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Reduction of pier scour using bed suction and jet injection

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The influence of a combined system of jet injection through the pier and bed suction on the reduction of local scour around a circular pier was investigated in a laboratory flume. Experiments were conducted for two water depths (10·5 and 28 cm) under 1-jet and 3-jet injection and different angles between the jets, with bed suction rate $Q_s/Q_0 = 2\%$, in turbulent flow and clear-water scouring conditions. The results show that the bed suction modifies the effect of jet scouring and reduces the local scour and sediment transport at the pier (36% for scour depth, 25 and 42% for the area and volume of scour hole). The maximum reduction of the scour depth was about 50% (about 20, 39 and 39% for the area, volume and the upstream slope of the scour hole respectively) in the best configurations for a combined countermeasure.

Notation

A_e, V_e, G_e	area, volume and gradient of scour hole at equilibrium with jet and suction
A_{e0}, V_{e0}, G_{e0}	area, volume and gradient of scour hole at equilibrium without jet and suction
D	pier diameter
d_{50}	median size of sediment particles
d_{16}	sediment size than which 16% of sediment is finer
d_{84}	sediment size than which 84% of sediment is finer
d_s	scour depth
d_{se}	equilibrium depth of local scour with jet and suction
d_{se0}	equilibrium depth of local scour without jet and suction
Fr	Froude number
h	mean approach flow depth
k	turbulent kinetic energy
l	length of scour hole in front of pier at the equilibrium
n	jet number
Q_0	undisturbed total flow rate
Q_j	individual injection flow rate
Q_s	suction flow rate
r_{A_e} and r_{V_e}	percentage scour variation at equilibrium of the scour area and the scour volume in front of the pier, respectively
r_{d_e} and r_{G_e}	percentage scour reductions at equilibrium of the depth and the scour hole gradient in front of the pier, respectively
Re	Reynolds number
t	time
U	mean approach flow velocity
U_c	critical mean approach flow velocity for entrainment of bed sediment
u^*	shear velocity
u_c^*	critical shear velocity
u', v', w'	fluctuating velocity components in the x, y, and z directions, respectively
W	width of flume
x, y, z	Cartesian coordinates in the longitudinal, lateral and vertical directions, respectively
θ	angle between jets
σ_g	geometric standard deviation of the sediment particle size distribution

1. Introduction

Water erosion causes scour holes around bridge piers, which results in many severely damaged highway bridges. Scour protection around bridge piers is a key problem for bridge protection. During recent decades, several investigations have been conducted to assess the adequacy of countermeasures against local scour at bridge piers (e.g., Chiew, 2004; Chiew and Lim, 2000; Dargahi, 1990; Dey, 1997; Dey and Raikar, 2007; Dey *et al.*, 2006; Gaudio *et al.*, 2012; Moncada-M *et al.*, 2009; Tafarojnoruz *et al.*, 2010, 2012; Wang *et al.*, 2011). On the other hand, bed suction or downward seepage happens through the permeable boundary in rivers or channels. It can have significant effects on the mean velocity, turbulence intensity, velocity and Reynolds stress distributions (Chen and Chiew, 2004). Nezu (1977) concluded that the dimensionless Reynolds stress associated with suction is less than that without suction. Rooney and Machemehl (1977) used suction to reduce cylindrical pier-scour in a sand bed. With a suction rate of about 0·1 l/s the scour was reduced by up to 50%, and with a suction rate of about 0·4 l/s it was eliminated completely. Chen and Chiew (2007) experimentally investigated velocity distributions of turbulent open channel flow with bed suction and showed that suction not only decreases the flow rate in the channel but also significantly modifies the turbulent flow characteristics. Lu and Chiew (2007) investigated suction effects on turbulent flows over a dune bed and observed that the streamwise velocity profile was more uniform than that without suction. Cheng (2003) found that with bed suction the sediment transport rate decreased. Lu *et al.* (2008) presented a comprehensive review of seepage effects on turbulent open-channel flow and sediment entrainment and found that the presence of suction caused an increase in the effective weight of the bed particles, enhancing the stability of bed particles. Chiew and Chen (2008) investigated effect of suction on clear-water scour at bridge piers and observed that suction has a profound effect on pier-scour development, especially when located upstream of the bridge pier, where the equilibrium scour depth is reduced by up to 50%. Similar to the effect of suction on the turbulence characteristics and sediment transport rate, it is assumed that suction can also modify the behaviour of both the flow and sediment transport around a bridge pier. Dey and Nath (2010) presented experimental observations on the turbulence characteristics in free-surface flows over an immobile rough boundary subjected to suction and injection from bed. Also, Dey *et al.* (2010) carried out an experimental study on turbulent flow characteristics in submerged plane wall jets subjected to injection and suction from the wall. Zheng *et al.* (2011) investigated separation control over a backward-facing step flow by continuous suction using the turbulence model of large eddy simulation numerically. In addition, jet injection or jets form one of the boundary layer control techniques that generate enough kinetic energy in the boundary layer to control flow separation and decrease the downflow strength as well as the horseshoe vortex effect. Soltani-Gerdefaramarzi *et al.* (2013) investigated a new method for weakening the horseshoe vortices around a circular cylinder using a constant water jet injection, and considered boundary layer control techniques in bridge pier scouring through blowing and injection systems. The findings showed that the scour depth was reduced by use of jets – by up to 37·5% for water depth 10·5 cm and 31·2% for water depth 28 cm.

The objectives of this study were to investigate the effect of suction and a combined system of bed suction and jet injection to decrease scouring depth and to determine how the distributions of turbulent kinetic energy and the Reynolds stress affect jet injection through the pier and bed suction.

