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Effect of L-shaped slots on scour around a bridge abutment

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Abstract

Local scour is the most significant cause of bridge failure. Providing a short abutment with a straight slot has proved to be an effective method for reducing scour at this abutment. In this study, laboratory experiments have been conducted to investigate the effectiveness of using L-shaped slots in comparison to the commonly used straight slot, on the scour reduction at short vertical-wall abutment under clear-water flow conditions and uniform bed materials. The slots were just above the bed and their diameters equal to half the abutment's length. The results illustrated that it is essential to have a straight slot in any combination of slots, as any configuration without one is inefficient. Also, a combination of a straight slot with one side slot in the middle of the abutment's width gives better performance than an individual straight slot, as it reduces the depth, area, and volume of the scour hole by about 32.6, 26.8, and 43.6% respectively, in comparison to 23.2, 20.7, and 35.3% for the straight slot alone.

Key words: abutment, scour, slot

Highlights

- Constructing a bridge across a river alternates the river flow pattern, and vortexes take place around the the abutments. These vortexes cause scour development.
- Few researches have studied the behaviour of straight-slotted abutments.
- The aim of the presented work is to investigate the behaviour of L-shaped abutment's slots in comparison to the commonly used straight slot.

INTRODUCTION

Constructing a bridge across a river alters the river's flow pattern, and vortexes occur around the piers and abutments. These cause scour, and this may lead to bridge failure. Two techniques can be used to reduce scour: bed armoring, and flow alteration. Flow-alteration countermeasures shift the scour from the vicinity of the piers and abutments, and/or reduce the scour-inducing mechanisms.

Experiments on flow-alteration countermeasures – collars, slots, sacrificial piles and vanes – have been conducted by many researchers trying to find an efficient process for protecting bridge abutments against scour (Bejestan *et al.* 2015; Mohamed *et al.* 2015; Fathi & Zomorodian 2018; Karami *et al.* 2018; Khosravinia *et al.* 2018).

Slots are common flow-altering countermeasures that reduce scour dimensions by minimizing the downward flow power on the upstream pier face, as part of the approaching flow passes through the openings in the pier (Tafarojnoruza *et al.* 2010). The approaching flow that enters the slot, deflects the downward flow away from the bed and thus decreases the power of the horseshoe vortex, as shown in Figure 1 (Khodabakhshi & Farhadi 2016).

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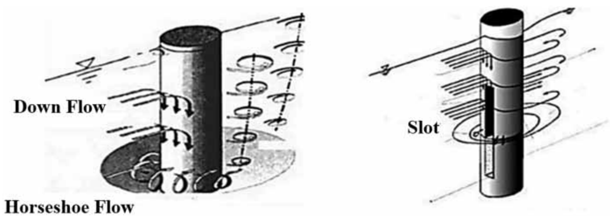

Figure 1 | Schematic diagram of flow Field around a pier and the operation of the slot (after Khodabakhshi & Farhadi 2016).

Previous researches on the effectiveness of slots in scour control around piers demonstrated that slot efficiency increases with increasing slot dimension, and slots near the bed are more efficient than those located near the water surface. Slot performance is enhanced further if it extends partly below the surface of the bed (Chiew 1992; Kumar *et al.* 1999; Moncada-M *et al.* 2009).

Grimaldi *et al.* (2009) examined a composite countermeasure consisting of a pier slot and a bed sill just downstream the pier, and showed that the scour in front of the pier was reduced by about 45%.

Chiew (1992), Kumar *et al.* (1999) and Moncada-M *et al.* (2009) examined the behaviour of a collar round the pier combined with slots. The combination proved to be effective in scour reduction around circular piers.

Elnikhely (2017) showed that about 89% reduction in scour depth could be achieved using a combination of a perforated sacrificial pile upstream of the pier with a hole angle of 45° and a pier with a hole angle of 45°.

Some experiments have been conducted to investigate three rectangular slot shapes – Y, T and Sigma – in circular piers, in comparison to the common straight slots (Setia & Bhatia 2013; Hajikandi & Golnabi 2018). The results suggested that straight slots were most effective in reducing downward flow upstream of the pier. Equally, neither T- nor Sigma -shaped slots offered much improvement in scour depth. On the contrary, Abd El-Razek *et al.* (2003) examined the effects of four shapes of circular slots in circular bridge piers – straight, Y-, T-, and Sigma shaped – on the scour round the pier, and indicated that the T-shaped slot gave the best performance.

Radice & Lauva (2012) investigated the effect of the position of a straight slot on scour at vertical-wall abutments and deduced that a slot below the bed had the best scour reduction effects. Osroush *et al.* (2019) investigated the effect of the vertical position and height of a straight abutment slot on scour reduction and showed that the closer the slot is to the bed, the more scour reduction is achieved. Also, a slot extending from the water surface to just below the bed surface gives the best performance.

Few researchers have studied slotted abutments. They have focused on the behaviour of straight slots and, as far as is known, there is no study on the behaviour of other slots shapes. The aim of this study was to investigate the behaviour of L-shaped abutment slots in comparison to the commonly used straight slots. Figure 2 shows sketches of the slot configurations used.

