Reducing bend scour using in-phase and out-of-phase hydraulic jets

Zeinab Tamoradi, Javad Ahadiyan, Mohsen Najarchi,
Houshang Hasounizadeh and Mohammad Mahdi Najafizadeh

ABSTRACT

This study investigated the effectiveness of a new method of reducing scour in river bends. In this method, a perforated tube was placed along the bend on the bed and water and air were separately injected into the bend flow from both ends of the tube. The goal was to make a water and air screen to block secondary flows and prevent them from reaching the outer bank. The air jet and water jet injection modes changed the location of maximum scour depth from the outer wall to the middle of the bend, which increased the navigable width. Increasing the spacing between tube ports decreased the maximum scour depth. A port spacing of 5 cm was determined to be the optimal amount. At a bend section of 90°, the decrease in maximum scour depth was estimated to be 85% and 91% under air jet injection ($q_a/Q = 2.74$) and water jet injection ($q_w/Q = 0.17$), respectively. At 170°, the decrease in maximum scour depth was 79% and 86% for the air jet and water jet, respectively. The results show that the optimal effect was obtained by water jet injection.

Key words | air jet injection, bend, scour depth, water jet injection

Zeinab Tamoradi
Mohsen Najarchi
Department of Civil Engineering, Arak Branch,
Islamic Azad University,
Arak, Iran

Javad Ahadiyan (corresponding author)
Faculty of Water Sciences Engineering,
Department of Water Structures,
Shahid Chamran University of Ahvaz,
Ahvaz, Iran
E-mail: *ja_ahadiyan@yahoo.com*

Houshang Hasounizadeh
Executive Director of Water Resources Division of K.W.P.A,
Ahvaz, Iran

Mohammad Mahdi Najafizadeh
Department of Mechanical Engineering,
Arak Branch,
Islamic Azad University,
Arak, Iran

NOMENCLATURE

Q	discharge in main channel
q_a	air injection discharge
q_w	water injection discharge
B	flume width
z	maximum scour depth
y	upstream water depth
d_{50}	average diameter of bed particles
d	spacing between ports
g	gravitational acceleration
Fr	Froude number
L	length of perforated tube
D	tube distance from outer wall
d_o	diameter of tube ports
μ	dynamic viscosity
ρ_s	sediment density
R	channel centerline radius
ρ	water density
x	transverse distance
θ	bend angle
Re	Reynolds number

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INTRODUCTION

Scouring is water-induced erosion that transports sediment from the beds and walls of rivers or channels (Boujia *et al.* 2017). Local scouring is a morphological change that occurs in the vicinity of barrier structures, which could endanger the safety of such structures (Karbasi & Azamathulla 2017). The flow entrance into the bend changes the morphology of the bed and walls at the bend so that the accumulation point of the streamlines gradually shifts from the inner bend through the centerline to the outer wall of the bend as a result of centrifugal force. In this flow pattern (spiral flow), the thalweg moves from the middle of the upstream straight to the outer wall of the bend. Scouring of the outer wall may cause instability in that wall. On the other hand, sedimentation near the inner wall can reduce the navigable width (Dugué *et al.* 2012a).

An air-bubble screen is a scour reduction method designed to modify river morphology (Dugué *et al.* 2012c). An advantage of this method is that it does not require construction of additional structures and progression across the river. In this method, the barrier constructed against secondary flow at the bend is not rigid and does not interrupt river usage, such as for shipping. This approach creates a non-rigid (fluid) barrier against the secondary flow in order to prevent it from reaching and destroying the bed and outer wall (Dugué *et al.* 2011). Dugué *et al.* (2012b) examined the effect of an air-bubble screen on scouring around a bridge pier. They recorded a 40% decrease in maximum scour depth around the bridge pier with an air-bubble screen, compared with the lack of a screen.

Dugué *et al.* (2012c) introduced an air-bubble screen to reduce erosion in open-channel bends. Their results showed that, for 90° and 180° bends, the scour hole shifted from the outer wall to the centerline of the flume. Dugué *et al.* (2012d) then studied the flow patterns caused by the bubble screen. They showed that the bubble screen created a flow pattern that modified the riverbed morphology. Velocity measurement showed that the bubble screen was able to modify the natural bend flow.

