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Study on scouring around bridge piers protected by collar using low density sediment

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Abstract

The efficiency of a collar in reducing the scour depth around circular and rectangular piers is studied at different flow intensities (ratio of upstream shear stress to sediment critical shear stress). Rectangular Piers aligned with the flow as well as skewed at 5º, 10º, 20º were examined. Previous studies had shown that with collar the equilibrium time of scouring increases considerably. To reduce the time of experiments low density sediment was used as the bed materials. Comparison between test results and available results with natural sediment showed that, though the relative equilibrium depths were approximately similar, the time to reach equilibrium condition diminished to less than 10 hours with low density sediment. Experimental results for circular and aligned rectangular pier showed that at u^*/u^*c= 0.95 to 0.75 the collar could reduce the maximum scour hole from about 20% to 60% respectively. In rectangular pier, by increasing the skew angle and/or the flow intensity, the efficiency of collar decreased.

Keywords: *Scour, Bridge pier, Collar, Flow intensity, Low density sediment, Time development*

1. Introduction

Every year, many bridges around the world fail due to scouring at their piers and abutments [1, 2]. Local scour around a pier results from a complex vortex system which forms around the pier. Flow pattern and mechanism of scouring around a bridge pier has been studied and reported by many investigators [3, 4, 5, 6 and 7]. Briefly, the approach flow velocity goes to zero at the upstream face of a pier and this cause an increase in pressure. As the flow velocity decreases from surface to the bed the dynamic pressure on the pier face also decreases downwards. This pressure gradient drives the flow down the pier resembling a vertical jet (Fig. 1). When this down flow impinges the streambed, it digs a hole in front of the pier and rolls up and by interaction with the coming flow forms a complex vortex system. This vortex extends downstream and passes the sides of the pier. Owing to its similarity to a horseshoe this vortex is called horseshoe vortex. The horseshoe vortex deepens the scour hole in front of the pier until the shear stress on the bed material becomes less than its critical shear stress. The accelerating flow at two sides of the pier creates two slots in the streambed, which facilitates the transport of removed sediment from the scour hole at the upstream perimeter of the pier. The separation of the flow at the sides of the pier creates so called wake vortices. These vortices are unstable and shed alternatively. These vortices act as little tornadoes lifting the sediment from the bed and form their own scour hole.

There are many methods to control scouring around bridge piers including collars. Collars are plates attached to the pier and act as a barrier to the down flow, preventing its direct impingement into the streambed. Several researches have studied the effect of collar in reducing local scour depth around piers with circular and rectangular sections [8, 9, and 10]. By applying a collar, not only the maximum scour depth decreases, but also the rate of scouring reduces considerably.

In brief, with a collar in place no scour hole is observed at the pier perimeter in the beginning of experiment. However, a scour hole is formed downstream of the pier under the action of wake vortices which slowly develops towards upstream [8, 11, 12, and 13]. This scour hole extends along

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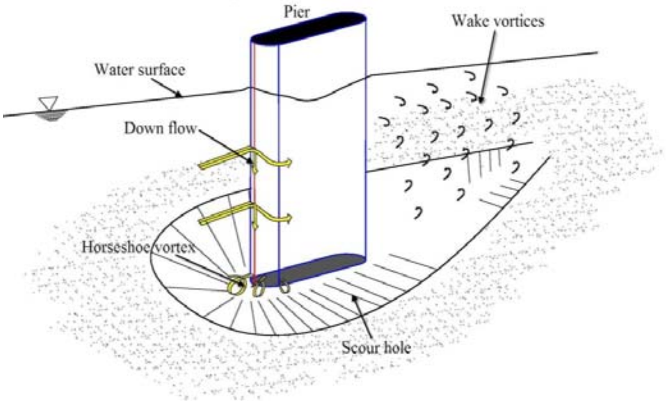

Fig. 1 Flow pattern around a rectangular pier

the rim of the collar until it reaches the front edge of the collar. After that, the flow penetrates below the collar and scouring rate increase. Depth of the scour hole increases till equilibrium condition is achieved.

