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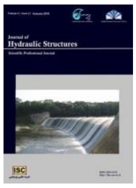

Mapping scour depth around group bridge pier under controlled conditions

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Abstract

As a destructive process, scouring exposes bridge foundations to failure and disastrous consequences. Control structures of various arrangements are capable to change and manage the adverse effects. The present work aims to probe the response of submerged vanes of a quasi-triangular arrangement (of heights 0, 4, and 6 cm), eppi, and sills (of height 4.5 and 9 cm) on scour development. All tests were executed in a rectangular slope-less flume covered with sediments of D50=1.8 mm. Temporal and equilibrium scour depth were mapped for Froude numbers: 0.15, 0.2, 0.25, and 0.6. Results clarified the aggregate effect of the eppies on the scour depth due to section contraction. Submerged vanes and sill were set up to deteriorate sediment transport. Although the vane of height 4 cm had the most superior performance, but the sill installation of height 4.5 cm greatly increased vane's effect, so that a remarkable reduction of scour was occurred at the first pier foundation.

Keywords: Sediment transport, Control structures, Scouring, Bridge pier.

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1. Introduction

As a linking structure, bridges play an undeniable role from transportation systems aspects. Scour around the pier is the dominant factor of bridge failure so that a vast range of studies has been performed to extract and developed effective factors on pier scouring. Zomorodian et al. [1] investigated the effects of various arrangements of submerged sacrificial piles on scour depth of cylindrical bridge piers. Their results showed that sacrificial piles length act effectively in scouring. Habib et al. [2] did an overview of self-protected pier as flow altering countermeasures for scouring protection. Their review consisted of analysis on the openings on pier including internal tubing, slot and pier groups, and modified pier shapes as the flow-altering, self-protected countermeasure alternatives. Solimani Babarsad et al. [3] investigated the effect of deflector structure on bridge pier scouring. They stated that changing the angle from 45 to 30 and 15 degrees reduces the local pier scouring and increases the deflector structure's effectiveness. Nikkhah et al. [4] performed experiments to estimate afflux equation in circular and semicircular nose and tail shape of piers by considering effective parameters. Results show that when Froude number is increased, efflux is increased as well. However, these changes are not the same in the two different bridge pier shapes. By examining Froude number in different path narrowing, it was found that generally, the amount of afflux is directly related to the Froude number. Rasaei and Nazari [5] performed a comparative study to investigate local scour around bridge pier of different shape at a 90° convergent meander. Their results demonstrated the shapes and sizes of the piers' effect on scour process. Piers of cubic shape had more scour depth than cylindrical ones during all tests. Extra scour depth was detected in convergence-induced contraction along with the placement of the piers at the meander. The numerical SSIIM-2 results were found to be in a good agreement with the experimental results. An experimentally research work was accomplished by Keshavarzi et al. [6] to investigate local scour around single and two-column bridge piers. The results revealed diminishing effect of the slot presence on the maximum scour depth. Estimation of time development of local scour around rectangular bridge pier in an unsteady flow condition was conducted by Karimaei Tabarestani and Zarrati [7]. Results showed that the sediment transport equation should be modified in order to determine the volume of transported sediment around bridge pier in an unsteady flow condition. The modification factor applied to sediment transport equation was a function of hydrograph characteristics such as time to peak, duration and time from peak to base flow as well as hydrograph peak flow intensity. Bahrami and Gomeshi [8] stated that the scour mechanism in the pier group is different and more complex than the single pier. In the earlier case, in addition to the effective parameters of local scouring, other factors such as the reinforcing factor of the vortexes, the compression of the horseshoe vortexes, and the relative distance of the piers are effective. Arab et al. [9] studied the sill's effect on scour depth around bridge piers under flood flow conditions. More distance between the pier and the sill declined the positive effect of the sill, significantly. This effect was more apparent in the group bridge pier. They claimed that flood condition declined that sill's effect on scour depth developing than uniform flow with clear water condition. Arab and Zomorodian [10] conducted an experimental research to illustrate interaction of bridge pier and abutment on local scour around them. The results showed that the proximity pier to abutment, increases scour depth of them and the minimum scour depth related to the circular pier and maximum scour depth related to the sharp edge pier. Memar et al. [11] performed experiments to assess the impact of bridge pier on depth of scour hole in abutment. They claimed that when the pier's diameter was about 50 percent of abutment's length, the minimum depth of scour was reached, and when the diameter of pier was bigger than abutment's length, maximum depth of scour in abutment was obtained. Tafarojnoruz et al. [12] investigated the effect of the piers group arrangement on the scour depth of the bridge pier and found that pier group arrangement has a significant impact on the scour depth and the developed scour depth behind the bridge pier so that the maximum scour occurs at the upstream of the piers and the around of the first pier. Movahedi et al. [13] studied experimentally local scouring around two side-by-side piers with raft footing. Their study focused on scouring around side-by-side piers with various spaces between them, and then the effect of raft footing on mechanism and amount of scour has been investigated. The results showed the scour depth decreases as the spacing between the piers increases and for G/D=6 become near the single pier. Hosseinzadeh Dalir et al. [14] stated that the number and spacing of the vanes and their changing angles are effective on the scour depth; they found that increasing the vane numbers to six showed a better performance in the scour depth control, as well as a change in angle improves their performance (51 percent). The effect of sill distance from the piers was examined by Grimaldi et al. [15]. They stated that a short distance between the sill and pier declines the depth, surface area, and volume of the scour. On the other words, In other words, reducing the distance between the sill and the pier has a positive effect on the decreasing trend of the scour depth. Ghorbani and Kells [16] performed an experimental study to investigate the effects of the vane angles and arrangements on scour depth. Their results revealed that the submerged vanes decline scour depth significantly round nose rectangular bridge pier. They explained that increasing the angle reduces the impact of the vanes. The maximum reduction of scour depth for the pier with 2.5 cm height and for the angles of 0, 5 and 10 degrees of submerged vanes was 45.57, 39.76, and 27.78 percent, respectively. Chiew and Lim [17] stated that the protective sills are effective as a method to avoid the bridge pier scouring; they performed their tests under clear-water and live bed conditions. Their results showed that the maximum efficiency of the sill in scour depth reduction under clear-water conditions is about 50 percent. Johnson et al. [18] studied experimentally the effect of the submerged vanes to protect side piers of bridges from scouring; they observed that the submerged vanes reduce the flow velocity and the shear stress of the bank and increase the flow velocity in the centerline of the channel. River-bend bank protection was studied by Odgard and Kennedy [19] using submerged vanes. They applied the Kutta-Joukowski theorem to calculate a simple torque to consider the effect of the vanes on the secondary flow. They derived a design relation to obtain the vane spacing. The relation was verified in an idealized, physical model of a bend of the Sacramento River, California.

