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ORIGINAL PAPER

Reducing local scour at bridge piers using an upstream subsidiary triangular pillar

Hesham Fouli[1] **· Ibrahim H. Elsebaie**[1]

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Abstract The objective of this experimental study was to examine the effect of an upstream subsidiary triangular pillar on the development of local scour at a single circular bridge pier. The triangular pillar was placed such that its apex faced the approach flow and its base length was equal to the pier diameter (D) in all experiments. The experiments were conducted to investigate the effect of the spacing between the base of the subsidiary pillar and the bridge pier (S) and the apex angle (α) of the triangular pillar on the dimensions of the scour hole and its temporal development at different Froude numbers. The experiments were conducted in a rectangular flume under clear-water scour conditions at Froude number ranging between 0.1 and 0.3. Relative spacing (S/D) of 0, 0.5, 1, 1.5, 2, and 3, as well as apex angle (α) of 60°, 90° and 120° were tested. The results show that the maximum scour depth at the pier could be minimized using three different combinations of spacing and apex angle. The highest reduction in the maximum scour depth (d_{sm}) of approximately 28 % was possible using S/D of 3 and α of 90° compared to the pier-alone case. Overall the performance of the 90° apex angle pillar surpassed the other two angles.

Keywords Local scour · Flow altering countermeasures · Bridge pier · Subsidiary pier · Scour hole development

✉ Hesham Fouli
hfouli@ksu.edu.sa

Ibrahim H. Elsebaie
elsebaie@ksu.edu.sa

[1] Department of Civil Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

Introduction

Streambed soil material generally experiences erosion due to flowing water in streams. In the context of bridges crossing waterways, the supporting piers help to develop excessive local erosion that leads to the formation of scour holes at the piers. Local scour at bridge piers is one of the most serious problems that affect the safety of bridges. Every year, many bridges worldwide fail not because of structural reasons, but due to scouring at their piers and abutments. While there are many studies available in literature that examined scour at piers and proposed countermeasures to reduce it, there is still a need for more feasible and practical ideas that can help reduce the development of scour holes at piers.

Scour may be defined simply as the removal of material from the bed and banks of streams by the erosive action of flowing water or tidal currents. The major damage to bridges at stream crossings occurs during floods. Damage is caused by various reasons, the main reason being streambed scour at the bridge foundations, namely piers and abutments, and is typically termed local scour. General scour, on the other hand, occurs irrespective of the existence of the bridge and can occur as either long-term or short-term scour; the two types are distinguished by the time taken for scour development (Melville and Coleman 2000).

Yang (2005) reported that the threat of local scour around bridge piers has been known for many years. According to Richardson and Davis (2001), local scour around bridge piers is one of the most common causes of bridge failures. It is a widespread problem and has the potential for tragic results. More than 85,000 bridges in the USA are vulnerable to scour. Local scour damaged or destroyed 17 bridges in New York and New England during the spring floods of 1987. During the last 30 years, more than 1000 of about 600,000 bridges in the USA have failed, and 60 % of those failures were due to scour. Melville and Coleman (2000) stated that in New Zealand, scour damages result in the expenditure of NZ$36 million per year.

Different countermeasures to reduce local scour at bridge piers are reported in literature. The major countermeasure techniques employed for preventing or minimizing local scour at bridge piers can be classified into two categories: (a) bed armoring and (b) flow altering. In the former case, the objective is to combat the erosive action of the scour by including mechanisms using hard engineering materials or physical barriers such as rock riprap. In the latter case, the objective is to either inhibit the formation of the scour-inducing mechanisms or to cause the scour to be shifted away from the immediate vicinity of the pier (Heidarpour et al. 2010). Bed armoring countermeasures include riprap stones, reno-mattresses, cabled-tied blocks, gabions, concrete-filled mats or bags, and concrete aprons. Of the many types of armoring countermeasures used for pier protection, a riprap layer consisting of large stones remains the most commonly used armouring countermeasure. Flow altering countermeasures include sacrificial piles and sills, collars, slots, etc. (Tang et al. 2009).

