Enhancing scour protection in river bends: a novel slotted bank-attached vane

Mohamad Azizipour, Farshid Amirsalari Meymani
and Mohammad Mahmoodian Shooshtari

ABSTRACT

One of the most effective approaches for bank control erosion is using bank-attached vanes. In spite of the superiority of the bank-attached vanes to spur dikes, the vanes' tips are still vulnerable to local scour caused by flow–structure interaction. In this study, slotted bank-attached vanes are proposed to reduce local scour at the tip of the triangular submerged vane. For this, a rectangular slot is created parallel to the chord of the vane with an area of ten percent of the effective area of the vane surface. Two types of conventional vanes and slotted vanes were installed at different angles of attack of 23, 30, 40 and 60 degrees in an arch flume. Experiments were carried out in clear water conditions with different flow regimes with Froude numbers of $Fr = 0.287$, 0.304 and 0.322. The results show that the slotted vane outperforms the conventional vane by reducing maximum scour depth by about 70, 20, 17 and 54 percent for different angles of attack of 23, 30, 40 and 60 degrees, respectively. The proposed slotted vane also resulted in reduction of scour hole volume around the vane and formed the scour hole away from the outer bank.

Key words | erosion, local scour, slotted vane, submerged vane

Mohamad Azizipour (corresponding author)
Faculty of Civil and Architectural Engineering,
Shahid Chamran University of Ahvaz,
Ahvaz,
Iran
E-mail: azizipour@scu.ac.ir

Farshid Amirsalari Meymani
Faculty of Water Science Engineering,
Shahid Chamran University of Ahvaz,
Ahvaz,
Iran

Mohammad Mahmoodian Shooshtari
Faculty of Civil and Architectural Engineering,
Shahid Chamran University of Ahvaz,
Ahvaz,
Iran

HIGHLIGHTS

- Slotted submerged vanes are introduced.
- Performance of slotted vanes are investigated.
- The conventional and slotted vanes are compared.

INTRODUCTION

Bank erosion is a great challenge in meandering rivers and typically occurs in outer river bends. Although limited lateral channel migration could be beneficial for some ecosystems (e.g., Piégay et al. 2005), unrestricted bank erosion may demolish an existing riparian ecosystem. To cope with this issue, stabilization of river banks is of great importance. There are many studies in the literature proposing different methods for bank erosion protection including spur dikes (Copeland 1983), riparian vegetation (Croke et al. 2017) and different types of vanes (Bhuiyan et al. 2010; Pagliara et al. 2014; Odgaard 2015, 2017).

In recent years, submerged vanes for the protection of riverbanks have increasingly been used because of their fast and easy way of installation compared with other traditional methods like dikes and groins (Biswas & Barbhuiya 2019). As an environment-friendly structure, submerged vanes are designed for habitat improvement as well. Various studies have been undertaken on vanes. The effectiveness of vanes in reducing near-bank velocity considering different angles of attack was investigated by Odgaard & Kennedy (1983), concluding that for a greater angle of attack than 20°, a scour hole is formed at the upstream edge of the vane. Odgaard & Spoljaric (1986) developed a

rational method for design of a system of submerged vanes to control depth in alluvial rivers. Odgaard & Mosconi (1987) proposed that the secondary flow in bends is modified by use of vanes, resulting in redistribution of sediment within the channel cross-section and consequently reduction of scour at the bends. A detailed numerical study was done by Sinha & Marelius (2000) to analyze flow past a submerged vane. Tan *et al.* (2005) conducted experiments in a large flume to investigate the flow and sedimentation characteristics around a submerged vane. They concluded that the success of a submerged vane in sediment diversion depends on the optimum skew angle to the approach flow for the purpose of sediment diversion, the vane shape and vane alignment to the approach flow. Gupta *et al.* (2010) used a collar at the leading edge of the vane and indicated that the scour at the leading edge of the collar was reduced to zero. The effects of log-vanes on the scour in straight rivers were studied by Pagliara *et al.* (2015) resulting in obtaining an equation to determine the scour parameters and morphology. Results of a study on bank erosion and protection using a submerged vane carried out by Dey *et al.* (2017) showed that a 15° vane angle produces the best results in reducing outer bank scour in a parabolic-shaped channel. More recently, Biswas & Barbhuiya (2019) carried out a series of experiments in a 180° bend to explore the effects of submerged vanes on the flow field and subsequent scour morphology in a river bend.

As is mentioned by many researchers, the shape of a submerged vane plays an important role in its performance improvement (e.g. Ouyang 2009; Shafai Bejestan & Azizi 2012; Teronpi & Misra 2015). Shafai Bejestan & Azizi (2012) compared the efficiency of rectangular and triangular vanes showing that the triangular vane outperforms rectangular vanes in scour reduction. In another study, the comparison of scour depth for both triangular shape vanes (TSV) and rectangular shape vanes (RSV) proved that the scour depth for TSV is 80 percent less than the scour depth of RSV (Badri 2014). Teronpi & Misra (2015) proposed that the maximum scour depth among rectangular, trapezoidal and curved submerged vanes takes place in the case of rectangular vanes.

