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Experimental investigation and flow analysis of clear-water scour around pier and abutment in proximity

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Abstract

Local scour around bridge piers and abutments is one of the most important causes of bridge failure. Despite a plethora of studies on scour around individual bridge piers or abutments, few studies focused on the joint impact of a pier and an abutment in proximity on scour. This study conducted laboratory experiments and flow analyses to examine the interaction of piers and abutments on clear-water scour. The experiments were conducted in a rectangular laboratory flume, including 18 main tests (combination of different types of piers and abutments) and five control tests (individual piers or abutments). Three types of piers (a rectangular pier with a rounded edge, a group of three cylindrical piers, a single cylindrical pier) and two types of abutment (a wing-wall abutment and a semi-circular abutment) were used. Acoustic Doppler Velocimeter (ADV) was used to measure the three-dimensional flow velocity for analyses of streamline, velocity magnitude, vertical velocity, and bed shear stress. The results showed the velocity near the pier and abutment increased by up to 80%. The maximum scour depth around the abutment increased by up to 19%. In contrast, the maximum scour depth around the pier increased significantly by up to l71%. The presence of the pier in the vicinity of the abutment led to an increase in the scour hole volume by up to 87% relative to the case with an individual abutment. The empirical equations were also derived to accurately estimate the maximum scour depth at the pier adjacent to the abutment.

Keywords: Abutment; ADV; Bridge scour; Laboratory experiment; Maximum scour depth; Pier

1. Introduction

Bridge scour is the erosion of streambeds or removal of bank materials from bridge foundations (Mays, 2001). Scour at bridge piers and abutments is recognised as one of the most causes of bridge failure, leading to substantial damage to bridges as a principal part of transportation infrastructures (Kumcu et al., 2014). Scour is the main cause for more than 60% of all bridge failures in the United States (Abid, 2017; Saha et al., 2018) and 70% in the United Kingdom (Lamb et al., 2019). Previous researches have proved that the scouring mechanism is similar at bridge piers and abutments (Melville, 1997). When approaching flow hits the upstream side of piers and abutments, a stagnation pressure is created due to the flow velocity that decreases through flow depth, causing the birth of a downflow. The resulting downflow forms horizontal horseshoes and vertical wake vortices that are the main causes of local erosion (Hamill, 2011).

Scour around river structures has attracted the attention of many researchers in this field (Karami et al., 2011). Melville and Raudkivi (1977) were one of the first scientists who analysed the flow characteristics around a cylindrical pier at the scour hole. They observed that the location of the maximum shear stress was where the scour first occurred. The primary vortex at bridge abutments, similar to the horseshoe vortex at bridge piers, is responsible for the scour hole growth (Kwan, 1988). Coleman et al. (2003) studied scour development at a bridge abutment and obtained a new formula for estimating scour at the abutment based on flow depth, abutment size, flow intensity, etc. Some studies have specifically focused on the scour depth caused by different shapes of piers or abutments (Melville, 1997; Melville and Coleman, 2000; Fael et al., 2016). More recently, Fael et al. (2016) introduced a shape factor (k_s) for the scour depth of different pier shapes relative to the single-cylinder pier scour depth. Melville (1997) previously suggested shape factor values of 0.75 for wing-walls and 0.45–0.6 for spill-through abutments.

Multiple research works have given empirical equations for estimating the local scour depth at piers and abutments (Froehlich, 1988; Melville, 1997; Richardson and Davis, 2001; Sheppard and Miller, 2006; Sheppard et al., 2014). Sheppard et al. (2014) evaluated 23 commonly used scour prediction equations with laboratory and field data. A new equation that obtained the least total error was proposed by melding and slightly modifying the equations of Sheppard and Miller (2006) and Melville (1997). However, the difference of the maximum scour depth predictions using different empirical equations was about 100%, indicating that more justifications or development of new equations are necessary (Pizarro et al., 2020).

Flow field analysis could provide better complementary insight into the scouring process and hence attract more attention of many researchers. Dey and Barbhuiya (2005b) measured the turbulent flow field around a short rectangular abutment using Acoustic Doppler Velocimeter (ADV). Pasupuleti et al. (2022) investigated flow characteristics and velocity field around circular

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piers in different layouts. They observed that flow separation occurred behind upstream piers, and primary vortex was generated due to the downflow in front of the upstream pier. Guan et al. (2019) presented principal characteristics of the horseshoe vortices and turbulent flow fields at a circular bridge pier when a scour hole was developing. They observed that the horseshoe vortices were also enlarged, strengthened, and reproduced as the scour hole grew, and the location of the core of the main horseshoe vortex was asymptotically stabilised after 24 h. Yang et al. (2020) observed that of the three pressure flow types (free surface flow, submerged office flow, and overtopping flow), submerged orifice flow had the highest velocity intensity whereas free surface flow had the lowest. Melville et al. (2021) studied the effect of streamwise abutment length on the scour and turbulence flow at a contraction section. They observed that the long contraction abutment caused most of the turbulent zone to move to the downstream abutment, and the equilibrium scour hole formed downstream.