In this research work, the simultaneous effects of the vanes, the eppi, and the sill on the scour depth variations for the bridge pier group have been investigated experimentally. The height, spacing, and location of mentioned structures have been assessed for scour depth tracking.

2. Materials and methods

2.1. Experimental Setup

A zero-slope rectangular flume of length 13 m, width 1.2 m and height 0.8 m was implemented to perform 29 tests of bridge pier scour. A bathometer of accuracy ±0.1 mm was utilized to measure scour depth. Flow discharge varies from 7 to 52 lit.s^{-1}. Figure 1 shows a schematic view of the laboratory equipment. Bed profile was surveyed at every four states using a three-dimensional scanner after finishing tests, drainage, and drying of bed materials. Figure 2 illustrates installed structures during experiments.

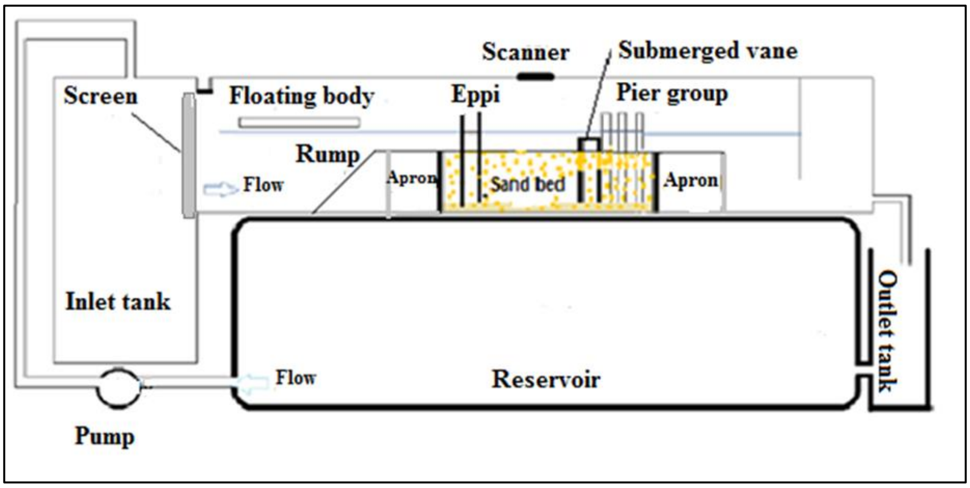

Figure 1. Schematic view of experimental set up

Figure 2. A view of installed pier and submerged vanes

To decline flow turbulence, a reservoir along with two screens were used at the beginning of the flume. While water surface oscillation was controlled and reduced using a floating body (Styrofoam) with a ramp above an apron, downstream flow depth was managed using a gate. The erodible sandy bed was created between two aprons of length 4.25 m and height 22 cm. Three cylindrical piers of diameter 9 cm were located at the flume centreline with a distance of 85 cm from the downstream erodible bed and centre-to-centre of 21 cm. The length, height, and thickness of each eppie were 20 cm, 25 cm, and 1cm, respectively. The eppies were installed at a distance of 60 cm from the upstream erodible bed with centre-to-centre of 50 cm. Three submerged vanes of heights 0, 4, and 6 cm with a distance of 12 cm were set up during the test. A distance of 2 cm was set between the first vane and first pier. The angle of each submerged vane than to flow direction was 160 degrees. Figure 3 displays an overview of the structures installed in the flume.

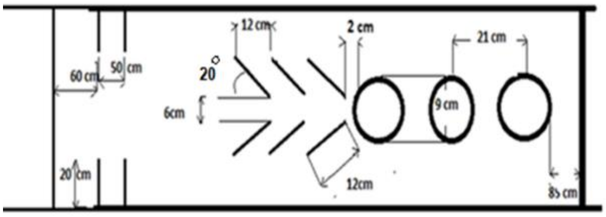

Figure 3. A schematic view of installed structures

The values of pier diameter were less than 10% of the flume width to eliminate the effect of the flume wall on the local scouring (Chiew and Melville [17]). The gradation of the sediment particles has been presented in Figure 4. Sediment particles were selected of size greater than 0.7 mm to avoid ripple formation. The values of D_{50}, C_u and δ_g of particles were 1.8 mm, 1.68 and 1.23, respectively.

