

Total scour at spill-through abutments under free surface and overtopping flow conditions

XIAOZHOU XIONG⁽¹⁾, BRUCE W. MELVILLE⁽²⁾ & HEIDE FRIEDRICH⁽³⁾

⁽¹⁾ *PhD student, Auckland University, Auckland, New Zealand 1142. Email: xxia529@aucklanduni.ac.nz*

⁽²⁾ *Professor, Auckland University, Auckland, New Zealand 1142. Email: b.melville@auckland.ac.nz*

⁽³⁾ *Lecturer, Auckland University, Auckland 1142, New Zealand. Email: h.friedrich@auckland.ac.nz*

ABSTRACT

A laboratory study of total scour around spill-through abutments situated on the floodplain of compound channels is presented, for situations where both local scour and contraction scour occur together. The experiments include abutments near the main channel bank and abutments set-back from the main channel. Free surface and overtopping flow conditions were investigated in a 45-m long recirculating laboratory flume. The tests were characterized by a live-bed scour regime in the main channel (0.46-m wide) and clear-water scour regime on the floodplain (1.08-m wide). The test models were designed to represent a two-lane bridge at a 1:45 geometric scale. Roughness elements on the floodplain, both upstream and downstream of the mobile section, were used to adjust the flow distribution. Riprap rocks were placed around the abutment, based on the FHWA-NHI-09-112 (US) guidelines. Five ultrasonic depth-sounders were used to obtain scour development in the vicinity of the abutment toe, the dynamic-equilibrium scour depth, detailed bed-scour contour plots and sand dune heights around the abutment. A 3D down-looking velocimeter and a side-looking acoustic Doppler velocimeter were used to measure the flow distribution upstream of the abutment. For tests with a short set-back abutment, the development and propagation of the sand dunes significantly affect scour development and the final scour bathymetry around the abutment, while for tests with a long set-back abutment, the effect of sand dunes is negligible and the effect of local turbulence on scour is minimal. For overtopping flow conditions, the countermeasures selected using the FHWA-NHI-09-112 (US) guidelines, were found to be inadequate. The need for additional experiments, quantifying the effect of overtopping and sand dunes propagation, is emphasized.

Keywords: abutment, compound channel, overtopping, live-bed, sand dunes

1. INTRODUCTION

Scour around abutments has been a long-standing problem due to its universality, inevitability, dangerousness and complexity. Despite a previous clear delineation of the dominant variables governing abutment scour (Sturm et al., 2011), the innate complexity of abutment scour in natural systems makes it difficult to fully simulate this scour process in laboratories. Simplified scenarios have been investigated to improve understanding of abutment scour, including use of idealized channels (e.g., prismatic channels) or simplified models (e.g., rigid abutment models). Most of these simplified scenarios did not use scour countermeasures, and the majority of these previous studies were conducted with a clear water scour regime and a free surface flow condition (Melville and Coleman, 2000). However rivers tend to evolve into compound cross-sections and the abutments are generally earth-filled and protected by launching aprons, constructed from riprap or alternative materials such as cable-tie blocks. Destructive abutment scour normally occurs in floods, during which live-bed scour prevails in the main channel, and clear-water prevails on the vegetated floodplain. During extreme floods pressure flows can occur i.e., submerged orifice flow when the bridge deck is partially inundated, and overtopping flow when fully inundated. For example, the extreme floods in Georgia, USA in 1994 and 2009, caused major damage to numerous bridges due to the overtopping.

Pressure flow scour at a pier has been previously studied (Abed et al. 1991, Jones et al. 1995, Arneson and Abt 1998). In contrast, the knowledge of abutment scour in pressure flows is inadequate. Abutment scour in overtopping flows consists of local scour due to turbulence, lateral contraction scour due to protrusion of the abutment into the channel, and vertical contraction scour due to a partially or fully submerged bridge deck. Local scour and contraction scour occur interdependently and concurrently (Schreider et al., 2001; Ettema et al., 2010; Hong 2005; Hong 2013). It has been proposed that the co-existence of the abutment scour process can significantly reduce the contraction scour depth (Schreider et al., 2001). Ettema et al. (2010) conducted a comprehensive investigation, physically and numerically, in compound channels, and, as suggested by Laursen (1963), treated abutment scour as an amplification of idealized long contraction scour depth. This scour predication method worked well for a free surface flow condition, but lacks further verification for pressure flow conditions. Hong (2013) conducted a series of tests to investigate scour developments in both free surface and pressure flow conditions, and the results have further confirmed that the method proposed by Laursen (1963) applies well to pressure flow conditions (Hong, 2013). However, these tests were confined to a clear-water scour regime.