Many studies have focused on the scour at individual piers or abutments. However, few research works have addressed the interaction of scour piers and abutments. Hong (2005) studied the interaction between local pier scour and contraction scour around a bridge pier and showed that the presence of the pier in the contracted flow area reduced the contraction scour depth by 25%. After scouring, flow redistribution in a high depth can also reduce the flow velocity and decrease the scour depth (Hong and Abid, 2016). Oben-Nyarko and Ettema (2011) performed laboratory experiments to clarify the impact of the interaction between a pier and an abutment (spill-through or wing-wall shape) on the scour depth and found that the pier close to the abutment had a minor influence on the maximum scour depth around the abutment. On the contrary, the scour depth around the pier can increase significantly compared to the state of an individual pier. Saha et al. (2018) showed the presence of a pier near an abutment had no impact on the location of scour but slightly decreased the maximum scour depth. Khajeh and Vaghefi (2020) showed that the maximum scour depth around an abutment in proximity of an inclined pier in a river bend occurred at the upstream side of the outer abutment. However, the impact of the distance between the pier and abutment was not analysed.

Although many studies have focused on the bridge scour at an individual pier or abutment, few studies conducted for the interaction between the pier and nearby abutment. In addition, the scour depth of this interaction can be mainly affected by the shapes of the pier and abutment. Therefore, further experimental tests are needed, and new relations should be derived. The flow field, velocity, and streamline under this interaction should be analysed as well. To the best of authors' knowledge, limited information is currently available on how a pier near an abutment affects the scour depth and flow characteristics at both piers and abutments. Therefore, this study aimed to conduct laboratory experiments, analyse streamlines, and derive new empirical equations on the effect of interaction between bridge piers and abutments on the scour depth and flow field. This paper also aimed to analyse the impact of the shape and layout of piers and abutments and their distance on the scour depth. To achieve these goals, three-dimensional (3D) flow characteristics were investigated using ADV measurements. Flow streamlines, velocities, and bed shear stress were also analysed for the experimental tests to justify the scouring processes around piers and abutments.

2. Materials and methods

All experiments in this study were conducted using a rectangular laboratory flume that was 14 m long, 1 m wide, and 1 m high. Fig. 1 shows the schematic side (longitudinal section) view and the flume plan with all dimensions. The real picture of the flume and its accessories are shown in Fig. A.1. Abutments and piers were placed in the flume far away from the channel entrance (i.e., 6 m downstream the entrance). In this way, a uniform flow was established in the test region, and fully turbulent flow was developed as per the equation suggested by Kirkgöz and Ardiçlioğlu (1997). Uniform sand with a median size of d_{50} = 0.88 mm and a geometric standard deviation of $\sigma_g = 1.3\sqrt{d_{84}/d_{16}}$ (with d_{84} and d_{16} denoting the diameter that 84% and 16% of the sediment is finer than that, respectively) was used as the uniform bed materials throughout the flume. A recessed section with a length of 2.4 m was provided as the test region. The thickness of the sand layer (bed materials) was 30 cm in the recessed section and 2 cm along the rest of the flume. The hydraulic characteristics and procedure of the tests are explained in Appendix A.

Fig. 1. Schematic side view (up) and plan view (down) of laboratory flume.

Two types of abutments and three types of piers, all made of transparent plexiglass at laboratory scales, were used in the experiments. Fig. 2 shows the following shapes and groups of piers and abutments: a rectangular pier with a rounded edge (R), a group of three cylindrical piers (G), a single cylindrical pier (S), a wing-wall abutment (W), and a semi-circular abutment (C). To remove the impact of the flume sidewall on the scour, Chiew and Melville (1987) suggested that the ratio of the pier diameter

(D) to the channel width (B) should be less than 0.1 ($D/B < 0.1$). Moreover, if the ratio of the flow depth (H) to the pier diameter (D) is greater than 3 ($H/D > 3$), the flow depth effect on the scour can be neglected (Chiew, 1995). According to Ettema (1980), if the pier diameter relative to the sediment mean diameter is greater than 50, sediment size has no impact on the scour. Therefore, a pier diameter of 5 cm was selected to remove the effects of sidewall, sediment size, and flow depth on the scour. The abutments were short, with their lengths (L_a) less than the flow depth (H) ($L_a/H < 1$). Thus, the scour depth became independent of the flow depth according to Melville (1992) and Melville and Raudkivi (1977).