Previous studies indicated that for flow intensities (u^*/u^*_c) less than about 0.5 no scouring occurs around a pier, where u^* is upstream undisturbed bed shear velocity, and u^*_c is the critical shear velocity of the bed material. It is also shown that scour depth does not change considerably when $0.8< u^* / u^*_c<1$ [14]. On the other hand, since a collar covers a limited area around a pier, development of scour hole around and below the collar strongly depends on bed shear stress. As shear stress on bed decreases, area of higher shear stress around the collar and consequently scouring and its rate decreases, or in another word, collar becomes more efficient. Since bridge piers are usually built in flood plains and shallow flows, flow intensities may be well below 1. Therefore for piers on the flood plain, a collar can very well protect a pier from scouring. Thus, studying the efficiency of collar at low flow intensities is necessary.

At lower bed shear stresses with lower rate of scouring, equilibrium time of scouring increases considerably. Mashahir et al (2006) conducted experiments on efficiency of a collar 3 times wider than the pier width installed at the streambed level on rectangular piers. They showed that to achieve equilibrium in flow intensities higher than 0.9, more than 150 hours test time is necessary. Alabi (2006) studied the efficiency of a similar collar on circular piers. For flow intensity of 0.7, the test was continued for 1000 hours to approach equilibrium condition. Since experiments on efficiency of collar at low flow intensities are too long, it is almost impossible to carry out a comprehensive number of tests on collars installed on different piers at different flow intensities.

A method to overcome this problem is to use low density sediment in the experiments instead of natural sediment. Low density sediment could reduce the equilibrium time of scouring around the piers. However, there is little information available on application of low density sediment in scour studies. Oliveto and Hager (2002) used natural sediment as well as low density sediment with density of 1450 kg/m³ in their experiments to study time development of scouring around bridge piers and presented the following equation:

$$\frac{d_s}{D^{\frac{2}{3}}y_1^{\frac{1}{3}}} = 0.068.N\sigma^{-0.5}\mathrm{F_d}^{1.5}\log\left(\frac{\sqrt{g}d_{50}}{D^{\frac{2}{3}}y_1^{\frac{1}{3}}}t\right) \quad (1)$$

where d_s is scour depth, D is pier diameter (Circular pier) or width (rectangular pier), y_1 is approach flow depth, N is shape factor equal to 1 for circular, and 1.25 for rectangular pier, σ is sediment non-uniformity coefficient, F_d is densimetric particle Froude number ($V/(g'd_{50})1/2$), V is approach flow velocity, d_{50} is mean grain size, g' is reduced gravitational acceleration= $g(\rho_s/\rho$-1), ρ and ρ_s are fluid and sediment density respectively, g is gravitational acceleration, and t is time.

In the present work, first, time development and maximum depth of scouring around piers located in low density are compared with some available data of natural sediment. In the next stage, the efficiency of collar on circular and rectangular piers is studied experimentally at different flow intensities.

2. Experimental setup

To investigate the efficiency of collar, the laboratory experiments were carried out in a straight masonry rectangular flume 9m long and 0.75m wide and 0.6m deep. The test section was in the form of a recess below the flume bed located 5m downstream of flume entrance, and was filled by uniform polystyrene material. Median size of this material was d_{50}=0.97 mm, with geometric standard deviation (σ) less than 1.2 and density of 1050 (Kg/m³). Furthermore direct shear test for this material showed that it was non cohesive and its angle of repose was φ=22.6º.

The pier models (rectangular and circular) made from Perspex was embedded vertically in the middle of the sediment recess. Diameter of the circular pier was 0.04m and the width of the rectangular pier was 0.05m. Width to length ratio of the rectangular pier was 1:5 with semi-circular head and tail. Aligned rectangular piers, as well as 5˚, 10˚, and 20˚ skewed piers were tested in this study. Following previous studies [10], collars with an effective width 'W' equal to three times the pier diameter (for circular pier) or width (for rectangular pier) 'D' were installed around the piers at the streambed level (Fig. 2). Though wider collars were more effective, they were considered to be impracticable. Collars were made from 2mm thick Perspex sheets.

Shear stress at the working section was determined by calculating water surface profile and slope of the energy line when the pier was not installed in the flume. To calculate water surface profile, first bed roughness coefficient was determined based on absolute bed material roughness d_{90}. The calculated water surface elevation upstream of the flume was then compared with measurement results and if they were different, the bed roughness coefficient was slightly modified. Critical bed shear stress was then found from the Shields' diagram knowing the bed shear velocity. Experiments were conducted at clear water condition with 4 flow intensities of 0.75, 0.85, 0.9 and 0.95. In all experiments discharge was constant (Q=7.83lit/s) and to change the flow intensity the flow depth in the flume was changed by a tail gate at the end of the channel.

