Estimating Scour from Tsunami at Bridges

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ABSTRACT

The potential tsunami hazard to bridges includes the erosion at foundations 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 develop a practical evaluation method for tsunami scour depth at bridge foundations. Capturing the amount of erosion during tsunamis requires consideration of tsunami flow conditions, bed material resistance, and the transient erosion process caused by rapidly changing hydrostatic and hydrodynamic forces. The majority of existing scour research results emphasize the equilibrium scour depth developed in a flood with sufficiently long duration or from the accumulated effect of multiple floods. The scour from tsunamis is developed in a short period and is not always near the equilibrium depth predicted by using the extreme flow parameters in scour equations. To estimate the tsunami scour depth, detailed observation of the scour development in its early stages is needed. This significantly increases the technical difficulty in numerical and experimental study. Numerical modeling of erosion around circular piers is conducted in this study as a representative case of scour at bridges during tsunamis. The process of the scour development is recorded and compared with experimental data with consistent parameters. The primary result of this study is an estimated time-dependent reduction factor applied to equilibrium scour to account for the short duration of a tsunami. With limited data availability, a number of assumptions are used, which imposes a limit on the accuracy of the estimate. The procedure and equations for a tsunami scour estimate are provided for consideration in the development of tsunami design

guidelines. Further verification and refinement will be included in the upcoming research tasks of the FHWA's scour program.

INTRODUCTION

The potentially destructive power of tsunamis has been a significant concern for the infrastructure of the Pacific coast of the United States. In order to obtain more confidence in the design methods and formulas for coastal bridges vulnerable to tsunami hazard, several States and the Federal Highway Administration (FHWA) invested in a Transportation Pooled Fund project that targeted validation of tsunami design guidelines for coastal bridges. To adequately assess bridge performance during and after a tsunami, both the force effect from the water/debris and the erosion of foundations must be considered.

A tsunami imposes hydraulic loads on materials at the bridge approaches and foundation consisting of various types of soil or rock layers. 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. Erosion hazards from tsunami events have been observed in post-event investigations. Capturing the amount of erosion from a tsunami with reasonable accuracy requires theoretical and laboratory/numerical studies using tsunami flow conditions, bed material resistance information, and the transient erosion process caused by rapidly changing hydrostatic and hydrodynamic forces.

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 0.4 m to 3 m of scour. The study indicated that, among the scour prediction methods, the pier scour equation used in HEC-18 (Richardson and Davis, 2001) was promising but needed reduction to account for a shorter duration of tsunami flow compared to riverine floods. Tonkin et al. (2013) indicated that the deepest field-observed scour was 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 4 m. Tsunami-induced liquefaction (pore pressure softening) also plays a role in tsunami scour.

Scour at bridge foundations and approach embankments develops through the entrainment of river bed materials when the hydraulic stress of the flow exceeds the resistance of the river bed materials. The resistance of soil types or rocks may also be reduced by the quarrying effect or pore pressure softening effect, therefore worsening the scour. While these scour mechanisms are shared between riverine bridges and coastal bridges, tsunami-induced scour develops under different environmental and flow conditions compared to bridge scour for typical riverine floods. In this study, the period of high flow after the first impact is assumed to be the primary source of scour, and erosion from the impact of the tsunami wave front is assumed less significant. The high flow period is in the range of 10 to 20 minutes and likely not long enough to reach equilibrium scour. The effect of the short duration of tsunami flow is studied through numerical simulations of scour development with respect to time. A reduction factor for scour depth with respect to equilibrium scour is used to modify the equilibrium scour equations to predict tsunami scour.

The primary result of this study is an estimated time-dependent reduction factor for the short duration of a tsunami. Past experiments showed that tsunami scour is a highly dynamic effect, for which the maximum scour depth during a tsunami run-up and drawdown may reach five times of the final observed depth (Kato et al. 2001). 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. 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 further verification and refinement through more research conducted by the FHWA's scour program.