In the context of bed armoring, Masjedi et al. (2010) studied the effect of using circular and square collars fitted to a single circular pier located within a 180° flume bend. They used collars having different width to pier diameter ratios placed at different elevations that ranged from the streambed to one pier diameter below the streambed. Their width to pier diameter ratios ranged between 1.5 and 3.0. They noted that the efficiency of the collar in reducing the scour depth increased with increasing the collar width. They also observed that for both the circular and square collars, the minimum scour depth occurred at the elevation of $0.1D$ below the streambed, where D is the pier diameter. Heidarpour et al. (2010) studied the development of scour hole around groups of two and three piers with a collar located at the bed level that was two and three times wider than the pier diameter. They concluded that collars were effective for two and three piers in line, and resulted in higher efficiency when the spacing between piers was completely covered with collars. They also concluded that the influence of collars in reducing scour depth at rear piers was more remarkable than the first pier. Zarrati et al. (2010) used riprap and combination of collar and riprap to control scour around piers. They concluded that there was no effect of collar diameter on riprap size in their experiments. They have shown that using a collar reduced the stable riprap size (d_R), when D/d_R was less than 7.5 (coarse riprap), D being the pier diameter. For $D/d_R \geq 7.5$ (fine riprap), the collar had no effect on reducing the stable riprap size. Therefore, collars seemed to be more effective in coarser riprap size by protecting the sides and upstream area of the pier. They concluded that using collars reduced the riprap extent in front and at the sides of piers. They also showed that the eroded riprap volume was 31 and 57 % less than that for an unprotected pier, when the collar widths were $2D$ and $3D$, respectively. More recently, Mohammed et al. (2015) investigated the combined effect of using multiple countermeasures to reduce local scour around multi-vent bridge piers. They attribute a 65 % reduction in scour depth to the collar effect and a 10 % reduction to the current deflector effect. They report 91 % reduction in scour depth using collars, current deflectors, and sacrificial pile upstream of the piers.

In the context of flow altering, Chiew and Lim (2003) examined the effect of placing a sacrificial sill upstream of the circular pier. They tested different dimensions and inclinations of the sill when the flow had a Froude number of 0.5; they used sand with a mean diameter of 0.96 mm for the channel bed. Their results indicated that the percentage reduction in scour depth reached a maximum of 50 % when the sill was vertical, the angle of attack was zero, the sill height was larger than 0.3 times the flow depth, and the clear distance between the sill and the pier was 4.4 times the pier diameter. Ataie-ashtiani and Beheshti (2006) studied different pile groups' arrangements upstream of a pier; they varied their spacing, the flow rate, and the sediment grain sizes in their experiments. They observed that the scour hole depth for some arrangements of the pile groups increased by two times more than its magnitude for the case of single pile. Haque et al. (2007) used sacrificial piles to mitigate scour around bridge pier. They examined alternative arrangements of groups of piles placed upstream of a rectangular pier under clear-water scour conditions. They found that when the group of piles was placed at a distance of twice the width of the pier, for which the percentage of blockage of the pier width was 60 %, the scour volume was reduced by up to 61 % and the maximum scour depth could be reduced by up to 50 %. Tang et al. (2009) used tetrahedral frames protection and reported that it was very effective in reducing the scour depths by 50 % or more. They also showed that the percentage reduction of scour depth decreased as the velocity ratio V/V_c decreased, with V being the mean flow velocity and V_c the critical flow velocity. In their experiments, V/V_c ranged between 0.581 and 1.168. Alshehri et al. (2013) studied the effect of a circular subsidiary pillar upstream of a circular pier on the maximum scour depth at the pier. They used different pillar-to-pier diameter ratios and variable spacing between the pier and the pillar and concluded that it was possible to reduce the local scour at the pier by up to 50 % using three different combinations of the diameter ratios and spacing. El-Ghorab (2013) investigated the effect of different arrangements of upstream and side openings within circular, rectangular, and square bridge piers on reducing local scour. El-Ghorab reported a 45 % reduction in scour depth using such method with opening diameter of 0.2 times the pier width when the vertical spacing between the openings was equal to the pier width. More recently, Arabani and Hajikandi (2015) investigated the effect of installing three vertical rectangular plates to a circular pier on reducing local scour. They tested two sizes of the plates and installed them such that two plates were tangential to the pier and the third was attached to its nose in the middle. All three plates were parallel to the flow direction and extended only upstream. They report that when the length of the lateral plates and middle plate are 1.14 and 1.714 times the pier diameter (d_p) respectively, the maximum scour depth reduces considerably. Their data shows 76 and 85 % reduction in maximum scour depth for 1.14d_p and 1.714d_p long side plates, respectively.

In the current study, the results of using a single subsidiary triangular pillar located upstream of a circular bridge pier, as one of the flow altering countermeasures to control the local scour at the pier, are presented. The triangular pillar was located such that its apex angle (α) faced the approach flow and its base faced the pier; the pillar base length and pier diameter (D) were equal in all experiments. Relative spacing (S/D) of 0, 0.5, 1, 1.5, 2, and 3, as well as apex angle of 60°, 90°, and 120° were tested. The effects of the relative spacing (S/D) between the pier and pillar, the apex angle (α), and Froude number on the progress of local scour around the pier were examined. All experiments were confined to sub-critical flow conditions with Froude number varying between 0.1 and 0.3.

