Parametric Study of Nonlinear Wave Loads on Submerged Decks

TEXAS A&M UNIVERSITY GALVESTON CAMPUS

Author: Kayley Treichel

Advisor: Dr. Masoud Hayatdavoodi

Department of Ocean Engineering - Undergraduate

Abstract

During a storm event, coastal bridges may become submerged by storm surge and can fail under the wave loads if they are large enough. When waves propagate over a submerged deck, they exert horizontal and vertical forces on the structure (see Figs. 1 and 2). In this study, the 2-D wave loads on submerged decks are calculated using the Level I Green-Naghdi (GN) equations, a system of nonlinear equations that describe the propagation of waves in variable water depth in shallow water. The GN equations are derived from the theory of directed fluid sheets, satisfy the boundary conditions exactly and are solved using finite difference methods.

A parametric study is conducted for storm waves on submerged decks by varying wave conditions and deck geometry. For engineering purposes, a simplified design-type equation to estimate the wave-induced loads, which would assist design engineers, is missing. Two empirical equations for the vertical force and horizontal force on a submerged deck due to storm waves is developed. The equations are optimized (using MATLAB) to give the smallest mean absolute error for the load. Results of the parametric study will be presented, along with comparison between the GN, empirical equations, and existing laboratory experiments.

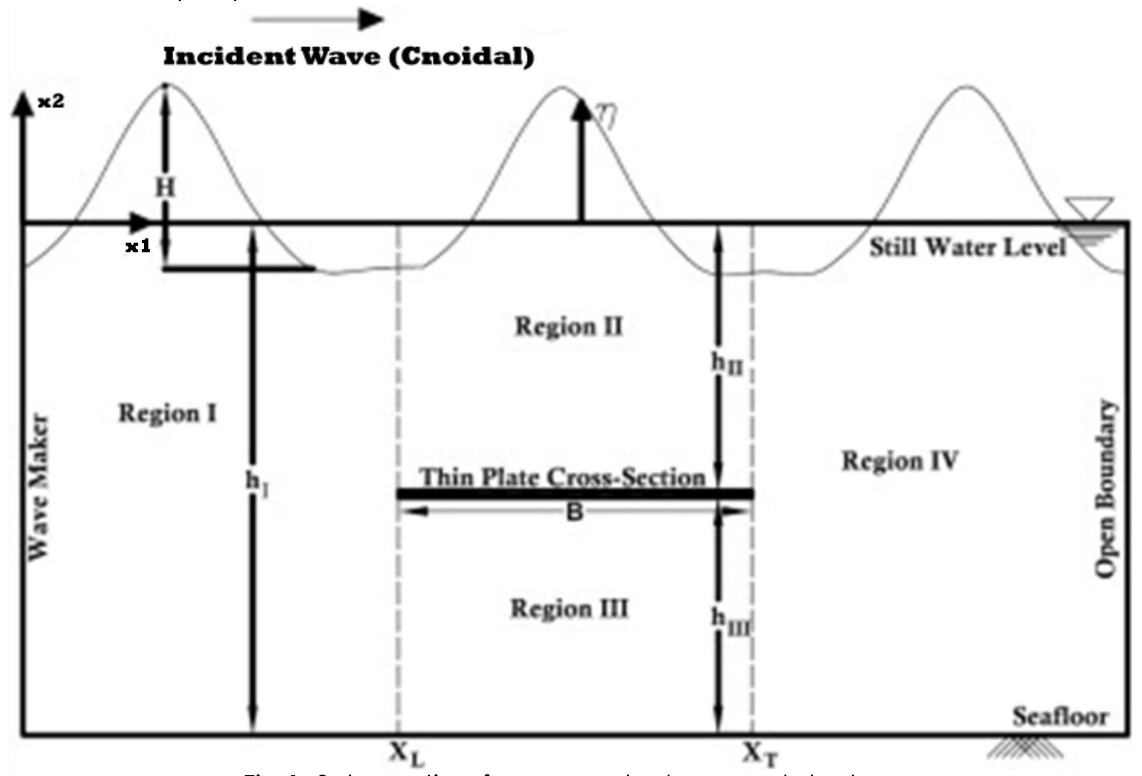

Fig 1. Schematic of wave and submerged deck

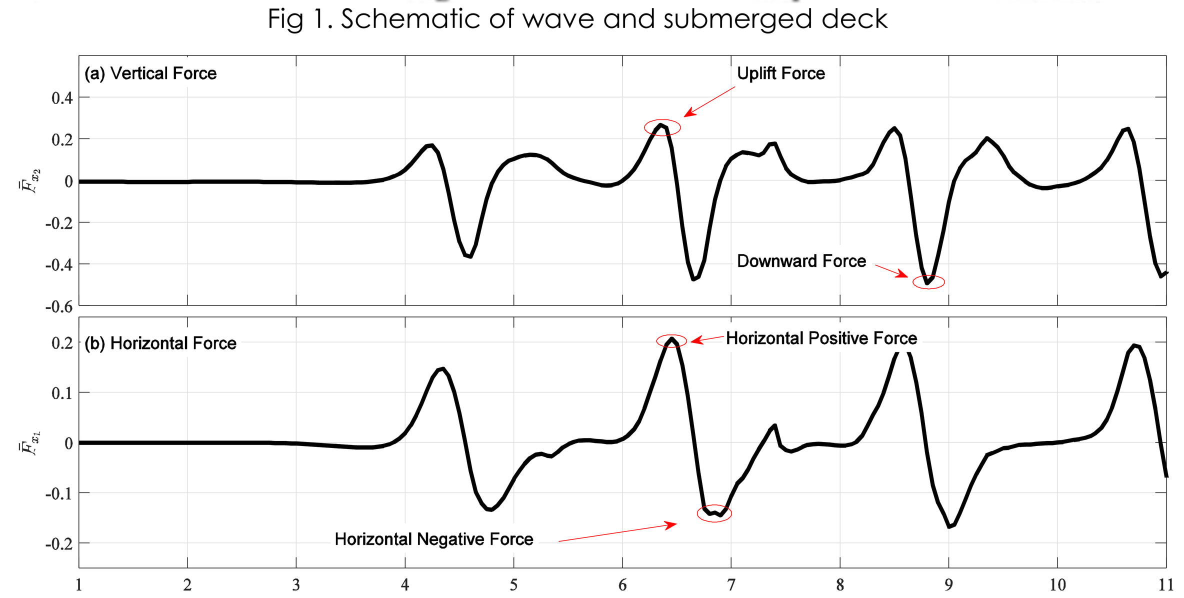

Fig 2. Force on submerged deck time series (Hayatdavoodi et al, 2015)

Nomenclature

- F_{x1}: The vertical force on submerged deck
- F_{x2}: The horizontal force on submerged deck
- M_{x3}: The overturning moment, with respect to center of deck
- ρ: Density of water
- g: Gravitational accleration
- Over bars indicate dimensionless parameter
- H: Wave Height
- h_{II}: Submergence Depth
- h_I: Water Depth
- T: Wave Period
- B: Deck Width
- L_p: Deck Length
- t_p: Deck Thickness

Parametric Study

A parametric study is conducted in order to determine how the forces on the submerged deck change with respect to the wave height, submergence depth, wave period, and deck width. For the parametric study, the variables are non-dimensionalized with respect to the water depth, water density and g, gravity. Variation of wave-induced loads with wave height (H) and plate width (B), are shown in Figs. 3 and 4, respectively.

