Scour Estimation for Tsunami at Bridges

White Paper Report

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Introduction

The potential hazard to bridges from a tsunami event may include inundation hazard to the traffic, force effect on the structure, erosion of the foundation caused by hydraulic load on soils or rocks, and erosion of the approach. This study uses a laboratory-validated hybrid numerical scheme that combines Computational Fluid Dynamics (CFD) with sediment transport analysis to provide a practical evaluation method for scour depth at bridge foundations.

The erosion from tsunami has been observed in post-event investigations in past tsunamis. ASCE 7 characterize a tsunami as "*a series of waves with variable long periods, typically resulting from earthquake-induced uplift or subsidence of the seafloor*." The effect on bridges and the materials near bridge foundations are produced by the tsunami wave or bore and the subsequent high velocity flow as a result of shoaling process in the estuary, stream channel, and flood plain where the bridge is located. Accurately capturing the amount of erosion during tsunamis requires theories and laboratory or numerical studies in tsunami flow conditions, bed material resistance, and the transient erosion process caused by rapidly changing hydrostatic and hydrodynamic forces.

Scour near the foundations of buildings and seawalls have been observed in the 2011 Tohoku Tsunami (Bricker et al. 2012[1]). The observed sites with sand, clay or gravel materials exhibited 0.4m to 3m of scour. Among the scour prediction methods, the pier scour equation used in HEC-18 (Richardson and Davis, 2001[2], *Note: previous version*) was found promising, but needing reduction to account for a shorter duration of tsunami flow compared to riverine floods. Tonkin et al. (2013[3]) indicated that the deepest field-observed scour is caused by overtopping flow (for walls) followed by local and then general scour. A correlation between scour depth and flow depth was also observed with a cap of 4m. The tsunami-induced liquefaction (pore pressure softening) also plays a certain role in the tsunami scour.

Scour at bridge foundations and approach embankments develops through the entrainment of soils or rocks when the static/dynamic hydraulic stress exceeds the soil/rock resistance. The resistance of soils or rocks may also be reduced by quarrying effect or pore pressure softening effect, therefore worsening the scour effect. While these scour mechanisms are shared between river-crossing bridges and coastal bridges, the tsunami-induced scour is developed under a very different environment than that producing scour in a riverine flood. In this study, the erosion from the impact of the tsunami wave front or the tsunami bore is assumed less significant. The period of high flow after the first impact is assumed to be the primary source of the scour. This high flow period is in the range of 10 to 20 minutes. It is much shorter than the amount of time needed to develop equilibrium scour. The effect of the short duration of the tsunami flow is studied through numerical simulation of the scour development with respect to time. The

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[1] Jeremy D. Bricker, Mathew Francis, Akihiko Nakayama (2012), Scour depths near coastal structures due to the 2011 Tohoku Tsunami, Journal of Hydraulic Research, 50:6, 637-641, DOI: 10.1080/00221686.2012.721015.
[2] Richardson, E.V., Davis, S.R. (2001). Evaluating scour at bridges. Hydraulic Engineering Circular No. 18. Federal Highway Administration, Washington, DC.
[3] Tonkin Susan P., Francis Mathew, Bricker Jeremy D. (2013) Limits on Coastal Scour Depths due to Tsunami, Proc. International Efforts in Lifeline Earthquake Engineering, 671-678, doi:10.1061/9780784413234.086

reduction of scour depth from equilibrium scour is used to modify the scour equations that predict equilibrium scour.

The primary result of this study is an estimated time-dependent reduction factor for the short duration of a tsunami. With limited data availability, a number of assumptions know to introduce inaccuracy to the estimate are used. For example, past experiment showed that the tsunami scour is a highly dynamic effect, for which the maximum scour depth during a tsunami runup and drawdown may reach five times of the final observed depth (Kato et al. 2001[4]). This study considers a single cycle of high flow in one direction. The sediment supply from far downstream and far upstream are not considered. The scour depth fluctuation from the effect of refill is therefore also not included. It is very likely that the scour estimate is greater than field observation because to negligence of sediment supply. The sensitivity of the estimate to sediment size and tsunami characteristics has not been completely tested. The result is to be used with caution, pending for further verification and refinement in the upcoming investigation through FHWA's scour program.