DIMENSIONAL ANALYSIS

The functional relationship containing the problem's main variables can be expressed as:

$$\varnothing(d_s, d_{ss}, l, b, B, D, S, y, V, Vc, g, \rho, \mu, d_{50}, \sigma_g, \rho_s, t, t_e) = 0 \tag{1}$$

where d_s : scour depth at the nose of the slotted abutment (cm), d_{ss}: scour depth at the nose of the solid (unslotted) abutment (cm), l : abutment length (cm); b: abutment width (cm), B: flume width (cm), D: slot diameter (cm), S: position of the slot exit relative to the abutment nose (cm), y: flow depth (cm); V: mean flow velocity (cm/s), Vc: threshold velocity of the bed sediment (critical flow

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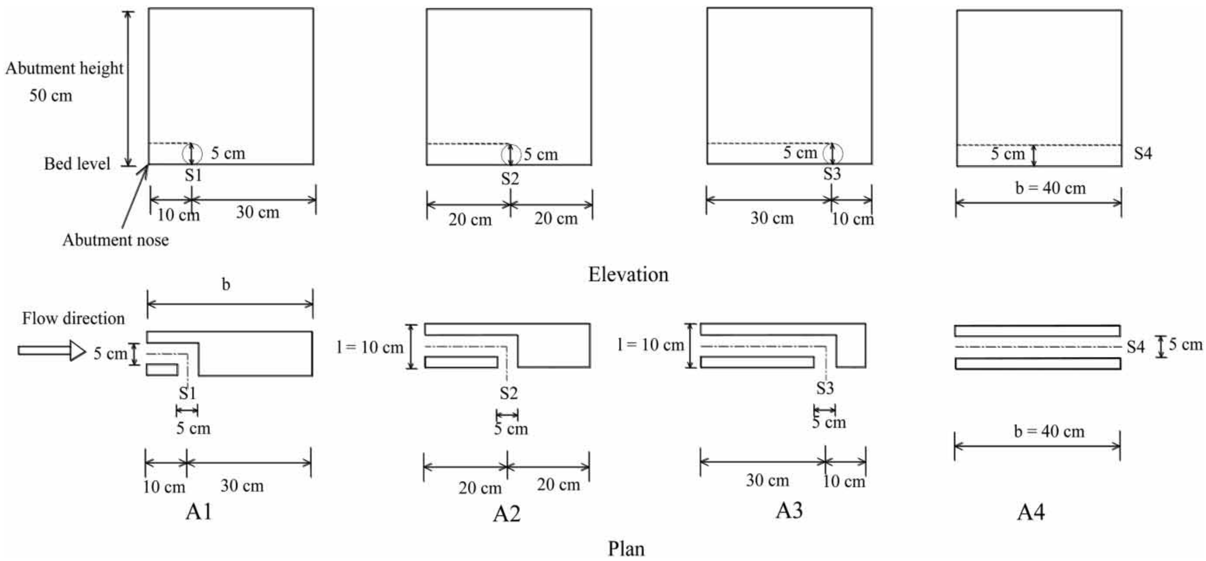

Figure 2 | Abutment slot configurations (Series A).

velocity) (cm/s), g: gravitational acceleration (cm/s^2), ρ: fluid density (gm/cm^3), μ: dynamic viscosity (gm/cm.s), d_{50}: median size of the bed material (cm), σ_g: sediment geometric standard deviation $= (d_{84}/d_{16})^{0.5}$ ($M^0 L^0 T^0$), ρ_s: sediment density (gm/cm^3), t: scour time (hours), t_e: equilibrium time (hours). Applying the principles of dimensional analysis, taking into consideration that the terms b/l, B/l, D/l, d_{50}/l, ρ_s/ρ, σ_g, and t/t_e are all constant, and omitting Reynold's number (R_n), as the viscous force is not significant in this study, yields Equation (2):

$$d_s/d_{ss} = f\ (V/Vc,\ Fn,\ y/l,\ S) \quad (2)$$

where ds/dss: relative scour depth ($M^0L^0T^0$), Fn: Froude number upstream the abutment ($M^0L^0T^0$).

MATERIALS AND METHODS

Experiments were implemented under clear water condition, so the biggest scour depth would take place. Under clear-water condition, scour depth increases with increasing flow velocity, and the maximum scour depth occurs at the threshold of sediment movement 'i.e., at the boundary between clear-water and live-bed conditions', so for this reason most experiments should be implemented at the threshold condition. Thus, for the present study *V/Vc* values were 0.97, 0.91, 0.85, and 0.72.

The critical velocity *Vc* was obtained by using Equation (3) (Chiew 1995)

$$\frac{Vc}{V{*}c} = 5.75\ log\left(\frac{y}{2\ d_{50}}\right) + 6 \quad (3)$$

where, V^*c : critical shear velocity (obtained from Shield's diagram), and y and d_{50} are as above.

In this study, the discharge was constant at 65 l/s, and four water depths 23, 24.5, 26, and 30 cm were used giving $V/Vc = 0.97$, 0.91, 0.85 and 0.72, respectively, with Fn values 0.24, 0.22, 0.19, and 0.16. Table 1 shows details of the experimental conditions.

In all experiments, the water depth (y) satisfied the short-abutment criterion '$l/y \leq 1$', and, to minimize the effect of flow depth on scour, y/l was maintained above 2, '$y/l > 2$' (Melville 1992).