Dimensional analysis

For the proposed approach of using a subsidiary triangular pillar to minimize local scour at bridge piers, the scour hole geometry at the pier depends on a multitude of variables including flume width, pier diameter, pillar side lengths (or internal angles) and orientation, inter-spacing, flow conditions (i.e., approach depth and discharge or velocity), sediment properties (mainly specific gravity and grain size), fluid kinematic and dynamic properties (i.e., density and viscosity), type of scour, and time. Therefore, for base length of the triangular pillar equal to the pier diameter and assuming the pillar is symmetric about its axis passing by its apex, i.e, its axis coincides with the flume centerline, the depth of scour d_s can be expressed as follows:

$$d_s = f(W, D, \alpha, S, y, V, g, d_{50}, \rho, \mu, \psi, t_o, t) \quad (1)$$

in which W is the flume width, D is the diameter of the pier, α is the apex angle of the subsidiary triangular pillar, S is the clear spacing between the pillar and the pier, y is the approach flow depth, V is the average velocity of flow, g is the gravitational acceleration, d_{50} is the median grain size, ρ is the density of fluid, μ is the dynamic viscosity of fluid, ψ represents the scour type, i.e., live bed scour or clear-water scour, t_o is the time corresponding to the asymptotic scour hole depth and t is the time of scour hole depth development. Using dimensional analysis, Eq. 1 can be written in non-dimensional form as:

$$\frac{d_s}{D} = f\left(\frac{W}{D}, \alpha, \frac{S}{D}, \frac{y}{D}, Fr, \frac{d_{50}}{D}, Re, \psi, \frac{t}{t_o}\right) \quad (2)$$

in which F_r is the approach flow Froude number ($F_r = V/\sqrt{(gy)}$), and R_e is its Reynolds' number ($R_e = \rho VR/\mu$; R being the hydraulic radius of the flume's cross section). After simplification of Eq. 2 and eliminating the variables that are not significantly relevant, i.e., R_e and those with constant values in this study, i.e., W, d_{50}, and y, one can obtain:

$$\frac{d_s}{D} = f\left(\alpha, \frac{S}{D}, Fr, \psi, \frac{t}{t_o}\right) \quad (3)$$

The dependence of d_s on each of the parameters in Eq. 3 has been studied.

Experimental setup and procedures

Experimental setup

The experiments were conducted in a rectangular flume having an overall length of 10.55 m. This length comprises the inlet, the outlet, and the working section (see Fig.1). The flume is 0.50 m deep, 0.30 m wide and is constructed on an adjustable steel frame, with its bed approximately 1.60 m above the floor. The flume is equipped with two controlling gates: one vertical sluice gate at the upstream end and a tailgate at the downstream end of the flume. The tailgate was adjusted to maintain a constant flow depth (y) of 0.20 m in all experiments. Water is delivered to the flume by a pump having a capacity range of 70–180 m^3/h. The discharge is measured by a V-notch installed at the downstream end in the outlet section. A point-gauge mounted on a sliding aluminum frame was used to measure surface elevations. An energy dissipating plate located at the flume inlet was used to reduce the flow turbulence. This, in addition to the length of the flume downstream of the inlet section and upstream of the testing section, resulted in having fully developed flow at the subsidiary pillar and the pier. A constant pier diameter of 0.03 m was chosen throughout the experiments, making $D/W = 0.1$. The apex angle (α) was chosen to be 60°, 90°, and 120° for ease of construction and practicality (see Fig. 2). In addition, six values for the spacing between the pier and the pillar were used; $S = 0$, 0.5D, D, 1.5D, 2D, and 3D.

A layer of sand approximately 0.20 m thick was placed in the working section. The sand had a median diameter (d_{50}) of approximately 0.9 mm. Raudkivi (1991) reported that scour depth increases as sediment becomes less uniform. Sediment uniformity is defined as:

$$\sigma_g = \sqrt{\frac{d_{84}}{d_{16}}} \quad (4)$$

From the sediment gradation curve of the used sand, the value of d_{84} is 1.04 mm, and the value of d_{16} is 0.59 mm; a uniformity factor (σ_g) was found to be 1.33. Raudkivi (1991) suggests the criterion for having uniform soil material is σ_g <1.35. Therefore, the sand used in this study can be