Numerical Modeling and Validation

A tsunami is a rapid, short duration event on the order of an hour compared to a typical river flood that may occur over a period of days to several weeks. While a typical river flood event may be long enough for scour at bridges to reach the equilibrium scour depth, due to its short duration, scour depth in a tsunami event may be far short of the equilibrium scour depth. For the purpose of planning and design, the lower scour depth risk due to short duration of the event would be very useful information. A time evolution of scour depth curve is needed to assess the reduced scour risk due to the short time duration of a tsunami event. In this study, a reduction factor is developed to apply to the result from using tsunami flow parameters in the pier scour equations of HEC-18. This factor may be affected by a number of factors, such as the sediment size, flow velocity, pier shape, the selection of scour prediction equations, and so on. With limited data and resources, some of such influences are neglected at this moment and pending for further improvements. One of such simplification is to use a lower flow rate than that during a tsunamic event and accept the added uncertainty in the reduction factor from different flow velocity. Tsunami conditions have flow velocities and bed shear stress that are typically larger that the critical value for onset of sediment motion by a factor of 10 to 100 or more. The extremely high shear stress will produce very high bed erosion rates initially. The bed load layer has a limited capacity for carrying sediment, and as the sediment carrying capacity is reached, the erosion rate will slow down toward a value much lower than that given by a clear water erosion rate or pickup function. This lower rate is governed by the rate at which sediment can be transported out of the local region undergoing scour by the fluid and sediment flow. Work is underway to extend the Argonne scour model to simulate erosion under the extreme flow conditions of a tsunami flow. While the basic model functions are present, a significant amount of work remains to be done to achieve a numerically stable simulation of scour processes under these conditions.

[4] Fuminori Kato, Shinji Sato and Harry Yeh (2001) Large-Scale Experiment on Dynamic Response of Sand Bed Around a Cylinder Due to Tsunami, Coastal Engineering 2000.

The following steps are used to validate and extend the numerical modeling to obtain the scour reduction factor:

1. Conduct a non-traditional scour testing on a circular pier that records several stages of scour and corresponding time. This is a very difficult task in the past but has been made possible with bathymetric measurement on-the-run equipment.
2. Create a CFD/sediment transport hybrid model to simulate the laboratory setup.
    a. CFD simulation with the current bed condition and pier in place. The simulation can be steady or unsteady that runs until a steady condition is reached. This is because the time scale of scour is much larger than that of the flow. The flow is always at a quasi-steady condition as scour develops.
    b. Obtain shear stress on every point of the bed and apply the stress to the entrainment function to calculate the erosion rate.
    c. Using the erosion rate map and a specified target bed displacement, calculate the time required for the location of the highest erosion rate to reach to target displacement. This is the time increment for the erosion step. The bed displacement everywhere on the bed is calculated using this time step and corresponding erosion rate at each point. Step c is done in a Python script outside the CFD platform.
    d. The bed boundary of the model is modified in accordance with the displacements calculated from step c.
    e. Repeat steps a through d until the scour reaches an asymptotic state with nearly zero scour rate in the scour hole.
3. Upon verifying the CFD/sediment transport result being consistent with the experimental result, produce variation of the model to investigate sensitivity to various factors. The only validated variation included in this report is a full-scale model based on a Oregon bridge.

This approach has been validated and used in a previous bridge scour study. Details can be found in the Argonne Technical Report ANL/ESD-16/18 (Lottes et al. 2016[5]). With the current version of the scour model, it is possible to obtain a reasonably good scour simulation of cylindrical and rectangular pier scour with sediment transport for inflow conditions that have the upstream velocity near the critical velocity. Cases with upstream velocity approximately 2 and 3 times critical have also been run but not verified against experimental data.

In the laboratory scale results, the simulated scour time vs scour depth for a single cylindrical pier is very close to the laboratory observed times to reach ¼ and ½, and consistent with the interpolated path between ½ of the equilibrium scour depth and ¾ of the equilibrium scour depth (see Figure 1). For the laboratory scale, the scour reaches halfway to equilibrium at about 20 minutes, and at about 60 percent in 1 hour. Including the established confidence on the model details from previous experience and the consistent result with lab data in a “blind run”, this is considered sufficient validation of this hybrid modeling scheme. Simulation through equilibrium is omitted for efficiency. The scanned scour hole shapes at various stages of scour from the lab experiment and those produced by the computer simulation are

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[5] Lottes S.A., Sinha N., Bojanowski C., Kerenyi K., Sharp J.A., Three-Dimensional Analysis of the Final Design of Pier Extensions and West Guide Wall to Mitigate Local Scour Risk at the BNSF Railroad Bridge Downstream of the Prado Dam Supplemental Report, ANL/ESD-16/18, June 2016 (source: https://publications.anl.gov/anlpubs/2016/09/130317.pdf)

shown in Table 1. The state of the scour hole after an hour of the simulation time (not equilibrium) is shown in Figure 3.

