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Reduction of local scour around bridge pier groups using collars

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Abstract

In this paper reduction of scour around group of two and three piers using circular collar has been carried out for the case of clear-water flow over uniform sediment. The efficiency of collars, with different sizes and spaces between piers is studied through experiments in group of two and three piers. The result reveals that collar has more influence in reduction of scour depth in rear piers than the first pier. Also, when the spacing between the piers increases the area without protection between the piers is washed away resulting deeper scour holes at the rear piers.

Key Words: Scour, Bridges, Group piers, Collar

1 Introduction

Recent scour-related bridge catastrophes through out the world have attributed general attention (Johnson and Dock 1996; Lagasse et al., 1995). The two major countermeasure techniques employed for preventing or minimizing local scour at bridge piers can be classified into two categories: (i) bed-armoring countermeasures and (ii) Flow-altering. In the former case, the objective is to combat the erosive action of the scour inducing mechanisms using hard engineering materials or physical barriers such as rock riprap. In the latter case, the objective is to either inhibit the formation of the scour inducing mechanisms or to cause the scour to be shifted away from the immediate vicinity of the pier. Chiew and Lim (2000), Lauchlan and Melville (2001), and Dey and Rajkumar (2007) focused on the first category and using armoring devices for reducing local scour at bridge piers. Efforts have been made to reduce scour by using submerged vanes (Odgaard and Wang, 1987), a delta-wing-like fin in front of the pier (Gupta and Gangadharaiah, 1992), and slot through the pier (Chiew, 1992; Kummar et al., 1999).

The primary objective for the present study is to determine the scour-reduction efficiency of collars in bridge pier groups. The second objective is to investigate the effects of space between two and three pier groups with or without collar on local scour.

The scour-reduction efficiency of collars was established in earlier studies of Schneible (1951), Chabert and Engeldinger (1956), Thomas (1967), Tanaka and Yano (1967), Neill (1973), Ettema (1980), Dey (1997), Kummar et al. (1999), Zarrati et al. (2004), Sani Khani et al. (2008), Alabi (2006), and Moncada-M et al. (2009). Local scour around bridge pier and pier groups was investigated by Timonoff (1929), Laursen and Toch (1956), Dietz (1973), Hannah (1978), Haney and Herbich (1982), Elliott and Baker (1985), Nouh (1986), Jones (1989), Fotherby (1992), Chan and Lam (1993), Fotherby and Jones (1993), Vittal et al. (1994), Sheppard et al. (1995), Dey et al. (1995), Nazariha (1996), Rahman and Haque (2003), and Ashtiani and Beheshti (2006).

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Zarrati et al. (2006) investigated the efficiency of collars (continuous or independent) on two pier groups, and combination of continuous collars and riprap. Their results showed that continuous collars and riprap have the most influence in scour reduction. In practice it is difficult to construct continuous collars on piers with large spacing, so it is better to use extra pier. However, the effect of collars with more than two pier groups is ignored by earlier researches. The present study considers the effects of collars in two and three pier groups with various sizes of collars and different spacing of pier groups under clear water conditions.

2 Local scour mechanisms and effect of collar

The flow pattern and mechanisms of scouring are very complicated and the complexity of flow increases with the development of the scour hole (Ghodsian and Vaghefi 2009). The basic mechanism causing local scour at piers is the down-flow at the upstream face of the pier and formation of the horseshoe vortex (HSV) at the base of the pier. The down-flow is believed to be the primary cause of scour at piers. The horseshoe vortex thus developed due to the separation of flow at the edge of the scour hole upstream rolls to form a helical flow, which is similar to the ground roller downstream of a dune crest. The horseshoe vortex is a consequence of scour, not the primary cause of scour, pushing the down-flow inside the scour hole closer to the pier. Separation of the flow at the sides of the pier also creates the so-called wake vortices. These vortices are unstable and shed alternatively from each side of the pier. They act as little tornadoes lifting the sediment from the bed and form a scour hole downstream of the pier (Heidarpour et al., 2003; Muzzammil et al., 2004; Raikar and Dey, 2004; Zarrati et al., 2006). Figure 1 shows the flow and scour pattern at a circular pier.

