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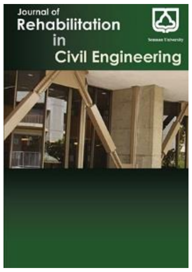

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Experimental Comparison of Sacrificial Piles and Submerged Vanes as Scour Countermeasures around Bridge Pier

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ABSTRACT

An experimental study has been conducted on the effectiveness of two types of flow-altering countermeasures placed around a cylindrical pier under clear water condition, which consists of sacrificial piles and submerged vanes. Their arrangements follow the optimal configurations recommended in the published articles with some modification. The temporal evolution of maximum scour depth and its equilibrium amount around the pile without and with two scour countermeasures were recorded; scour depth reduction rates and changes in bed topography were then computed. It can be concluded that pursuant to the result which has been earned from the experiments of this study, submerged vanes had better performances compare with the sacrificial piles in all of investigated aspects. By applying submerged vanes 75% of the scour only occurred in first 5 minute. Presence of submerged vanes played more efficient role in reducing scour depth as subjected scour depth reduction was 17% more than one subjected to sacrificial piles. The length of changes downstream the pier (L) were 12, 13.2 and 6 times of pier diameter (D) corresponding to pier with no protection, sacrificial piles and submerged vanes respectively, which revealed the effectiveness of submerged vanes in reducing the area affected by pier scour. Also the maximum changes of bed level were -6.9 cm to 3.9 cm in unprotected pier test, -4.4 to 3.5 cm in protection by sacrificial piles test and -3 to 3.2 cm in protection by submerged vanes.

1. Introduction

Scour is local lowering of streambed elevation that occurs around structures that are constructed in flowing water. The local scour has the potential to weaken the foundation of bridge piers. Excessive scour

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would undermined the structural integrity of the bridge. Bridge scour has been extensively investigated for more than 100 years. The knowledge necessary for predicting scour depths and the development of countermeasures that protect against scour related problems have progressed rapidly over the past 50 years (Park et al., 2016).

With the purpose of protecting piles against scour and guarantee their safety, different measures have been suggested. The countermeasures against pier scour are collected into flow-altering and bed-armoring countermeasures (Chiew (1995), Melville and Coleman (2000), Tafarojnoruz et al. (2010), Tafarojnoruz et al. (2012) and Liang et al. (2015)). The former causes the reduction in the power of the down flow and the horseshoe vortexes which are the main reasons of pier scour like sacrificial piles arranged in a triangular pattern upstream of piers (Chabert and Engeldinger, (1956), Melville and Hadfield (1999)), a collar placed around the pier (Zarrati et al. (2004), Jahangirzadeh et al. (2014)), combined system of slot and bed sill (Grimaldi et al. (2009)), submerged vanes (Lauchlan (1999), Ouyang and Lin (2016)), rectangular slots through piers (Kumar et al. (1999)). Instead, bed-armoring countermeasures make physical barriers (like riprap, gabions, cable-tied blocks, etc.) against possible pier scour (Liang et al. (2015) and Tafarojnoruz et al. (2012)).

In this paper, an experimental study has been conducted to inspect two types of flow-altering countermeasures which consists of sacrificial piles and submerged vanes under clear water condition. Submerged vanes were applied basically for the fixing of rivers and channels. Gradually they have been used to control the local scour beside bridge abutments and bridge piers (Johnson et al. (2001) and Espa and Magini (2000)). Their efficiencies in reducing scour are completely related to their shape, dimensions, and geometric arrangement.

Tan et al. (2005) according an experimental study revealed if the height of the vane are more than two to three times of the bed form height, it can reduce scouring significantly. Otherwise for lower height of the vanes, the efficiency will decrease significantly. Ouyang (2009) inspected the consequences of dimension and shape modification in controlling the sediment by applying a rectangular plate, a trapezoidal tapered plate, and a plate in the shape of a parallelogram with its top swept forward or backward to the approaching flow. Samimi Behbahan (2011) presented better performane of angled and curved vanes in stabilizing river banks compare to flat ones. However, Azizi et al. (2012) indicated the effect of flat plate vanes to decrease local scour around the structures. Shojaee et al. (2012) examined the application of submerged vanes as a pier scour protection device in clear-water condition. Two different vane aspect ratios (length to height of 2 and 3) and one placed at streambed level and dissimilar arrays of vanes with dissimilar angles to main flow direction were employed. Results revealed that reduction of scour with different arrays of six vanes was 0.4% to 51%. The greatest reduction occurred in application of six vanes in the layout of each row of vanes with different angles. Ouyang and Lin (2016) inspected the effects of submerged vane shapes on the created transverse bed profiles and also the interaction of vanes by using a numerical model. Khaple et al. (2017) investigated the effects of a full-depth vane length and thickness, sediment median sizes and pier diameters on the scour depth around a circular pier. They proved that the equilibrium scour depth declined by increasing in vane length, irrespective of sediment sizes and pier diameters, but it remained constant by changing the vane thickness.

