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Comparison of Bridge Piers Shapes According to Local Scour Countermeasures

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Abstract: Comparison of experimental study was carried out between bridge piers to find out the efficient bridge pier to countermeasures the local scour. In addition the present study is to provide a new method to reduce scour depth in front of bridge pier .The idea of this method is dependent on change the position of two piers (normal pier (10-4) cm and straight aero foil shaped pier) with respect to flow direction (named after here as opposite bridge pier and opposite aero foil pier). The down flow deflected away from the front the opposite piers and the horseshoe vortex becomes small and does not affect the piers.In the present study five piers (normal pier (10-4), opposite pier (4-10), straight aero foil, opposite aero foil and circular) were tested under live-bed condition with flow intensity 58 l/sec. for duration 3 hrs. The velocity field measurements were obtained using an Acoustic Doppler Velocimeter. The results showed that the opposite piers reduce the local scour around the piers. For opposite pier the reduction of scour depth was about 40% compared with normal pier and 54% compared with circular pier. The reduction of the scour hole volume was about 83% compared with circular pier and 23.6% when normal pier compared with circular. For opposite aero foil the maximum depth of scour reduced 58% compared with straight aero foil and 69% compared with circular pier. The reduction of the scour hole volume was about 89% compared with circular pier and straight aero foil reduced scour hole volume about 27% when compared with circular pier.It is clearly from the comparison that the opposite piers are effective countermeasures for reducing local scour depth and scour hole volume, especially opposite aero foil pier. We hope that the results of the present study will be benefitted by the designers and engineers.

Keywords: Bridge pier position, Scour reduction, Local scour, Aero foil pier

Introduction

A common reason of bridge failures is local scour around bridge foundations such as piers and abutments. Local scour erodes the soil around the piers and reduces the lateral capacity of the foundations (Rambabu et al 2003). Local scour is the engineering term for erosion of the soil surrounding an obstruction caused by flowing water. The key element in the scour process is the formation of vortices due to pressure differences that occur when the water velocity profile meets the obstruction.

According to our knowledge, the present study is the first experimental work to place bridge pier in opposite direction according to flow direction. The idea behind the change the position of pier (opposite bridge pier) is that a significant amount of the flow will be deflect away from the pier, which will sufficiently prevent the mechanisms of local scour, particular the down flow and horseshoe vortex.

Scour countermeasures can be basically divided into two groups: armoring countermeasures and flow altering countermeasures. The main idea behind flow altering countermeasures is to minimize the strength of the down

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flow and subsequently horseshoe vortexes, which are the main causes of pier scour. In contrast the principle of armoring countermeasures is to provide a protection layer acts as a resistant layer to hydraulic shear stress and therefore provides protection to the more erodible materials underneath. It has been long established that the basic mechanism causing local scour at bridge piers is the down flow at the upstream face of the pier and subsequent formation of vortices at the base of pier. Muzzammil, Gangadharaiah and A.K. Gupta (2004).

Tafarojnoruz et al. 2012. Evaluated experimentally the performance of six different types of flow-altering countermeasures against pier scour. They found some countermeasures, which were recommended as highly efficient in the literature; do not perform well under test conditions Chen et al. (2012) examined the use of a hooked collar for reducing local scour around a bridge pier. The efficiency of collars was studied through experiments and compared with an unprotected pier. The velocity field measurements were obtained using an Acoustic Doppler Velocimeter. Results showed that a hooked-collar diameter of 1.25b has effectiveness similar to a collar diameter of 4.0b used by Zarrati et al. (1999) where b is the pier width. With hooked collar installed at the bed level, there was no sign of scouring and horseshoe vortex at the upstream face of the pier. In contrast, with unprotected pier, the down flow and turbulent kinetic energy were reduced under the effects of the hooked collar.

Application of aerofoil and opposite pier as a countermeasure for local scour at bridge piers

Drysdale (2008) applied dimensional analysis to examine the effectiveness of an aerofoil shaped bridge pier by comparing a scaled circular pier with a scaled aero foil shaped pier of the same diameter. Drysdale found that for the same flow condition, the vortex shedding from the aero foil shaped pier was significantly less than the circular pier.

Christensen (2009) examined the effectiveness of a slotted aero foil shaped bridge pier in reducing local scour, as compared to an aero foil and circular pier. Christensen concluded that, the aero foil shaped pier reduces local scour by a volume of 27% when compared to the circular shaped pier. The slotted aero foil shaped pier had a reduction in the scour hole volume of 85% when compared to the circular shaped pier.

Gibson (2010) examined the effectiveness of skirted, straight aerofoil shaped bridge pier in reducing local scour. Results demonstrate that symmetrical aero foil shaped piers are an effective countermeasure in the reduction of local scour hole volume.

