EFFECT OF COLLAR ON TIME DEVELOPMENT AND EXTENT OF SCOUR HOLE AROUND CYLANDRICAL BRIDGE PIERS

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Abstract An experimental approach was carried out to study the time development and extension of scouring around a circular pier protected by collars. The experiments included the study of scouring around an unprotected pier as well as the pier protected with collars located at different levels. Width of collars was 3 times the pier diameter. It was found that with collars, though the scour depth and the rate of scouring decrease, extent of the scour hole increases. Number of collars and their levels are effective factors on the equilibrium depth and extension of scouring. Different collar arrangements were tested for an optimum result. Best results were found with one collar at the bed level and another one at one pier diameter below the bed level. In this arrangement, scouring did not penetrate below the lower collar even after 200 hours. Therefore, with the lower collar at 1D below the bed level scour depth reduced by more than 50% whereas, the area of scouring increased by 30% compared with an unprotected pier.

Keywords Local scour; Application of collars; Time development of scour depth; Extent of scour hole.

چکیده در این تحقیق از روش آزمایشگاهی برای مطالعه توسعه زمانی و گستردگی حفره آب‌شستگی در اطراف پایه استوانهای شکل پل استفاده شده است. به این منظور آزمایش‌هایی بر روی پایه محافظت نشده و محافظت شده با طوق انجام گرفت. عرض طوق مورد استفاده ۳ برابر قطر پایه می‌باشد. بررسی نتایج حاصل نشان می‌دهد که استفاده از طوق موجب کاهش عمق و نرخ آب‌شستگی و در عین حال افزایش گستردگی حفره آب‌شستگی می‌شود. همچنین، آزمایش‌هانشان داد که تعداد طوق‌های نصب شده و تراز نصب آنها به عنوان فاکتورهائی مهم بر روی عمق و گستردگی نهایی حفره آب‌شستگی موثر می‌باشند. بر این اساس آرایش مختلف طوق‌ها برای رسیدن به نتیجه بهینه مورد آزمایش قرار گرفتند. بهترین نتیجه برای شرایطی حاصل شد که دو طوق یکی در تراز بستر و دیگری در ترازی به میزان قطر پایه در داخل بستر نصب می‌شوند. در این حالت حتی بعد از گذشت ۲۰۰ ساعت، آب‌شستگی به زیر طوق دوم راه نیافت. در نتیجه با نصب طوق دوم با عمقی به میزان قطر پایه در داخل بستر در مقایسه با پایه محافظت نشده، عمق آب‌شستگی نهایی به میزان بیش از ۵۰٪ کاهش یافته و از طرفی گستردگی حفره در اطراف پایه به میزان ۳۰٪ افزایش می‌یابد.

1. INTRODUCTION

Scouring is one of the most important causes of bridge failure and the major factor that contributes to the total construction and maintenance costs of bridges in the world [1]. This phenomenon results from a complex vortex system which forms around the bridge piers. There are two types of vortices around a pier. Horse shoe vortex at the front side of the pier, and wake vortices due to separation area at sides and downstream of the pier [2]. Numerous methods have been studied to control local scouring around bridge piers. Collars as an effective scour countermeasure are plates which are attached to a pier and act as a barrier to the down flow, thereby prevent its direct impingement into the streambed [3- 6]. In addition to reducing the scour depth, collars increase considerably the time development of scouring. Collars may therefore be very effective in reducing the risk of bridge failure when duration of the flood flow is not long.

A Collar attached to the pier at the bed level prevents scouring around the pier in the beginning of the experiment. However, a scour hole is then formed downstream of the collar which slowly develops towards upstream. This scour hole extends along the rim of the collar until it reaches the front edge of the collar. The scour hole then penetrates below the collar and undermines it. When the collar is undermined, flow penetrates below the collar and scouring rate increases again. Depth of the scour hole increases till equilibrium condition is achieved [7, 8].