Particle size distribution has a significant effect on local scour depth. To prevent ripple formation, the mean sediment size, d_{50}, must be $\geq$0.7 mm (Raudkivi 1998), and to eliminate the effects of

Table 1 | Experimental conditions

y (cm)	*V* (cm/s)	*Vc* (cm/s)	*V/Vc*	Fn
23	35.3	36.2	0.97	0.24
24.5	33.2	36.5	0.91	0.22
26	31.3	36.8	0.85	0.19
30	27.1	37.5	0.72	0.16

sediment particle size on scour depth, l/d_{50} should exceed 50 (Melville 1992). In this study it was found that $l = 10$ cm and $d_{50} = 0.9$ mm satisfied the required conditions.

Sediment uniformity can be described by the geometric standard deviation, σ_g, as '$\sigma_g = (d_{84}/d_{16})^{0.5}$'. Non-uniform sediment mixtures ($\sigma_g > 1.5$–2.0) lead to less scour depth than uniform sediment and sediments with $\sigma_g < 1.3$ are effectively uniform (Melville 1992). In this study $\sigma_g = 1.28$.

EXPERIMENTAL SETUP

Experiments were executed in a recirculating rectangular channel 0.8 m wide, 0.9 m deep, and 23.2 m long. There was a sediment recess 0.8 m wide, 0.16 m deep, and 4.0 m long, which contained uniformly graded soil, 12 m downstream of the channel inlet, and the 10 cm long by 40 cm wide steel abutment was located at its midpoint. Discharge was measured using a calibrated V-notch weir at the end of the channel – see Figure 3.

At the beginning of each experiment, the appropriate abutment model was installed at the channel side, and the 16 cm deep sandy soil (sediment) was leveled. The channel was then filled slowly with water to saturate the bed material, after which the pump was turned on and the discharge increased gradually up to the desired rate. The water depth was adjusted using the end tailgate. After each run, the pump was turned off and the channel allowed to drain slowly without disturbing the sediment bed's topography. Finally, the scour topography was measured with a point gauge – a ± 1 accuracy – on a grid with a 5 × 5 cm mesh.

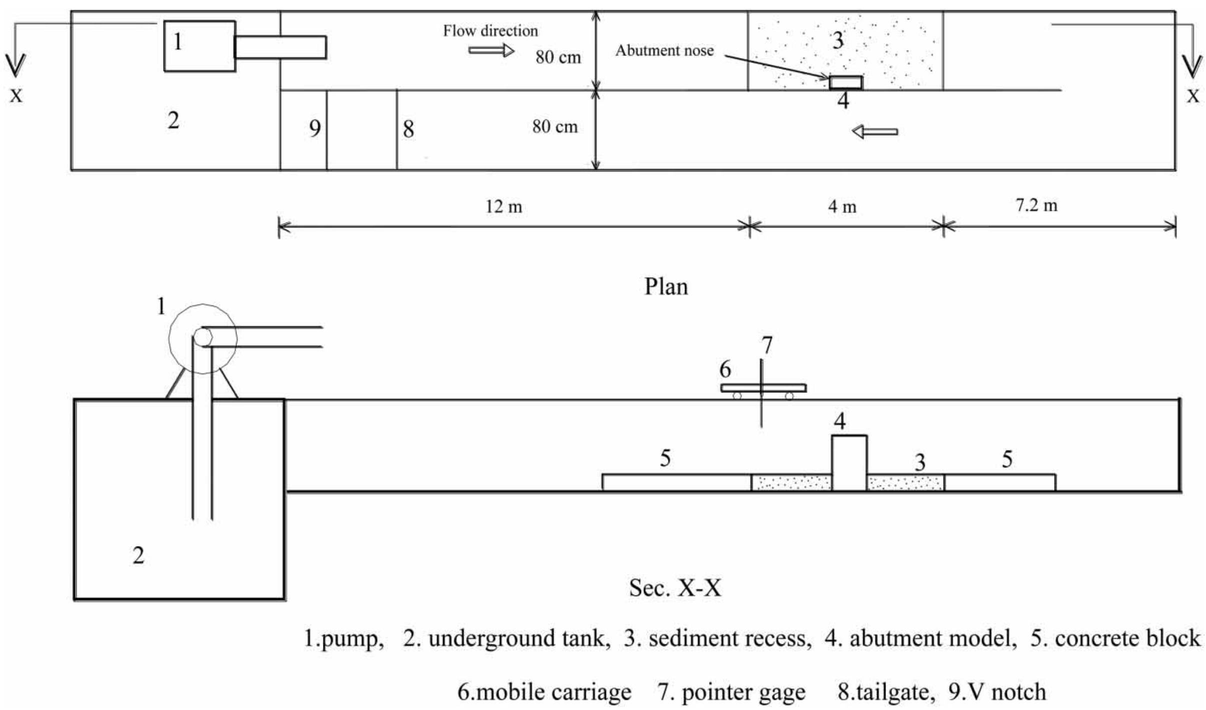

Figure 3 | Experimental setup.

A test was conducted using the solid abutment to determine the equilibrium scour time, which was taken as the time at which scour depth was 95% of the maximum (Hosseini *et al.* 2016). The graph of the time-scour relation (Figure 4) was used, and 4 hours was chosen as the experiment duration.