Despite the rich literature in the field of rectangular submerged vanes, there are only a few studies in the field of triangular submerged vanes. In a laboratory investigation,

Bhuiyan *et al.* (2010) installed low-angle and bank-attached triangular vanes in a mobile bed channel, concluding that when a single vane or an array of vanes is installed, the scour hole at the base of the outer bank is filled and the thalweg is relocated toward the center of the river. Moreover, the deposition is formed at the downstream side of the vanes, due to plunging flow over the crest of the vanes. The components of flow velocity in a 90° mild bend were experimentally studied by Bahrami Yarahmadi & Shafai Bejestan (2015), for cases of both with and without a submerged vane. The results showed that the location of the maximum depth-averaged velocity was shifted from the near-outer bank toward the channel midpoint after installing a single triangular vane. Also, the single vane decreased the depth-averaged velocity near the outer bank both upstream and downstream of the vane.

The main drawback associated with using submerged vanes is the local scour around their tips which may cause destruction of the structure. This paper aims at introducing a novel approach to reduce the local scour around the vane's tip and to increase the effectiveness of the triangular submerged vane in protecting riverbank erosion. This is achieved through creating a slot in the structure to modify the flow pattern around the submerged vane. Although using a slot to control local scour around a bridge pier was first introduced by Chiew (1992), to the best of our knowledge, there is no study in the literature investigating the effect of the slot on scour around a submerged vane. In this study, the effect of a slot in a submerged vane on bed topography and its skew angle is experimentally investigated. Results show that the proposed slotted vanes are superior to conventional vanes in protecting a bank from erosion by reducing the maximum scour depth.

MATERIALS AND METHODS

The experiments were conducted in a single-bend flume with 90 degrees of curvature. Since the ratio of the bend radius to the flume width $\left(\dfrac{R}{B} = \dfrac{2.8}{0.7}\right)$ is equal to 4, according to (Rozovskii 1957), the flume falls into the category of a mild bend. The length and width of the flume are 12.4 and 0.7 metres, respectively. The length of the straight

reaches at the upstream of the bend is 5 m while the downstream part of the bend is 3 m long. It is notable that the flume's side walls are made of transparent Plexiglas providing a rectangular cross-section. The schematic representations of the flume and vanes are illustrated in Figures 1 and 2, respectively.

The discharge Q to the flume is adjusted via an ultrasonic flowmeter with an accuracy of ± 0.01 l/s, installed on the entrance pipe to the flume. At the outlet section, the flow is drained into a reservoir and the water is recycled to the system, as shown in Figure 1. The flume bed is covered by uniform sand with median diameter (d_{50}) of 1.5 mm and geometric standard deviation σ of 1.22 for all the experiments. As shown in Figure 2 (a_1), the depth of the sediment bed layer is fixed at 20 cm. A fixed slide gate at the end of the flume is employed to control the flow depth (h). The flow depth is kept constant, for all experiments, at 14 cm from the bed level, which is equal to the vane crest level at the outer bank in the bend.

The triangular vanes are made of Plexiglas with a thickness of 4 mm. To investigate the effect of a vane, a single vane was installed at the section 72° from the beginning of the bend on the outer bank in which the maximum scour

usually occurs (Bahrami Yarahmadi & Shafai Bejestan 2016). All experiments were carried out for both cases of conventional and slotted triangle vanes. The conventional and proposed slotted triangular vanes are shown in Figure 2. As shown in Figure 2 (a_2), a rectangular slot is created on the vane parallel to the chord. The slot surface is equal to ten percent of the effective surface of the vane, which is defined as the surface that is exposed to the approaching flow. The ratio of length to width of the slot is considered as 4 $\left(\dfrac{a}{b} = 4\right)$. As illustrated in Figure 1, the effective length is the perpendicular distance between the vane's tip to the outer bank, which is taken as 14 cm ($L_e = 14$ cm), for all experiments.

