TECH**BRIEF**

Pier Scour Estimation for Tsunami at Bridges

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This TechBrief provides the most recent research product in scour formation and offers an interim support for foundation design of bridges vulnerable to scour caused by tsunamis. This research supplements the product from the Transportation Pooled Fund study TPF5-(307), *Validation of Tsunami Design Guidelines for Coastal Bridges*, which developed an evaluation method for tsunami loading for bridge design (Lynett et al. 2021). The formulas developed in this study, which can be used to assess tsunami-related scour depths at bridge foundations, are derived from a small number of experimental and numerical tests with a limited scope. More research with a broader parametric variation is underway.

INTRODUCTION

The Seismic and Multi-Hazard Resilience Program provides assistance to State and local governments and metropolitan planning organizations in improving highway network resilience against extreme events and to best utilize the funding from federal highway programs to protect lives and boost economic growth. It offers technical support, guidance development, research facilitation, and accelerated innovation deployment to accomplish the program goal.

The Scour Program is an integrated national effort to address or mitigate erosion of streambed or bank material due to flowing water, including erosion localized around bridge abutments and piers. The program's primary goal is to improve safety and resilience of the Nation's bridges.

The potential hazards to bridges from a tsunami event may include an inundation hazard for traffic, the force effect on the structure, and erosion caused by hydraulic loads on riverbeds, which has the potential to undermine bridge foundations. This TechBrief presents results of a Federal Highway Administration (FHWA) study that uses a laboratory-validated, hybrid numerical scheme that combines computational fluid dynamics (CFD) with sediment transport analysis to provide a practical method for evaluating tsunami-related scour depths at bridge foundations.

The American Society of Civil Engineers (ASCE) *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE/SEI 7-16) characterizes a tsunami as "a series of waves with variable long periods, typically resulting from earthquake-induced uplift or subsidence of the seafloor" (ASCE 2016). The erosion near bridge foundations is produced by the tsunami wave, or bore, and the subsequent high-velocity flow that results from shoaling in the estuary,

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stream channel, or flood plain where the bridge is located. Accurately estimating the amount of erosion during a tsunami requires theoretical and laboratory or numerical studies of tsunami flow conditions, bed material (consisting of various soil and rock layers), resistance, and the transient erosion process caused by rapidly changing hydrostatic and hydrodynamic forces.

Erosion hazards from tsunami events have been observed in postevent investigations. Scour near the foundations of buildings and seawalls was observed in the 2011 Tohoku tsunami (Bricker et al. 2012). The observed sites with sand, clay, or gravel materials exhibited 1.3 ft to 9.8 ft of scour. The same study indicated that, among the scour prediction methods, the pier scour equation used in the FHWA guide *Evaluating Scour at Bridges* (HEC-18) was promising, but needed to be adjusted to account for the shorter duration of tsunami flow compared to riverine floods (Bricker et al. 2012; Richardson and Davis 2001). Tonkin et al. (2013) indicated that the cause of the deepest field-observed tsunami scour is overtopping flow (for walls), followed by local and then general scour. The same study found the envelope of local scour to be approximately 1.2 times the flow depth up to a maximum of 13.1 ft. The tsunami-induced liquefaction (i.e., pore pressure softening) also played a role in the tsunami scour. This effect enhanced the scour effect during the drawdown phase of a tsunami.

Scour develops at bridge foundations and approach embankments through the entrainment of riverbed material into the flood waters when the static or dynamic hydraulic stress of the flow exceeds the resistance of the riverbed materials. Tsunami-induced scour develops under different environmental conditions than bridge scour in a typical riverine environment. The estimation method presented in this TechBrief assumes the erosion from the impact of the tsunami wave front, or bore, is a less significant source of scour than the period of high flow that follows the first impact. This high-flow period is in the range of 10 to 20 min, a much shorter time than is needed to develop equilibrium scour. (FHWA considers equilibrium scour to be the vertical distance between the deepest point in the scour hole and the stable bed level.) In the live-bed scour, the scour depth reaches equilibrium quickly and oscillates with time because of the movement of the bed forms. FHWA studied the effect of the short duration of the tsunami flow through numerical simulations of the scour development with respect to time. The study found the predicted tsunami scour value equaled the reduction of scour depth from riverine equilibrium scour.