The present study the same aerofoil shaped pier was investigated experimentally and compared with circular pier, the result showed the aero foil pier reduces local scour .In spite of aero foil reduces the local scour the opposite aero foil more effective in reducing local scour .Beside a comparison between opposite pier and opposite aerofoil was conducted. It is clearly from the comparison that the opposite piers are effective countermeasures for reducing local scour depth and scour hole volume, especially opposite aerofoil pier.

Dimensional Analysis

Dimensional analysis was used to define the dimensionless parameters based on the selection of all variables governing the maximum scour depth at upstream of the bridge pier.

ds= $f_1(v, \rho, h, g, d_{50}, ks)$ (1)

In which, v is the flow velocity, ρ is the density of fluid, h is the flow depth, g is the gravitational acceleration, d_{50} is the mean size of sand particles,ks and is the pier shape factor.
The maximum relative depth of scour was assumed to be correlated to the other independent parameters as given by Eq. (2).

ds/ h = $f_2(Fr, \frac{d_{50}}{h}, ks)$ (2).

ds = maximum depth of scour and Fr=Froude number.

Experimental Work

The experiments were carried out in the Hydraulic laboratory of Civil Engineering Department of Gaziantep University. The flume is 12 m long, 0.8m width and 0.9 m depth as shown in Figure 3 with glass sides and steel bottom.

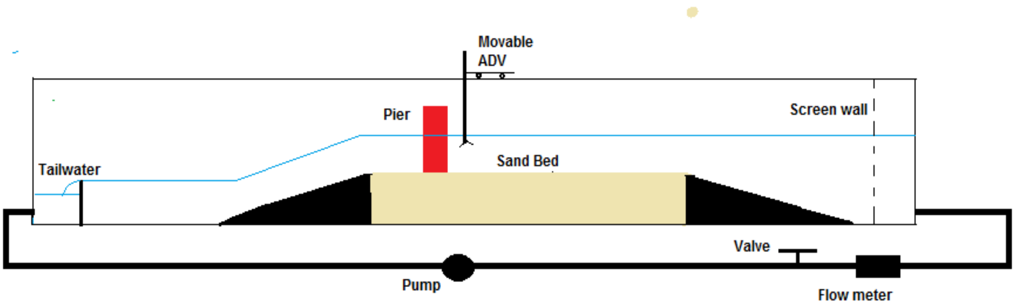


Figure 3. Schematic layout of the flume

The test section was made with a ramp which is located at the beginning and the end of the section. The test section is 3 m long and 0.2 m depth as shown in Figure 3.

The test section was filled with sediment of median particle size $d_{50} = 1.45$ mm and standard deviation, $\sigma g = 3.16$ with the specific gravity of 2.65, the sieve analysis of the sand is given in Figure 4.

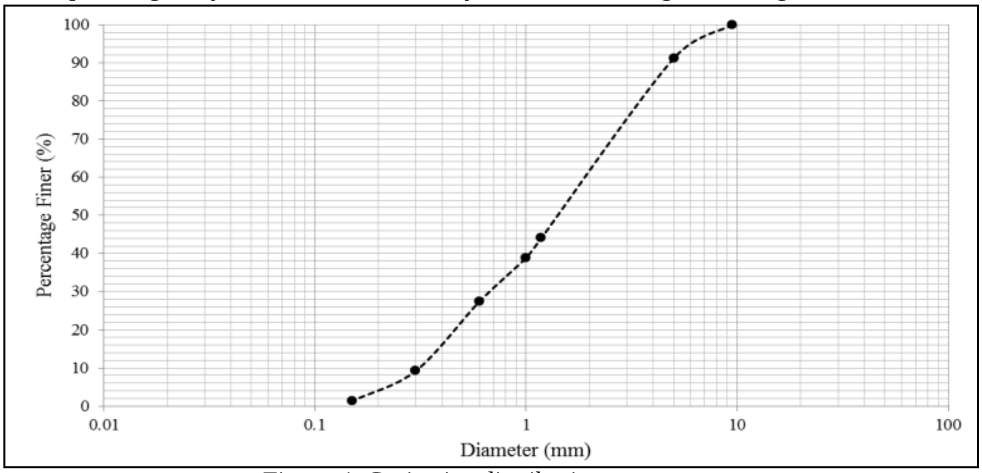
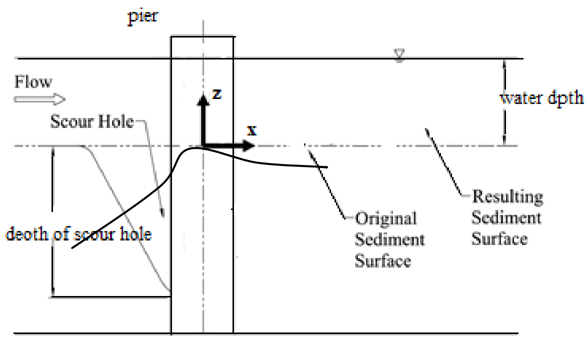


Figure 4. Grain size distributions

Flume discharge was measured by a Magnetic flow meter installed in the pipe system before the inlet of channel. The scour hole and the elevation of the bed was measured by laser meter, the instrument mounted on a manually moving carriage sliding on rails on the top of the flume wall. Depth of scour hole at the center line, extension of scour hole and a cross-section of the resulting scour were measured Figure 5.



