Storm Wave Forces on Selected Prototype Coastal Bridges on the Island of Oahu

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Abstract

Hydrodynamic study of storm wave loads on four selected coastal bridges (prototype scale) around the Island of Oahu is presented here. These include New Makaha Stream bridge, New South Punaluu Stream bridge, Maili Stream (Maipalaoa) bridge and Kahaluu Stream bridge on the Island of Oahu. Maximum water level at the location of the selected bridges is determined under extreme conditions of a Category 5 Hurricane making landfall on the island. The maximum wave height and wave period are estimated theoretically based on the highest water level. Several different scenarios are considered for each of the selected bridges. The wave loads on the bridges are calculated by use of several theoretical methods. One is based on Euler's equations coupled with the Volume of Fluid method, for which OpenFOAM, an open access computational fluid dynamics (CFD) package is used to perform the computations, and another one is based on the Green-Naghdi (Level I) nonlinear shallow water wave equations, and is applied to the cases in which the bridge is fully submerged. Existing theoretical and empirical relations, including the Long-Wave Approximation for a fully submerged bridge, developed based on the linear potential theory, and the empirical relations for an elevated bridge deck are also used. Results are compared with each other. The condition that results in the maximum wave forces for each of the bridges is summarized at the end of the report.

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Nomenclature

$\bar{p}$ Pressure on bottom surface of the fluid sheet.

$\boldsymbol{U}$ Three-dimensional velocity vector.

η Surface elevation.

$\hat{p}$ Pressure on top surface of the fluid sheet.

λ Wave Length.

∇ Gradient vector.

ρ Water mass density.

h_T Height of the numerical wave tank in OpenFOAM, including water and sir above the SWL.

L_B Bridge length, into the page and perpendicular to the wave propagation direction.

L_T Length of the numerical wave tank in OpenFOAM.

t_D Deck thickness.

t_G Girder height.

u Horizontal component of water particle velocity.

x Coordinate axis directed to the right in a Cartesian coordinate system.

z Coordinate axis directed to the opposite direction of gravitational force in a Cartesian coordinate system.

A Wave Amplitude.

a Deck clearance, measured from the SWL to the bottom of the bridge when elevated.

B Bridge width, in the wave propagation direction.

Fx Wave-induced horizontal force on the bridge.

Fz Wave-induced vertical force on the bridge.

g Gravitational acceleration.

H Wave height.

h Constant water depth.

hII Submergence depth, measured from the SWL to the top of the bridge.

SWL Still-water Level.

T Wave period.

1 Introduction

A combination of storm surge and surface waves are known to be the ultimate agent of failure of decks of coastal bridges during a major storm event, see for example Douglass et al. (2006), Robertson et al. (2007*a*), Robertson et al. (2007*b*), DesRoches (2006), Padgett et al. (2008) and Chen et al. (2009). The event becomes more serious when lives are lost as a result of this kind of structural failure. Losing road network connections, particularly in islands where connecting roads are very limited, creates a dramatic situation after each destructive ocean event.

The wave-induced force on the deck of coastal structures has vertical and horizontal components. Structural failure happens if any of these force components exceeds the resistance in that direction. In the horizontal direction, the resisting force is usually due to the bent cap connections, friction and inertia. In the vertical direction, however, the weight of the span is the dominant resisting force. Some bent connection may be used as well. Post storm observations (Douglass et al. (2006) for instance) have shown that the vertical load component can become larger than the span weight, causing the bridge span to be lifted up. From this point, even a small horizontal force can sweep the semi-floating span off of its foundation.

Aside from the hydrodynamic loads, buoyancy load can also contribute to deck failure if the structure becomes partially or fully submerged. This load is proportional to the submerged volume of the deck. The buoyancy force is always upward. In addition, air pockets might become entrapped between the girders, which increases buoyancy and will modify the wave force, see *e.g.* Seiffert et al. (2014).

Due to the complexities associated with the problem of interaction of nonlinear waves with an elevated deck or a deck on the surface, theoretical studies mainly include empirical relations which are developed by conducting laboratory experiments or expanding some existing empirical relations (such as the equations of Morison et al. (1950)). These include the empirical relations given by Wang (1970), Kaplan et al. (1995), Bea et al. (1999), Douglass et al. (2006) and McPherson (2008). Aside from the empirical relations, Baarholm & Faltinsen (2004) and Meng (2008) used the linear potential flow theory, subjected to appropriate boundary conditions, to estimate the wave loads on an elevated deck. Meng (2008) and Huang & Xiao (2009) calculated the wave loads on specific prototype bridge decks by solving the Reynolds Averaged Navier-Stokes (RANS) equations by use of computational fluid dynamics approach. Recently, solitary wave forces on a bridge deck are determined by solving Euler's equations by use of the CFD program OpenFOAM by Seiffert, Hayatdavoodi & Ertekin (2014*b*) and Hayatdavoodi et al. (2014*b*).

For a fully submerged deck, Siew & Hurley (1977) considered a thin flat plate and solved the Laplace equation, assuming long-wave condition, to determine the velocity potential. The final form of the wave forces were given later by Patarapanich (1984). This theory is known as the Long-Wave Approximation. Hayatdavoodi & Ertekin (2012) and Hayatdavoodi & Ertekin (2014*b*), recently, developed a model based on the nonlinear shallow water Level I Green-Naghdi equations to solve the problem of wave loads on a fully submerged plate.