NUMERICAL MODELING AND VALIDATION

A typical riverine flood event may be long enough to scour close to the equilibrium scour depth. Also, erosion due to various flow conditions over a bridge's life may accumulate and reach the level predicted by scour equations. Due to a tsunamis' short duration, scour depth from a tsunami event may be far less than the equilibrium scour depth. For planning and design, a lower scour depth than that predicted by scour equations should be considered to account for the short duration of the event. A time evolution of the scour depth curve is needed to establish a scour reduction factor. In this study, a reduction factor is developed 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. The recommended procedure neglects some influences that will be investigated in the future to improve the methodology. For example, the simulations were conducted using a lower velocity than that of a tsunami because of the limited availability of a validated model for extreme high flow velocity. Work is underway to extend Argonne National Laboratory's (ANL) scour model to simulate erosion under extreme high flow conditions. The current best guide for the scour-time relation is obtained from less extreme flood flow conditions than those of a tsunami.

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

1. Conduct laboratory scour testing on a circular pier that records several stages of scour and the corresponding time. This was a very difficult task in the past but had been made possible with equipment capable of doing bathymetric measurement on-the-run.
2. Build a bed deforming CFD model to simulate the scour development of the laboratory setup.
    a. Use CFD software to calculate the shear stress distribution over the bed for the current bed bathymetry and flow conditions. If eddy shedding is occurring from the pier, use a moving average in time to get the bed shear stress for a scour time step.
    b. Calculate the bed erosion rate distribution from a sediment pickup function and the shear stress distribution at every point on the bed.

c. Using the erosion rate distribution and a specified small target bed displacement (the maximum discrete erosion step size less than the vertical grid spacing), calculate the time required for the location of the highest erosion rate to reach the 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 the corresponding erosion rate at each point. Step c is done in a Python program external to the CFD software.

d. The bed boundary of the model is modified using the displacements calculated in step c, the volume mesh is regenerated with the new bed position, and the CFD flow solution is interpolated/extrapolated to the regenerated mesh as the initial guess for flow with the new bathymetry.

e. Repeat steps a through d until the scour reaches an asymptotic state with nearly zero scour rate in the scour hole(s).

3. After verifying that the CFD scour model is consistent with the experimental results, test variations of the model to investigate sensitivity to various factors. The only variation included in this study is a full-scale model based on an Oregon bridge.

This scour modeling 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). In this study, the model was validated through a laboratory experiment conducted at the J. Sterling Jones Hydraulics Laboratory of FHWA, then used to interpolate the scour depth at any specified time before equilibrium scour is reached.

In the laboratory experiment, the time and scoured stream bed are recorded when the deepest point of the scour hole reaches approximately ¼, ½, and ¾ of the equilibrium scour depth, and when equilibrium is reached. The CFD modeling was validated at ¼, ½, and ¾ of equilibrium scour with the experiment measurements, and then used to develop the formula for scour depth as a function of time. Simulation to equilibrium was omitted for efficiency. Figure 1 shows the scour depth as a fraction of equilibrium scour. The scanned scour hole shapes at various stages of scour from the laboratory experiment and those produced by the computer simulation are shown in Table 1. Further technical details of the developed scour computation methodology are presented in Argonne Technical Report ANL/ESD-16/18.