Plan view

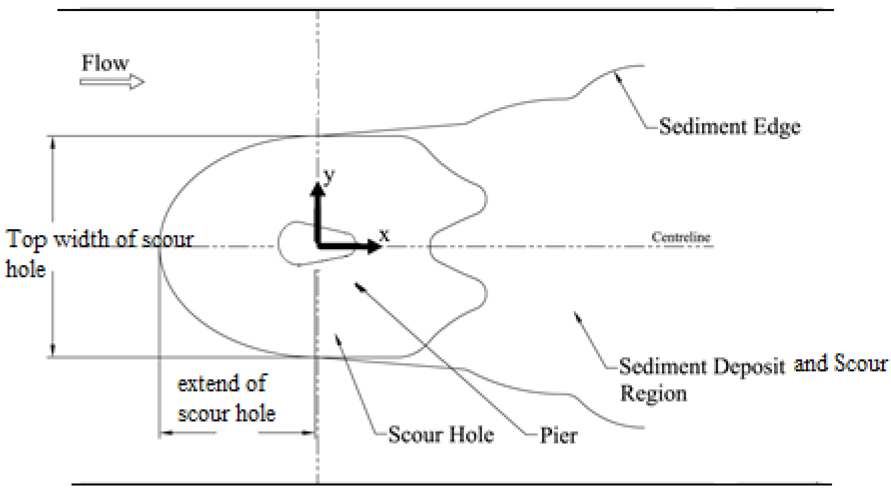
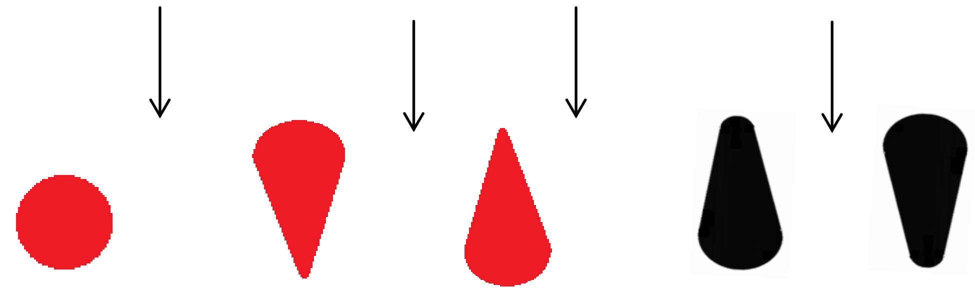


Figure 5. Centerline profile and plan view of a typical scour hole and deposit region

Five piers circular, opposite, normal piers, straight aero foil and opposite aerofoil as shown in Figure 6 were tested.

Direction of flow



Circular pier straight aero foil pier opposite aero foil pier opposite pier normal pier

Downstream

Figure 6.Views of tested piers

Experiments were performed under a live-bed water scour regime. The discharge was measured as 58 l/s with 12.5 cm flow depth. Initial bed elevations were taken randomly to check the leveling of the test section by using laser meter. The flume was first filled with water until desirable flow depth to avoid undesirable scour. Inlet flow to the flume was then gradually increased until the desired discharge, and the temporal variation of scour was monitored. The scour depth was measured under an intense light. The progress of scour depth was observed 3 hrs. At the end of each test, the pump was shut down and the water was slowly drained without disturbing the scour topography. The test section was then allowed to dry and frozen by pouring glue material (varnish).

Acoustic Doppler Velocimeter Measurements

During each experiment, the velocity is periodically monitored using an Acoustic Doppler Velocimeter (ADV). Stream velocity is measured upstream of the pier using the ADV in the center of the flume. The typical ADV setup is shown in Figure 8.

The ADV probe was then positioned above the scour hole and velocities were recorded for a period of 180 seconds. The sample period of 180 seconds was chosen to ensure that sufficient flow variations were captured.