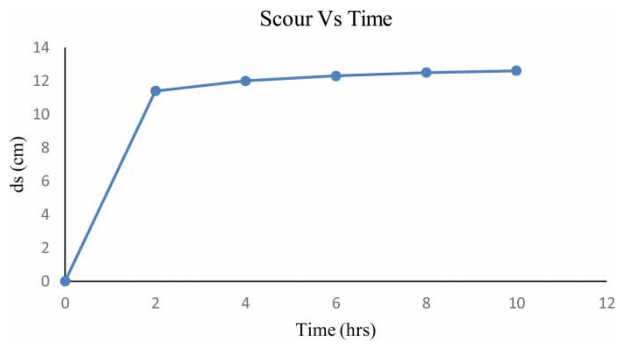

Figure 4 | Time-scour relationship.

Two test series, A and B, were used in the study, the main difference being the number of slots used. Test 'S0', involving just the solid abutment, was considered the reference for all cases.

For series A, five models – one solid and four slotted – were tested for the four Froude numbers. Each slotted model has a single slot with a 5 cm diameter. For all slotted abutments, the upstream opening of the slot was located at the middle of the abutment length l, aligned with the flow direction. Four outlet positions were considered, one on the opposite face from the inlet, creating a straight slot (S4 – see Figure 2), the others with openings on the abutment side, creating L-shaped slots (Figure 2 – S1, S2 and S3). The L-shaped slot outlets were 0.25 b (S1), 0.5 b (S2), and 0.75 b (S3) from the abutment nose (b = abutment width). All slots were just above bed level. Combinations of more than one outlet opening were tested with series B, for Fn = 0.16 and 0.22 – see Figures 5 and 6 and Table 2. Each model from those have the best performance (B22, B32, B41) tested twice for each Fn to be sure of the results, so the total number of runs is 36.

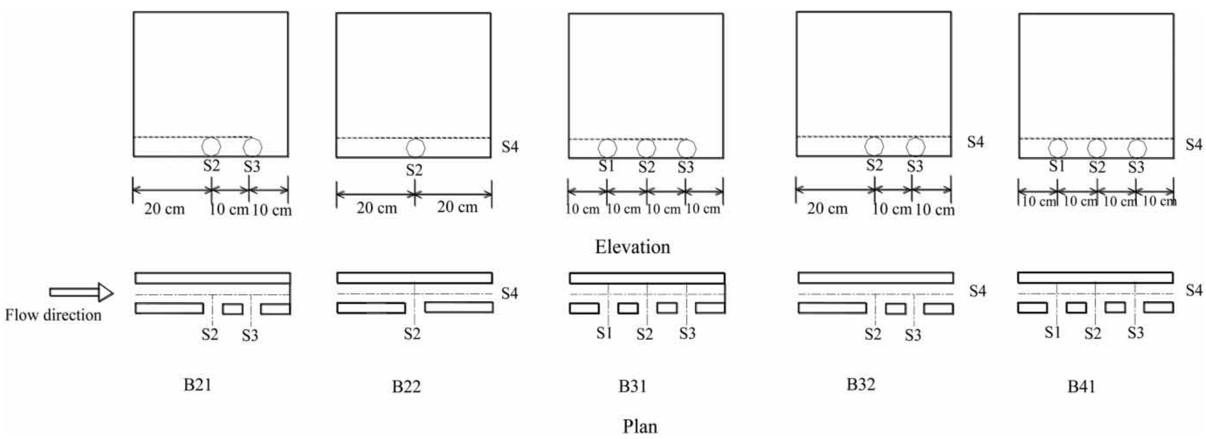

Figure 5 | Series B slot configurations.

RESULTS

Figure 7 shows the relationship between the Froude number and dimensionless scour depth for the solid model and series A's abutment models. Clearly, scour depth increases with the Froude number, and model S4, which has a straight slot, gave the best performance for reducing scour depth at the nose.

For series A, the longitudinal scour hole profiles around the abutments were plotted for the different slot models and that with no slot – see Figure 8. It is obvious from Figure 8 that the maximum scour

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Figure 6 | Examples of slot models.

Table 2 | Test descriptions

Test	Outlet slot position	Fn	ds (cm)
S0	Solid (no slot)	0.16	6.00
	Solid (no slot)	0.19	9.20
	Solid (no slot)	0.22	10.80
	Solid (no slot)	0.24	12.00
A1	S1	0.16	6.30
	S1	0.19	9.60
	S1	0.22	10.80
	S1	0.24	12.00
A2	S2	0.16	5.00
	S2	0.19	8.00
	S2	0.22	10.10
	S2	0.24	11.00
A3	S3	0.16	5.00
	S3	0.19	8.30
	S3	0.21	10.40
	S3	0.24	11.50
A4	S4	0.16	4.50
	S4	0.19	7.00
	S4	0.22	8.50
	S4	0.24	10.20
B21	S2&S3	0.16	4.50
	S2&S3	0.22	8.50
B22	S2&S4	0.16	4.20
	S2&S4	0.22	7.00
B31	S1&S2&S3	0.16	4.30
	S1&S2&S3	0.22	8.50
B32	S2&S3&S4	0.16	4.00
	S2&S3&S4	0.22	6.80
B41	S1&S2&S3&S4	0.16	4.00
	S1&S2&S3&S4	0.22	7.50

Note – those models that gave the best performance – i.e., B22, B32 and B41 – were each tested twice to try to ensure that the ds values (column 4 of the table) were correct.