A rectangular sharp crested weir and a manometer were used to measure the flow discharge. Bed profiles were recorded using a laser bed profiler with accuracy of 1 millimeter.

Since time to reach equilibrium scour depth (T_e) with low-density sediment is much less than natural one, especially in lower flow intensities (e.g. u^*/u^*_c=0.75), therefore a new definition for equilibrium time of scouring was needed. Melville and Chiew (1999) defined equilibrium time of scour depth in natural sediment as a time when depth of the scour hole do not change more than 5% of the pier diameter over a period of 24 hours. However, with low-density sediment in most of the experiments no motion of particles and increase in scour depth was observed after less than10 hours, though some of the tests were carried out up to 50 hours. Therefore all experiments were continued until no motion of particles was observed and in another word the equilibrium scour depth (d_{se}) was achieved. Maximum scour depth and time development of scouring in circular and rectangular piers and their comparison with available data of natural sediment are discussed in the following sections.

Experiments were carried out in two parts. In the first part, scour tests were conducted with unprotected circular and rectangular piers (without collar) in all 4 flow intensities. In the second part, a collar was installed at each pier and similar tests as on unprotected piers were carried out to determine its efficiency.

3. Comparison of scouring result in low density and natural sediment

Before presenting the results of experiments for efficiency of collar at different flow intensities, some of results of scouring in unprotected and protected piers with low density sediment are compared with available results of experiments with natural sediment.

3.1. Unprotected pier

Table 1 shows the relative maximum scour depth d_{se}/D, where d_{se} is equilibrium scour depth and time to reach equilibrium condition (T_e) in circular pier with low density sediment. The available results of scouring with natural sediment are also given in this Table. It can be seen from Table 1, that the maximum difference between depth of scouring measured in low-density and natural sediment is about 10% at the lowest flow intensity. On the other hand, time to reach equilibrium condition decreased considerably in low-density sediment. The effect of sediment density in decreasing times of equilibrium was more at lower flow intensities (Table 1). For instance, time of equilibrium at flow intensity of 0.75 in low density sediment is 8 hours (Table 1), whereas according to Alabi (2006) time of equilibrium based on Melville and Chiew (1999) definition at flow intensity of 0.7 is about 200 hours. It can also be concluded that time to reach equilibrium increases as flow intensity decreases. Figs. 3 and 4 show the temporal variation of scouring at highest (u^*/u^*_c=0.95) and lowest

Table 1 Experimental result with unprotected circular pier

Flow intensity	Low-density sediment		Natural sediment		
(u_*/u_{*c})	d_{se}/D	Te (hr)	d_{se}/D	Te (hr)	Reference
0.95	2.3	5.5	2.3	45	Mokalaf (2007)
0.9	2.21	6	2.27	45	Mashahir et al (2010)
0.85	1.94	7	2.25	50	Mokalaf (2007)
0.8	-	-	2.15	77	Mokalaf (2007)
0.75	1.6	8	-	-	Alabi (2006)
0.7	-	-	1.34	200	Alabi (2006)

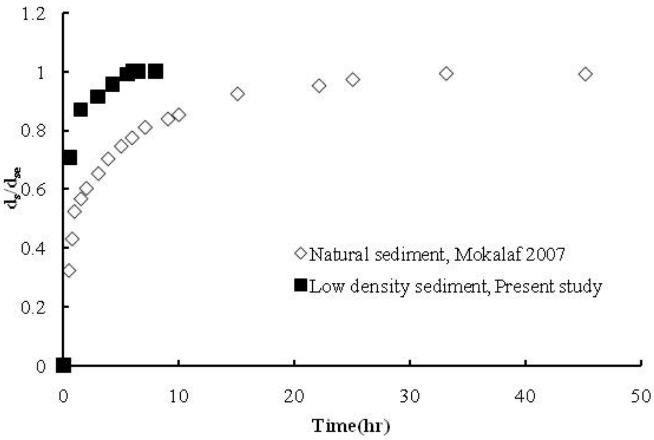

Fig. 3 Time development of scouring in natural and low-density sediment at flow intensity of 0.95 around a circular pier