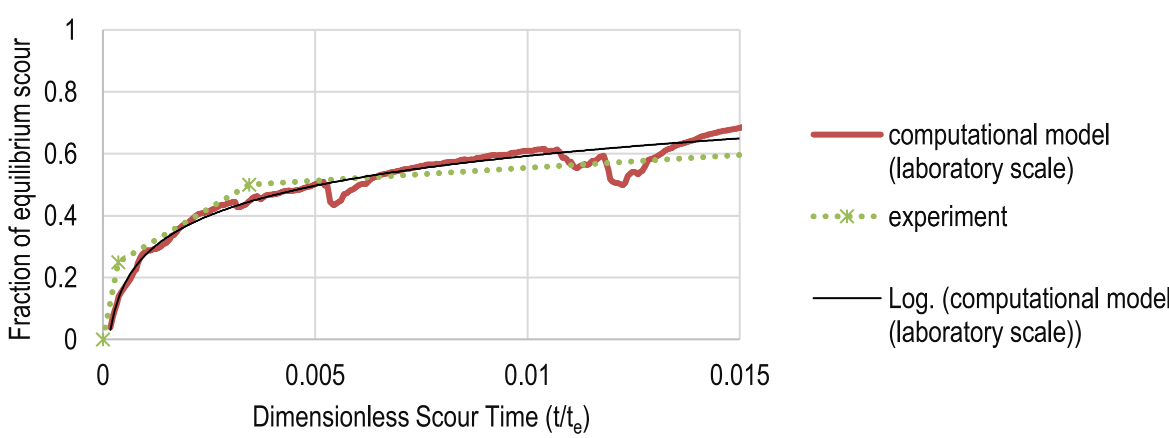
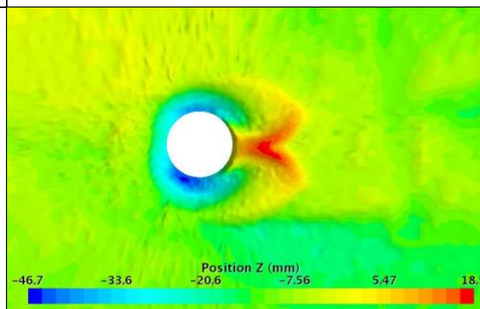
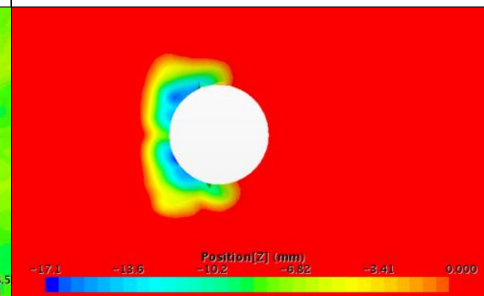
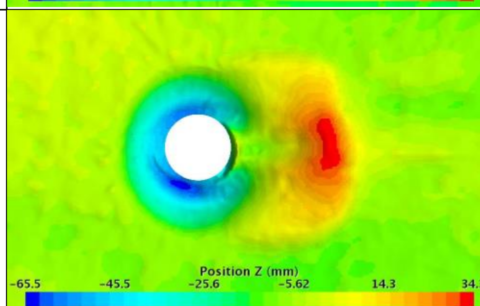
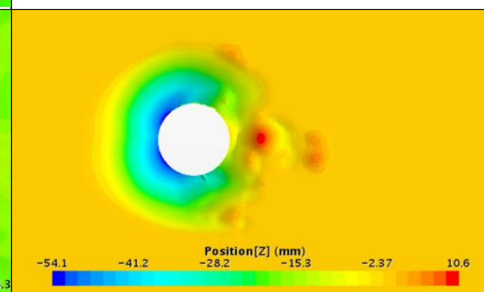
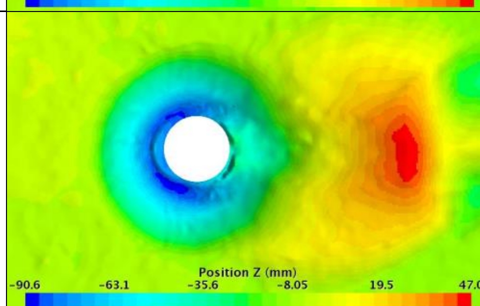
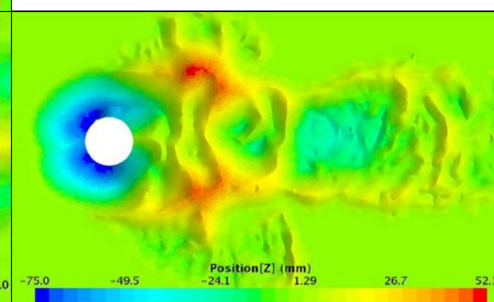
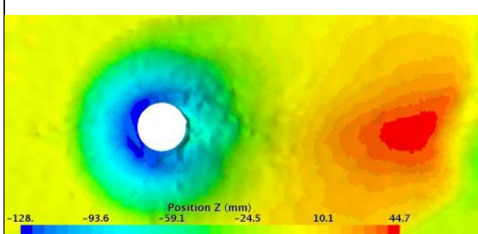
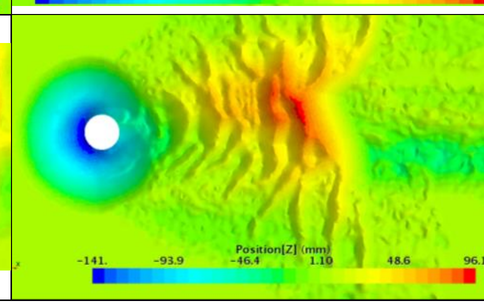


Figure 1. Fraction of equilibrium scour vs. dimensionless time.