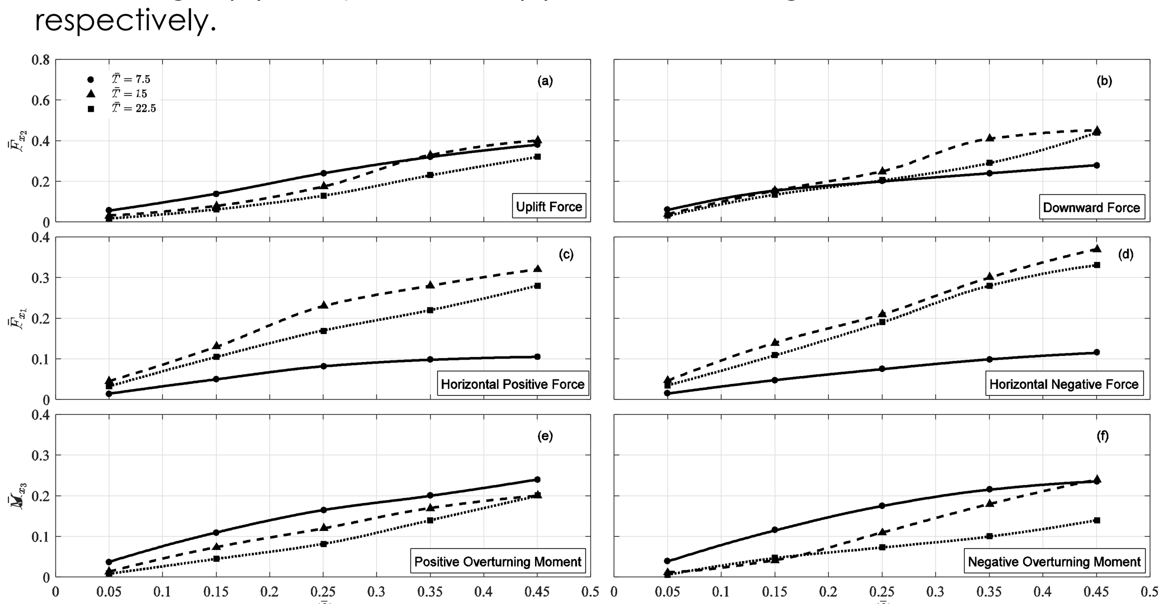

Fig 3. Loads on submerged deck vs wave height

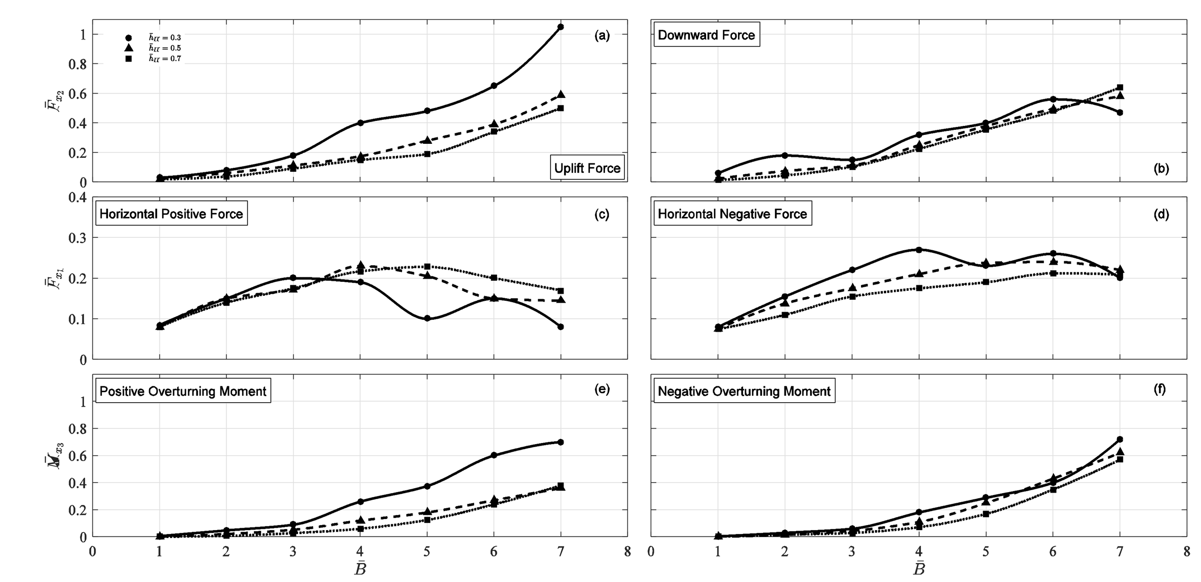

Fig 4. Loads on submerged deck vs deck width

The Empirical Equations

Typically, a computational fluid dynamics (CFD) program is used to determine the loads on a submerged deck. Empirical equations that estimate the loads on the deck based on deck geometry and wave conditions would help engineers in the design process by saving time that it would have taken for the CFD program to run. Hence, a design-type equation to estimate the loads on a submerged deck is of interest. Using the results of the parametric study, the general forms of the empirical equations are determined. Empirical equations are developed to describe the uplift force and horizontal positive force given by the Level I GN equations. MATLAB is then used to optimize coefficients in the general form to minimize the mean absolute error of the load. The optimization process is performed by using nested loops that calculate and compare the load for different combinations of coefficients to the results of the parametric study. The final form of the dimensionless empirical equations are given in Eqs. (1) and (2).

