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Riprap Protection Around Bridge Piers in a Degrading Channel

By

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ABSTRACT

This study shows the behavior of a riprap layer around bridge piers in a degrading channel. The major failure modes found in riprap layers in a stable channel, such as shear failure, edge failure, winnowing failure and bed feature destabilization, are also present here. An additional feature that is unique to riprap layers around bridge piers in a degrading channel is the net degradation of the bed level that consists of finer sediment particles, while the larger riprap stones remain intact. This causes the formation of a riprap mound around the pier. Although this mound appears to serve its function in protecting the pier against erosion, the study shows that additional floods with large dunes translating past the pier can have dire consequences on the integrity of the riprap mound. Observations showed that the riprap layer had disintegrated significantly when two floods of similar magnitude were allowed on the riprap layer cum bridge pier. This result suggests that recurrent maintenance is necessary to ensure the effectiveness of the riprap layer in protecting the pier against scour in a degrading channel.

INTRODUCTION

Bridge failure due to pier scouring can often be attributed to the combination of general and local scour. The former is defined as the degradation of the riverbed in the absence of a pier, whereas the latter is defined as scour due to the 3-dimensional boundary layer separation around the structure. Much research and investigation on local scour at bridge piers has been conducted worldwide over the last half century and the information gained has been comprehensive. However, there is comparatively little information on the relationship between general scour and bridge pier failure. The present experimental study aims to provide an improved understanding of the effect of general scour on pier protection when riprap material is used. To date, the study of riprap protection around bridge piers has been conducted under the condition where the bed level remains unchanged under both clear-water and live-bed conditions, i.e., without general scour. While this condition may be applicable

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in certain rivers, it is clearly not universal. The failure of Koaping Bridge in southern Taiwan is an excellent example of the important correlation between riverbed degradation and bridge pier stability. Figure 1 reveals how bed degradation has exposed the pile foundation, while Figures 2(a) and 2(b) show the eventual demise of the bridge on August 28, 2000. The cause of failure of Kaoping Bridge is complex but it would not be erroneous to state that it is closely related to the combined effect of general and local scouring.

The main objective of this experimental study is to examine how bed degradation affects the effectiveness of a riprap layer in protecting bridge pier against scouring.

EXPERIMENTAL SETUP AND PROCEDURE

The experiments were conducted in a flume that was 18 m long, 0.6 m wide and 0.6 m deep. The longitudinal bed slope of the flume is adjustable. Water in the flume was re-circulated using an axial flow pump driven by an AC motor. A variable speed electronic unit was used to control the speed of the motor. An adjustable weir at the downstream end of the flume controlled the depth of flow in each test. Figure 3 shows the schematic layout of the flume used in the study.

The circular model pier had a diameter, D = 50 mm and was constructed from clear perspex tube. The bed sediment consisted of cohesionless coarse sand with a median grain size, d_{50} = 0.91 mm and a specific gravity, Ss = 2.65. The particle size distribution of the bed sediment is uniformly distributed with a geometric standard deviation, $\sigma_g = \sqrt{d_{84.1} / d_{15.9}}$ = 1.24. The sediment used to simulate the riprap stones is medium gravel with a median grain size, d_{50R} = 10.4 mm, σ_g = 1.10 and Ss = 2.65. The choice of the riprap material is based on the design recommended by the U.S. Federal Highway Administration (Richardson et al. 1995). The riprap material is designed for an undisturbed approach velocity U = 1.4 times the critical mean velocity for bed sediment entrainment, U_c. For the bed sediment used in the present study, this corresponds to a mean velocity of 0.48 m/s. The critical velocity, U_c is computed from the critical shear velocity (determined from the Shields Curve) using the mean velocity equation, with the undisturbed approach flow depth, y_o = 150 mm. Using the U.S. FHWA guideline stated in Richardson et al. (1995), the minimum riprap size is 11 mm and the cover and thickness of the riprap layer is 5D and 3 d_{50R}, respectively. Figure 4 shows the layout of the model pier and the riprap layer.

Three types of test were conducted for each series of run for a given flow condition. They are (1) run without pier or riprap layer; (2) run with pier only; and (3) run with both pier and riprap layer. In all the test runs, the sand bed was first leveled before commencement of the experiment. In the Type 2 and 3 tests, the pier and riprap layer is placed at the location approximately 12 m downstream from the entrance to the flume. Three different velocity ratios, at U/U_c = 1.2, 1.4 and 1.7 were tested in this study. However, the present paper only describes the observations and results for test conducted with U/U_c = 1.4, i.e., the condition whereby the riprap layer is designed for.