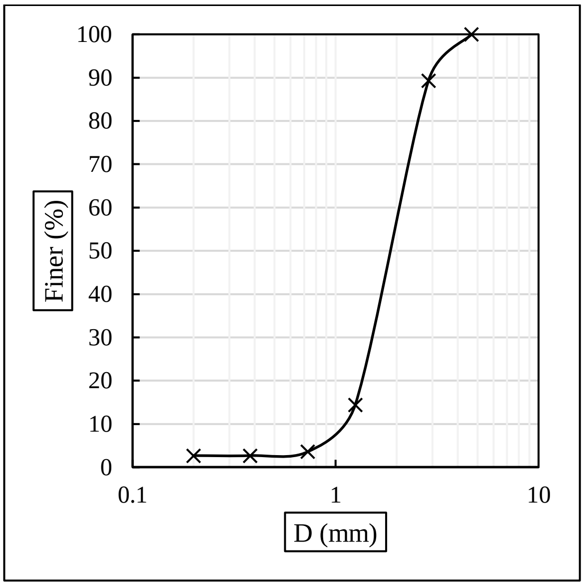

Figure 4. Gradation curve of bed sediment particles

Critical tension and Shields parameter were τ_{cr}=0.038 N.m^{-2} and τ_*=0.1329. The critical velocity V_c was determined from Equation 1 (Melville and Sutherland [17]):

$$V_c=5.75V_{*c}\log 5.53\frac{y}{D_{50}} \quad (1)$$

Where V_{*c} is the critical shear velocity which can be calculated using the following relationship (Melville [20]):

$$V_{*c} = 0.0115 + 0.125D_{50}^{0.25} \quad \text{For } 0.1 \text{ mm} < D_{50} < 1 \text{ mm} \quad (2)$$
$$V_{*c} = 0.0305D_{50}^{0.5} - 0.0065D_{50}^{-1} \quad \text{For } 1 \text{ mm} < D_{50} < 100 \text{ mm} \quad (3)$$

Where V_{*c} and D_{50} are in m.s^{-1} and mm, respectively. Four scenarios were implemented for the present research work: (a) the reference sample (only three piers) (b) the three piers and the eppies (c) the three piers, the eppies and the submerged vanes (d) the three piers, the eppies, and the sill. Table 1 illustrates the summary of experiments statistics.

Table 1. Experimental dataset domain

Experiment	**Models***	**Q**	**Fr**	**y**	**V**	**V_c**	**$\frac{V}{V_c}$**
		Lit.s^{-1}	**-**	**m**	**m.s^{-1}**	**m.s^{-1}**	**-**
1	RS	15	0.15	0.089	0.14	0.25	0.56
2	RS	25	0.2	0.103	0.2	0.25	0.8
3	RS	30	0.15	0.141	0.18	0.26	0.67
4	RS	45	0.25	0.131	0.29	0.26	1.09
5	RS	45	0.6	0.073	0.51	0.24	2.11
6	ERS	15	0.15	0.089	0.21	0.33	0.64
7	ERS	25	0.2	0.103	0.3	0.34	0.89
8	ERS	30	0.15	0.141	0.27	0.35	0.76
9	ERS	45	0.25	0.131	0.43	0.35	1.23
10	ERS	45	0.6	0.073	0.77	0.32	2.41
11	$ERSV_0$	15	0.15	0.089	0.21	0.33	0.64
12	$ERSV_0$	25	0.2	0.103	0.3	0.34	0.89
13	$ERSV_0$	30	0.15	0.141	0.27	0.35	0.76
14	$ERSV_0$	45	0.25	0.131	0.43	0.35	1.23
15	$ERSV_0$	45	0.6	0.073	0.77	0.32	2.41
16	$ERSV_4$	15	0.15	0.089	0.21	0.33	0.64
17	$ERSV_4$	25	0.2	0.103	0.3	0.32	0.89
18	$ERSV_4$	30	0.15	0.141	0.27	0.35	0.76
19	$ERSV_4$	45	0.25	0.131	0.43	0.35	1.23
20	$ERSV_4$	45	0.6	0.073	0.77	0.32	2.41
21	$ERSV_6$	15	0.15	0.089	0.21	0.33	0.64
22	$ERSV_6$	25	0.2	0.103	0.3	0.34	0.89
23	$ERSV_6$	30	0.15	0.141	0.27	0.35	0.76
24	$ERSV_6$	45	0.25	0.131	0.43	0.35	1.23
25	$ERSV_6$	45	0.6	0.073	0.77	0.32	2.41
26	$ERSS_1$	15	0.15	0.095	0.2	0.317	0.6
27	$ERSS_1$	45	0.25	0.143	0.13	0.33	0.4
28	$ERSS_2$	15	0.15	0.095	0.2	0.317	0.6
29	$ERSS_2$	45	0.25	0.143	0.13	0.35	0.4

* E: Eppy y: Flow depth Fr: Froude number RS: Reference sample V_o: Vane of height 0 V_4: Vane of height 4 V_o: Vane of height 6 S_1: Sill of height 9 S_2: Sill of height 4.5

The end gate was used to control Fr and y during experiments. Scour depth was measured every 15 minutes at the beginning of scour hole formation and then every half hour. Equilibrium values of d_s were happened when its variation was less than 1 mm. To achieve more precise results, each test was performed twice. Figure 5 illustrates the d_s developing for RS model with Fr=0.15 for instance.