Investigations by Zarrati et al. [9] with rectangular pier showed that lowering the collar below the streambed level did not increase the efficiency of collar considerably. This is since the distance above the collar will itself become a part of the scour hole and is washed away very fast. On the other hand, lowering the collar from the streambed increases the extension of the scour hole around the pier, and the depth of the scour hole downstream of the collar. Therefore, they suggested that the best efficiency for a collar is when it is at the streambed level.

Application of double collars to increase their performance was investigated by Zarrati et al. [9]. They preformed an experiment on a rectangular pier with double collar installing at different levels above the bed and found that the efficiency of collars improved in comparison with a single collar.

Mashahir et al. [10] studied experimentally the efficiency of single as well as double collar on cylindrical piers. With about 80 hours duration of experiments, they reported that the most efficient arrangement for reducing scour depth was when a collar was at the streambed level, and another one installed one pier diameter below the bed level.

Despite previous research works, there is not still enough information in literature about the dimensions of the scour hole around a pier when collar is located at different elevations. The extension of the scour hole as well as its depth is important for studying the stability of the piers at the bridge location. Studying the extent of the scour hole around the pier is also important to determine the extension around a pier which may need further protection for example by riprap. In the present work, an experimental investigation is conducted on effect of single and double collars attached to circular pier at different elevations on extent and depth of the scour hole.

2. EXPERIMENTAL SETUP

Experiments were conducted in a straight masonry rectangular flume 10m long, 0.73m wide and 0.5m deep. The test section was in the form of a recess below the flume bed located at the 5m downstream of flume entrance, and was filled by uniform sand. Median size of sand was d_{50}=0.85 mm, with geometric standard deviation of sediment grading $\sigma_g = \sqrt{d_{84}/d_{16}}$ =1.3, where d_a is the size of sediment for which a percent of material by weight are finer, and density of 2650 (Kg/m^3). A circular Perspex pipe was used in this study as the pier model with 0.04m diameter. Collars were made from 2mm thick Perspex sheets with an effective width 'W' equal to three times the pier diameter 'D' were installed around the pier (Figure 1) at various levels from the stream bed. Although wider collars are more effective, construction of collars wider than 3 times the pier diameter was considered impracticable.

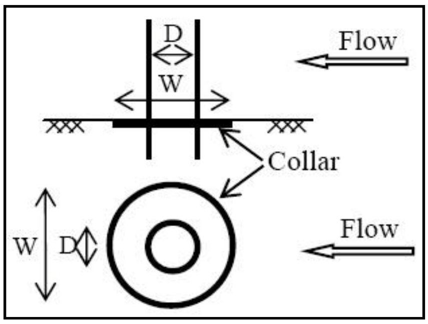


Figure1. Pier with a collar at stream bed

Five different tests were carried out with or without collar at the same flow conditions. These experiments included scouring around an unprotected circular pier as well as the pier protected with single and double collars at different elevations. Experiments were conducted with one collar at or half of the pier diameter below the bed level, and combination of two collars at different levels. All tests conducted in the present study are summarized in Table (1).

Time of experiments was set based on Melville and Chiew [11] definition. According to this definition when depth of the scour hole did not change by more than 5% of the pier diameter over a period of 24 hours, equilibrium condition was achieved. It should be mentioned that since with collar, the scour rate is very low at the beginning of tests, this criterion was considered only after the collar was undermined. Using this criterion, some tests were run for more than 200 hours.

TABLE 1. Summery of experiments

Test No.	Elevation of Collar #1	Elevation of Collar #2	Time of Experiment (h)
(1)	-	-	60
(2)	At the bed level	-	100
(3)	At 0.5D* below the bed	-	250
(4)	At the bed level	At 0.5D below the bed	170
(5)	At the bed level	At D below the bed	200

*D is the pier diameter

Shear stress at the working section u_* was determined by calculating the water surface profile and slope of the energy line along the flume when the pier was not installed. To calculate water surface profile bed roughness was determined based on absolute bed material roughness d_{90}. The calculated water elevation upstream of the flume was then compared with the measurement result, and if they were different, the bed roughness was slightly modified. Knowing the bed shear stress, critical bed shear stress u_{*c} was found from the Shields' diagram. Experiments were conducted at clear water condition with an average relative shear stress u_*/u_{*c}=0.8. 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.