RESULTS AND DISCUSSION

Since the velocity ratio, U/U_c used in the test was 1.4, the bed sediment will move. Because there is no sediment re-circulation in the test, the bed will undergo degradation. The objective of the Type 1 test was to determine how much degradation the bed will undergo when it is subjected to the given flow condition. At the beginning of the test, transport of sediment particles occurred with the formation of dunes on the bed. With time, the sediment particles moved away from the test section, causing bed degradation and a corresponding reduction in flow velocity. As this took place, the sediment transport rate decreased with an eventually disappearance of the sand dunes on the approaching bed as sediment transport eventually ceased when the mean flow velocity approached the critical velocity for sediment entrainment. Figure 5 shows the equilibrium bed profile of both the Types 1 and 2 tests measured after duration of 216 and 192 hours, respectively. The data show that the extent of bed degradation or general scour is similar, confirming that the pier, whose center is located at X = 8.24 m, has little influence on general scour. The equilibrium bed degradation is approximately equal to 70 mm. It must be pointed out that the large scour hole that forms at $X \approx 3$m is due to the rigid bed (false floor) upstream of X = 0. This phenomenon is common in laboratory studies that consist of a rigid-loose bed boundary.

In the Type 2 test, the measured equilibrium depth of pier scour (local + general scour depth) was found to be 169 mm below the original bed level. For tests conducted in a stable channel, Chiew and Melville (1987) found that the dimensionless time-average depth of pier scour, d_{av}/D was 1.95 for a similar flow condition. For a circular pier with diameter = 50 mm, this yields an equilibrium pier scour depth of 97.5 mm. The results show that the depth of scour associated with a degrading channel is 1.73 times higher than that when bed degradation is not present at U/U_c = 1.4. An interesting point to note from the above data is that the sum of general scour depth (70 mm) and the expected depth of pier scour (97.5 mm) observed by Chiew and Melville (1987) is 167.5 mm. This value is almost identical to the total scour depth of 169 mm measured in the present study. This feature is most likely to be coincidental.

In the Type 3 test, a riprap layer is placed around the bridge pier and its geometrical layout shown in Figure 4. When the pier cum riprap layer is subjected to a flow at U/U_c = 1.4 and y_o = 150mm, the first sign of weakness occurs on the finer bed sediment at the edge of the riprap layer. As the bed sediment was eroded, a small indentation forms, causing the riprap stone to drop into it. This observation is consistent with those described in the literature, for example, Chiew (1995). With time, bed feature destabilization, caused by the propagation of dunes past the pier and the riprap layer, sets in resulting in damages to the riprap layer. This phenomenon was described in detail in Chiew and Lim (2000) and Lim and Chiew (2001). In this test, an additional dimension, which was not observed in these previous studies, is present in that the sediment bed is also subject to degradation. Although the entire bed degrades, the riprap layer did not because it is designed to withstand the flow at $U = 1.4\ U_c$, i.e., shear failure of the riprap stones did not occur. As a result of this, a mound consisting of the riprap stones forms around the pier. This phenomenon is often observed in the field. The photographs in Figure 6 show the formation of the riprap mound around the pier. Figure 6(a) shows the layout of the riprap layer around the cylindrical bridge pier before commencement of the test. The second figure (Figure 6b) shows a close-up view of the riprap mound after general degradation of the bed level, while the large stones making up the riprap layer remain intact. Figure 6(c) shows the side view of the riprap mound with a dune approaching it. At this stage the riprap mound is generally stable because general scour has rendered a lower velocity excess for the given steady flow condition in the study. Moreover, the rate of sediment transport has also decreased markedly.