A total number of 24 experiments were carried out for both cases of conventional and slotted vanes. Different angles of attack of 23°, 30°, 40° and 60° were considered for both cases, with different Froude numbers of $Fr = 0.287$, 0.304 and 0.322. Table 1 summarizes characteristics of all tests conducted in this study. Each test takes about three hours to be completed and the water is then gradually drained out of the flume to avoid any disturbance in the bed topography. The bed profile is then measured by using a laser distance meter (Bosch GLM 30) with an accuracy of 1 mm, which is installed on a rail on the top of the flume.
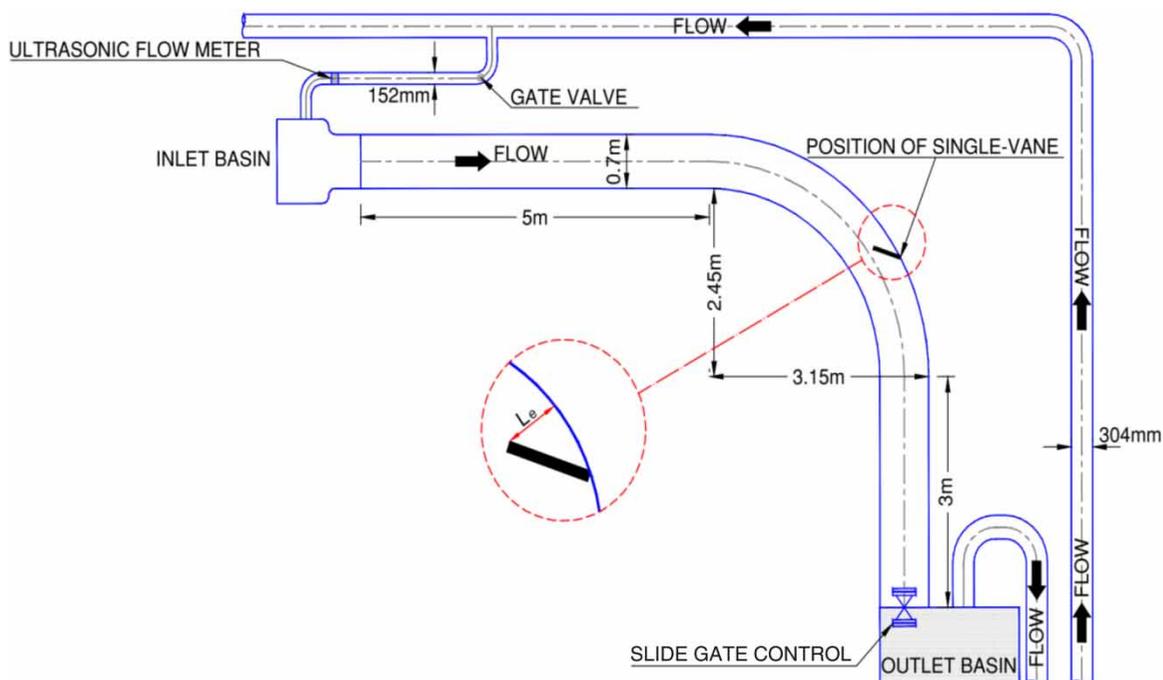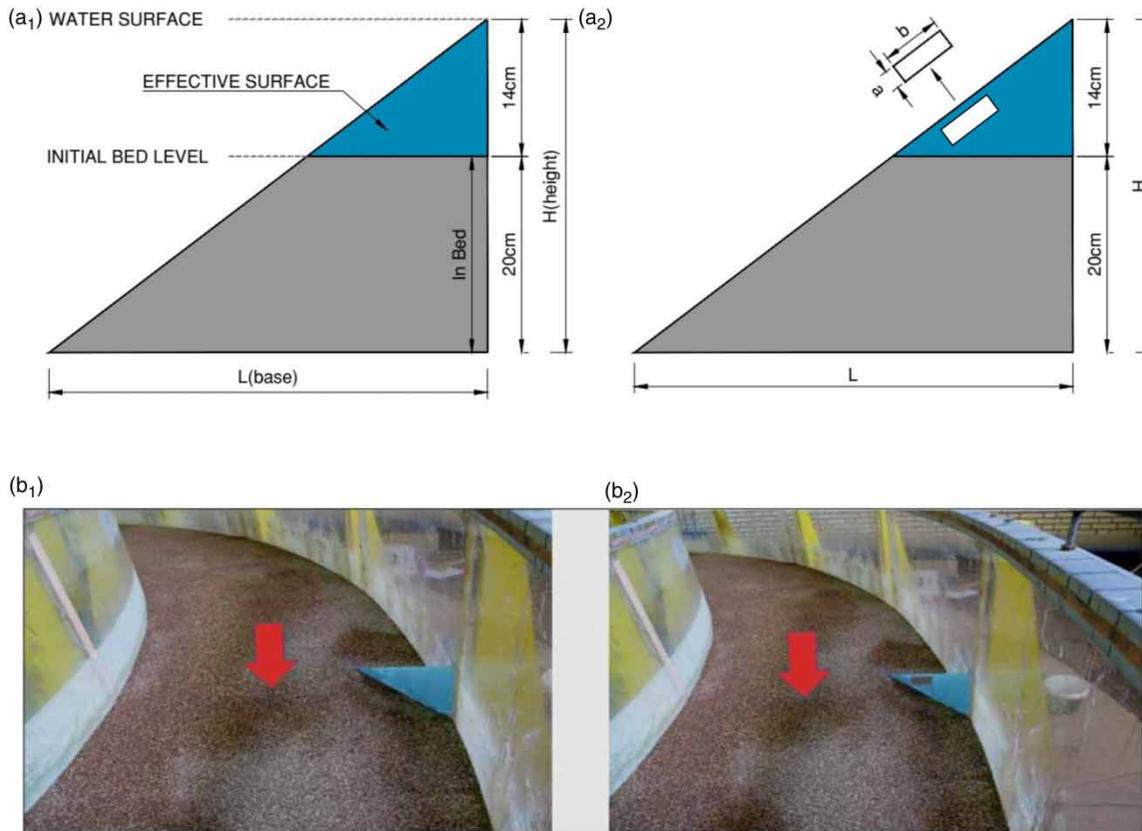

Figure 1 | Experimental setup; plan view of the flume.

Figure 2 | The single vane that was installed at an angle of 30 degrees, without slot (b$_1$), with slot (b$_2$).

RESULTS

Scour morphology

The bed morphology and contours of the scoured beds for both cases of slotted and conventional vanes, for a constant Froude number of 0.322, are illustrated in Figure 3.

As shown in the figure, for an angle of attack of 23°, there is no scouring at the upstream of the vane and the scour hole is completely transferred to the downstream of the vane. Experimental observations showed that regardless of the value of the Froude number, the scour hole is only formed at the downstream of the vane. It should be mentioned that the minimum scour volume is obtained when using a vane with an angle of attack of 23°.

It is clearly seen in Figure 3 that for all angles of attack, the scour depth around the slotted vane is much less than the case of using a conventional vane. Creating a slot in the vane also caused scour hole volume reduction around the vane for different angles of attack. Moreover, the scour hole around the tip of the structure in the slotted vane is less developed in comparison with the conventional vane.