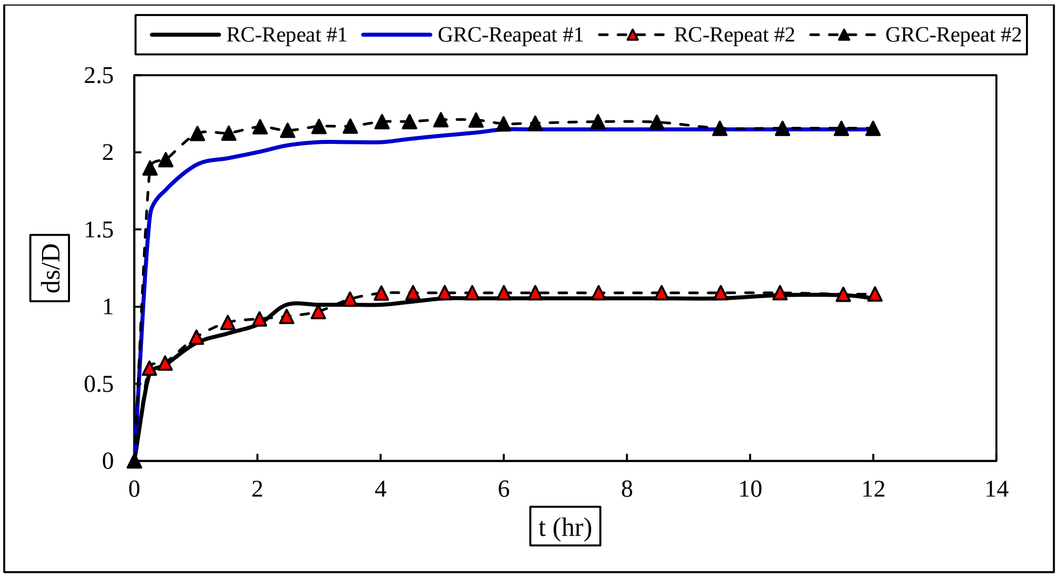

Figure 5. The temporal development of the scouring phenomena for Fr=0.15

3. Results and discussion

3.1. The maximum value of ds

3.1.1. The effect of the submerged vanes and the eppi on the ds

Table 2 shows the submerged eppi performance about d_s for various flow conditions. A graphical representation has been presented in Figure 6. Similar behavior is visible for d_s trend for piers so that a sharp rise from Fr=0.15 to Fr=0.2 and a sudden fall from Fr=0.2 to Fr=0.6 occurs. The guard acting of the first pier declines the values of d_s for the third pier. Out of the three graphs, the second one experiences severe variations. On the other hand, Flow contraction and raising the negative gradient amplify the horseshoe and wake vortexes. The balance of the erosion and sedimentation rate simultaneously with the increase of Fr leads to a decrease in the percentage of scour depth changes.

Table 2. Variation of d_s under the eppi installation effect (in percent)

Pier	Fr			
	0.15	0.2	0.25	0.6
1	4.3	45.5	51.2	16.5
2	5.5	89.1	48.8	2.1
3	4.5	18.2	28.3	2.3

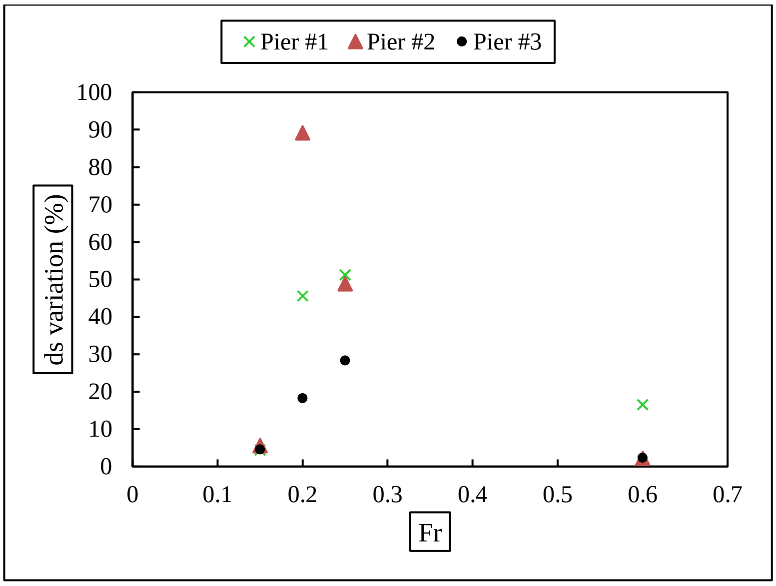

Figure 6. Variation of d_s vs Fr for ERS model

Three submerged vanes of heights 0, 4, and 6 cm were set on the flume to reduce or eliminate the additive effect of the eppi on the d_s. .

Table 3 shows the variation of d_s. A graphical representation of d_s for ERSV model has been presented in Figure 7.

Table 3. Variation of d_s for ERSV model (in percent)

Pier number	Vane type	Fr			
		0.15	0.20	0.25	0.60
	V0	47.8	20.9	34.6	51.5
#1	V4	50	58	49.2	55.5
	V6	34.7	57.2	41.4	26.2
	V0	5	4.7	19.3	32.2
#2	V4	50	73.9	47	67.8
	V6	47.5	64.1	27.7	60.1
	V0	4.3	12.3	10.4	14.8
#3	V4	21.4	18.8	25.5	32.4
	V6	12.8	14.1	15.9	17.2

