USING SEEPAGE AS AN AUXILLIARY METHOD FOR PIER-SCOUR COUNTERMEASURE

YAN LU AND YEE-MENG CHIEW
School of CEE, Nanyang Technological University
Singapore 639798

Published studies have identified five main failure mechanisms associated with riprap failure around bridge piers. They are shear failure, winnowing failure, edge failure, bedform-induced failure and bed-degradation induced failure. In a straight alluvial channel consisting of fine bed sediment where large dunes are present, a riprap layer is most vulnerable when subjected to bedform-induced failure. This type of failure mechanism is prompted by the fluctuation of the bed level due to the propagation of bed features past the pier. The study shows that the dimension of bedforms and the turbulence characteristics of the flow over bedforms are significantly influenced by seepage. The experimental data revealed that injection can reduce the height of dunes by up to 50%. Such a reduction may have a significant influence in decreasing the threat of bedform-induced failure of the riprap layer. The distance needed for the propagating bedforms to respond to injection is also investigated and the study shows that dunes require a minimum distance of approximately three times the fully developed dune height to settle to an equilibrium geometry.

1 Introduction

The damage to bridges at a river crossing can often be attributed to the formation of a scour hole around its piers. The scour hole can seriously affect the integrity of the bridge foundation, sometimes leading to a complete failure of the bridge. A frequently accepted engineering method to deal with pier-scour problems is to place riprap material around the foundation. However, field experience has shown that riprap stones often disappear with time, a phenomenon collectively known as riprap failure. Based on results from experimental studies conducted in both clear-water and live-bed conditions, Chiew (1995, 2002, 2004) has identified five different types of failure mechanisms to describe failure of a riprap layer:

1. Shear failure: the riprap stones are entrained by the local flow around the pier due to their limited size;
2. Winnowing failure: the underlying finer bed material are winnowed through the voids or interstices of the riprap stones;
3. Edge failure: the riprap stones at the edge of the layer are eroded, which affects the stability of the riprap layer;
4. Bedform-induced failure: riprap stones are disturbed by the fluctuation of the bed level due to the propagation of bedforms, such as ripples or dunes past the pier; and
5. Bed-degradation induced failure: riprap failure due to general scour.

For a bridge sited in a straight channel consisting of fine bed sediment with large bedforms, Chiew (2002) stated that bedform-induced failure is the most critical in affecting riprap stability. Such a failure type is also identified by Lim (1998) and Lauchlan (1999) in their study. It occurs when the trough of the propagating dunes approaches the riprap layer, at which point the coarser riprap stones at the edge lose support and become embedded. As a result of losing stones to the trough of the dunes, the riprap layer becomes thinner, eventually leading to its complete breakdown. Additionally, the high level of turbulence generated at the separation zone of the flow over the dune significantly enhances entrainment.

Published studies have identified that bedform-induced failure is the dominant failure mode of pier-riprap if it is subjected to high flows accompanied by large dunes (Lauchlan and Melville, 2001). Moreover, its vulnerability under such a condition may not be overcome merely through the use of larger stones (Chiew, 2002). Under such a condition, an alternative designed consideration must be adopted to safeguard the pier against riprap failure. To that end, if one were able to reduce their height as dunes migrate past the bridge pier, the threat of bedform-induced failure of the riprap layer may be considerably reduced. This paper explores a new and practical method to reduce the size of propagating bedforms past the pier.

Many previous studies on seepage flow were aimed at investigating the effect of either injection or suction on mean flow and turbulence characteristics, as well as the threshold of sediment transport in open-channel flow (Cheng and Chiew, 1998; 1999 and Chen and Chiew, 2001; 2004). A general observation is that seepage can result in an additional hydrodynamic force on the bed sediment particles. This may further exert significant influence on the processes of sediment transport, such as incipient motion and formation of bedforms. The objective of this study is to examine whether seepage would decrease the size of the propagating dunes, thereby reducing the threat of bedform-induced failure of the riprap layer.

2 Experiments Setup and Procedure

The experiments in this study were conducted in a 30-m-long, 0.7-m-wide, and 0.6-m-deep glass-sided horizontal flume. Water was circulated through a submersible pump installed in a laboratory reservoir. The flow rate, which was monitored using an electromagnetic flow meter, was controlled via a speed inverter and a valve. At the entrance to the flume, pipe straighteners were set to achieve uniform flow and to minimize large scale turbulence and circulations. Located at the middle of the flume was the test section in the form of a recess that is 2 m long and 0.2 m deep, which spans the flume width. The permeable bed in the seepage zone was leveled to the elevation of the adjacent bed.