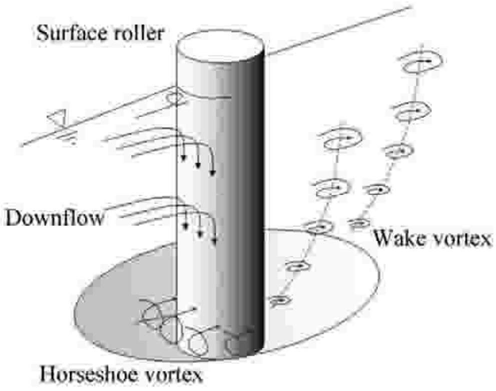

Fig. 1 Illustration of the flow and scour pattern at a circular pier

In addition to parameters affecting scouring around a single pier, for a pier that is a part of group piers, group effects are also important. For two or more than two piers in line (aligned with the flow), reinforcement and sheltering, are additional parameters that affect the depth of the local scouring. Reinforcement is when a downstream pier is placed so that piers' scour holes overlap. This aids in the removal of the sediment from around the upstream pier increasing its scour depth. The presence of the upstream pier causes a sheltering effect and reduction of the effective approach velocity for the downstream pier. This effect reduces the scouring of the downstream pier.

A collar at any level above the bed divides the flow into two regions above and below the collar (Fig. 2). For the region above the collar, the countermeasure acts as an obstacle against the down flow due to which the down flow loses its strength on impingement at the bed. For the region below the collar, the down flow and the horseshoe vortex strength are reduced. However, the efficacy of a collar depends on its size and the location on the pier with respect to the bed. The efficiency of a collar increases at lower elevations since less flow can penetrate below it (Tanaka and Yano, 1967; Moncada-M et al., 2009). In particular, when a collar is installed below the bed level, although the scour depth in front of pier may reduce with respect to the case of a collar set at the original be level, the extension of the scour hole at the pier and the scour depth downstream of it may increase (Kumar et al., 1999).

Zarrati et al. (2004) in their work with rectangular piers showed that lowering the elevation of collar below the streambed level increases the extension of the scour hole around the pier, and the depth of the scour hole downstream of the collar. In this study collars were installed at the initial bed level for all experiments.

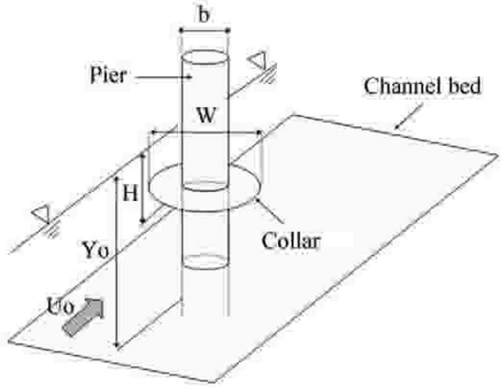

Fig. 2 Collar on pier

3 Experimental setup

The experiments were carried out in a 7 m long, 0.32 m wide, and 0.36 m deep, Plexiglas-sided flume. The working section, in which piers were located, was 1 m long with a recess on the bed 0.1 m deep and was situated 3 m downstream from the entrance of the flume in order to generate fully developed flows. The recess was filled with uniform sediment with the mean particle sizes of 0.72 mm and geometric standard deviation of particles was σ_g=1.23. Based on Raudkivi and Ettema (1983), for non-ripple-forming sediments ($d_{50} \geq 0.7$ mm), experiments can be run successfully with a flow condition, $u_*=0.95u_{*c}$, without the upstream bed being disturbed by the approach flow where u_* is the shear velocity and u_{*c} is the critical shear velocity. According to Chiew and Melville (1987) when geometric standard deviation of particles are lower than 1.3, the effect of non-uniformity sediment on the depth of scour hole becomes negligible. The water depth in the flume is adjusted by the position of the sluice gate at the downstream end of the flume.

Cylindrical Perspex pipes with diameter of 20 mm were used as pier models. According to Chiew and Melville (1987) the pier diameter should not be more than 10% of channel width. Pier diameters were selected so that the effect of flume sidewalls on the depth of scour hole becomes negligible. Since b/d_{50} (b: pier diameter and d_{50}: diameter of bed material) was more than 20-25 (b/d_{50}=27.8) the effect of sediment size on the depth of scour hole becomes negligible (Raudkivi and Ettema, 1983).

