EFFECT OF SUCTION ON CLEAR-WATER SCOUR AT BRIDGE PIERS

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This experimental study investigates how suction affects local scour around bridge piers in clear-water conditions. Traditional pier-scour countermeasures often can induce secondary scour failure mechanisms, such as winnowing and edge failure. Utilization of suction may be able to eliminate such effects while at the same time offer a reliable means to protecting bridge pier against scour. The empirical data show that the equilibrium scour depth at a circular bridge pier is reduced by up to 50% with $Q_s/Q_o = 2\%$, where Q_s and Q_o = suction flow rate and undisturbed total flow rate, respectively. The data also show that the performance of suction in reducing pier-scour is dependent on the location of the suction source, with the most effective location being near to the pier at $x/D < \sim 2.4$, and at the section where $x/D = 6.4$, where x = horizontal distance between suction source and pier centre and D = pier diameter. The reason is because suction influences pier-scour both directly and indirectly. The former has a direct impact on the downflow and horseshoe vortex that form at the pier, while the latter is related to suction effects on general sediment transport rate.

***Key Words**: Bridge pier scour; Suction; Bridge pier protection; Sediment transport.*

1. INTRODUCTION

The formation of a scour hole around bridge piers is a natural response of the local sediment particles to interactions between the incoming flow and the pier structure. In certain instances, the scour hole may develop to such an extent that it becomes a threat to the integrity of the bridge foundation, sometimes leading to the complete demise of the entire structure. Traditional methods in dealing with such threats include placement of large riprap stones around the pier, but more recent research investigations have devoted efforts into exploring unconventional techniques. One of the reasons for the departure from traditional armoring countermeasures, such as dumping of riprap stone is because such methods induce other failure mechanisms associated with the use of armoring countermeasures. These secondary, but not necessarily insignificant failure mechanisms associated with pier-scour protection has been intensively studied over the past 2-3 decades, and summarized by Chiew (2002). They are edge failure, winnowing failure, bedform-induced failure and bed-degradation induced failure. The use of flow-altering countermeasures such as sacrificial piles (Hadfield, 1999) or sacrificial sills (Chiew and Lim, 2003) has the potential of avoiding such failure mechanisms, but their effectiveness becomes extremely sensitive to the angle of attack of the approaching flow. For example, Chiew and Lim (2003) showed that the effectiveness of a sacrificial sill becomes completely redundant when the angle of attack exceeds 15°. Similar problems exist with the use of sacrificial piles as a large angle of attack often can eradicate its effectiveness altogether. To this end, the study explores the use of a new countermeasure method in the form of suction to protect bridge piers against scouring.

A distinctive advantage of using suction is that the structural device used to induce suction need not be exposed to the flow. This clearly is a very important advantage because introduction of structural devices, such as riprap stones or sacrificial sills or piles, often can and do lead to undesirable consequences such as the induction of secondary failure mechanisms, as is discussed in the preceding paragraph. Since the device used to produce suction is buried beneath the undisturbed mean bed level, it is completely invisible to the on-coming flow, hence eliminating the initiation of secondary failure. The idea of using suction as a pier-scour countermeasure arises from results obtained from an extensive research program in seepage effects on turbulent open-channel flow and sediment transport carried out at the Nanyang Technological University by the author and his co-workers over the past 15 years. Those studies have shown that the turbulent characteristics of the flow are significantly modified even when the seepage flow rates, either as suction or injection, are only a small fraction of the main flow rates in the channel. A summary of these results may be found in Lu et al. (2008). Additionally, the studies also show that the incipient sediment motion and dune geometry change with seepage (Lu and Chiew, 2007). More recently, experimental studies also have shown a very important correlation between seepage and sediment transport rate (Liu and Chiew 2007; Francalanci et al., 2008). Results of these findings have given the impetus for applying suction as a pier-scour countermeasure. Similar to its effect on the turbulence characteristics and sediment bedload transport rate in a 2-dimensional flow, it is surmised that suction likewise can modify the behavior of both the flow and sediment transport around a bridge pier. If such changes can be exploited to realistically and radically restrict pier-scour development, suction will become a preferred scour-countermeasure because it is not subjected to the secondary effect that its counterparts experience.