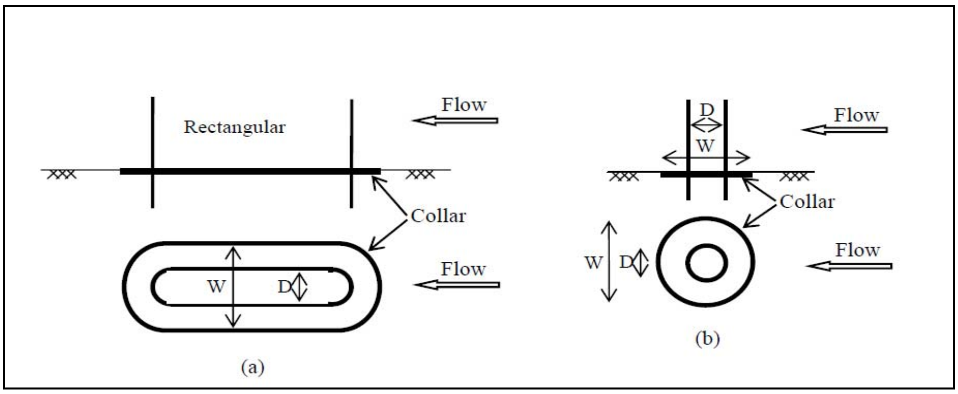

Fig. 2 Schematic view of pier with collar a) rectangular b) circular (Mashahir et. al. 2007)

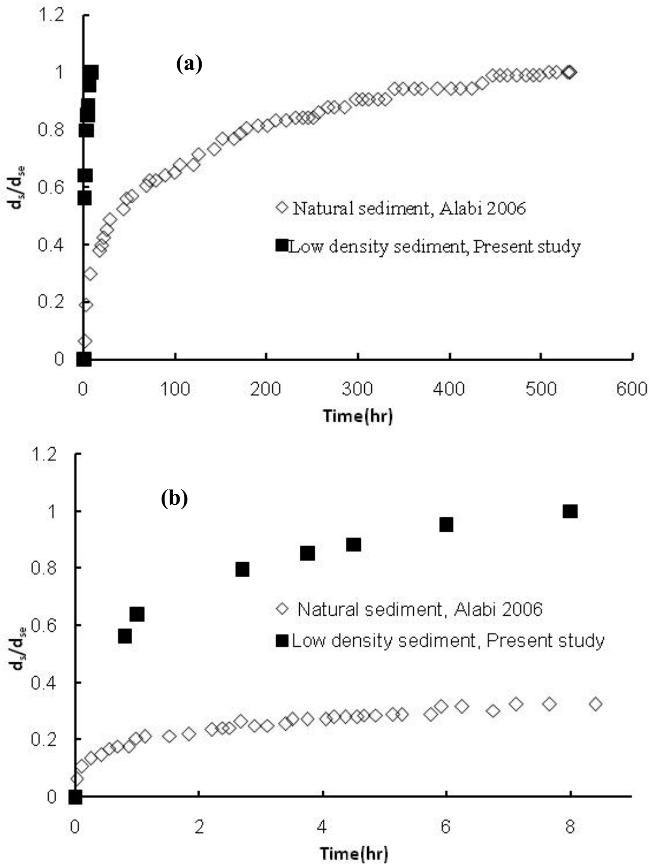

Fig. 4 Time development of scouring in natural and low-density sediment at flow intensity 0.7 and 0.75 respectively around a circular pier a) Total experiment time, b) The first 9 hours of the experiment

(u^*/u^*_c=0.75) flow intensities respectively.

Measured time development of scouring in the present study for flow intensity of 0.95 with low density sediment is compared with Eq. 1 developed by Oliveto and Hager (2002) in Fig. 5. This equation considers the effect of sediment density on scour time development. As can be seen from this figure the agreement is good verifying the results of the present experiments. In Fig. 5, X and Y are $((g'.\ d_{50})1/2)/\ (D^{2/3}y_1^{1/3})\ \times t$ and $(d_s\ .\sigma^{1/2})/\ (D^{2/3}y_1^{1/3}Fd^{3/2})$ respectively.

