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Submerged-Flow Bridge Scour under Maximum Clear-Water Conditions (I): Experiment

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ABSTRACT

Submerged-flow bridge scour at clear water threshold condition has been studied experimentally. The experiments were conducted in a self contained recirculating tilting flume where two uniform sediment sizes and two model bridge decks with eight different inundation levels were tested for scour morphology. The experiments showed that the longitudinal scour profiles before the maximum scour depth can be approximated by a 2-D similarity profile, while the scour morphology after the maximum scour depth is 3-D. Finally, two empirical similarity equations for scour profiles were proposed for design purpose, and the collected data set could be used for analytical studies of bridge scour.

INTRODUCTION

Bridges are a vital component of the transportation network. Evaluating their stability and structural response to hydrodynamic loading is critical to highway safety in design phase and after flooding. The studies of bridge scour usually assume an unsubmerged bridge flow, but the flow regime can switch to submerged flow when the downstream edge of a bridge deck is partially or totally inundated during large flood events. For example, a submerged bridge flow occurred in the Cedar River in Iowa after heavy rains in June 2008 (Figure 1), which interrupted traffic on I-80. Submerged flow most likely creates a severe scouring capability because to pass a given discharge, the flow under a bridge can only scour the channel bed to dissipate its energy.

Investigations on submerged-flow bridge scour have been reported by Arneson and Abt (1998), Umbrell et al. (1998), and Lyn (2008). Arneson and Abt (1998) did a series of flume tests and proposed the following regression equation

$$\frac{y_s}{h_u} = -0.93 + 0.23 \left(\frac{h_u}{h_b} \right) + 0.82 \left(\frac{y_s + h_b}{h_u} \right) + 0.03 \left(\frac{V_b}{V_{uc}} \right) \quad (1)$$



Figure 1: Bridge-submerged flow in Iowa in 2008

where y_s = maximum equilibrium scour depth, h_u = depth of approach flow before scour, h_b = vertical bridge opening height before scour, V_b = velocity through a bridge before scour, and V_{uc} = upstream critical approach velocity defined by

$$V_{uc} = 1.52\sqrt{g(s-1)d_{50}}\left(\frac{h_u}{d_{50}}\right)^{1/6} \quad (2)$$

where g = gravitational acceleration, s = specific gravity of sediment, and d_{50} = median diameter of bed materials. Although Eq. (1) has been adopted in the FHWA manual (Richardson and Davis 2001), it suffers from a spurious correlation where both sides of the equation include y_s/h_u . In the meanwhile, Umbrell et al. (1998) also conducted a series of flume tests in the FHWA J. Sterling Jones Hydraulics Laboratory. Using the mass conservation law and assuming that the velocity under a bridge at scour equilibrium is equal to the critical velocity of the upstream flow, they presented the following equation

$$\frac{y_s + h_b}{h_u} = \frac{V_u}{V_{uc}} \left(1 - \frac{w}{h_u}\right) \quad (3)$$

where V_u = approach flow velocity that is less than or equal to the critical velocity V_{uc} , and w = depth of weir flow when flow overtops a bridge deck and $w = 0$ for partially submerged flow. By comparing Eq. (3) with their flume data, Umbrell et al. modified Eq. (3) as follows

$$\frac{y_s + h_b}{h_u} = 1.102 \left[\frac{V_u}{V_{uc}} \left(1 - \frac{w}{h_u}\right) \right]^{0.603} \quad (4)$$

where the critical velocity is estimated by Eq. (2) except that the coefficient, 1.52, is replaced by 1.58. Eq. (3) or (4) was based on the mass conservation law, but the dynamic law of momentum or energy was overlooked, which weakens the foundation of predictions because scour is a dynamic process. Besides, Umbrell's tests were run only for 3.5 hours which is not enough time for equilibrium scour to develop although they extrapolated their results to equilibrium states. The latest study was reported by Lyn (2008), who reanalyzed Arneson's and Umbrell's data sets and proposed the following power law

$$\frac{y_s}{h_u} = \min \left[0.105 \left(\frac{V_b}{V_{uc}} \right)^{2.95}, 0.5 \right] \quad (5)$$

where V_b and V_{uc} are the same as in Eq. (1). Lyn's equation is empirical, but he identified the spurious regression of Eq. (1) and the low quality of Umbrell's data.