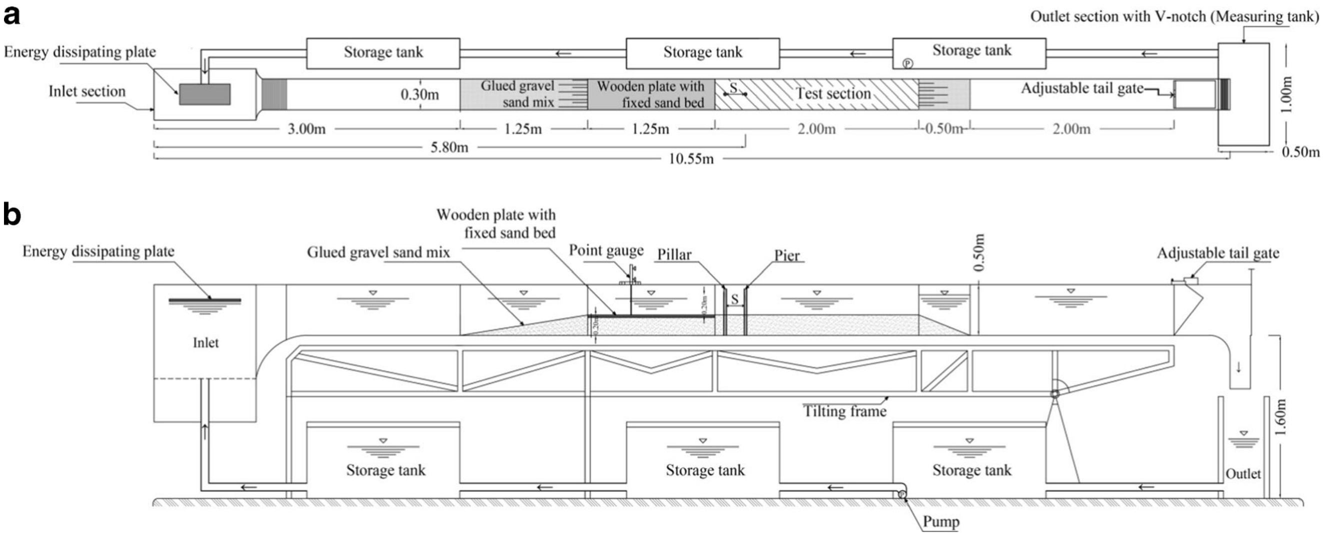

Fig. 1 The experimental setup. **a** Plan view. **b** Side view

considered uniform, and hence, sediment non-uniformity will not affect the scour depth.

Description of experiments

Twenty six experiments were conducted under different flow conditions as listed in Table 1. The experiments were conducted on two stages: (a) stage 1, which included experiments 1 to 4 with a single pier only and (b) stage 2, which included experiments 5 to 26 with the pier and the subsidiary pillar. During stage 1, experiments 1 and 2 were conducted to compare between live bed and clear-water scour, in addition to estimating the time of equilibrium scour (t_o). Experiments 2, 3, and 4 were conducted to investigate the effect of Froude number on the scour hole dimensions and to observe the temporal development of the scour hole under clear-water scour conditions. Experiments 1 to 4 were started by allowing water

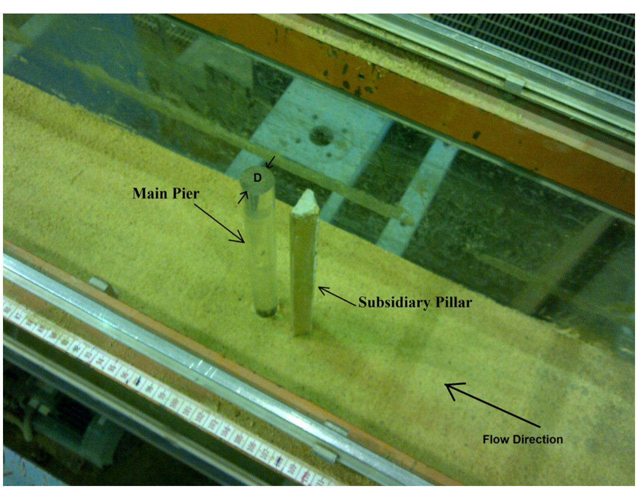

Fig. 2 Photo of the experimental setup showing the triangular pillar upstream of the pier along the channel

to flow over the horizontal bed for different times (5, 15, 30, 60, 240, 360, and 720 min), to estimate the time to reach the equilibrium scour depth. In experiment 1, the pier was located

Table 1 List of the experiments and their main results

Exp. no.	D (m)	Apex angle, α (°)	S/D	F_r	d_{sm} (m)	d_{sm}/D
1*	0.03	–	–	0.1	0.029	0.967
2	0.03	–	–	0.1	0.034	1.13
3	0.03	–	–	0.2	0.052	1.73
4	0.03	–	–	0.3	0.074	2.46
5	0.03	60	0.0	0.2	0.051	1.700
6	0.03	60	0.5	0.2	0.058	1.933
7	0.03	60	1.0	0.2	0.055	1.833
8	0.03	60	1.5	0.2	0.044	1.467
9	0.03	60	2.0	0.2	0.045	1.500
10	0.03	60	3.0	0.2	0.049	1.633
11	0.03	90	0.0	0.2	0.045	1.500
12	0.03	90	0.5	0.2	0.050	1.667
13	0.03	90	1.0	0.2	0.055	1.833
14	0.03	90	1.5	0.2	0.048	1.600
15	0.03	90	2.0	0.2	0.039	1.300
16	0.03	90	3.0	0.2	0.037	1.233
17	0.03	120	0.0	0.2	0.068	2.267
18	0.03	120	0.5	0.2	0.060	2.000
19	0.03	120	1.0	0.2	0.056	1.867
20	0.03	120	1.5	0.2	0.056	1.867
21	0.03	120	2.0	0.2	0.047	1.567
22	0.03	120	3.0	0.2	0.041	1.367
23	0.03	90	1.0	0.15	0.045	1.500
24	0.03	90	3.0	0.15	0.038	1.267
25	0.03	90	1.0	0.25	0.064	2.133
26	0.03	90	3.0	0.25	0.060	2.000