The bed morphology contours for 40° and 60°, presented in Figure 3, reveal that the scour around the conventional vanes reached to the outer bank for all cases considered in this study, while by using 40° and 60° slotted vanes, the scour only reached to the outer bank in the case of the largest Froude number, and the scour depths were much less than those of conventional vanes.

The scoured bed profile for different angles of attack and constant Froude number of 0.322 is presented in Figure 4 for the cross-section in which the maximum scour depth occurred. The dashed and continuous lines represent the scour bed for slotted and conventional vanes, respectively. The outer bank is considered to be at $x = 0$, while $x = 70$ cm is the location of the inner bank in the bend. Figure 4

Table 1 | Details of conducted tests

Test number	Vane type	α (degree)	Fr
1	Conventional vane	23	0.287
2	Conventional vane	23	0.304
3	Conventional vane	23	0.322
4	Conventional vane	30	0.287
5	Conventional vane	30	0.304
6	Conventional vane	30	0.322
7	Conventional vane	40	0.287
8	Conventional vane	40	0.304
9	Conventional vane	40	0.322
10	Conventional vane	60	0.287
11	Conventional vane	60	0.304
12	Conventional vane	60	0.322
13	Slotted vane	23	0.287
14	Slotted vane	23	0.304
15	Slotted vane	23	0.322
16	Slotted vane	30	0.287
17	Slotted vane	30	0.304
18	Slotted vane	30	0.322
19	Slotted vane	40	0.287
20	Slotted vane	40	0.304
21	Slotted vane	40	0.322
22	Slotted vane	60	0.287
23	Slotted vane	60	0.304
24	Slotted vane	60	0.322

α = angle of single vane to the upstream bank; Fr = Froude number.

indicates that the slotted vane has superior performance to conventional vanes in decreasing scour, regardless of angle of attack. The superiority of slotted vanes to conventional vanes was observed not only for $Fr = 0.322$, but also for all hydraulic conditions considered. It is also obviously seen from Figure 4 that the maximum scour depth is reduced by using the slotted vane for all cases.

Characteristics of scour hole

Determining maximum scour depth is of great importance in design of in-stream structures. This, therefore, necessitates the careful investigation of the location and the depth of maximum scour. However, prediction of maximum scour depth and its location is complicated especially in river bends where helical flow is formed due to the presence of centrifugal forces.

Table 2 summarizes the results of maximum scour depth for all experiments carried out in this study, for slotted and conventional vanes. The maximum scour depth reduction which is obtained by using the slotted vane rather than the conventional vane is also reported in Table 2. Although the percentage of maximum scour depth reduction varies by different angle of attack and different hydraulic conditions, the slotted vane outperforms the conventional vanes in all tests. The average reductions of maximum scour depth for different Froude numbers are 70, 20, 17 and 54 percent for angles of attack of 23°, 30°, 40° and 60°, respectively. The best performance of the slotted vane is achieved while the angle of attack is set to 23°. As shown in the table, regardless of the angle of attack, the maximum scour depth is proportionate to Froude number, which coincides with previous research in the literature (e.g. Bahrami Yarahmadi & Shafai Bejestan 2015).

Since the maximum scour depth plays an important role in the stability of the in-stream structures, it could be concluded that the slotted vane is much more stable than the conventional vane.

The location of maximum scour depth and its distance from the bank of the river are also crucial parameters needing to be considered besides the maximum scour depth. A closer scour hole to the bank endangers the safety of in-stream structures. The closeness of the scour hole to the bank was investigated for the proposed slotted vane and the results are illustrated in Figure 5. The figure shows the dimensionless distance of maximum scour depth (d/h) versus different angles of attack, in which d is the distance of the maximum scour depth from the outer bank of the bend. This figure indicates that increasing Froude number moves the scour hole away from the outer bank. Moreover, it is clearly seen from Figure 5 that there is an angle of attack, between 30° and 40°, in which the furthest scour hole is formed.

