig. 7, the F_r was recorded 20 cm downstream the pier. No significant differences in curves pattern were noticed. The figure emphasized that the efficiency of splitter to minimize the local scour was increased by the increase of vertex angle under any given F_r which found in good consistency with the introduced in Section 3.1.2.

3.3. Effect of tested bridge pier model on the bed configurations

The idea of using splitters was presented mainly to minimize the local scour around the bridge piers. Therefore, the next subsections were given to discuss the influence of splitters in terms of splitter length and angle on the bed topography.

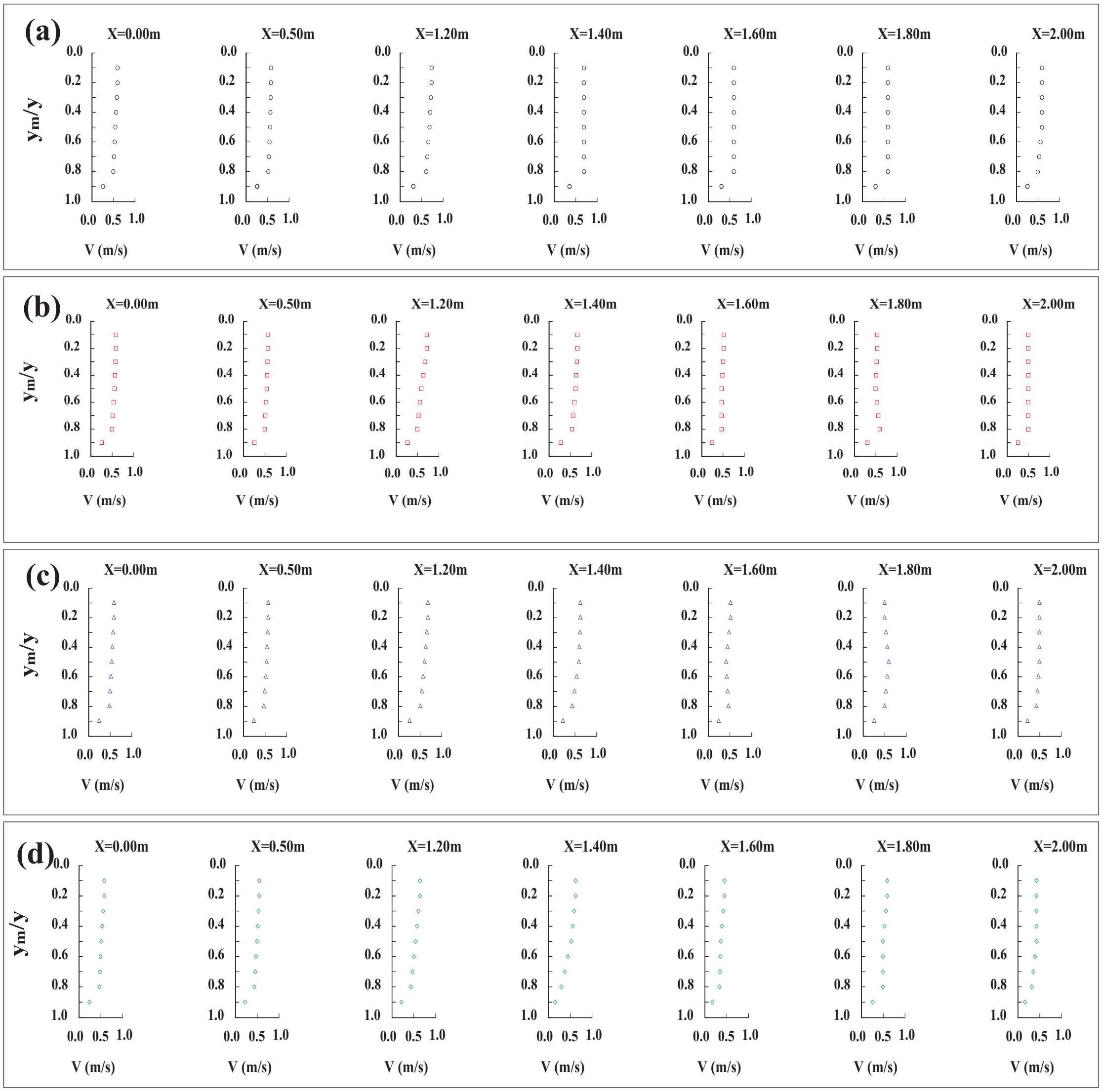

Fig. 5 Velocity distribution at θ = 30° for different splitter plate lengths, $\frac{L}{D}$ =: (a) 0.0; (b) 0.5; c) 1.0; and d) 1.5D.