1.1 The mechanism of scouring

The mechanism of the jet effect on scouring can be found in the paper by Soltani-Gerdefaramarzi *et al.* (2013), where the effectiveness of jets as a countermeasure to reduce local scouring was discussed. In general, the effective weight and bed shear stress control the stability of bed particles, and both are changed by seepage downwards. Suction increases the effective weight of bed particles, increasing the stability of bed particles. Lu *et al.* (2008) indicated that the stability of bed particles is related to the relative magnitude of effective weight and shear force. If the weight is more than the shear force, the stability of the sediment particles will increase. However, if the weight of particles is less than the shear force, the stability of the sediment particles will decrease, and thus the rate of sediment transport will be enhanced. On the other hand, horseshoe vortices are formed at the junction of the pier immersed in the flow as a result of the boundary layer separation. Suction is a useful method for preventing vortices, reducing the boundary layer thickness and increasing momentum exchange (Schlichting and Gersten, 2001). Jets also divide the flow into two regions (Soltani-Gerdefaramarzi *et al.*, 2013). For the both regions the jet diminishes the downflow effect when it impinges the bed. If jets contribute to controlling separation, they generate a drag increase. Separation control has a great effect on prevention of scouring around piers. It seems that a combined system of suction and jet injection as a countermeasure to modify the stability of bed particles by decreasing downflow and horseshoe vortex effects will reduce scouring around piers.

2. Experimental measurements

A glass-sided horizontal flume 30 m long, 0·7 m wide and 0·6 m deep at the Hydraulic Modelling Laboratory at Nanyang Technological University was used to conduct the experiments. Water is circulated through a submersible pump installed in the laboratory reservoir. The flow rate was controlled using a speed inverter and a valve and was monitored using an electromagnetic flow meter. Uniform sediments were used in the tests with median diameter $d_{50} = 0{\cdot}48$ mm and geometric standard deviation $\sigma_g = (d_{84}/d_{16})^{0{\cdot}5} = 1{\cdot}33$. All tests were conducted under clear-water conditions with an undisturbed shear velocity (0·81 times the critical shear velocity for bed sediment entrainment). The latter was determined to be 0·017 m/s by a trial and error process using the Shields diagram where dimensionless stress is 0·032. The experiments were conducted for two depths: shallow-water flow of 10·5 cm (Amini *et al.*, 2012; $h/W = 0{\cdot}15$) and high-flow of 28 cm (Ettema, 1980; $h/D \approx 4$). This study assumes that the flow is steady, uniform and at equilibrium condition during the measurement process. A summary of experimental and flow conditions for four series A, B, C and D are presented in Table 1. Test series A and B were carried out with water depth of 10·5 cm and series C and D were carried out with water depth of 28 cm. The diameter of the glass circular pier was $D = 7{\cdot}5$ cm, containing one or three 3 mm-diameter holes at 1 cm above the bed level and a flow rate of 0·015 l/s for each jet. The angle between the jets for each case was 45, 60, 90 and 120° for 3-jet injection experiments. The seepage zone was located at the middle part of the flume to ensure uniform seepage velocity over the entire area. The seepage zone is in the form of a recess 2 m long, 0·7 m wide and 0·4 m deep. Sand with median grain size $d_{50} = 2{\cdot}47$ mm and depth of 0·2 m was placed on top of a filter cloth, which overlay a perforated metal plate. Water was allowed to seep through the sand layer, filter net, and perforated plate before being drained by 12 identical

Test series	h: cm	Q_0: l/s	U: m/s	Re	Fr	Q_s: l/s	U/U_c	Explanation
A	10·5	17·5	0·238	29 300	0·23	0·35	0·81	Injection only
B	10·5	17·5	0·238	29 300	0·23	0·35	0·81	Jet and suction
C	28	53·5	0·273	88 628	0·16	1·07	0·81	Injection only
D	28	53·5	0·273	88 628	0·16	1·07	0·81	Jet and suction

Table 1. Summary of experimental conditions

pipes, fitted uniformly in the bottom of the recess to control suction charge. The results of Chiew and Chen (2008) were used to determine the location and rate of suction. Consequently, the relative suction rate $Q_s/Q_0 = 2\%$ ($2\% \times 17{\cdot}5 = 0{\cdot}35$ and $2\% \times 53{\cdot}5 = 1{\cdot}07$ l/s are for flow depths 10·5 and 28 cm respectively), located in the region $0 < x/D < 2{\cdot}4$ (where Q_s and Q_0 are suction flow rate and undisturbed total flow rate, respectively). Only a pair of suction holes at the same horizontal distance from the bridge pier was active in suction tests. The location of the suction hole (x) was defined as positive upstream and negative downstream with respect to the pier. The suction rate is determined by manually collecting the volume of water that discharges from the pipe over a fixed duration. Figures 1 and 2 show the layout and plan view of the seepage zone. The details of the equipment and experiment can be found in the paper by Soltani-Gerdefaramarzi *et al.* (2013). Experiments were conducted for more than 48 h in each test; however, the rate of scouring was negligible after 48 h. Therefore, 48 h was selected as the fixed duration for all the tests. Scour contours for a circular pier for $h = 10{\cdot}5$ cm with bed suction and 3-jet injection ($\theta = 45°$) after 48 h are shown in Figure 3. Also, two control tests were first conducted in which the suction rate, Q_s, and individual jet flow rate, Q_j, were zero for both water depths 10·5 and 28 cm, revealing the scouring depth without suction and injection effects. At the end of each test, the extent of the scour hole and its length in front of pier were measured by a point gauge with ±1 mm accuracy installed on moving carriages at several points around the pier. Subsequently, the area (A_e) and the volume (V_e) were plotted using the 'Surfer 8' software from Golden Software, Golden, CO, USA (http://www.Goldensoftware.com/Surfer8TrainingGuide.pdf). The percentage scour reductions or increases of equilibrium depth in front of the pier r_{d_e}, in the scour hole gradient r_{G_e}, at equilibrium area r_{A_e}, and for the scour volume r_{V_e}, is defined as follows.