Some researchers (e.g. Dey 2001; Dey and Kumar 2002) studied the incipient motion of sediment particles. Since the maximum depth of scour occurs at the threshold of bed material motion, all the tests were conducted at this condition (Raudkivi, 1990). The threshold of bed material motion was found by experiment when the pier was not installed. Threshold of material motion was defined as a condition such that although finer bed materials move, the overall average elevation of the bed is not lowered more than 2–3 mm during the period of the experiment. These tests showed that with a flow depth of 0.12 m and a flow rate of 11 lit/s, the bed material would be at incipient motion condition. The ratio of shear velocity in these experiments to the critical shear velocity calculated from Shields' diagram was about 0.95. Development of the scour hole at the pier perimeter was measured by a periscope installed inside the pier. Tests were conducted on a group of two and three piers in line (aligned with the flow) (Fig. 3). For each group the spacing S/b of the piers was varied, where S=the distance between center of the piers sections and b=pier diameter. Development of a scour hole around group of two and three piers with a collar located at the bed level and 2 and 3 times wider than the pier diameter was studied. The tests are summarized in Table 1.

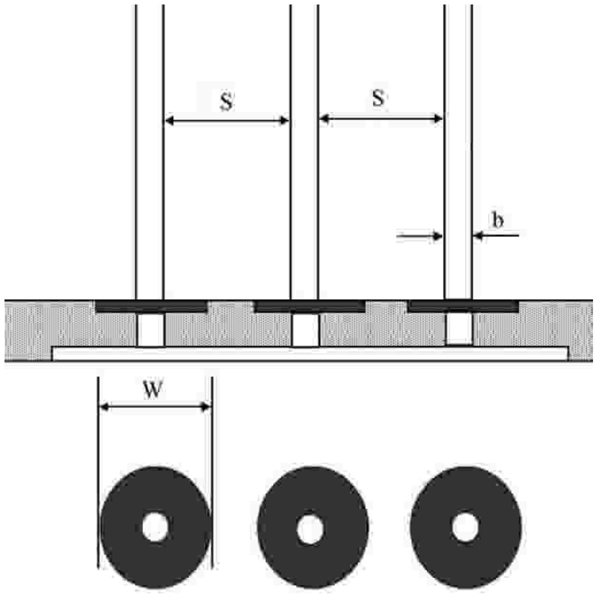

Fig. 3 Three piers in line with collar

Table 1 Summary of experiments

Row	Piers arrangement	Collar	*S/b*	*W/b*
1	Single	without	–	–
2	In line(2 piers)	without	3,4	–
3	In line(2 piers)	With	3,4	2,3
4	In line(3 piers)	without	3,4	–
5	In line(3 piers)	With	3,4	2,3

4 Time of experiments

The definition of time to scour equilibrium adopted for a given test plays an important role in the results obtained and also in the conclusions reached. Several researchers have come up with different definitions of time to equilibrium scour depth. Based on timescale studies on local scour, Melville and Chiew (1999) concluded that 50–80% of the equilibrium scour depth develops at a stage after 10% of the time to equilibrium, depending on the approach flow velocity. For instance, it can be stated that if a design flood lasts for a period of 10% of the time to equilibrium then the design scour depth is 20–50% less than the equilibrium scour depth, depending on the prevailing flow intensity. Therefore, determination of scour depth development corresponding to a peak flood flow and time-to-peak of flood hydrograph is important. Melville and Chiew (1999) defined the equilibrium time when the scour depth did not change by more than 5% of the pier diameter over a period of 24 h, Eq. (1) present above definition mathematically:

$$\frac{d(ds_e)}{dt} \leq \frac{0.05b}{24h} \tag{1}$$

In which ds_e= equilibrium scour depth, and b=pier diameter.

Melville and Chiew (1999) developed the following equation for predicting the time to reach the clear-water equilibrium scour depth.

$$\frac{ds}{ds_e} = \exp\left\{ -0.03 \left| \frac{u}{u_c} \ln \frac{t}{t_e} \right|^{1/6} \right\} \tag{2}$$

In which ds= scour depth, u= mean velocity, u_c=critical velocity, and t=time.

Figure 4 shows comparison of experimental values of ds/b and calculated values using Eq. (2). It can be seen from the figure the depth of scour increases with time and there is a good agreement between experimental data and Eq. (2) in equilibrium time. It was found that 36 hours was necessary for reaching equilibrium scour depth, and observed that 90% equilibrium scour depth occurred in 1/3 equilibrium time.