3. EXPERIMENTAL RESULT

Figure (2) shows the formation of local scour around a pier protected with a collar. The results of all experiments are presented in Table (2). In this table, scour depth as well as its extension at the end of each experiment are given relative to similar values in the unprotected pier. The scour extension in this table includes scour hole area all around the pier "A_{se}" at the stream bed level, scour hole length "L" at upstream face of the pier (distance from the pier upstream surface to upstream edge of the scour hole) and scour hole width "S" (the distance from the pier side surface to side edge of the scour hole). Furthermore, scour extension as well as scour depth around the pier in all experiment are illustrated in Figure (3).

Figure (4) shows the development of scour depth at the upstream face of the pier in all experiment. Horizontal lines in the graphs show constant scour depth at the upstream face of the pier in each experiment before the collar was completely undermined and rate of scouring increases again. However, by increasing the scour depth, the rate of scouring decreases again and tends to zero in equilibrium condition.

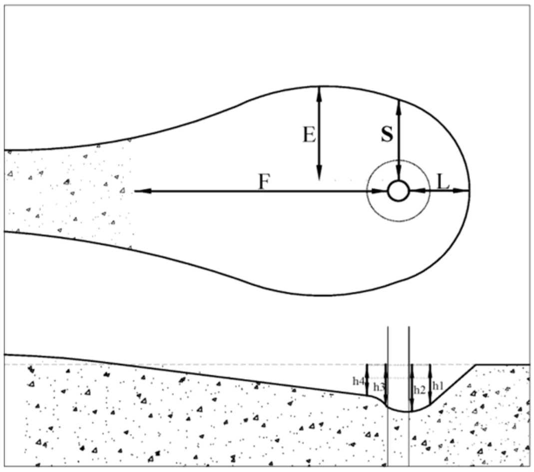
Experimental results in each test are summarized in the following sections:

Figure 2. Formation of local scour around a pier protected with a collar

3.1. Unprotected Pier (Test No. 1) This is a reference test to check the effect of collar on scour depth and extension around the pier. For this test, equilibrium scour depth "d_{se}" was observed at the upstream nose of the pier after 60 hours (Table 1), but more than 90% of d_{se} occurred after 20 hours from the beginning of the experiment (Figure 3). The relative maximum scour depth "d_{se}/D" was measured 2.18, which was in good agreement with empirical equations and previous investigations such as Melville and Sutherland, [12] and Mashahir et al. [10]. Measurements at the end of experiment showed that the relative scour length "L/D" and width "S/D" were about 2.4 and 3.75, respectively. Furthermore, the relative scouring area "$A_{se}/(L\times S)$" was measured about 11.52.

TABLE 2. Results of experiments

Test No.	Time at which scouring penetrated below the collar (h)		Relative scour extension			relative maximum equilibrium scour depth
	upper collar	lower collar	Width	Length	Area	
(1)	-	-	1	1	1	1
(2)	15	-	1.07	1.20	1.15	0.79
(3)	105	-	1.47	1.56	1.48	0.92
(4)	5	50	1.67	1.63	1.72	0.92
(5)	15	not undermined	1.4	1.35	1.31	0.46



Test	L	S	E	F	h1	h2	h3	h4
No. 1	2.40D	3.75D	4.60D	11.5D	-	2.18D	1.90D	-
No. 2	2.90D	4.00D	5.13D	12.0D	1.4D	1.73D	1.40D	1.13D
No. 3	3.75D	5.50D	6.00D	12.5D	1.5D	2.00D	1.38D	0.88D
No. 4	3.90D	6.25D	6.50D	13.5D	2.0D	2.00D	1.38D	1.20D
No. 5	3.25D	5.25D	5.5D	11.5D	1.5D	D	0.8D	0.8D

