DEVELOPMENT OF TSUNAMI DESIGN CRITERIA FOR OREGON COASTAL BRIDGES

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Based on research and documents by Solomon Yim[2] et al

Abstract

This paper describes Oregon Department of Transportation (ODOT) efforts to develop guidelines for estimating tsunami forces on bridges. ODOT contracted with Oregon State University (OSU) to conduct two studies. First we needed a model of the potential tsunami wave characterized by a height, direction and speed. Second, we needed a model to develop uplift and horizontal forces on a bridges generated from a wave with the three tsunami wave characteristics. OSU developed a numerical code to perform modeling of tsunami impact on bridge superstructures on four bridges located on US Highway 101 in the Siletz Bay area on the Oregon Coast. The numerical results were incorporated into a mathematical formula to provide a simplified, approximate method for estimating tsunami forces on bridge superstructures.

Introduction

The Oregon coast is vulnerable to large seismic events from the Cascadia Subduction Zone (CSZ) which shares common seismic characteristics with those at Sumatra that generated large tsunamis in the Indian Ocean in December 2004. Studies of tsunami deposits and evidences of coastal subsidence indicate that an average of large seismic events in CSZ occurs once every 300-500 years (Goldfinger et al. 2003). The most recent large seismic event in the CSZ occurred in 1700; therefore, there is a relatively high probability that a large seismic event will occur in the near future that could damage structures along the coastal area in the Pacific Northwest.

The bridges along the Oregon Coast are an important part of the transportation system. Any major damage to these bridges would result in traffic disruption and impede post-event emergency response. Since these bridges, mostly built in the 1950-70's, were not designed to resist large seismic or tsunami loads, they are at the risk of being severely damaged during large seismic events. However, unlike seismic loads, currently there is no specific design standard for estimating tsunami forces on bridge superstructures in the US in general and in Oregon in particular. Therefore, an understanding of tsunami impact on bridge superstructures is of major interest to the practicing engineering community. Consequently, the Oregon Department of Transportation (ODOT) initiated a research program to develop guidelines for estimating tsunami forces on bridge superstructures in the tsunami run-up zone along the Oregon Coast.

The study first developed numerical models to simulate tsunami impact on bridge superstructures, and calculate reaction forces due to tsunami loads on four selected bridges on

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the Oregon Coast. The four bridges – Schooner Creek Bridge, Drift Creek Bridge, Millport Slough Bridge, and Siletz River Bridge – are located on Highway 101 in the Siletz bay area. The study also developed a guideline for estimating tsunami forces on bridge superstructures to be used as preliminary guidance for design of bridges in the tsunami run-up zone. The developed guidance is based on existing literature and the time-history results obtained from the numerical models calculated in the first part.

OSU had conducted a previous case study of tsunami design criteria on the Spencer Creek Bridge, on US 101 in Oregon, conducted by Nimmala et al. (2006). The Spencer Creek project was conducted by developing numerical models of tsunami impact on bridge deck to determine the time-history forces on the bridge by using LS-DYNA software. The analysis is revisited in this paper to examine the applicability of the guideline developed in the present work.

Tsunami Flow Simulation

The input tsunami flow fields, water surface elevation and water velocity time-histories, for the simulation models were obtained from tsunami numerical models developed by Cheung and associates from the University of Hawaii (Cheung et al. 2010). The nonlinear shallow-water model by Yamazaki et al (2009) was utilized to capture hydraulic processes – wave overtopping, hydraulic jump formation, and bore propagation – describing flow conditions at the interested bridge sites.

The development of a rupture model based on 500-year return period CSZ earthquake scenarios from the National Seismic Hazard Maps. These rupture boundaries extend approximately 1,100 km from Cape Mendocino in northern California to Vancouver Island in British Columbia. The western boundary of the rupture is specified along the trench at the base of the continental slope. Additional conditions are provided by Wang et al (2003) to define the eastern rupture boundaries at the midpoint of the transition zone (MT) and the base of the transition zone (BT). Moreover, a global analog (GA) of shallow-dipping subduction zones, from Tichelaar and Ruff (1993), is used to define the eastern rupture boundary at 123.8°W at 30 km depth.

The tsunami flow model developed by Cheung included four hours of data simulating a 500-year Cascadia tsunami event at the Siletz Bay for six different scenarios. The six tsunami scenarios are based on four rupture configurations at moment magnitude (Mw) 9.0 and two additional moment magnitude 8.8 and 9.2 events at the rupture based on global analog zone. The first configuration assumes the rupture occurs within the locked zone (LZ) only. The eastern rupture occurs at the midpoint of the transition zone (MT) and at the base of the transition zone (TZ). The fourth rupture configuration is assumed to occur at 30 km depth based on global analog (GA).

A relative weight distribution probability of occurrence for the rupture configurations (0.1, 0.2, 0.2 and 0.5 for LZ, MT, BT and GA, respectively) and moment magnitudes (0.6, 0.2 and 0.2 for Mw 9.0, 8.8 and 9.2) are assigned based on the logic tree in the Pacific Northwest seismic source model in Cheung et al. (2010).

Currently, there is no specific code of practice to estimate forces on bridge superstructures due to tsunami loads. However, there is some relevant literature of wave forces on highway bridge decks and offshore platforms, and some literature on tsunami forces for other types of structures such as vertical walls, elevated slabs, and columns of different shapes.