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

Approx. % of equilibrium scour	Elapsed time (sec)	Experimental result	Computational result
25	120		
50	1140		
75	11.1k		
100	86.4k		

Note: The first two computational results are from a recent simulation with solver parameters set to better track the initial development of the scour hole. The images do not have the same length scale. More of the domain is shown for the later times.

SCOUR DEPTH PREDICTION FOR A SHORT FLOOD DURATION

The rising stage of live bed local scour can be formulated with logarithmic functions (Ballio et al. 2010). Observation from the clear water scour data in TFHRC lab experiments show that there is a small curvature in the fitting that may be modeled by a power law function (see Figure 2):

$$\frac{y_s(t)}{y_{se}} = \left(\frac{t}{t_e}\right)^{0.152}.$$

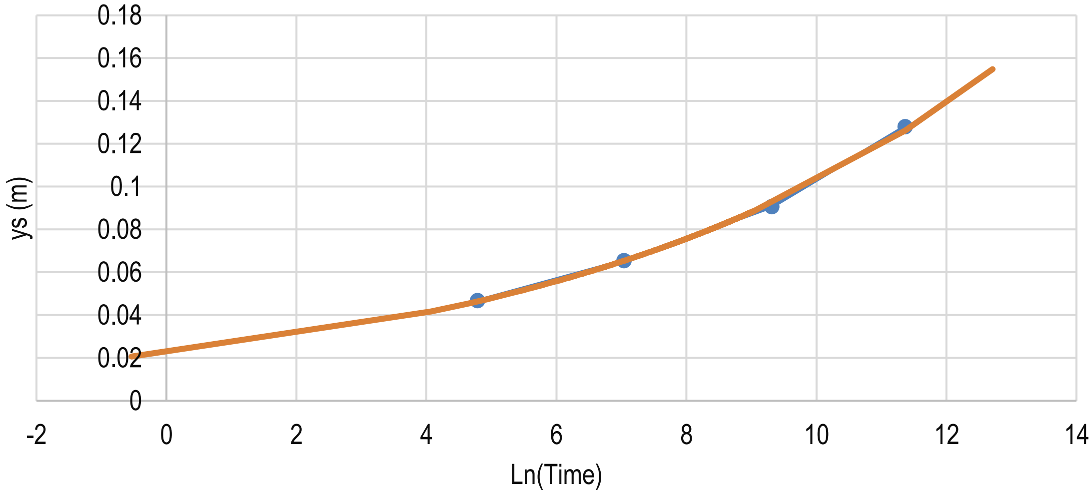


Figure 2. Curve fitting for TFHRC Experimental Data. The markers represent experimental data

The equilibrium scour depth, y_{se}, and the time needed for equilibrium scour to develop, T_e, are needed for the calculation of scour depth at any given time. The equilibrium scour depth from various scour equations have safety margins embedded to envelope lab and field data. If scour equations are used to determine the equilibrium scour depth, these safety margins need to be removed to obtain mean scour for use with the evaluation of scour in a short time.

For the equilibrium scour development time, T_e, Melville and Chiew (1999) showed that it increased linearly with velocity in clear water scour. Combining datasets from multiple experiments, a relationship was found:

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

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

where T_e is time to equilibrium scour in days, a is the pier diameter, 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

$$V_c = 6.19 y_1^{1/6} D^{1/3},$$

where D is the representative particle size of the granular bed materials. Note that these equations are developed for clear water conditions and the tsunami flow is likely a live bed condition. Further development is needed to provide a better estimate.

The study suggested that the equilibrium scour development time for live bed decreased quickly after flow velocity exceeds critical velocity of the bed materials, although no formulas were offered. Ballio et al. (2010) showed that the live bed abutment scour curve had a clear decreasing trend in log scale as flow velocity increased, but it was not continuous with the clear water scour development time, and the available data was not yet sufficient to produce a formula.