In a live-bed scour regime, scour around the abutment can be affected by propagation of sand dunes. Previous live-bed abutment scour experiments (van Ballegooy 2005, Ettema et al. 2010) have demonstrated that sand dunes pass through the scour hole, resulting in periodic fluctuations of the scour depth. It should be noted that these experiments were mainly conducted without a launching apron, and the abutment was rigid. In compound channels, the sloping bank may collapse quickly, and the launching apron or other protection around the abutment would spread out, dynamically protecting the abutment toe. Knowledge of the sand dunes' propagation is still limited in this more realistic scenario.

This paper presents a set of experiments conducted in a compound channel. Live-bed flow prevails in the main channel, and clear-water flow prevails on the vegetated floodplain. The abutment was protected by a launching apron designed using FHWA recommendations (Lagasse et al. 2009). This study has the following objectives: to physically simulate the abutment scour during floods, under conditions simulating those at typical bridge sites; to better understand the differences between free surface and overtopping flow conditions; and to increase knowledge of how sand dunes propagate through the bridge section.

2. EXPERIMENTAL SETUP AND MEASUREMENT

All tests were conducted in a 1.54-m wide, 1.2-m deep and 45-m long flume in the Fluid Mechanics Laboratory at The University of Auckland. The two supporting castellated-beams of the flume are centrally pivoted so that the slope of the flume is adjustable. A 1.08-m wide floodplain, a 0.26-m wide sloping bank (2:1) and a 0.2-m wide main channel were built along the flume (Fig. 1 and 2). Starting at 30-m downstream from the inlet section, a 4.6-m long test section was located as shown in Fig. 1. Within this test section the floodplain and main channel were formed in uniform sand with a median size $d_{50} = 0.84$ -mm and geometric standard deviation $\sigma_g = 1.35$. Outside this test section, the floodplain was immobilized and roughened using uniform rocks to simulate vegetation, and the sloping bank was made of metal sheets coated with the same sand as in the main channel. The entire main channel was filled up to its pre-test bed level with the uniform sand. At the inlet section, wave skimmers were used to suppress surface waves. The transported sediment was re-circulated by a sand pump, and guided back into the main channel. The flow discharge in each test was mainly controlled by the water pump, using a speed controller.

The test models were designed to represent a prototype, two-lane bridge at a 1:45 geometric scale (Fig. 2). A launching apron was used as a scour countermeasure and the apron dimensions and the apron-rock size were determined based on FHWA-NHI-09-112 (Lagasse et al. 2009).

Scour-depth development and the equilibrium bed surface around the abutment were measured using five ultrasonic depth sounders. Hong (2013) found that the before-scour turbulence intensity profiles at CS5 (see fig.1) could be used as a final scour depth predictor. Thus in this study, five ultrasonic depth sounders were placed at five suitable lateral positions (see Cartesian coordinate system in Fig.1) across CS5 to record scour development in the main channel, on the sloping bank and on the floodplain. Scour depth measurements were recorded for the duration of the experiments, until dynamic equilibrium was reached.

Depth-averaged velocities were measured at the approach section (CS.1), which was located at 3-m upstream of the bridge section. A four-receiver Vectrino+ down-looking acoustic velocimeter and a three-receiver Vectrino+ side-looking acoustic velocimeter (ADV, Nortek, AS, Rud, Norway) were used to measure the velocity distributions.