In this report, the storm wave forces on four selected coastal bridges on the Island of Oahu, Hawaii, are calculated by use of several different approaches. These bridges include New Makaha Stream bridge and Maili Stream (Maipalaoa) bridge on the leeward (west) side of Oahu and New South Punaluu Stream bridge and Kahaluu bridge on the windward (east) side of the island. Firstly, the extreme environmental conditions (storm surge and wave condition) due to a major hurricane are determined at the location of these bridges. Then, the wave-induced forces are calculated by use of the CFD program OpenFOAM, existing empirical relations, the Green-Naghdi model and the linear Long-Wave Approximation, depending on the storm surge and whether the bridge deck is submerged in water or is above the still-water level. Several possible cases are considered for each bridge to determine the maximum possible wave loads on the deck of these bridges. Results obtained by different approaches are compared with one another.

2 Theory

The theoretical and computational methods that are used to determine the wave forces on the deck of the selected bridges are introduced in this section. The bridge model is assumed to be two-dimensional, and waves approach the structure perpendicularly. This gives the maximum possible wave forces on the structure (when compared with oblique incoming waves). The two-dimensional bridge model is assumed to be fixed and rigid in all cases.

2.1 The Euler Equations (OpenFOAM)

For all the cases considered in this report, we will use a CFD program (OpenFOAM) to calculate the wave-induced forces on the selected bridges. Such an approach to calculate wave forces on a bridge deck is first introduced and used by Seiffert, Hayatdavoodi & Ertekin (2014*b*) and Hayatdavoodi et al. (2014*b*) for solitary wave forces, and by Hayatdavoodi et al. (2014*a*) and Seiffert, Hayatdavoodi & Ertekin (2014*a*) for cnoidal waves. Euler's equations coupled with the Volume of Fluid (VOF) interface tracking method are used to compute the wave forces on bridge decks. Here, we shall use the same model to compute the cnoidal wave forces on a flat plate. The calculations are performed by use of the *interFoam* solver of OpenFOAM, an open source computational fluid dynamics software. In these calculations, the fluid is assumed to be incompressible and inviscid, and its motion is governed by Euler's equations:

$$\nabla \cdot \boldsymbol{U} = 0 \,, \tag{1}$$

$$\frac{\partial \left(\rho \boldsymbol{U}\right)}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{U} \boldsymbol{U}\right) = -\nabla p_d - \boldsymbol{g}.\boldsymbol{x} \nabla \rho^* \,, \tag{2}$$

where $\boldsymbol{U}$ is the velocity vector, $\boldsymbol{g}$ is the gravitational acceleration vector, $\boldsymbol{x} = (x, y, z)$ is the position vector, p_d is the dynamic pressure and ρ^* is the density of the fluid, which may vary throughout the domain as there are multiple phases of air and water. To track the free surface of the cnoidal waves, a Volume of Fluid (VOF) interface capturing method is used. Details on the model and the numerical wave tank used for the calculations can be found in Seiffert, Hayatdavoodi & Ertekin (2014*b*) and Hayatdavoodi et al. (2014*a*).

2.2 The Level I Green-Naghdi Equations

Recently, Hayatdavoodi (2013) and Hayatdavoodi & Ertekin (2014*b*) developed a nonlinear shallow-water model based on the Level I GN equations to calculate the horizontal and vertical wave forces and overturning moment on a fully submerged deck located in water of finite depth. Results of this model were compared with the existing laboratory measurements of solitary and periodic waves (of different height and wave period) and showed a close agreement for a range of submergence depth and deck dimension, see also Hayatdavoodi (2013) and Hayatdavoodi & Ertekin (2014*a*).

The GN equations for propagation of nonlinear water waves are originally developed based on the theory of directed fluid sheets by Green & Naghdi (1974, 1976). In this theory, the fluid is assumed to be incompressible and inviscid, although viscosity of the fluid is not a constrain in the general form of the theory. No assumption of irrotationality of the flow is made, even though such assumption may be made to develop a specialized form of the equations, known as Irrotational Green-Naghdi equations, see Kim & Ertekin (2000) and Kim et al. (2001).

The final form of the Level I GN nonlinear shallow-water wave equations were first given by Ertekin (1984) who coined them the Green-Naghdi equations:

$$\eta_t + \{(h+\eta-\alpha)u\}_x = 0\,, \tag{3a}$$

$$\dot{u} + g\eta_x + \frac{\hat{p}_x}{\rho} = -\frac{1}{6}\{[2\eta+\alpha]_x\ddot{\alpha} + [4\eta-\alpha]_x\ddot{\eta} + (h+\eta-\alpha)[\ddot{\alpha}+2\ddot{\eta}]_x\}\,, \tag{3b}$$

where $\eta(x,t)$ is the surface elevation measured from the still-water level (SWL), $u(x,t)$ is the horizontal particle velocity, $\hat{p}(x,t)$ is the pressure on the top surface of the fluid sheet, $\alpha(x)$ is the bottom surface of the fluid sheet and h is the water depth. The fluid is assumed homogenous with constant mass density (ρ), and is subject to constant gravitational acceleration g. Superposed dot in (3) denotes the two-dimensional material time derivative and double dot is defined as the second material time derivative. All lower case latin subscripts designate partial differentiation with respect to the indicated variables.