at 6.20 m from the start of the inlet channel and live bed scour occurred. In experiment 2, the pier was moved gradually further upstream until no live bed scour was observed. The new location for clear-water scour in experiments 2 to 26 was 5.80 m from the start of the inlet channel. As an additional precaution to avoid live bed scour, a wooden plate with fixed sand bed and glued gravel-sand mix was installed upstream of the test section as shown in Fig. 1. Also, a wooden plate with fixed sand bed connected between the sloping frame and the test section (see Fig.1).

During stage 2, experiments 5 to 26 were performed to examine the effect of the subsidiary pillar on local scour at the pier. The experiments were repeated at increasing clear distance between the pier and the subsidiary pillar and with different apex angle of the subsidiary pillar. The preliminary results from experiments 1 to 4 were used as a guide in performing experiments 5 to 26. This refers to the time of equilibrium (t_o), the location of the pier for clear-water scour to occur, and the appropriate Froude number. Table 1 lists the summary of the experiments and their conditions, as well as the main results discussed in the following section. Experiments 2, 3, and 4 were repeated few times to ensure repeatability; based on the scour depth measurements, the error in measuring d_s was estimated to be within ±3 mm. It is to be noted here that the results listed in Table 1 for experiments 2–4 are replicates of those shown in Fig. 4 at the same t_o used in the previous experiments of Alshehri et al. (2013). By comparing the d_{sm}/D values in Table 1 with those presented in Fig. 4, the relative errors were found to be approx. 2.7, 12.8, and 13.8 % in experiments 2, 3, and 4, respectively.

Results and discussion

Figure 3 shows the change in scour depth with time in experiment 1 (live bed scour) and experiment 2 (clear-water scour) at $F_r = 0.1$. It can be seen that in experiment 1, the scour depth fluctuated with time. One can distinguish between three zones:

i) Zone 1, where there is an initial rapid development of the scour depth d_s (d_s increased from zero to 33 mm in 30 min, i.e., at a rate of 66 mm/h).
ii) Zone 2, where there is a cyclic fluctuating behavior of d_s whose amplitude decays gradually with time. An initial deposition is observed at an estimated rate of 15.4 mm/h. This deposition is followed by erosion at an estimated rate of 2.5 mm/h until t of 240 min. Afterwards, a second cycle of deposition is observed at an estimated rate of 2.3 mm/h.
iii) Zone 3, where there is minimal change in d_s resulting in very slow erosion rate of 0.5 mm/h. The cyclic erosion-deposition-erosion behavior would have continued, but at much slower rates had the experiment lasted for longer times than 720 min.

In experiment 2 (clear-water scour), the scour depth development showed a continuously increasing depth with time, i.e., erosion only. An initial linear rapid increase in d_s of 32 mm occurred in 5 min (at a rate of 372 mm/h). This high rate is followed by a very low rate of erosion estimated at 0.34 mm/h until the end of the experiment. A change in d_s of only 2 mm occurred in 6 h, between 360 and 720 min. Based on the results of experiments 1 and 2, 94 % of d_s occurred during 360 min. Due to time constraints in the lab facility, the time to equilibrium (t_o) was considered to be 360 min and the maximum scour depth (d_{sm}) in the following experiments was measured at that time. It is important to note that the maximum scour depth presented in Table 1 corresponds to $t_o = 360$ min.

Figure 4 shows the temporal development of the scour depth in experiments 2, 3, and 4 with Froude numbers of 0.1, 0.2, and 0.3, respectively. In Fig. 3, the time was normalized by the time to equilibrium scour (t_o) and the scour depth

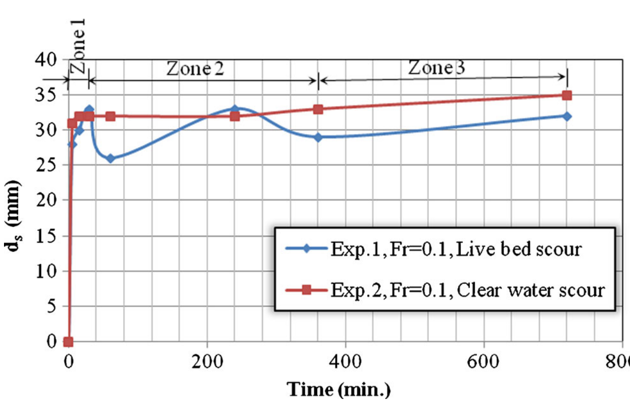

Fig. 3 The temporal development of the scour hole depth in experiments 1 and 2 (reproduced from Alshehri et al. 2013)