Some researchers investigated effectiveness of sacrificial piles to reduce scour. Hadfield (1997) revealed that the pile triangular arrangement with five sacrificial piles of diameter 0.167D had the best application. In a similar study, Melville and Hadfield (1999) noticed sacrificial piles with a triangular arrangement of five piles can be effective in controlling scour. They manifested that the amount of scour reduction is dependent on the velocity flow angle and flow intensity. Chiew and Lim (2003) indicated that the sacrificial piles with the height being 30% of the water depth can be so effective to reduce scour depth. Haque et al. (2007) persuaded that three side-by-side piles positioned upstream of a rectangular pier can reduce up to half of the scour depth.

In many experimental studies related to protecting pier against scour, only one countermeasure has been investigated. It is a common practice to alter configuration and/or numbers of that special protection to ameliorate the efficiency of scour protection. It is accomplished by examining more realistic constraints consistent with the phenomenon. Few experimental works comparing the efficiency of two countermeasure schemes have been reported.

Despite the efforts of previous researchers, only a single study (Tafarojnoruz et al. (2012)) is reported to been comparing the effect of sacrificial piles and submerged vanes in laboratory condition which has been focused in present study. Tafarojnoruz et al. (2012) examined six types of flow-altering countermeasures against local scour at bridge piers, including submerged vanes and sacrificial piles, among others. Regarding sacrificial piles, Haque et al. (2007) proposed a pattern of three piles with a 60% blockage ratio, placed in front of the piles. Furthermore, in another test the number of piles increased to 5, to acquire a blockage ratio of 100%. The obtained efficiency was 32.2 and as low as 5.5% respectively. In assessing submerged vanes, they compared the effect of applying one at a short distance in front of a pier and two attached ones with the same characteristics recommended by Ghorbani and Kells (2008). Efficiencies were obtained as low as 11% and 12.4%, respectively.

In present study, the arrangement of sacrificial piles was extracted from the optimum configuration of triangular arrangement of sacrificial piles reported by Liang et al. (2015). It is further improved to gain more efficiency. Based on the results reported by Shojaee et al. (2012), six submerged vanes have been adopted and optimum parameters have been chosen to properly control the scour depth. The parameters were further optimized to meet the requirement of cylindrical pile examined herein. The obtained efficiency of sacrificial piles and submerged vanes were 36% and 53% respectively. The suggested patterns were reported to improve the efficiency of scour protection by changing the number and the configuration of vanes and sacrificial piles.

2. Material and Methods

Flow pattern of scouring around a bridge pier is affected by the vortex system and the caused down-flow. At the upstream face of the pier, the pressure increases because of reducing its flow velocity. On the other hand as the flow velocity declines from the surface to the bed, the dynamic pressure on the pier face decreases downwards as well. This flow makes a hole in front of the pier (Beg and Beg, 2013) (Figure 1).

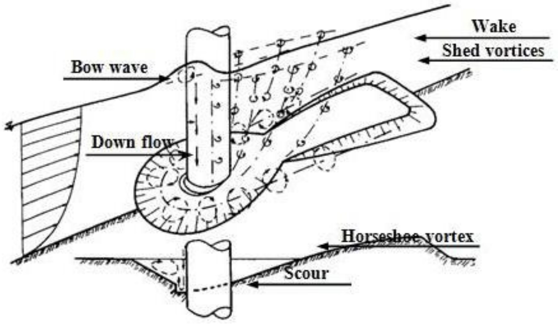


Fig. 1. Diagrammatic flow pattern at a cylindrical pier (Raudkivi, 1990)

2.1. Experimental Procedures

2.1.1. Experimental Setup

A series of laboratory experiments were performed in a rectangular re-circulating flume with 11 m long, 50 cm wide and 60 cm deep with a constant longitudinal slope of 0.0001. The channel walls were made of Plexiglas. This study is accomplished in the hydraulics laboratory of engineering college, Arak University (Figure 2). The existing bed level is elevated by 20 cm on upstream and downstream, which is prepared a 2.5 meter length erodible bed at distance of 3.5 m downstream of the flume beginning and is filled with sediment. The flow rate was measured by an ultrasonic flow meter. The water surface was controlled by a sluice gate at the downstream extremity of the flume and was measured applying point gauge which is sensitive to the variations of 0.1 mm.