In more recent years, Webster et al. (2011) derived and presented the higher-Level GN equations, which are used to solve some nonlinear problems, see *e.g.*, Zhao et al. (2014).

In the context of applying the GN equations to the problem of wave propagation over a fully submerged bridge deck, Hayatdavoodi & Ertekin (2014*b*) assumed a thin plate and divided the continuous domain into four separate regions, namely upwave and downwave, above the plate and below the plate. The GN equations, specific to each region, are then solved simultaneously, and a uniform solution throughout the domain is obtained by use of the appropriate jump and matching conditions at the discontinuity curves. The governing equations, vertical particle velocity (v_3), integrated pressure (P) and the bottom surface pressure ($\bar{p}$) are given by

$$\eta_t + \{(h+\eta)u\}_x = 0\,, \tag{4a}$$

$$\dot{u} + g\eta_x = -\frac{1}{3}\{(2\eta_x\ddot{\eta}) + (h+\eta)\,\ddot{\eta}_x\}\,, \tag{4b}$$

$$v_3 = \frac{z}{(h+\eta)}\dot{\eta}\,, \tag{4c}$$

$$P = \left(\frac{\rho}{6}\right)(h+\eta)^2\,(2\ddot{\eta} + 3g)\ , \tag{4d}$$

$$\bar{p} = \left(\frac{\rho}{2}\right)(h+\eta)\,(\ddot{\eta} + 2g)\ , \tag{4e}$$

where $h = h_I$, a constant water depth, in upwave and downwave regions, and $h = h_{II}$, the submergence depth, in the region above the plate. The submergence depth is defined as the distance from the SWL to the top of the plate. In the region underneath the plate, the unknown top pressure and the horizontal velocity are given by

$$\hat{p}(X_{III},t) = \left(\frac{\hat{p}(X_T,t) - \hat{p}(X_L,t)}{X_T - X_L}\right)X_{III} + \hat{p}(X_L,t), \quad X_L \le X_{III} \le X_T\,, \tag{5a}$$

$$u(x,t) = u(t) = -\rho\int \hat{p}_x(t)\,dt, \quad X_L < x < X_T\,, \tag{5b}$$

where $\hat{p}(X_L,t)$ and $\hat{p}(X_T,t)$ are the top pressures in the region at the leading and trailing edges of the plate, respectively. Condition (5) is similar to the one found in Couette flow.

The system of the equations in the entire domain is solved by the central difference approach, second-order accurate in space, and by the modified Euler method for time integration. Further details on modeling and solution can be found in Hayatdavoodi & Ertekin (2014*b*), Hayatdavoodi & Ertekin (2014*c*) and Hayatdavoodi (2013). The forces and moment are then calculated by integrating the pressure around the plate at each time step.

2.3 The Long-Wave Approximation

The wave forces on a fully submerged bridge deck are also calculated by use of a linear theory. Siew & Hurley (1977) studied the problem of propagation of long waves over a flat plate by assuming an inviscid and incompressible fluid and irrotational flow. The solution was obtained by utilizing the linear potential theory subjected to appropriate (linear) boundary conditions. Once the Laplace equation is solved, the velocity potential is found everywhere in the domain, and then the pressure distribution around the plate is calculated from Euler's integral. The final form of the wave loads on the submerged plate is given by Patarapanich (1984) as

$$F_x = -i \exp(-ikl) \exp(-i\omega t)\, 2P \quad , \tag{6a}$$

$$F_z = -i \exp(-ikl) \left(\frac{\sin k'l - k'l \cos k'l}{k'l \cos k'l} \right) \exp(-i\omega t)\, Q \quad , \tag{6b}$$

$$M_y = -i \exp(-ikl) \left(\frac{\sin k'l\,(3 - (k'l)^2) - 3k'l \cos k'l}{6(k'l)^2 \sin k'l} \right) \exp(-i\omega t)\, P \quad , \tag{6c}$$

where F_x and F_z are the two-dimensional horizontal and vertical forces, respectively, and M_y is the overturning moment. k and k' are the wave numbers in the upwave and above the plate regions, respectively, $l = B/2$, ω is the incident wave frequency, and P and Q are complex constants given in Patarapanich (1984).

2.4 The Empirical Relations

The wave forces on a bridge deck located on or above the SWL are estimated by use of three empirical relations, given by Douglass et al. (2006), McPherson (2008) and AASHTO (2008). The hydrostatic empirical relations suggested by Douglass et al. (2006) are similar to that given earlier by Wang (1970), and later by Overbeek & Klabbers (2001) and McConnell et al. (2004), and they depend on the difference of η_{max} (where η_{max} is the maximum water surface elevation) and elevation height z^* (or deck clearance). The empirical relation of Douglass et al. (2006) for the vertical uplift and horizontal positive forces read as

$$F_z = C_z \left(\rho g(\eta_{max} - z^*)A_z\right) \,, \tag{7}$$

$$F_x = C_x \left(1 + C_r(N-1)\right) \left(\rho g(\eta_{max} - (z + \frac{t_p}{2}))A_x\right) \,, \tag{8}$$

where C_x and C_z are the empirical coefficients (recommended value is 1, suggested to use 2 for conservative calculations), $C_r = 0.4$ a reduction coefficient, N is the number of girders, and A_x and A_z are the projection area of the deck onto the vertical and horizontal planes, respectively.