In brief, the two existing data sets are insufficient to develop a general description of submerged-flow scour, especially for a scour profile. Moreover, all the existing methods lack understanding of the physical mechanism of submerged flow scour. Therefore, the objectives of this study were to collect a detailed data set of submerged-flow scour at a model bridge in a flume, and to develop a theoretical

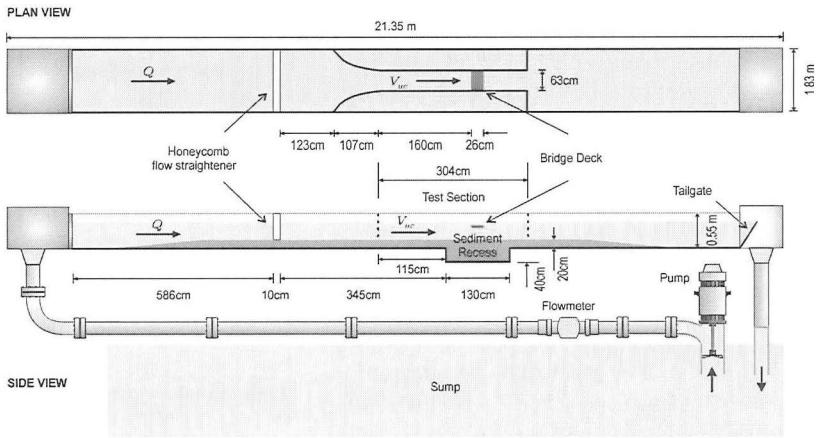


Figure 2: Experimental flume

model for the maximum scour depth under threshold clear water conditions. This paper emphasizes the experimental study that includes the experimental setup, results, discussion, and conclusions. A theoretical model for equilibrium scour profile is discussed in a separate paper.

EXPERIMENTAL SETUP

The experiments aimed to understand the flow and scour phenomena of submerged bridge flow by collecting scour data at a model bridge in a flume under controlled flow conditions. Specifically, the experiments tried to answer how sediment size, bridge girders and bridge inundation affect the longitudinal scour profile and maximum scour depth of submerged bridge flow.

The experiments were conducted in the FHWA J. Sterling Jones Hydraulics Laboratory, located at the Turner-Fairbank Highway Research Center in McLean, VA. The experimental flume (Figure 2) had a length of 21.35 m, width of 1.83 m, and depth of 0.55 m, with clear sides and a stainless steel bottom whose slope was about horizontal. In the middle of the flume was installed a test section that consists of a narrowed channel with length of 3.04 m and width of 0.63 m, a 40-cm sediment recess, and a model bridge above the recess. A honeycomb flow straightener and a trumpet-shaped inlet were carefully designed to smoothly guide the flow into the test channel. The water in the flume was supplied by a circulation system with a sump of 210 m³ and a pump with capacity of 0.3 m³/s; the depth of flow was controlled by a tailgate; and the experimental discharge was controlled by a LabView program and checked by an electromagnetic flowmeter.

To test the effect of sediment size on scour morphology, two uniform sands (the coefficient of gradation $C_g < 1.5$, and the coefficient of uniformity $C_u < 5$)