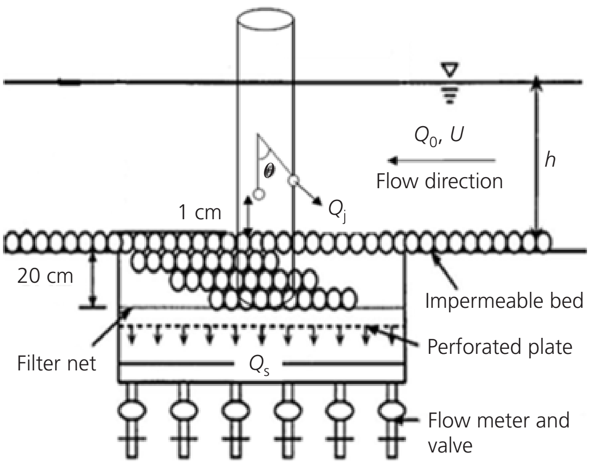

Figure 1. Layout of the seepage zone

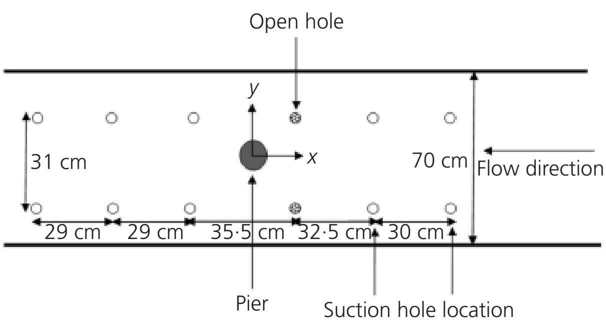

Figure 2. Plan view of the seepage zone

1. $$r_{d_e} = \frac{d_{se0} - d_{se}}{d_{se0}} \times 100$$

2. $$r_{G_e} = \frac{G_{e0} - G_e}{G_{e0}} \times 100$$

3. $$r_{A_e} = \frac{A_{e0} - A_e}{A_{e0}} \times 100$$

4. $$r_{V_e} = \frac{V_{e0} - V_e}{V_{e0}} \times 100$$

where the subscript 0 denotes experiments without any countermeasure (refer to Notation). A three-dimensional acoustic Doppler velocimeter (ADV) was used with sampling frequency 50 Hz and sampling volume 5 cm located below the probe. For each point a typical duration 240 s was used for measuring three-dimensional

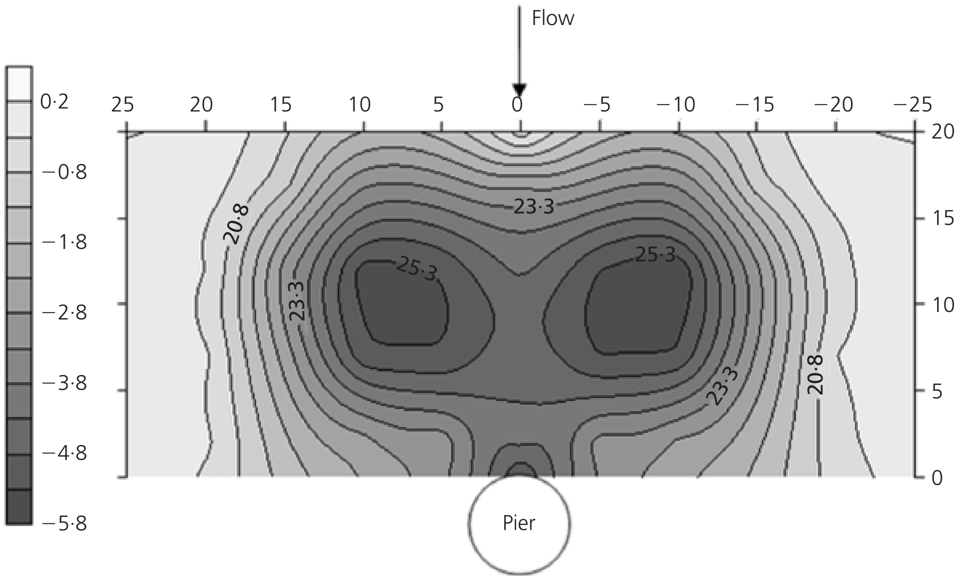

Figure 3. Equilibrium scour hole profile for bed suction and 3-jet injection with $h = 10{\cdot}5$ cm for $\theta = 45°$ (test B2) (units in cm)

instantaneous turbulent flow properties. The measurements were conducted in the equilibrium scour hole ($d_{se} = 9{\cdot}2$ cm) and 28 cm water depth under clear-water scour conditions, which had been established for 2 days under constant water jet injection and bed suction. Four methods of filtering ADV data were investigated, including acceleration threshold, maximum/minimum threshold, SNR/correlation, and phase-space; the SNR/correlation method was used in this study. WinADV (Wahl, 2000) was used to filter and process the velocity and turbulence data. Data with an average correlation coefficient of less than 70% and average SNR of less than 15 dB were filtered out. Two experiments, an unprotected and a protected experiment with suction and 3-jet injection located 1 cm above the bed material, were conducted to investigate variations of the turbulence flow characteristics around the bridge pier. The angle between jets and the individual flow rates of jets were 90° and 0·015 l/s, respectively. Vertical distributions of the normalised Reynolds stress ($-\overline{u'w'}/u_*^2$), and the turbulent kinetic energy ($\frac{1}{2}(\overline{u'u'} + \overline{v'v'} + \overline{w'w'})$) were plotted for each experiment at different vertical sections along the central line of the flume for six locations in front of the cylinder ($0{\cdot}67D \leqslant x \leqslant 3{\cdot}33D$). Here, only three vertical lines upstream of the pier with and without jet injection and suction were shown to represent clearly the normalised Reynolds stress and turbulent kinetic energy.

3. Results

In recent years, several researchers have investigated the effect of bed suction on the sediment entrainment and stability of bed particles (Cheng, 2003; Lu *et al.*, 2008; Maclean, 1991; Ramakrishna Rao and Nagaraj, 1999; Willetts and Drossos, 1975). However, to the authors' knowledge protection from the scour phenomenon under combined effect of bed suction and jet injection through the pier has not yet been studied. In this section, the bed suction effect and the combination of bed suction and jet injection through the pier surface as a countermeasure on scouring reduction are presented.