McPherson (2008) modified the empirical relations of Douglass et al. (2006) by adding the weight of the overtopping water on top of the plate for the vertical force, and by considering the difference between the leading edge and trailing edge hydrostatic forces for the horizontal forces. The final form of the empirical relation for the vertical force is given as

$$F_z = F_H + F_B + F_A \,, \tag{9}$$

where F_H, F_B and F_A are the hydrostatic force, bridge buoyancy force and the air entrapment force (assumed zero throughout this report), respectively, and are calculated as

$$F_H = \gamma \delta A_z - F_w \,, \tag{10}$$

$$F_w = 0.5 \gamma \delta A_z \,, \tag{11}$$

$$F_B = \gamma \mathrm{Vol}_B \,, \tag{12}$$

where γ is the specific weight of water, δ is the distance from the top of the bridge deck to the top of the wave crest, and Vol_B is the volume of the bridge, including the deck and the girders. The horizontal force is given by

$$F_x = F_{HF} + F_{HB} \,, \tag{13}$$

where F_{HF} and F_{HB} are the hydrostatic force on the front and back sides of the deck, respectively, and are calculated by

$$F_{HF} = 0.5 \left[(\eta_{max} + h - h_G) + (\eta_{max} + h - h_D)\right] A_x \gamma \,, \tag{14}$$

$$F_{HB} = 0.5 \left(h - h_G\right)^2 L_B \gamma \,, \tag{15}$$

where, η_{max} is the elevation of the wave crest from the SWL, h is the water depth, h_G and h_D are the distance from the bottom of the deck and girders to seafloor, respectively. A_x is the bridge area (in the vertical plane) and L_B is the length of the bridge (into the page). Note that in all cases considered in this report, the top surface of the deck is above the SWL, and η_{max} is above the top surface of the deck. Also, we do not consider the force due to entrapment of air pockets. Further details about these equations can be found in McPherson (2008).

Based on a series of laboratory experiments, American Association of State Highway and Transportation Officials (AASHTO), developed a guide specification for bridge vulnerability to coastal storms and provided empirical relations for calculating the wave-induced horizontal and vertical forces and the over turning moment on a coastal bridge, see AASHTO (2008). The AASHTO guide specification includes a series of equations to generate a design wave based on the wind field and bathymetry. Once the wave conditions are determined for a specific site, the wave forces are calculated for two major design cases using different sets of empirical relations. In the first design case, the maximum vertical force is calculated, along with the associated horizontal force and moment. In the second design case, the maximum horizontal force is calculated, along with the associated vertical force and the overturning moment. Note that AASHTO makes the assumption that the maximum horizontal force and vertical force do not necessarily occur at the same time. These empirical relations, along with details about the choice of different coefficients applied in these equations can be found in Section 6.1 of AASHTO (2008). Here, we shall use the relation given by AASHTO for both design cases, and consider the maximum value of the horizontal and vertical forces of any of these cases.

In this study, we refer to the relations given by Douglass et al. (2006), McPherson (2008) and AASHTO (2008) simply as Douglass, McPherson and AASHTO relations, respectively. We use these relations only for those cases that the bridge is on or above the SWL, i.e., we do not use these relations if the bridge is fully submerged. Details on the calculations of all these relations are given in the Appendix sections. In all of the calculation of the empirical relations, the maximum elevation of the water surface above the SWL (ηmax) is defined as $\eta max = 0.7H$. In the calculation of Douglass method, $C_x = 1$ and $C_z = 1$ are used for the empirical coefficients. Calculations related to AASHTO's method, closely follow the method and details given in Lum et al. (2011). Note that although the wave conditions considered in this report differ from those in Lum et al. (2011), (and so do the final values of the forces for AASHTO equations), calculations and details on choosing different coefficients remain the same. For consistency, we only consider the bridge deck and girders (when they exist) in force calculations, *i.e.*, in AASHTO's relation, we do not consider the side railing of the decks.

3 Selected Bridges

On the Island of Oahu, the hydrodynamic analysis of wave-induced forces on the deck of coastal bridges is performed for four selected bridges which are *Kahaluu Stream Bridge*, *New South Punaluu Bridge*, *Makaha Stream Bridge* and *Maili Stream (Maipalaoa) Bridge*. Location of these bridges is shown in Fig. 1.