Characteristics of deposition zone

The process of scouring the outer banks in river bends is always associated with deposition of point bars on the
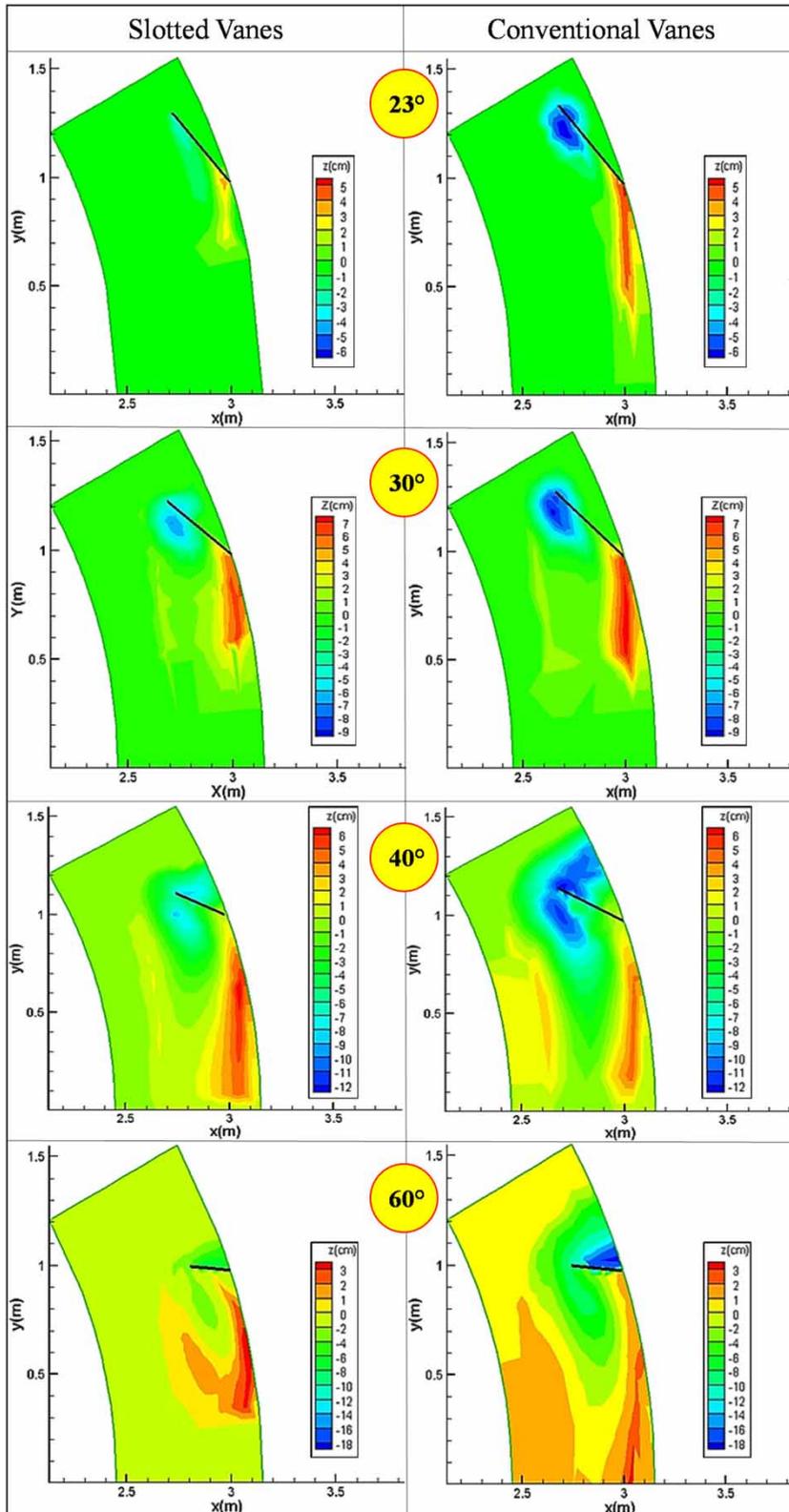
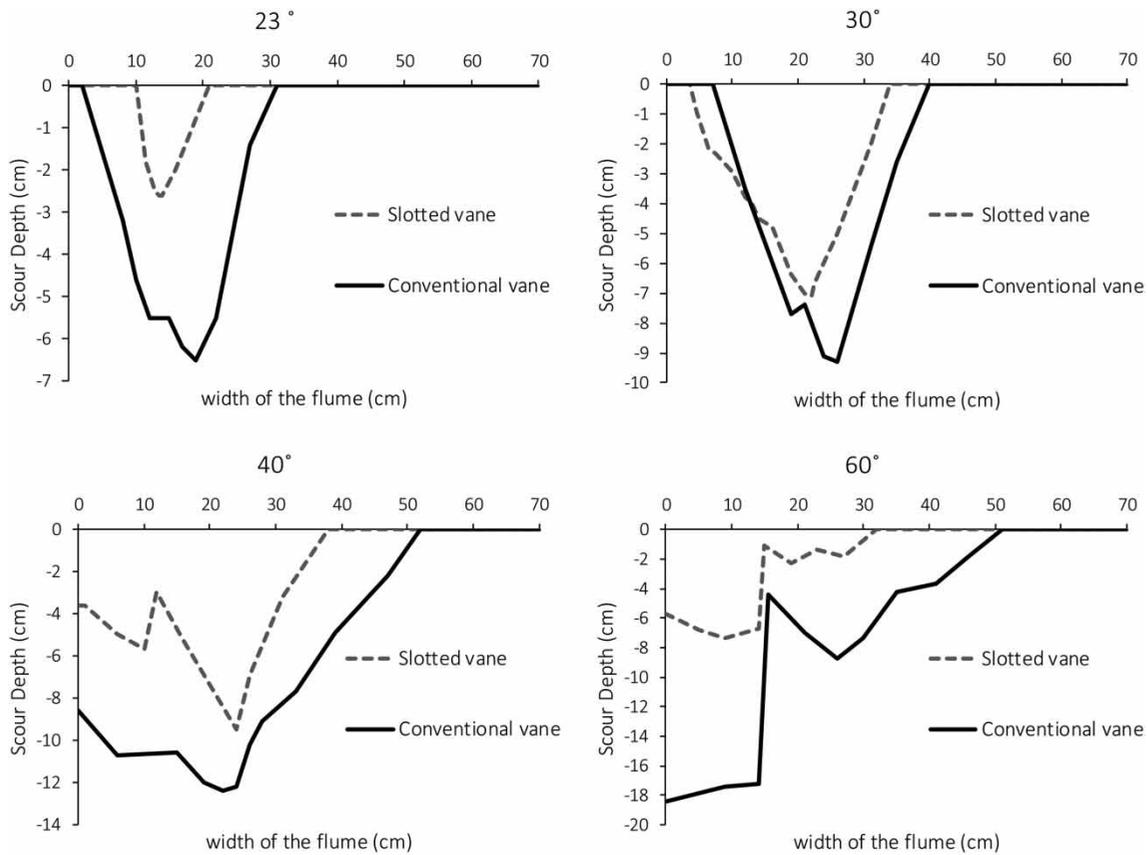**Figure 3** │ Bed morphology around the conventional and slotted vanes at different angles ($Fr = 0.322$).

