Depth of Scour at Groups of Two Bridge Piers

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Local scour around bridge piers occurs by the action of a complex vortex system. Local scour around bridge piers, has been extensively studied from different points of view and under different flow conditions. However, most of the previous studies were focused on a single pier. In addition to parameters affecting scouring around a single pier, for a pier that is a part of a group of piers, group effects are also important. In the present study the scour depth at groups of two piers is investigated in long term experiments. Piers aligned with the flow and transverse to the flow were considered with spacing "S/b" of 2, 3 and 4, where S is the space between the piers and b is diameter of the piers. Ratio of maximum scour depth to pier diameter (Ys/b) at upstream face of the front pier for two piers in line was measured 2.58, 2.55 and 2.53 for piers with S/b of 2, 3 and 4 respectively. For the rear pier in the same spacing Ys/b was 2.3, 2.28 and 2.25 respectively. Depth of the scour hole measured at the rear pier was more than previously reported. For two piers transverse to the flow the results of the present study showed Ys/b = 3.25, 2.88 and 2.7 for S/b= 2, 3 and 4 respectively which are also deeper than what reported before. Deeper scour holes measured in these studies are attributed to longer time of experiments and higher stresses imposed.

I. INTRODUCTION

A high percentage of bridge failures in recent years have been attributed to scouring [1]. Pier scour is the erosion of the streambed in the vicinity of pier foundations due to a complex vortex system. Researchers have extensively studied local scouring from different points of view and in different flow conditions [2,3,4,5]. Briefly, Local scour around a solid pier results from the down flow at the upstream face of the pier and the horseshoe vortex (HSV) at the base of the pier. The horseshoe vortex deepens the scour hole in front of the pier until the stresses on the bed material become less than their critical shear stress. Separation of the flow at the sides of the pier also creates 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 (Fig 1).

Most of the previous studies were focused on a single pier. In addition to parameters affecting scouring around a single pier, for a pier that is a part of a group of piers, group effects are also important. For two piers in line (aligned with the flow), reinforcement and sheltering, are additional parameters, which affect the depth of the local scour. Reinforcement is when a downstream pier is placed so that piers' scour holes overlap. This aids in 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.

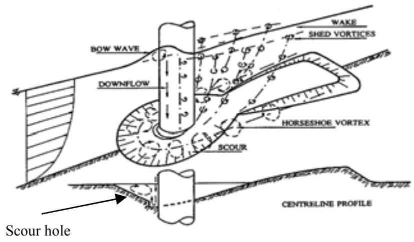

Figure 1. Vortex system around a cylindrical bridge pier [7].

When piers are placed transverse to the flow, compressed arms of the HSV play a vital role in local scouring. In this case, each pier will have, except for very close spacing, its own HSV. The interaction between piers in the group intensifies the strength of HSV arms and therefore the depth of the scour hole [6].

Useful insight into the local scour processes at pier groups was provided by studies of Hannah (1978) [7] which are also reported by Raudkivi (1998)[6]. Hannah used cylindrical piers in a steady flow to study the depth of scour at bridge pier groups. Bed material in Hannah experiments was uniform sand with 0.75mm diameter. According to [6] Hannah tests were performed in condition where u*/u*c was 0.72 where u* is bed shear velocity and u*c is the threshold of bed material motion found from the shields diagram. With performing a long-term test in 24 hours with a single pier, Hannah showed that with a single pier, 80% of scour depth occurred in first 7 hours. All tests with pier groups were therefore performed in 7 hours and results were extrapolated to find the maximum depth of scour hole.

The primary objective of the present study was to estimate maximum depth of the scour hole at groups of two piers in long term experiments and at near threshold of bed material motion. Piers aligned with the flow and transverse to the flow were tested.

II. EXPERIMENTAL SETUP

Experiments were carried out in a 10m long, 0.6m deep and 0.74m wide horizontal glass-sided flume. A triangular weir and a manometer were used to measure the flow discharge. A point gauge was used to measure flow and scour depth in the flume. The piers used in this study were a 0.04m diameter Perspex pipe. The flume had a working section in the form of a recess below its bed which was filled with sediment and was located 6m downstream from the flume entrance. Median size of the sediment was 0.95mm, with geometric standard deviation of sediment grading, less than 1.2. All tests were conducted at about threshold of sediment motion where maximum depth of scour hole is expected [7].

The threshold of sediment motion was found by experiment. Threshold of sediment motion was defined as flow condition at which the bed elevation, while the pier was not installed, does not change more than 2 to 3mm after a long period of experiment (for example 5 to 10 hours). Tests showed that with 0.13m flow depth and 0.030m3/s discharge bed materials would be at initiation of motion. Therefore, this condition was selected for all experiments. In these experiments, the ratio of shear velocity to the critical shear velocity, calculated from the shields' diagram was about 0.923. Shear stress at the working section was determined by calculating the water surface profile and slope of the energy line.

In a preliminary experiment, single circular pier was tested. In the next stage, two piers aligned with the flow and transverse to the flow were considered with spacing "S/b" of 2, 3 and 4, where S is the space between the piers and b is diameter of the piers.

III. TIME OF EXPERIMENTS

To find the maximum depth of scouring, experiments were continued until the equilibrium condition, that is when the variation of scour depth was negligible. This time was assumed based on Melville and Chiew [8] definition. According to this definition when depth of the scour hole does not change by more than 5% of the pier diameter over a period of 24 hours, equilibrium condition is achieved. About 40 hours was necessary in experiments of the present study to reach the equilibrium condition.