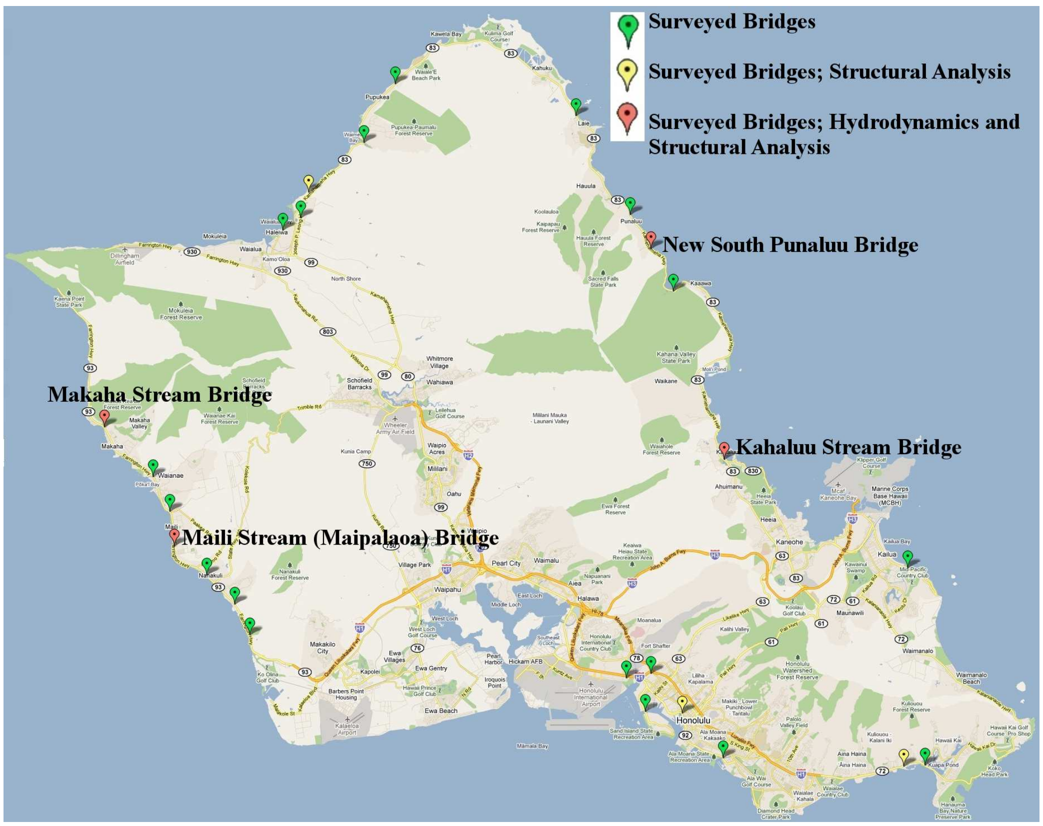

Figure 1: Location of the four selected bridges for hydrodynamic analysis on the Island of Oahu, Hawaii.

Table 1 shows the bridges' dimensions which are required for the wave force calculations. Deck width (B) is measured in the direction of wave propagation (from ocean side towards mountain side), and deck length (L) refers to the length of the deck span into the page. Zero number of girders refer to a slab, with no girders.

Table 1: Dimensions of the selected bridges. Punaluu Bridge is considered a slab with no girders. (NA: Not Applicable.)

	Bridge Name	Kahaluu Stream	Punaluu Bridge	Makaha Stream	Maipalaoa Bridge
Deck Dim.	Length (m)	32.31	17.69	21.34	15.26
	Width (m)	14.02	15.24	14.27	19.61
	Thickness (m)	0.15	0.8	0.61	0.25
Deck Elevation	Seafloor to the bottom of the deck(m)	5.34	2.03	Leading:2.36, Trailing:2.88	3.76
	Seafloor to the top of the deck(m)	5.49	2.30	Leading:2.97, Trailing:3.49	4.01
Girder Dim.	Number of Girders	8	30	0	16
	Girder Height (m)	1.37	NA	NA	0.96
	Girder Width (m)	Bottom:0.66, Top:0.51	NA	NA	0.2
	Spacing, from the edge to the first girder (m)	Bottom:0.52, Top:0.595	NA	NA	0.55
	Spacing between girders, side to side (m)	Bottom:1.1, Top:1.25	NA	NA	1.02

4 Wave Conditions

Wave forces on the selected bridges around the Island of Oahu are determined for several extreme events. These potential severe events are chosen such that a number of tropical cyclones and hurricanes with different intensity, path and central pressures make landfall on the island. Kennedy et al. (2012) performed such a study and used two sets of models to construct such destructive events: the first suite was the combined SWAN+ADCIRC large-scale models, and the second was a Boussinesq model to compute the shoreline runup. Results are given in Kennedy et al. (2012), Smith et al. (2012), and on the *Hawaii Storm Atlas* online website (https://www3.nd.edu/~swims/).

In this study, we obtain the maximum storm surge from the data presented in Kennedy et al. (2012) and on the *Hawaii Storm Atlas* online website. The maximum water level is then calculated by adding the still-water level, maximum high tide, and the maximum storm surge at the location of the selected bridges, given in Table 2. This is the highest potential water level at the location of the bridges. In this study, we do not consider the increase in water level due to sea-level rise.

Once the highest water depth is determined, the maximum breaker wave height and minimum breaker wave period are estimated by use of the analytical relations given by Weggel (1972). We chose a slightly smaller wave height and larger wave period so that the waves do not break prior to the interaction with the structure. Table 3 shows the extreme wave conditions chosen for the selected bridges.

Table 2: Maximum water level at the location of the selected bridges. Foundation of Makaha Stream bridge is located 0.9m above the SWL.

Bridge Name	Kahaluu Stream	New South Punaluu	Makaha Stream	Maipalaoa Bridge
Still Water Level (m)	2	0	-0.9	1.14
Maximum High Tide (m)	1	1	1	1
Maximum Storm Surge (m)	2.7	2.7	2.8	2.8
Maximum Water Level (m)	**5.7**	**3.7**	**2.9**	**4.9**

Table 3: Extreme wave conditions at the location of the selected bridges.