According to Ettema (1980) there were three distinct phases of the scour process. He referred to the three phases as the initial phase, the erosion phase, and the equilibrium phase. In the initial phase, rapid scouring occurs due to the down-flow at the pier face impinging on the planar bed. This phase is characterized by a steep on the graph. The second phase, which is known as the principal eroding phase, starts when the horseshoe vortex commences to dominate the scouring process. The main erosion occurs at the front of the pier. During the erosion phase, the scour hole develops as the horseshoe vortex grows in both size and strength. The slope of the line in this phase is considerably less than that of the previous phase. In the final stage, called the equilibrium phase, the equilibrium depth has been reached and hence no further scour occurs as the horseshoe vortex ceases to excavate further. At this point, the slope of the line is zero. Melville and Chiew (1999) concluded that both the time required to reach equilibrium scour and the depth of scour at equilibrium are influenced similarly by the same set of flow and sediment parameters.

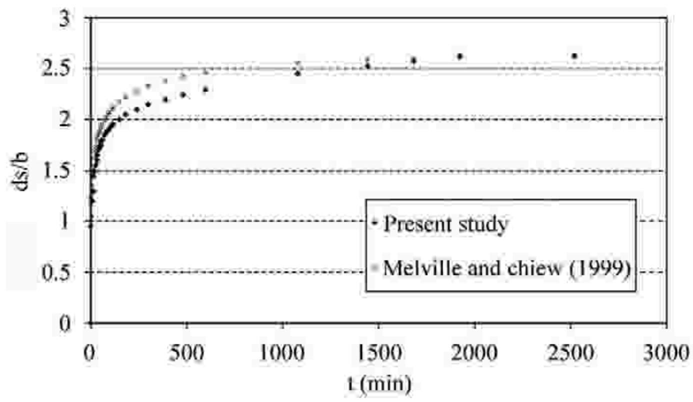

Fig. 4 Comparison of the experimental values of *ds* with the calculated ones by Melville and Chiew's equation

Faruque and Nago (2003) stopped their experiments when there was less than 1 mm scour by 1 h. Kumar et al. (1999) stopped their experiments when the scour depth did not change by more than 1mm over a period of 3 h. In this study the criteria of Kumar et al. (1999) was employed for equilibrium scour time.

5 Experimental results

5.1 Group piers without collar

Experiments could be classified in two groups: the group piers without collar and with collar. In this case, two different group piers with two and three piers in line were tested with spacing $S/b=3$ and compared with single pier, as shown in Fig. 5. In group of two piers during the experiment, scour depth of first pier is greater than single pier due to the reinforcing effect, and because of sheltering effect scour depth of the second pier is less than the single pier. In group of three piers the scour depth of the second pier is equal to the single pier due to the interaction of reinforcing and sheltering effect, and the equilibrium scour depth for the first and the third piers is equal to front and rear pier in group of two piers respectively.

Results of experiments in the present study were compared with an earlier work by Hannah (1978). Hannah studied the depth of scour hole around two piers in line and two transverse piers with different spacing, without collar. In these tests 33 mm diameter circular piers were used. Diameter of bed material was 0.75 mm with geometric standard deviation equal to 1.32. The ratio of shear velocity of these experiments to that calculated from Shields' diagram was 0.92. Flow velocity in this condition was 0.285 m/s and flow depth was 140 mm. With performing a long-term test in 24 h with a single pier, Hannah (1978) showed that 80% of scour depth occurred in first 7 h and all tests with pier groups were carried out for 7 h. Results were then extrapolated to find the maximum depth of scour. Figure 6 shows the ratio of group piers scour depth ($ds(g)$) to single pier scour depth (ds) versus S/b. As shown in Fig.6, the trend of experimental results is the same as Hannah's study (1978).