Fig. 2. Schematic representation of different shapes and dimensions of piers and abutments used in tests: (a) rectangular pier with rounded edge; (b) group of three cylindrical piers; (c) single cylinderial pier; (d) wing-wall abutment; (e) semi-circular abutment, and (f) definitions of D, L_a, and X.

According to dimensional analysis using the Buckingham theorem, the local scour around a pier or an abutment is a function of different non-dimensional variables:

$$f\left(\frac{d_s}{D},\frac{U}{U_{cr}},\frac{D}{d_{50}},\frac{L_a}{D},\frac{B_a}{D},\frac{X}{D},K_{sa},K_{sp},\sigma_g,\frac{U}{\sqrt{gD}},\frac{\rho_s}{\rho},\frac{Ut}{D},s,\frac{U\rho D}{\mu},\frac{H}{D}\right)=0 \quad (1)$$

where d_s is the scour depth; U is the mean flow velocity; U_{cr} is the critical flow velocity; L_a is the abutment length perpendicular to the flow direction; B_a is the abutment width; X is the distance between the pier and abutment; K_{sa} is the abutment shape factor; K_{sp} is the pier shape factor; g is the gravitational acceleration; ρ_s is the bed material density; ρ is the density of water; t is time; s is the flume slope; μ is the water dynamic viscosity. Given that this study mainly focused on the interaction of scour between the pier and abutment considering the effects of their shapes and distance, all influencing variables were set constant except for X/D, K_{sa}, K_{sp}, and d_s/D that were varied to determine the effects of the shape and the distance between the pier and abutment.

The first group of experiments included five control tests in which individual piers or abutments were used as a benchmark. The control tests were compared with eighteen main tests in which piers and abutments were placed together. Table 1 lists the the information and results of all experiments (23 tests). Tests were named starting with "T" for control tests and "S" for main tests, followed by the acronyms defined above for the pier and abutment shapes and groups. Main tests were conducted at three different distances between the pier and the abutment (X defined in Fig. 2(f)) for each shape combination. X was set as 1.5, 3.0, and 6.0 times the pier diameter (D), denoted by "1", "2", and "3" in the test names, respectively. Based on several trial runs of the control tests, the run time of all 18 main tests was set as 27 h during which the scour depth was equal to or greater than 80% of the maximum scour depth. The actual equilibrium time was around 10%–20% longer than this run time. However, given a long time to achieve equilibrium as per the recommendation of Dey and Barbhuiya (2005a), a 27-h duration of each test was set for the time required to reach more than 80% of the equilibrium scour depth based on a large number of main tests. The detailed description of the temporal evolution of the scour depth in the control and main tests are provided in Appendix A. The maximum scour depths at a pier and an abutment (d_{sp} and d_{sa}, respectively) were assigned as the depths of the scour holes at a pier and an abutment at the end of each test.

Table 1

Information and results of laboratory experiments.

Test category	Test No.	Test name	X/D	Observed relative maximum scour depth		Estimated relative maximum scour depth		Scour volume (cm^3)
				Abutment	Pier	Eq. (3)	Eq. (4)	
Control test	1	TW		3.4				26 954
	2	TC		3.6				26 474
	3	TS			1.66			3 560
	4	TG			1.96[a], 1.74[b], 1.56[c]			8 283
	5	TR			1.46			3 554
Main test (pier combined with wing-wall abutment)	6	SWS3	6.0	3.30	2.46	2.48*	2.40*	34 477
	7	SWG3	6.0	3.20	2.22[a], 1.92[b], 1.68[c]	2.78*	2.43*	35 630
	8	SWR3	6.0	3.42	2.04	2.28*	2.25*	31 199
	9	SWS2	3.0	3.52	2.62	2.79*	2.69*	31 102
	10	SWG2	3.0	3.40	2.94[a], 2.24[b], 1.90[c]	3.09*	2.72*	42 035
	11	SWR2	3.0	3.30	2.68	2.59*	2.52*	29 832
	12	SWS1	1.5	3.92	4.22	3.76*	4.21*	49 535
	13	SWG1	1.5	3.92	4.20[a], 4.26[b], 3.28[c]	4.06*	4.25*	48 751
	14	SWR1	1.5	3.40	3.96	3.56*	3.94*	37 673
Main test (pier combined with semi-circular abutment)	15	SCS3	6.0	3.50	2.12	2.48*	2.11*	32 622
	16	SCG3	6.0	3.86	2.22[a], 1.94[b], 1.70[c]	2.78*	2.13*	43 287
	17	SCR3	6.0	3.64	2.10	2.28*	1.97*	33 372
	18	SCS2	3.0	3.80	2.32	2.79*	2.36*	32 352
	19	SCG2	3.0	3.90	2.28[a], 2.48[b], 2.00[c]	3.09*	2.38*	47 183
	20	SCR2	3.0	3.76	2.12	2.59*	2.21*	32 471
	21	SCS1	1.5	3.78	3.80	3.76*	3.69*	36 306