3.3.1. Effect of splitter length on the bed configurations

The effect of the splitter plate length of L = 0.5D, 1D, and 1.5D on bed configurations showing the longitudinal cross section and the plan view were presented in Fig. 9. The figure was plotted for tests with constant Q = 125 l/s, y = 12.5 cm, and θ = 30° which were the same conditions of velocity distribution presented in Fig. 5 to investigate the correlation between velocity distribution and the associated developed scour.

Emphasizing Fig. 9 (a) that showed the relative scour depth d_s/y along the centerline of the bed area against normalized length x_1/X. The locations of the maximum relative scour depths d_s/y were found at the pier was installed regardless the existence of splitter at any given length. However, the maximum values of d_s/y were recorded as −1.5, −1.29, −1.11, and −1.02 for $\frac{L}{D} = 0$, 0.5, 1.0, and 1.5, respectively. Consequently, it was demonstrated that the scour depth decreased with the increase of splitter length. Accordingly, the reduction in relative maximum scour depth were ranged between 14% and 32%. Fig. 9 (b) presented the plan view for the developed scour hole geometry generated around the utilized bridge pier model. The figure confirmed the findings of Fig. 9 (a); the scour geometry in terms of length and width was also decreased by the splitter length increase. Considering the splitter length of minimum scour from the plan view; $\frac{L}{D} = 1.5$, the figure declared that the maximum relative scour hole length (x_1/X) and width (b/B) were decreased by 44.31% and 10.79%, respectively considering the referenced case. Consequently, it was concluded that the (b/B) was less sensitive to the splitter compared to the (x_1/X); as the flow was assumed 1-D. Involving the findings of the splitter influence on the velocity distribution discussed previously, it was noticed that the scour geometry in terms of depth, width, and length were decreased according to the corresponding decrease in velocity specifically the near bed ones. Therefore, the results of scour and velocity were found in a good consistence. Finally, it was demonstrated that using splitter plate at any given length has remarkable merits in reducing the scour geometry. However, changing the splitter length has limited impact on the scour width.