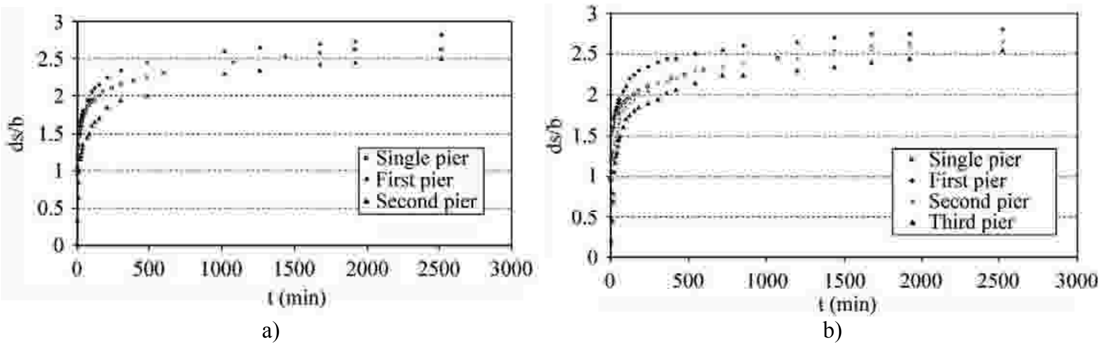

Fig. 5 Time development of scouring at a) single pier and group of two piers, b) single pier and group of three piers

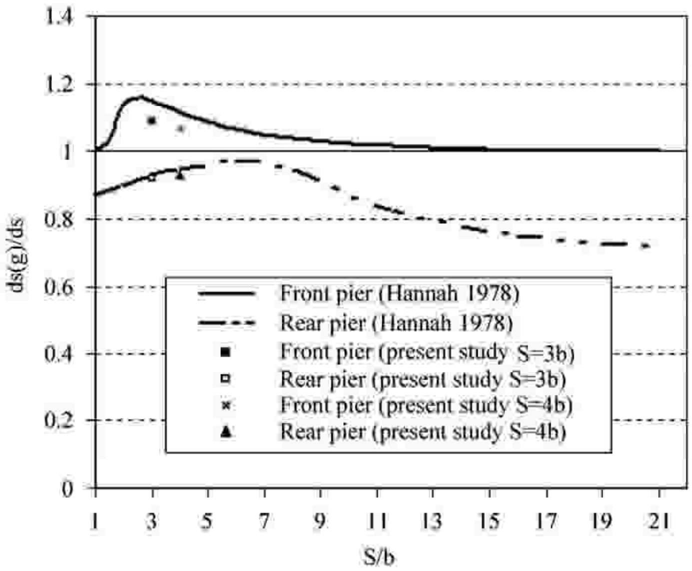

Fig. 6 Comparison of the present study with Hannah's study (1978)

5.2 Group piers with collar

Experiments with collar showed delay in scouring in all of the three piers. Figure 7 shows comparison of scouring depth at group of three piers with and without collar with S/b=3 and w/b=3.The delay of third pier is more than first and second piers. At the beginning of the test, wake vortices swept up sediments at the back of the first pier, and after several seconds they swept up sediments between second and third piers however, the scouring rate is less than rate of scour hole between first and second piers. The scour hole was developed at back of the third pier. Two grooves were also gradually developed at the down stream rim of the front pier's collar. They gradually developed and extended upstream and eventually reached at upstream edge of the front collar. At this moment, the flow was intensified through the groove, reducing the side slope of the groove and with sediment removal from the grooves the scour hole extended upstream of the pier and below the collar. By penetration of the flow beneath the front edge of the collar the rate of sediment removal increased. Maximum depth of scour hole was in front of the first pier and equal 5.6 cm.

In all experiments with collar the equilibrium time was longer than those without collar because scouring mechanism started with delay for the collar case. According to Fig. 7, the pier without collar has steeper slope in initial and erosion phases (defined by Ettema, 1980), so it can be inferred that collar reduce down-flow and horseshoe vortex in each three piers. Maximum scour depth in the first pier with and without collar is equal; therefore reinforcement effect counteracted the effect of the collar in this case. In the second and the third piers due to the sheltering effect, collar decreases scour depth considerably. Reduction of scour depth is increased in the third pier because the sheltering effect is increased as well. Reduction of scour depth in the second and the third pier is 19% and 45% respectively.