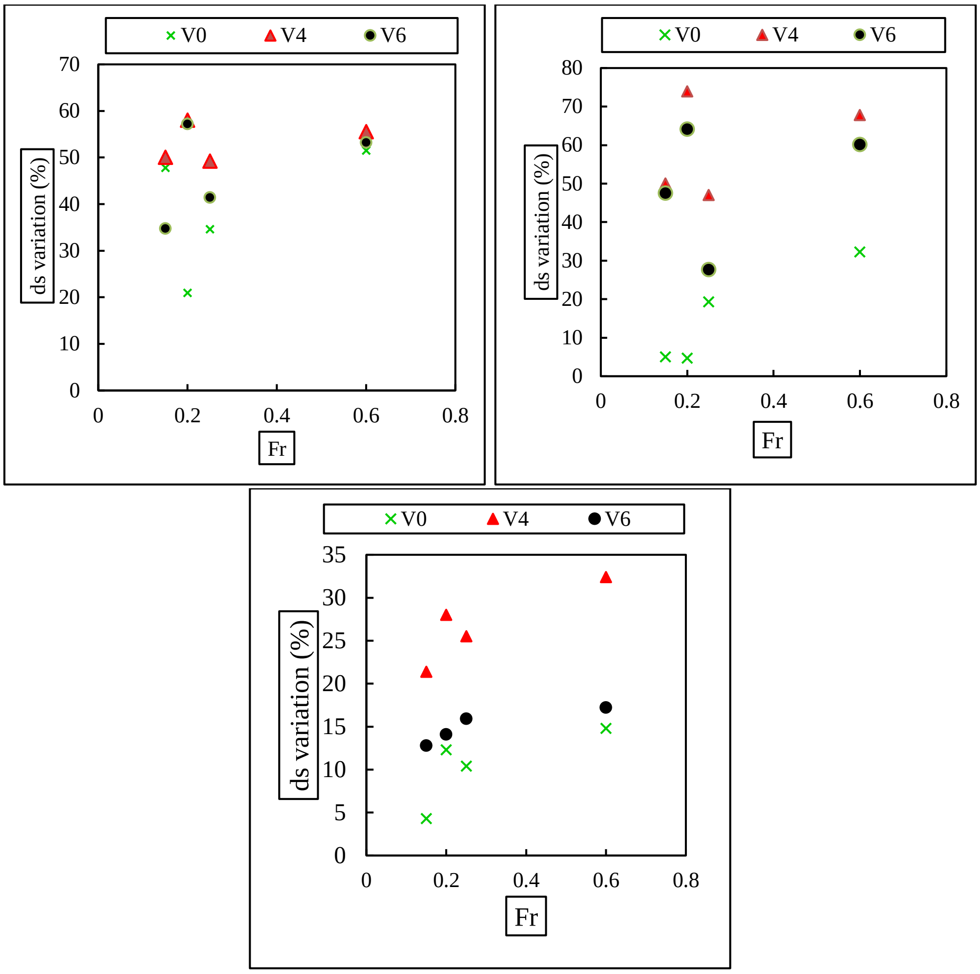

Figure 7. Variation of d_s for the three piers vs Fr for ERSV model

A declining trend of d_s for three piers was observed. The highest and lowest performance rates belong to V0 and V4, respectively. In the other words, V4 has the best performance than the others. The second pier experiences the maximum reduction of d_s. According to the above-mentioned results, the eppies installation has increased the scour depth because of flow contraction and leading to amplify the horseshoe vortex and wake vortex. Submerged vanes weakens flow vortex and improve eppies' performance.

3.1.2. The effect of the sill installation on d_s

ERSV4 model was set up in the flume to track the sill performance. Table 4 display the d_s variations for the first pier with a graphical representation in Figure 8. The presence of the sill involves a distinctive effect on d_s reduction (shown in ERSV4S2 model). The sill creates a stilling basin downstream of the piers which decline significantly sediment transportation, but the low height of the sill provides smooth movement of sediment particles that reduce scour depth.

Table 4. The d_s variation due to the sill installation in ERSV4 model for the first pier (in percent)

Submerged vanes and Sill	Froude number			
	0.15	0.2	0.25	0.6
V4	50	58	49.2	55.5
S2	71.7	77.8	88	92.1
S1	52.6	60.5	65.8	73.2

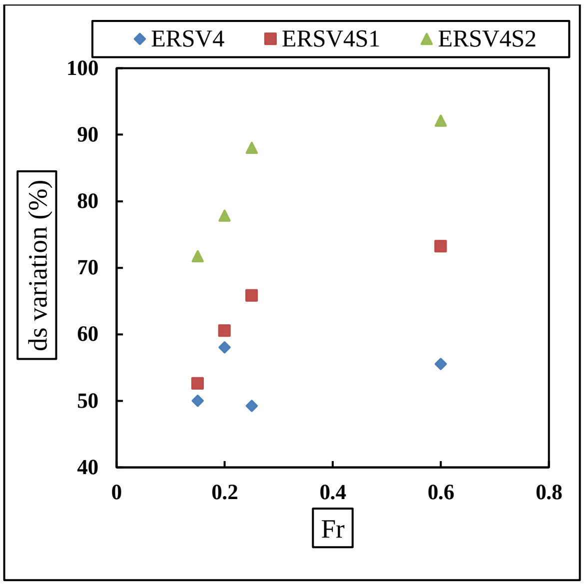

Figure 8. The effect of sill installation on the ERSV4 model's scour behaviour

3.2. Temporal variation of the scour around the bridge piers group

In this section, temporal variation of d_s along with control structures (vane, the sill and eppi) has been considered for two values of Fr i.e. 0.15 and 0.25.