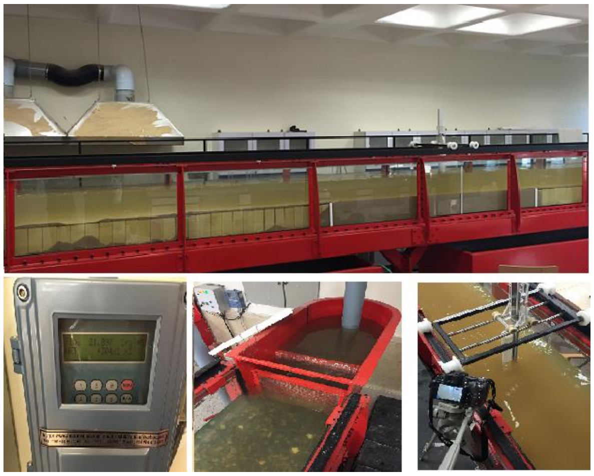


Fig. 2. The flume of hydraulics laboratory located on the Arak University; Below: (left) ultrasonic flow meter, (middle) stilling basin, (right) point gauge

For experimental evaluation, some criteria should be applied, which are listed below. Based on Chiew and Melville (1987) recommendations, to avoid wall effects on the rate of scour, the maximum diameter of the pier (D) should be set to 10% of the width of the flume (W). Also Rauhdkivi and Ettema (1983) suggested the maximum value of this ratio equal to 0.16 so the diameter set to 5 cm in this research which satisfied both of suggestions. The median diameter of sediment particles (d_{50}) should be such to create the maximum scour depth. Melville (1997), Raudkivi and Ettema (1983) and also Lee and Sturm (2009) suggested $D/d_{50} > 25$ condition for this issue. Moreover, in order to avoid ripple formation, the sediment size should not be less than 0.7 mm (Breusers and Raudkivi 1991). Briefly, to contemplate sediment as uniform, the geometric standard deviation of the particle size distribution (σ) must be less than 1.5. Considering all these criteria, noncohesive uniform sediment with d_{50} equal to 1 mm and specific density equal to 2.65 was applied as the bed material. Melville and Chiew (1999) have resulted the maximum scour depth cannot be more than

2.4 D so that the sediment height is needed to be more than this amount. In this study, the flume filled with sediment height of 22.6 cm in the working section and 2.6 cm outside the control block (on the false bed). Also stones with different sizes were used at entrance to damp carefully disturbances.

2.1.2. Hydraulic Characteristics

The water depth in the flume should be sufficient to not occur any modifications to the scour depth. Chiew (1995) has suggested $\frac{y}{D} > 3$ to satisfy this criterion. Furthermore, Hager and Oliveto (2002) recommended water depths greater than 20 mm to avoid any effect of roughness. In this study, in all experiments, the water depth of 20 cm were contemplated .

To perform the experiments under clear-water conditions it was necessary that flow intensity of V/V_c be less than 1 where V is the average velocity of the flow and V_c is the critical flow velocity for sediment movement. Mellvile and Chiew (1999) suggested $0.3\ V_c<V<V_c$ to have this condition. The critical velocity (V_c) can be computed based on the expressions given by Melville (1997) from the logarithmic form of the velocity profile:

$$\frac{V_C}{U_{*C}} = 5.75 \log\left(5.53\frac{y}{d_{50}}\right) \qquad (1)$$

Here U_{*C} is critical shear velocity of the bed materials based on d_{50} .The shear velocities are determined applying the Shields diagram for the respective sizes. A beneficial approximation to the Shields diagram for quartz sediments in water at 20ºC is:

$$U_{*C} = 0.0115 + 0.0125{d_{50}}^{1.4}$$

$$0.1\text{ mm} < d_{50} < 1\text{mm} \qquad (2)$$

$$U_{*C} = 0.0305{d_{50}}^{0.5} - 0.0065{d_{50}}^{-1}$$

$$1\text{ mm} < d_{50} < 100\text{ mm} \qquad (3)$$

Where U_{*C} is in m/s and d_{50} is in mm.

Such as flow level, the same velocity were used for each test of this study. By having the discharge of 22 lit/s, the depth of flow and flow velocity were controlled by 20 cm and 0.22 m/s respectively. These characteristics as well as other essential ones have been summarized in table 1.

Table 1. Experimental Conditions and Dimensionless Groups used in the present study

D (cm)	d_{50} (mm)	y (cm)	V (m/s)	V_c (cm/s)	V/V_c	D/d50	$Fr=\frac{V}{\sqrt{gy}}$	$Re=\frac{VR}{\upsilon}$	y/D
5	1	20	0.22	0.42	0.52	50	0.2	24444	4

2.1.3. Experimental Tests

At first, the pier installed in the flume at the desired location. The sediment of the bed levelled throughout the entire length of the flume and particularly at the vicinity of the pier utilizing levelling gear that had the same width as the flume.In order to start the examination, the flume was filled with water to the required flow depth as a slow pace. Consequently, the pump was started and its speed increased gradually to a point which the desired flow rate is achieved, then the tailgate slowly was opened and was adjusted so as to maintain the desired flow depth in the flume. The scour depth was measured at different time interval by point gauge and also a measuring tape which was placed at the bridge pile.