22	SCG1	1.5	4.30	3.80[a], 4.10[b], 3.02[c]	4.06[*]	3.73[*]	45 756
23	SCR1	1.5	3.90	3.54	3.56[*]	3.46[*]	38 143

Note: data with the superscripts "a", "b", and "c" are the observed relative maximum scour depths at the first, second, and third piers in the group of three cylindrical piers, respectively; and data with the superscript "*" are the estimated maximum scour depth at the first pier in the group of three cylindrical piers.

At the end of each test, water was carefully drained off from the flume to ensure that no disturbance occurred in the scour hole region. Afterwards, the maximum scour depth and bed geometry were measured using a laser meter with an accuracy of ±1.5 mm. In 3D velocity measurement experiments, bed materials were fixed by spraying resin to prevent any scouring, and a 25-Hz SonTek ADV was used to measure the 3D flow velocity on a flat fixed bed. A total of 1 700 points with distances from 1 to 10 cm were measured at five different depths. The location and spacing of the velocity measurement points are shown in Fig. A.2.

3. Results and discussion

3D flow characteristics of the main tests were analysed. The impacts of the pier and abutment in proximity on the maximum scour depth at the abutment and piers were discussed separately. These impacts was also analysed in terms of scour hole characteristics and the relationship between scour volume and cross-section. Several empirical equations for prediction of the scour depth at a pier near an abutment were derived from experiments. The effect of the pier and abutment in proximity on the temporal evolution of the scour hole was also discussed in Appendix A.

3.1. Streamline analysis

Fig. 3 shows the near-bed (z/H = 0.033 with z denoting the depth of the flow velocity measurement) streamlines for an individual pier, an individual abutment, and a pier and an abutment in proximity with X/D = 3. As shown in Fig. 3(b), the streamlines around the individual abutment tended to bend leftward, reaching the abutment upstream. After passing through the abutment, flow separation started at the downstream edge of the abutment. A vortex formed in the abutment wake region with a core located at x/L_a = 1.83 and y/L_a = 0.5 (with x and y denoting Cartesian coordinates in flow direction and perpendicular to it, respectively. The origin of coordinate system is at abutment centreline end right.) immediately downstream the abutment, and the streamlines inclined to the left because of the high transverse velocity. These deviated streamlines were visible across the half width of the flume. According to Fig. 3(c), the streamlines are more aligned streamwise when the pier was located near the abutment. After bending to the left facing the abutment, the streamlines met the pier in the way and turned again towards the stream direction. On the other hand, the presence of the pier channelised the flow between the pier and abutment. Hence, few streamlines could reach the flume mid-line. The location of the wake vortex core was the same as the case with the individual abutment. It still had a small width perpendicular to the flow due to the confining effect of the pier downstream the abutment region. The presence of the pier caused the flow separation to move to the right side from the downstream edge of the abutment. Comparison of Fig. 5(a) and (c) shows that the flow field of the pier changed completely when affected by the nearby abutment.

Fig. 3. Near-bed streamlines for (a) an individual pier, (b) an individual abutment, and (c) a pier and an abutment in proximity with X/D = 3.