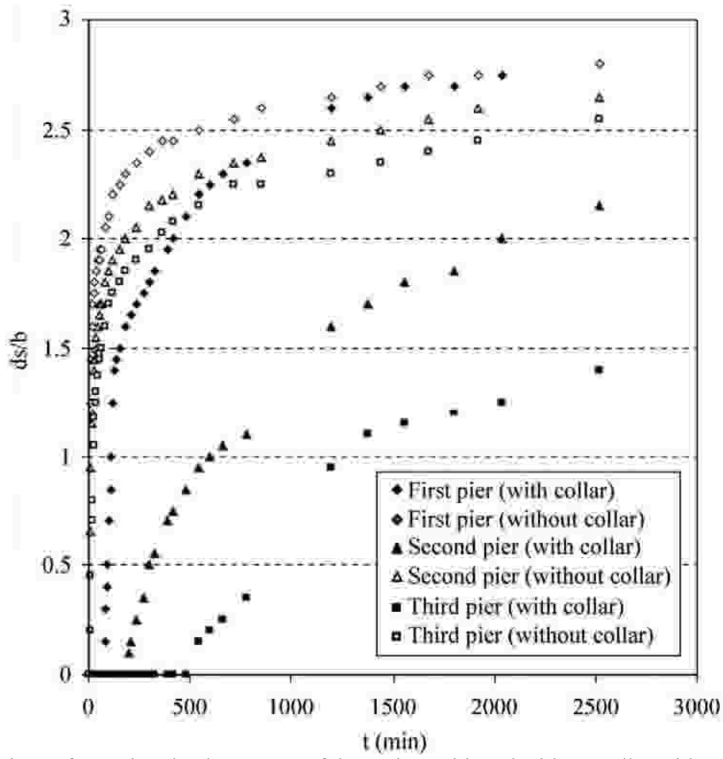

Fig. 7 Comparison of scouring depth at group of three piers with and without collar with *S/b*=3 and *w/b*=3

In group of three piers with collar for *S/b*=3 and *w/b*=2 (Fig. 8), the delay time is decreased and the rate of the reduction of scour depth in the second and the third piers is also decreased, so it can be concluded that when the size of the collar is decreased the efficiency of collar in reduction of scour depth is decreased as well. Reduction of scour depth in the second and the third piers was 4% and 8% respectively. It was observed that in the experiment where the space between two piers uncovered by the collar, in the second pier, the slope of diagram was changed from the initial phase to the erosion phase sooner than the one where the space between two piers covered by the collar (Fig. 7).

To investigate the influence of collar size, two different sizes of collar (*w/b*=2 and 3) with the same space between pier *S/b*=3 were compared in group of three piers without collar, as shown in Fig. 9. Figure 9-a reveals that using collar caused the delay in scouring mechanism and when the size of collar increased the delay time is increased. First pier with *w*=3*b* has longer equilibrium time due to the longer delay time. In the first pier, collar can not cause reduction in maximum scour depth due to the reinforcement effects counteract the effect of collar. In the first pier collar only caused reduction in scour depth in initial time. In the second and the third piers when the size of collar is increased, the delay time and equilibrium time are increased similar to the first pier. In the second and the third piers with increasing the size of collar the maximum scour depth is decreased as well. The efficiency of collars to reduce the scour depth in the third pier is greater than the second pier due to increasing the sheltering effect.

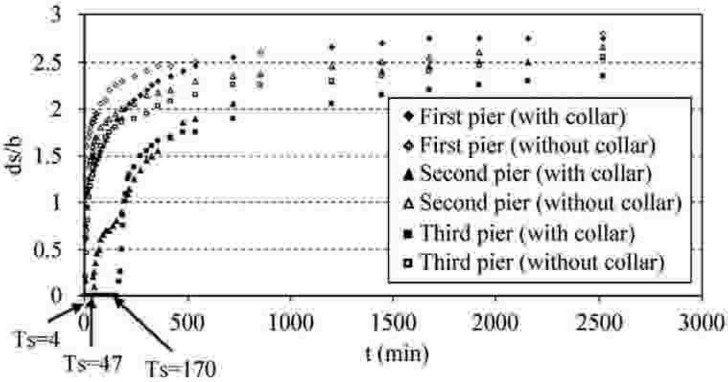

Fig. 8 Time development of scouring depth at group of three piers with and without collar with *S/b*=3 and *w/b*=2