Figure 3. Extension and equilibrium scour depth around the pier in each experiment

3.2. Pier with a Collar at the Stream Bed Level (Test No. 2) In this experiment, at the beginning of the experiment, scouring started downstream of the pier at the vicinity of the collar due to wake vortices similar to reports by [8, 10, 13]. As shown in Table (2), after 15 hours scour hole penetrated below the collar and reached the front nose of the pier. After this stage, the rate of scouring at upstream face of the pier increased considerably due to action of the horse shoe vortex so that in 10 hours at least 70% of final scour depth occurred (Figure 4). This test continued for 100 hours and the maximum scour depth in this test was reduced by about 20%.

Meanwhile, measurements showed that the scouring area around the pier increased by about 15% (Table 2). Therefore, the scour hole through shallower was more extended around the pier.

Figure (3) shows, the scour hole was wider and longer in the presence of the collar in comparison with unprotected pier. The effect of collar on scouring region is more noticeable for its length at the pier nose rather than its width. The length of the scour hole increased by 20% compared with 7% of its width.

3.3. Pier with one Collar 0.5D below the Bed (Test No. 3) At the beginning of this experiment, the scouring rate was very high so that in less than a minute all materials above the collar were washed away and the upper side of the collar was exposed. However, after that, the collar prevented further scouring and the scour hole was extended gradually in horizontal direction around the collar.

In contrast to the previous experiment (collar at the streambed), in this test the grooves were first formed beneath the collar at the front of it and penetrated beneath the collar till it was completely undermined. As shown in Table (2), it took more than 100 hours for scouring to penetrate beneath the collar and after 155 hours the collar was completely undermined. The equilibrium scour depth was reached after 250 hours. The rate of scouring in this test, after the collar was undermined was significantly less than in Test No. 2 (Figure 4).

The equilibrium scour depth in this test was only about 8% less than unprotected pier. On the other hand, due to the effect of vortices around the pier, the scouring area increased by about 48% with the length and width of the scour hole increased about 56 and 47%, respectively.

3.4. Pier with Double Collars, one at the Bed and one 0.5D below the Bed Level (Test No.4) In this experiment, at first, similar to Test No. 2, scouring started at downstream of the upper collar. Then, two grooves were formed and developed, and after 3 hours they reached the rim of the upper collar. After this stage, by less than an hour, the rim of lower collar was exposed at the downstream side of the pier, and the materials between two collars were washed away quickly. Comparing with Test No. 2, it can be concluded that the lower collar accelerated the material removal at the region between the two collars. It took almost 5 hours for scouring to begin at the pier nose beneath the upper collar (14 hours for Test No. 2) and 20 hours that the upper collar was completely undermined.

The material beneath the lower collar was removed from upstream side of it, similar to Test No. 3. This action proceeded until after about 50 hours from the beginning of the experiment the scour hole reached beneath the lower collar (Table (2) and Figure (4)). The experiment reached the equilibrium condition after about 170 hours. Figure (4) shows two horizontal lines for time development curve in the present experiment due to effect of the two collars. Although, the equilibrium scour depth in this experiment was similar to Test No. 3, the scour hole reached beneath the lower collar faster (Figure (4)). Since the upper collar caused the scour hole to be wider in a shorter time and also the elevation of lower collar was not deep enough, the scour hole undermined it faster compared with Test 3. Hence, compared with Test 3, it can be concluded that the upper collar was not much useful to postpone the scouring process.