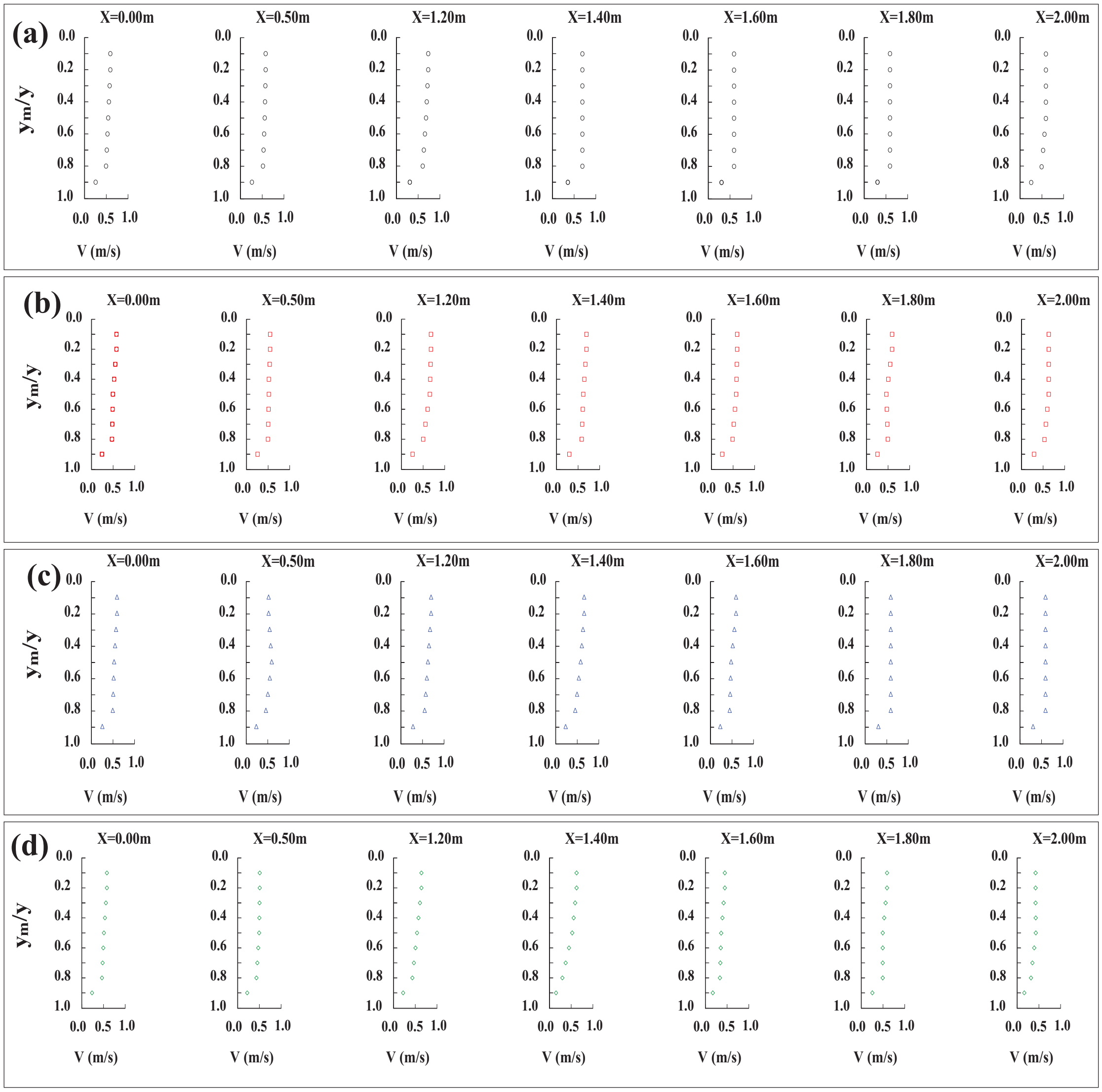

Fig. 6 Velocity distribution for different angles of splitter plates for $\frac{L}{D} = 1.5$ at: (a) No splitter; (b) $\theta = 0°$; (c) $\theta = 15$; and (d) $\theta = 30°$.

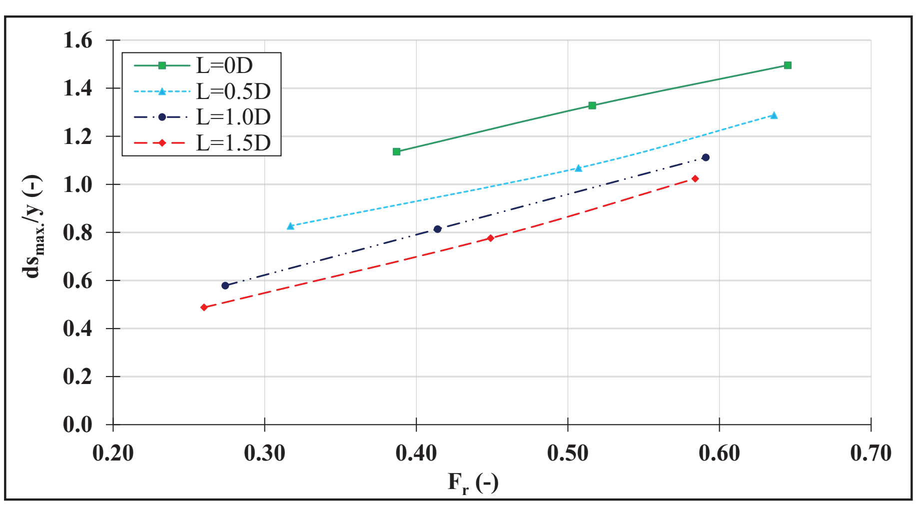

Fig. 7 Relation between Froude No. and maximum relative scour depths for different splitter lengths.