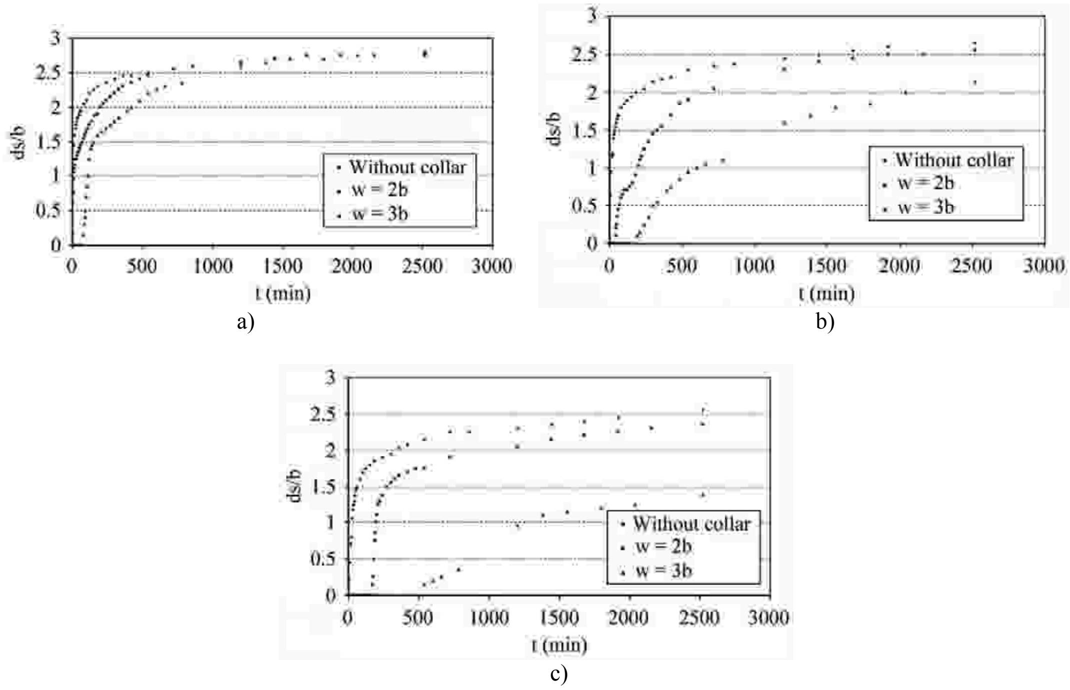

Fig. 9 Time development of scouring depth at group of three piers with and without collar
a) First pier, b) Second pier, c) Third pier

In this case, two different spacings of *S/b*=3 and 4 were tested for a group of three piers in line with *w/b*=2. In this experiment the space between two piers were not completely covered with collar. In the first pier, both spaces had the same delay time and maximum scour depth because the space between piers had no effect on efficiency of collar. In the second and the third piers, with increasing the space between the piers, the delay time was increased and with decreasing this space, the scour depth was decreased due to increasing the sheltering effect. As the spacing between the piers increases the area without protection between the piers is washed away resulting deeper scour hole at the rear pier. According to Hannah (1978) in group of two piers without collar, increasing the pier spacing in the range of 2<*S/b*<4 did not affect significantly the scour depth of the front pier. The same result was observed by Zarrati et al. (2006) in the case of group of two piers with or without collars.