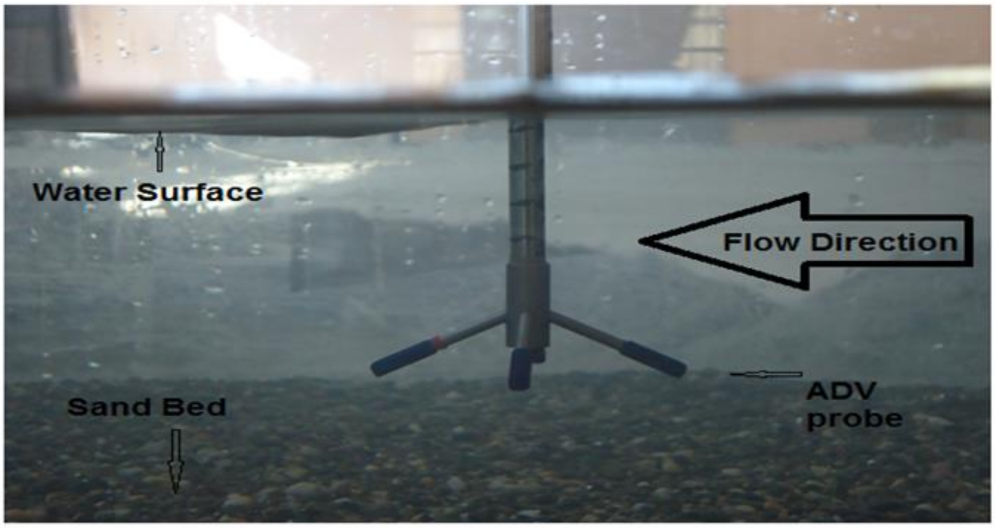


Figure 8. Typical ADV setup

Prediction of Scour Depth

Using step-wise regression (squared + Interaction Method), Eq. (3) was developed to correlate the relative maximum scour depth to the Froude number, Fr, and the pier shape factor, Ks

$$\frac{ds}{h} = 0.567 + 28.3 * d_{50} * Fr * lnK_s - 5.02 * K_s * \frac{d_{50}}{h} * lnK_s \qquad (3)$$

The correlation coefficient (R^2) and the standard error of estimate for Eq. (3) are 84% and 0.032 respectively. Figure 7 presents the predicted values of ds/h using Eq. (3) versus the measured ones .Figure 7 indicate that Eq. (3) represented the measured data very well and hence could be used safely to predict the relative maximum depth of scour for different shape of piers.

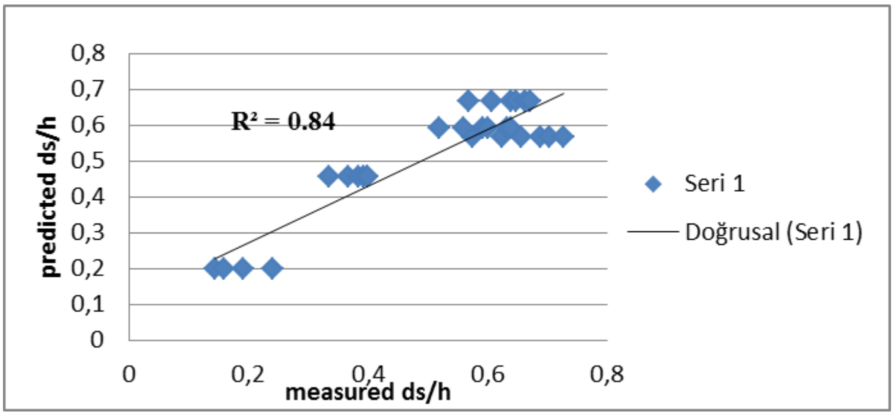


Figure 7. Measured ds/h versus predicted ds/h

Results and Discussion

Dimensions of the scour holes for each run of experiments were measured. The top width of scour in the transverse direction, distance from upstream face to front outer edge of hole, and depth at upstream face were compared for each of the five bridge piers as shown Table 1. The results of elapsed time taken from the start of each experiment for the scour hole to develop for five piers is given in Table 2.

Table 1. Scour hole dimensions from physical modeling

Scour Hole Dimensions	Opposite bridge pier Diameter = 4-10 cm.	Normal bridge pier Diameter =10-4 cm.	Straight Aerofoil Diameter =10 cm	opposite aero foil Diameter =10 cm	Circular bridge pier Diameter =10 cm.
Top Scour Hole Width	**= 30 c m**	**= 36 c m**	**= 34 cm**	**=24 cm**	**= 50 cm**
Distance from Upstream face to front outer edge of hole	**= 7.0 c m**	**= 16 cm**	**=12 cm**	**=4 cm**	**= 18 cm**
Depth at Upstream face	**= 5.0 cm**	**= 8.4 cm**	**= 8.0 cm**	**= 3.4 cm**	**= 10.9 cm**