At the completion of each test, the pump was shut down to allow the flume to slowly drain without disturbing the scour topography. The flume bed was then allowed to dry and the equilibrium scour depth were measured across the affected area in the 1cm × 1cm network by laser distance meter and point gauge. At the end of each test, morphological bed changes around a pier were shown in the form of contour lines and three-dimensional modelling applying the Surfer software.

After the base experiment, two types of countermeasures were performed, respectively. At equilibrium, the difference in scour depth with and without the countermeasure in terms of scour depth reduction, R_d, was computed from:

$$R_d(\%) = \frac{d_{so} - d_{sp}}{d_{so}} 100 \quad (4)$$

Where d_{so} is maximum scour depth with protection, and d_{sp} is maximum scour depth without protection (Tafarojnoruz et al, 2012).

3. Results and Discussions

3.1. Baseline Experiment

As a first experiment, an unprotected pile test was performed. An equilibrium scour time, when the depth does not increase significantly, has chosen according this test. To identify the equilibrium scour time, recommendation of Melville and Chiew (1999) has applied . They contemplated that the equilibrium maximum scour depth is attained when the maximum scour depth don’t change more than 0.05D for a period of 24 hours (Melville and Chiew, 1999). So in this study, the baseline test performed over a period of 24 hours. Figure 3 indicated the scour depth development around the bridge pier versus time for no countermeasure. During this test the scour depth did not change more than 5% of the pier diameter after 8 hours. Therefore, the duration of other experiments was set to 8 hours.

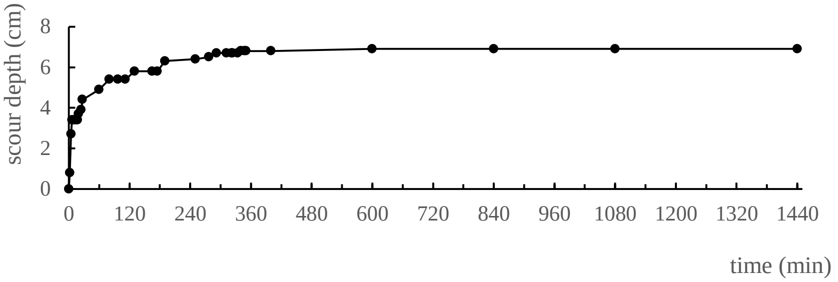
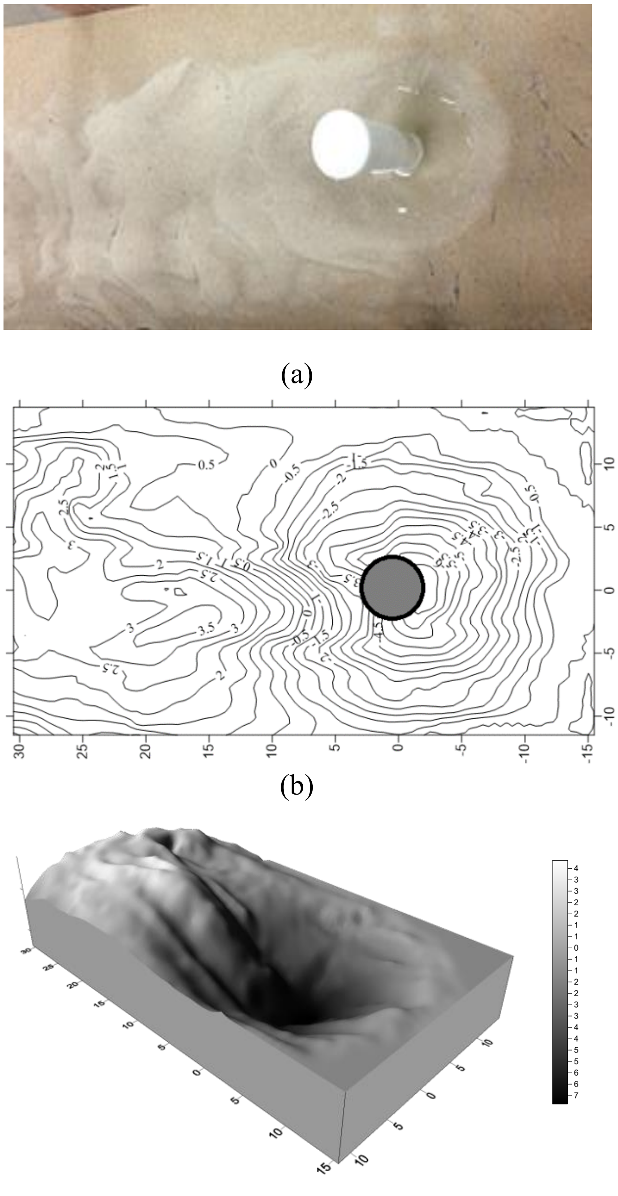