Figure 4 | Scoured bed profile for slotted and conventional vanes at maximum scour depth cross-section ($Fr = 0.322$).

Table 2 | Results of maximum scour depth for conventional and slotted vanes

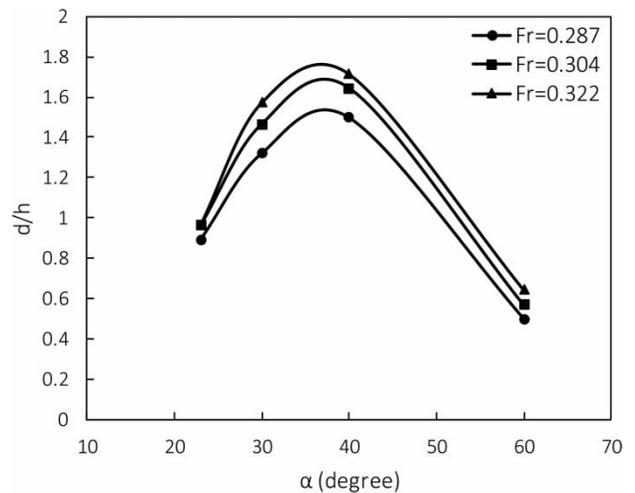|		Maximum scour depth (cm)		
α (degree)	*Fr*	Conventional vane	Slotted vane	Maximum scour depth reduction (%)
23	0.287	3.2	0.8	75
	0.304	5.2	1.3	75
	0.322	6.5	2.6	60
30	0.287	4.3	3.3	23
	0.304	6.2	5.4	13
	0.322	9.3	7.1	24
40	0.287	8.2	7.2	12
	0.304	10.3	8.8	15
	0.322	12.4	9.5	23
60	0.287	10.6	4.8	55
	0.304	11.4	5.9	48
	0.322	18.4	7.4	60

Figure 5 | Variations of normalized maximum scour depth distance from the outer bank versus angle of attack at different Froude numbers.

inner banks. Characterizations of point bars including prediction and control of how much and where the sediment deposition occurs are as important as scour hole considerations, for efficient design of in-stream structures.

Figure 6 displays the effect of orientation of the proposed slotted vane on dimensionless maximum point bar height (H_{max}/h). As shown in the figure, the maximum height of the point bar takes place at an angle of attack between 30° and 40°, which matches with the scour hole maximum depth, shown in Figure 5. The figure also indicates that increasing Froude number leads to forming a point bar with larger H.

Vane performance

The bank of the river in meanders is protected by vanes such that the flow is diverted from the river banks toward the middle of the river. The flow diversion is associated with formation of a highly turbulent rotational zone which is developed around the vane tip. The scour, therefore, occurs around the tip and scoured bed particles are deposited downstream of the vane. Although the local scour is considered a threat to the stability, durability, and function of the vane, the river banks at the downstream of the vane are naturally protected by sediment deposition. The performance of the proposed slotted vane structures is therefore evaluated considering both scour and deposition values. For this, the performance of the vane is defined as
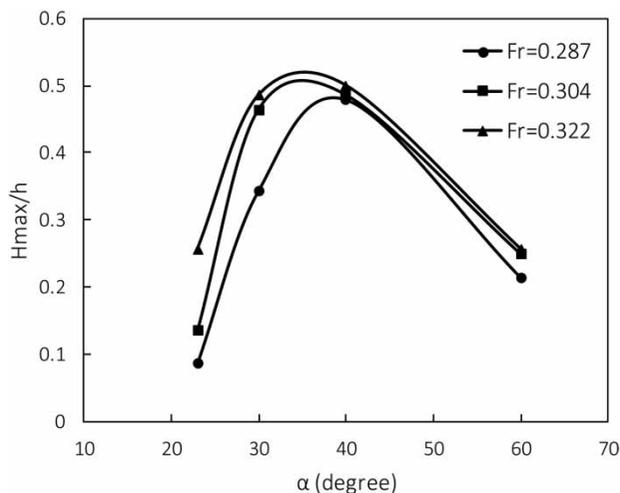

Figure 6 | Variations of normalized maximum point bar height of slotted vanes versus angle variations at different Froude numbers.

Table 3 | Results of performance index for conventional and slotted vanes

| α (degree)	Fr	P_v Conventional vane	Slotted vane
23	0.287	1.03	1.50
	0.304	0.96	1.46
	0.322	0.80	1.38
30	0.287	1.02	1.52
	0.304	0.77	1.20
	0.322	0.85	0.96
40	0.287	0.90	0.93
	0.304	0.63	0.77
	0.322	0.39	0.74
60	0.287	0.47	0.63
	0.304	0.46	0.59
	0.322	0.19	0.49

the ratio of maximum deposition (H_{max}) to maximum scour (Z_{max}), which can be mathematically formulated as $P_v = H_{max}/Z_{max}$. The higher the value of P_v, the better the performance of the vane.