Table 2. Time evolution of the maximum scours depth

Time (min.)	Depth of scour for Straight aero foil 10 cm	Depth of scour for Opposite aero foil 10 cm	Depth of scour for circular pier 10 cm	Depth of scour for normal pier(10-4) cm	Depth of scour for opposite pier(4-10) cm
5	6.5	1.8	8.6	7.1	4.2
15	7.0	2.0	9.2	7.5	4.6
30	7.4	2.4	9.8	8.0	4.8
60	7.5	3.0	10.2	8.1	4.9
120	7.9	3.2	10.4	8.3	5.0
180	8.0	3.4	10.9	8.4	5.0

Experimental results of the model piers within cohesion less bedding material will be compared and discussed in this section. The results are a comparison of scour and sediment scour hole depths for the circular, straight aero foil and normal piers were quite similar as expected, due to the identical shape on the upstream side of the pier as illustrated in Figure 9. A 54 % reduction in scour hole depth of the opposite pier was observed as compared to the circular pier and 40 % reduction as compared to the normal pier. For opposite aero foil 69% reduction in scour hole depth as compared to circular and 58% reduction as compared straight aero foil.

In addition to a reduction of the scour depth, the rate of scouring is also reduced considerably for both opposite aero foil and opposite pier as in Figure 9. Reduction in the rate of scouring can reduce the risk of pier failure when the duration of floods is short (Melville and Chiew, 1999).

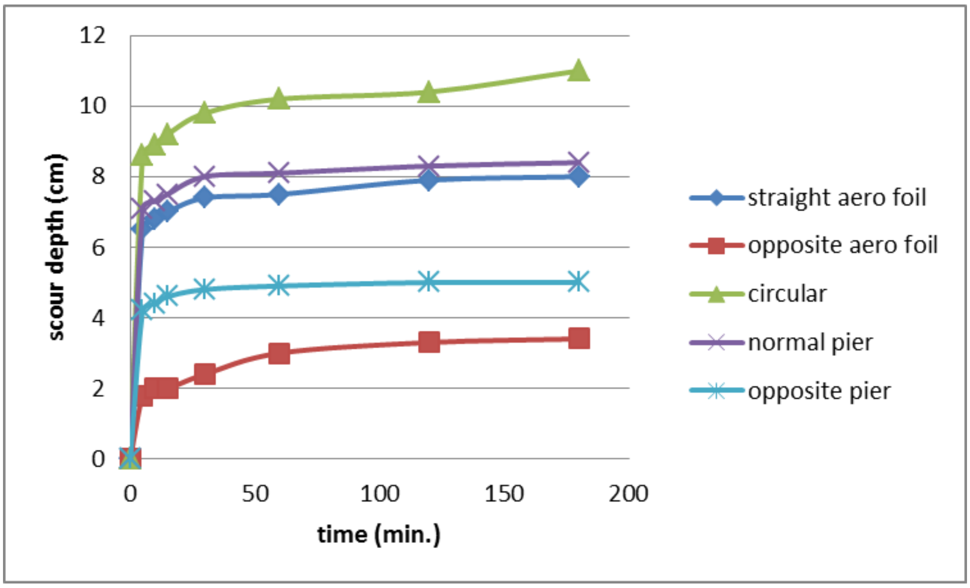


Figure 9. Scour hole development measured at the upstream face of each tested pier

Figure 10 demonstrate the top scour holes of five bridge piers .The top scour hole width of opposite pier was 20 cm or 40% less than the circular pier and 6.0 cm or 17 % less than the normal pier. For opposite aero foil top scour hole width was 52% less than the circular pier and 29% less than straight aero foil because the effect of the horseshoe vortex was reduced due to the down flow being deflected away from the base of opposite pier.