Fig. 3. Temporal evolution of maximum scour depth at the pier without scour countermeasures

Pursuant to figure 3, it can be observed that the change of scour depth was so rapid in the beginning of the test but gradually reduced over time so that 75% scour occurred only in the first 70 minutes. Moreover, only 1 mm scour changes has measured after 8 hours. At the end of the test the morphological bed changes was recorded which has illustrated in figure 4. The maximum scour depth occurred in front of the pier, corresponds to 6.9 cm. The changes of bed level has started 12 cm before pier center ($\frac{L}{D}$= 2.4) and has continued 60 cm after it ($\frac{L}{D} = 12$). Furthermore, the extensive of topographic changes in the cross section of the pier were measured 10 cm on both sides (from pier center).



(a)

(b)

(c)

Fig. 4. Morphological bed changes around a pier without protection: (a) Laboratory pattern, (b) contour lines (c) Three-dimensional modelling (units: cm)

3.2. Sacrificial Piles

The sacrificial piles protect the pier from scour by deflecting the high velocity flow and creating a wake region behind them

The number of piles arranged upstream of the pier reduces the horse-shoe vortex power. This action decreases scour depth meaningfully (Beg and Beg, 2013). The efficiency of applying this device is function of some criteria such as number of sacrificial piles, their arrangement, piles diameter and angle of arrangement. In this study the idea of the arrangement of sacrificial piles extracted from the optimum configuration of triangular arrangement of sacrificial piles reported by Liang et al. (2015) with some differences (figure 5(a)).

Five sacrificial piles applied and arranged trapezoidal upstream of the pier same as figure 5(b) which its laboratory set up has presented in figure 5(c) as well. The piles were always non-submerged and their diameters were 0.167D (according suggestion of Hadfield (1997)), viz. 8 mm. The temporal evolution of maximum scour depth at the pier which has recorded in this test in compare with other tests has portrayed in figure 6. As it can be observed in figure 6, 75% of equilibrium depth has happened only in 40 minutes and increasing the scour hole continued by a very slow paced upward trend. After starting the test, it can be seen that in addition to scour hole vicinity of the pier, other scour holes have occurred just around the sacrificial piles. During the first 8 minutes, the most portion of eroded bed materials around the piles accumulated on two sides of the pier in cross section as bed level increased about 3 cm in this regions but the scour hole exactly in front of the pier started to deepen since the first moment.

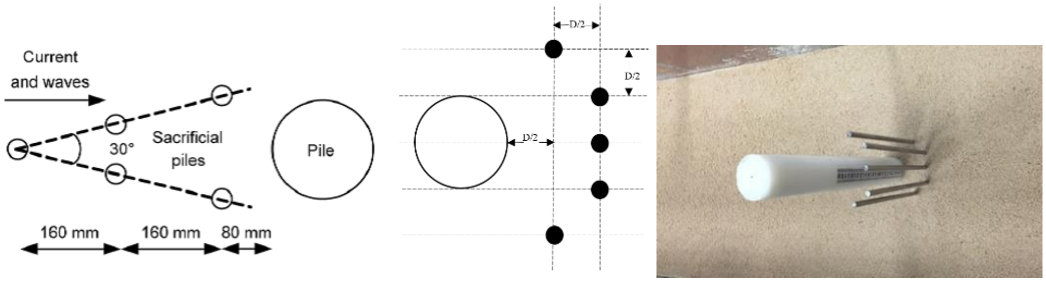


Fig. 5. Sacrificial piles: (a) Liang et al., 2015 (b) Used dimensions in this study, (c) Laboratory set up