There were three groups of experiments, one group for each of three abutment lengths (i.e., three set-back distances). For each group, a free surface flow test and an overtopping flow test were undertaken (Table 1). All three free surface flow tests had the same approach-section flow depth, as did all three overtopping flow tests (Table 1). In all the tests, velocity in the main channel was set as slightly larger than sediment incipient velocity, thus live-bed scour regime prevailed. On the floodplain, roughness rocks were used to regulate the discharge distribution and clear-water regime prevailed. The same amount of roughness rocks was used in all the tests. Because the main channel, sloping bank and floodplain in the test section were all formed with uniform sand, the results presented here are relevant only to natural rivers in which the soil in the main channel and floodplain is non-cohesive and of similar erodibility.

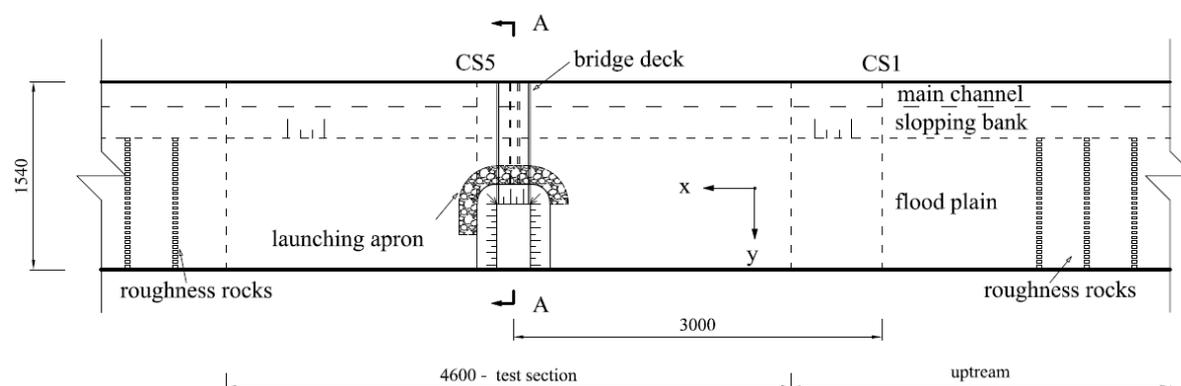


Figure.1 Plain view of the test section (abutment length varies in different tests), unit: mm