Development of Equations to Estimate Forces from Tsunami Waves

Bea et al. (1999) presented a modification of the American Petroleum Institute (API) guidelines for estimating wind-induced wave forces on a platform deck of offshore structures by separating the total wave force into two components, horizontal force and vertical force. The horizontal force consisted of slamming force, drag force, and inertia force. The slamming force and drag force depended on the horizontal velocity of the waves while the inertia force depended on the acceleration. The vertical force consisted of a buoyant force and a lifting force, which depends on the vertical velocity of the waves.

Wave Forces on Bridge Decks

Douglass et al. (2006) presented a method for estimating wave forces on typical U.S. coastal bridge spans due to wind waves and storm surge to offer a preliminary guidance for design engineers. The estimated horizontal and vertical forces in that method mainly depend on the elevation of the wave crest. Other than water elevation, the horizontal force is also dependant on the number of girders supporting the bridge deck. This recommended approach was verified with post-storm damage on U.S. 90 Bridge across Biloxi bay, Mississippi by Hurricane Katrina.

$$F_H = [1 + C_r (N - 1)](C_{h-va} + C_{h-im})\gamma(\Delta h) A_h$$
$$F_V = (C_{v-va} + C_{v-im})\gamma(\Delta h) A_v$$

where C_r is a reduction factor for forces distribution on the internal girders; N is number of girders supporting bridge deck; C_{h-va} and C_{v-va} are empirical coefficients for slow varying horizontal and vertical force respectively; C_{h-im} and C_{v-im} are empirical coefficients for horizontal and vertical impact force respectively. The other parameters are generally defined in notation.

Previous Research on Wave Forces

FEMA P646 (2008), guidelines for design of structures for vertical evacuation from tsunamis, summarized the relevant design code, and presented equations for estimating tsunami forces on vertical evacuation structures. It also provided some suggestions on how to combine tsunami force with other loads such as dead load and live load. Load effects that had to be considered for tsunami forces consisted of hydrostatic, hydrodynamic, impulsive, buoyant and uplift forces. The hydrostatic force depended on water elevation and would be considered to be zero when water fills up on two opposite sides. Unlike the wave forces due to storm surge, the hydrodynamic force due to tsunamis depended on flux momentum (hu^2) where h is elevation of water crest and u is horizontal velocity. The impulsive force due to tsunami could be estimated by taking 1.5 times the corresponding hydrodynamic force for conservatism.

Douglass et al. (2006) developed a method for the Federal Highway Administration (FHWA) to estimate wave forces on highway bridge decks due to storm surge. Their approach was developed based on laboratory experiments of a scaled bridge deck model in a 3D wave basin. The resulting predictions were shown to be adequate for estimating the wave force induced by storm as verified by measured field damages from Hurricane Ivan and Katrina. However, the equations presented in that method depended only on wave crest elevation without considering the importance of water velocity, which is an important factor in tsunamis.

Numerical Models for Tsunami Impact Loads on Bridges

The models are developed to perform numerical testing of tsunami impact on realistic bridge superstructures to predict the magnitude of tsunami forces that could occur on specific types of bridge superstructure. This section presents details development of the numerical models, bridge descriptions as well as time-history of fluid loads on bridge superstructures under various tsunami flow fields. Effects of different cross-sectional bridge types and the effect of bridge rails to fluid loads are discussed followed by cumulative probabilities of tsunami forces and overturning moments. Furthermore, computational efforts are also summarized and presented in this section.

Two-dimensional (2-D) numerical models are developed using a finite-element based code. The provided tsunami flow velocities are assumed to be uniform over depth and resolved in the direction perpendicular to the longitudinal span of the bridge. The cross-section of the bridge superstructure normal to the longitudinal span is modeled by assuming simply supported under external girders.

In general, a simulation model consists of two major material parts: a fluid part and a rigid structure part. The fluid part is a composition of water and air materials which are demonstrated by appropriate material type combining with equation of states. For computational efficiency, an approximating rigid body material was used to represent the bridge part and reaction forces are determined by replacing four rigid elements at supports by elastic material. The OSU study focused on quantifying the maximum value of the horizontal force, vertical force, and overturning moment due to tsunami loads on the selected bridges; thus, the simulation began at a time immediately prior to first water impact the superstructure and terminated after obtaining the peak values of the time-history of the loads.

The Lagrangian-Eulerian coupling algorithm combined with an Arbitrary Lagrangian-Eulerian (ALE) solver was used in the numerical models as it is the most mature formulation to simulate the problem involving interaction between fluid with high velocity and rigid structure. The basic concept of the Lagrangian-Eulerian coupling algorithm is to track the relative displacements of the corresponding coupling points defined at the interfaced between the Lagrangian surface (bridge superstructure part) and inside the Eulerian elements (fluid part).

FIGURE 1 shows an example of the numerical model of the Millport Slough Bridge developed in this research. The model consists of three material parts: water, air, and bridge parts. Material properties for each part – such as material mass density, pressure cut-off, fluid viscosity, modulus of elasticity, and Poisson's ratio – are specified appropriately as they are used in the ALE differential equation and in calculating of interface stiffness. Even though the numerical model is two dimensioned, it could be thought of as a three dimensional rectangular cross-section with unit thickness in z-direction. The cross-section is composed of water and air material parts with a bridge part inside.