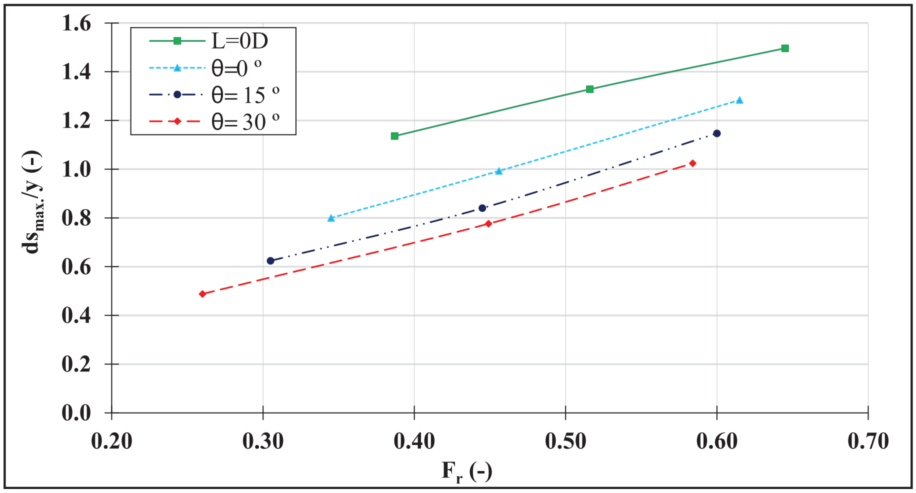

Fig. 8 Relation between Froude No. and maximum relative scour depths for different splitter angles.

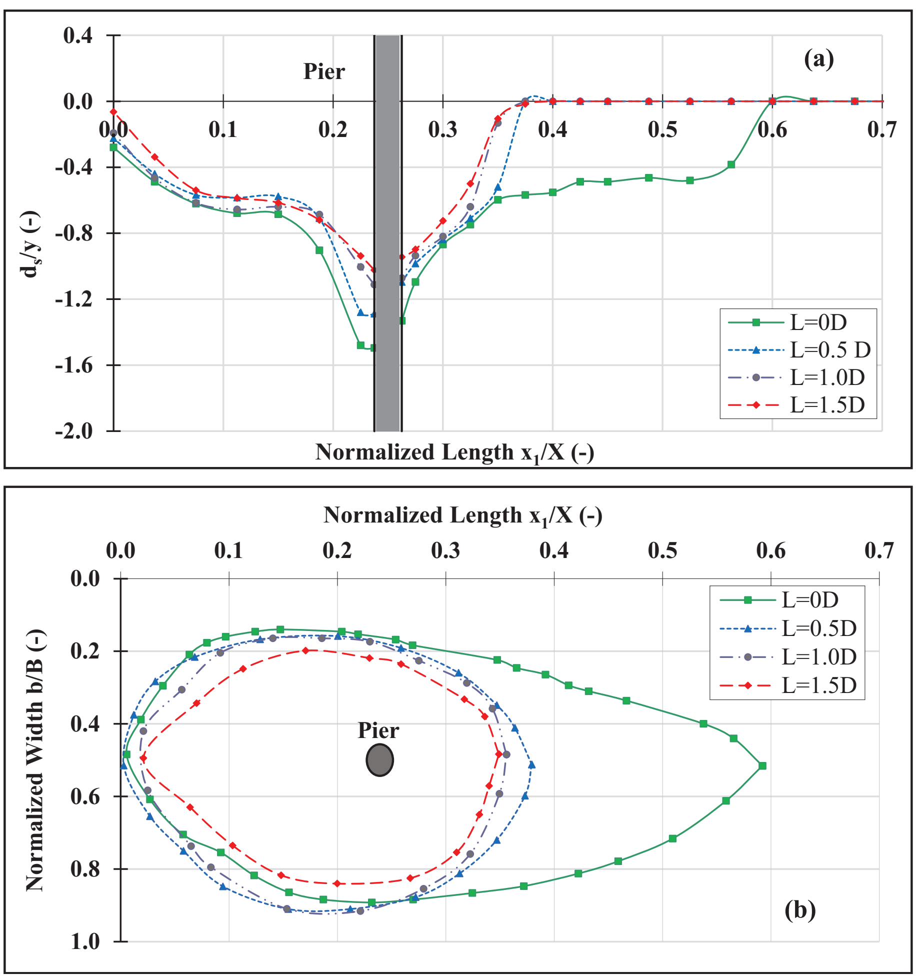

Fig. 9 Effect of splitter length on bed configurations: (a) longitudinal section; (b) plan view.