were used in the experiments: a median diameter $d_{50} = 1.14$ mm with $C_g = 1.45$ and $C_u = 1.77$, and a median diameter $d_{50} = 2.18$ mm with $C_g = 1.35$ and $C_u = 1.59$. The effect of bridge girders was examined by a three-girder deck and a six-girder deck (Figure 3). Both decks had rails at the edges (Figure 3c) that could pass overflow on the deck surface whose elevation was adjustable, permitting the deck to have eight different inundation levels. A LabView program was used to control an automated flume carriage that was equipped with MicroADV for records of velocities and a laser distance sensor for depths of flow and scour. The MicroADV (SonTek 1997) measures 3-D flow in a cylindrical sampling volume of 4.5 mm in diameter and 5.6 mm in height with a small sampling volume located about 5 cm from the probe; the range of velocity measurements is from 1 mm/s to 2.5 m/s. In this study, velocity measurements were taken in a horizontal plane located at a cross-section 22 cm upstream of the bridge. The LabView program was set to read the MicroADV probe and the laser distance sensor for 60 seconds at a scan rate of 25 Hz. According to the user's manual, the MicroADV has an accuracy of $\pm 1\%$, and the laser distance sensor has an accuracy of ± 0.2 mm.

Two discharges were applied in the experiments. They were determined by a critical velocity and the flow cross-section in the test channel that had a width of 0.63 m and a constant flow depth of 0.25 m. The critical velocity was preliminarily calculated by Neill's (1973) equation and adjusted by a trial-and-error method. The critical velocity of sediment $d_{50} = 1.14$ mm was approximately 0.41 m/s and the corresponding experimental discharge Q was 0.0646 m³/s. The critical velocity of sediment $d_{50} = 2.18$ mm was approximately 0.53 m/s and the corresponding experimental discharge was 0.0835 m³/s. The experimental conditions are summarized in Table 1 where the Froude and Reynolds numbers mean the approach flows were subcritical turbulent flows.

The experiments proceeded as follows: 1) Filled the sediment recess with sand and evenly distributed sand on the bottom of the flume until the depth of sand was 60 cm in the sediment recess and 20 cm in the test channel. 2) Installed a bridge deck at a designated elevation and positioned it perpendicular to the direction of flow. 3) Pumped water gradually from the sump to the flume to the experimental discharge that was checked with the electromagnetic flowmeter. 4) Ran each test for 36-48 hours and monitored scour processes by grades in a clear side wall; an equilibrium state was attained when scour changes at a reference point were less than 1 mm for three continuous hours. 5) Gradually emptied water from the flume and scanned the 3-D scour morphology using the laser distance sensor with a grid size of 5 cm \times 5 cm.

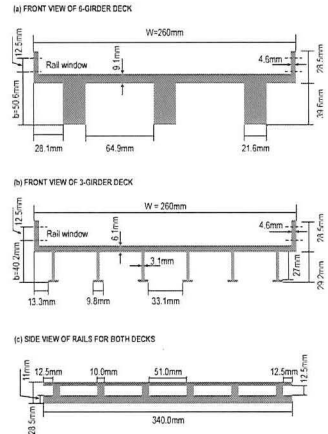


Figure 3: Decks of bridge models

Table 1: Test conditions of approach flow, bridge deck and sediment

Approach flow	3-girder deck	6-girder deck
$V_{uc} = 0.41$ m/s	$d_{50} = 1.14$ mm	$d_{50} = 1.14$ mm
$Q = 64.6$ l/s	$C_g = 1.45, C_u = 1.77$	$C_g = 1.45, C_u = 1.77$
$R_h = 13.9$ cm	$h_b = (21.0, 19.5,$	$h_b = (22.0, 20.5,$
$Re = 5.7 \times 10^4$	$18.0, 16.5, 15.0,$	$19.0, 17.5, 16.0,$
$Fr = 0.17$	$13.5, 12.0, 10.5)$ cm	$14.5, 13.0, 11.5)$ cm
$Q = 83.5$ l/s		$d_{50} = 2.18$ mm
$R_h = 13.9$ cm		$C_g = 1.35, C_u = 1.59$
$V_{uc} = 0.53$ m/s		$h_b = (22.0, 20.5, 19.0,$
$Re = 7.37 \times 10^4$		$17.5, 16.0, 14.5,$
$Fr = 0.22$		$13.0, 11.5)$ cm

Note: $h_u = 0.25$ m, $Fr = V_{uc}/\sqrt{gh_u}$, $Re = R_h V_{uc}/\nu$ where $R_h =$ hydraulic radius, and, $\nu =$ kinematic viscosity of water.