3.2.1. The effect of the eppi and submerged vanes

Figure 9 displays variations of $(\frac{d_s}{D})$ vs. $(\frac{t}{t_e})$ for the first pier (D: the bridge pier diameter, t_e: elapsed time for steady state scouring). An increasing trend in d_s is observed due to flow convergence caused by the eppi installation. The vane of height 4 cm (i.e. V4) shows the most effective performance. A rocket increase of d_s is visible up to $\frac{t}{t_e}$=0.1. An oscillating state is observed for $\frac{t}{t_e}$ from 0.1 to 0.6. Then, the equilibrium situation is reached through a moderate slope up to $\frac{t}{t_e} = 1.0$. Figure 10 shows the temporal variation of the d_s for the first pier for Q=45 (lit/s) and Fr=0.25. Despite the significant increase in $\frac{d_s}{D}$, the same effects of V4 are observed for decreasing equilibrium scour depth for the bridge pier. A sharp increase in scour depth developing is occurred up to $\frac{t}{t_e} = 0.1$ with a fluctuation from 0.1 to 0.6.

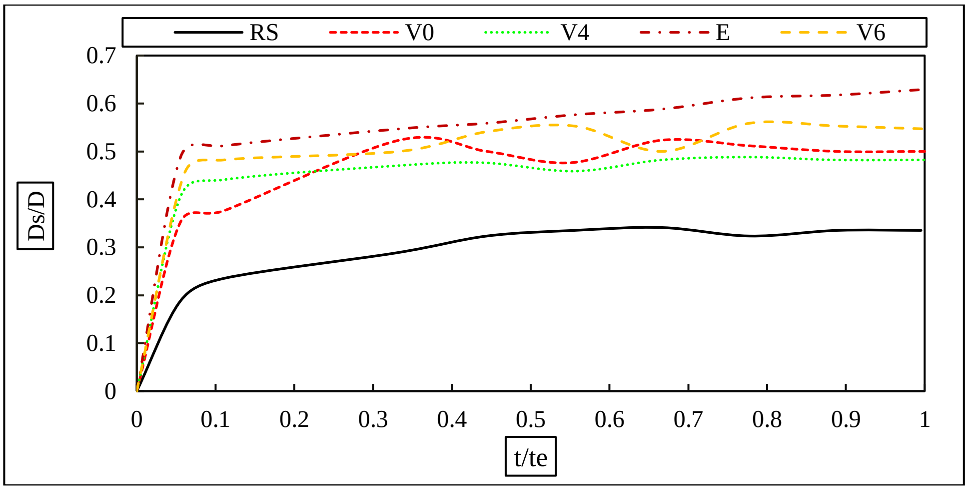

Figure 9. Temporal development of scour depth for the first pier (Q= 30 lit/s; Fr=0.15)

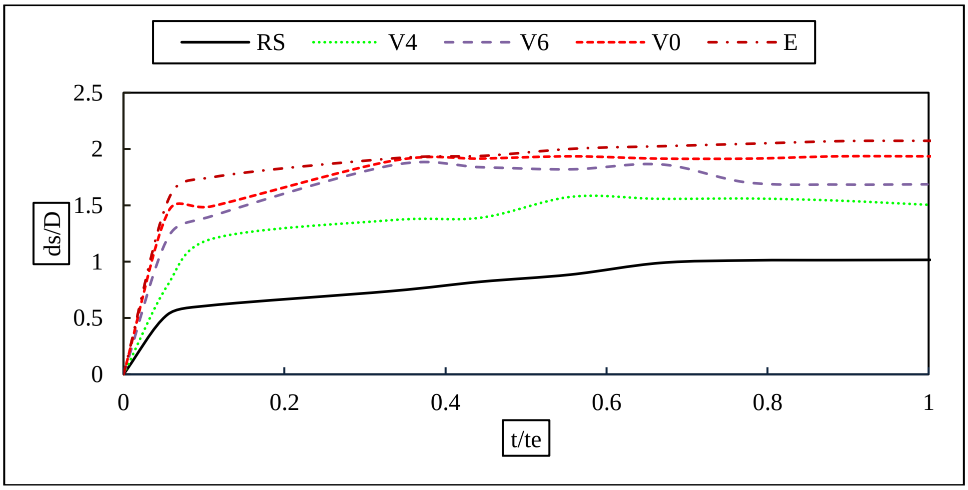

Figure 10. Temporal development of scour depth for the first pier (Q= 45 lit/s; Fr=0.25)

Temporal variation of the local scour depth for the second pier for (Q=30 (lit/s); Fr=0.15) and (Q=45 (lit/s), Fr=0.45) have been shown in Figure 11 and Figure 12, respectively. The increasing effect of the eppi installation and the decreasing effect of the V4 in the d_s are clearly evident in the figures. The fisrt pier has the lowest difference level between the RS and E in the sense the submerged vanes installation has relative less effect on the d_s due to the supportive effect of the first pier to the second one. About the third pier, the temporal development of scour depth for Fr=0.15 and Fr=0.25 have been shown in Figure 13 and Figure 14, respectively. Duplicate trend of the moest effect of the V4 is apparent. It is observed an additive/subtractive fluctuation effect on the d_s due to the balance between erosion and sedimentation.