2. SUCTION AS A PIER-SCOUR COUTNERMEASURE

A thorough literature search shows that Rooney and Machemehl (1977) appear to be the only researchers who have toyed with the idea of using suction as a form of pier-scour countermeasure. It must, however, be stated at the outset that the principle behind their method is completely different from that advocated in the present study. The concept of boundary layer control, which is extensively used in aerodynamic engineering, presumably is the motivation behind their technique. It involves removal of fluid (particularly from the downflow) from the surface of the pier by internal suction. In their tests, six holes at five different levels that extend downwards from just above the undisturbed bed level were drilled along the circumference of a 100-mm diameter hollow circular cylinder. Suction was created by pumping water from inside the cylinder, which operated as the model pier. Two suction rates at 0.1 and 0.4 L/s were tested. The results were extremely promising in that the scour depth was reduced by 50% with the lower suction rate, and almost altogether eliminated with the higher suction rate. However, it must be pointed out that the experiments were only conducted for a maximum of 90 minutes and that the tests were conducted under a live-bed condition.

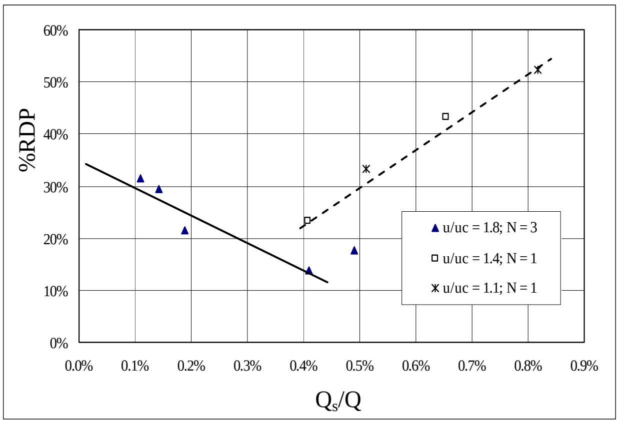

Fig.1 Effect of suction on riprap layer degradation (Chiew and Lu, 2005)

The only other study that explores suction effects on pier-scour is that by Chiew and Lu (2005), who examine how riprap protection around a bridge pier is affected by suction. It aims to investigate if suction can enhance riprap as a successful pier-scour countermeasure. The experimental results, as shown in Fig.1, reveal how suction significantly affects riprap layer degradation. The following 2 conclusions were drawn from the study:

(a) In the case of a plane bed where winnowing failure is the dominant mode of failure mechanism, suction decreases the level of turbulence intensities around bridge piers, resulting in an increase of %RDP. The experimental results show that %RDP can reach a value in excess of 50%; and

(b) In the case of a dune bed where destabilization of a riprap layer by the propagation of dunes past the pier is the dominant failure mode, suction increases the height of dunes resulting in an increase in the threat of bedform-induced failure and at the same time a reduction of the turbulence intensity around the pier. The overall effect is dependent on the relative magnitude of these two opposing influences.

Despite significant improvements as shown in Fig. 1, suction cannot eliminate the secondary failure mechanisms, such as winnowing failure associated with the presence of a riprap layer. In order to eliminate the secondary failure mechanisms, such as winnowing or edge failure, the present study explores how suction affects local scour around bridge piers. In this study, only clear-water scour around a circular cylindrical pier with uniform sediments is investigated.