For the field scale, the scour for a cylindrical pier reaches about 40 percent of equilibrium in half an hour and about 50 percent in an hour (see Figure 2). Compared to the lab data and lab-scale model, the scour development at field scale is somewhat lower, but at a comparable level. Conceivably, this may come from the effect of scaling (1:26). There is a distortion in the model to obtain proper critical velocity, which is common is scour experiment and modeling. There may also be some effect from the difference in flow velocity with respect to critical velocity. The experiments usually use a significantly lower upstream velocity than critical velocity to prevent unexpected live bed actions. This is matched in the lab scale modeling. The field scale model uses critical upstream velocity. As previously stated, further higher velocities, which are more representative for tsunami flow conditions, are not simulated because they were not fully validated.

Further technical details of the developed scour computation methodology were presented in Argonne Technical Report ANL/ESD-16/18.

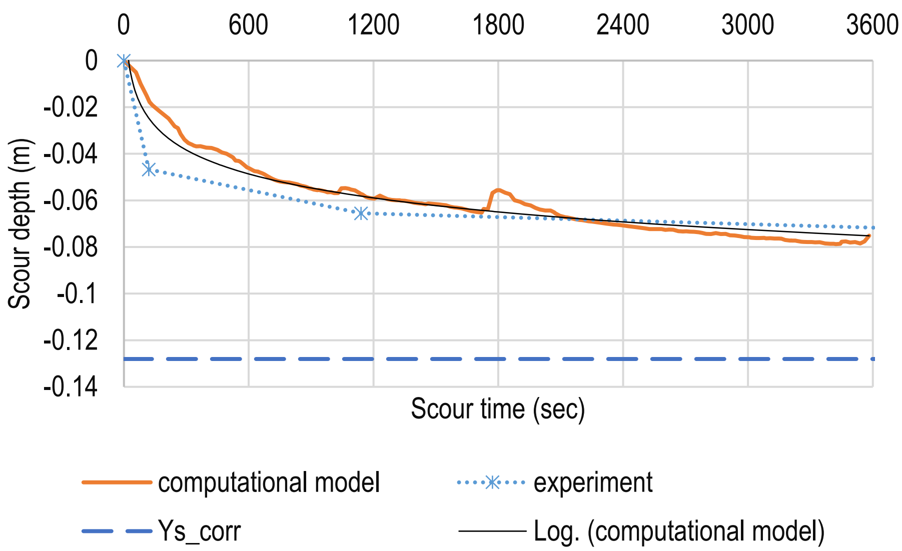


Figure 1. Scour progress around a cylindrical pier in the first hour obtained in a laboratory experiment and computations (as is, and smoothed out), as compared to the corrected HEC-18 prediction.