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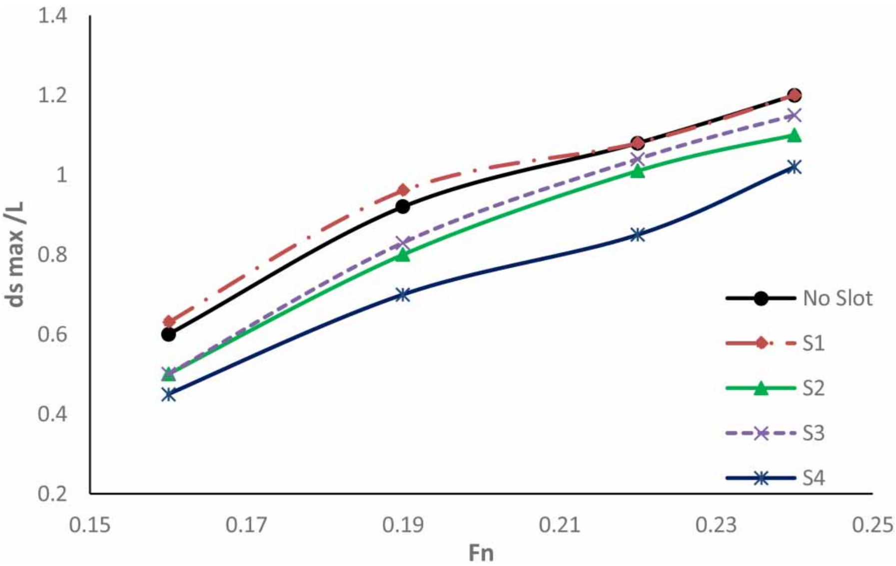

Figure 7 | Relationship between the Froude number and the maximum scour depth at abutment nose.

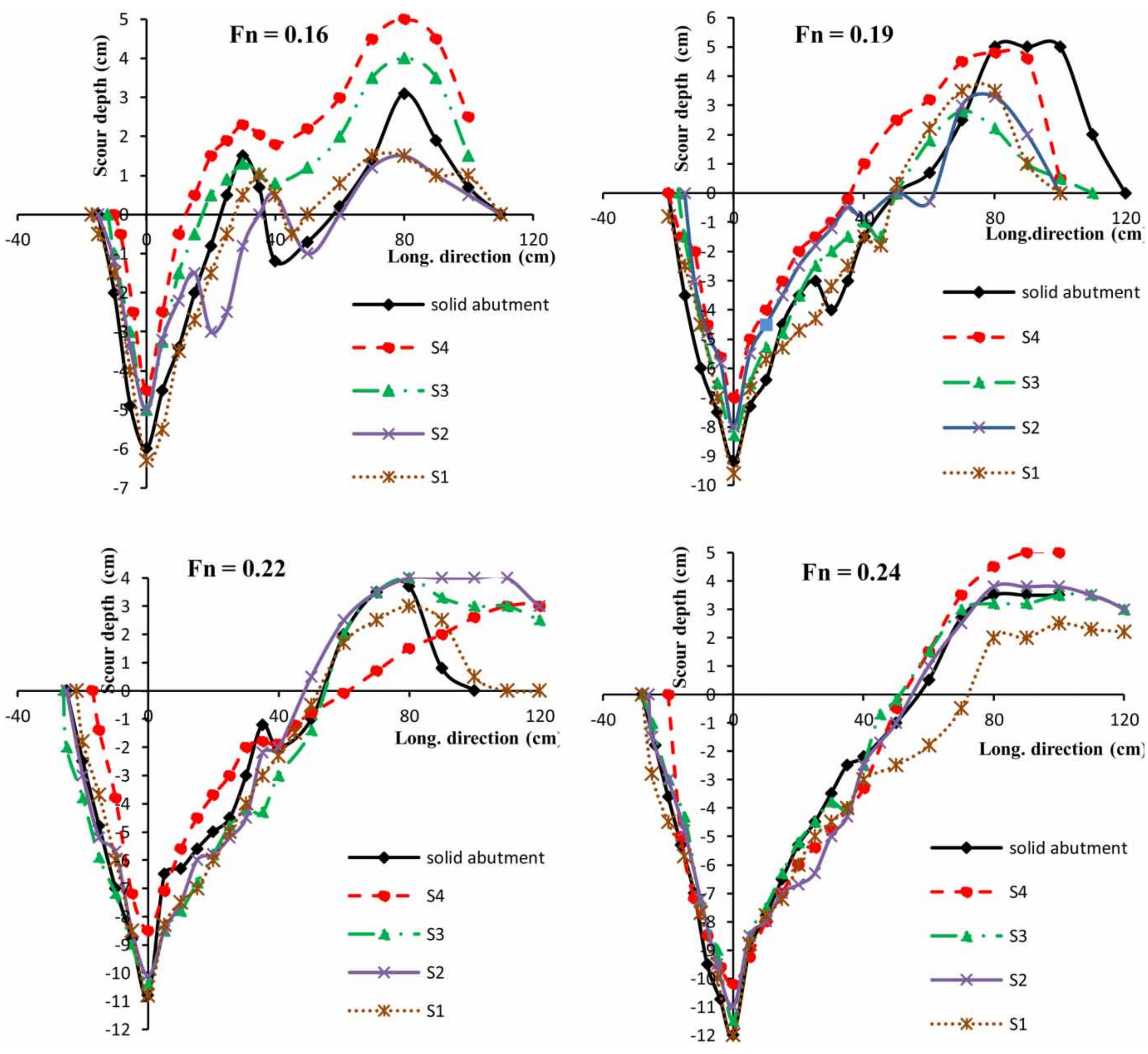

Figure 8 | Longitudinal scour hole profiles around the abutment (series A).