$$\bar{F}_{x2} = \frac{0.14(1.68-\bar{h}_{II})\bar{H}\bar{B}^{1.17}}{e^{0.09\bar{B}(1.71\bar{h}_{II}-0.20\bar{B})}}\left(1-e^{-0.64\bar{T}}\right) \qquad (1)$$

$$\bar{F}_{x1} = 2.75\bar{H}^2\bar{h}_{II}^{-0.11}\left(1-e^{-0.09\bar{T}}\right)\left(1-e^{-\bar{B}}\right) \qquad (2)$$

The dimensional form of the empirical equations for the uplift force and positive horizontal force are given in Eqs. (3) and (4), respectively.

$$F_{x2} = \bar{F}_{x2}\rho g h_I^2 L_p \qquad (3)$$

$$F_{x1} = \bar{F}_{x1}\rho g h_I t_p L_p \qquad (4)$$

Results of The Empirical Equations

Using the results of the parametric study, Eqs. (1) and (2) are compared against the results from the level I GN equations for a set of wave conditions and deck characteristics in Figs. 5 and 6. Overall, the forces obtained from the empirical equations are in good agreement with the parametric study results. There is better agreement at larger wave periods and larger submergence depths.

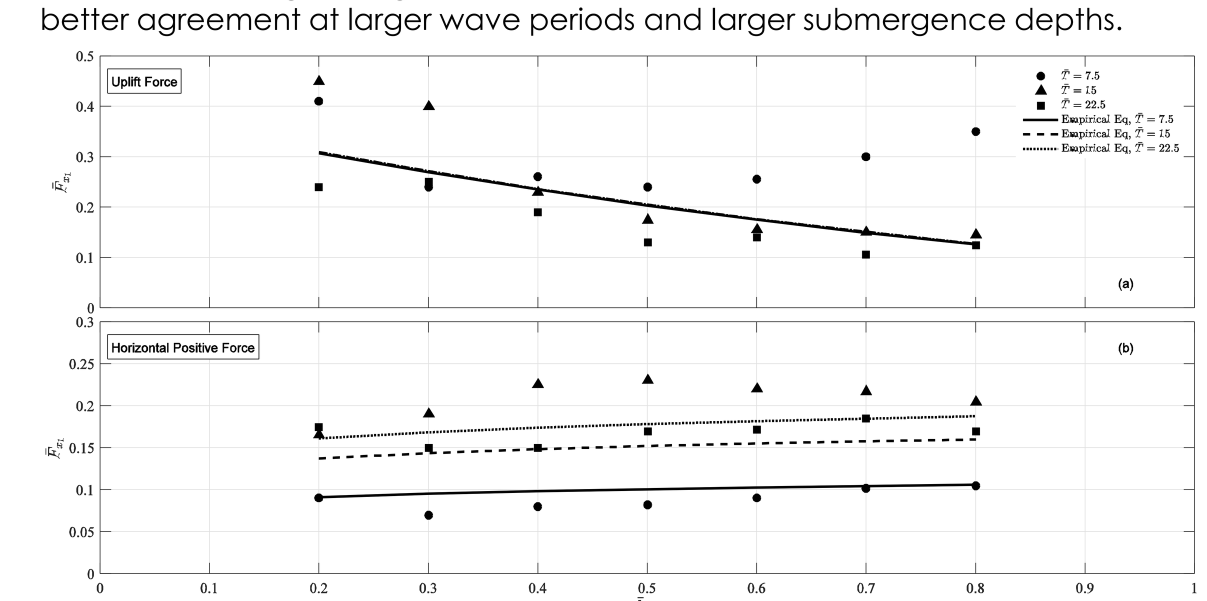

Fig 5. Empirical equations and parametric study results on submerged deck vs submergence depth