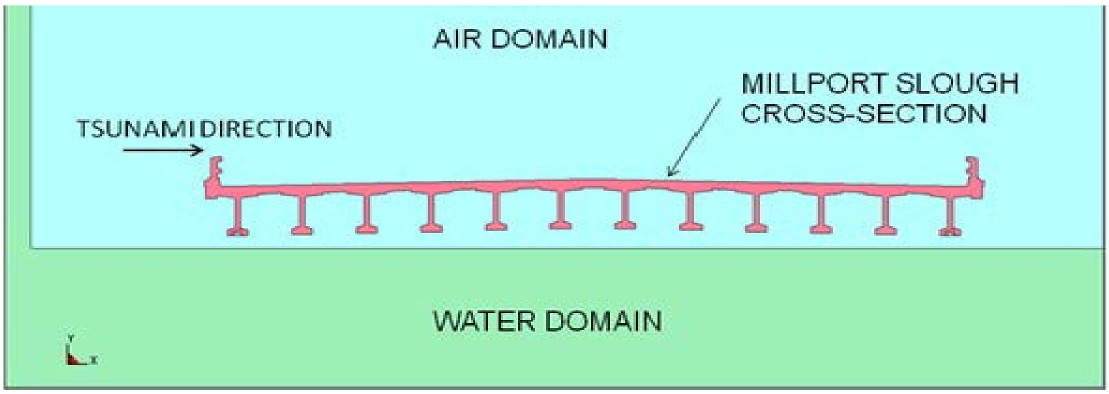

FIGURE 1, MILLPORT SLOUGH EXAMPLE SIMULATION MODEL

Example Bridges and Waves

Numerical models of four selected bridges in the Siletz bay are developed for this tsunami load estimation study. The first is the Schooner Creek Bridge located close to the open channel of the bay facing directly toward the incoming tsunamis. The reference bridge elevation measured at the support of the lowest (west-most) bridge girder is approximately 18 feet above mean sea level (MSL).

The second bridge is the Drift Creek Bridge located southeast of the Schooner Creek in a more open area. The bridge geometry is similar to that of the Schooner Creek Bridge (deck-girder section) with a smaller cross-sectional width and less number of girders supporting the bridge deck. The bridge is designed for a 2% slope with a reference elevation of approximately 14 feet above MSL. The third bridge is the Millport Slough Bridge located at the south end of the Siletz Bay on Highway 101. The bridge has a 2% slope crown with a reference elevation of 15 feet above MSL. Finally, the fourth bridge is the Siletz River Bridge. This bridge, which is a box section, with a reference elevation of approximately 33 feet above MSL, is at a higher elevation compared to the other three bridges.

Six different tsunami flow fields are provided for each bridge site (GA Mw 8.8, GA Mw 9.0, GA Mw 9.2, LZ Mw 9.0, MT Mw 9.0 and TZ Mw 9.0). However, the maximum water surface elevations generated in some scenarios are lower than the reference bridge elevation, and can be neglected because tsunamis in these scenarios would not induce forces on the superstructures. In particular, five tsunami scenarios – GA Mw 9.0, GA Mw 9.2, LZ Mw 9.0, MT Mw 9.0 and TZ Mw 9.0 – are applicable to the Schooner Creek Bridge, and the three of these scenarios – GA

Mw 9.2, LZ Mw 9.0 and MT Mw 9.0 – are also applicable to the Drift Creek Bridge and the Millport Slough Bridge. On the other hand, the tsunami flow of all six tsunami scenarios were below the beam elevation of the Siletz River Bridge, so no tsunami loads were modeled for that bridge.

Example Tsunami Force Time-History

Time-histories of the predicted horizontal and vertical reaction forces due to tsunami loads on the three affected bridges were calculated from the numerical models. The Schooner Creek horizontal tsunami forces are shown in FIGURE 2. The forces on the box section (black line) show a pattern of a short duration high intensity force at the time immediately after water impacting the bridge followed by fluctuating drag forces similar to those reported by Yeh et al. (2005). The impact forces on the box section are approximately 1 to 2.5 times the corresponding drag forces; whereas the maximum impact horizontal forces on the deck-girder section are sometimes smaller than the corresponding maximum drag force. A comparison of the vertical tsunami force time-histories on both box section and deck-girder for Schooner Creek is shown in FIGURE 3. The vertical tsunami forces on both sections show similar pattern as they are rapidly increased at the time water impacts the structure followed by steady forces for a while until the water subsides. Similar results were obtained for Drift Creek and Millport Slough.