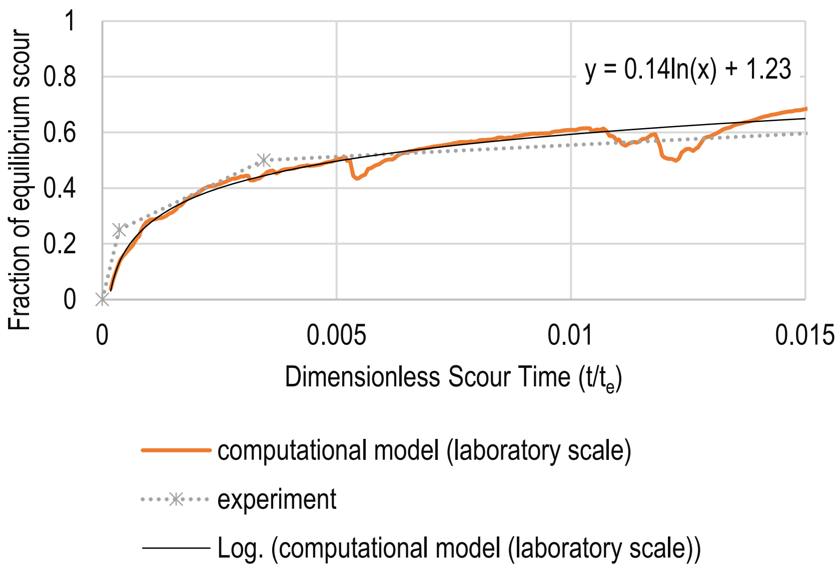
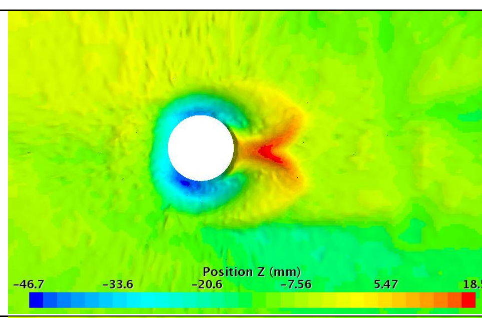
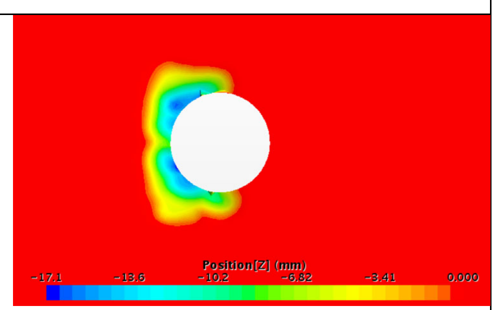
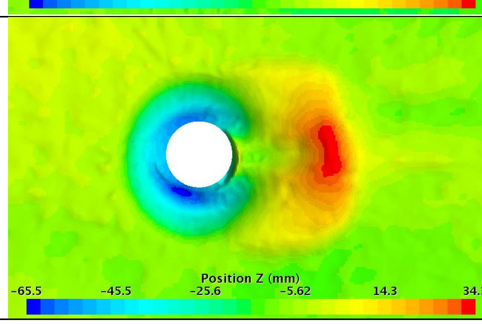
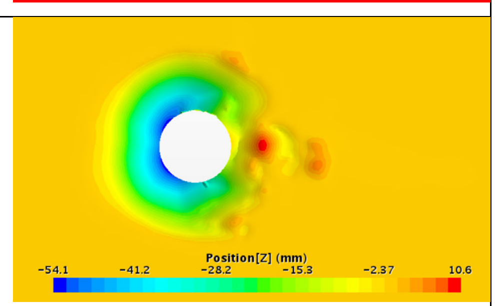
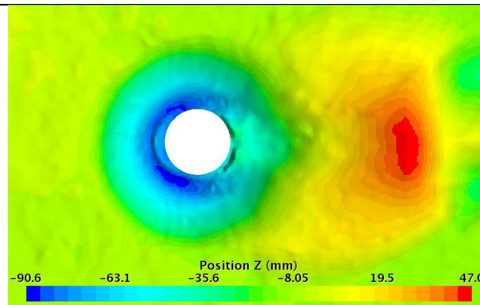
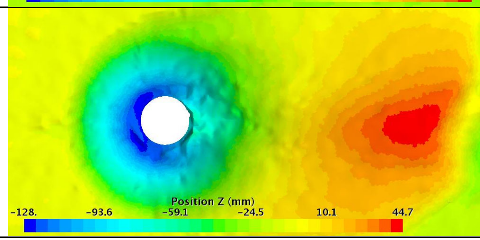


Figure 2. Fraction of equilibrium scour vs. time.

Table 1. Contour plots of bed elevation obtained from the experiment and computational model, at the time of 25%, 50%, 75%, and 100% of the experimental equilibrium scour.

Approximate percentage of equilibrium scour	Elapsed time (sec)	Experimental result	Computational result
25	120		
50	140		