3.1 Effect of bed suction on scouring

Suction imposes a downward force directly onto the bed sediment particles to effectively increase their self weight. This, in turn, increases the threshold velocity for sediment entrainment. When suction was applied to bridge pier scour, it was anticipated that the application of suction in the direct vicinity of the hole would result in a significant reduction of the pier-scour depth. Figure 4 shows the dimensionless time evolution of the scour depth in front of the pier, Ut/D versus d_s/D for water depths 10·5 and 28 cm. In this figure A0 and C0 represent experiments without

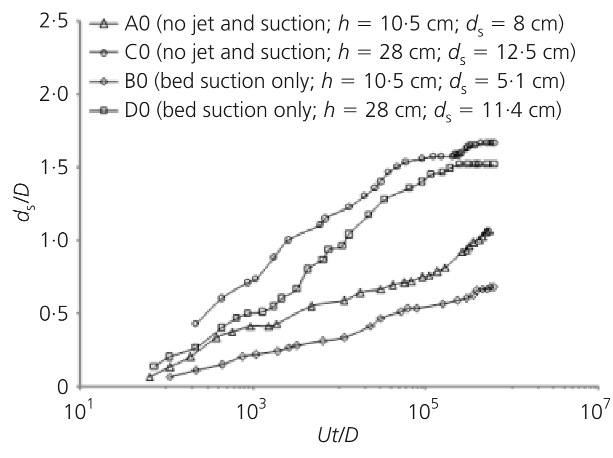

Figure 4. Dimensionless time evolution of the scour depth in front of the piers for water depths 10·5 and 28 cm

injection and suction, which were used as a reference to assess the reduction of scouring. Also, B0 and D0 represent experiments with bed suction only for water depths 10·5 and 28 cm, respectively. During the scour process the values of d_s/D for the experiments with suction were always smaller than without it (Figure 4), indicating that the bed suction affects the local scouring from the beginning of the process. As Table 2 shows, suction (experiments B0 and D0) decreased the scour depth at the front of the pier by up to 36·25 and 9% for 10·5 and 28 cm water depths, respectively. Also, suction reduced the area and volume of the scour hole respectively by up to 25 and 42% for 10·5 cm and 9% and 16·5% for 28 cm water depth when compared to experiments with jet injection only. In experiments with jets, the area of the equilibrium scour hole was larger than in the case without jets, especially at water depth 10·5 cm. In the presence of bed suction, the evolution of the longitudinal dimension of the scour hole is slower than that of the vertical dimension; therefore, the length of the scour hole in front of the pier decreases, especially for water depth 10·5 cm. These results show that bed suction increases the stability of the bed by increasing the

Test	n	θ	d_s: cm	l: cm	A_e: cm^2	V_e:cm^3	G_e: degree	r_{d_e}: %	r_{G_e}: %	r_{A_e}: %	r_{V_e}: %	Explanation
A0	0	—	8	14·5	553·9	1227·5	28·8	—	—	—	—	Without jet and suction
A1	1	0	5·1	16·5	582·8	922·3	17·2	36·25	40·3	−5·2	**24·9**	Injection only
A2	3	45	5·3	18·5	915·8	2144·0	16·0	33·75	44·5	−65·3	−74·7	Injection only
A3	3	60	5·5	21·7	1090·1	2348·3	14·2	31·25	50·6	−96·8	−91·3	Injection only
A4	3	90	5	22	745·9	1049·3	12·8	**37·5**	**55·6**	-34·7	14·5	Injection only
A5	3	120	6·6	16	659·3	1437·0	22·4	17·5	22·2	−19·0	−17·1	Injection only
B0	0	—	5·1	9·1	416·6	710·2	29·3	**36·25**	−1·7	**24·8**	**42·1**	Bed suction only
B1	1	0	6	17	646·8	930·2	19·4	25	32·6	−16·8	**24·2**	Jet and bed suction
B2	3	45	5·3	20	1002·3	2486·9	14·8	33·75	48·5	−81·0	−102·6	Jet and bed suction
B3	3	60	5·2	21·5	1009·6	2192·1	13·6	**35**	52·8	−82·3	−78·6	Jet and bed suction
B4	3	90	5·3	22	636·2	1007·1	13·5	33·75	**53·1**	−14·9	18·0	Jet and bed suction
B5	3	120	6·3	23·5	916·3	1661·5	15·0	21·25	33·1	−65·4	−35·4	Jet and bed suction
C0	0	—	12·5	19·5	902·9	2825·1	32·7	—	—	—	—	Without jet and suction
C1	1	0	9·8	22·2	845·0	1216·5	23·8	21·6	27·2	**6·4**	**56·9**	Injection only
C2	3	45	9·7	22	959·7	2374·8	23·8	22·4	27·2	−6·3	15·9	Injection only
C3	3	60	10	22·1	912·4	2262·1	24·3	20	25·7	−1·0	19·9	Injection only
C4	3	90	8·8	22·1	873·1	1996·5	21·7	**29·6**	**33·6**	3·3	29·3	Injection only
C5	3	120	11·5	21·7	1127·1	2881·6	27·9	8	14·7	−24·8	−2·0	Injection only
D0	0	—	11·4	20	823·3	2360·0	29·6	8·8	9·5	8·8	16·5	Bed suction only
D1	1	0	10·3	22	947·1	1783·5	25·1	17·6	23·2	−4·9	36·9	Jet and bed suction
D2	3	45	6·2	17	717·9	1735·2	20·0	**50·4**	**38·7**	**20·5**	**38·6**	Jet and bed suction
D3	3	60	9·5	19	817·8	2311·9	26·6	24	18·7	9·4	18·2	Jet and bed suction
D4	3	90	9·2	18	766·6	2136·0	27·1	26·4	17·1	15·1	24·4	Jet and bed suction
D5	3	120	10·6	18·3	884·6	2754·8	30·1	15·2	8·0	2·0	2·5	Jet and bed suction

Note: Numbers in bold type indicate maximum scour reductions and minus sign shows increased variation for r_{A_e}, r_{V_e} and r_{G_e}. Test series A and B are for water depth 10·5 cm and series C and D are for 28 cm. (refer to Notation).