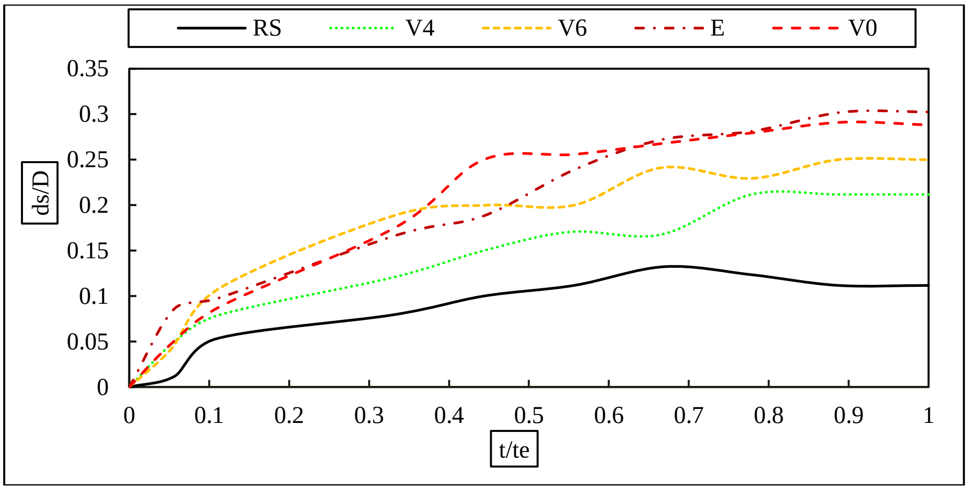

Figure 11. Temporal development of scour depth for the first pier (Q= 30 lit/s; Fr=0.15)

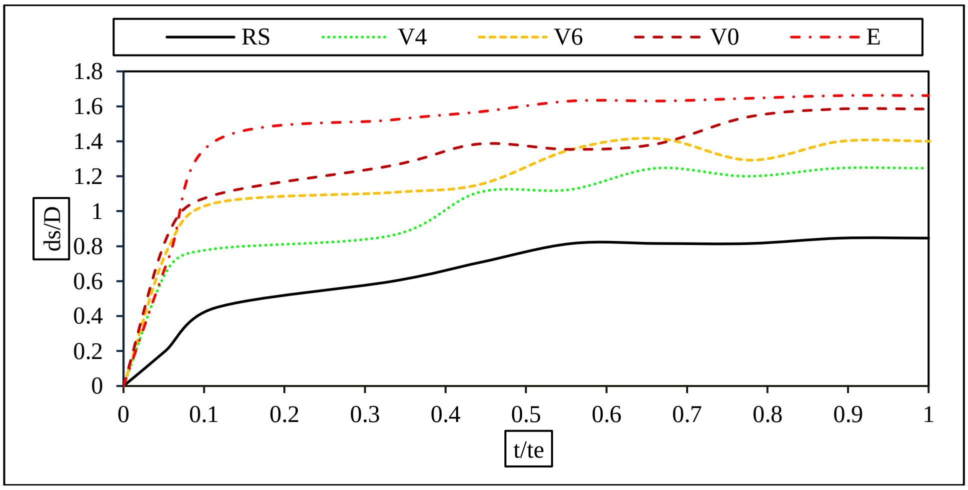

Figure 12. Temporal development of scour depth for the second pier (Q= 45 lit/s; Fr=0.25)

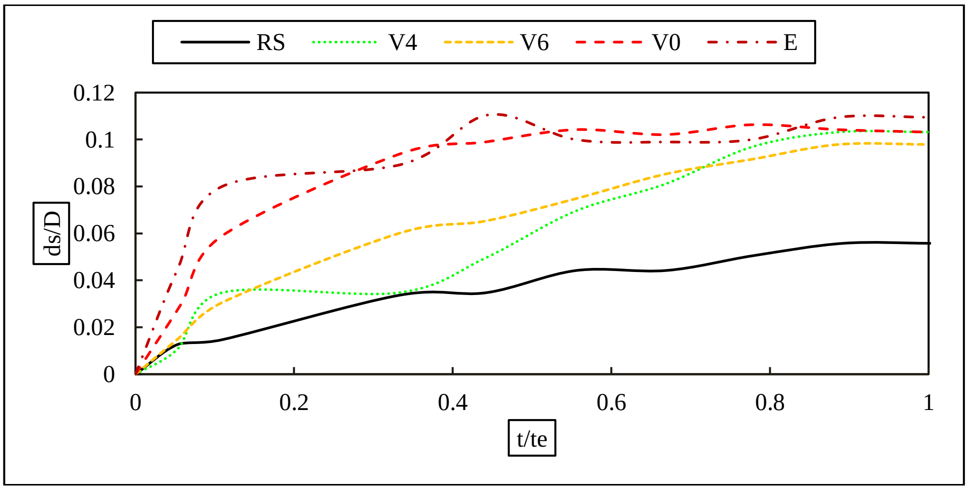

Figure 13. Temporal development of scour depth for the third pier (Q= 30 lit/s; Fr=0.15)

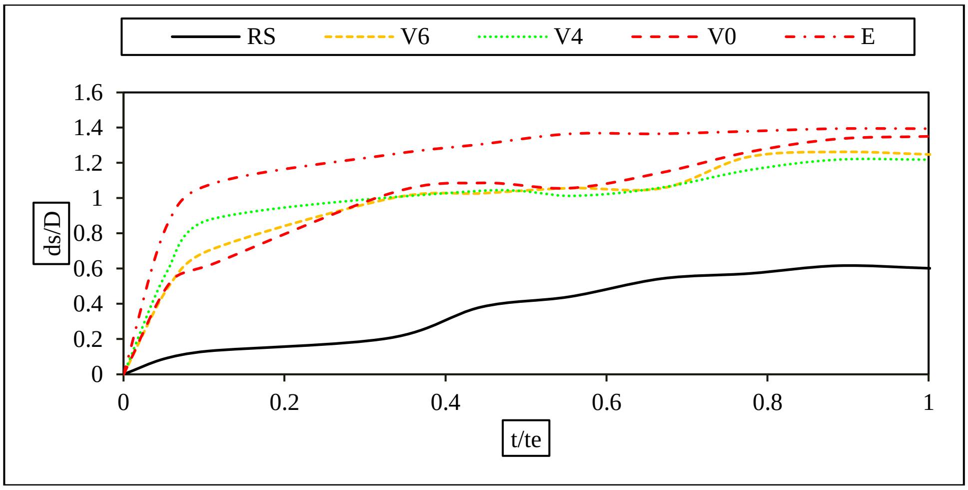

Figure 14. Temporal development of scour depth for the third pier (Q= 45 lit/s; Fr=0.25)

3.2.2. The effect of the sill and the eppi

In this section, the effect of the eppi and the sill installation of heights 4.5 and 9 cm have been considered for Fr=0.15 and Fr=0.25 along with V4. Temporal developments of ds under sill installation situation for two values of Fr are presented in Figure 15 and Figure 16.