Bridge Name	Kahaluu Stream	New South Punaluu	Makaha Stream	Maipalaoa Bridge
Water Level (m)	5.7	3.7	2.9	4.9
Wave Height (m)	3.2	2.0	1.5	2.7
Wave Period (s)	7.0	6.0	5.5	6.5

5 Wave Forces

Results of the wave force calculations are presented in this section. All calculations are performed in two-dimensions. The forces, however, are presented as the total force on the entire bridge deck, *i.e.*, they are multiplied by the bridge span length (into the page). OpenFOAM is used for all cases, while other methods are used when applicable. The OpenFOAM grid study is performed and given for one case (New South Punaluu Bridge). All the forces and wave conditions are given in SI units.

5.1 New South Punaluu Stream Bridge

Wave forces on the Punaluu Stream Bridge are presented here. Maximum water level at the location of this bridge ($h = 3.7$m) is such that the bridge may become fully submerged during a storm event. Therefore, two cases are considered for the calculations: Case I, which refers to the highest possible water depth ($h = 3.7$m), and Case II, when the SWL is level with the top of the bridge deck ($h = 2.3$m). Extreme wave heights and wave periods are calculated for each of these cases.

Next, we will first present the OpenFOAM grid study for this bridge, followed by the results for each of these cases.

5.1.1 OpenFOAM Grid Study

In the OpenFOAM calculations, the two-dimensional physical domain is discretized by use of an unstructured mesh, finer around the body and free surface. A 1:1 scale of the selected bridges (prototype scale) is used. A numerical wave tank of length $L_T = 125$m and height $h_T = 6.7$m is used for the grid study.

Keeping the tank and bridge dimensions fixed, three different mesh configurations are considered to assess the grid independency and convergence study. In all three mesh configurations, ratios of the change in grid sizes in all directions of the unstructured meshes are kept constant. Cell size on the deck is kept the same in all configurations. Also, the maximum Courant number ($Cr_{max} = 0.2$) is kept constant throughout the calculations. Table 4 provides cell information of these three mesh configurations. The horizontal and vertical forces on the Punaluu Stream Bridge (Case I) are calculated using each of these mesh configurations, and are shown in Fig. 2. We chose mesh II configuration for the calculations presented here.

In the calculations discussed in the next sections, the length of the computational wave tank is kept fixed at $3.5\lambda + B$, where λ is the wave length and B is the bridge width (in the direction of wave propagation). The upwave region has a length of 2λ, and downwave region is 1.5λ long. A wave generation zone of λ long is used at the wavemaker side of the numerical tank, and a wave absorber zone of length $\lambda/2$ is set on the opposite side of the two-dimensional tank. The height of the tank is adjusted in each case. The cell size, however, is fixed in all cases. Simulations are performed for approximately $5.5T$ duration, where T is the wave period. All OpenFOAM

Table 4: Mesh configurations used in the grid study for the Punaluu Stream Bridge (Case I).

Mesh ID	I	II	III
Δx on the bridge (m)	0.02	0.02	0.02
Δz on the bridge (m)	0.02	0.02	0.02
Total cells, x direction	2591	3506	6250
Total cells, z direction	335	335	335
Total number of Cells	837505	1144030	2063270

calculations in this report are performed by use of OpenFOAM v. 2.1.1. For the cases studied in this report, the OpenFOAM computations take about 1-2 months on a 8 CPU workstation (Intel Core i7-4770 processors on a PC).

5.1.2 Bridge Geometry

The Punaluu Stream Bridge deck consists of a deck with 30 longitudinal girders. A schematic of the bridge is shown in Fig. 3. Due to the large number and small width of the girders, in the calculations, the bridge deck is assumed to be a slab with the thickness equal to the sum of the deck thickness and girder height.

5.1.3 Results

In this subsection, wave forces on Punaluu Stream Bridge are presented for the two cases.

Case I: In this case, $h = 3.7$m and the bridge is fully submerged. This is the highest possible water depth for this bridge. A summary of the wave conditions for this case is given in Table 5. Snapshots of the interaction of waves with the bridge in the OpenFOAM numerical wave tank are shown in Fig. 4.

Surface elevation recorded at a series of wave gauges upwave and downwave of the bridge are shown in Fig. 5. In this figure, surface elevation is given in the presence of the bridge and in the absence of the bridge. In the absence of the bridge, the waves are smooth and continuous, indicating