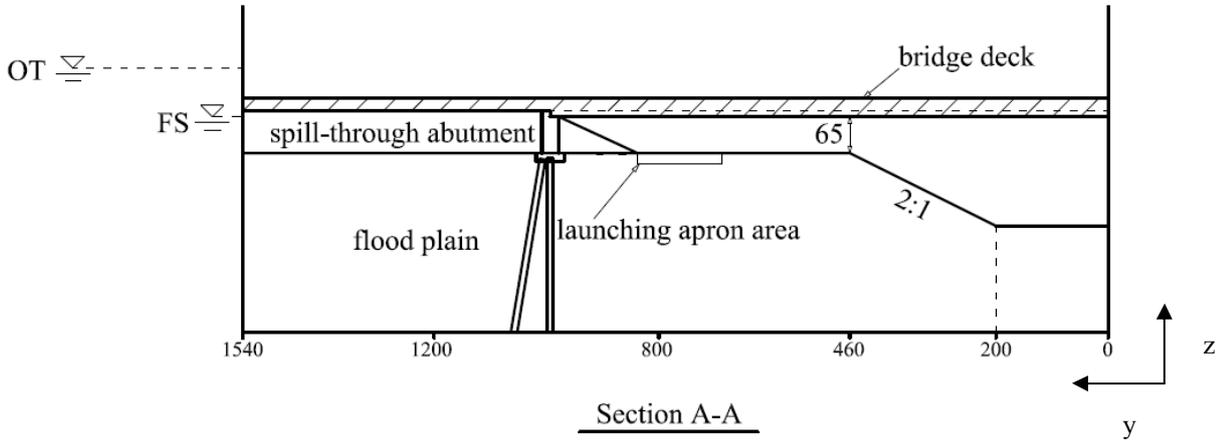


Figure.2 Side view of the bridge section, unit: mm

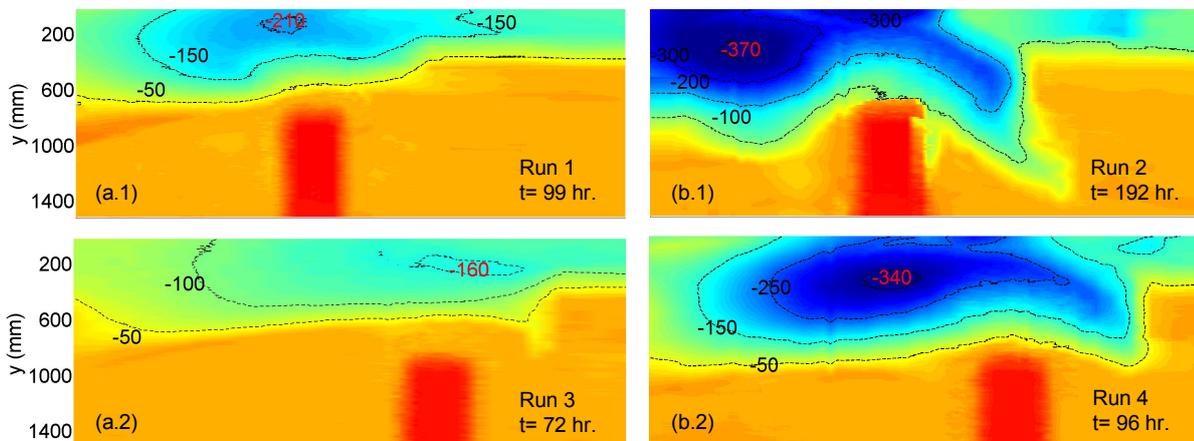
Table1. Experiment conditions

	La/Bf	Flow type	water depth on FP	water depth in MC	V1/Vc on FP	V1/Vc in MC	discharge	experiment duration
			yf1 (mm)	ym1 (mm)	Vf1/Vfc	Vm1/Vmc	Q (L/s)	hours
Run1	0.8	FS	65	195	0.49	1.00	36.1	99
Run2	0.8	OT	150	280	0.75	0.99	84.4	192
Run3	0.65	FS	65	195	0.54	1.04	38.1	72
Run4	0.65	OT	150	280	0.76	1.06	89.0	96
Run5	0.5	FS	65	195	0.58	1.08	40.2	72
Run6	0.5	OT	150	280	0.77	1.13	93.7	96

Note: La = abutment length; Bf = floodplain width; FP = floodplain; MC = main channel; FS = free surface flow; OT = overtopping flow; subscript f denotes floodplain; subscript m denotes main channel; 1 denotes CS1.