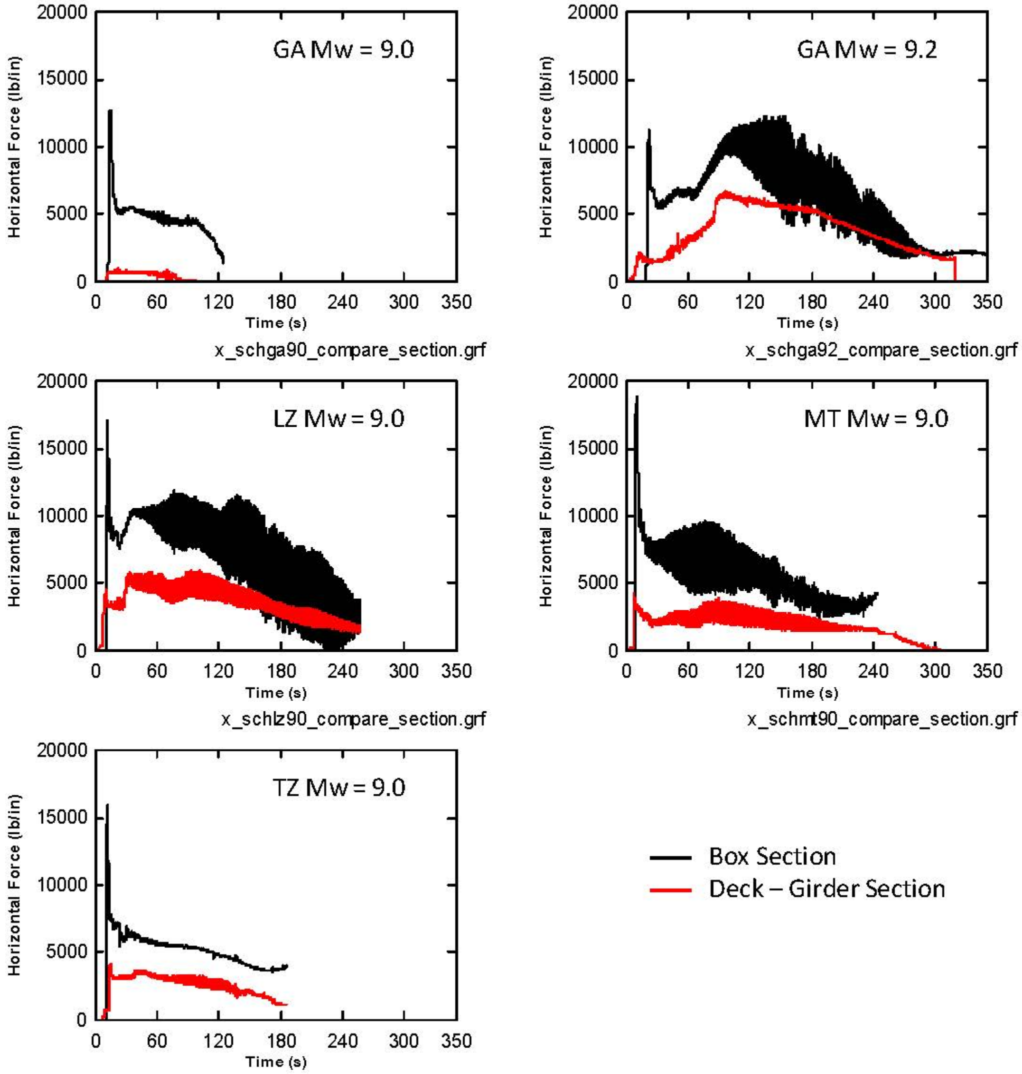

FIGURE 2, SCHOONER CK HORIZONTAL TSUNAMI FORCE TIME-HISTORIES

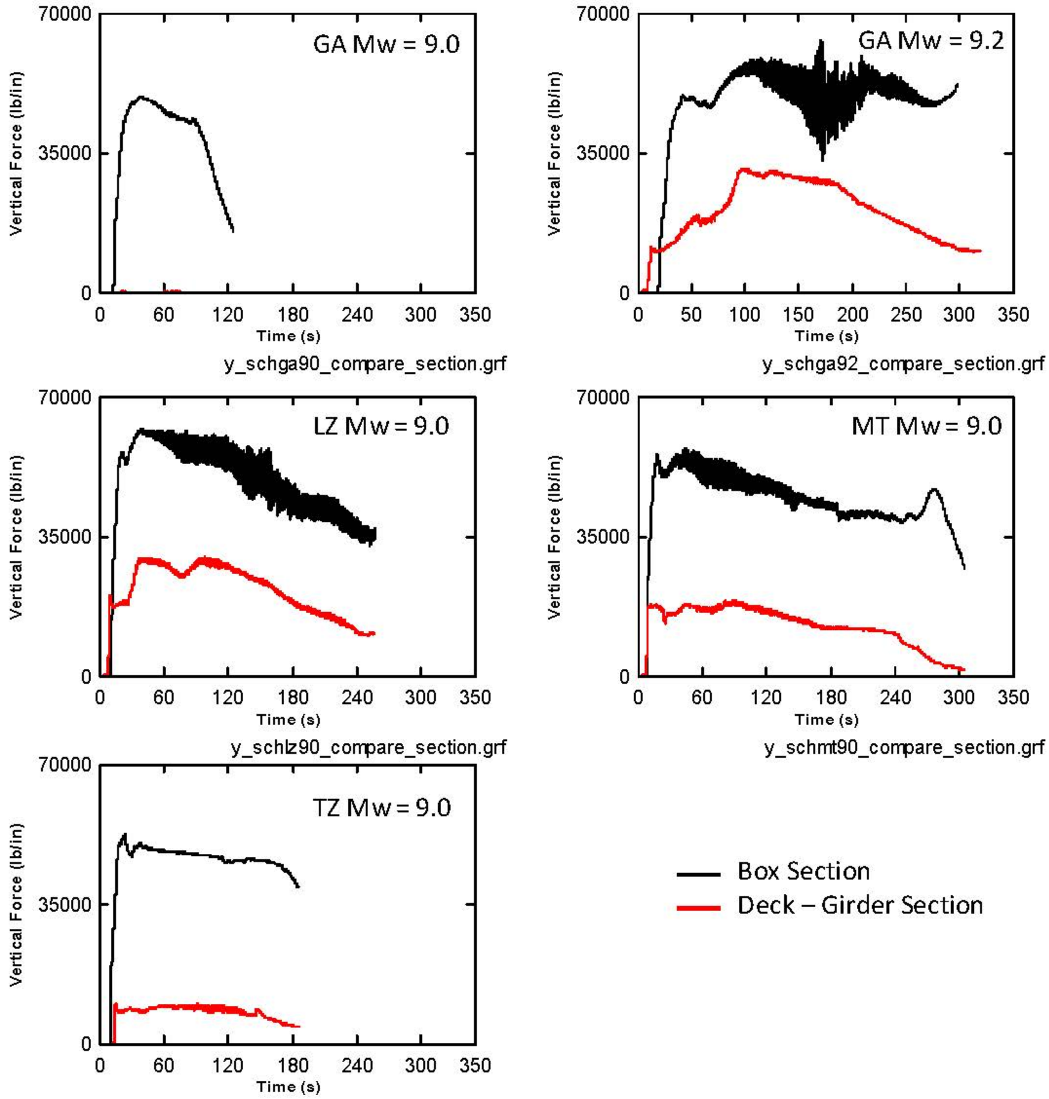

FIGURE 3, SCHOONER CK VERTICAL TSUNAMI FORCE TIME-HISTORIES

To summarize, tsunami forces on the superstructure of the selected bridges are quite difference given the same tsunami scenario. According to the results discussed above, the Siletz River Bridge could survive a 500-years Cascadia tsunami event because the designed reference elevation of the bridge superstructure is sufficiently high to avoid tsunami loads while the other three bridges are inundated in some scenarios. The Schooner Creek Bridge and the Drift Creek Bridges were subjected to large tsunami forces, compared to the forces on the Millport Slough Bridge, because they are located in an open area close to the inlet channel of the bay facing directly to the incoming tsunamis while the Millport Slough is located far from the inlet channel. A regression line relating the maximum horizontal forces and the corresponding maximum flux momentums is plotted in FIGURE 4. It is reasonable to assume that the maximum horizontal force is approximately linearly proportional to the maximum flux momentum as suggested in FEMA (2008) and PBTE (2010).