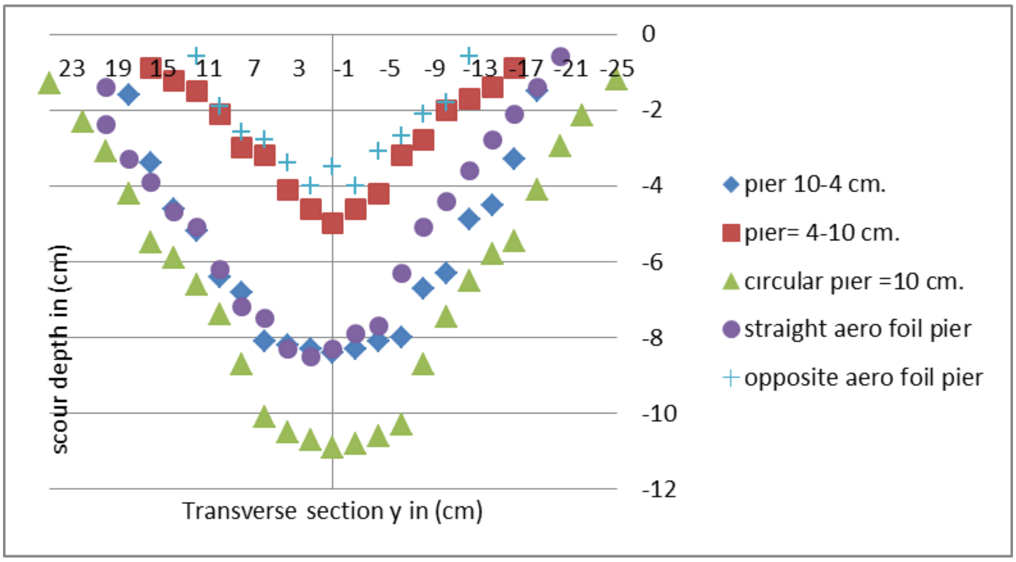


Figure 10. Transverse scour holes of three bridge piers

The effect of sediment gradation on local scour was investigated by many researchers, such as Ettema (1980), Chiew (1984), Dey (1995), and Molinas (2003). The general conclusion was that both the scour rate and the scour depth decrease as the geometric standard deviation (σg) increases. At a higher value of ($\sigma g > 1.3$) (Melville and Raudkivi, 1997) (for non-uniform sediment), armoring occurs on the upstream bed and at the bottom of the scour hole, resulting in a considerable reduction of the scour depth as illustrated in Figure 11.

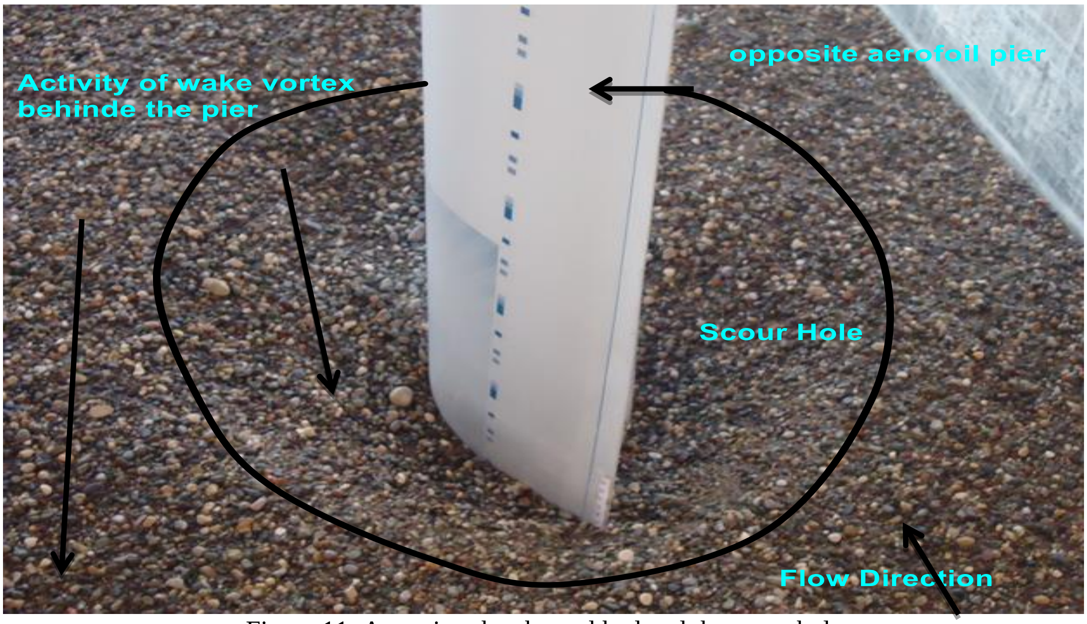


Figure 11. Armoring the channel bed and the scour hole

From Figure 12 it was observed that the activity of vortices (horse shoe vortex and wake vortex.) At the upstream face of normal, straight aero foil and circular piers a strong horseshoe vortex was detected, positioned at the base of piers. In contrast for opposite pier and opposite aerofoil the effect of horseshoe vortex reduced (not so visible) due to the down flow being deflected away from the base of opposite piers. It was seen from Figure 12 that, a strong wake vortex was visible and leading into scour hole in the downstream reach of circular, opposite aero foil and opposite piers.

Figure 13 shows the scour pattern around the normal, straight aerofoil, opposite aerofoil, opposite pier and circular piers. The opposite pier and opposite aerofoil minimize the scour depth, producing a little scour in the front and on the sides of the pier, but the scour in the pier's rear was more than that of straight aerofoil and normal pier due to the separation of flow occurred with a small amount at the beginning (upstream face)and then increased gradually according to the shape of opposite pier. In contrast for straight aerofoil and normal pier the separation increased and then decreased, producing a little scour at the wake region.