The primary result of this FHWA study is an estimated scour time reduction factor that can be applied to pier scour estimates to account for the short duration of a tsunami. (Note that abutment-scour estimates will be developed in future tsunami research.) The results of this study suggest the potential for achieving further refinement of the tsunami scour estimate by considering more conditions and variabilities of site conditions. For example, past (non-FHWA) experiments showed that tsunami scour is a highly dynamic process in which the maximum scour depth during a tsunami runup and drawdown may reach five times that of the final observed depth (Kato et al. 2001). However, this study considered only a single cycle of high flow in one direction and did not consider the sediment supply from far downstream and far upstream, and therefore it did not include the scour depth fluctuation from the effect of refill. The authors of this TechBrief hypothesize that the scour estimate that results from the method developed in this study would likely be greater than scour depths observed in the field because the sediment supply from far downstream and upstream was not considered when developing the method. The authors also acknowledge that they have not completely tested the sensitivity of the estimate to various sediment sizes and tsunami flow. FHWA advises caution in using the method presented in this TechBrief pending further verification and refinement through more research conducted by the Scour Program. Nevertheless, this TechBrief provides some new insights for the scour research community.

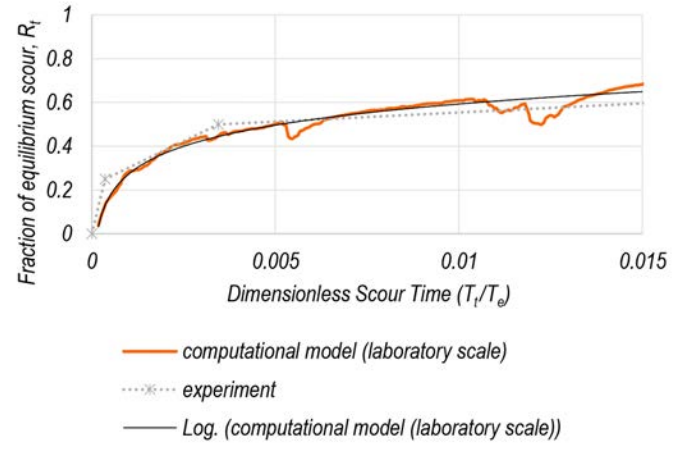
EXPERIMENTAL AND NUMERICAL RESEARCH

A tsunami is a short-duration event lasting only a fraction of an hour. This differs from a riverine flood, which may occur over a much longer period. A typical riverine flood event may be long enough to allow equilibrium scour depth to develop. Due to a tsunami's short duration, the resulting scour depth at bridge piers may be far less than the equilibrium scour depths expected for the tsunami flow parameters. Research was needed to develop a time evolution of the scour-depth curve to assess the reduced scour that results from the short duration of a tsunami event. In this study, FHWA developed a scour time reduction factor that can be applied to the HEC-18 pier scour equations using tsunami flow parameters. This factor may be affected by a number of parameters, such as sediment size, flow velocity, pier shape, the selection of pier scour prediction equations, and so on. Due to the limited scope of this study, the variation of many of these parameters were not fully considered.

FHWA intends to investigate the effect from these variations in the future to improve the evaluation method. For example, the study conducted tsunami simulations with lower velocities than those estimated for tsunami events because of the limited availability of validated models with extreme high-flow conditions. Work is underway to extend Argonne National Laboratory's (ANL's) scour model to simulate erosion under extreme high-flow conditions. At this time, the best available guidance for estimating the relationship between time and scour depth is based on less extreme flood-flow conditions than those in a tsunami.

Researchers at ANL developed an experimentally-validated numerical method to simulate scour formation (Lottes et al. 2016). The same numerical modeling method was used in this study and further validated with experiments conducted at FHWA's J. Sterling Jones Hydraulics Research Laboratory. Researchers then used the validated CFD model to interpolate the scour depth at any specified time before reaching equilibrium scour. Figure 1 shows a close correlation of the computational model results and the laboratory results.

Figure 1. Graph. Fraction of equilibrium scour versus time (Lottes et al. 2019).