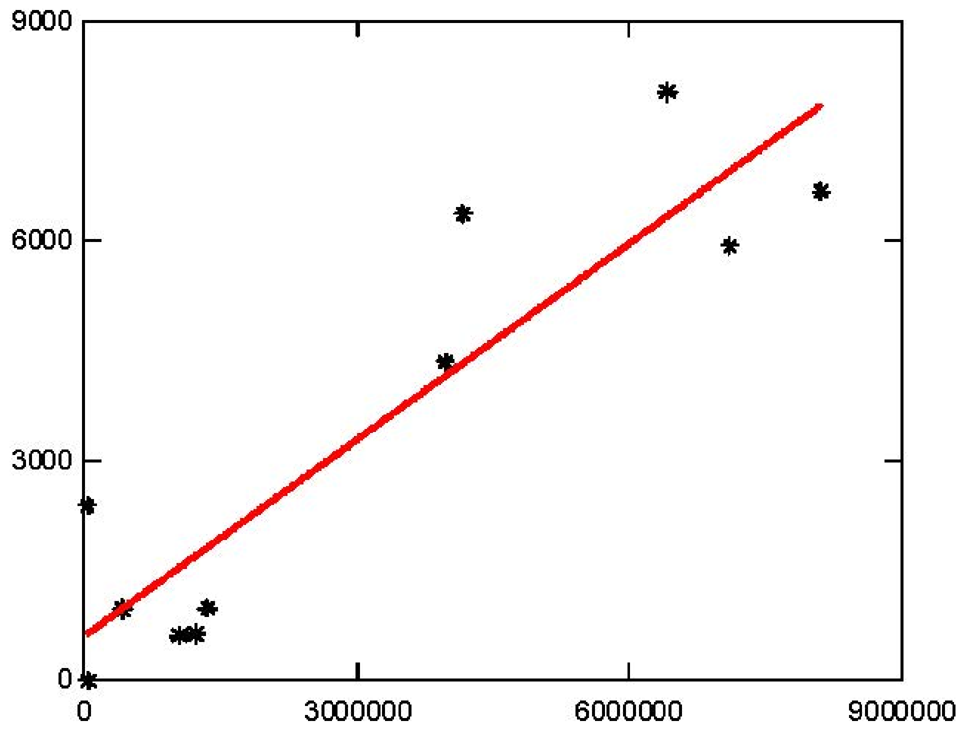

FIGURE 4, MAXIMUM FLUX (Horizontal axis, in^3/sec^2) VERSUS MAXIMUM HORIZONTAL TSUNAMI FORCE (Vertical axis, pounds/in)

According to the numerical results, the magnitude of the tsunami forces on a bridge superstructure generated from different rupture configurations and moment magnitudes can be significantly different.

Estimation of Tsunami Forces on Bridge Superstructures

This section presents a development of a guideline for estimating tsunami forces on superstructures for preliminary design of bridges in a tsunami run-up zone along the Oregon Coast. This approach is developed by incorporating the relevant existing literature and the tsunami forces obtained from the numerical models developed in the OSU Study for Oregon DOT.

The total tsunami force on a bridge superstructure can be considered separately as horizontal and vertical components. The horizontal component acts perpendicularly at the center of gravity of the longitudinal span of the bridge superstructure while the vertical component acts in upward and downward directions at the center of gravity of the superstructure normal to the wave direction.