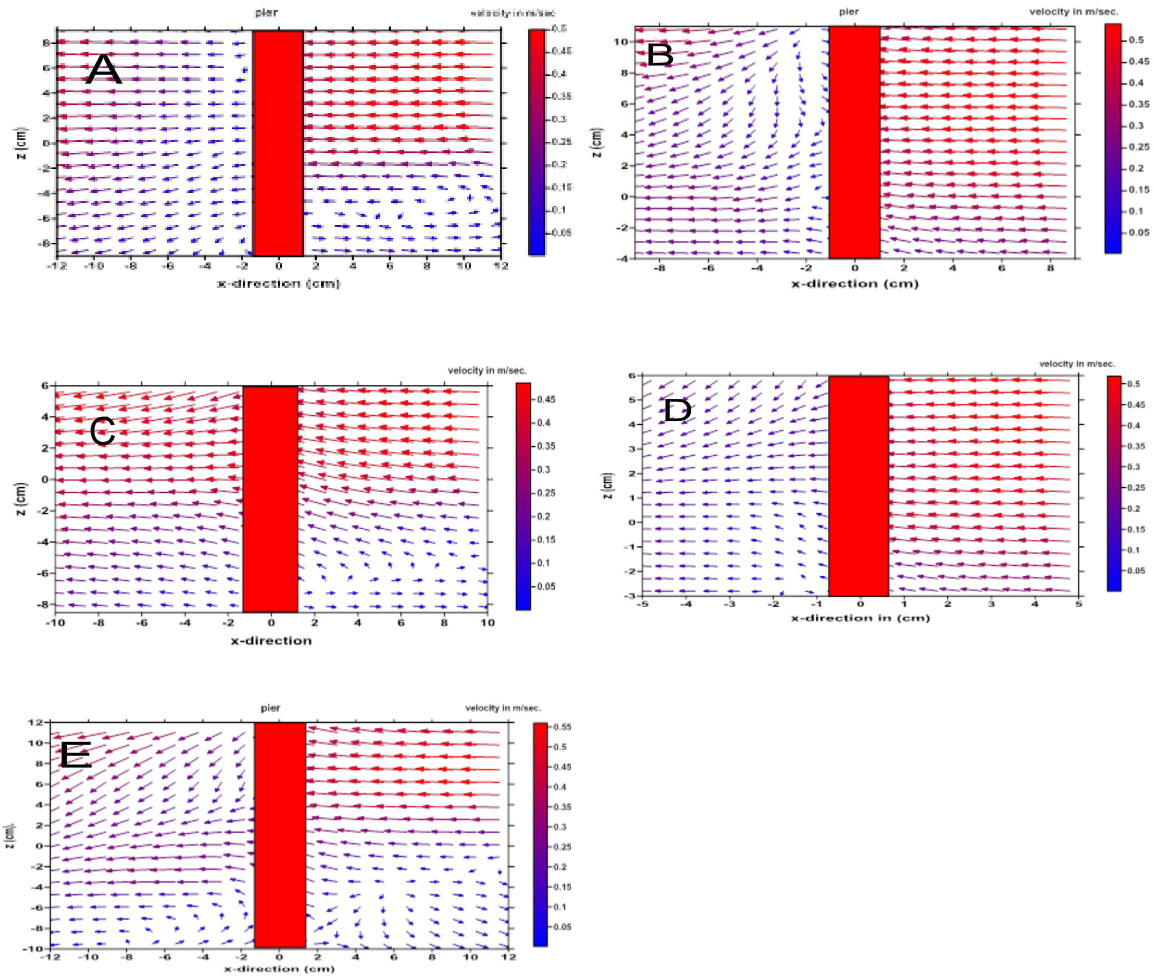


Figure 12 Velocity vectors at vertical plane for three tested piers

. (A) normal pier. (B) opposite pier,(C) straight aerofoil,(D) opposite aerofoil (E) circular pier.