Unprotected aligned rectangular piers as well as skew at 5˚, 10˚ and 20˚ were also tested with low density sediment and with similar flow intensities as the circular pier. The results of

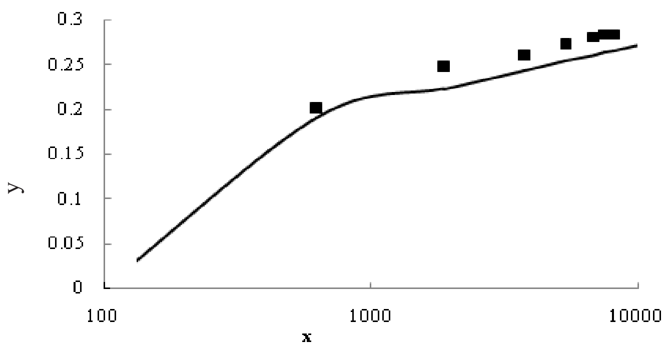

Fig. 5 Comparison of Eq. [1] with present experiments and for circular pier at u^*/u^*_c = 0.95

Table 2 Experimental results with unprotected rectangular pier

Flow intensity (u_*/u_{*c})	Low density sediment							
	(d_{se}/D)				T_e (hr)			
	0º	5º	10º	20º	0º	5º	10º	20º
0.95	1.83	1.9	2.88	3.9	5.5	5.5	5	4.5
0.9	1.8	1.86	2.64	3.2	6	6	5.5	5
0.85	1.56	1.7	2.4	2.78	7	7	6.5	6
0.75	1.26	1.4	2.1	2.62	8	8	7.5	7

Table 2 Experimental results with unprotected rectangular pier (continued)

Flow intensity (u_*/u_{*c})	Natural sediment						
	(d_{se}/D)			T_e (hr)			
	0º	5º	10º	0º	5º	10º	Reference
0.95	1.9	2.3	3.25	45	45	45	Zarrati et al (2004)
0.9	1.9	2.2	3.2	50	50	50	Zarrati et al (2004)

these experiments are given in Table 2 together with all available data in natural sediment. The differences in depth of scouring measured in low density and natural sediment at different pier angles are between 3 to 20% where the least for aligned pier and the highest for 10o skewed pier.

For all flow intensities, experiments showed that for the aligned and 5° skewed pier, the location of maximum scour depth occurred at the nose of the pier and in 10° and 20° skewed pier it was located along the leeward face of the pier. Zarrati et al. (2004) have reported similar results for natural sediment.

3.2. Protected piers

The long time of equilibrium in protected piers especially in lower flow intensities is a restriction to collect enough data. Alabi (2006) reported that 1000 hours was needed to achieve equilibrium at flow intensity of 0.7 for a protected circular pier. Using low density sediment as mentioned before reduces the experiment time and makes these kinds of tests possible.

Fig. 6 shows the time development of scouring around protected circular pier in natural and low density sediments at flow intensity of 0.95. In both experiments there is a lag time in scouring till the scour hole undermines the collar and reaches the piers periphery. For other flow intensities similar results were achieved.

Experiments also showed that the maximum scour depth is similar in both natural and low density sediment. According to Zarrati et al (2004) and Mashahir (2007) the maximum scour depth around protected circular pier at flow intensity of 0.95 is equal to 1.7D. Approximately the same result was achieved for low density sediment in the same flow condition (i.e. 1.8D). Table 3 compares the maximum scour depth at both circular and rectangular sediment in natural (Previous works) and low density sediments (Present study). Though the relative equilibrium depths are approximately similar, the time to reach equilibrium condition diminishes to less than 10 hours in low density sediment.