3.3.2. Effect of splitter angle on the bed configurations

Fig. 10 presented the longitudinal bed profile along the flume center and the plane view for the generated local scour hole around the circular pier without and with splitters of various vertex angles. The figure was plotted for constant Q = 125 l/s, y = 12.5 cm and $\frac{L}{D} = 1.5$, where the most critical scenario was found. The used vertex angles were θ = 0°, 15°, and 30°. Focusing on the longitudinal profile, Fig. 10 (a) showed that the relative maximum and minimum scour depth d_s/y were −1.50 and −1.02 for the base case and the splitter plate with θ = 30°, respectively which indicated 32% reduction in the scour depth. Taking into account splitters with θ = 0° and 15°, the reduction percentages were 5.3% and 11.3%, respectively.

Exploring Fig. 10 (b), it was noticed that no remarkable changes in trend regardless the tested angle. The maximum normalized scour lengths along the flow direction (x_1/X) were ranged between 0.35 and 0.60. However, regarding the transverse direction, the maximum (b/B) were found between 0.64 and 0.71. Installing pier with splitter of θ = 30° showed high performance in decreasing the scour area compared to other tested angles as the x_1/X and b/B were decreased by 44.31% and 10.79%, respectively. Consequently, Fig. 10 (a) and (b) were in good consistence, where the scour geometry was inversely proportional to the splitter vertex angle. The higher vertex angle indicated higher efficiency in separating the main flow for longer distance upstream the pier location and direct larger part of flow to the flume side walls. Therefore, lower turbulences and eddies at the pier base were monitored and the scouring action was reduced, which was proved in Fig. 6.

Fig. 11 showed visualization for the developed bed configurations for Cases (A) and (J) using contour maps and 3-D views under fixed critical tested hydraulic conditions; Q = 125 l/s and y = 12.5 cm. The figure confirmed the findings discussed in the previous subsections and generally highlighted the merits of splitter plate in controlling the local scour around the bridge pier with specific attention to the superiority of splitter with the geometrical characteristics of Case (J).

Table 2 showed the volume of the scour hole around the bridge pier with different splitter plate vertex angles for constant Q = 125 l/s, y = 12.5 cm and $\frac{L}{D} = 1.5$. The outcomes were compared to the basic case to calculate the percentage of reduction in the scour volume. The table confirmed the previous results as the higher vertex angle developed smaller volume of scour hole. The results were in good agreement with Section 3.1.2.