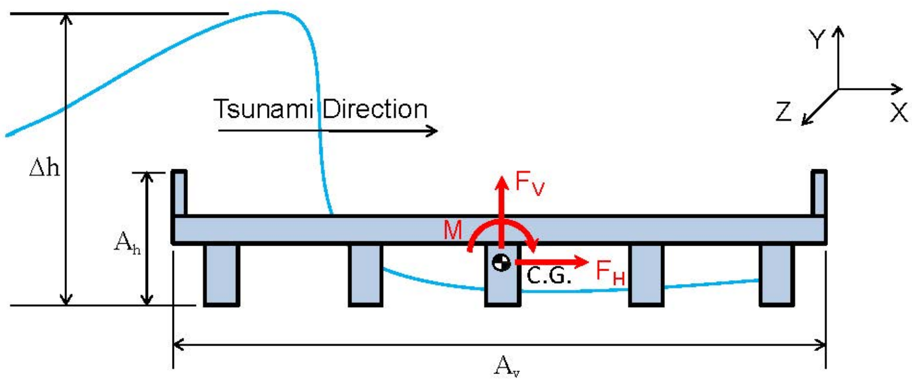

FIGURE 5, SIMULATED HORIZONTAL AND VERTICAL TSUNAMI FORCES

Horizontal Forces

The total horizontal forces on the bridge superstructures due to tsunami loads are a combination of hydrostatic and hydrodynamic pressures. The hydrostatic pressure is induced by gravity, and increases with water depth. The total force due to hydrostatic pressure is a result of imbalanced pressure, which could be considered zero when water filled up both side of the structure. The hydrodynamic pressure is induced by horizontal water velocity which is a significant factor in the tsunami events. The hydrostatic and hydrodynamic forces are considered linearly proportional to the water elevation and the flux momentum (hu^2), respectively.

The total horizontal wave-induced force on bridge superstructures presented by Douglass et al. (2006) is estimated by combining the hydrostatic pressure on the seaward external girder and the total pressure on the internal girders. The total force on the internal girders can be estimated by multiplying reduction factor with the corresponding force on the seaward external girder. The horizontal force due to hydrostatic (Douglass et al. 2006) and hydrodynamic (Yeh 2007) pressures, therefore, can be formulated as shown below.

$$F_h = (1 + C_r(N - 1))C_h F_h^*$$
$$F_d = 0.5 C_d \rho b (\Delta h u^2)_{max}$$

Where C_r = 0.4 reduction coefficient for pressure on internal girders; N = number of girder supporting bridge deck; $F_h^* = \gamma(\Delta h_{max}) A_h$; C_d = empirical drag coefficient; ρ = seawater mass density; and $(hu^2)_{max}$ = maximum flux momentum.

The total horizontal force due to tsunami loads consists of hydrostatic force (water elevation-dependent term) and hydrodynamic force (flux momentum-dependent term). Even though the maximum of these forces might not occur exactly at the same time, combining these maximum forces together is considered reasonable (and conservative) for design purpose. Therefore, the maximum horizontal force on bridge superstructure due to tsunamis can be estimated by combining the equations above as follows:

$$
\begin{aligned}
F_H &= F_h + F_d \\
&= (1 + C_r(N-1))F_h^* + 0.5C_d \rho b(\Delta hu^2)_{\max}
\end{aligned}
$$

An empirical drag coefficient, C_d, for bridge superstructures were evaluated in this research based on the time-history results obtained from the numerical models. A plot between the total horizontal force and flux momentum can be considered separately into two parts. The first part is where the horizontal force increases rapidly with a small change in the flux momentum (flux momentum-independent part). The second part is where the horizontal force increases proportionally to the corresponding flux momentum (flux momentum-dependent part) as shown in FIGURE 6. The empirical coefficient was estimated from the slope of the graph between flux momentum and the total horizontal force as $0.5C_d\rho b\ (= \text{slope})$. Therefore, the drag coefficient is approximately 1.0 for the deck-girder bridge type.

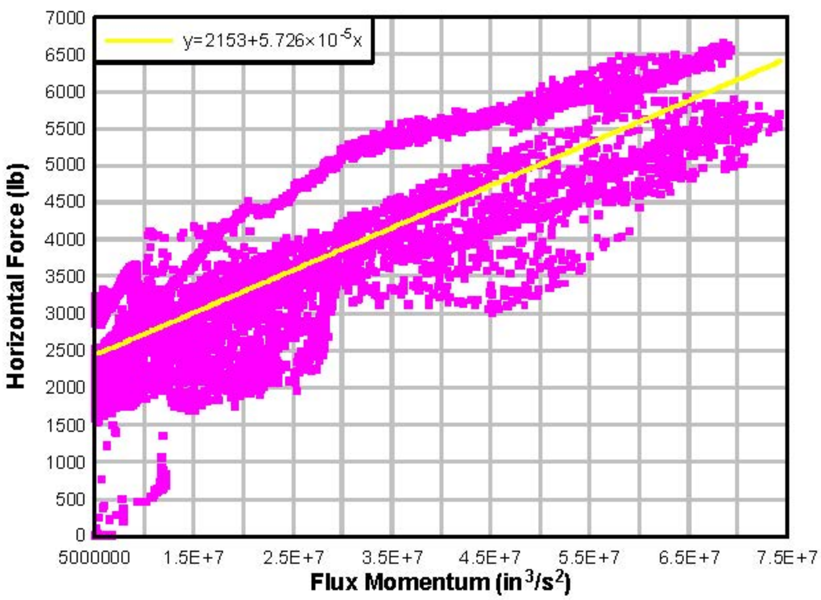

FIGURE 6, TOTAL HORIZONTAL FLUX VERSUS FLUX MOMENTUM

In determination of wave forces due to wind wave and storm surge, it is recommended that the total horizontal pressure on internal girders could be estimated as 40% of the pressure on the external seaward girder. However, horizontal pressure time-history results at the bottom of bridge girders are determined to evaluate an appropriate reduction coefficient for the distributed pressure on the internal girders under tsunami loads. The results (refer to the figures that show these results) show that the maximum pressure on the internal girders is approximately 20% to

50% of the corresponding pressure on the external seaward girder. Therefore, the reduction coefficient, C_r, for this study was taken as 0.4 until further information is obtained.