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depth is always found at the upstream abutment corner. The bed topography around the solid and slotted abutments is similar, but, as part of the down-flow is conveyed through the slot openings, the horseshoe vortex force and, consequently, the scour depth are reduced.

It could also be concluded that S1 is not a suitable configuration as it may increase the scour depth. This may be because a slot near the bed diverts the down-flow through itself and the approach flow at the bottom boundary layer accelerates, behaving as a horizontal jet. As the down-flow at the abutment is perpendicular to the jet, the jet deflects it away from the bed, leading to scour reduction. But, due to the short length of slot S1, the approach flow at the bottom boundary layer did not accelerate or behave as a horizontal jet. Meanwhile, the flow released from the lateral slot opening S1 may lead to increasing scour depth near the nose.

The results also showed that S2 and S3 have very similar scour reduction effects, and give less improvement than the straight slot (S4). In other words, the commonly used straight slot (S4) is more efficient in reducing scour than slots S1, S2 and S3.

The tests in series B were executed to study the efficiency of using more than one outlet slot. Figure 9 shows the longitudinal scour hole profiles around the abutments for Fn = 0.16 and 0.22, for the different slotted and the straight slotted models. Model B32 produced the least scour depth at the abutment nose, with B22 ranked a close second and B41 third. The average scour depth reductions produced by

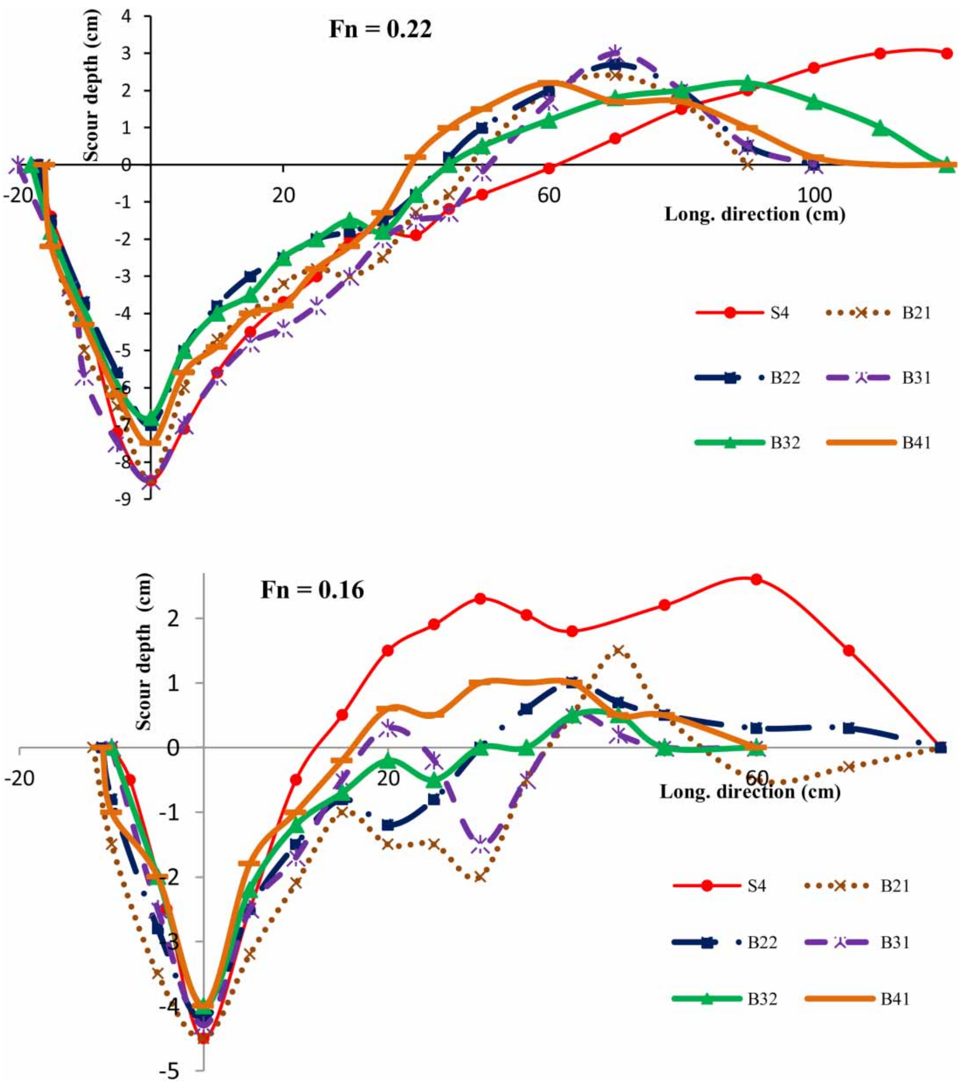

Figure 9 | Longitudinal scour hole profiles around the abutments for S4 and series B.

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B32, B22 and B41 were 35.2, 32.6 and 31.9%, respectively, compared to the solid model (S4), which produced an average scour depth reduction of 23.2% under the same flow conditions.

The other slot combinations (B21, B31) did not yield any noticeable efficiency increase over S4.