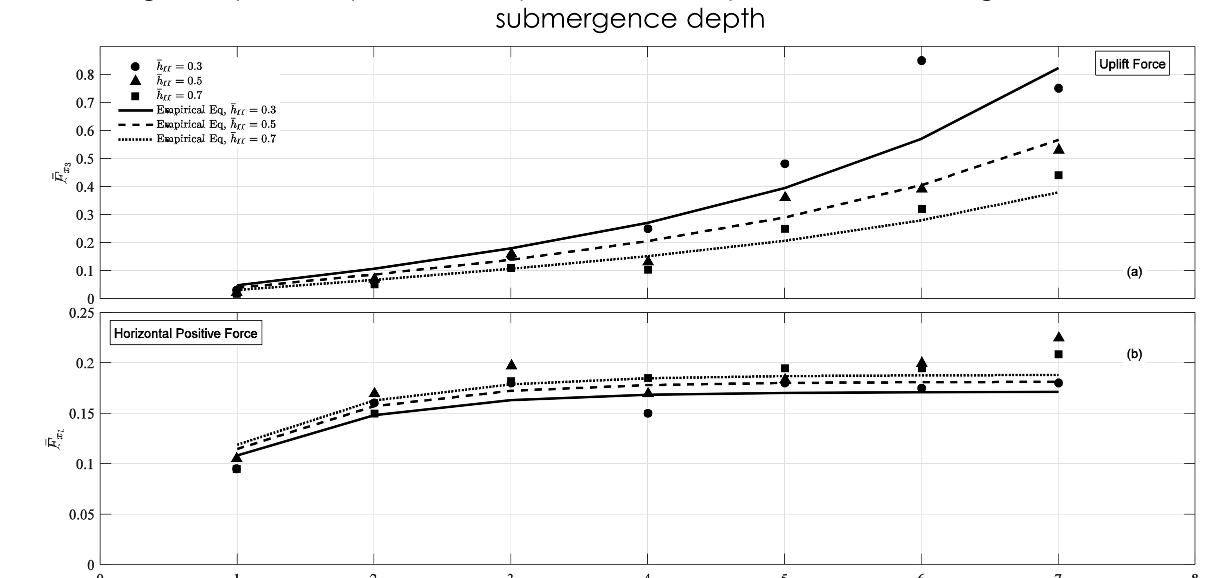

Fig 6. Empirical equations and parametric study results on submerged deck vs deck width

A comparison of the wave loads calculated by using the empirical equations with all data of the parametric study results of the GN equations is shown in Figs. 7 and 8. Ideally, the plot points should follow the 1:1 ratio line displayed. The F_{x2} empirical equation has a mean absolute percentage error of 6.15% and the F_{x1} has a mean absolute percentage error of 5.14%.

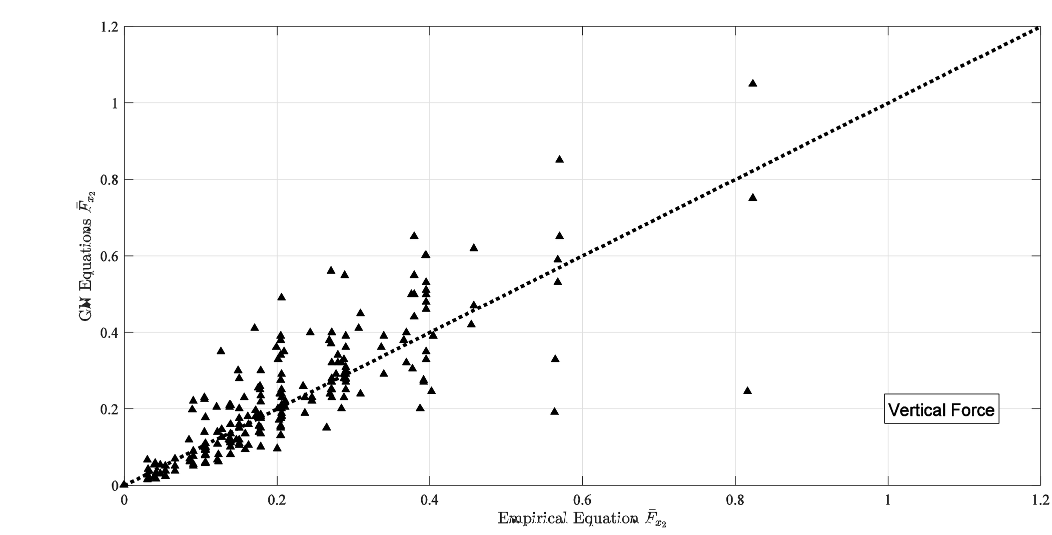

Fig 7. Empirical equation results vs level I GN equations results for vertical force