3.2. Velocity magnitude

Fig. 4 shows the velocity magnitudes relative to the upstream mean velocity (U_{mean}) at different depths (z/H = 0.033, 0.200, and 0.500). The flow velocity in the case with an individual pier showed no significant change and was close to the mean velocity in most of the flume area (Fig. 4(a) through (c)). On the near-bed plane (z/H = 0.033), the individual pier increased the velocity by no higher than 6% (with a maximum U/U_{mean} of 1.06). When the height for flow velocity measurements was increased, the velocity magnitude was found to increase by 30%. In contrast, in the case with an individual abutment, the velocity magnitudes increased by 52% on the near-bed plane (

Fig. 4(d)) and by 61% at z/H = 0.500 (

Fig. 4(f)). When the pier and abutment were both in place, the velocities increased by 62% on the near-bed plane (

Fig. 4(g)) and by 80% at z/H = 0.500 (Fig. 4(i)). Due to the protruding abutment and flow contraction, a high-velocity region formed at the upstream edge of the individual abutment, developed downstream, and leaned to the left (Fig. 4(d) through (f)). In the case with a pier and an abutment in proximity, two high-velocity regions (Fig. 4(g) through (i)) formed on the upstream right side of the pier and at the upstream abutment edge, respectively. As discussed in Section 3.1, a high-velocity zone was established between the pier and abutment, causing the detached shear layer to contract. Compared to the case with an individual abutment, the wake region and reverse flow were compacted in the case with a pier and an abutment in proximity. Furthermore, the high-velocity region expanded significantly in the flume and might cause a wide scour hole to be produced. The velocity magnitude was higher on the left side of the pier than the individual pier due to the higher transverse velocity with $U/U_{mean} = 1.8$.

Fig. 4. Time-averaged velocity relative to upstream mean velocity (U/U_{mean}) in different tests and at different depths: (a) individual pier at z/H = 0.033, (b) individual pier at z/H = 0.200, (c) individual pier at z/H = 0.500, (d) individual abutment at z/H = 0.033, (e) individual abutment at z/H = 0.200, (f) individual abutment at z/H = 0.500, (g) pier and abutment at z/H = 0.033, (h) pier and abutment at z/H = 0.200, and (i) pier and abutment at z/H = 0.500.

3.3. Vertical velocity

Fig. 5 shows the contours of the relative vertical velocity (the ratio of the near-bed vertical velocity (w) to the flow mean velocity). The downflow upstream of the pier (Fig. 5(a)) was responsible for the generation of the horseshoe vortices digging the scour hole. In the wake region of the individual pier, high vertical velocity in the upward direction indicated that the wake vortices moved away the bed materials. Similarly, the downflow across the upstream edge of the individual abutment (Fig. 5(b)) showed that the primary vortices were the main cause of the scour around the abutment. According to Fig. 5(c), the downflow and primary vortices were stronger when the pier was located at $X/D = 3$ than the cases with an individual pier and an individual abutment. The maximum relative downflow velocities were −0.15 for the individual pier, −0.19 for the individual abutment, and −0.21 for the pier and abutment in proximity. The primary vortices for the abutment that extended over the left upstream of the pier were the predominant cause of the scour at the pier. In addition, the flow structure around the pier was completely changed, leading to a scour hole that was different from that in the case with the individual pier.

Fig. 5. Distributions of relative vertical velocities (w/U_{mean}) at $z/H = 0.2$ for (a) individual pier, (b) individual abutment, and (c) pier and abutment in proximity at $X/D = 3$ (with a positive w value denoting velocity in upward direction).

3.4. Bed shear stress

The scouring of bed materials is basically attributed to the bed shear stress. A bed shear stress that exceeds the critical shear stress can cause bed materials to move. Hence, the bed shear stress was analysed to investigate the relationship between the scour phenomena and the bed shear stress as a principal parameter in scour. The bed shear stress can be estimated using the near-bed shear stress obtained from the measured 3D flow velocities. The mean bed shear stress (τ) on the fixed-bed plane was calculated by the following equation used by Dey and Barbhuiya (2005b) and Zhang et al. (2021) with $z/H = 0.033$:

$$\tau = \sqrt{\tau_x^2 + \tau_y^2} \qquad (2)$$

where τ_x and τ_y are the mean bed shear stresses in the x and y directions, respectively, with $\tau_x = -\rho(\overline{u'v'} + \overline{u'w'})$ and $\tau_y = -\rho(\overline{v'u'} + \overline{v'w'})$ where u', v', and w' are longitudinal, lateral, and vertical velocity fluctuations, respectively. Fig. 6 shows the calculated near-bed shear stresses relative to the critical bed shear stress for the cases with the individual pier, individual abutment, and pier R located at $X/D = 3$ near abutment W. The critical bed shear stress ($\tau_{cr} = 0.466$ Pa) was calculated using the Shields parameter approach. According to Fig. 6(a), τ was far from τ_{cr} in most areas of the test field. In the case of the individual wing-wall abutment, τ increased significantly near the upstream of the abutment. In a region with an area of about $0.85L_a \times 3L_a$, the bed shear stress exceeded the critical value and reached a maximum value of $4.85\tau_{cr}$ at $x/L_a = -1$ and $y/L_a = 1.31$ (Fig. 6(b)). As shown in Fig. 6(c), locating the pier near the abutment also caused a significant increase in the bed shear stress, but the region with a high bed shear stress shrinked to an area of approximately $0.5L_a \times 2L_{a,}$ and the maximum bed shear stress decreased to $3.83\tau_{cr}$ at $x/L_a = -1$ and $y/L_a = 1.31$. In both cases with an individual abutment and with a pier and an abutment in proximity, the location of the maximum bed shear stress was near the upstream edge of the abutment where the scour process started first and the maximum scour depth were recorded.