Dugué *et al.* (2013) investigated scour reduction at a 193° bend using an air-bubble screen. Velocity measurement at a 70° bend showed that the bubble-induced flow pattern moved the secondary flow near the outer bend to the inner bend and significantly reduced its power. A 50% decrease occurred in the maximum scour depth. Dugué *et al.* (2014) studied the effect of flow patterns on riverbed morphology using the air-bubble screen method. They compared the size and power of a bubble-induced flow cell in a moving bed with those in a fixed bed. They found that the size and the power of the bubble-induced flow cell in a moving bed were greater than those in a fixed bed.

Yarahmadi & Bejestan (2016) studied the effect of the installation of triangular vanes on bed topography at a channel bend. They observed an increase in the maximum scour depth with an increase in the vane spacing and increase in the Froude number. They concluded that spaces up to five-fold larger than the effective length were optimal. Dey *et al.* (2017) studied wall erosion and protection using submerged vanes placed at an optimal angle in a 180° flume. They found that the maximum scour depth occurred at 120° to 180° of the outer bend. Moreover, the 15° angle of the vanes was optimal to decrease the secondary flow and reduce outer bend scour.

Mehraein *et al.* (2017) examined the flow pattern and score hole dimensions around a T-shaped spur dike at a 90° bend angle. They reported that the score hole dimensions increased as the ratio of channel bend radius to channel width, spur dike length to channel width, mean flow velocity to threshold velocity and Froude number increased. The score hole dimensions decreased as the ratios of submergence, spur dike length to mean size of sediment, and spur dike wing length to spur dike length increased. These secondary flows generated at the bend were prevented from reaching the outer bank.

The water injection technique has all the advantages of the air-bubble screen method, including ease of operation, did not require construction of additional structures and progression along the river and maintained river conditions. The injection of water instead of air from a supply of water from the same area was expected to cause no change in the area in terms of the fluid phase, temperature and chemical properties such as water-soluble oxygen and environmentally adverse effects. A water jet injection method to reduce scour at river bends is used for the first time in this study. Air jet injections have been used previously. The present study also changed the channel bend to 180° and considered the effect of variables such as port spacing.

MATERIALS AND METHODS

Dimensional analysis

In order to determine the relationship among contributory factors to scouring, dimensional analysis was carried out on the relevant parameters. The main factors affecting the scouring are as follows:

$$f(B, y, Q, q, z, \mathrm{g}, \rho, \rho_s, \mu, d_{50}, L, d_o, d, D, \theta) = 0 \quad (1)$$

where B is flume width, y is upstream water depth, Q is discharge in the main channel, q is injection discharge, z is maximum scour depth, g is gravitational acceleration, ρ is water density, ρ_s is sediment density, μ is dynamic viscosity, d_{50} is the average diameter of bed particles, L is the length of the perforated tube, d_o is the diameter of the tube ports, d is the spacing between ports, D is the tube distance from the outer wall and θ is the bend angle.

The remaining variables and the three repetitive variables were combined to produce the following dimensionless parameters:

$$f\left(\frac{z}{y}, \frac{B}{y}, \frac{d_{50}}{y}, \frac{d}{y}, \frac{d_o}{y}, \frac{D}{y}, \frac{L}{y}, \mathrm{Fr}, \frac{\rho_s}{\rho}, \frac{q}{Q}, \mathrm{Re}, \theta\right) = 0 \quad (2)$$

After eliminating the constant parameters, the final relation is as follows:

$$\frac{z}{y} = f\left(\frac{d}{y}, \mathrm{Fr}, \frac{q}{Q}, \theta\right) \quad (3)$$

Experimental setup

The laboratory model was rectangular and 0.6 m wide with a mild bend of 180° with an R/B ratio of 3.5, an upstream straight length of 2.6 m and a downstream straight length of 2.4 m. The sediment used in the experiments was roughly homogeneous silica sand with a diameter of 1 mm. A perforated tube with a length of 7 m having ports with diameters of 2 mm was placed on the bed at bend angles of 0° to 180° at a distance of 2.5 cm from the outer wall of the bend. Figure 1 shows the experimental model and the tube placement at the bend.