Figure 10 shows the scour hole contours around the solid model, the straight-slotted model (S4), and the most efficient series B models (B22, B32, B41), all operating under the same flow conditions.

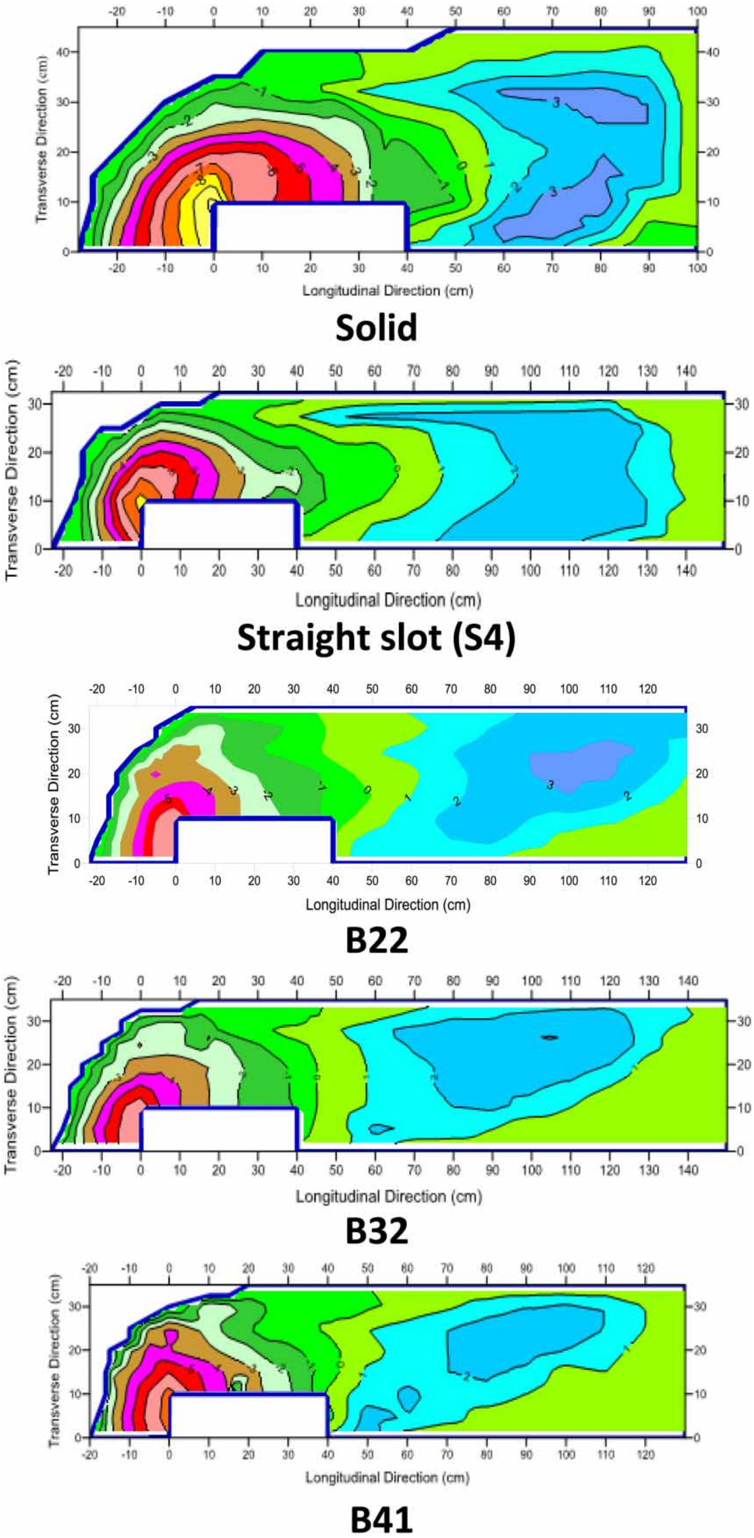

Figure 10 | Scour hole contours produced by different models, for Fn = 0.22.

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Surfer software was used to draw the topographic contours, and calculate the area and volume of the holes (Golden Software 2019).

A maximum scour volume reduction of 43.6, 43.2 and 40.2% was obtained for models B22, B32, and B41, respectively, compared with the 35.3% reduction for the straight slotted model (S4). Regarding the maximum scour area, B22, B32 and B41, respectively, produced 26.8, 26.5 and 29% reduction compared with 20.7% for S4.

CONCLUSIONS

In this study, the effectiveness of L-shaped slots in reducing scour at a short wall abutment was evaluated in the laboratory. The straight slotted model proved to be the best configuration of the single slotted models. Introducing an outlet slot near the abutment nose is not recommended, as it leads to increased scour hole size.

No combination of side slots is more efficient than an individual straight slot. Therefore, a straight slot must be included in any slot combination, as any configuration without a straight one is less efficient than the straight slot alone.

For the multi slotted models, B22 and B32 were the best configurations, with nearly the same efficiency, on which basis B22 is the best configuration as it has the fewest slots. B22 leads to depth, area, and volume reductions of about 32.6, 26.8, and 43.6%, respectively, while the straight slot (S4) reduces them by about 23.2, 20.7, and 35.3%. It is noting that performance might be enhanced further by burying part of the slot below bed level.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Abd El-Razek, M., Mohamed Abd El-Motaleb, M. A. & Bayoumy, M. 2003 Scour reduction around bridge piers using internal openings through the pier. *Alexandria Engineering Journal* **42**(2), 241–248.