Source: ANL.

PRACTICAL TSUNAMI SCOUR EVALUATION METHOD

The tsunami-induced scour for a pier, y_{s_t}, is a function of the duration of the high flow from the tsunami. It is calculated using the scour time reduction factor (all units in feet and seconds):

$$y_{s_t} = R_t y_{s_{corr}} \tag{1}$$

where $y_{s_{corr}}$ is the expected scour depth, for which

$$y_{s_{corr}} = 0.68 y_{s_{CSU}} \tag{2}$$

or

$$y_{s_{corr}} = 0.75 y_{s_{FDOT}} \tag{3}$$

where $y_{s_{CSU}}$ is the scour prediction from the equations given in Section 7.2 of HEC-18, while $y_{s_{FDOT}}$ is the scour prediction from the equations given in Section 7.3 of HEC-18 (Arneson et al. 2012).

R_t is the scour time reduction factor developed in this study and shown in figure 1. It can be evaluated as:

$$R_t = T_t^{*0.1520} \tag{4}$$

where T_t* is the normalized tsunami high-flow duration:

$$T_t^* = \frac{T_t}{T_e} \tag{5}$$

T_t is the period of time for the high flow of a tsunami that is potentially capable of generating considerable scour (10–20 min may be considered a reasonable general length in absence of further information).

T_e is the time required to reach equilibrium (Melville and Chiew 1999).

If $\frac{V_1}{V_c} \leq 1$, then

$$T_e = 48.26 \cdot 86{,}400 \frac{a}{V_1}\left(\frac{V_1}{V_c} - 0.4\right) \quad \text{when} \quad \frac{y_1}{a} > 6 \tag{6}$$

$$T_e = 30.89 \cdot 86{,}400 \frac{a}{V_1}\left(\frac{V_1}{V_c} - 0.4\right)\left(\frac{y_1}{a}\right)^{0.25} \quad \text{when} \quad \frac{y_1}{a} \leq 6 \tag{7}$$

where a is the pier diameter, y_1 is the flow depth before reaching the pier, V_1 is the flow velocity before reaching the pier, and V_c is the critical velocity for the channel, which can be estimated by:

$$V_c = 11.17 y_1^{1/6} D_{50}^{1/3} \tag{8}$$

where D_{50} is the representative particle size of the granular bed materials.

If $\frac{V_1}{V_c} > 1$, the time required to reach equilibrium is (regression conducted using data from Ballio, Radice, and Dey (2010)):

$$T_e = \frac{78{,}590a}{V_1}\left(\frac{V_1}{V_c}\right)^{5.0802\ln\left(\frac{V_1}{V_c}\right)} \cdot \left(\frac{V_1}{V_c}\right)^{-9.2594} \tag{9}$$

APPLICATION EXAMPLE

In this example, the scour time reduction factor and the evaluation method described previously are used to estimate scour at a bridge pier with a diameter of 3.28 ft. The bed material is fairly uniform, with a representative particle size of 0.39 inches. The tsunami hazard is represented in terms of maximum flow depth and maximum flow velocity at a specific bridge site. For this example, the maximum flow depth and velocity are 4.49 ft and 5.49 ft/s, respectively. Since the maximum flow velocity does not normally occur at the same time as the maximum flow depth, two cases of load combinations may be used to represent the likely worst situation (Lynett et al. 2021).

Load Case 1

In this load case, the estimated scour depth is calculated using a maximum flow velocity of 5.49 ft/s and 2/3 the maximum flow depth (2/3 of 4.49 ft = 2.99 ft):

$$y_{s_{CSU}} = 5.44\ \text{ft} \tag{1.1}$$

$$y_{s_{FDOT}} = 5.75\ \text{ft} \tag{1.2}$$

$$y_{s_{corr}} = 0.68 y_{s_{CSU}} = 3.70\ \text{ft} \tag{1.3}$$

or

$$y_{s_{corr}} = 0.75 y_{s_{FDOT}} = 4.31\ \text{ft} \rightarrow \text{Use this value.} \tag{1.4}$$