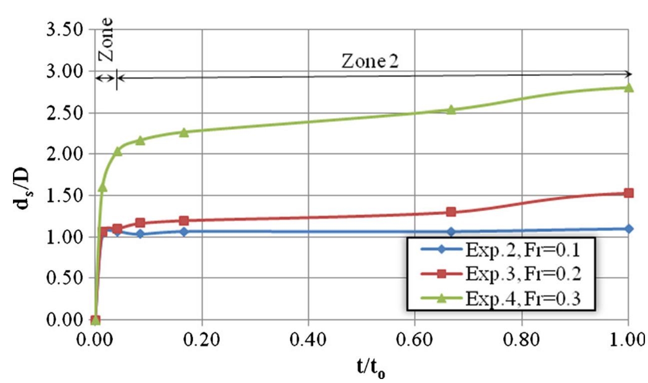

Fig. 4 The temporal development of the scour hole depth at different F_r (reproduced from Alshehri et al. 2013)

was normalized by the pier diameter (D). From Fig. 3, the development pattern of the scour hole depth (d_s) seems similar for the different Froude numbers. However, it appears that the time of initial rapid development of d_s (zone 1) is longer for $F_r = 0.3$ than for $F_r = 0.1$ and 0.2. It is also noticeable that for $F_r = 0.1$ and 0.2, this time of initial development is almost the same. For $F_r = 0.1$ and 0.2, d_s/D was 1.1 at t/t_o of 0.01, while for $F_r = 0.3$, d_s/D was 2.2 at t/t_o of 0.04. In zone 2, however, the value of d_s/D increased non-linearly with increasing Froude number at any given time. At equilibrium ($t/t_o = 1.0$), the value of d_s/D increased from 1.1 to 1.53 for an increase of Froude number from 0.1 to 0.2. However, when Froude number increased from 0.2 to 0.3, d_s/D increased to 2.8.

The spatial pattern of the scour hole was also examined at different Froude numbers at the equilibrium time (t_o). Figure 5a, b shows the dimensions and shape of the scour hole across the channel and in the stream direction, respectively, for different Froude numbers. From Fig. 5a, it is obvious that there is a quasi-linear rate of decrease of d_s with Y that is almost the same for $F_r = 0.1$ and 0.2 and is estimated at a slope of 0.4 mm/mm. However, for $F_r = 0.3$, the rate of decrease of d_s with Y increased to approximately 0.6 mm/mm. While the measurements in Fig. 5a were taken only up to Y/D = ±3 ($Y = \pm 9$ cm), the profiles were observed visually to maintain the slopes away from the pier and up to the flumes sides. The profiles reflect similarity of the flow field across the stream at either side of the pier.

Figure 5b shows the profiles of the scour hole in the flow direction. The scour hole extended upstream of the pier up to the wooden plate for $F_r = 0.3$, also in the cross direction (see Fig. 5a). In addition, underneath erosion occurred below the wooden plate. All profiles upstream of the pier were observed to maintain steep slope closer to the pier up to a certain location beyond which the slope became milder; in the case of $F_r = 0.1$, it became an even adverse slope reflecting signs of deposition. For $F_r = 0.2$, the upstream profile showed almost flat bed starting at X/D = 3.3. Therefore, it was decided to use F_r of 0.2 in experiments 5 to 22, as it provided larger scour depths than $F_r = 0.1$, yet the scour hole profiles were still within the flume's boundaries and did not extend to the sides or the wooden plate upstream. On the downstream side of the pier, the profiles showed an approximately flat bed very near to the pier, followed by a steep slope then a mild slope. The flat bed extended to approximately $X/D = -1.0$ for $F_r = 0.1$ and to $X/D = -1.33$ for $F_r = 0.2$ and 0.3. However, the steep slope part extended to only $X/D = -2.3$ for Fr = 0.3, whereas it reached $X/D = -3.0$ for $F_r = 0.1$ and 0.2. It is also