A comparison between the estimated maximum horizontal forces and the predicted forces calculated from the numerical models are shown in FIGURE 7. The straight line in that graph**Error! Reference source not found.** represents a perfect fit between estimated force and the predicted force. It can be observed that the estimated forces could be overestimated or underestimated in some cases because the recommended empirical coefficients are based on an average value of the scattering data as shown above.

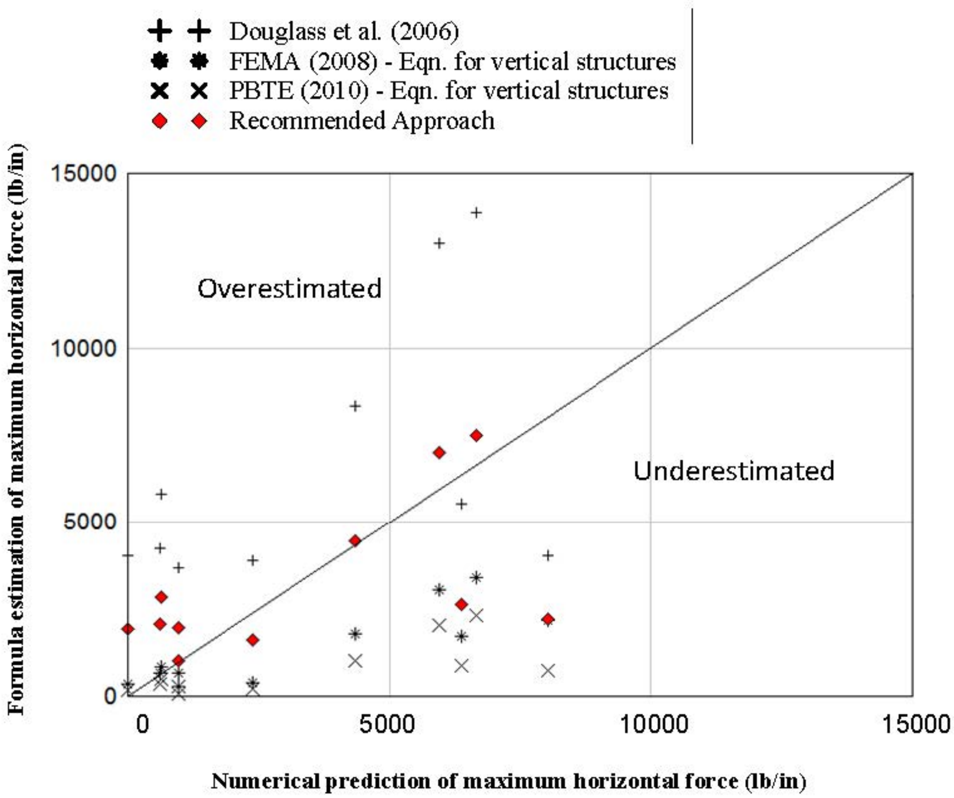

FIGURE 7, CCOMPARISON OF NUMERICAL PREDICTION OF HORIZONTAL FORCE VERSUS RECOMMENDED FORMULA ESTIMATE

Vertical Forces

Load effects due to tsunamis that must be considered for estimating vertical force under bridge girders consist of hydrostatic and hydrodynamic pressure. The hydrostatic pressure is induced by water elevation as mentioned earlier while the hydrodynamic pressure is induced by horizontal and vertical water velocity. The summation of estimated pressures under the bridge superstructure can be estimated by following equation.

$$P = \gamma(\Delta h) + \frac{1}{2}\rho u_x^2 + \frac{1}{2}\rho u_y^2$$

However, the hydrodynamic force induced by the vertical component of water velocity is relatively small compared to the corresponding hydrostatic and hydrodynamic forces due to horizontal velocity; thus, it can be neglected. Consequently, the maximum vertical force due to tsunami loads can be estimated by the simplified equation below.

$$F_V = \{\gamma(\Delta h_{\max}) + \frac{1}{2}\rho u_{x,\max}^2\} A_v$$

It is important to remember that these maximum forces might not occur at exactly the same time. It is considered appropriately conservative to combine these maximum forces together for design purpose until model testing is conducted to verify the recommendations developed by the research.

In general, the provided tsunami flow field data – water velocity and water elevation – is based on tsunami flow without obstruction (which is a bridge superstructure in this study). The results from the numerical models suggest that the output water elevation and water velocity of tsunami waves near the bridge are higher than the input values. FIGURE 8 shows a plot between input value of water velocity and the output value of water velocity obtained from the numerical models. The output water velocities are measured near the bottom of the seaward external girder as pressures at this location represent up to 80% of total pressure under the bridge cross-section. It can be interpreted that the output water velocity near the bridge superstructure is approximately 3.5 times the input water velocity, based on scattering data shown in FIGURE 8. The relationship between these input and output water velocity can be formulated as shown in the following equation.

$$u_{x,\max} \cong 3.5 u^*_{x,\max}$$

where $u_{x,\max}$ = adjusted horizontal water velocity (output water velocity); and $u^*_{x,\max}$ = input horizontal water velocity.