3. RESULTS AND DISCUSSION

3.1 Bed morphology in the dynamic-equilibrium state



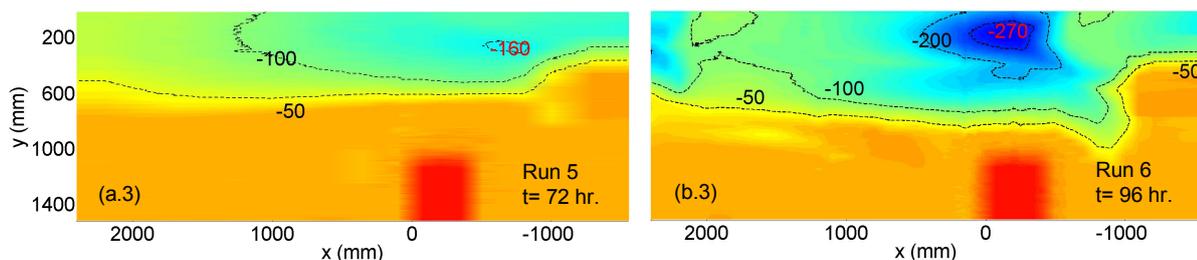


Figure3. Bed morphology in the dynamic-equilibrium state

Morphology measurement was conducted after dynamic equilibrium had been reached (see Fig.5). After the first two tests the abutment model was moved upstream to provide more detail of scour downstream of the abutment (see Fig. 3). For the three free surface flow tests (Run 3, 5), scour around the abutment mainly occurred in the main channel and on the sloping bank. Local scour at the toe of the abutment was insignificant, and the probable reasons are (a) a relatively small portion of slowly-moving discharge was obstructed by the abutment; (b) the sloping banks at, and downstream of, the bridge section collapsed quickly, relieving the flow; and (c) the launching apron provided protection in the high-turbulence area. It should be noted that under similar flow conditions, the non-cohesive sandy sloping bank at the upstream side of the abutment collapsed, as demonstrated by van Ballegooy (2005). Therefore, on the upstream side of the abutment, the sloping bank was protected by cable-tie blocks, to ensure that the velocity distribution did not change significantly because of a quickly collapsing sloping bank. The cable-tie blocks used are flexible and can deform along with the scour, resulting in limited influence on the abutment scour. For Run1, the deepest scour hole is located slightly downstream of the bridge section (Fig. 3.a.1), while for the longer set-back abutments (Runs 3 and 5), general erosion rather than scour holes are found (Fig. 3.a.2 and 3.a.3). These after-scour results indicate the importance of flow re-distribution and countermeasures when considering the position, geometry and the maximum depth of abutment scour. In addition, soil erodibility should also be considered.

For the three overtopping flow tests (Runs 2, 4, 6), scour holes spread laterally into the floodplain. Compared with the three free-surface flow tests, the scour holes in overtopping flow tests are situated further downstream and are much deeper than those for the corresponding free surface tests. This is because for the overtopping flow tests, flow is deeper, and also because of the vertical contraction. It should be noted that these two effects are co-existing. The scour hole in Run 2 (short set back group) was the deepest, and was located furthest downstream of the abutment. Because a geotextile filter was not used in this study, sand winnowing finally resulted in failure at the abutment toe (see Fig. 3.b.1). This failure happened more than 48 hours after starting the experiment, at which time the scour hole had already reached its dynamic equilibrium (see Fig. 5.b.1). Fig. 3.b.3 clearly shows that the deepest area in Run 6 is due to the combined contribution of the scour hole and the troughs of propagating sand dunes.

The propagation of sand dunes could not be clearly detected in every test in Fig. 3. However, based on laboratory observations, sand dunes could impact the scouring process in three different ways (illustrated in Fig. 4). In the dynamic equilibrium state, riprap stones tend to spread out in a fan shape as the erosion undermines the edge of the apron, and the scour hole occurs mainly downstream of the abutment. Sand dunes either maintain their shape and dimensions when passing by the bridge section and the scour hole (Fig. 4.a), or are deflected towards the scour hole after passing by the bridge section (Fig. 4.b), or are deflected towards the launching apron when passing by the bridge section (Fig. 4.c). The last scenario, illustrated in Fig. 4.c, is of concern in terms of abutment safety, because a sand crest situated in the bridge section could reduce the flow area and result in further erosive force on the apron rocks. One or a combination of these three mechanisms occurred in each test. However, based on the limited number of tests carried out, the general dynamic characteristics of these dunes cannot be clearly defined.