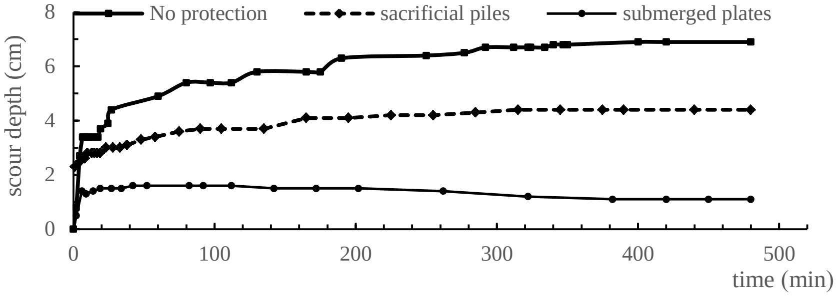
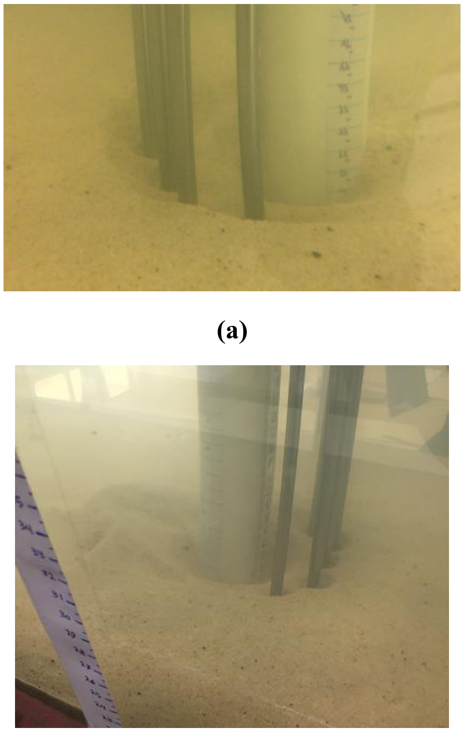


Fig. 6. Comparison of the temporal evolution of maximum scour depth at the pier without and with two scour countermeasures

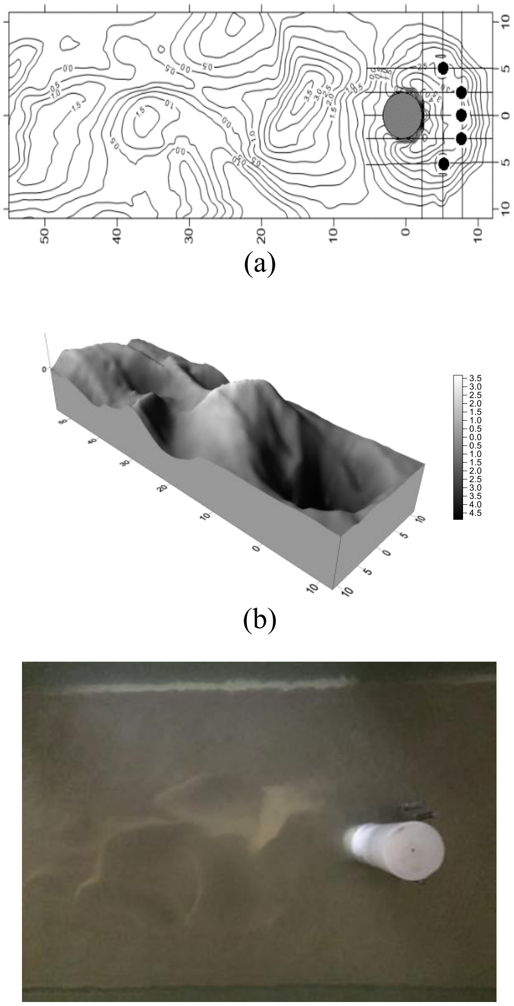
Over time, a portion of scoured sediments around the piles were deposited at the pier location; this accumulation could reduce scour depth around the pier. A portion of eroded material around piles and pier was deposited after the pier. The hole exactly in front of pier started and continued to deepen slowly but the holes in the cross sectional sides of pier started to deepen rapidly and continued with slow rate (Figure 7(a)). By continuing this action the holes around the sacrificial piles were connected each other (Figure 7(b)). At the end of the test, the scour depth was 4.4 cm ($\frac{d_s}{D}$ = 0.88) in front and 3.5 cm at left and right sides vicinity of the bridge pier. Moreover, the maximum scour depth among piles was 3.1 cm in front of middle pile in the first row. So the scour depth reduction rate R_d at the pier was 36.0%($\frac{6.9-4.4}{6.9}$).



(a)

(b)

Figure 7. Pier protected by sacrificial piles: (a) 16 minutes and (b) 110 minutes after starting test



(a)

(b)

(c)

Fig. 8. Morphological bed changes around a pier protected by sacrificial piles: (a) Laboratory pattern, (b) contour lines (c) Three-dimensional modelling (units: cm)

It is similar to result which has been acquired by Liang et al. (2015) at their best configuration with triangular arrangement. The equilibrium bed topography for sacrificial piles protection is given in figure 8. Scour started 13 cm before pier center ($\frac{L}{D} = 2.6$) and continued 66 cm after it ($\frac{L}{D} = 13.2$). Furthermore, it is extensive on either side of the bridge pier in cross section were measured 11 cm ($\frac{L}{D} = 2.2$), scour hole width was 22 cm. The highest accumulated sediment was measured 15 cm after the pier (from pier center), viz. 3.5 cm.