The results of performance evaluation of the proposed slotted vane are presented in Table 3 and compared with those obtained for conventional vanes, for different angles of attack (α) and various hydraulic conditions. The table indicates that the proposed slotted vane performs more efficiently than conventional vanes regarding the value of P_v for all cases considered in this study. In other words, the slotted vanes have been able to deposit the eroded sediments with proper height at the outer bank.

DISCUSSION

The presented results show that by using the slotted vane the scouring potential is significantly reduced. The performance of the slotted vane in decreasing scour potential can be attributed to either diverting downflow away from the bed, or creating an upward flow pattern.

There are three types of approaching streamlines to the vane illustrated in Figure 7. The streamlines with higher elevation than slot elevation collide with the vane forming a downflow which has the main impact on scouring potential. A part of such streamlines is deflected to the downstream of the vane through the slot, before hitting the bed, and the
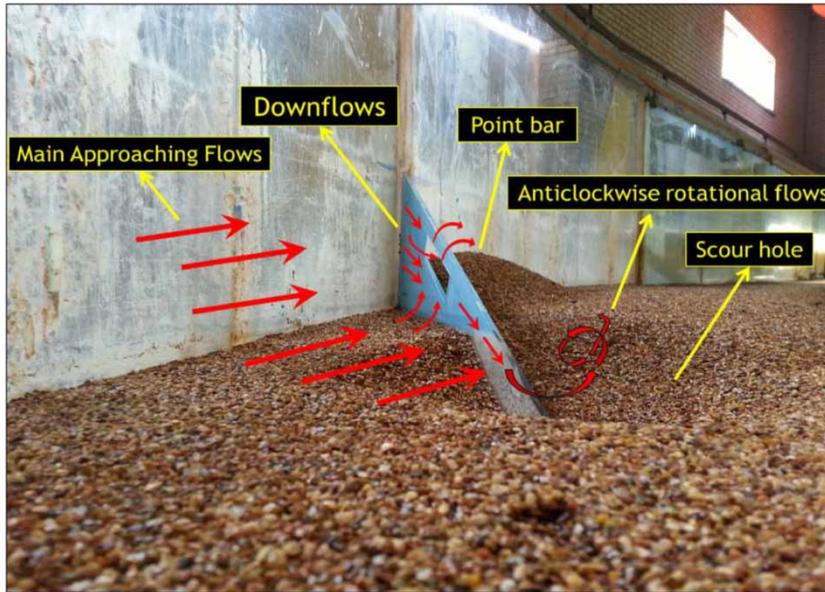
Figure 7 | Approaching streamlines to the slotted vane.

scouring potential is, therefore, reduced. The streamlines with the same elevation as the slot can directly transfer to the downstream without colliding with the vane and forming downflow. The approaching streamlines to the vane with lower elevation than the slot create an upward flow. The appearance of the upward flow can neutralize a part of the downflow leading to scour potential reduction. It can be concluded that creating a slot in the vane redistributes the flow pattern such that the effect of critical shear stress as well as destructive vortices are lessened and the scour potential is consequently decreased. This in fact is vindicated by the experimental results presented in the previous sections.

As was investigated by various researchers (e.g., Bhuiyan *et al.* 2010; Dey *et al.* 2017), the smaller the angle of attack, the better the performance of the vane, which is matched by the observations in this study. However, considering the fixed effective length of the vane, the smaller angle of attack leads to a longer vane, which is not efficient from an economic point of view. The proposed slotted vane provides an alternative to the conventional vane while economically outperforming the conventional vane. The performance of the 23° conventional vane is approximately equal to the 60° slotted vane in decreasing scour depth, while the surface area of the conventional vane is 2.2 times greater than that of the slotted vane. This implies that using a slotted vane decreases the size of the vane by up to 55% in comparison with the conventional vane.

More numerical and experimental research could extend the current research to understand the effect of size and location of the slot and how it could be optimized for different hydraulic conditions.

CONCLUSION

A modified submerged vane was proposed for local scour protection with a rectangular slot in the effective surface of the vane. Experiments were carried out in two stages of with and without a slot on the vane, and four different angles of attack of flow were considered. The results of the experiments show the capability of the proposed slotted vane in decreasing scour depth as well as scour volume. The angle of attack of flow with 23, 30, 40 and 60 degrees led to decreasing scour depth of 70, 20, 17 and 54 percent, respectively, of those of the conventional vane. It is also noteworthy that the maximum scour depth around the tip of the slotted vanes has the lowest and highest value at the angles of 23 and 40 degrees, respectively. The slotted vanes also performed better than the conventional vanes in creating a balance between maximum scour depth and maximum point bar height.

REFERENCES

Badri, P. 2014 *Experimental Investigation of the Effect of Longitude Space between Triangular Vane on Bed Topography of a 90-Degree Bend*. Master's thesis. Retrieved from Dissertations and Theses Database, Shahid Chamran University of Ahvaz, Iran.

Bahrami Yarahmadi, M. & Shafai Bejestan, M. 2015 Sediment management and flow patterns at river bend due to triangular vanes attached to the bank. *Journal of Hydro-Environment Research* 10, 64–75. doi:10.1016/j.jher.2015.10.002.