75	11.1k		
100	86.4k		

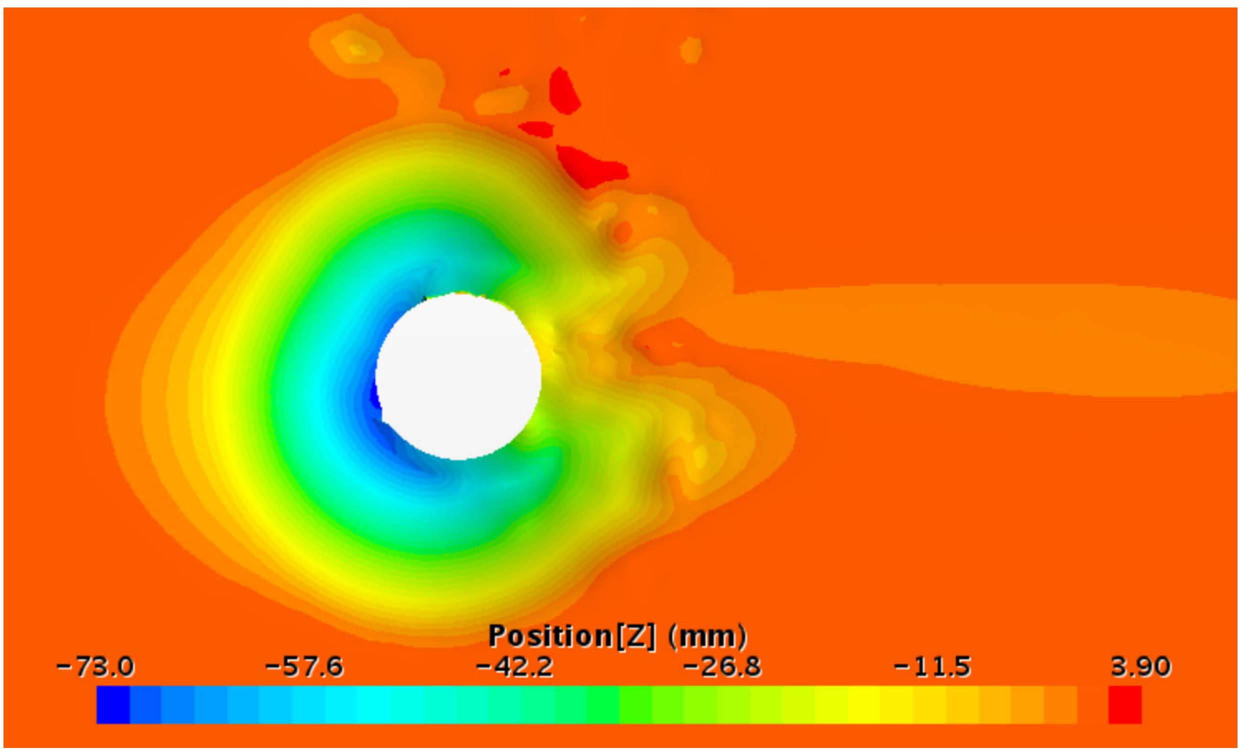


Figure 3. Bed elevation at 3600 seconds of simulated time obtained from the computations.

Figure 2 shows the scour depth in fraction of equilibrium scour. It is important to note that scour prediction equations usually have significant embedded conservatism. The experimental data, field observation, and computational simulation results do not have this safety margin. When the scour equations are used to determine the equilibrium scour depth for which the time-reduction factor can be applied to, it must be adjusted to a depth that represents an expected depth. The ratio of the expected scour to nominal scour from equations is a bias factor. The bias factor of the HEC-18 pier scour equation (a.k.a. CSU pier scour equation) and that of the FDOT pier scour equation from Section 7.3 of HEC-18 have been developed in NCHRP 24-34 project (Lagasse et al. 2013[6]). The value of the bias factor for the scour depth from HEC-18 equation, $y_{s_{CSU}}$ is 0.68, while that from FDOT equation, $y_{s_{FDOT}}$ is 0.75. There is no additional conservatism embedded in these corrected scour depths after applying bias factors, which makes them suitable for use in the tsunami extreme event limit state.

Recommended Design Procedure

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

$$y_{s_t} = R_t y_{s_{corr}}$$

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

$$y_{s_{corr}} = 0.68 y_{s_{CSU}}$$

or

$$y_{s_{corr}} = 0.75 y_{s_{FDOT}}$$

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.

R_t is the time-reduction factor developed shown in Figure 2. It can be evaluated as:

$$R_t = 0.14 \cdot \ln(T_t^*) + 1.23$$

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

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

T_t is the period of time for the high flow of tsunami that is capable of generating significant scour. 10 to 20 minutes 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[7]):

$$T_e = 48.26 \cdot 86400 \frac{a}{V_1}\left(\frac{V_1}{V_c} - 0.4\right) \qquad \text{when } \frac{y_1}{a} > 6$$

$$T_e = 30.89 \cdot 86400 \frac{a}{V_1}\left(\frac{V_1}{V_c} - 0.4\right)\left(\frac{y_1}{a}\right)^{0.25} \qquad \text{when } \frac{y_1}{a} \leq 6$$ [8]

where a is the pier diameter,

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[6] Peter F. Lagasse; Michel Ghosn; Peggy A. Johnson; Lyle W. Zevenbergen; Paul E. Clopper (2013), *Reference Guide for Applying Risk and Reliability-Based Approaches for Bridge Scour Prediction*, NCHRP Report 761, https://www.nap.edu/catalog/22477/reference-guide-for-applying-risk-and-reliability-based-approaches-for-bridge-scour-prediction

[7] Bruce W. Melville and Yee-Meng Chiew (1999), Time Scale for Local Scour at Bridge Piers, J. Hydraul. Eng., 1999, 125(1): 59-65, ASCE

[8] Note that these equations are developed for clear water conditions. The tsunami flow is likely a live bed condition. Further development is needed to provide better estimate.

y_1 is the upstream flow depth,

V_1 is the upstream flow velocity,

V_c is the critical velocity for the channel, which can be estimated by:

$$V_c = 6.19y^{1/6}D^{1/3}$$

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