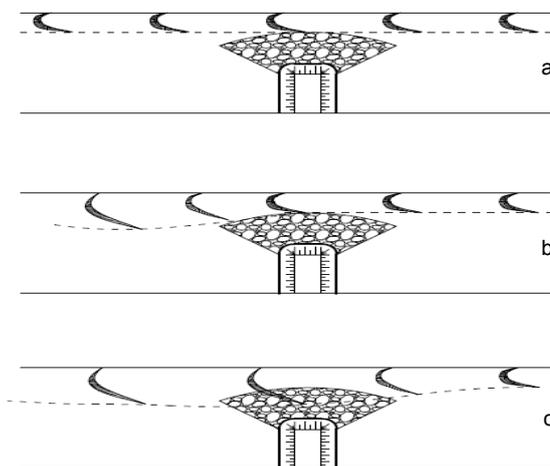


Figure4. Sand dunes propagating through the bridge section

3.2 Scour development at the bridge section

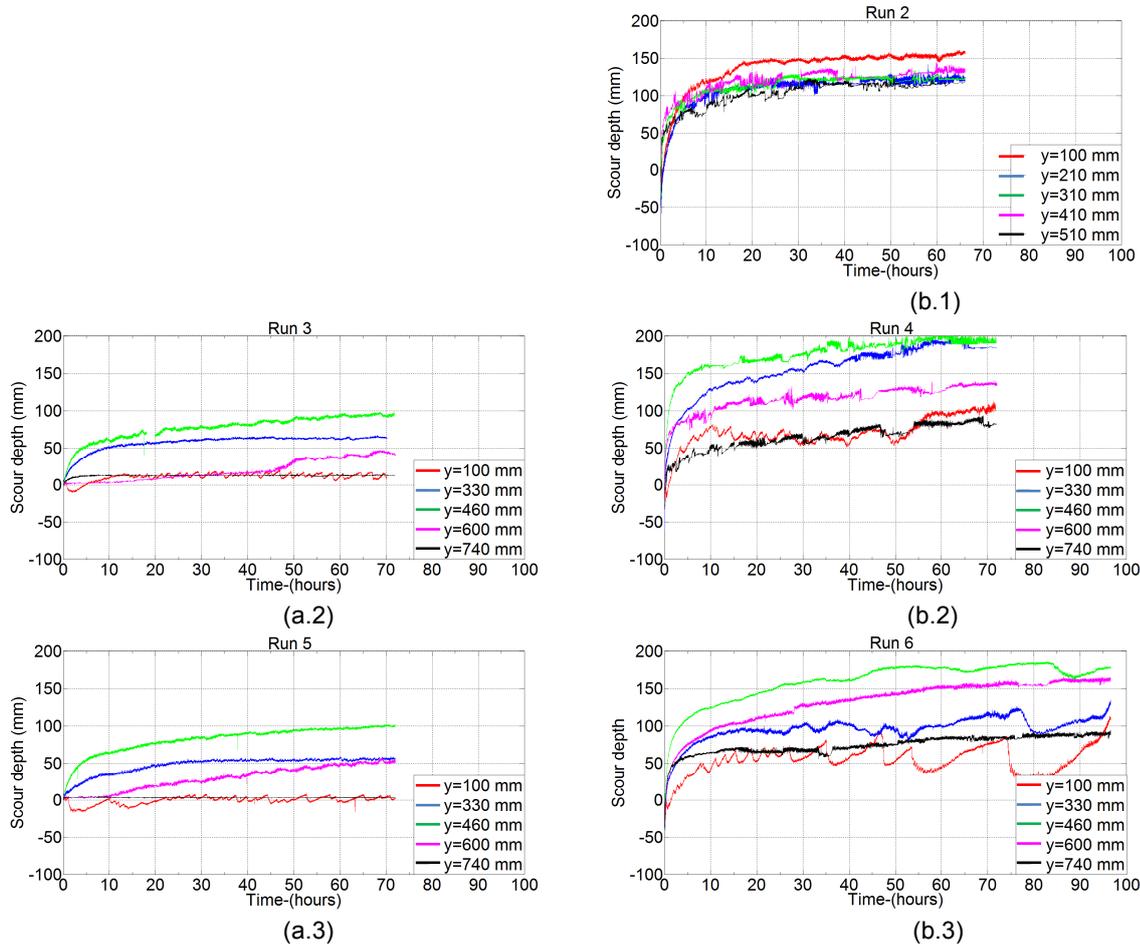


Figure5. Temporal development of scour at CS5

For an abutment with countermeasures, the scour hole is normally situated some distance downstream of the abutment, and this distance was found to be strongly dependent on the test environment (van Ballegooy 2005, Hong 2013). Therefore, it is difficult to predict where the deepest scour hole would finally be situated. Compared with the scour hole at the downstream side of the bridge, scour and the corresponding reaction of the countermeasures at the bridge section are directly related to the abutment's stability. Figure 5 shows the temporal development of scour (for Runs 2 to 6) at CS5 as measured by ultrasonic depth sounders, situated at distances (y) from the edge of the main channel, as shown in Fig.2. The presence of negative values in Fig. 5 indicates aggradation at the measurement positions. Aggradation can occur at the beginning of the test because the scour rate at CS5 is slower than that at the bridge section where the flow is most contracted.