Table 2. Summary of experimental results

effective weight of particles and decreasing sediment entrainment. The results for the scour depth and the area and volume of the scour hole indicated that bed suction had no considerable effect on scouring for a flow depth of 28 cm (9% reduction of scour depth), but did for a flow depth of 10·5 cm (up to 36%). The explanation is that the greater flow depth produces a stronger horseshoe vortex. This leads to lower efficacy of the countermeasure in cases of deeper approach flow. On the other hand, the suction locations and rates have important influence on the scour protection; the results reveal that higher suction rate contributed more effectively to the reduction of scour in water with flow depth 28 cm than in that with flow depth 10·5 cm. More detailed investigation is needed to clarify this contribution.

3.2 Combined countermeasure: jet injection and bed suction

According to Soltani-Gerdefaramarzi *et al.* (2013), the scour at a circular bridge pier can be reduced by a system of constant jet injection, with maximum efficiency of $r_{d_e} = 37{\cdot}5\%$ and $r_{V_e} = 15{\cdot}5\%$ for flow depth 10·5 cm, and of $r_{d_e} = 29{\cdot}6\%$ and $r_{V_e} = 29{\cdot}3\%$ for flow depth 28 cm. When jet injection was applied to the pier, it weakened the horseshoe vortices around a circular cylinder, especially the vortices close to the bed, decreasing the downflow strength by diverting it. The bed suction increased the stability of the bed sediment due to increase in the effective weight of bed particles and decreased the boundary layer thickness around the pier. These results suggested tests combining jet injection and bed suction as a countermeasure. Apparently, the combined countermeasure affects the downflow and horseshoe vortices, modifying the flow structure and reducing scouring depth compared with jet injection or bed suction only. Table 2 shows that the percentage of the scour reduction was larger for cases of jet injection and bed suction. For the experiments with jet injection only, the area and volume of the scour hole increased; however, the bed suction and jet injection combination reduced the area and volume of the scour hole for water depth 28 cm, demonstrating that the bed suction modified the effect of jet scouring and decreased local scouring. Combination of jet injection and bed suction produced no significant effect on r_{d_e} for water depth 10·5 cm compared with application of jet injection or suction only, showing r_{d_e} values of 37·5, 36 and 35% for jet injection, bed suction and combination of jet and suction, respectively. Accordingly, use of jet injection or bed suction for low flow was more effective than their combination for scour depth reduction. However, a combined system of jet and suction demonstrated a significant effect on scouring depth for water depth 28 cm, showing values of 30, 9 and 50·4% for jet injection, bed suction, and combination of jet and suction, respectively.

3.2.1 Effect of the jet number, *n*, on scour

Figure 5 shows the dimensionless time evolution of the scour depth in front of the piers, Ut/D against d_s/D. In this figure, A0 and C0 show experiments without jet injection and bed suction for the water depths of 10·5 and 28 cm, respectively. B1 and D1 show 1-jet injection experiments with bed suction, and B2 and D2 show 3-jet injection and bed suction experiments with angle between the jets equal to 45° for the two water depths. In these series of experiments, eight tests were conducted with one or three 3 mm diameter holes located 1 cm above the bed level for jet flow rate of 0·015 l/s and bed suction rate $Q_s/Q_0 = 2\%$, located in the region $0 < x/D < 2{\cdot}4$. As Figure 5 shows, the time evolutions of the scour depth for tests with unprotected piers (C0) and for tests with combined countermeasure (1-jet injection and bed suction; D1) are almost parallel, indicating that bed suction and 1-jet injection affect the flow structure and the scouring rate. Table 2 shows that 1-jet injection with bed suction (tests B1 and D1) decreased the scour depth at the front of the pier by up to 25 and 17·6% for water depths 10·5 and 28 cm, respectively. When the number of jets was increased in the 3-jet injection case, (tests B2 and D2) the scour depth reached 34 and 50% less than the unprotected pier cases for water depths 10·5 and 28 cm, respectively. As Figure 5 shows, increasing the number of jets from 1 to 3 exhibited no considerable effect on scouring depth for water depth 10·5 cm (25–35%) but did so for water depth 28 cm (18–50%). Also, increasing the number of jets from 1 to 3 not only extended the area and volume of scour hole but also enhanced scouring depth for water depth 10·5 cm. However, for water depth 28 cm a considerable reduction in scour depth (50%) and reduction in the area and volume of the scour hole by 20 and 39%, respectively, were observed due to the decrease of downflow strength by 3-jet injection. As a result, 1-jet injection with bed suction for water depth 10·5 cm and 3-jet injection with bed suction for water depth 28 cm were more suitable for scour depth reduction.

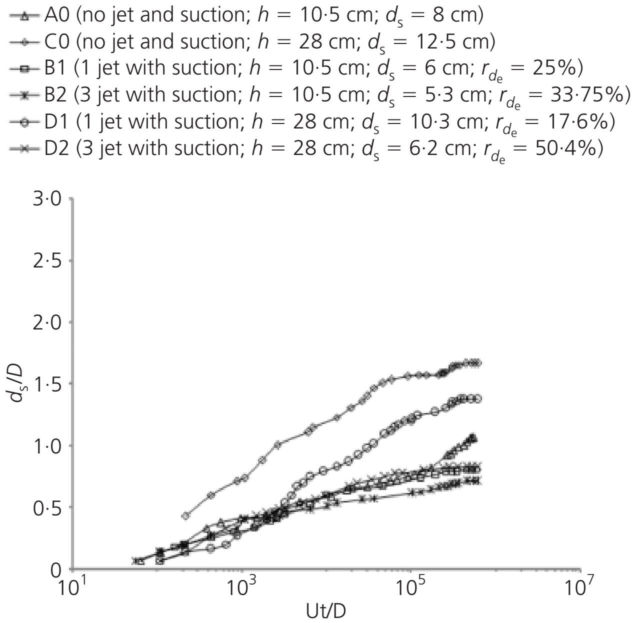

Figure 5. Dimensionless time evolution of the scour depth in front of the pier for water depths 28 cm (series D) and 10·5 cm (series B)

The upstream slope of the scour hole, equal to the angle of repose of the sediment, showed smaller values for all experiments with jet injection and bed suction than for those without a countermeasure. This is why the longitudinal dimension of the scour hole increased while the vertical dimension decreased (see Table 2), causing the angle of the upstream slope of the scour hole (G_e) to become smaller. This slope reduction was especially significant for tests conducted with 3-jet outlets combined with bed suction for a higher approach flow depth (28 cm). Also, the results revealed that experiments with combination of 1-jet injection and bed suction (tests B1 and D1) reduced the upstream slope of the scour hole by up to 19·4 and 25·1° for water depths 10·5 and 28 cm, respectively. When the number of jets was increased to 3 (tests B2 and D2) the upstream slope of the scour hole became 48·5 and 38·7% less than the unprotected pier cases in the water depths 10·5 and 28 cm, respectively.