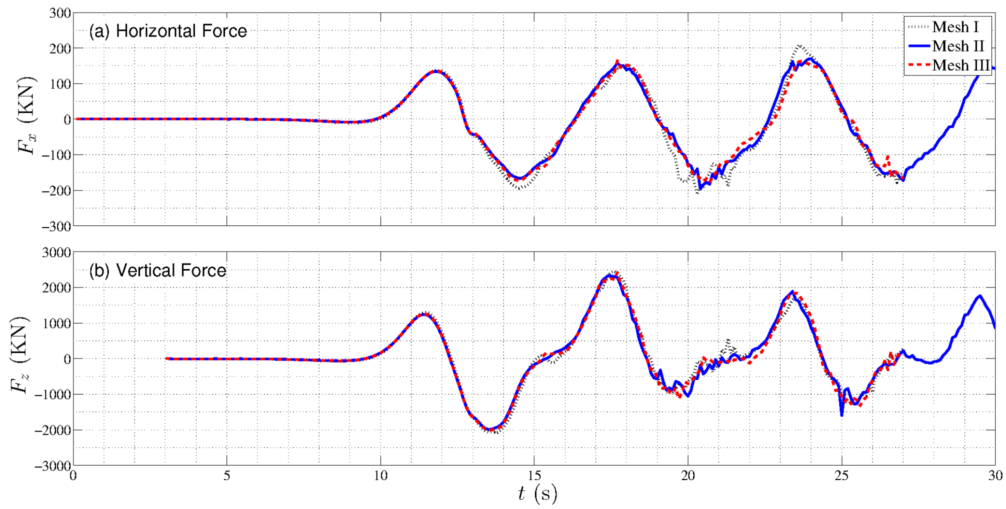

Figure 2: Grid Study, Punaluu Stream Bridge, $h = 3.7$m.

the applicability of the wavemaker and the numerical wave tank in these cases. Some reflection of the waves from the bridge model, and from the open boundary can be observed.

The total vertical and horizontal forces on the bridge, calculated by use of OpenFOAM, are given in Figs. 6 and 7, respectively. The magnitude of the horizontal positive force (in the direction of wave propagation) and horizontal negative force (in the opposite direction of wave propagation) are very close in this case. The uplift force, however, is slightly larger than the downward force on the bridge, shown in Fig. 7.

The wave-induced force on the Punaluu Stream Bridge, Case I, are also calculated by use of the GN equations and the LWA. Results are compared with the OpenFOAM calculations and are shown in Fig. 8. A close agreement is observed between the GN results and the OpenFOAM calculations. Note that the computations of OpenFOAM on an 8 CPU workstation takes about three weeks or 457 hours (for this case), while the GN computations are accomplished in about one minute. The LWA has slightly overestimated the magnitude of both the vertical and horizontal forces, when compared to OpenFOAM and the GN results. Also, the period of the forces determined by LWA differ from those of the GN and Euler's equations. This is due to the difference in the linear and nonlinear wave diffraction on top of the bridge predicted by different equations. In addition, the wave height is very large

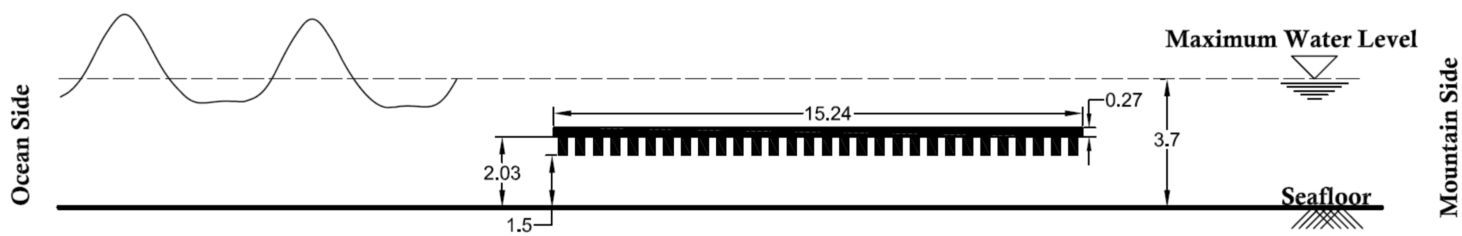

Figure 3: Schematic of the New South Punaluu Stream Bridge. Dimensions are in meter.

Table 5: Punaluu Stream Bridge, Case I wave condition.

h (m)	H (m)	T (s)	λ(m)	Submergence Status
3.7	2.0	6	36.70	Fully Submerged

Table 6: Punaluu Stream Bridge, Case II wave condition.

h (m)	H (m)	T (s)	λ(m)	Submergence Status
2.3	1.24	5	24.50	Deck on the surface

and it is expected that the linear solution (LWA) gives unrealistic results.

Case II: In this case, $h = 2.3$m, and water depth is level with the top surface of the deck. A summary of the wave condition of this case is presented in Table 6. The OpenFOAM results of the vertical and horizontal forces on the bridge deck are shown in Figs. 9 and 10, respectively. The positive horizontal force on the bridge is significantly (about two times) larger than the negative horizontal force. The downward force, on the other hand, is larger than the uplift force, see Fig. 10.

We also used the empirical relations of Douglass et al. (2006) (Eqs. (7) and (8)) and McPherson (2008) (Eqs. (9) to (14)) and AASHTO relations (equations of Section 6.1 of AASHTO (2008)) to calculate the forces in this case. The calculations are given in the Appendix section of this report. In Douglass method, the distance of SWL to the bottom of the deck is assumed to be zero, since the method is primarily applicable to fully elevated decks. This assumption holds for other bridges as well, when the bottom of the deck is below the SWL. These results are presented in Table 7. The horizontal force is significantly underestimated by these methods (when compared with OpenFOAM results), with the Douglass results being the closest among the empirical relations. The vertical force, on the other hand, is overestimated by the empirical relations, with McPherson's results being the closest.