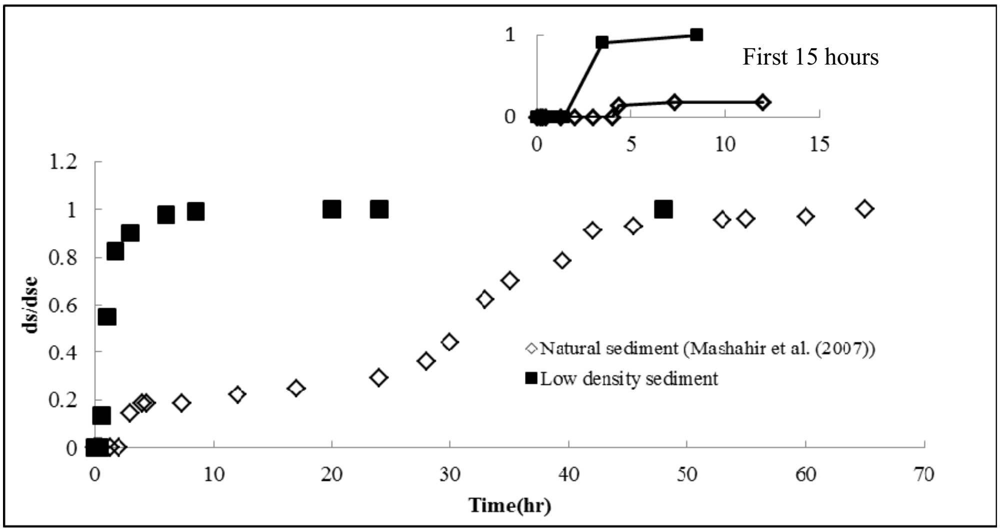

Fig. 6 Time development of scouring around a protected circular pier in natural and low density sediments at flow intensity 0.95

Table 3 Maximum scour depth at protected circular and aligned rectangular piers in natural (Zarrati et al, 2004 and Mashahir et al., 2007) and low density sediments (the present study)

Flow intensity (u_*/u_{*c})	Circular pier		Rectangular pier					
	d_s/D		d_s/D					
	Natural sediment	Low density sediment	Natural sediment			Low density sediment		
			0	5	10	0	5	10
0.95	1.7	1.8	1.4	1.6	2.4	1.36	1.45	2.26
0.9	1.65	1.58	1.1	0.98	2.1	0.94	0.96	1.76

4. Efficiency of collar

4.1. Circular pier

In all flow intensities, at the beginning of the experiment, scouring started downstream of the collar under the action of wake vortices and then grooved towards upstream along the rim of the collar. In flow intensities u^*/u^*_c=0.75 and 0.85 the collar was not undermined and maximum scour depth was observed downstream of the collar. At u^*/u^*_c of 0.9 and 0.95 collar was eventually undermined and maximum scour depth happened at the pier nose. Table 4 summarizes the tests results. The results contain relative scour depth, location of maximum scour depth and scour reduction in comparison with unprotected pier. The later shows the efficiency of the collar. From this table, it is obvious that the efficiency of collar increases by decreasing the flow intensity.

Table 4 Experimental results in circular pier protected with a collar

Flow intensity	d_{se}/D	location of maximum scour depth	Scour reduction (%)
0.95	1.8	nose of pier	21%
0.9	1.58	nose of pier	28%
0.85	0.93	downstream of collar	53%
0.75	0.6	downstream of collar	63%

4.2. Rectangular pier

In these test series, the rectangular pier protected with a collar was installed aligned with the flow and at different angles. Table 5 shows the summary of all experimental results.

For aligned pier the trend of scouring was similar to a circular pier; scouring began at the downstream end of the pier due to wake vortices, extended towards rim of the collar and upstream face of the collar. The process of scouring development for rectangular pier was longer than the circular pier. It can be seen that, the efficiency of collar increased from 26% to 60% as the flow intensity decreases from 0.95 to 0.75. Furthermore only in u^*/u^*_c=0.95 the collar was undermined.

Experimental results with the pier skewed at 5°, 10° and 20° showed that scouring was first occurred along the leeward side of the pier under the sucking effect of the wake vortices. Later in the experiment and in higher flow intensities the collar was undermined and the deepest scour hole eventually occurred upstream of the pier face at 5° to downstream face at 20°. In addition, by increasing the skew angle of the pier the maximum scour depth increased.

As is shown in Table 5, at u^*/u^*_c=0.95 to 0.75 and with 5° skewed pier, collar could reduce the maximum scour hole from 24% to 50% respectively. Similar to aligned pier, the 5o skewed pier was undermined only in u^*/u^*_c=0.95. Experimental results for the pier skewed at 10° showed that in all flow intensities except 0.75, the collar was undermined. Furthermore in 10° skewed pier, collar reduced the maximum

Table 5 Experimental results with rectangular pier protected with a collar

Angle of attack	0˚			5˚		
Flow intensity	d_{se}/D	Location of maximum scour depth	Maximum scour Reduction (%)	d_{se}/D	Location of maximum scour depth	Maximum scour Reduction (%)
0.95	1.36	nose of pier	26	1.44	nose of pier	24
0.9	0.94	downstream of collar	47	1.28	downstream of collar	31
0.85	0.72	downstream of collar	54	0.92	downstream of collar	45
0.75	0.5	downstream of collar	60	0.7	downstream of collar	50

Table 5 Experiments result with rectangular pier (continued)