Fig. 6. Relative near-bed shear stresses at $z/H = 0.033$ for tests: (a) individual pier, (b) individual abutment, and (c) pier and abutment in proximity.

3.5. Effect of X/D on maximum scour depth around abutment

Fig. 7(a) shows the variation of the relative maximum scour depth at the abutment (d_{sa}/d_{sa0}, with d_{sa} and d_{sa0} denoting the maximum scour depths around an abutment in the main tests and control tests, respectively) versus X/D with three shapes of piers in proximity. The scour depth slightly decreased as the distance between the piers and the abutment increased. More specifically, when X/D was 1.5 in the cases using piers S and G, d_{sa} at the wing-wall abutment was 15% greater than that in test TW with no pier. In contrast, no significant change was observed in the case using pier R. The maximum scour depth was 19% higher in test SCG1 than in test TC. Nevertheless, d_{sa} increased by approximately 1%–7% in other cases with large X/D values (Table 1). These results indicated that the pier in proximity to the abutment did not lead to a substantial increase of d_{sa} in the cases with $X/D > 3$. According to

Fig. 4 and 5, the maximum flow velocity around the abutment with a nearby pier was similar to that around the individual abutment. Thus, a similar scour depth was expected when a pier was placed nearby. This result agreed with the findings of Oben-Nyarko and Ettema (2011) on the long wing-wall and spill-through abutments and the rectangular pier. They reported a marginal increase of the abutment scour depth by 5%–7%. They also reported increasing abutment scour depths in some situations, whereas the scour depth decreased slightly in other cases. When the pier was very close to the abutment ($X/D = 1.5$), the horseshoe and wake vortices induced by the pier strengthened the abutment scour process. When the distance between the pier and abutment increased, the flow field around the pier slightly changed the flow field around the abutment, indicating a minor impact of the pier (Fig. 3). Abid (2017) also found a difference of ±15% between the scour depth around an abutment with a nearby pier and the scour depth around an individual abutment. This slight difference of the scour depth was shown in the case with $X/D \geq 3.0$. However, in the case with $X/D = 1.5$, the G pier and the abutment jointly obstructed the flow with a longer obstacle in front of the flow and stronger vortices, leading to a deeper scour hole. Rahimi et al. (2021) reported a 31% increase of the scour depth around a vertical wall abutment when a circular pier was at $X/D = 1.7$, but the scour depth only increased by less than 10% in the case with $X/D > 3.0$.

Fig. 7. Relative maximum scour depths at abutment for various combinations of pier and abutment (a) and relative maximum scour depth at pier for various combinations of pier and abutment (b).

3.6. Effect of X/D on maximum scour depth around pier

Fig. 7(b) shows the relative maximum scour depth around the pier (d_{sp}/d_{sp0}, with d_{sp} and d_{sp0} denoting the maximum scour depths around a pier in the main tests and control tests, respectively) verus X/D for various combinations of pier and abutment. Unlike the scour around the abutment, the presence of the pier in the proximity of the abutment significantly influenced d_{sp}. With $X/D = 1.5$, d_{sp} in the main test SWR1 was 2.71 times d_{sp0} of the control test TR. This difference of the maximum scour depth was significantly greater than the case with longer distances between the pier and abutment (i.e., $X/D \geq 3.0$). This indicated that when a pier was placed in the influence region of the abutment scour hole, the scour depth around the pier was highly affected, and its value was similar to the scour depth around the abutment. The impact was evident at piers R and S with a short relative distance (i.e., $X/D = 1.5$). Rahimi et al. (2021) conducted an experiment with a single circular pier and a vertical abutment in proximity and reported only a 31% increase in the maximum scour depth around the pier for $X/D = 1.65$, which was much lower than the results of this study and Oben-Nyarko and Ettema (2011). Further analysis on the scour depth around the pier is provided in Appendix A.