Figure 1 shows the setup of the recess. Sand was placed on top of a filter net, which in turns, overlays a perforated metal plate. Water was allowed to seep through the perforated plate, filter net and sand layer to ensure uniform seepage flow through the granular material. In the case of suction, twelve identical pipes with valves were fixed onto the bottom of the recess to drain water uniformly downwards.

A separate submersible pump was used to supply upward seepage (injection); its flow discharge was monitored using a flow meter. On the other hand, downward seepage discharge was controlled using the 12 valves and the rate measured manually. The water depth at the test section was determined using a depth gauge.

Located downstream of the test zone was a settling basin that was specially designed to collect the transported sediment particles. A sand pump was used to re-circulate these sediment particles to ensure sand transport equilibrium in the flume.

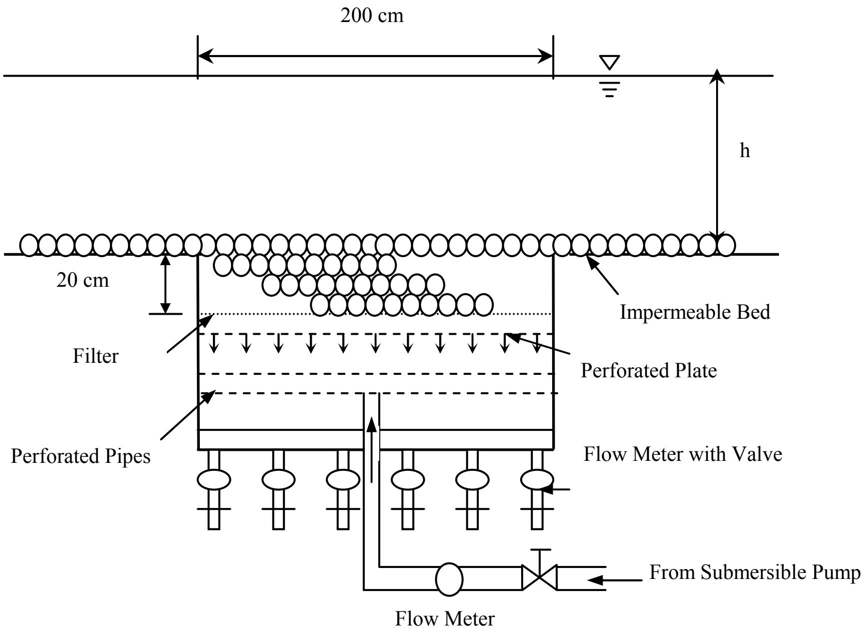

Figure 1. Schematic diagram of experimental setup

Before each run was started, the sand bed was first leveled. The inlet discharge was then introduced gradually. Once the predetermined discharge was obtained, the required seepage flow, either suction, injection or no-seepage was introduced. During the experiment, the transport of sediment in the flume was kept in equilibrium using the sand pump. After reaching the steady state, the height of dunes was measured using a bed profiler along the seepage zone. In the measurement, it was necessary to trace each dune as it propagated from the upstream to downstream end of the seepage zone because the dimension of dune changes through the seepage zone. In other words, the height of dunes at the position along the seepage zone was documented. For each run, at least 10 dunes were investigated to obtain the mean value so that the dune dimensions can be quantified in statistical terms. This was repeated for different seepage rates including the no-seepage condition. Altogether, a total of 14 runs are documented in this study.

Table 1 summarizes the flow variables for all the experiments conducted herein. In the table, the seepage discharge, $q_{s,}$ is taken as positive for injection and negative for suction; Q is the main flow discharge; h_0 is the water depth without seepage, and is measured from the water surface to the mean bed level; h is the water depth with seepage at the centerline of seepage zone; d_{50} is the median grain diameter of the bed sediments used in the experiment; and l is the distance measured from the leading edge of the seepage zone and is taken as negative for distances upstream of the leading edge.