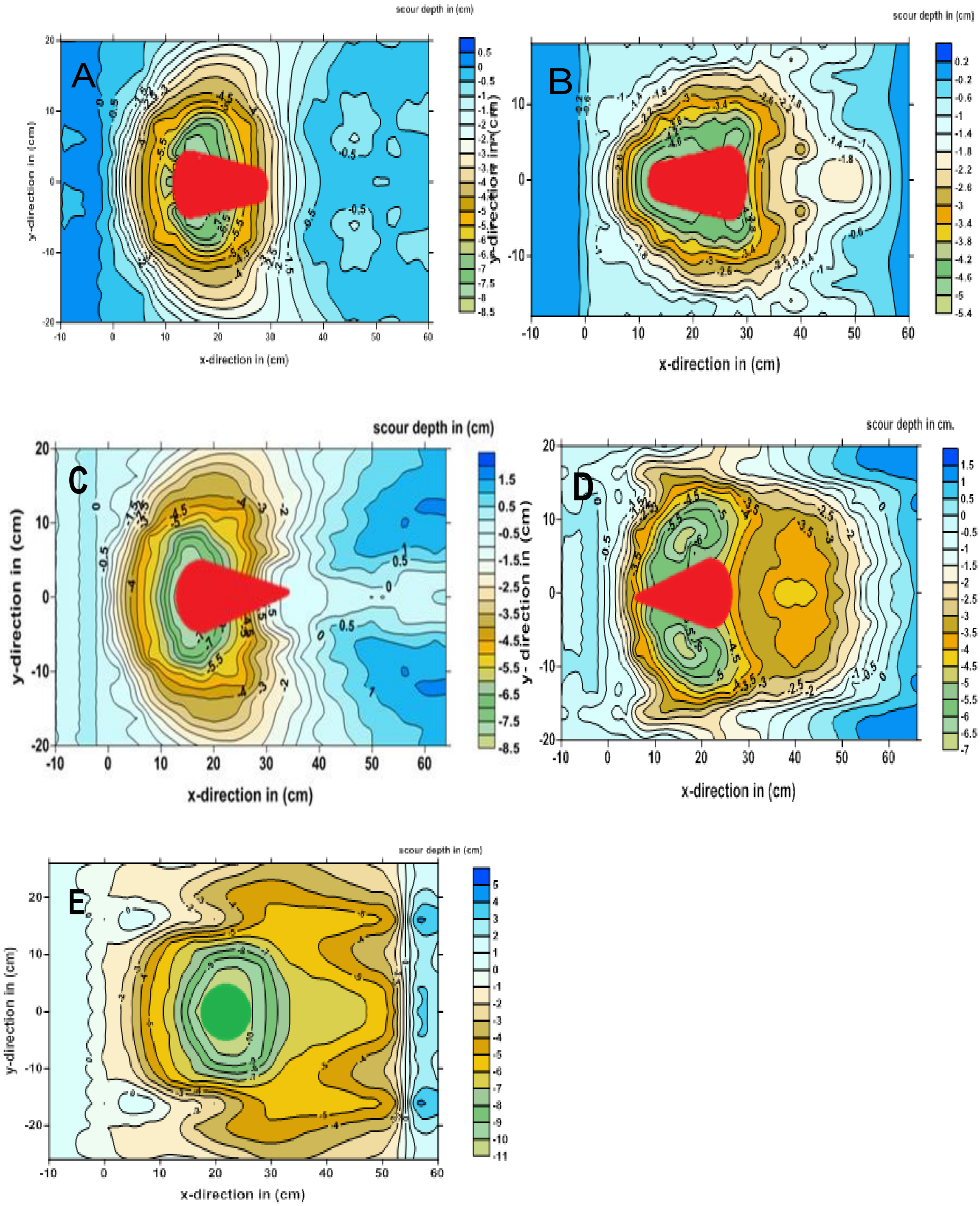


Figure 13 The scour pattern around (A) normal, (B) opposite (C) straight aerofoil, (D) opposite aerofoil,(E) circular piers.

Conclusion

Comparison between five bridge piers was carried out to find out the efficient bridge pier to countermeasures the local scour and the paper experimentally examined the application of a new method of placing the pier in the opposite direction of flow to reduce local scour on bridge pier. Changing the position of pier is not only effective for reducing scour but it is also much more economic when it is compared to countermeasure techniques like riprap and slot.

Opposite pier and opposite aerofoil have effectiveness as a countermeasure to decrease local scour. Compared to straight aerofoil and normal pier, the down flow was reduced under the effect of changing the position of pier, with the new method there was a very little sign of down flow and horseshoe vortex at the upstream side of pier. For opposite pier the maximum depth of scour reduced 40 % and 54 % as compared with normal pier and circular pier respectively. The reduction in the scour hole volume for the opposite pier was 83% as compared with the circular pier. Opposite aerofoil reduces depth of scour 58% and 69% as compared with straight aerofoil and circular pier, and the scour hole volume reduced 89% as compared with circular pier.

The top scour hole width of opposite bridge pier was 40% less than the circular pier, and 17% for normal pier. For opposite aerofoil the top scour hole width was 52% less than the circular pier and 29% less than straight aero foil It is clearly from the results that opposite aerofoil and opposite pier are effective countermeasure the scour depth, particularly opposite aerofoil because a big amount of downflow deflected away the pier, resulting the strength of horseshoe decreased and the scour depth reduced.The present experimental study does not need to countermeasure the scour depth by armoring or flow altering devices, the new idea only to change the position of pier according to flow direction.

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