3.3. Submerged Vanes

Submerged vanes (Figure 9) generate secondary flow circulation, change the magnitude and direction of bed shear stress and modify velocity distribution, flow depth and sediment transport rate (Odgaard and Wang 199l). The array of vanes located upstream of the pier retard the process of scouring by leading the eroded sediment into the scour hole. The major controlling parameters are: vane height h_v, aspect ratio h_v/l_v (here l_v is the submerged vane length), angle with respect to the approach flow α, spacing (e_v), displacement from the upstream pier-face (a), lateral spacing between vanes z_v, vane submergence, channel resistance and densimetric Froude number (Lauchlan 1999). If $l_v/h_v < 1$, the flow system upstream of the pier is disrupted, reducing the strengths of the downflow and the horseshoe vortex. If $l_v/h_v > 1$, then the vanes interact with the sediment bed rather than the approach flow to reduce scour depth. Lauchlan (1999) discovered that if $l_v/h_v > 1$ vanes offer greater potential for scour protection than otherwise. In this study based on the results of research reported by Shojaee et al. (2012), 6 vanes (n=6) have been applied and parameters have chosen according the arrangement with highest efficiency of that work in controlling scour depth, although the values modified according the pile diameter of this study (Figure 9 and Table 2).

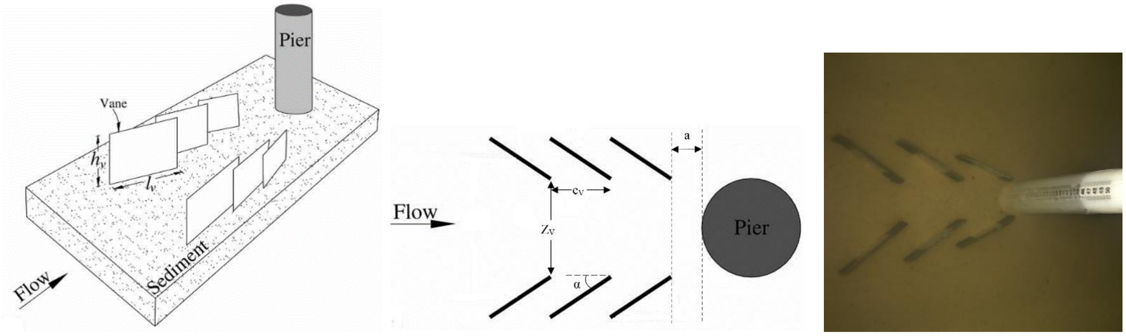


Fig. 9. Submerged vanes: (a) general configuration, (b) plan view (Lauchlan 1999), (c) Configuration of this study

Table 2. Submerged vane controlling parameters of this study

n	L_V/H_V	α (°c)	H (cm)	e_V (cm)	Z_V (cm)	a (cm)
6	3	35°, 30°, 20°	3	7.5 (=1.5D)	5 (=D)	0

The maximum scour depth around the pier was measured over time. The equilibrium time has indicated in figure 6 with compare to other tests. After starting the test, the maximum scour occurred on the outside of the third row vanes (farthest one from the pier) however, after about 15 minutes the maximum depth transferred inside of it. After passing 43 minutes the scour depth vicinity of the pier reached the maximum amount of 1.6 cm, which 75% of this amount occurred only in 5 minutes. Until this time, as figure 10 indicates, sediment level beside first and second row vanes didn't change significantly although small stacks are created inside of them but the scour depth inside the third row vane was 2 cm and height of stack outside of it was 2 cm too. Afterward, the depth of scour hole vicinity of the pier remained constant for 70 minutes and the accumulated materials beside of vanes transferred toward the pier so that the scour depth vicinity of the pier began to reduce gradually and eventually reached 1.1 cm $(\frac{d_s}{D} = 0.22)$ on the right side of cylinder. By applying this countermeasure the scour depth reduction rate R_d obtained $53\%(\frac{6.9-1.1}{6.9})$.