Before more data is collected to develop a live bed equilibrium scour time formula that includes all driving factors, we tentatively use the data provided in Ballio et al (2010) to estimate the scour reduction factor for the short tsunami flow duration. Although the data from Ballio et al. (2010), which includes a dataset from Cunha (1975) were produced from experiments for a rectangular abutment, a conversion may be made to a pier scour. This is based on an equivalency of an abutment with the symmetric half representation of a pier in the center of a channel (Melville, 1997). If we examine the Colorado State University (CSU) equation for pier scour and the Froehlich equation for abutment scour, we can find significant similarity in the formulation:

$$\text{CSU pier scour equation: } \frac{y_s}{y_1} = 2.0K_1K_2K_3\left(\frac{a}{y_1}\right)^{0.65} Fr_1^{0.43}$$

$$\text{Froehlich abutment scour equation: } \frac{y_s}{y_a} = 2.27K_1K_2\left(\frac{L'}{y_a}\right)^{0.43} Fr_1^{0.61} + 1$$

It is assumed that the abutment length, L', is equivalent to half of the size of a rectangular pier. A bias factor of 0.68 is applied to the CSU equation to remove the conservatism (Lagasse et al. 2013). The "+1" in the Froehlich equation was removed for the same reason. This leads to a conversion factor, K_{CF}, that adjusts the abutment length to fit the pier scour equation.

$$a_{equiv} = K_{CF} \cdot 2L',$$

$$K_{CF} = 0.9497 \cdot \left(\frac{L'}{y_1}\right)^{-0.3548} Fr_1^{0.2769}.$$

Note that the pier scour is subject to the upper limit of 2.4 times of pier size when the upstream Froude Number is less than or equal to 0.8, or 3.0 times of pier size when the upstream Froude Number is greater than 0.8. It translates to lower limits on the conversion factor:

$$K_{CF} > \frac{0.1296 y_1 Fr_1^{1.2286}}{L'} \text{ for } Fr_1 \leq 0.8$$

$$K_{CF} > \frac{0.0685 y_1 Fr_1^{1.2286}}{L'} \text{ for } Fr_1 > 0.8$$

These lower limits of K_{CF} are generally very small and do not control the values. Using the conversion factor to adjust the data used in Ballio et al. (2010), the scour equilibrium time can be plotted as shown in Figure 3.

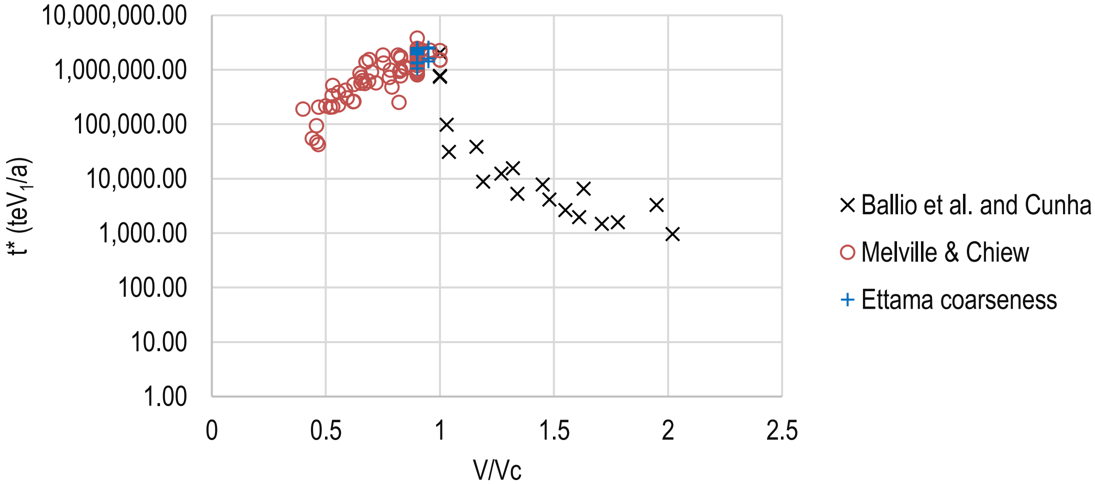


Figure 3. Equilibrium scour development time

The live bed portion of Figure 3 may be fitted with a quadratic equation between logarithm scale of normalized time and velocity ratio:

$$\ln(t^*) = 5.0802\ln\left(\frac{V_1}{V_c}\right)^2 - 9.2594\ln\left(\frac{V_1}{V_c}\right) + 11.272.$$

This translates to a prediction formula for the live bed equilibrium time:

$$T_e = \frac{78590a}{V_1}\left(\frac{V_1}{V_c}\right)^{5.0802\ln\left(\frac{V_1}{V_c}\right)} \cdot \left(\frac{V_1}{V_c}\right)^{-9.2594}.$$

The best-fit formula shown above is plotted in Figure 4.