Bejestan, M. S., Khademi, K. & Kozeymehnezhad, H. 2015 Submerged vane-attached to the abutment as scour countermeasure. *Ain Shams Engineering Journal* **6**, 775–783. doi:10.1016/j.asej.2015.02.006.

Chiew, Y. M. 1992 Scour protection at bridge piers. *Journal of Hydraulic Engineering* **118**(9), 1260–1269. doi:10.1061/(ASCE)0733-9429(1992)118:9(1260).

Chiew, Y. M. 1995 Mechanics of riprap failure at bridge piers. *Journal of Hydraulic Engineering* **121**(9), 635–643. doi:10.1061/(ASCE)0733-9429(1995)121:9(635).

Elnikhely, E. A. 2017 Minimizing scour around bridge pile using holes. *Ain Shams Engineering Journal* **8**(4), 499–506. doi:10.1016/j.asej.2016.06.016.

Fathi, A. & Zomorodian, S. M. A. 2018 Effect of submerged vanes on scour around a bridge abutment. *KSCE Journal of Civil Engineering* **22**(7), 2281–2289. doi:10.1007/s12205-017-1453-5.

Golden Software. 2019 *Surfer User's Guide*. Golden Software, LLC, 809 14th Street, Golden, Colorado 80401-1866, U.S.A. www.GoldenSoftware.com

Grimaldi, G., Gaudio, R., Calomino, F. & Cardoso, A. H. 2009 Countermeasure against local scouring at bridge piers: slot and combined system of slot and bed sill. *Journal of Hydraulic Engineering* **135**(5), 425–431. doi:10.1061/(ASCE)HY.1943-7900.0000035.

Hajikandi, H. & Golnabi, M. 2018 Y-shaped and T-shaped slots in river bridge piers as scour countermeasures. *Water Management* **171**(5), 253–263. doi:10.1680/jwama.16.00063.

Hosseini, K., Karam, H., Hosseinjanzadeh, H. & Ardeshir, A. 2016 Prediction of time-varying maximum scour depth around short abutments using soft computing methodologies – a comparative study. *KSCE Journal of Civil Engineering* **20**(5), 2070–2081. doi:10.1007/s12205-015-0115-8.

doi: 10.2166/wpt.2021.037

Karami, H., Hosseinjanzadeh, H., Hosseini, K. & Ardeshir, A. 2018 Scour and three-dimensional flow field measurement around short vertical-wall abutment protected by collar. *KSCE Journal of Civil Engineering* **22**(1), 141–152. doi:10.1007/s12205-017-0521-1.

Khodabakhshi, A. & Farhadi, A. 2016 Experimental study on effect of slot on bridge pier structures. *Applied Research Journal* **2**(5), 238–243.

Khosravinia, P., Malekpour, A., Hosseinzadehdalir, A. & Farsadizadeh, D. 2018 Effect of trapezoidal collars as a scour countermeasure around wing-wall abutments. *Water Science and Engineering Journal* **11**(1), 53–60. doi:10.1016/j.wse.2018.03.001.

Kumar, V., Ranga Raju, K. G. & Vittal, N. 1999 Reduction of local scour around bridge piers using slots and collars. *Journal of Hydraulic Engineering* **125**(12), 1302–1305. doi:10.1061/(ASCE)0733-9429(1999)125:12(1302).

Melville, B. W. 1992 Local scour at bridge abutments. *Journal of Hydraulic Engineering* **118**(4), 615–631. doi:10.1061/(ASCE)0733-9429(1992)118:4(615).

Mohamed, Y. A., Naser-Allah, T. H., Abdel-Aal, G. M. & Awad, A. S. 2015 Investigating the effect of curved shape of bridge abutment provided with collar on local scour, experimentally and numerically. *Ain Shams Engineering Journal* **6**(1), 403–4011. doi:10.1016/j.asej.2014.10.011.

Moncada-M, A. T., Aguirre-Pe, J., Bolívar, J. C. & Flores, E. J. 2009 Scour protection of circular bridge piers with collar and slots. *Journal of Hydraulic Research* **47**(1), 119–126. doi:10.3826/jhr.2009.3244.

Osroush, M., Hosseini, S. A., Kamanbedast, A. A. & Khosrojerdi, A. 2019 The effects of height and vertical position of slot on the reduction of scour hole depth around bridge abutments. *Ain Shams Engineering Journal* **10**(3), 651–659. doi:10.1016/j.asej.2019.02.004.

Radice, A. & Lauva, O. 2012 On flow-altering countermeasures for scour at vertical-wall abutment. *Arch Hydro-Eng Environ Mech* **59**(3–4), 137–153. doi:10.2478/heem-2013-0008.

Raudkivi, J. A. 1998 *Loose Boundary Hydraulics*. A.A. Balkema, Rotterdam, The Netherlands.

Setia, B. & Bhatia, K. 2013 Scour protection by a slot through a model bridge pier. *Journals – Indian Water Resources Society* **33**(1), 9–15.

Tafarojnoruza, A., Gaudioa, R. & Deyb, S. 2010 Flow-altering countermeasures against scour at bridge piers: a review. *Journal of Hydraulic Research* **48**(4), 441–452. doi:10.1080/00221686.2010.491645.

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