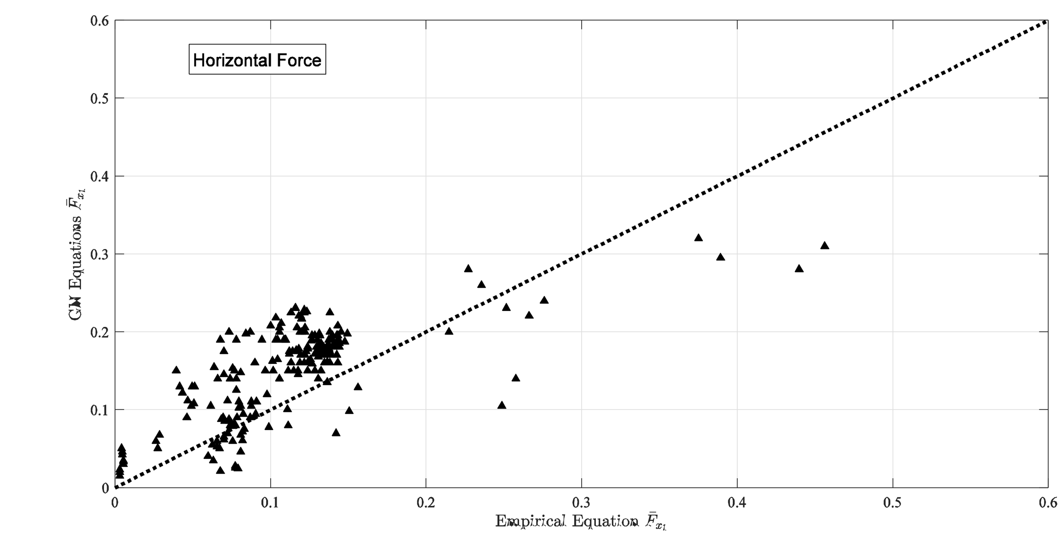

Fig 8. Empirical equation results vs level I GN equations results for horizontal force

Comparisons

The empirical equations are compared against laboratory experiment data and wave loads on prototype bridge cases. The laboratory experiment data also includes a comparison against the Level I GN equations and long-wave approximation (LWA) (see Fig. 9). The comparison of time series of storm load calculated by OpenFOAM (a computation fluid dynamics program), Level I GN equations and the empirical equations for the Maipalaoa bridge on Oahu in Hawaii is shown in Fig. 10. The results show good agreement between the empirical equations and laboratory data while Equation (1) slightly overestimates the horizontal force on the Maipalaoa bridge.