3. EXPERIMENTAL SETUP AND PROCEDURE

The experiments were conducted in a glass-sided horizontal flume that was 30m long, 0.7m wide and 0.6m deep. Water was circulated through a submersible pump installed in the laboratory reservoir. The flow rate was controlled using a speed inverter and valve, and monitored using an electromagnetic flow meter. Pipe straighteners were installed at the entrance of the channel to prevent the occurrence of large-scale disturbances and to achieve uniform entrance flow. The water depth in the flume was regulated using a tailgate weir. Located at a distance 16m from the upstream end of the flume was the test section or the suction zone, which was in the form of a recess that was 2m long, 0.7m wide and 0.4m deep, as shown in Figs. 2(a) and (b).

The sediment particle used in this study is fine sand with a median grain size, d_{50} = 0.48 mm. With a total thickness of 300 mm, the sand was placed on top of a filter net in the recess, which in turns, overlaid a perforated metal plate as shown in Fig.2(a). Water was allowed to seep through the sand layer, filter net, and perforated plate before being drained by 12 identical pipes that were fitted uniformly onto the bottom of the recess. Valves were installed on each drainage pipe to regulate the flow rate such that the drainage rate could be controlled to ensure a uniform seepage velocity (see Fig.2b). The sand surface in the test region was leveled to the same elevation as those upstream and downstream of the test section. As a result, the undisturbed mean bed level is 180 mm above the bottom of the flume.

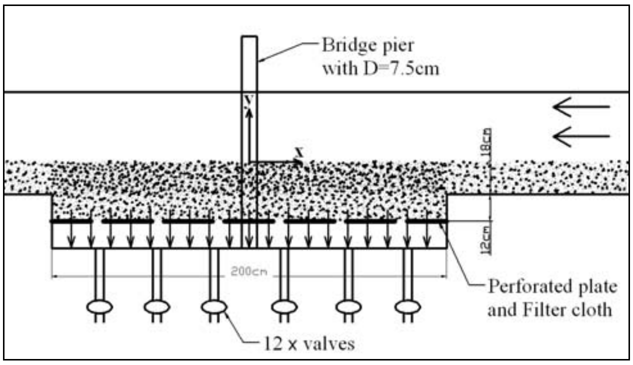

Fig.2(a) Longitudinal view of bridge pier in suction zone

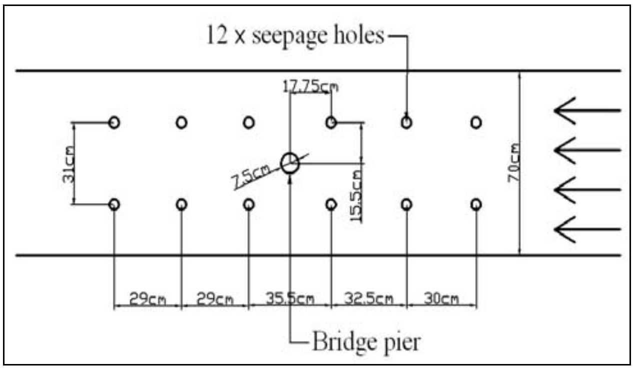

Fig.2(b) Plan view of bridge pier in suction zone

The coordinate x in Fig.2(a) refers to the horizontal distance between the center of the seepage holes and that of the pier. By opening a particular valve in the recess and moving the bridge pier accordingly, the x-value may be varied for each experimental run. A positive x means that the suction inlet is located upstream of the center of the pier. A cylindrical Perspex pipe with diameter = 75 mm, was used as the model bridge pier. A tape was affixed to the cylinder surface for measurement of the scour depth.

A total of twelve experimental runs were conducted in this study. They were all conducted under a clear-water condition with a shear velocity ratio, u_*/u_{*c} = 0.81 and an undisturbed approach flow depth, y_o = 105 mm. The undisturbed shear velocity, u_* is computed from the velocity profile measured at the centre-line of the suction zone. The critical shear velocity is calculated using the customary Shields Diagram. All the 12 experimental runs were subjected to the identical flow conditions and the only variables are the suction rates and the horizontal distance x as defined earlier.