Angle of attack	10˚			20˚		
Flow intensity	d_{se}/D	Location of maximum scour depth	Maximum scour Reduction (%)	d_{se}/D	Location of maximum scour depth	Maximum scour Reduction (%)
0.95	2.26	along the pier	21	3.12	along the pier	20
0.9	1.76	along the pier	33	2.12	along the pier	33
0.85	1.2	along the pier	50	1.74	along the pier	37
0.75	0.92	downstream of collar	56	1.06	downstream of collar	60

scour hole from 21% to 56% compared with the unprotected pier as flow intensity reduced from 0.95 to 0.75. In experiment with 20° skewed pier similar to the pier skewed at 10˚ the deepest scour hole was observed near the pier's tail and collar was undermined in all flow intensities. Results showed that collar reduced the maximum scour hole from 20% to 60% as flow intensity decreased from 0.95 to 0.75.

Fig. 7 summarizes all results of tests at different flow intensity and skewed pier. This figure shows that by increasing the skew angle of pier, efficiency of collar decreases.

5. Conclusion

Scouring around piers protected with a collar installed at the streambed level was studied. Experiments were conducted at various flow intensities and with circular and rectangular piers aligned as well as skewed at different angles. The collar was 3 times wider than the circular pier diameter or rectangular pier width in all experiments. Since time of equilibrium increases considerably with a collar (more than 1000 hours in lower flow intensities), low density sediment was used to accelerate the scouring development.

Comparison with available results of natural sediment showed that, though the relative equilibrium depths were approximately similar, the time to reach equilibrium condition diminished to less than 10 hours with low density sediment.

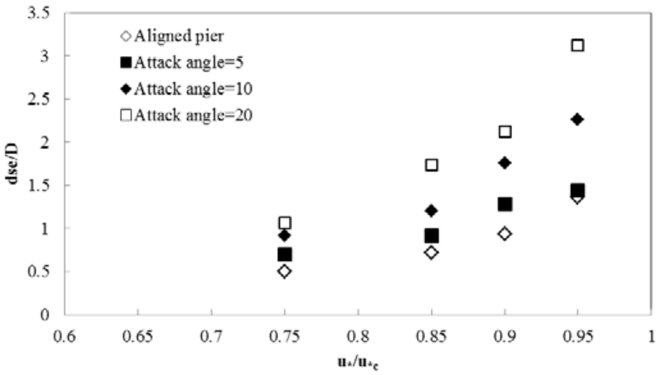

Fig. 7 Variation of maximum scour depth (d_{se}/D) at different flow velocity (u^*/u^*_c) and different pier skew angles in protected rectangular pier

Results of the present study are summarized as follows:

1) In circular piers, collar reduced the scour depth from 21% to 63% for flow intensity of 0.95 to 0.75 in comparison with unprotected pier. Therefore by decreasing the flow intensity, the efficiency of collar increased. The collar was undermined only at flow intensities of 0.9 and 0.95.

2) In aligned rectangular pier, collar reduced the scour depth from 26% to 60% for flow intensity of 0.95 to 0.75 in comparison with unprotected pier. In this case the collar was only undermined in flow intensity of 0.95 and therefore the maximum scour depth occurred at the pier nose. In lower flow intensities the collar was not undermined and max scour depth occurred at downstream of the pier location.

3) By increasing the skew angle of rectangular pier, the efficiency of collar decreased. For example at flow intensity of 0.9 by increasing the pier skew angle from aligned to 20° the collar efficiency decreased from 47% to 33%.

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Notation

d_{50} = median sediment grain size;
d_s= depth of scour hole;
d_{se}= equilibrium scour depth;
Y_1= upstream flow depth;
D = pier diameter (Circular pier) or width (rectangular pier);
σ_g = geometric standard deviation of sediment grading;
u^* = upstream undisturbed bed shear velocity;
u^*_c = critical shear velocity of the bed material;
N = shape factor equal to 1 for circular, and 1.25 for rectangular pier;
F_d = densimetric particle Froude number $(V/(g'd_{50})^{1/2})$;
V = approach flow velocity;
g' = reduced gravitational acceleration $g((\rho_s/\rho)$-1);
ρ = fluid density respectively;
ρ_s = sediment density;
g = gravitational acceleration;
t = time.
u^*/u^*_c = flow intensity;
Q = discharge;
T_e =time to reach equilibrium scour depth;