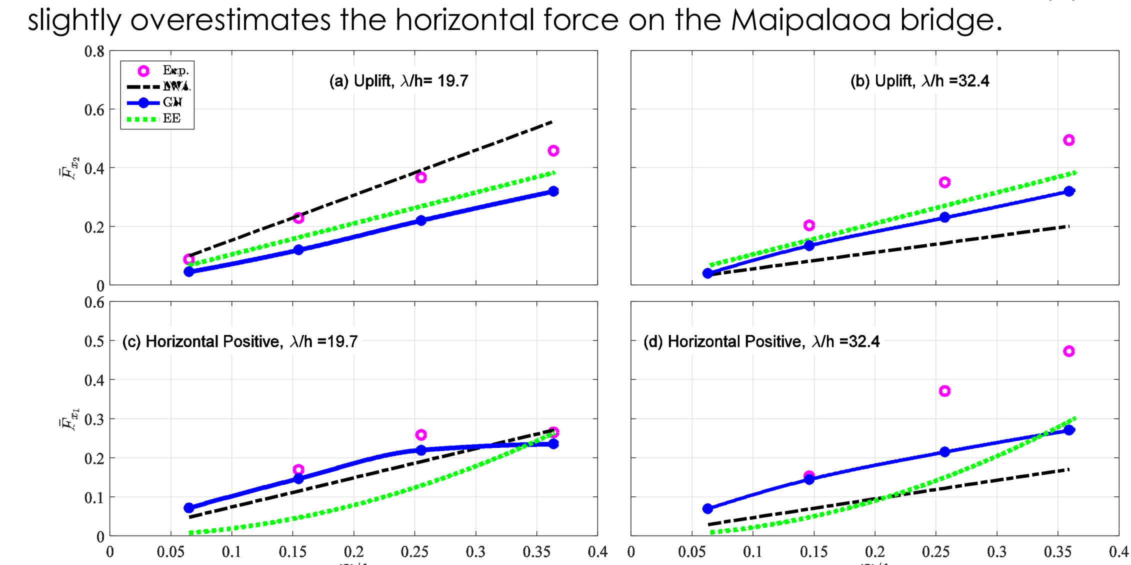

Fig 9. Comparisons with laboratory experiment data, Level I GN equations and LWA

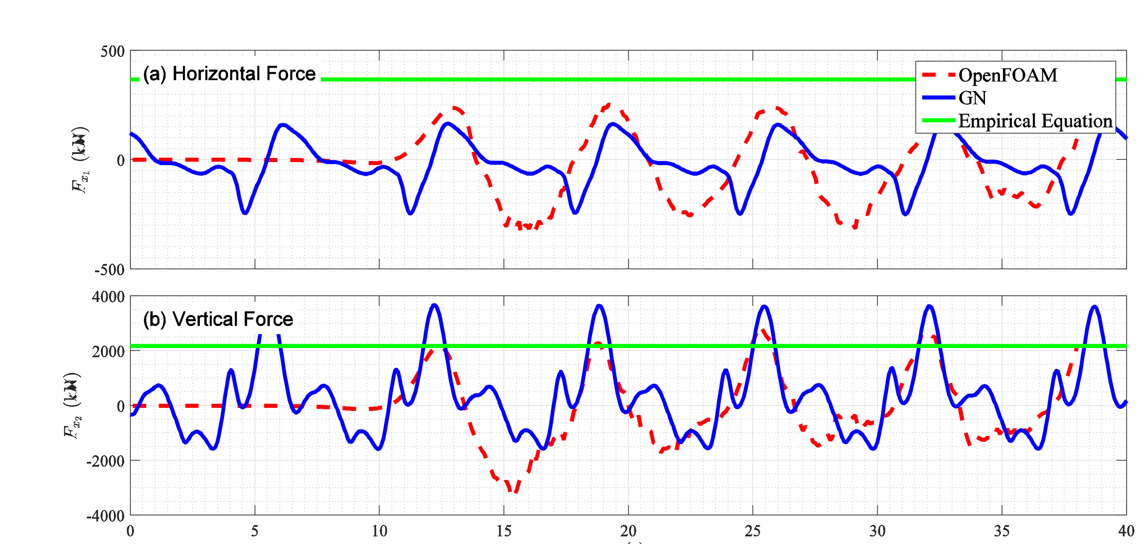

Fig 10. Comparisons for an existing bridge

Conclusion

- A parametric study for storm waves is conducted by varying wave conditions and deck geometry.
- A design-type equation to estimate the loads on a submerged deck is determined. The results of the empirical equations are in good agreement with the Level I GN equations, laboratory experiment data and bridge prototype cases.
- The design-type equations can be used by engineers when designing new bridges or jetties.

References

Hayatdavoodi, M., & Ertekin, R. C. (2015). Wave forces on a submerged horizontal plate-Part I: Theory and modelling. *Journal of Fluids and Structures*, *54*, 566-579.

Hayatdavoodi, M., Ertekin, R. C., Robertson, I. N., & Riggs, H. R. (2015). Vulnerability assessment of coastal bridges on Oahu impacted by storm surge and waves. *Natural Hazards*, *79*(2), 1133-1157.

Hayatdavoodi, M., Seiffert, B., & Ertekin, R. C. (2015). Experiments and calculations of cnoidal wave loads on a flat plate in shallow-water. *Journal of Ocean Engineering and Marine Energy*, *1*(1), 77-99.