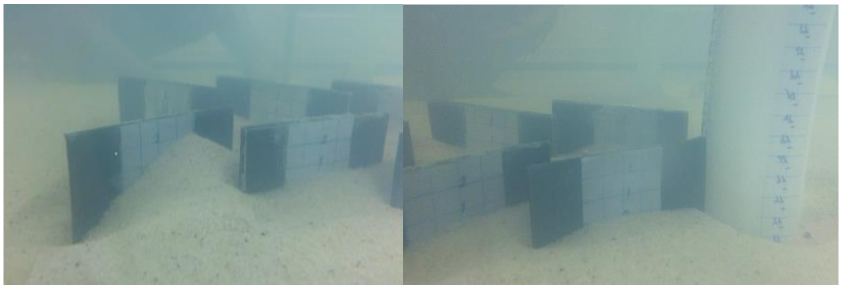
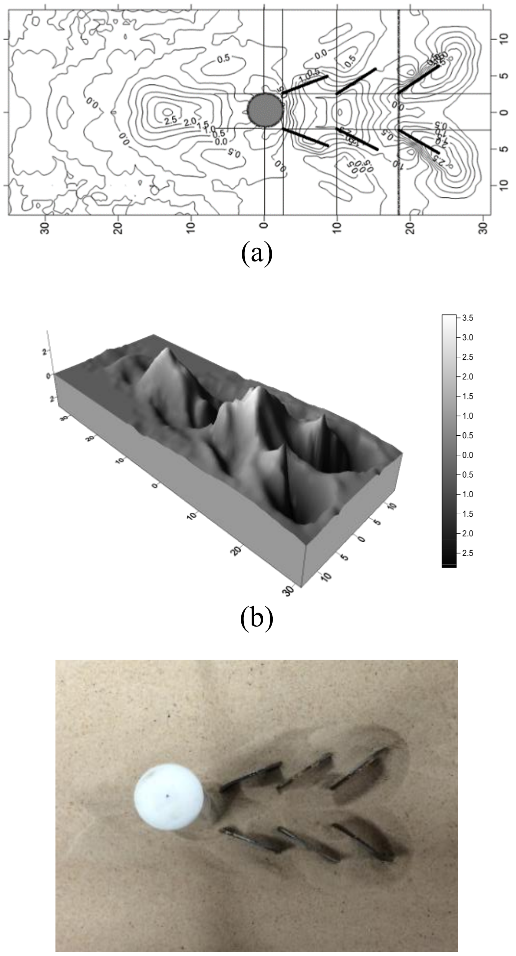


Fig. 10. Pier protected by submerged vanes; 43 minutes after starting test

The final bed changes beside the vanes recorded from -2 to 2 cm outside and from -2.9 to -1.2 inside the farthest ones from pier. The effect of using this solution on scour depth and bed topography has portrayed in Figure 11.



(a)

(b)

(c)

Fig. 11. Morphological bed changes around a pier protected by submerged vanes: (a) Laboratory pattern, (b) contour lines (c) Three-dimensional modelling (units: cm)

This protection could decrease the area of changes in bed topography dramatically in compare to other two tests. Morphological bed changes started 20 cm before pier center ($\frac{L}{D}$ = 4) and continued 30 cm after it ($\frac{L}{D}$ = 6). In cross sections, the maximum width of bed level changes has been observed 23 cm in upstream area and 11 cm in downstream area of the pier.

4. Conclusion

In present study the scouring around a cylindrical pier protected with sacrificial piles and submerged vanes in clear water condition was examined experimentally. The following results can be drawn which also has been summarized mostly in the form of dimensionless in table 3.

Both of scour countermeasure had a smaller equilibrium time scale of scour at the pier than the corresponding unprotected pier. Especially by submerged vanes most of the scour, about 75%, only occurred in first 5 minute.

Table 3. Summary of significant results from present study

		$\frac{d_s}{D}$	**Bed topography changes ($\frac{L}{D}$)**			$t_{\%75}$ **(min)**	R_d **(%)**
			Longitudinal section		**Cross section**		
			Before pier	**After pier**			
Pier with	**no countermeasure**	1.38	2.4	12	4	70	
	sacrificial piles	0.88	2.6	13.2	4.4	40	36
	submerged vanes	0.22	4	6	4.6 (in downstream) 2.2 (in upstream)	5	53

R_d subjected to submerged vanes is much more than one subjected to sacrificial piles, viz. 17%. It reveals that presence of submerged vanes plays more efficient role in reducing scour depth.

By applying sacrificial piles compare with submerged vanes, the amount of sediment deposition in the pier scour hole is reduced, as is the efficiency, owing to the fact that the scoured bed material is mostly transported downstream of the pier.

From the aspect of morphological changes area, the area affected by pier scouring protected by submerged vanes dramatically decrease; the length of changes downstream the pier (L) are 12, 13.2 and 6 times of pier diameter (D) corresponding to pier with no protection, sacrificial piles and submerged vanes respectively.

Submerged vanes indicates better performance in reducing the changes of bed level, the maximum changes of bed level were -6.9 cm to 3.9 cm in unprotected pier test, -4.4 to 3.5 cm in protection by sacrificial piles test and -3 to 3.2 cm in protection by submerged vanes.

5. Acknowledgment

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