Table 1. Summary of experimental data

Run No	Q (cm^3/s)	q_s (cm^3/s)	h_0 (cm)	H (cm)	d_{50} (cm)	l (cm)
1	80	-1.21	23.4	23.5	0.09	-70~250
2	80	-2.83	23.4	23.2	0.09	-70~250
3	80	-4.01	23.4	23.0	0.09	-70~250
4	80	0	23.4	23.4	0.09	-70~250
5	80	2.61	23.4	23.9	0.09	-70~250
6	80	3.52	23.4	24.5	0.09	-70~250
7	80	4.39	23.4	25.0	0.09	-70~250
8	80	-0.87	18.6	18.3	0.09	-70~250
9	80	-2.01	18.6	18.7	0.09	-70~250
10	80	-2.56	18.6	18.2	0.09	-70~250
11	80	0	18.6	18.6	0.09	-70~250
12	80	2.57	18.6	19.1	0.09	-70~250
13	80	3.47	18.6	19.7	0.09	-70~250
14	80	4.47	18.6	20.4	0.09	-70~250

3 Experiments Setup and Procedure

When a dune moves into the seepage zone, it changes its shape. This is because the dune is subjected to seepage effects. This eventually leads to the formation of an equilibrium shape for a given seepage rate as the dune migrates downstream across the seepage zone. The distance taken for a dune to reach equilibrium when subjected to seepage is important in determining the position and length of the seepage zone when it is introduced to minimize dune size as an auxiliary pier-scour countermeasure. If $l = 0$ and $l = L = 2$ m (length of seepage zone in this study = 2 m) represent the beginning and end of the seepage zone, the development of the dune height H_l along the seepage zone with injection or suction is shown in Figures 2 and 3, respectively, where H_l and H is the developing and fully developed height of dune, respectively.

The curves in Figures 2 and 3 show that the seepage zone is long enough for the dunes to reach their fully developed stage for any given seepage rate in this experiment. In subsequent analyses of the seepage effect on the height of dunes, only the data of the equilibrium dunes, i.e., the fully developed height H, with corresponding seepage rates, are used.