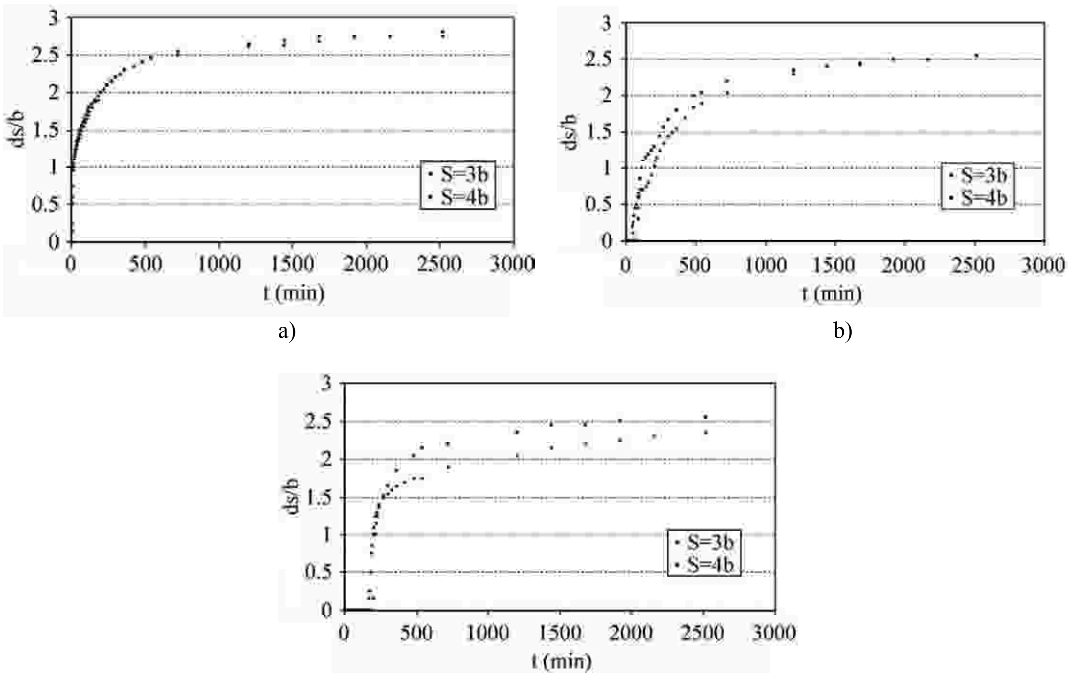

Fig. 10 Time development of scouring depth at group of three piers with collar
a) First pier, b) Second pier, c) Third pier

Reduction of maximum depth at group of three and two piers with *S/b*=3 and *w/b*=3 was shown in Fig. 11. The efficiency of collar in reduction of scour depth in rear pier is larger than the other piers due to a weaker down flow at upstream face of the rear pier, in the presence of a collar. Thus, the scour depth was reduced at the rear pier resulting less reinforcing effect. Nevertheless, the maximum scour depth was observed at upstream face of the front pier for both cases. Comparison of reduction in scour depth at group of three and two piers was shown in Table 2. The best efficiency of collar was observed when the space between collars completely covered with collar, in the case of *S/b*=3 and *w/b*=3 reduction of scour depth in the first, the second, and the third piers is 0%, 19%, and 45% respectively.

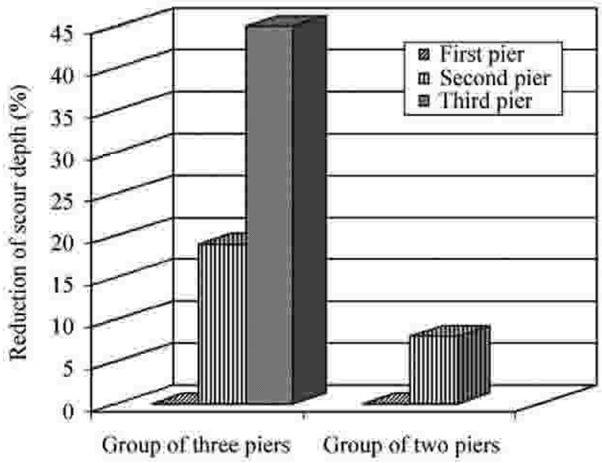

Fig. 11 Reduction of scour depth at group of three and two piers with collar with *S/b*=3, *W/b*=3

Table 2 Reduction of scour depth at group of three and two piers

Group pier	Number of pier	*S/b*	*w/b*	Reduction of scour depth (%)
3	1	3	3	0
	2	3	3	19
	3	3	3	45
3	1	3	2	0
	2	3	2	4
	3	3	2	8
3	1	4	3	7
	2	4	3	17
	3	4	3	6
3	1	4	2	0
	2	4	2	0
	3	4	2	0
2	1	3	3	0
	2	3	3	8
2	1	3	2	0
	2	3	2	4
2	1	4	3	4
	2	4	3	44
2	1	4	2	4
	2	4	2	24

6 Conclusion

Collars are not only effective at reducing scour but are also much more economic when they are compared to countermeasure techniques like riprap. In this paper reduction of scour around group of two and three piers using circular collar has been carried out for the case of clear-water flow over uniform sediment.

Collars are effective on two and three piers in line, and reveal more efficiency when the space between piers completely covered with collars. The influence of collar in reduction of scour depth in rear piers is more remarkable than the first pier due to a weaker down flow at upstream face of the rear piers.

Using collar caused the delay in scouring mechanism and by increasing the size of collar the delay time was increased as well. As the spacing between the piers increases, the area without protection between the piers is washed away resulting deeper scour holes at the rear piers.

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Notation

The following symbols are used in this paper:
b = pier diameter;
S = distance between center of the piers sections;
ds = depth of the scour hole;
$ds(g)$ = group piers scour depth;
ds_e= equilibrium scour depth;
u = velocity;
u_c= critical velocity;
w = collar diameter; and
t = time.