3.2.2 Effect of the angle between jets on scour depth

The angle for 3-jet injection (θ) plotted against percentage scour reduction in the equilibrium depth in front of the pier, (r_{d_e}) is shown in Figure 6 for four series of experiments, A, B, C and D. Experiments in series A and C were carried out only for injection conditions and those in series B and D for combined jet injection and bed suction, for water depths of 10·5 cm (A, B) and 28 cm (C, D), and for angle between jets of 45, 60, 90 and 120°. The flow rate of jets in all experiments was 0·015 l/s with an inner diameter 3 mm located 1 cm above the bed material. As Figure 6 shows, when only injection was applied (series A and C) a specific trend for the both water depths was observed; however, in the presence of bed suction (series B and D) different trends were seen. These results show that bed suction affects the scouring process when combined with jet injection. In the best configurations for a combined countermeasure, a jet angle of 45° exhibited the best effect in controlling boundary layer separation around the pier, decreasing the downflow and horseshoe vortex in front of the pier. This caused reductions in the scour depth and area, volume and gradient of the scour hole in front of the pier by up to 50·4, 20·5, 38·6 and 38·7%, respectively, for series D (water depth 28 cm). Also, an angle of 90° showed the best efficacy, decreasing the scour depth and volume and gradient of the scour hole in front of the pier by up to 33·75, 18 and 53·1% for series B for water depth 10·5 cm. It seems that the optimum value of this parameter depends on the experimental conditions, including the flow depth and velocity field. An angle of 120° between jets produces the same results as 1-jet injection only, with no considerable effect on scour depth reduction.

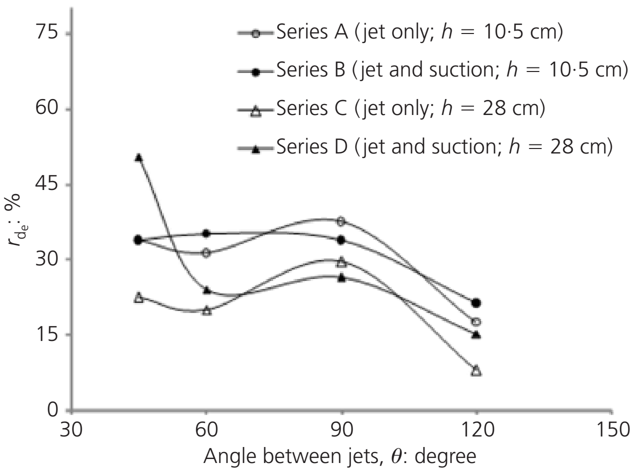

Figure 6. Effect of jet angle, θ, on r_{d_e} with three jet outlets ($Q_j = 0{\cdot}015$ l/s)

3.2.3 Reynolds stress distribution at the upstream of pier

The results obtained for the distribution of normalised Reynolds stress at the upstream plane of the pier for flows subjected to 3-jet injection and suction are shown in Figure 7. The data were made dimensionless using the undisturbed approach shear velocity, u^* and the approach flow depth, h. This figure shows a linear distribution for the normalised Reynolds stress in the upper part of the bed, $z > 0$ and significant bulges in the lower part, $z < 0$, for jet injection and bed suction experiments. Moving downstream and towards the bottom of the pier, the scatter increased significantly within the scour hole as a result of the turbulent mixing of fluid in this region. The normalised Reynolds shear stresses increased with distance from the bed up to a maximum value (6·31) reached at a distance of approximately $-0{\cdot}063h$ at $x = 2D$. Beyond this value, the Reynolds shear stress decreased towards zero at the water surface. Graf and Istiarto (2002) and Raikar and Dey (2010) also reported a similar trend in their studies. In the presence of suction and injection, the normalised Reynolds stress profiles displayed the same trend but at lower values than those without any suction and jet injection. The

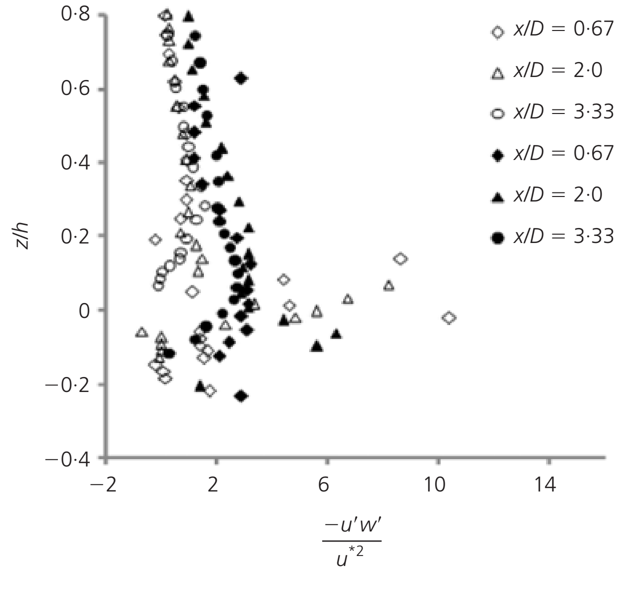

Figure 7. Normalised Reynolds stress profiles in the upstream plane of the cylinder (solid symbols, no jet and suction; open symbols, with jet and suction)

reduction was more significant within the scour hole region and near the pier than that near the jet location, decreasing from 6·31 to −1·25 for $z/h = -0{\cdot}06$ at $x/D = 2$. Accordingly, the results reveal that jet injection and bed suction increased the stability of the sediment particles and reduced the rate of scouring. The more significant change of Reynolds shear stresses near the pier and scour hole was due to suction and injection effects that predominantly occurred in this region rather than near the free surface. Compared with experiments without injection and suction, the response of Reynolds shear stresses to suction and injection was slower and required a longer distance to exert a significant effect on the scouring process.