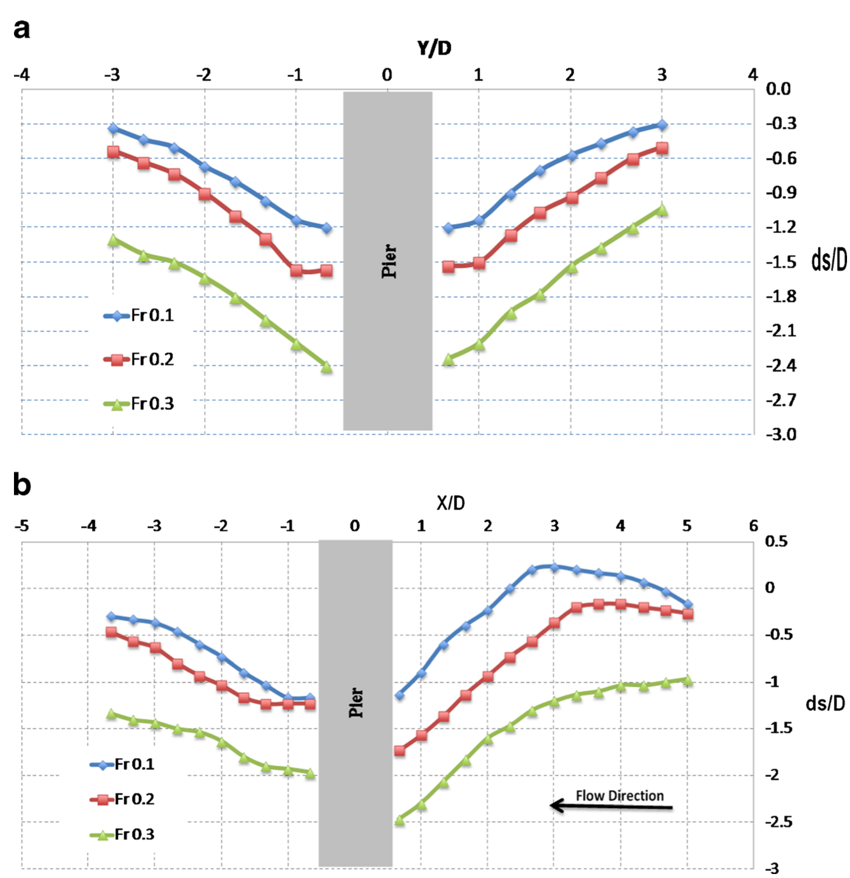

Fig. 5 The scour hole dimensions and profiles at equilibrium for different Froude numbers for the pier-alone reference case. **a** Across the channel. **b** Streamwise

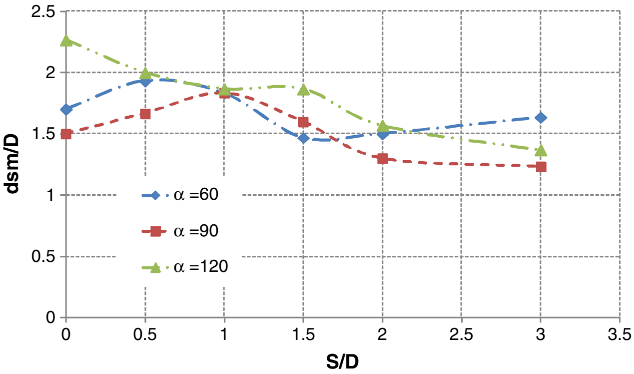

Fig. 6 d_{sm}/D against S/D for different apex angles of the subsidiary triangular pillar

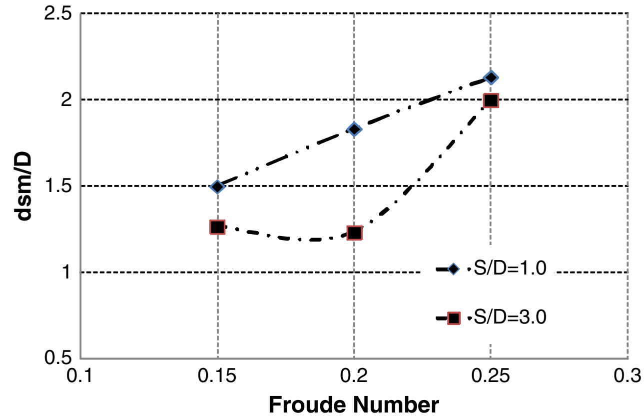

Fig. 8 Variation of maximum scour depth (d_{sm}/D) with Froude number for spacing between the pier and pillar of $S/D = 1$ and 3

noticeable that d_s/D was almost the same right downstream of the pier for $F_r = 0.1$ and 0.2, while it increased to 1.6 times larger for $F_r = 0.3$.

Figure 6 illustrates the maximum scour depth normalized by the pier diameter (d_{sm}/D) against the relative spacing S/D for different apex angles (α) of the subsidiary triangular pillar for $F_r = 0.2$. The maximum scour depth was observed and measured right upstream of the pier. The results of experiments 5 to 10 with apex angle, α, equals 60° show that the maximum scour depth increases then decreases, then increases in a cyclic pattern with increasing S/D, with a minimum value at $S/D = 1.5$. The results of experiments 11 to 16 with apex angle, α, equals 90° show that the maximum scour depth increases to the highest value at $S/D = 1.0$, then it decreases to minimum at $S/D = 3.0$. No cyclic pattern is observed in this case. The results of experiments 17 to 22 with apex angle, α, equals 120° show that the maximum scour depth decreases monotonically with increasing S/D. Overall, α of 120° seems to result in the largest scour depths for S/D ranging from 0 to 2; beyond which d_{sm}/D became intermediate between $\alpha = 60°$ and 120° at $S/D = 3.0$. Generally, for all investigated spacing between the pier and subsidiary pillar, it is seen that $\alpha = 90°$ resulted in the minimum scour depth at the pier. It is to be noted that at S/D of 1.0, all three selected apex angles of the subsidiary pillar resulted in the same scour depth at the pier. This may suggest that the flow field at this spacing does not vary much with the apex angle. The authors recommend numerical simulations for future studies to verify this observation. Because the minimum scour depth at the pier occurred at S/D of 3.0 for two of the chosen three apex angles, i.e., $\alpha = 90°$ and 120°, sample longitudinal profiles of the scour hole at $S/D = 3.0$ were selected to be presented in Fig. 7.