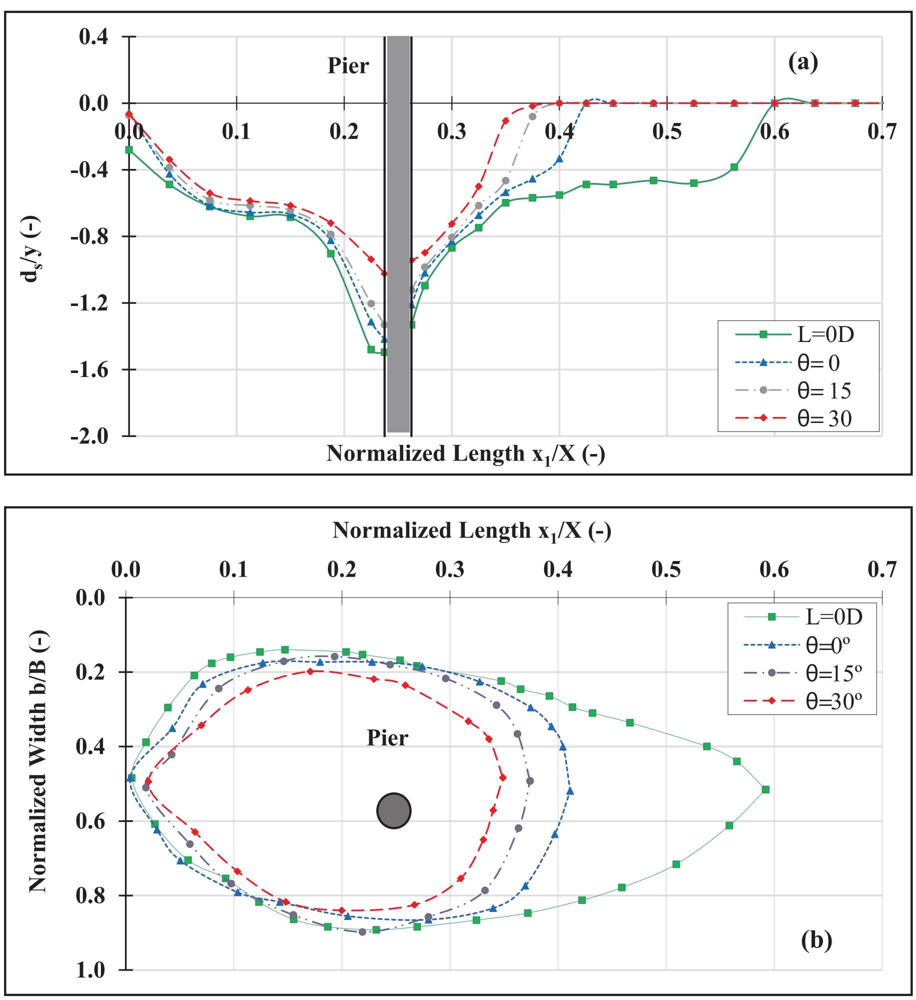

Fig. 10 Effect of splitter angle on bed configurations: (a) longitudinal section; (b) plan view.

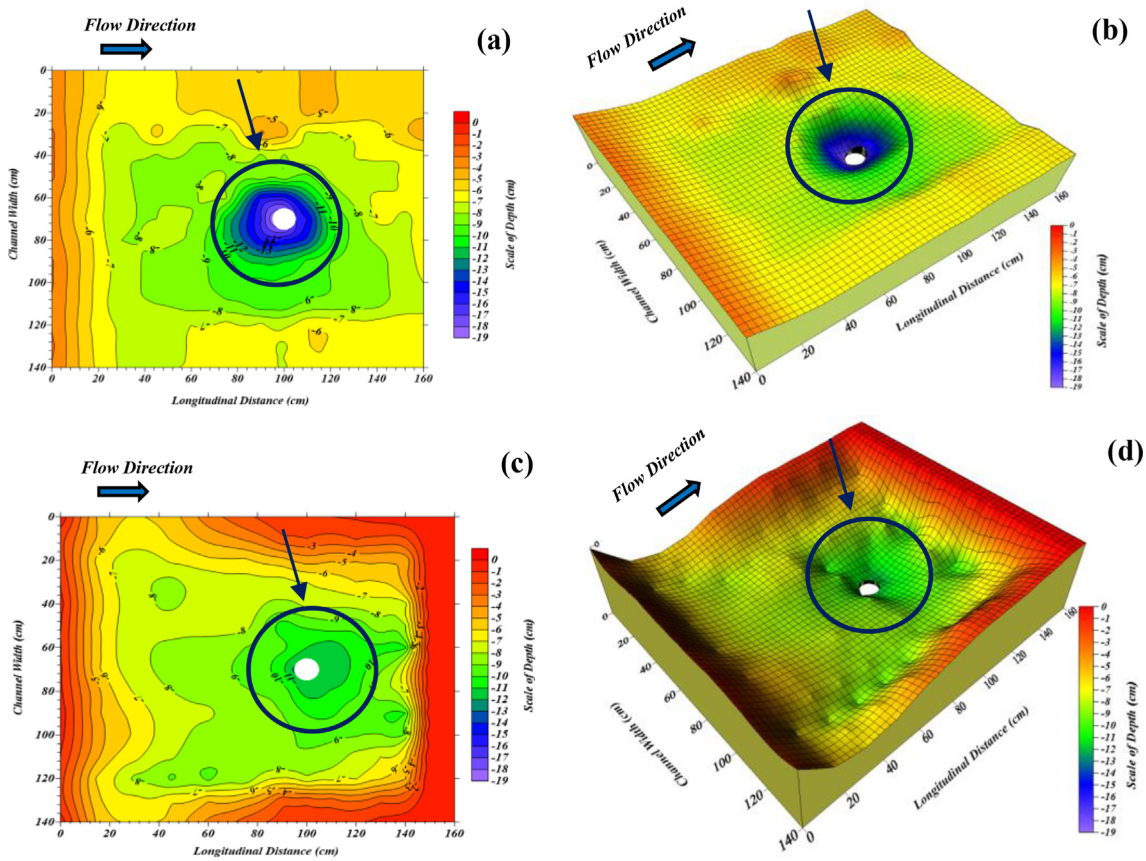

Fig. 11 Bed Configuration as: (a) contour map for Case (A); (b) 3-D view for Case (A); (c) contour map for Case (J); (d) 3-D view for Case (J).