3.2.4 Turbulent kinetic energy distribution upstream of the pier

The turbulent kinetic energy is defined as

$$k = \frac{1}{2}(\overline{u}\overline{u}' + \overline{v}\overline{v}' + \overline{w}\overline{w}') \quad (5)$$

Figure 8 illustrates the distribution of turbulent kinetic energy of the flow upstream of the pier for experiments with (open symbols) and without (closed symbols) injection and suction. These results show that turbulent energy profiles were approximately linear and changed rather insignificantly in the upper part of the flow depth close to the water surface. Approaching the pier (where downflow occurs), the turbulent energy became increasingly strong, especially at the location of jet issue. The profiles of the turbulent kinetic energy were characterised by bulges below the original bed level. Also, within the scour hole, turbulent kinetic energy decreased due to bed suction and jet injection through the pier, showing a strong anisotropy pattern at the bottom of the pier in this region. The turbulent kinetic energy does not show any especial trend for the injection and bed suction tests. Compared with the results of Soltani-Gerdefaramarzi *et al.* (2013) using only jet injection through the pier, it seems that bed suction influences the effectiveness of jet injection and modifies the turbulent flow structure within the scour hole due to significant turbulence anisotropy.

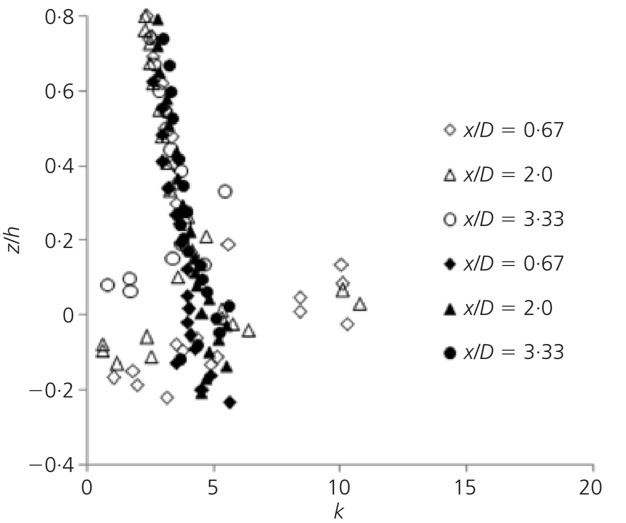

Figure 8. Turbulent kinetic energy in the upstream plane of the cylinder (solid symbols, no jet and suction; open symbols, with jet and suction)

4. Discussion

One of the reasons for the departure from traditional armouring countermeasures, such as dumping of riprap stone, sacrificial sill or piles, is because such methods induce other failure mechanisms associated with the use of armouring. According to the boundary layer concept, suction is one much-explored method of decreasing separation because it is easy to apply the various strengths of surface mass flow to perturb the reversed flow around the pier. However, the optimal suction rate to diminish the boundary layer separation is not clear. If the rate of suction or injection is increased, the boundary layer separation can be decreased or delayed. However, a large rate of suction or injection seems uneconomic from a practical point of view. For this reason, in this study the results of Chiew and Chen (2008) were used. Application of different suction rates (from 1 to 5%) revealed that maximum effectiveness occurs at $Q_s/Q_0 = 2\%$, causing 50% reduction of scouring depth. Furthermore, Soltani-Gerdefaramarzi *et al.* (2013) found that the effect of injection rate on the scouring is reduced when $Q_j/Q_0 \geqslant \sim 0{\cdot}027\%$ and reduces significantly up to a horizontal line for $Q_j/Q_0 \geqslant 0{\cdot}035\%$. Accordingly, a suction rate of 2% caused 36% scour depth reduction for water depth 10·5 cm with application of bed suction only. It seems that the bed suction was also effective in removing the decelerating fluid particles caused by the positive pressure gradient around the pier, increasing the effective weight of bed particles to reduce scouring depth. However, increase in the water depth influences the effectiveness of bed suction in reducing scouring due to the significant role of horseshoe vortices for water depth 28 cm. The jet injection causes a reduction in shear stress, controlling the flow separation and reducing scour power. Increasing the number of jets from 1 to 3 had no considerable effect on scouring depth for the water depth 10·5 cm (36–37·5% and 21–30% for water depths 10·5 and 28 cm, respectively), showing that jet injection increased the friction drag and scouring. Injection also has the capability to decrease the downflow strength, reducing the scour depth. If downflow strength decreases more than the friction drag increases, the scour depth will decrease. In low flow depth the downflow has less energy, so more scouring is expected on increasing the number of jets; however, for high flow depth, increase of the jet number reduces downflow power, reducing the rate of scouring. As a result, use of 1-jet injection with low flow depth and 3-jet injection with high flow depth seems to be effective for scour depth reduction. Another distinctive advantage of using jet injection and bed suction is that the structural device used to induce suction need not be exposed to the flow. Possible difficulties including service and maintenance of the pumping system can be overcome by providing flexible management and control near the bridge.

5. Summary and conclusions

The effects of bed suction and the combined countermeasure were tested to find the best configuration for modifying the flow structure and sediment transport as well as weakening the horseshoe vortices around a circular cylinder. Bed suction modified the effect of jet scouring and reduced sediment transport due to local scour. Also, separation within the scour hole can be decreased by suction since the low-energy fluid in the boundary layer is removed. The results showed that scour depth was reduced, by up to 50·4%, in front of the pier with a combined system of jet injection and bed suction. When jet was applied with bed suction the reduction in area and volume of the scour hole was greater than in jet only or suction only experiments. The results showed that 1-jet injection for flow depth 10·5 cm and 3-jet injection for flow depth 28 cm in systems combining bed suction and jet injection was more effective for scour depth reduction. For water depth 28 cm with aspect ratio equal to 2·5, the secondary flow affected the efficacy of jet injection in decreasing downflow strength and reduced its effect for the jet-only application cases (series C). However, in series D (combination of jet and bed suction) with the same aspect ratio, the results improved with the use of bed suction. Bed suction modified the effect of secondary flow and helped scour reduction. This study showed that turbulence properties, such as Reynolds shear stresses and turbulent kinetic energy of the flow within the scour hole, decreased with bed suction and jet injection, causing a reduction in scour depth. Finally, the combination of 3-jet injection from the pier surface and bed suction displayed the best response in terms of scouring reduction (35 and 50·4% scour depth reduction for water depths 10·5 and 28 cm, respectively), reducing downflow power as well as weakening the zone of high shear stress.