Scour at the different lateral positions develops simultaneously, but at different rates. Scour at the right margin of the floodplain (y = 46-mm in Fig. 5) developed the fastest (in Run 2, scour at y = 46-mm developed fastest in the first two hours). This is mainly because this position adjoins the sloping bank and has relatively shallow water, and sand particles at this position have the lowest critical shear stress velocity. Close to the launching apron (y = 74-mm in Fig. 5.a.2, b.2, a.3, b.3), scour development was soon interrupted by the sliding apron rocks, and the corresponding scour depth is normally the shallowest. The scouring process and the final scour depth at each position is the combined effect of contraction scour, local scour and the presence of countermeasures, indicating that abutment scour is a more complex process than portrayed in the literature.

Temporal developments of the two free surface flow tests (Fig. 5.a.2 and a.3) are relatively mild and similar to each other, as corroborated by the bed morphologies in Fig. 3.a.2 and a.3. Scour at y = 60-mm and y = 74-mm in Run 3 and Run 5 is mainly induced by local turbulence, which is minimal. In contrast, scour at y = 60-mm and y = 74-mm in Run 4 and Run 6 is the combination of vertical scour and local scour, which can be significant. Local scour is more obvious for the long set-back abutment, as can be seen from the scour difference on the floodplain in Fig. 5.b.2 and b.3. Fig. 5.b.3 shows that sand dunes started in the main channel at $t = 7.5$ - hours, then spread to the centre of the sloping bank at $t = 28$ - hours. Thereafter, the sand dune reached the floodplain margin at $t = 42$ - hours, but with small amplitude. This indicates that the sand dune widens and flattens over time when propagating through the bridge section, as illustrated diagrammatically in Fig. 4. In the short set-back abutment test (Run 2 in Fig.3.b.1), contraction scour dominates for the whole bridge section, and scour developed approximately uniformly at the different measurement positions.

3.3 Scour development rate at the bridge section

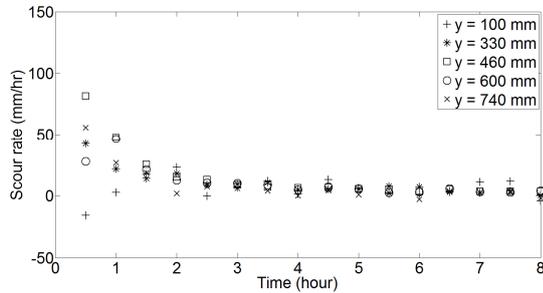


Figure.6 scour rate at CS5 in Run 6

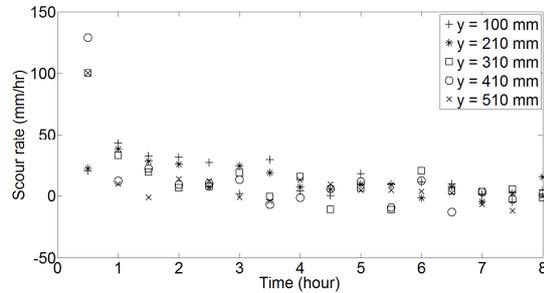


Figure.7 scour rate at CS5 in Run 2

Fig. 6 and Fig. 7 show the scour development rate over time at CS5 in Run 6 and Run 2, respectively. The scour rate here is a time-averaged term (scour rate = scour depth difference/time). The duration of time is chosen as 8 hours, to reduce the influence of propagating sand dunes. For the long set-back test in Fig.6, scour at $y = 600$ -mm and at $y = 740$ -mm developed relatively faster at the beginning of the test, indicating that local scour dominants. Afterwards, scour developed slower over time, and then the scour rate at different lateral positions was approximately constant at about 5mm/hour. For the short set-back test in Fig.7, the overall scour rate was about twice that for the long set-back test. For Run 2, scour rates at different positions decreased relatively slowly and were accompanied with fluctuations. These fluctuations are probably because the sand dunes developed soon after the start of the test.