Table 2 Effect of splitter plate vertex angle on scour volume.

The tested case	Scour Hole volume (m^3)	Reduction (%)
(A)	0.220	———
(H)	0.154	29.76
(I)	0.135	38.57
(J)	0.109	50.50

3.4. Effect of discharge and tailwater depth

From the previous discussions, it was observed that the minimum scour depth around the bridge pier was recorded for Case (J). Table 3 showed the effect of the flow discharge; Q on the maximum scour depth compared to the referenced case for the pier without splitters, Case (A). The table was presented under fixed y = 12.5 cm. The table illustrated that the pier with splitter plate effectively acted in decreasing the ds_{max}/y in the case of lower discharges as the velocity were smaller under fixed cross-sectional area.

Emphasizing the effect of splitter plate on the maximum scour depth under different tailwater depths; Table 4 was presented for Cases (A) and (J) for constant Q = 125 l/s. It was seen that the efficiency of splitter in decreasing the scour depth was increased by the increase of the tailwater depth. That resulted due to the higher water depth created lower velocity distribution where the flume area was constant.

3.5. Developing an empirical equation

The experimental outcomes relate the diverse dimensionless variables for developing empirical formula to predict the maximum relative scour depth generated around the bridge pier

Table 3 Maximum relative scour depth for different flow discharges.

Q (l/s)	$ds_{max.}/y$		Reduction (%)
	Case (A)	Case (J)	
75	1.14	0.48	57.89
100	1.33	0.78	41.35
125	1.49	1.02	31.55

Table 4 Maximum bed scour depth for different tailwater depths.

y (cm)	$ds_{max.}$ (cm)		Reduction (%)
	Case (A)	Case (J)	
12.5	18.7	12.8	31.55
15.0	17.4	8.39	51.78
17.5	17.0	7.25	57.35

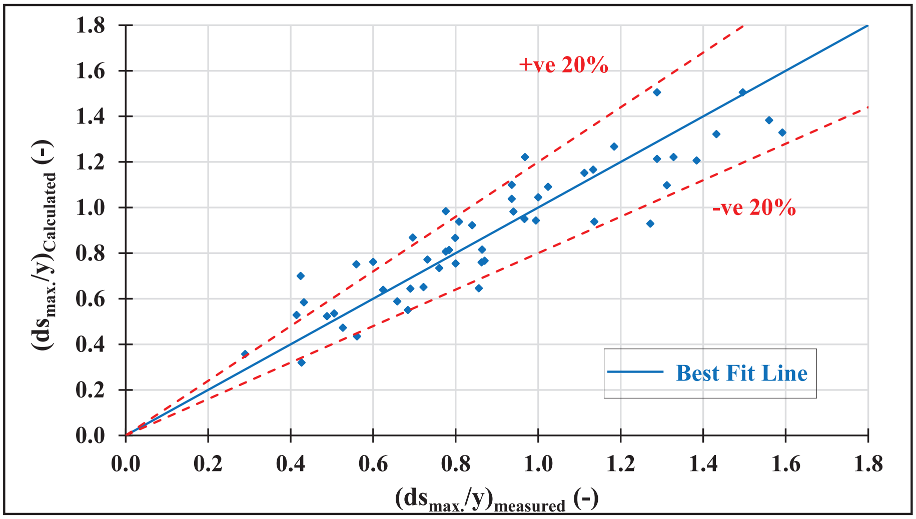

Fig. 12 Comparison between measured and calculated maximum relative scour depth.

with splitter considering the length and the vertex angle. With the assistance of implementing nonlinear regression analysis, the developed formula can be expressed as follow:

$$\frac{ds_{max.}}{y} = -0.1224\frac{L}{D} - 0.0077\theta + 2.1997Fr + 0.0866 \quad (9)$$

The coefficient of determination; $R^2 = 0.828$, the standard Error of Estimate; SEE = 0.141. The developed equation is valid for the following conditions: $0 \le \frac{L}{D} \le 1.5$; $0° \le \theta \le 30°$; $0.234 \le Fr \le 0.645$. The developed equation concluded that the ds_{max}/y was inversely proportional to $\frac{L}{D}$ and θ. The effect of splitter length was significant compared to the vertex angle.