The riprap mound that formed around the pier shown in the present study is not uncommon in many field conditions. It forms because the entire bed degrades due to general scour while the riprap stones remain intact. This is because the latter is designed to resist the flood flow. At this juncture, the riprap layer appears to be able to function as it was intended. In this study, a second flood with a similar U/U_c-value as the first was simulated after the formation of the riprap mound to examine whether it can protect the pier against further erosion. Besides this, because much of the sand has already been eroded from the flume, additional sand was placed in the flume at a location upstream of the pier and riprap mound. When the flow was initiated, dunes were formed and they propagate past the riprap mound. When the dune approached the mound, water flowed over the dune crest and reattached onto the riprap layer. Observations show that this reattached flow is very important in destabilizing the riprap stones, as was also observed in the study by Chiew and Lim (2000). When this takes place, the exposed riprap stones were eroded and transported downstream exposing the layer to winnowing failure, where the underlying fine sediment was lifted through the voids formed by the interstices of the larger stones. This causes the stones to self-embed, leading to its eventual failure. Figure 7 shows the riprap mound after it was subjected to a second flood of a similar magnitude. The first photograph shows the riprap mound just before the dune arrives at the pier. At this point in time, the riprap layer is subjected to high erosion, due partly to the reattachment of flow over the dune crest. This flow is very efficient in eroding the large riprap stones, especially for those that are exposed. Many stones were eroded by the reattached flow over the dune crest. The second photograph shows that the riprap layer was completely embedded by the propagating sand dune. At this juncture, it is surmised that little erosion was taking place, but some form of position readjustment was probably unavoidable. The last photograph shows the remains of the riprap mound after subsidence of the second flood. Clearly the riprap mound is significantly different from that shown in Figure 6. Many of the stones making up the riprap layer were entrained and transported downstream. A large degradation, which resembles the lee-wake scour associated with erosion around a submarine pipeline (Chiew, 1990; Sumer et. al, 1988), can be seen downstream of the pier. A comparison of the riprap mound in Figure 7(c) and those in Figures 6(b) and 6(c) reveals significant differences between them. It is not unreasonable for one to infer from this study that further floods will eventually cause the complete demise of the riprap layer.

An important deduction from this result is that a riprap layer may appear to function adequately at first glance after the passage of a designed flood, it, nevertheless, may be found wanting when subjected to subsequent floods. The study calls for regular maintenance of the riprap layer in order to ensure the effectiveness of the riprap layer in protecting the bridge pier against scouring.

CONCLUSIONS

The experimental study shows how a riprap layer around a bridge pier would respond to the flow in a degrading channel. The main difference between such riprap layers and those found in a stable channel is the net degradation of the bed level; while the riprap layer, when subject to the designed flow, would remain intact. This phenomenon results in the formation of a riprap mound around the bridge pier. The study shows that a second flood accompanied by dunes translating past the bridge pier can cause further erosion to the riprap mound. It is surmised that further floods may cause the eventual failure of the riprap layer.

For the case where there is no riprap layer around the bridge pier, the test conducted with a velocity ratio, $U/U_c = 1.4$ in a degrading channel shows that the total depth of pier scour below the original bed level is 1.7 times that encountered in a stable channel with the same flow condition.

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Figure 1. Bed Degradation at Kaoping Bridge, Taiwan causing exposure of pile foundation

(a) Looking downstream

(b) Looking upstream

Figure 2. Failure of Kaoping Bridge, Taiwan due to a combination of general and local scour (Courtesy of Professor C. Lin)