Experimental Run 1 was conducted with suction rate, Q_s = 0. Recognizing that the temporal development of clear-water scour depth at a bridge pier is highly sensitive to time during the earlier period of the scour hole development, but not so when the period of testing extends beyond a certain threshold (Melville and Chiew, 1999), the total duration of testing in this study was taken to be 48 hours. The result shows that the scour depth after 48 hours of testing is 106 mm. This measured data is used to compare with results calculated using Chiew's (1995) equation for the prediction of equilibrium clear-water scour depth around a circular cylinder. For the given flow conditions, the computed equilibrium scour depth = 111 mm, which is marginally higher that the experimental result. A possible reason is that the duration used in the study is lower that that needed to attain true equilibrium. Notwithstanding this slight variation, all the tests in this study were conducted with the same duration, i.e., 48 hours.

For the remaining experimental tests runs, the scour hole is allowed to develop with the application of suction. In all instances, only the valves attached to the two pipes with the same distance from the pier center along the streamwise direction are opened with a pre-determined suction rate for a given test run. The suction rate is determined by manually collecting the volume of water that discharges from the pipe over a fixed duration. A total of three suction flow rates were tested, at 0, 0.17 and 0.35 L/s. These rates are very small when compared with the undisturbed flow rate without suction, Q_o of 17 L/s.

Table 1 Experimental Data

Test Run	Q_s (L/s)	x, mm	d_{se}, mm	time (hr)	x/D	%RDP
1	0	NA	106	48	NA	0%
2	0.17	177.5	87.5	48	2.4	17.5%
3	0.35	0	52.5	48	0	50.5%
4	0.35	90	54	48	1.2	49.1%
5	0.35	177.5	54	48	2.4	49.1%
6	0.35	220	62	48	2.9	41.5%
7	0.35	325	73	48	4.3	31.1%
8	0.35	480	55	48	6.4	48.1%
9	0.35	480	56	48	6.4	47.2%
10	0.35	480	55	48	6.4	48.1%
11	0.35	625	74	48	8.3	30.2%
12	0.35	800	85	48	10.7	19.8%

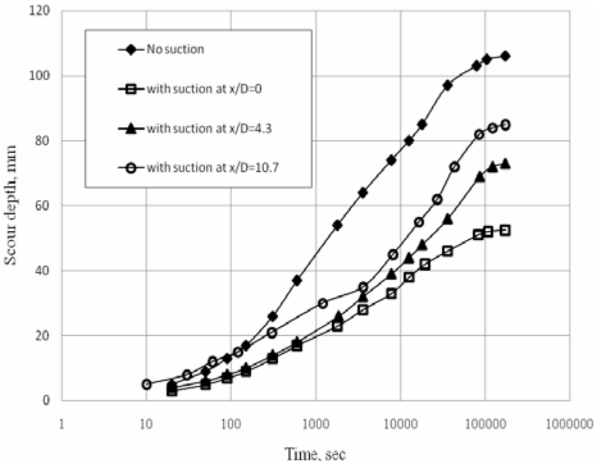

Fig.3 Temporal development of pier-scour depth for test with and without suction

4. EXPERIMENTAL RESULTS AND DISCUSSION

Table 1 summarizes all the experimental results obtained from this study. They show that suction has a profound influence on the equilibrium scour depth, as is clearly confirmed by the experimental data plotted in Fig.3. The data are plotted in terms of the customarily used variable known as percentage

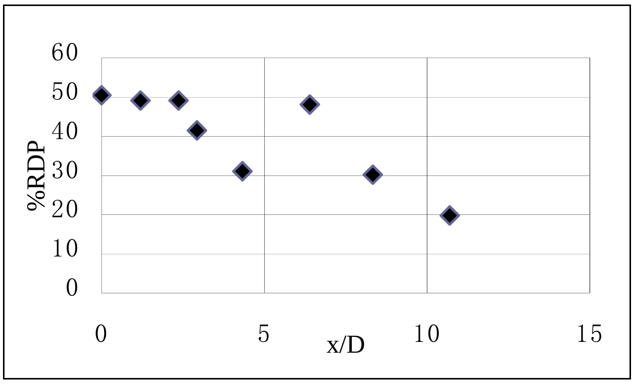

Fig.4 Effect of x/D on %RDP (Q_s/Q_o = 2%)