RESULTS

The results include the records of 3-D scour morphology, the width-averaged 2-D longitudinal scour profiles, and the width-averaged maximum scour depths. A representative 3-D scour morphology is shown in Figure 4 that was measured for a test of six-girder deck

under conditions $V_{uc} = 0.41$ m/s, $h_b = 17.5$ cm and $d_{50} = 1.14$ mm. The width-averaged longitudinal scour profiles of 26 tests are plotted in Figure 5 where $x = 0$ is at the maximum scour point that is 4 cm from the downstream deck edge, and $y = 0$ is at the channel bed before scour. The most important results, the width-averaged maximum scour depths, are shown in Figure 5 and will be detailed in Guo et al. (2010).

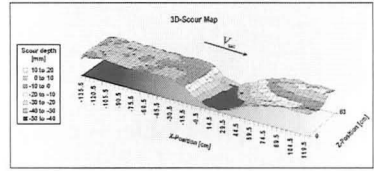


Figure 4: A representative of 3-D scour

DISCUSSION

Figure 4 shows that the scour morphology before the maximum point is approximately 2-D, after the maximum scour point it is 3-D. Furthermore, it is found that the 2-D scour morphology is subjected to pressurized flow while the 3-D scour morphology corresponds to free surface flow where the flow just exits the bridge, as shown in Figure 5, which plots 26 measured width-averaged longitudinal scour profiles. From Figure 5 one can see that: (1) The measured data are reproducible, as shown in subplot (a) where the data of two tests with $h_b = 15$ cm almost collapse into a single curve; similarly, a reproduction for two tests with $h_b = 20.5$ cm in subplot (b) can also be found before the maximum

scour point, the difference after the maximum scour point is due to the effect of free surface. (2) The longitudinal scour profiles are bell-shaped curves, but not symmetrical because the eroded materials deposit approximately two to three times the deck width downstream of the bridge. (3) The scour decreases with increasing sediment size, though the approach velocity in subplot (c) is larger than that in subplot (b). (4) The number of bridge girders has little effect on scour, as shown in subplots (a) and (b), but further test of this hypothesis is needed later since the values of h_b in the two plots are not the same. (5) The scour increases as bridge opening height, h_b , decreases, which means the scour increases with deck inundation level, $h_u - h_b$. (6) The maximum scour point occurs at 15% of bridge width (or 4 cm for the present experiments) to the downstream bridge edge.

Moreover, by looking at all the profiles in Figure 5, it is hypothesized that a similarity profile may exist for the 2-D profiles before the maximum scour point by scaling the horizontal length, x , with the deck width, W , and the local scour depth, y , with the maximum equilibrium scour value, y_s . This hypothesis is tested in Figure 6 (where the shallowest scour profile in Figure 5c is excluded because of large relative measurement errors), which confirms the similarity for $x \leq 0$. A least-squares curve-fitting process with MatLab gives a mean similarity equation

$$\frac{y}{y_s} = -\exp\left(-1.1 \left|\frac{x}{W}\right|^{2.41}\right) \tag{6}$$

where $x \leq 0$. The corresponding correlation coefficient is $R^2 = 0.995$ and the standard deviation is $\sigma_1 = 0.032$, which implies that 68% of the data can be described by Eq. (6) with an error of ± 0.032 , and 95% of the data with an error of ± 0.064 . Accordingly, the scour depth at the upstream edge of a bridge deck where $x/W = -0.846$ is approximately

$$\frac{y}{y_s} = -0.479 \pm 0.064 \tag{7}$$

with 95% confidence interval. Eq. (7) may be used for field scour evaluation. Considering that a significant scour starts at $y/y_s = -0.1$, from Eq. (6) and considering 95% confidence interval the x -coordinate of the initiation of scour is between $-1.58 \leq x/W \leq -1.23$.