Bahrami Yarahmadi, M. & Shafai Bejestan, M. 2016 Study of the effect of effective length variations of triangular vanes on erosion and deposition patterns in a 90° mild bend. *Journal of Civil Engineering (Journal of School of Engineering)* 27 (1), 87–100.

Bhuiyan, F., Hey, R. D. & Wormleaton, P. R. 2010 Bank-attached vanes for bank erosion control and restoration of river meanders. *Journal of Hydraulic Engineering* 136 (9), 583–596. doi:10.1061/(ASCE)HY.1943-7900.0000217.

Biswas, P. & Barbhuiya, A. K. 2019 Effect of submerged vane on three-dimensional flow dynamics and bed morphology in river bend. *River Research and Applications* 35 (3), 301–312. doi:10.1002/rra.3402.

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).

Copeland, R. 1983 *Bank Protection Techniques using Spur Dikes*. Miscellaneous Paper HL-83-1, Office, Chief of Engineers, US Army, Washington, DC, USA.

Croke, J., Thompson, C. & Fryirs, K. 2017 Prioritising the placement of riparian vegetation to reduce flood risk and end-of-catchment sediment yields: important considerations in hydrologically-variable regions. *Journal of Environmental Management* 190, 9–19. doi:10.1016/j.jenvman.2016.12.046.

Dey, L., Barbhuiya, A. K. & Biswas, P. 2017 Experimental study on bank erosion and protection using submerged vane placed at an optimum angle in a 180° laboratory channel bend. *Geomorphology* 283, 32–40. doi:10.1016/j.geomorph.2017.01.022.

Gupta, U. P., Ojha, C. S. P. & Sharma, N. 2010 Enhancing utility of submerged vanes with collar. *Journal of Hydraulic Engineering* 136 (9), 651–655. doi:10.1061/(ASCE)HY.1943-7900.0000212.

Odgaard, A. J. 2015 River channel stabilization with submerged vanes. In: *Advances in Water Resources Engineering* (C. T. Yang & L. K. Wang, eds), Springer International Publishing, Cham, Switzerland, pp. 107–136. doi:10.1007/978331911023-3_3.

Odgaard, A. J. 2017 River management with submerged vanes. In: *River System Analysis and Management* (N. Sharma, ed.), Springer, Singapore, pp. 251–261. doi:10.1007/978-981-10-1472-7_13.

Odgaard, A. J. & Kennedy, J. F. 1983 River-bend bank protection by submerged vanes. *Journal of Hydraulic Engineering* 109 (8), 1161–1173. doi:10.1061/(ASCE)0733-9429(1983)109:8(1161).

Odgaard, A. J. & Mosconi, C. E. 1987 Streambank protection by submerged vanes. *Journal of Hydraulic Engineering* 113 (4), 520–536. doi:10.1061/(ASCE)0733-9429(1987)113:4(520).

Odgaard, A. J. & Spoljaric, A. 1986 Sediment control by submerged vanes. *Journal of Hydraulic Engineering* 112 (12), 1164–1180. doi:10.1061/(ASCE)0733-9429(1986)112:12(1164).

Ouyang, H. T. 2009 Investigation on the dimensions and shape of a submerged vane for sediment management in alluvial channels. *Journal of Hydraulic Engineering* 135 (3), 209–217. doi:10.1061/(ASCE)0733-9429(2009)135:3(209).

Pagliara, S., Mahmoudi Kurdistani, S. & Sagvand Hassanabadi, L. 2014 Scour characteristics downstream of in-stream river restoration structures: log and J-hook vanes comparison. In: *ICHE 2014, Proceedings of the 11th International Conference on Hydroscience & Engineering* (R. Lehfeldt & R. Kopmann, eds), Bundesanstalt für Wasserbau, Karlsruhe, Germany, pp. 859–864.

Pagliara, S., Sagvand Hassanabadi, L. & Mahmoudi Kurdistani, S. 2015 Log-vane scour in clear water condition. *River Research and Applications* 31 (9), 1176–1182. doi:10.1002/rra.2799.

Piégay, H., Darby, S. E., Mosselman, E. & Surian, N. 2005 A review of techniques available for delimiting the erodible river corridor: a sustainable approach to managing bank erosion. *River Research and Applications* 21 (7), 773–789. doi:10.1002/rra.881.

Rozovskii, I. L. 1957 *Flow of Water in Bends of Open Channels*. Academy of Sciences of the Ukrainian SSR, Kiev, Ukraine (English translation: Israel Program for Scientific Translations, Jerusalem, Israel, 1961).

Shafai Bejestan, M. & Azizi, R. 2012 Experimental investigation of scour depth at the edge of different submerged vanes shapes. In: *World Environmental and Water Resources Congress* (E. D. Loucks, ed.), ASCE, Reston, VA, USA, pp. 1376–1385. doi:10.1061/9780784412312.138.

Sinha, S. K. & Marelius, F. 2000 Analysis of flow past submerged vanes. *Journal of Hydraulic Research* 38 (1), 65–71. doi:10.1080/00221680009498360.

Tan, S. K., Yu, G., Lim, S. Y. & Ong, M. C. 2005 Flow structure and sediment motion around submerged vanes in open channel. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 131 (3), 132–136. doi:10.1061/(ASCE)0733-950X(2005)131:3(132).

Teronpi, J. & Misra, U. K. 2015 Experimental investigation of local scour around submerged vanes. *International Journal of Innovative Research in Advanced Engineering* 2 (7), 21–24.