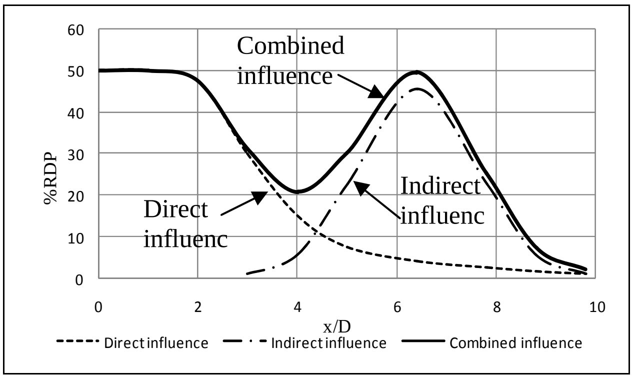

Fig.5 Influence of suction on scouring

reduction, %RDP, which is defined as $\%\mathrm{RDP} = \frac{(d_{se})_o - (d_{se})}{(d_{se})_o}$, as a function of the relative horizontal distance, x/D, in which $(d_{se})_o$ and d_{se} = equilibrium depth of scour without and with suction, respectively. The result for Q_s = 0.17 L/s or Q_s/Q_o = 2% is plotted in Fig.4. In the figure, x/D = 0 denotes the condition where the inlet of the suction is located directly beneath the center of the pier. The tests were conducted with a positive x-value, implying that the suction inlets are all located upstream of the pier. The trend of the data show that %RDP decreases with increasing x/D, which seems reasonable as one would expect $\%\mathrm{RDP} \to 0$ when $x/D \to \infty$. What is unexpected from the plot is the presence of a turning point at $x/D \approx 6.4$. In order to ensure that this unexpected result is not due to experimental errors, two additional runs (see Test Runs 9 and 10 in Table 1) were repeated under the same flow conditions, but the results were found to be the same. Thus, it may be inferred from the empirical data that the maximum %RDP of approximately 50% occurs at $0 \le x/D <$ ~2.4 and x/D = 6.4.

One may infer from the experimental data that suction does play an important role in causing a reduction in clear-water scour depth at bridge piers. Moreover, the presence of two local maximum points show that suction has two distinctive effects in influencing the scour hole development. It is surmised that the first peak or plateau, which occurs at x/D = 0 to 2.4, is due to a *direct influence* of suction on the scour mechanism, namely the downflow and horseshoe vortex. On the other hand, the second peak, which occurs at $x/D \approx 6.4$, is due to an *indirect influence* of suction on scouring.

(I) Direct Suction Influence on Scouring

Published experimental data have shown that the upstream angle that a pier-scour hole makes with the horizontal datum is approximately equal to the angle of repose of the bed sediment. For the given flow conditions in this study, the equilibrium scour depth without suction is found to be 106 mm. Moreover, the angle of repose of the bed sediment with d_{50} = 0.48mm is found to be approximately 32°. Using simple trigonometry, the horizontal distance from the edge of the scour hole to the upstream face of the circular bridge pier, L is computed to be 170 mm (L = 106/tan 32°). In view of this, one may note that the first three points in Fig.4, i.e., x/D = 0, 1.2 (x = 90 mm) and 2.4 (x = 178 mm) are all within or at least close to the extent of the scour hole formed without suction, and that the resulting %RDPs are essentially identical. Under this condition, suction causes a direct influence on the downflow and its associated horseshoe vortex, resulting in a reduced scour hole. One may hypothesize from this result that the direct influence of suction on the scour hole formation is only significant if the source of suction is confined within the original scour hole that forms without suction. If the suction source is outside the scour hole (x > 170 mm in this study), this direct suction influence dwindles abruptly, as is illustrated by the dashed curve in Fig.5. Another important effect of suction is its ability to increase the threshold condition for sediment entrainment in the scour hole, making the sediment particles less susceptible to erosion. This feature, which has been proven by the experimental data of Liu and Chiew (2007), is also expected to contribute to the reduced scour depth.