The formula for the relative maximum scouring depth was validated using the measured and calculated values, as plotted in Fig. 12. The experimental data were in good agreement where most values were located in range ± 20%.

4. Comparative study

To confirm the validity of the present method in controlling the local scour at the bridge pier, Fig. 13 was plotted. The recorded results of ds_{max}/y were compared to the calculated from the developed equations using other techniques listed in the literature. Similar trends were observed, and the measured data were within the range of the calculated values in other studies. However, noticeable differences in values were underscored because the limitation range for application were not identical for the used equations.

5. Conclusions

In the present study, the influence of the angled splitter plate on the velocity distribution and bed topography were explored.

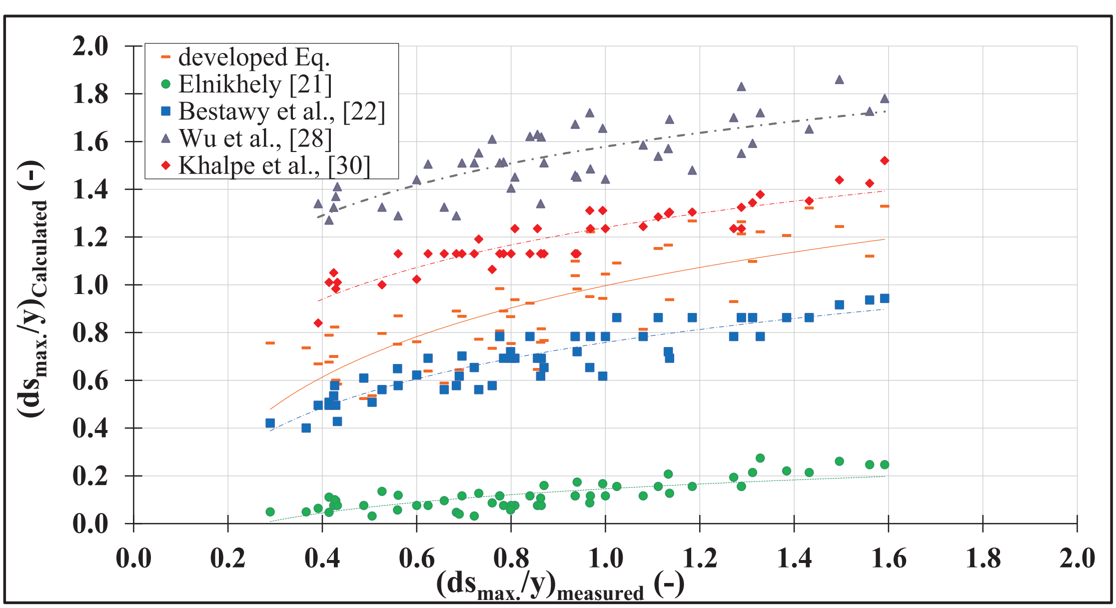

Fig. 13 Comparison between calculated ($ds_{max.}/y$) for the present study and other formulas.

Ten circular bridge pier models were tested under different hydraulic conditions considering 3 discharges and 3 tailwater depths. Based on the study results analysis, the bridge pier with splitter plate at any given length and angle can minimize the longitudinal velocities and the local scour around the bridge pier specifically at the downstream taking into account the pier without splitters. The splitter installation showed insignificant influence on bed configurations upstream the pier. The tested pier model with splitter length equal to 1.5 times the pier diameter and 30° vertex angle; Case (J) recorded the minimum velocities and proved superior performance in controlling the local scour compared to other splitter lengths and angles. The Case (J) effectively decreased the scour volume up to 50.5%. The local scour geometry was inversely proportional to the splitter length and the vertex angle. The impact of splitter length on decreasing scour was under estimation compared the splitter vertex angle. The measured maximum relative scour depth data have good correlation with the previous studies data. The results were applicable for bridges constructed over single circular piers or multi-circular piers with long span length and limited for the tested data range.

6. Recommendations

For future studies, it is recommended to explore the influence of angled splitter plates with different heights and various diameters of circular bridge pier in terms of flume width on the bed geometry and flow characteristics. Also, other pier shapes may be examined with splitters.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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