3.7. Analysis of scour holes

Analysis of the scour holes can help to better understand the physical processes of the scour mechanism and estimate the maximum scour depth. Fig. 9 shows the scour topography of the control tests using semi-circular and wing-wall abutments after 27 h of the experiment. The maximum scour depths were at the upstream edge of the wing-wall abutment and with an angle of 35°–40° to the flow direction for the semi-circular abutment. Dey and Barbhuiya (2005a) also reported similar results with 45° for the wing-wall abutment and with 40°–50° for the semi-circular abutment. The primary vortices that were created upstream the abutment controlled the location of the maximum scour depth at the upstream edge of the abutment. In the cases with a pier and an abutment in proximity, the locations of these vortices did not change. Thus, the location of the maximum scour depth around the abutment did not change.

Fig. 8. Scour topographies of control tests for (a) wing-wall abutment and (b) semi-circular abutment (with circles representing locations of maximum scour depth at piers in main tests, dashed line A denoting location of upstream head of rounded rectangular pier and group of three piers, and dashed line B standing for location of the upstream head of single cylindrical pier).

Fig. 9 shows the 3D views and contours of the scour hole topographies when pier S was at different distances from abutment W. With X/D = 6 (i.e., SWS3), two distinct scour holes, one around the pier and another around the abutment, were observed. Table 1 shows the scour volume, defined as the difference between the volume of the conical scour hole and the initial bed surface level, for all tests. These data showed that a pier placed in the vicinity to an abutment resulted in a 12%–87% increase of the scour hole volume relative to that in the case using an individual abutment. The increase of the scour hole volume did not significantly affected the maximum scour depth around the abutment in the main tests. Therefore, the presence of the pier in the influence region of the scour hole around the abutment had an insignificant influence on d_{sa} but significantly affected the extent of the scour hole (Fig. 10).

Fig. 9. 3D views and contours of scour hole topographies of main tests SWS1, SWS2, and SWS3.

Fig. 10. Lateral cross-sections of scour holes for maximum scour depths around pier and abutment (at longitudinal reaches of x = 570.0 cm and 582.5 cm) with different relative distances from abutment (X/D = 1.5, 3.0, and 6.0) for main tests (a) SWS1, SWS2, SWS3, (b) SWG1, SWG2, SWG3, c) SWR1, SWR2, SWR3, d) SCS1, SCS2, SCS3, e) SCG1, SCG2, SCG3, f) SCR1, SCR2, SCR3.

Fig. 10 shows the lateral cross-sections of the scour holes for the maximum scour depths around the pier and abutment (i.e., at reach lengths of 570.0 cm and 582.5 cm in the flume that corresponded to sections A and B in Fig. 9Fig. 9 , respectively) with different pier distances (i.e., 22.5 cm for X/D = 1.5, 30.0 cm for X/D = 3.0, and 45.0 cm for X/D = 6.0). The abutment control tests showed that almost no scour occurred in the area 6D away from the abutment and the scour hole around the abutment is almost unchanged. However, adding a pier at X/D = 6.0 led to the formation of an additional local scour hole. Therefore, the scour hole was wider in the case of X/D = 6.0 than in other cases due to the combination of the pier scour hole and the abutment scour hole. This impact on d_{sa} was trivial in the case of $X/D \geq 3.0$ and in some cases of X/D = 1.5 (i.e., SCS1, SCR1, and SWR1). A separate scour hole around the pier was found when $X/D \geq 3.0$. However, when X/D = 1.5, the scour hole around the abutment changed, and a joint large scour hole formed around both the pier and abutment instead of two separate scour holes.

Oben-Nyarko and Ettema (2011) used Large-Scale Particle Image Velocimetry (LSPIV) images of flow and found that a relatively small amount of flow passed through the area between the pier and the abutment when the pier was close to the abutment (e.g., X/D = 1.5). The discharge passing through the pier and abutment increased when the pier was located further away from the abutment. When the pier was close to the abutment (X/D = 1.5), the pier and abutment could be resembled as a united obstacle in front of the flow and lead to a single large scour hole. Therefore, no separate scour hole formed around the pier.