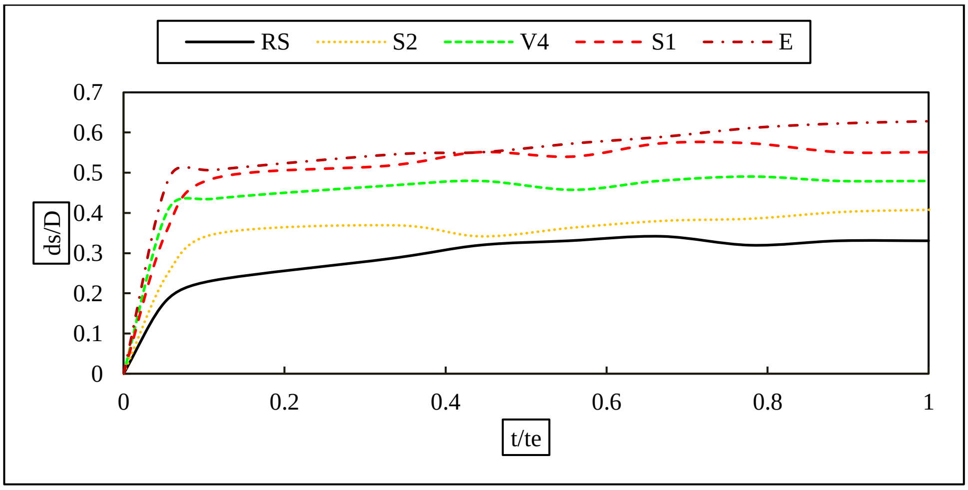

Figure 15. Temporal development for ERSV4S model for the first pier (Q= 30 lit/s; Fr=0.15)

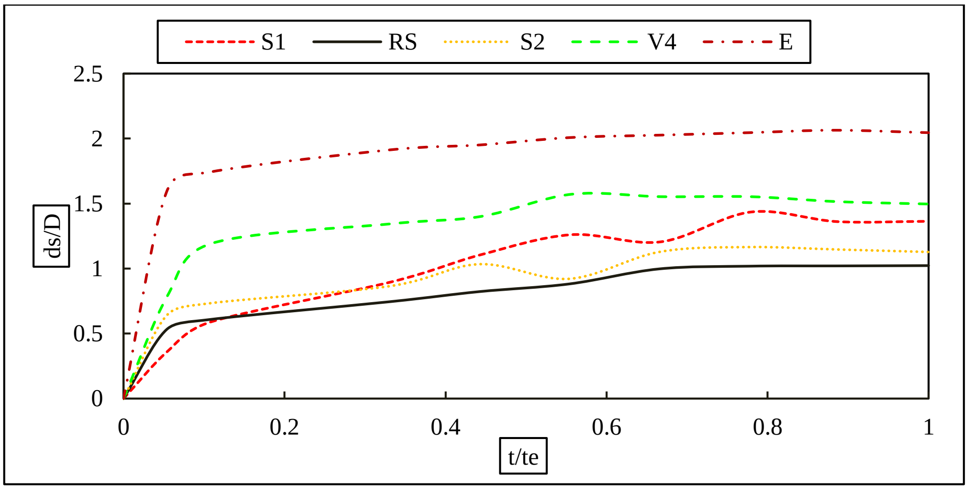

Figure 16. Temporal development for ERSV4S model for the first pier (Q= 45 lit/s; Fr=0.25)

The superior performance of S2 is visible in terms of scour depth declination. The temporal developing curves of Fr=0.15 is located upper than Fr=0.25; it indicates that the effect of the vanes and the sill are more in Fr=0.25; the sill of height 4.5 cm is more effective than the submerged vane of height 4 cm for Fr=0.25.

4. Conclusion

Due to the irreplaceable role of bridges in road communication issues, the issue of their structural stability is very important and crucial. As a destructive phenomenon, scour hole endanger the safety of the bridge that is why various methods and structures are used to prevent the creation and development of scour hole. In the present paper, the performance of the submerged vanes, the eppi, and the sill were investigated experimentally to control scour depth around the bridge pier group. Results showed that

- Submerged eppi leads to an increase in the scour depth for $Fr \leq 0.2$. Flow contraction enhances flow turbulence and sediment particles movement. By increasing the Froude number from 0.2, a significant decrease in the gill depth value was observed. Increase in the sediment transfer power from upstream and their deposition at the bridge pier is the main cause of this phenomena.
- Among the three vanes installed in the flume bed, the vane of height 4 cm was able to significantly reduce the increasing effect of eppi on scour depth.
- The sill was installed at the downstream of the piers. It created a stilling basin and the the sill of height 4.5 cm had a better performance. On the other words, using ERSV4S2 model indicated the best performance for the scour control around the bridge piers.

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