As can be seen from Fig. 7, the profiles are similar in that the maximum scour occurred at the pillar; hence, the pier was protected and smaller scour depths occurred near the pier. Deposition occurred between the pier and the pillar with its peak at distances of $X/D = 1.67$ for α of 60°, X/D = 1.16 for α of 60° and $X/D = 1.5$ for α of 120°. Also, d_s/D was minimum both upstream and downstream of the pier for α of 90°. The profile hit the original bed level at $X/D = -3.0$ for both α of 90° and α of 120°, while it did so at $X/D = -2.1$ for α of 60°.

Since the subsidiary triangular pillar with apex angle, α, of 90° showed the best performance in terms of minimizing the scour depth at the pier, it was chosen to be used for the rest of experiments 23–26 exploring the effect of other Froude numbers at the spacing that resulted in the maximum and minimum scour depths S/D = 1.0 and 3.0, respectively (review

Fig. 7 The scour hole dimensions and profiles at equilibrium for $F_r = 0.2$ and $S/D = 3.0$ for the pier-pillar configuration in the streamwise direction

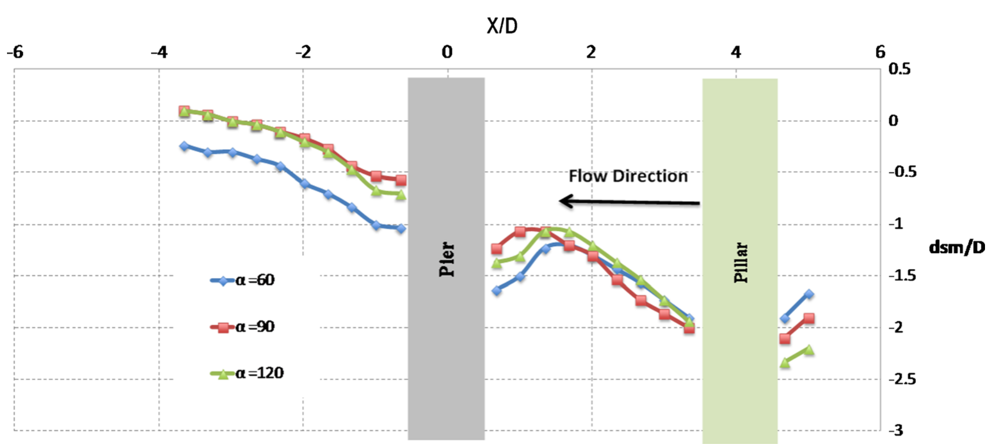

Fig. 6). Froude numbers of 0.15 and 0.25 were tested in addition to F_r of 0.2. Figure 8 shows the results of these experiments where it can be seen that the depth of scour at the pier (d_s) seems to linearly increase with a larger Froude number when the relative spacing, *S/D*, equals 1.0. On the other hand, the relation becomes non-linear when the relative spacing, *S/D*, increases to 3.0.

Conclusions

In this paper, reduction of scour around a circular bridge pier with diameter, *D*, using a subsidiary triangular pillar has been examined experimentally under clear-water scour conditions using uniform sandy soil. The experiments were performed under sub-critical flow conditions, mainly at Froude number, F_r, of 0.2. However, other experiments that investigated the relation between the maximum scour depth at the pier and other F_r of 0.1, 0.15, 0.25, and 0.3 were also performed. Three subsidiary triangular pillar configurations with apex angle, α, of 60°, 90°, and 120° were used at different relative spacing (*S/D*) between the pier and pillar of 0, 0.5, 1.5, 2.0, and 3.0. The base length of the pillars was constant in all experiments and equalled the pier diameter.

Based on the results of the present study, it is recommended, for having minimum local scour depths at the pier, to use a pillar with α of 90°. Except for *S/D* of 1.5 where the pillar with α of 60° performed better, the pillar with α of 90° resulted in minimum scour depths at all other spacing values. At *S/D* of 1.0, the selected apex angles of the subsidiary pillar provided the same scour depth at the pier. Numerical simulations are recommended for future studies to investigate this finding, as well as to examine the effect of other angles, for example, 30°, 105°, and 135°.

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