3.8. Empirical equations for prediction of pier scour depth

Typical design practices suggest that individual scour components can be added together to calculate the overall scour depth for the combination of the pier and abutment (Hong and Abid, 2016). However, the joint interaction of these components in the main tests revealed that this method might overestimate d_{sp}. In addition, the overall scour depth estimation using typical design practices ignores the distance between the pier and abutment, which can significantly affect the estimation accuracy. Table 1 shows that the sum of the maximum scour depths of an individual pier and an individual abutment largely overestimated d_{sp} or d_{sa}. Hence, the following equation was derived from the tests to estimate the scour depth around the pier when influenced by the abutment using the principle of superposition:

$$\frac{d_{sp}}{D} = \frac{d_{sp0}}{D} + \left| \frac{d_{sa0}}{D \tan\phi} - \left(\frac{X}{D} + \frac{1}{2} \right) \right| \tan\phi \qquad \frac{X}{D} \leq 6.0 \qquad (3)$$

where ϕ is the angle of repose of the bed materials. Eq. (3) can estimate the maximum scour depth at a pier located at any distance of X away from an abutment given d_{sp0}, d_{sa0}, and the angle of repose of the bed materials. The calculated values of the relative pier scour depth are given in Table 1. This equation was derived from the geometric relationship in the scour cross-section profile. Further details of this derivation are provided in Fig. A.4.

Fig. 11(a) shows the scatter plot of the measured d_{sp}/D versus the calculated d_{sp}/D using Eq. (3). The dashed lines represent the ±10% error band. Eq. (3) rationally estimated the scour depth within the acceptable range, and the errors of most calculated d_{sp}/D were less than 10%. The mean absolute error (*MAE*), root mean square error (*RMSE*), and the coefficient of determination (R^2) were 0.30, 0.37, and 0.86, respectively. The scour process occurs layer by layer, and the scour profile is geometrically self-similar (Dey and Barbhuiya, 2005a). Thus, Eq. (3) can be used not only to estimate d_{sp} but also to calculate the scour depth at any time of the scour progress given the scour depths around an individual pier and an individual abutment at that time.

Fig. 11. Comparison between measured and calculated scour depths using (a) Eq. (3) and Eq. (4).

Comparison of Table 1 and Table A.1 reveals that existing prediction formulas could lead to considerable errors in estimating the scour depth when the pier was within the interaction region of the abutment. Hence, Eq. (3), derived from the experiments, can be considered a better method with a high confidence level. The above formulas used constant shape coefficients. Similarly, regression analysis was conducted on the results to derive the following equation that can predict the scour depth around a pier near an abutment according to the shape, type, and arrangement of the pier and abutment:

$$\frac{d_{sp}}{D} = K_{sa}K_{sp}\left[0.19\left(\frac{X}{D}\right)^2 - \frac{1.8X}{D} + 6.2\right] \quad (4)$$

where K_{sa} is abutment shape factor with K_{sa} = 1.14 for abutment W and K_{sa} = 1.00 for abutment C; and K_{sp} is pier shape factor with K_{sp} = 0.94, 0.95, and 0.88 for piers S, G, and R, respectively. This equation accurately estimated d_{sp} in the vicinity of the abutment with *RMSE* = 0.12, *MAE* = 0.10, and R^2 = 0.98 (Fig. 11(b)). The advantage of Eq. (4) is that this equation can calculate the scour depth given the distance between the pier and abutment and their shapes. Table 1 shows the scour depth calculated by Eq. (4). The uncertainty and limitations of Eq. (4) are further described in Appendix A.

4. Conclusions

This study conducted laboratory tests and analysed the maximum scour depth and scour pattern in clear-water conditions when piers and abutments with various shapes and layouts were combined. The flow streamline, velocity, bed shear stress, scour topography, and lateral scour hole cross-section were measured and analysed. The main conclusions are as follows:

(1) When a pier was located near an abutment, the flow characteristics around the pier changed, and primary vortices generated by the abutment led to a deeper and broader scour hole around the pier and abutment. High flow velocities appeared in the two regions upstream left of the abutment and the pier, which caused a wider scour hole.

(2) The presence of the pier in the vicinity of the abutment had a minor impact on the maximum scour depth around the abutment although the scour hole volume increased by up to 87%. The maximum scour depth increased slightly when X/D = 1.5.

(3) The presence of the pier near the abutment significantly increased the scour depth around the pier. When the distance between the pier and abutment decreased, the maximum scour depth around the pier increased by up to 175% for X/D =1.5.

(4) Using the principle of superposition of the scour depths around an individual pier and around an induvial abutment, the empirical equations were derived to accurately estimate the maximum scour depth at a pier adjacent to an abutment.

Appendix A. Supplemental information and discussion

Supplemental information and discussion to this article can be found online at https://doi.org/.

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Declaration of competing interest

The authors declare no conflicts of interest.

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