Experiments

The experiments were conducted under clear water conditions. The water depth was 10 cm in all experiments. The experiments were carried out in in-phase and out-of-phase modes. In each experiment, the bed sediment particles had diameters of 1 mm (Figure 2(a)) and were spread along the bend and then leveled off. The water was then allowed to slowly enter the flume. After reaching the required depth and discharge, the end gate was opened to adjust the water level. The predicted equilibrium time was 3 h (Figure (2(b)). In both injection modes, the pressurized air and water were injected into the flume flow from both

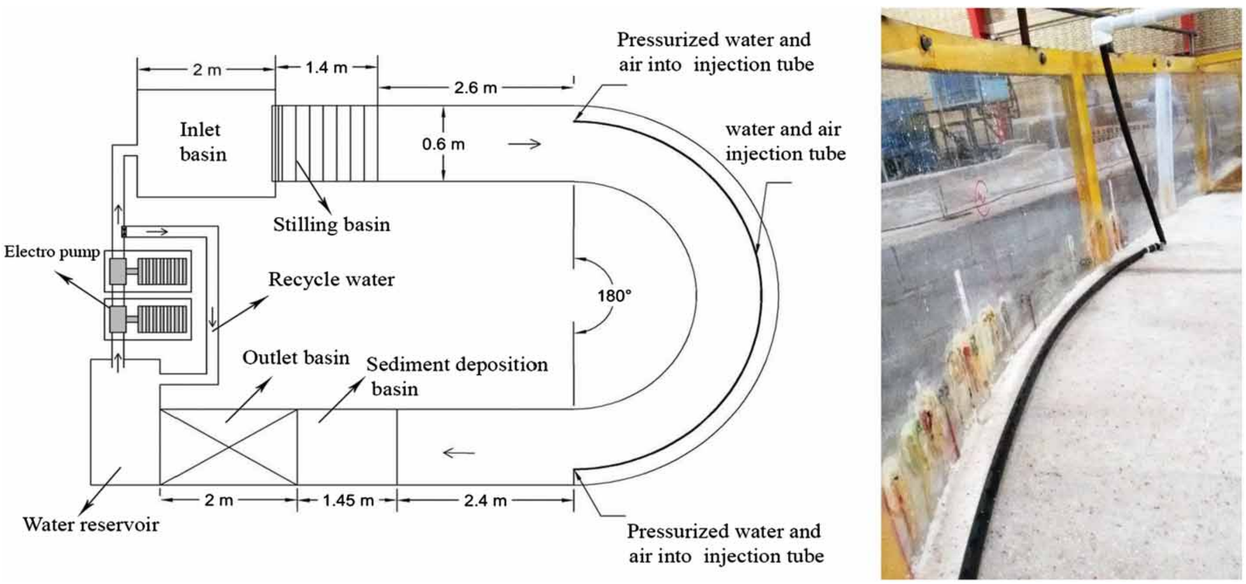

Figure 1 | Experimental model.

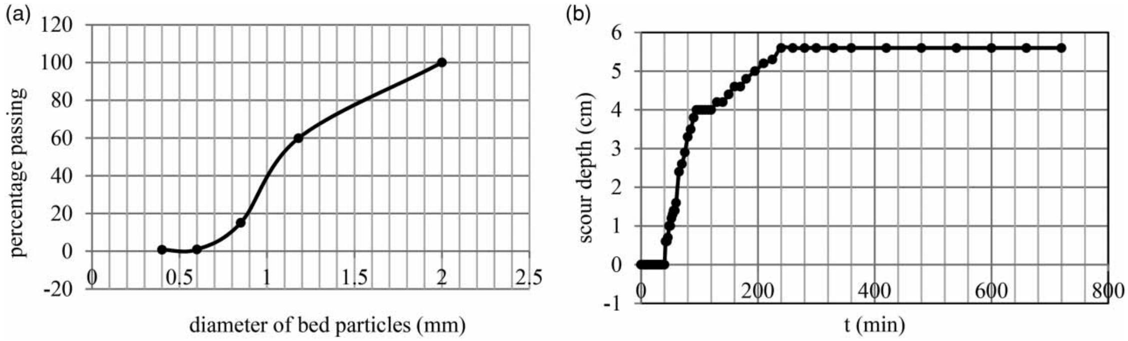

Figure 2 | (a) Grading curve; (b) equilibrium time curve.

ends of the perforated tube using an air injection system and a pump, respectively. The air and water injection discharge was determined using an air rotameter and a water rotameter, respectively. Upon completion of the experiments after reaching morphological equilibrium and water drainage, the bed topography was determined using a laser distometer. The amounts of discharge into the main channel, air and water jet injection discharge and spacing of the ports are shown in Table 1.

RESULTS AND DISCUSSION

This study investigated the effect of the water and air jet injection and the spacing of the ports on the reduction of scouring at river bends using the in-phase and out-of-phase hydraulic jet technique.