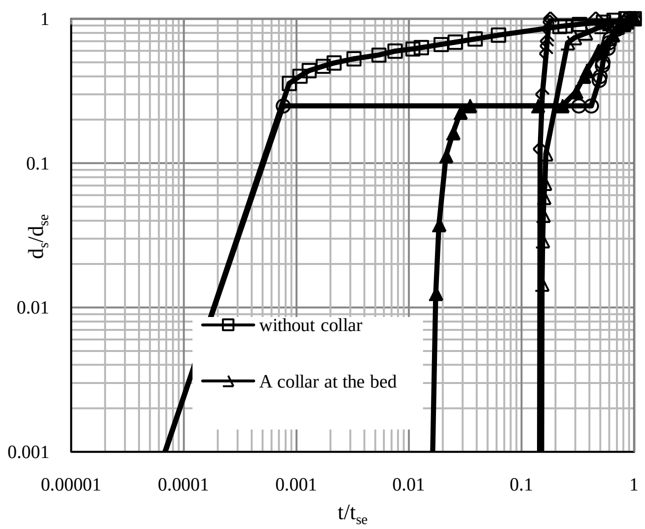


Figure 4. Time development of scouring at the upstream face of the circular pier (d_s is scour depth at time t and d_{se} is equilibrium scour depth)

As shown in Table (2) and Figure (3), effect of the second collar on the extent of scour hole is considerable. The scouring area in the present experiment was the largest of all tests and was about 72% larger than unprotected pier (Test No. 1) and 16% larger than Test No. 3, though the scour depth was not much reduced. Furthermore L and S were about 67 and 63% larger than unprotected pier respectively.

3.5. Pier with Double Collars one at the Bed and another at 1.0D below the Bed (Test No. 5) In this experiment, since the lower collar was deeper, development of scouring below the upper collar was similar to Test No. 2. Eventually, similar to Test No. 2, the scour undermined the upper collar after 15 hours. After the upper collar was undermined the scour rate increased so that after only 6 hours, materials between two collars at upstream of the pier were completely washed away and the surface of lower collar was exposed. However, scouring did not penetrate below the lower collar even after 200 hours (Figure (4)).

Furthermore, at this time, downstream face of the lower collar was not still exposed and relative scour depth at the pier side (d_{se}/D) was 0.8 (Figure (3)). Therefore, the equilibrium scour depth at the pier nose in the present experiment was 54% smaller than unprotected pier.

Measurement for the extent of scouring showed that with this arrangement the scouring area increased for about 31% in comparison with unprotected pier with L and S about 35 and 40% larger than the unprotected pier respectively (Table (2) and Figure (3)). Comparing with Test No. 4, the efficiency of the collars in this test was considerably increased and in the same time the scour area was reduced by 24 %.

4. SUMMARY AND CONCLUSION

In the present study, in order to investigate the collars performance on scouring five different experiments were carried out with a circular pier and single as well as double collars. Furthermore, an experiment was also carried out with an unprotected pier as a reference test to check collars efficiency. The collars were 3D wide and flow intensity in all experiments was equal to 0.8. With collars, the development of the scour hole was considerably postponed. Experimental results also showed that:

1. For a collar at the bed level, equilibrium scour depth decreased about 20% meanwhile the extent of scour increased about 15% in comparison with unprotected pier. On the other hand, the equilibrium time increased about 60%.
2. In experiment with collar at 0.5D below the bed level, though the equilibrium time increased more than 200%, the equilibrium scour depth did not reduce significantly. However, the scouring area around the pier increased about 48%.
3. Efficiency of double collars depends on the elevations of the collars.
4. Applying double collars, one at the bed and another one at 0.5D below the bed level, showed that the collars were undermined faster in comparison with when collars were used individually. With more than 100% longer duration of experiment the equilibrium scour depth decreased about 10%; however, the scouring area around the pier increased more than 70% in comparison with unprotected pier.
5. Applying double collars, one at the bed and another at one of pier diameter (D) below the bed level was the most efficient arrangement for reducing scouring rate and depth. In this test the scour depth reduced by 50% whereas the scour area increased by only 30%.

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