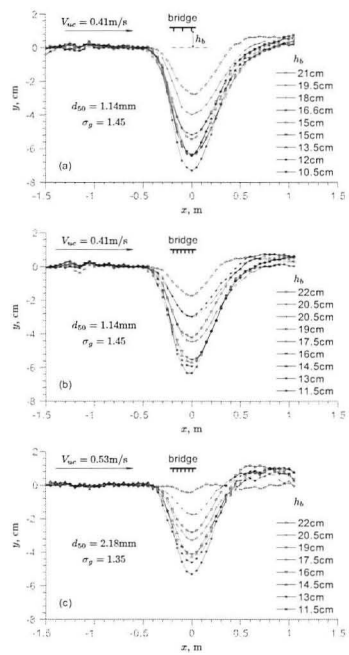


Figure 5: Measured width-averaged longitudinal scour profiles

For the 3-D profiles where $x > 0$ in Figure 6, a similarity profile does not exist, which results from the effect of free surface at the downstream of bridge. A mean profile equation for $x > 0$ does not have any meaning in practice. Thus, only a lower envelope equation is proposed for engineering design

$$\frac{y}{y_s} = -\exp\left[-\frac{1}{3}\left(\frac{x}{W}\right)^2\right] \quad (8)$$

which is plotted in Figure 6 and denoted by the dashed line. Note that although the width of deck in the experiments was constant, it was the only length in the flow direction so that it is natural to be the horizontal length scale. It is expected that Eqs. (6)-(8) are valid for similar bridge decks that are neither very thin like a sluice gate nor very wide like a water tunnel where a uniform scour profile may be developed after an entrance region.

Briefly, the horizontal scour range of a submerged flow depends on the width of bridge deck, but the design of a scour profile by Eqs. (6) and (8) needs the maximum scour depth y_s , which may be calculated by the methods reviewed in the introduction. Comparisons between the existing methods and the maximum scour depths in Figure 5 are plotted in Figure 7, which shows that: (1) the Arneson and Abt method has an adverse tendency with the test data, which means the functional structure of the equation is not correct; (2) the Umbrell et al. method, in general, agrees with the present data, in particular for sediment $d_{50} = 1.14$ mm; and (3) the Lyn method underestimates most of the present data. For a better estimation of y_s , a theoretical model, based on the mass and energy conservations, will be proposed in Guo et al. (2010).

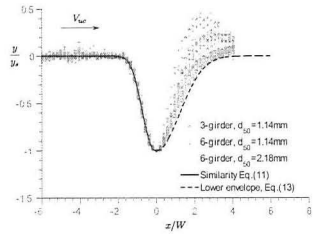


Figure 6: Test of similarity of hypothesis

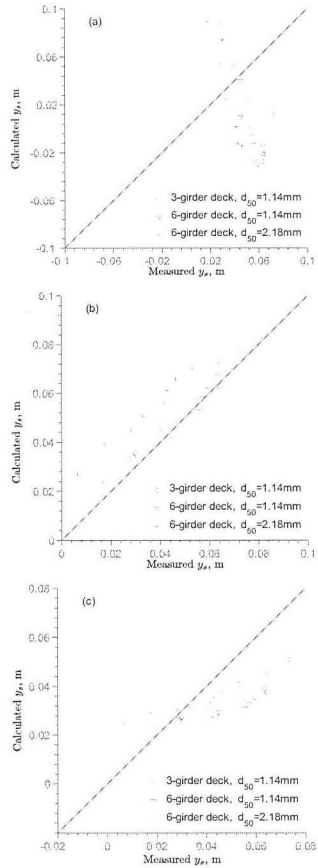


Figure 7: Comparison of existing methods with measured data

CONCLUSIONS

The experiments showed that under threshold clear water conditions: (1) a similarity longitudinal scour profile, Eq. (6), for submerged flows exists before the maximum scour point that is approximately 15% of deck width to the downstream bridge edge; (2) after the maximum scour point, scour morphology is 3-D and the lower envelope of scour can be empirically described by Eq. (8); (3) the maximum scour depth increases with deck inundation level, but decreases with increasing sediment size; and (4) the maximum scour depth is independent of the number of deck girders.

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