Sedimentary bed topography

The two-dimensional topography of sedimentary beds with and without protective structures was plotted using Tecplot engineering software. Figure 3 shows the sedimentary bed topography after scouring without a protective structure. Due to the effects of bend curvature, influx of the secondary flow into the outer bend and lack of a protective structure caused the outer wall of the bend to undergo erosion. The maximum scour depth at a bend angle of 90° was 5.6 cm with a distance of 0.5 cm from the outer wall of the bend. The sediment separated from the outer wall and accumulated around the inner wall and formed sedimentary hills, decreasing the navigable width.

To control outer bend scouring, a protective structure was made using water and air jet injection. The secondary flows induced by this structure overcame the curvature-induced secondary flow and caused them to diverge from the outer wall. As a result, the maximum scour depth at the outer bend decreased and bed morphology was modified. With the structure, the navigable width increased for both in-phase and out-of-phase modes of water and air injection. Figure 4(a)–4(c) show the sedimentary bed

Table 1 | Variable values

Q (l/s)	q_a (l/min)	q_w (m^3/hr)	d_o (cm)
16	46	2	3
17.5	48	3	4
19	50	4	5

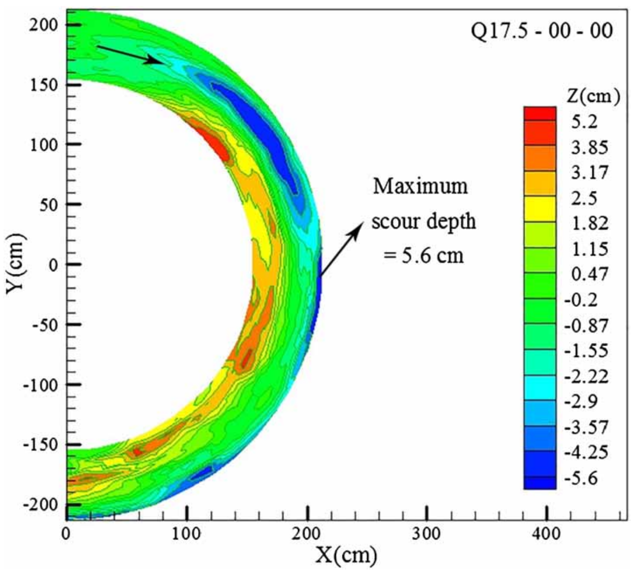

Figure 3 | Sedimentary bed topography in control experiment.