$$V_c = 11.17 \cdot 2.99^{1/6} \cdot 0.033^{1/3} = 4.31\ \text{ft/s} \tag{1.5}$$

$$\frac{V_1}{V_c} = 1.27 > 1\ (\text{Live Bed}) \tag{1.6}$$

$$T_e = \frac{78{,}590 \cdot 3.28}{2.99} \cdot (1.27)^{5.0802 \ln(1.27)} \cdot (1.27)^{-9.2594} = 6{,}690\ \text{s} \tag{1.7}$$

$$T_t^* = \frac{20 \cdot 60}{6{,}690} = 0.1794 \tag{1.8}$$

$$R_t = 0.1794^{0.1520} = 0.7702 \tag{1.9}$$

$$y_{s_t} = R_t y_{s_{corr}} = 0.7702 \cdot 4.31 = 3.32\ \text{ft} \tag{1.10}$$

The scour depth for load case 1 equals 3.32 ft.

Load Case 2

In this load case, the estimated scour depth is calculated using a maximum flow depth of 4.49 ft and 4/5 the maximum flow velocity (4/5 of 5.49 ft/s = 4.39 ft/s):

$$y_{s_{CSU}} = 5.23\ \text{ft} \tag{2.1}$$

$$y_{s_{FDOT}} = 6.06\ \text{ft} \tag{2.2}$$

$$y_{s_{corr}} = 0.68 y_{s_{CSU}} = 3.55\ \text{ft} \tag{2.3}$$

or

$$y_{s_{corr}} = 0.75 y_{s_{FDOT}} = 4.54\ \text{ft} \rightarrow \text{Use this value.} \tag{2.4}$$

$$V_c = 11.17 \cdot 4.49^{1/6} \cdot 0.033^{1/3} = 4.61\ \text{ft/s} \tag{2.5}$$

$$\frac{V_1}{V_c} = 0.95 < 1\ (\text{Clear Water}) \tag{2.6}$$

$$\frac{y_1}{a} = \frac{1.37}{1} < 6 \tag{2.7}$$

$$T_e = 30.89 \cdot 86{,}400 \cdot \frac{3.28}{4.39} \cdot (0.95 - 0.4) \cdot \left(\frac{4.49}{3.28}\right)^{0.25} = 1{,}192{,}221\ \text{s} \tag{2.8}$$

$$T_t^* = \frac{20 \cdot 60}{1{,}192{,}221} = 0.001007 \tag{2.9}$$

$$R_t = 0.001007^{0.1520} = 0.3503 \tag{2.10}$$

$$y_{s_t} = R_t y_{s_{corr}} = 0.3503 \cdot 4.54 = 1.59\ \text{ft} \tag{2.11}$$

The scour depth for load case 2 equals 1.59 ft. Therefore, load case 1 controls with a scour depth of 3.32 ft.

GLOSSARY AND SYMBOLS

Clear-water scour: scour at a pier or abutment (or contraction scour) when there is no movement of the bed material upstream of the bridge crossing at the flow causing bridge scour.

Drawback: the stage after tsunami reaches the runup limit and flow reverses toward the shore.

Live-bed scour: scour at a pier or abutment (or contraction scour) when the bed material in the channel upstream of the bridge is moving at the flow causing bridge scour.

Runup: the inland limit of the tsunami wave, or the process of tsunami reaching this limit.

y_{s_t}: tsunami-induced pier scour depth.

R_t: scour time reduction factor from equilibrium scour considering short scour period.

$y_{s_{corr}}$: expected (mean) equilibrium pier scour depth.

$y_{s_{CSU}}$: scour prediction from the equations given in Section 7.2 of HEC-18.

$y_{s_{FDOT}}$: scour prediction from the equations given in Section 7.3 of HEC-18.

T_t: duration of the flow that produces scour.

T_t^*: duration of the flow that produces scour normalized by the time required for reaching equilibrium scour.

T_e: time required for reaching equilibrium scour.

V_1: flow velocity before reaching the bridge pier.

V_c: critical velocity below which the bed material cannot be eroded.

a: cross-sectional size of the pier.

y_1: flow depth before reaching the bridge pier.

D_{50}: representative particle size of the granular bed materials.

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