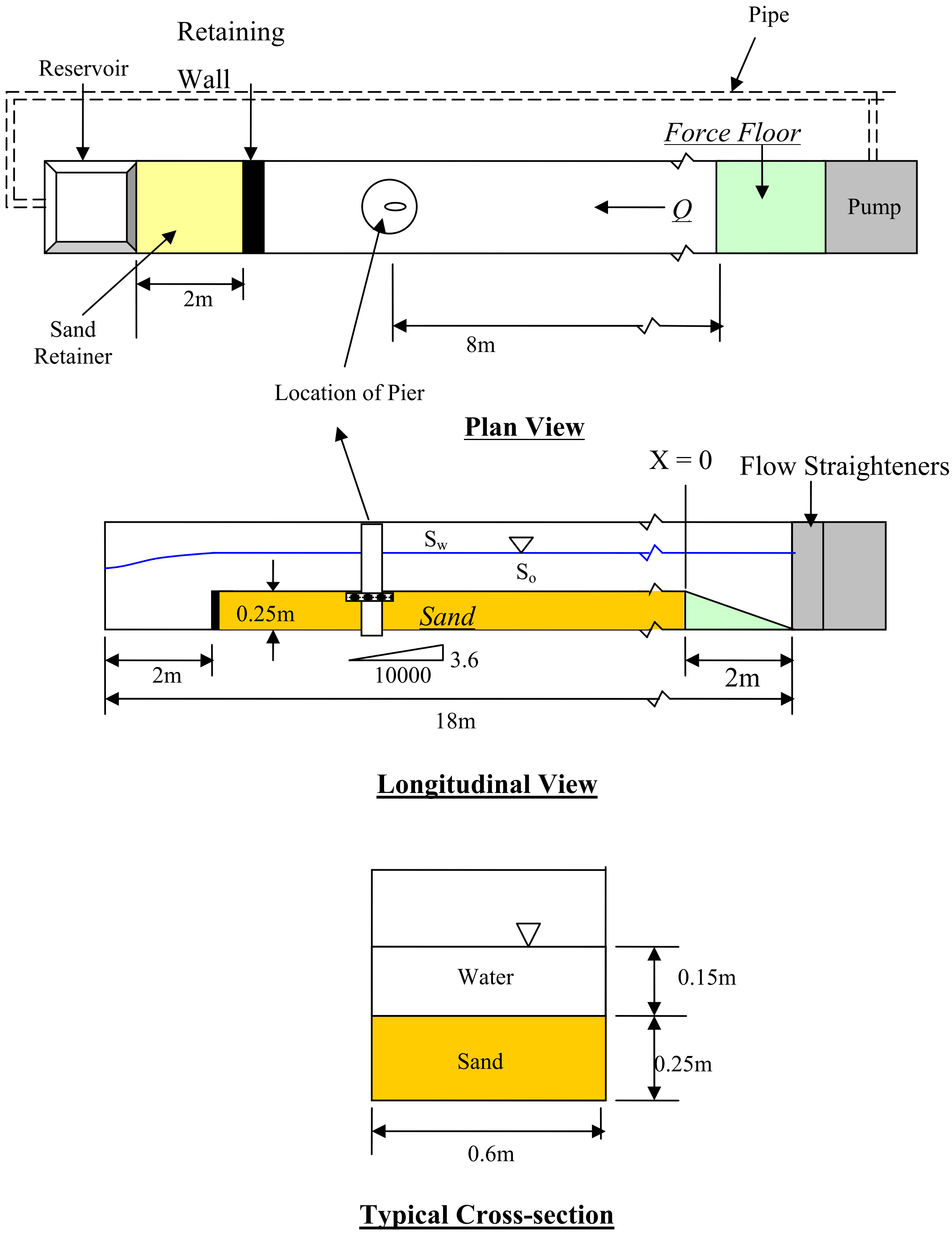


Figure 3 : Schematic Layout of Flume Used in Study

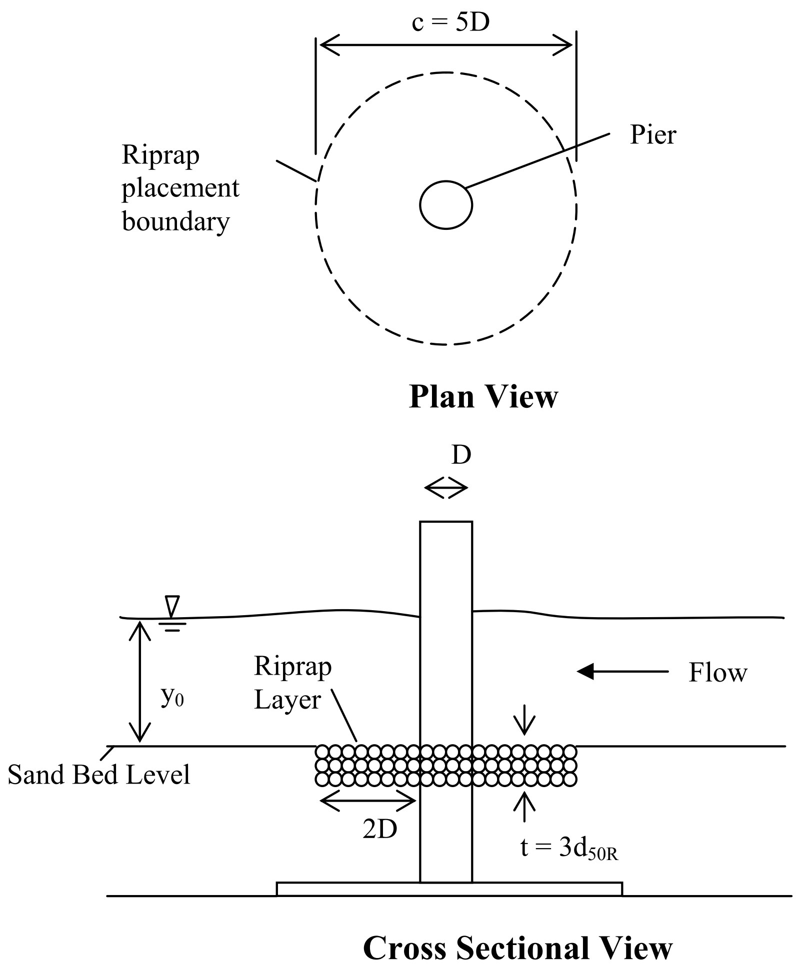


Figure 4. Layout of model pier and riprap layer

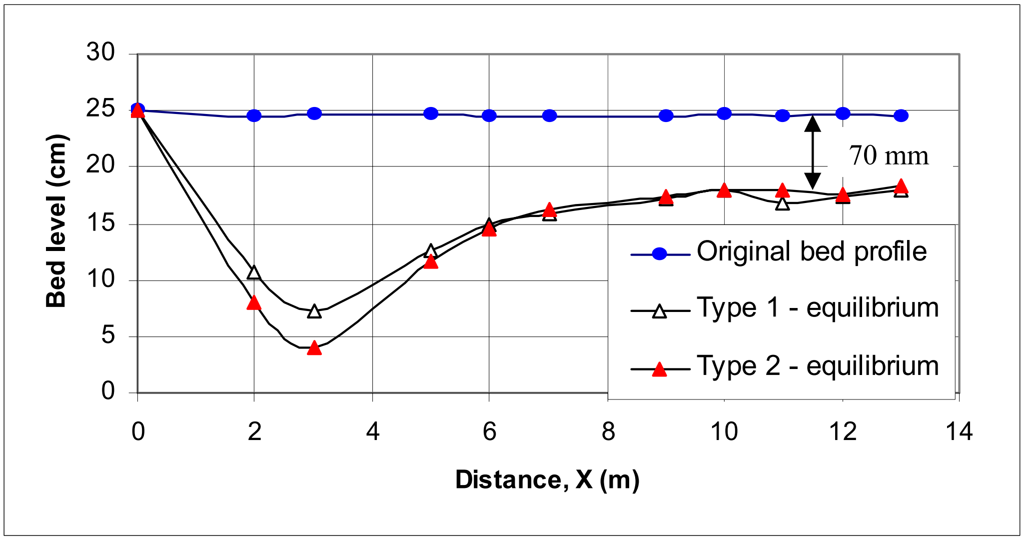


Figure 5. Equilibrium bed profile of Type 1 and 2 Tests ($U/U_c = 1.4$)

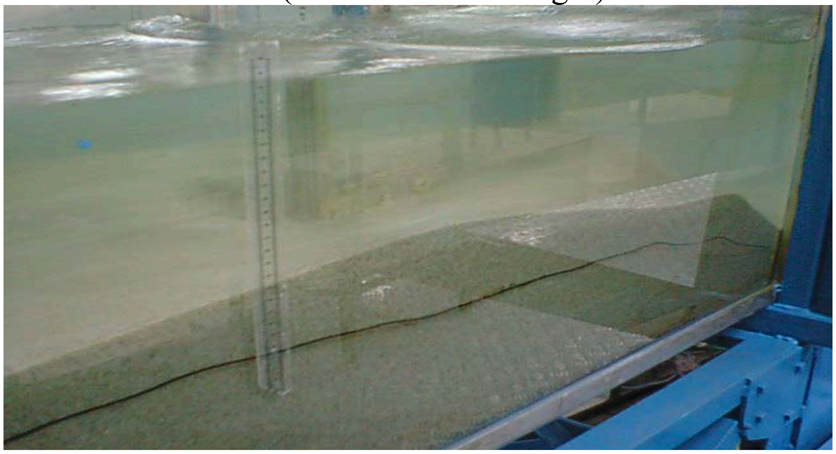
(a) Riprap layer at the commencement of test

(b) Formation of riprap mound around pier (flow from right to left)

(c) Dune approaching the riprap mound which is generally stable
(flow from right to left)

Figure 6. Formation of riprap mound around bridge pier in a degrading bed

(a) Dune from second flood approaching the riprap mound
(flow from left to right)



(b) Dune completely bury the riprap mound
(flow from left to right)

(c) Remains of the riprap mound after subsidence of the second flood
(flow from right to left)

Figure 7. Effect of second flood on riprap mound