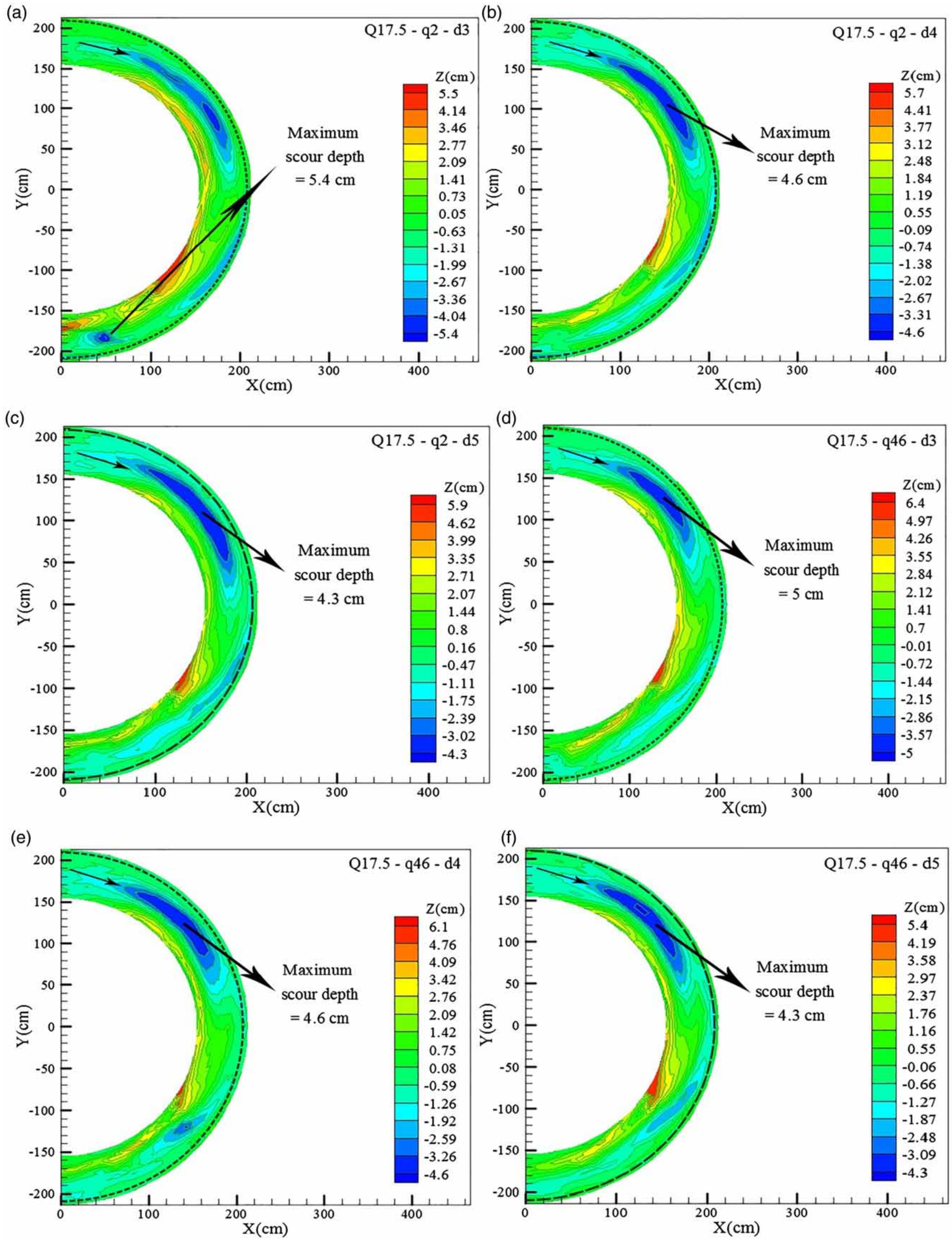

Figure 4 | Sedimentary bed topography: (a) to (c) under water jet injection conditions; (d) to (f) under air jet injection conditions.

topography in the water jet injection experiments for port spaces of 3, 4 and 5 cm, respectively. Figure 4(d)–4(f) show the sedimentary bed topography for the air jet injection experiments for port spaces of 3, 4 and 5 cm, respectively.

The results showed that the maximum scour depth in the main experiments decreased compared with the control experiments. The location of maximum scour depth in all the three cases shifted from 0.5 cm from the outer wall in the control experiment to the middle in the main experiments. This increased the navigable width. On the other hand, the maximum scour depth decreased with an increase in the tube port spacing. In all three cases, the maximum height of the sedimentary hill moved to downstream of the bend near the inner wall at a bend angle of 120°. The maximum scour depth decreased as the tube port spacing increased at a constant injection discharge. This could be explained by the fact that, for a constant tube length, the number of ports decreased with an increase in the spaces between the ports. This caused the flow injected into the tube to be discharged from fewer ports, which increased the amount leaving the ports. This increased the power to deviate the secondary flow from the outer bend and further decreased scouring.

Transverse profiles

To determine the maximum scour depth of the holes in the outer wall of the bend after the construction of the protective structure, dimensionless transverse graphs were plotted. Figure 5(a) and 5(b) show the maximum scour depth versus the transverse distance under water injection in the control and main experiments at bend angles of 90° and 170°, respectively. Figure 5(c) and 5(d) show the maximum scour depth versus the transverse distance in the control and main experiments with air jet injection at bend angles of 90° and 170°, respectively. These sections were selected based on the formation of two deep scour holes in the control experiment. As this study mainly aims to control scouring at the bend in the control experiment,