3.4 Scour countermeasures for overtopping flows

In the overtopping flow tests, the embankment and the bridge deck combine as a submerged weir. The oncoming flow on the floodplain is deflected upwards over the bridge deck, and then impinges (downwards) on the sediment bed downstream of the bridge. During this process, a horizontal vortex occurs at the upstream side of the abutment, inducing scour in the area "A" in Fig. 9. In addition, the downward impinging flow induces jet scour in the area "B" in Fig. 9. On this basis, the FHWA-NHI-09-112 (US) guidelines (see Fig.8), were found to be inadequate for the overtopping flow conditions. For this study, the riprap apron on the upstream toe of the abutment was extended an additional 15-cm towards the channel wall (A in Fig. 9), while that on the downstream side of the abutment was extended to the glass wall (B in Fig. 9). It should be noted that the required dimensions of these two areas are flow dependent, and further research is needed to quantify them.

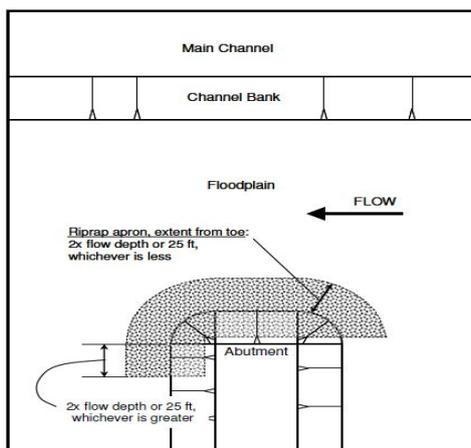


Figure8. Plan view of the extent of rock riprap apron represented from Lagasse et al. 2006

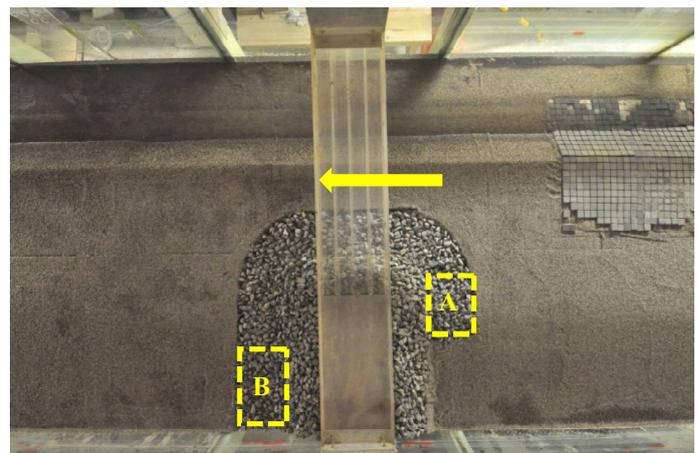


Figure9. Plan view of the extent of rock riprap apron used in Run 4 figure-

4. CONCLUSIONS

A set of experiments was conducted to investigate the scour characteristics of free surface and overtopping flow conditions for three different set-back distances. Each test was undertaken with live-bed scour regime in the main channel and clear-water scour regime on the floodplain. The after-scour results indicate the importance of flow re-

distribution and countermeasures in the development of the position, geometry and the maximum depth of abutment scour. Three different modes of sand dune propagation through the bridge section were observed in the laboratory, and it was also observed that the sand dunes do not necessarily pass through the scour hole. The countermeasures based on the FHWA-NHI-09-112 (US) guidelines, were found to be inadequate for the overtopping flow conditions. Extra protection is needed at both the upstream and downstream sides of the abutment.

Scour at the bridge section develops rapidly. Therefore, the before-scour turbulence characteristics could be further studied to explain the temporal development differences at different lateral positions and under different flow conditions. Further research could also focus on the effect of soil erodibility, and submerged orifice flow and overtopping flow with different overtopping magnitudes.

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