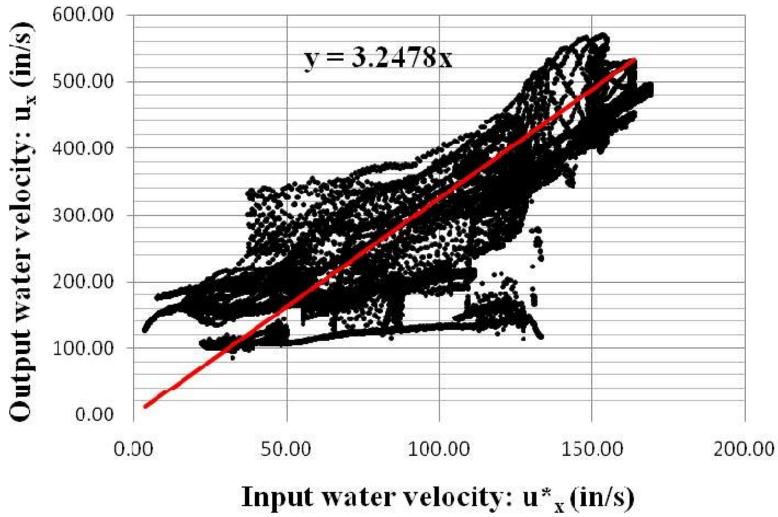

FIGURE 8, COMPARISON OF HORIZONTAL WATER VELOCITY WITH AND WITHOUT OBSTRUCTIONS (BRIDGE SUPERSTRUCTURE)

A comparison of the estimated maximum vertical force and the predicted maximum vertical force obtained from the simulations is shown in FIGURE 9. The estimated vertical forces are observed to be overly conservative for small values and slightly under-estimated for large values. However, the recommended equation is considered appropriate for estimating vertical force due to tsunamis until further study.

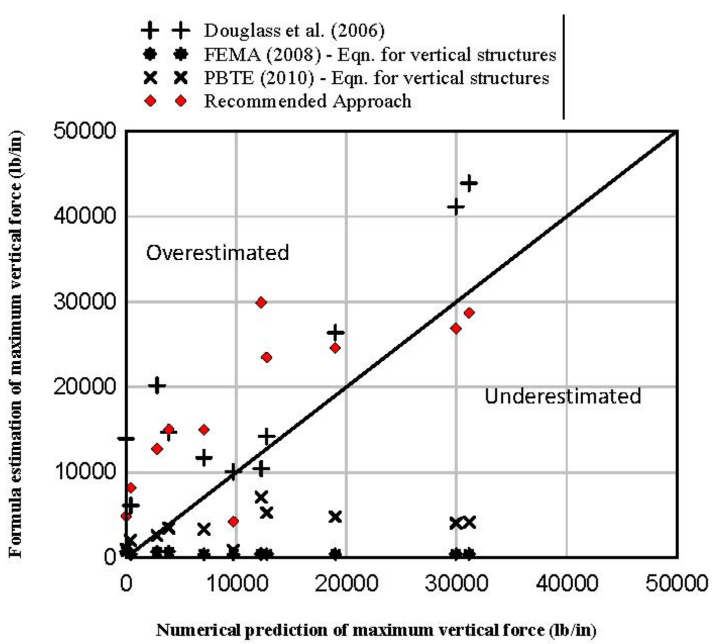

FIGURE 9, CCOMPARISON OF NUMERICAL PREDICTION OF VERTICAL FORCE VERSUS RECOMMENDED FORMULA ESTIMATE

The maximum percentage values of pressure distribution time-histories under each girder along the cross-section of the deck-girder bridges are not evenly distributed along the cross-section. The model found that a maximum 70 to 100% of total pressure is applied to the external seaward girder and it rapidly decreases for the internal girders. However, the total vertical force is assumed to interact with the bridge at the centroid of the cross-section for simplification at this time.

Conclusions

The recommended approach is intended to be used for estimating tsunami forces on bridge superstructures as preliminary guidance for design. This approach is developed by incorporating those proposed in literature and the time-history of the tsunami forces on bridge superstructures calculated from the numerical models developed in the OSU research. Given the uncertainties in tsunami flow field and lack of laboratory results on realistic bridge model, an appropriate factor of safety should be added into these equations.

The input parameters required for estimating tsunami forces by the recommended approach consist of maximum water elevation, horizontal water velocity, maximum flux momentum, and elevation of bridge superstructure. Moreover, tsunami waves usually loosen sediment saturated with seawater while surging inland increasing the effective fluid density above that of typical seawater. Thus, FEMA (2008) recommended the fluid density be set equal to 1.2 times typical freshwater density for tsunami forces calculation.

The recommended empirical coefficients are given here. The reduction factor for forces on internal girders, C_r, is given as 0.4 which corresponds to that presented in Douglass et al. (2006) as the maximum fluid pressure on the internal girders is approximately 20% to 50% of the pressure on the seaward external girder. The drag coefficient $C_d - 1$ was obtained for bridge superstructures under tsunami loads in this study.

The recommended approach is developed based on the deck-girder bridge section only. It might not be appropriate to apply these recommended equations directly to calculate tsunami forces on other types of bridge superstructures.

ODOT considers the research to be a good start in developing design criteria. However the proposed formulas for estimating forces need to be verified and the coefficient needs to be calibrated to actual experience. Wave tank model testing is one way we are considering to refine the results of the OSU research.

Acknowledgements

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Engineering, University of Hawaii. This paper is a summary of research report to be published in late 2011 by Oregon DOT.

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