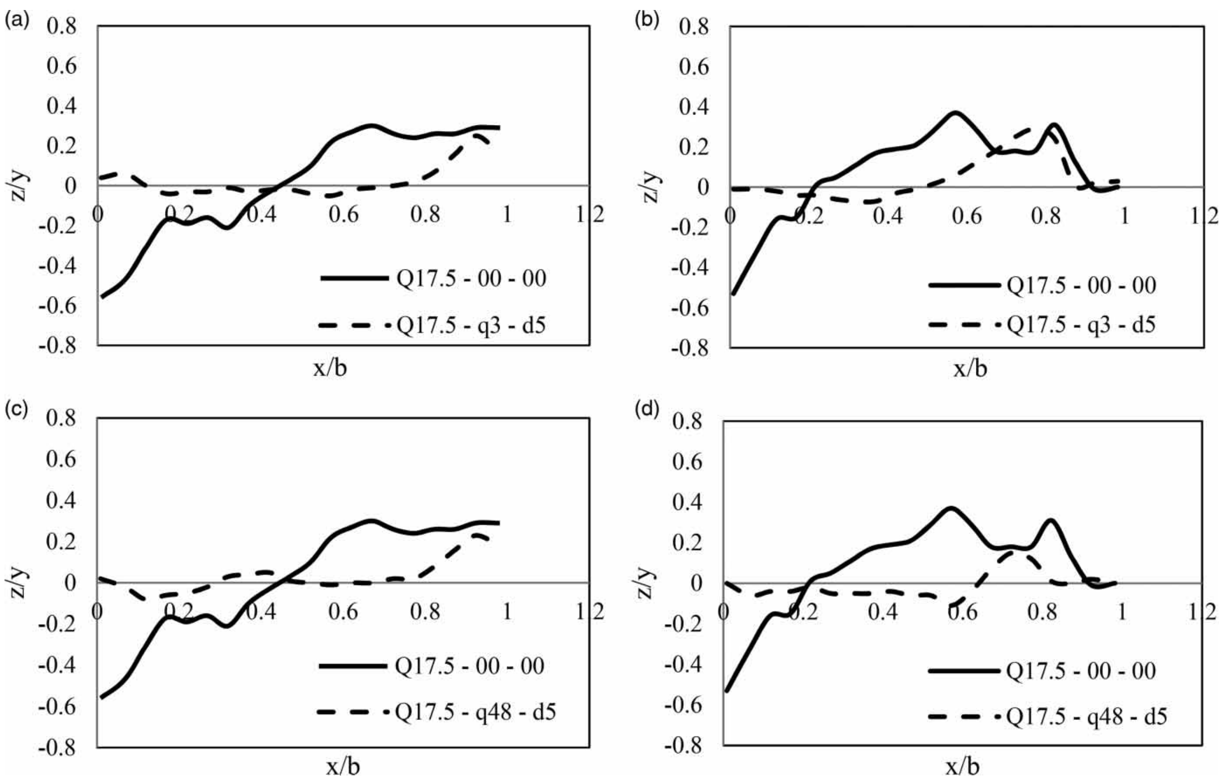

Figure 5 | Maximum scour depth versus transverse distance in control and main experiments in water and air jet injection modes: (a) $\theta = 90°$; $q_w/Q = 0.17$; (b) $\theta = 170°$; $q_w/Q = 0.17$; (c) $\theta = 90°$; $q_a/Q = 2.74$; (d) $\theta = 170°$; $q_a/Q = 2.74$.

the effect of the protective structure on control of scouring in these two sections was investigated.

Comparison of the results of the water jet injection experiments shows that the maximum scour depth in the main experiment for bend angles of 90° and 170° decreased by 91% and 87%, respectively, compared with the control experiments. The corresponding values for air jet injection at bend angles of 90° and 170° were 86% and 80%, respectively. As stated, the protective structure forms a water or air screen so that the secondary flow diverged from the outer wall of the bend to minimize the negative effect of the curvature at the bend inlet and outlet.

The experimental results show a shift in the location of the maximum scour depth from the outer wall to the middle of the flume can increase the navigable width. The results of the water jet and air jet injection experiments indicate that water injection is more effective than air injection. This can be explained by the in-phase conditions. In other words, the phase similarity of the injected water into the flume with the flow inside the flume was stronger for water jet injection than air jet injection and was better able to diverge the secondary flow from the outer bend. In this regard, the maximum scour depth further decreased. The results of the air jet injection method were consistent with those obtained by Dugué et al. (2013) except that, in their work, the maximum scour depth decreased by 50%; however, in the present study, the construction of a protective structure further reduced the maximum scour depth by 91% at some points.

CONCLUSION

The results showed that the use of a perforated tube caused the protective structure to overcome the curvature-induced secondary flow and decreased the maximum scour depth along the outer bend. Moreover, increasing the spacing between the tube ports decreased the maximum scour depth. In this regard, the optimal port spacing was 5 cm. The location of maximum scour depth in the main experiments shifted from the vicinity of the outer wall to the middle of the bend, which could increase the navigable width. The scour depth at a bend angle of 90° decreased by 85% and 91% for air and water jet injection experiments, respectively. The scour depth at a bend angle of 170° in the experiments decreased by 79% and 86%, respectively. These results indicate an optimal effect for the water jet injection over that of the air jet injection. The application of the in-phase and out-of-phase hydraulic jet technique is practically and economically feasible for real rivers to address the problem of scouring.

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