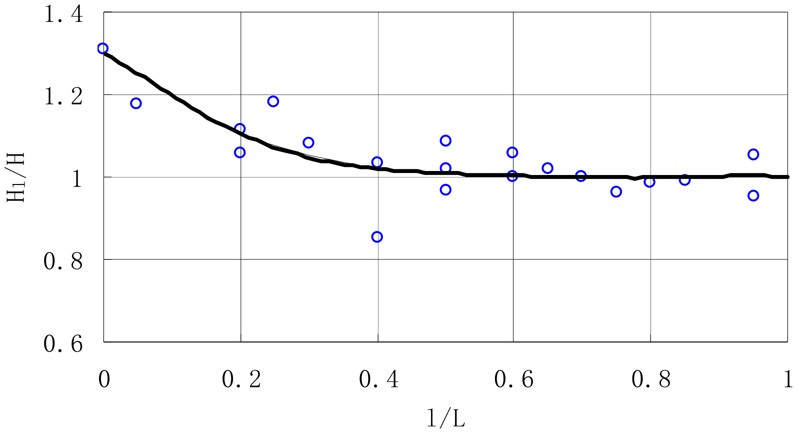

Figure 2. Development of dune height with injection

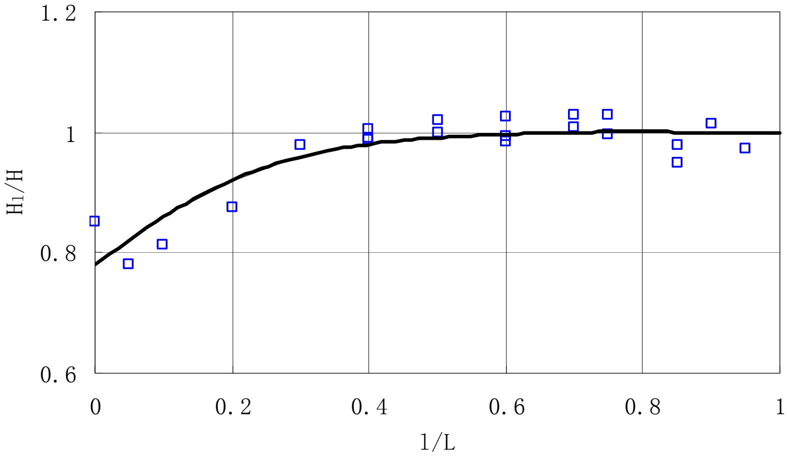

Figure 3. Development of dune height with suction

With regard to seepage effects on the height of dunes, the experimental data of the ratio of the developed dune height to water depth h are plotted against the dimensionless seepage hydraulic gradients. The latter are taken as positive for injection in Figure 4, in which h_0 is the water depth without seepage, and i_c is the seepage hydraulic gradient for quick condition. Lu et al. (2003) described the quick condition as the situation with a large enough seepage rate so that the seepage force acting on a particle of sediment resting on a horizontal bed just balances its submerged weight force. Figure 4 shows how the height of dune is reduced and increased with injection and suction, respectively.

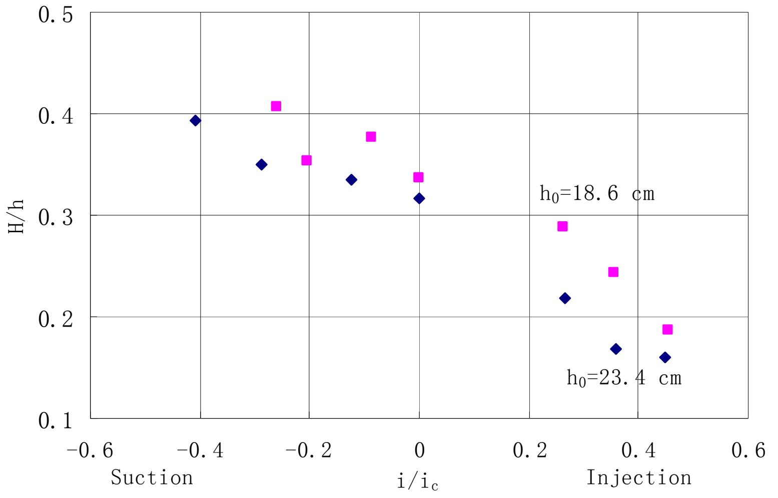

Figure 4. Seepage effect on dune height

The data in Fig. 4 clearly show that it is feasible to reduce the size of bedforms through the use of injection. A reduction of approximately 50% is achievable for $i/i_c \approx 0.45$. To this end, it is plausible to reduce the threat of bedform-induced failure of a riprap layer through the reduction of the height of the bedforms as they translate past a hydraulic structure, such as piers, abutments, etc. Further experiments on measurements of the turbulent flow characteristics over dunes were also conducted in the study. Preliminary results show that the rms-values of velocity fluctuations increase when injection is introduced; a finding that is consistent with the results of Cheng and Chiew (1998) obtained for tests conducted on a flat bed in the absence of bedforms. From this perspective, introduction of injection may have a negative influence on pier-riprap protection as it increases the local turbulence intensity. Thus, when applying injection as a supplementary pier-scour countermeasure, one must be careful not to allow this effect to have an undesirable influence on entrainment of the riprap stones. A separate experimental study currently is being undertaken by the second author to examine the effect of injection on riprap as a pier-scour countermeasure. Whether injection will offer a significant improvement to riprap protection at bridge pier remains uncertain presently.

Figures 2 and 3 depict the growth of dunes along the seepage zone. The data clearly show that the dunes may not reach their fully developed stage if the injection zone is not long enough. In other words, a certain length of the injection zone is necessary to ensure the minimum height of the dune is achieved for a given seepage rate. However, information on the length of the injection zone cannot be determined from this figure for engineering practice in a general sense. To this end, the development of dunes along the injection zone is re-plotted in Figure 5 in which the distance, l is normalized with the height of the fully developed dunes instead of the total length of the seepage zone used in the experiment. Figure 5 indicates that the injection length needed to reach the fully developed stage is approximately 3 times the height of the fully developed dunes for a given seepage rate.