IV. EXPERIMENTAL RESULTS

A. *Single cylindrical pier*

In the first experiment, a long-term test on a single pier was performed to compare its results with group of two piers. Scouring around the pier started simultaneously at the upstream face of the pier due to the down flow and HSV and downstream of the pier under the action of wake vortices. The ratio of maximum scour depth at the upstream face of the pier to pier diameter Ys/b was measured equal to 2.4. The maximum depth of scour hole measured in this experiment was in good agreement with empirical equations such as Melville and Sutherland (1988).

B. *Two Piers in line*

In these experiments, three different spacing S/b= 2, 3 and 4 were tested for groups of two piers in line. At the beginning of experiments, similar to a single pier, the vortex system including horseshoe and wake vortex excavated scour holes around the piers. Down flow at the upstream face of the piers impinged the streambed and dug a hole in front of the piers. Also, flow separation downstream of the piers formed the wake vortices. Except for the case with S/b=2, scour holes around the piers were independent. The ratio of maximum scour depth at the upstream face of the front pier to the pier diameter was measured 2.58, 2.55 and 2.53 for S/b= 2, 3 and 4 respectively (Table 1). Also, Ys/b at the upstream face of the rear pier was measured 2.3, 2.28 and 2.25 for S/b= 2, 3 and 4 respectively.

Considering depth of the scour hole at the front pier, results are similar to Hannah (1978) work. For the rear pier however, scour depths reported by Hannah (1978) are less than what measured in the present experiments (Table 1). Longer experiments and higher stresses imposed could be the reason for deeper scour holes measured at the rear pier in the present work. Since the front pier scour depth similar to what reported by Hannah [7] in shorter time experiments, it can be concluded that a longer time has been necessary for the rear pier, being in the shelter of the front one, to reach equilibrium condition.

Comparing with a single pier, it can be concluded that reinforcement and sheltering effects were dominant factors in the local scouring process for two piers in line. The reinforcement effect caused an increase in the local scour depth of the front pier by 7% for S/b=2, which decreased in more spacing. The sheltering effect caused reduction of local scour depth at the rear piers up to about 6% (Table 1).

C. *Two Piers transverse*

In these experiments also the three different spacing S/b=2, 3 and 4 were tested for groups of two piers transverse. In these experiments, similar to pervious tests, down flow and wake vortices caused the scour holes around the piers. In this arrangement sediment material that placed between the piers was removed faster than other places. With spacing S/b=2, 3 and 4 the ratio of maximum scour depth which was at the upstream face of the pier to pier diameter Ys/b was 3.25, 2.88 and 2.7 respectively.

Comparing with Hannah (1978) (Ys/b=2.71, 2.62 and 2.48 for S/b=2, 3 and 4) deeper maximum scour depth were measured in the present work (Table 1). Based on these results, time of experiment in Hannah (1978) (7 hours and extrapolating to 24 hours based on single pier experiment) was not enough for achieving the maximum scour depth. Moreover, higher stresses were imposed on bed material in the present study. It can also be seen from Table 1 that the difference between the present results and Hannah (1978) increases as piers spacing decrease. Where at S/b=4, the present experiments shows 8% deeper scour hole comparing with Hannah, for S/b=2, 16% deeper hole was measured. This shows that time of equilibrium and effect of bed shear stresses increases at closer spacing of the piers.

Comparing with a single pier, the pier spacing and HSV compression were a dominant factor in local scouring for two piers transverse. For the S/b=2, the HSV compression

TABLE I.
SUMMARY OF RESULTS OF THIS STUDY AND HANNAH (1978)

	Two piers in line (Ys/b)				Two piers transverse (Ys/b)	
	Hannah (1978)		This study		Hannah (1978)	This study
S/b	Front Pier	Rear Pier	Front Pier	Rear Pier	-	-
2	2.57	2.03	2.58	2.3	2.71	3.25
3	2.59	2.03	2.55	2.28	2.62	2.88
4	2.48	2.07	2.53	2.25	2.48	2.7

effect increased the local scour depth by 35%. With increasing the pier spacing, effect of this factor was decreased up to 12% for S/b=4 (Table 1).

V. Conclusion

In the present study, the scour depth around groups of two piers was investigated. Piers aligned with the flow and transverse to the flow were tested with spacing "S/b" of 2, 3 and 4, where S is the space between the piers and b is piers' diameter. In these experiments the ratio of shear velocity to the critical shear velocity of bed material calculated from Shields' diagram was 0.923. All tests were carried out for 40 hours to satisfy Chiew and Melville criteria of equilibrium condition [8]. Results showed that the scour depth at the rear pier of two piers aligned with the flow were greater than that reported before by Hannah (1978), while the scour depths at the front pier were similar. Deeper scour hole measured in the present study compared with previous works is attributed to longer time of experiment and higher stresses. Comparing with a single pier in the range of spacing tested, results show an increase of about 7% in scour depth at the front pier under reinforcement and 6% reduction in scouring at the rear pier under sheltering effect. For two piers transverse to the flow also the results of the present study showed deeper maximum scour depth compared with previous works, especially at lower spacing. This is again due to long time of experiment at the present work. Comparing with a single pier, compression of horse shoe vortex caused the scouring to be more in group of two piers. Comparing the result with pervious work on groups of two piers shows that time of equilibrium and effect of bed shear stress are more to the rear pier in two piers in line and transverse piers with closer spacing.

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Key Words

Scouring, bridge pier, two piers in line, two piers transverse, time of equilibrium, bed shear stress.