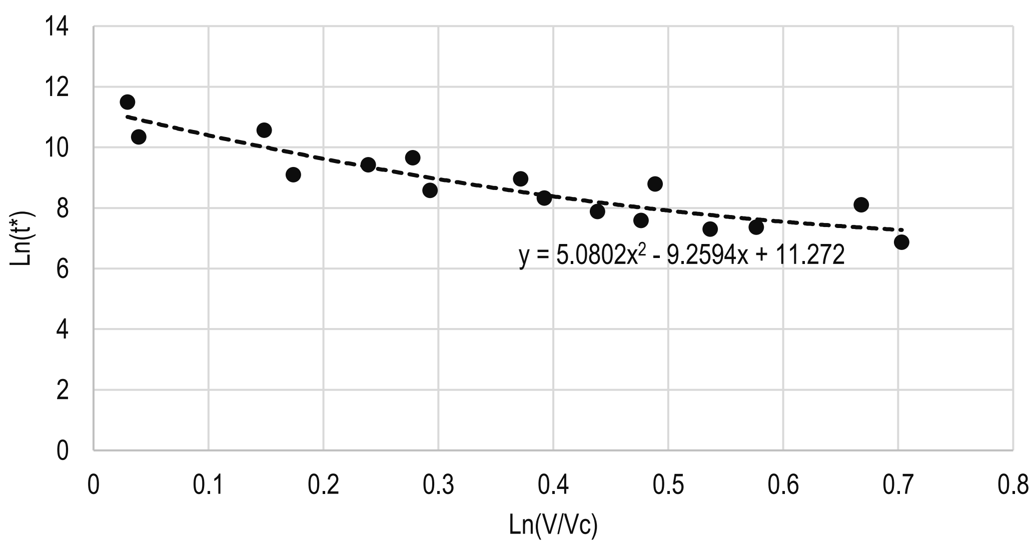


Figure 4. Live bed equilibrium scour development time

RECOMMENDED DESIGN PROCEDURE

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 time reduction factor (all units in m and 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 and shown in Figure 1. It can be evaluated as:

$$R_t = T_t^{*0.1520},$$

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. A time of10 to 20 minutes may be considered a reasonable general length in absence of further information. T_e is the time required to reach equilibrium:

If $\frac{V_1}{V_c} \leq 1$:

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

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

where a is the pier diameter, 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

$$V_c = 6.19 y_1^{1/6} D^{1/3},$$

where D is the representative particle size of the granular bed materials.

If $\frac{V_1}{V_c} > 1$, the time required to reach equilibrium is:

$$T_e = \frac{78590a}{V_1}\left(\frac{V_1}{V_c}\right)^{5.0802\ln\left(\frac{V_1}{V_c}\right)} \cdot \left(\frac{V_1}{V_c}\right)^{-9.2594}.$$

The estimated scour depth occurs during a tsunami event. The effect to the foundation may be considered in combination with the tsunami load on bridge structures as an extreme event.

CONCLUSION

A simple procedure for estimating bridge pier scour during a tsunami was developed. Data from experimental study and CFD scour simulation were used to establish a temporal reduction factor relative to the equilibrium scour depth. Conservatism in scour prediction equations was removed to align with bridge design practice for extreme events. The results offer an approach to account for the shorter duration of tsunami flow than the period used to evaluate bridge scour from riverine floods. The tsunami scour effect to bridge foundation may be considered in combination with the tsunami load to bridges within the inundation distance. The applicability and accuracy of the recommendation is limited by currently available data. Additional experimental testing and numerical simulation of live bed scour progress over various durations of floods are recommended to further refine the formulas and clarify the influence from participating variables. Further investigations on temporal scour development for more bridge substructure types, stream geometries, and bed materials are also recommended. These further investigations will benefit not only scour evaluation for tsunamis, but also that for riverine or coastal floods.

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