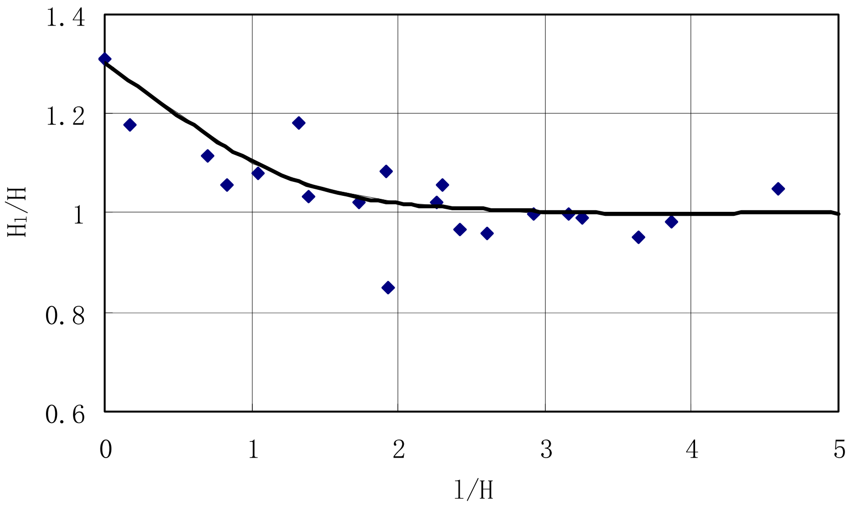

Figure 5. Assessment of minimum of the injection length needed

4 Conclusions

The influence of seepage on the height of dunes is investigated experimentally in this study. The results show that suction increases the equilibrium height of dunes, and injection reduces it. The experimental data show that an increase and reduction of up to approximately 25% and 50% in dune height are possible for suction and injection, respectively. Therefore, it may be feasible to introduce bed injection to reduce their size as dunes migrate past the bridge pier, thereby reducing the threat of bedform-induced failure of the riprap layer. However, it must be stated that the turbulence intensity of the flow over dunes is found to increase with injection. To this end, one may need to be careful when applying this auxiliary pier scour countermeasure method. As far as the authors aware, no experimental data are available presently to categorically prove the effectiveness of using injection as an auxiliary pier scour countermeasure.

This study also explores how dunes grow along the seepage zone. The data show that the dunes may not reach their equilibrium stage until they traveled a certain distance in the injection zone, which is found to be at least 3 times the height of the fully developed dunes for a given seepage rate. This distance may reasonably be taken as the minimum length of the injection zone needed to maximize the height reduction of the migrating dunes.

References

Chen, X. W., and Chiew, Y. M. (2001). “Bed Shear Stress in Open Channel Flow with Bed Suction.” Proc. XXIX IAHR Congress, Theme D, Vol. 1, Beijing, 276-281.

Chen, X. W., and Chiew, Y. M. (2004). “Velocity Distribution of Turbulent Open-Channel Flow with Bed Suction.” *J. Hyd. Engrg, ASCE*, 130(2), 140-148.

Cheng, N. S., and Chiew, Y. M. (1998). “Turbulent Open-Channel Flow with Upward Seepage.” *J. Hyd. Res., IAHR*, 36(3), 415-431.

Cheng, N. S., and Chiew, Y. M. (1999). “Incipient Sediment Motion with Upward Seepage.” *J. Hyd. Res., IAHR*, 37(5), 665-681.

Chiew, Y. M. (1995). “Mechanics of Riprap Failure at Bridge Piers.” *J. Hyd. Engrg, ASCE*, 121(9), 635-643.

Chiew, Y. M. (2002). “Failure Mechanisms of Riprap Layer Around Bridge Piers.” 1st Int. Conf. on Scour of Foundations, ICSF-1, Texas A&M University, College Station, Texas, USA, November 17-20, 2002.

Chiew, Y. M. (2004). “Local Scour and Riprap Stability at Bridge Piers in a Degrading Channel.” *J. Hyd. Engrg, ASCE*, 130(3), 218-226.

Lauchlan, C. S. (1999). “Countermeasure for Pier Scour.” Ph.D Thesis, University of Auckland, Auckland, New Zealand.

Lauchlan, C. S., and Melville, B. W. (2001). “Riprap Protection at Bridge Piers.” *J. Hyd. Engrg, ASCE*, 127(5), 412-418.

Lim, F. H. (1998). “Riprap Protection and Its Failure Mechanisms.” A thesis submitted to the School of Civil and Structural Engineering, Nanyang Technological University, Singapore in fulfillment of the requirement for the degree of Doctor of Philosophy.

Lu, Y., Chiew, Y. M., and Cheng, N. S. (2003). “Seepage Effect on Angle of Repose of Cohesionless Sediments.” XXX IAHR congress, Greece, 24-29 August 2003, 549-556.