(II) Indirect Suction Influence on Scouring

The presence of the second peak at $x/D \approx 6.4$ points towards a completely different effect, which must be distinct from the direct suction influence described in the preceding section. This is because if the direct influence of suction is the only reason for the scour depth reduction, the %RDP at this location must be correspondingly lower. We hypothesize this unexpected phenomenon to suction's effect on the upstream sediment transport rate. With a 2-dimensional flow, as is the case at $x/D = 4.6$, the local sediment transport rate is a function of the local shear velocity excess, $(u_{*s}-u_{*cs})$ where u_{*s} = shear velocity with suction and u_{*cs} = critical shear velocity for sediment entrainment with suction. Clearly, the bedload transport rate increases with the shear velocity excess. If the latter is less than or equal to zero, sediment transport rate = 0. Research conducted at the Nanyang Technological University by the first author and his co-workers have shown that suction increases both u_{*s} and u_{*cs}, and the resulting sediment transport can often be less than that without suction. Some of the data associated with suction effects on measured bedload transport rates are reported in Liu and Chiew (2007); they showed that suction has the ability to increase bedload transport rate.

Because of this interesting effect of suction on bedload transport rate, one may conjecture that at $x/D = 6.4$, the local sediment transport rate is increased leading to the entrainment and transport of sediment particles into the scour hole even though the undisturbed velocity ratio is only 0.81. In fact a corollary of the experimental data is that at $x/D = 4.6$, the influx of sediment into the scour hole is the highest, leading to the most significant reduction in the scour depth, and hence the peaked-%RDP at 50%. This indirect suction influence is qualitatively illustrated by the dashed-dotted curve in Fig. 5.

The overall response of the scour hole development to suction must therefore be due to the combined *direct and indirect suction influence*. By adding these two effects together as shown in Fig. 5, one will get the combined suction influence of the pier-scour hole development, which clearly reflects a double peaked curve, as is also shown by the actual empirical results in Fig. 4. At this juncture, the above explanation to account for the unexpected empirical data in Fig. 4 remains hypothetical at best. At present, plans are underway to collect more data to either confirm or refute the hypothesis.

(III) Effect of Suction Rates on %RDP

An additional test was conducted with a different suction rate so as to investigate whether the rate of suction plays a role in affecting pier-scour development. The test was conducted with $Q_s = 0.17$ L/s at $x/D = 2.4$ (see Test Run 2 in Table 1). The experimental results show that the resulting equilibrium depth of scour = 88 mm (%RDP = 17.5%) is significantly higher when compared with its counterpart with $Q_s = 0.35$ L/s (d_{se} = 54 mm or %RDP = 49.1%). With the limited test runs, it appears that the rate of suction also plays a role in affecting the equilibrium scour depth, i.e., a larger suction rate leads to a higher %RDP.

5. CONCLUSIONS

The following conclusions are drawn from this study of suction effects on clear-water scour at bridge piers:

(a) Suction has a significant effect in reducing clear-water scour depth at bridge piers.
(b) Both the suction rate and location of the source of suction play a role in affecting the scour hole development.
(c) For $Q_s/Q_o = 2\%$, the experiment data show that the %RDP reaches a maximum of 50% for $0 \leq x/D \leq 2.3$ and $x/D = 6.4$.
(d) The reason for the existence of two peaks or plateau is due to the direct and indirect suction influences on the scour hole.
(e) A small Q_s/Q_o at 1% resulted in a significantly lower %RDP of 17.5 % when compared with that of 49.1% with $Q_s/Q_o = 2\%$ at $x/D = 2.4$.

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