REFERENCES

Amini A, Melville BW, Thamer MA and Ghazali AH (2012) Clear-water local scour around pile groups in shallow-water flow. *Journal of Hydraulic Engineering* **138(2)**: 177–185.

Chen XW and Chiew YM (2004) Velocity distribution of turbulent open-channel flow with bed suction. *Journal of Hydraulic Engineering* **130(2)**: 140–148.

Chen XW and Chiew YM (2007) Turbulence characteristics of open-channel flow with bed suction. *Journal of Engineering Mechanics* **133(12)**: 1388–1393.

Cheng NS (2003) Application of Ergun equation to computation of critical shear velocity subject to seepage. *Journal of Irrigation and Drainage Engineering* **129(4)**: 278–283.

Chiew YM (2004) Local scour and riprap stability at bridge piers in a degrading channel. *Journal of Hydraulic Engineering* **130(3)**: 218–226.

Chiew YM and Chen YY (2008) Effect of suction on clear-water scour at bridge piers. *Fourth International Conference on Scour and Erosion, Tokyo, Japan*, pp. 388–394.

Chiew YM and Lim FH (2000) Failure behavior of riprap layers at bridge piers under live-bed conditions. *Journal of Hydraulic Engineering* **126(1)**: 43–55.

Dargahi B (1990) Controlling mechanism of local scouring. *Journal of Hydraulic Engineering* **116(10)**: 1197–1214.

Dey S (1997) Local scour at piers, part 1: A review of development of research. *International Journal of Sediment Research* **12(2)**: 23–44.

Dey S and Nath T (2010) Turbulence characteristics in flows subjected to boundary injection and suction. *Journal of Engineering Mechanics* **136(7)**: 877–888.

Dey S and Raikar VR (2007) Clear-water scour at piers in sand beds with an armor layer of gravels. *Journal of Hydraulic Engineering* **133(6)**: 703–711.

Dey S, Mutlu Sumer B and Fredsoe J (2006) Control of scour at vertical circular piles under waves and current. *Journal of Hydraulic Engineering* **132(3)**: 270–279.

Dey S, Nath TK and Bose SK (2010) Submerged wall-jets subjected to injection and suction from the wall. *Journal of Fluid Mechanics* **653**: 57–97.

Ettema R (1980) *Scour at Bridge Piers*. PhD thesis, Auckland University, Auckland, New Zealand.

Gaudio R, Tafarojnoruz A and Calomino F (2012) Combined flow-altering countermeasures against bridge pier scour. *Journal of Hydraulic Research* **50(1)**: 35–43.

Graf WH and Istiarto I (2002) Flow pattern in the scour hole around a cylinder. *Journal of Hydraulic Research* **40(1)**: 13–20.

Lu Y and Chiew YM (2007) Suction effects on turbulence flows over a dune bed. *Journal of Hydraulic Research* **45(5)**: 691–700.

Lu Y, Chiew YM and Cheng NS (2008) Review of seepage effects on turbulent open-channel flow and sediment entrainment. *Journal of Hydraulic Research* **46(4)**: 476–488.

Maclean AG (1991) Bed shear stress and scour over bed-type river intake. *Journal of Hydraulic Engineering* **117(4)**: 436–451.

Moncada-M AT, Aguirre-Pe J, Bolivar JC and Flores EJ (2009) Scour protection of circular bridge piers with collars and slots. *Journal of Hydraulic Research* **47(1)**: 119–126.

Nezu I (1977) *Turbulent Structure in Open Channel Flow*. PhD thesis, Kyoto University, Kyoto, Japan.

Raikar RV and Dey S (2010) Kinematics of horseshoe vortex development in an evolving scour hole at a square cylinder. *Journal of Hydraulic Research* **46(2)**: 247–264.

Ramakrishna Rao A and Nagaraj S (1999) Stability and mobility of sand-bed channels affected by seepage. *Journal of Irrigation and Drainage Engineering* **125(6)**: 370–379.

Rooney DM and Machemehl JL (1977) Using suction to minimize sand-bed scour. *Journal of the Hydraulics Division ASCE* **103(HY4)**: 443–449.

Schlichting H and Gersten K (2001) *Boundary Layer Theory*, 8th edn. Springer-Verlag New York, NY, USA.

Soltani-Gerdefaramarzi S, Afzalimehr H, Chiew YM and Lai JS (2013) Application of jet to control scour around circular bridge piers. *Canadian Journal of Civil Engineering*, in press.

Tafarojnoruz A, Gaudio R and Dey S (2010) Flow-altering countermeasures against scour at bridge piers: a review. *Journal of Hydraulic Research* **48(4)**: 441–452.

Tafarojnoruz A, Gaudio R and Calomino F (2012) Evaluation of flow-altering countermeasures against bridge pier scour. *Journal of Hydraulic Engineering* **138(3)**: 297–305.

Wahl TL (2000) Analyzing ADV data using WinADV. *Proceedings of Joint Conference on Water Resources Engineering and Water Resources Planning and Management, Minneapolis, MN, USA*, pp. 1–10.

Wang CY, Cheng JH, Shih HP and Chang JW (2011) Ring columns as pier scour countermeasures. *International Journal of Sediment Research* **26(3)**: 353–363.

Willetts BB and Drossos ME (1975) Local erosion caused by rapid forced infiltration. *Journal of the Hydraulics Division* **101(12)**: 1477–1488.

Zheng CR, Zhang YC and Zhang WY (2011) Large eddy simulation of separation control over a backward-facing step flow by suction. *International Journal of Computational Fluid Dynamics* **25(2)**: 59–73.