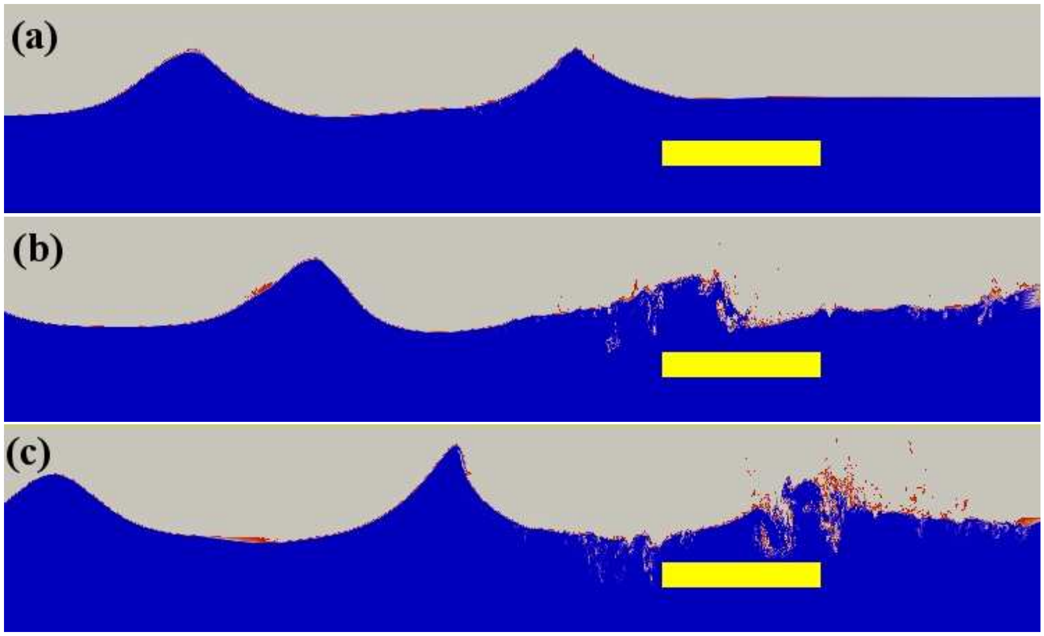

Figure 4: OpenFOAM snapshots of the interaction of surface waves with Punaluu Stream Bridge, Case I ($h = 3.7$m), (a) prior to the interaction of the first wave with the bridge, (b) a wave crest at the leading edge of the bridge and, (c) a wave passing on top of the bridge. Note: For a better display of the wave-bridge interaction, the vertical dimension in this figure is enlarged by a factor of three.

Table 7: Horizontal and Vertical forces on Punaluu Stream Bridge, Case II, calculated by use of the empirical relations and OpenFOAM (see Figs. 9 and 10).

Method	F_x (KN)	F_z (KN)
Douglass	4.17E+01	2.35E+03
McPherson	3.38E+01	1.91E+03
AASHTO	1.06E+01	3.32E+03
OpenFOAM	1.00E+02	7.00E+02

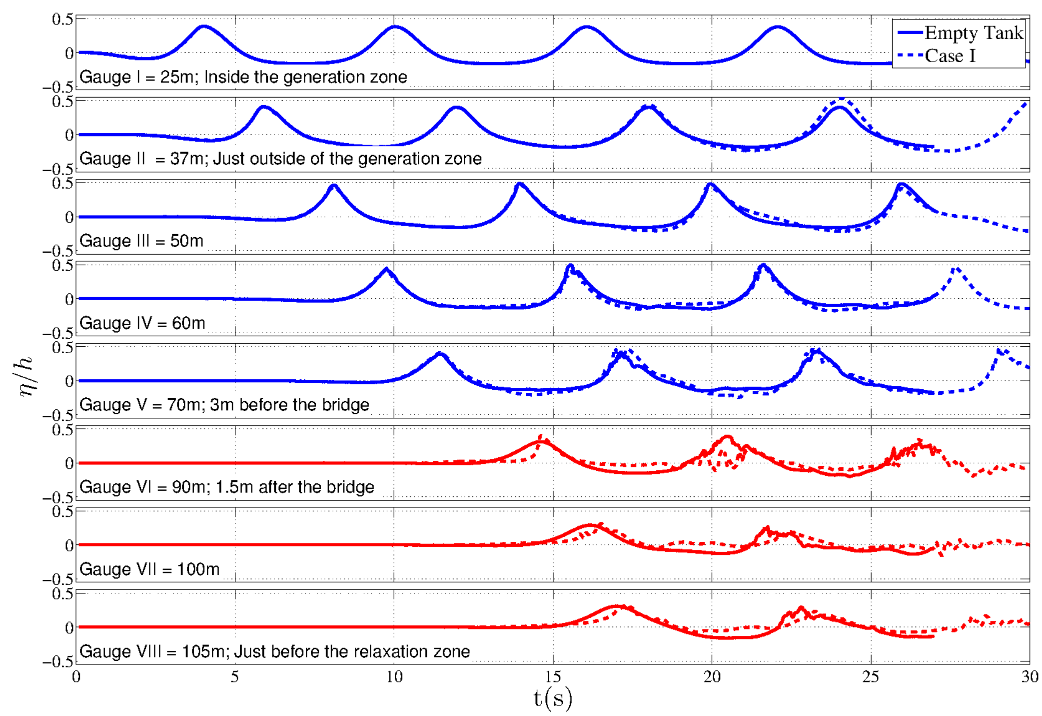

Figure 5: Water Surface Elevation, Punaluu Stream Bridge, in the tank with and without the bridge. The leading edge of the bridge is located at $x = 73$m.

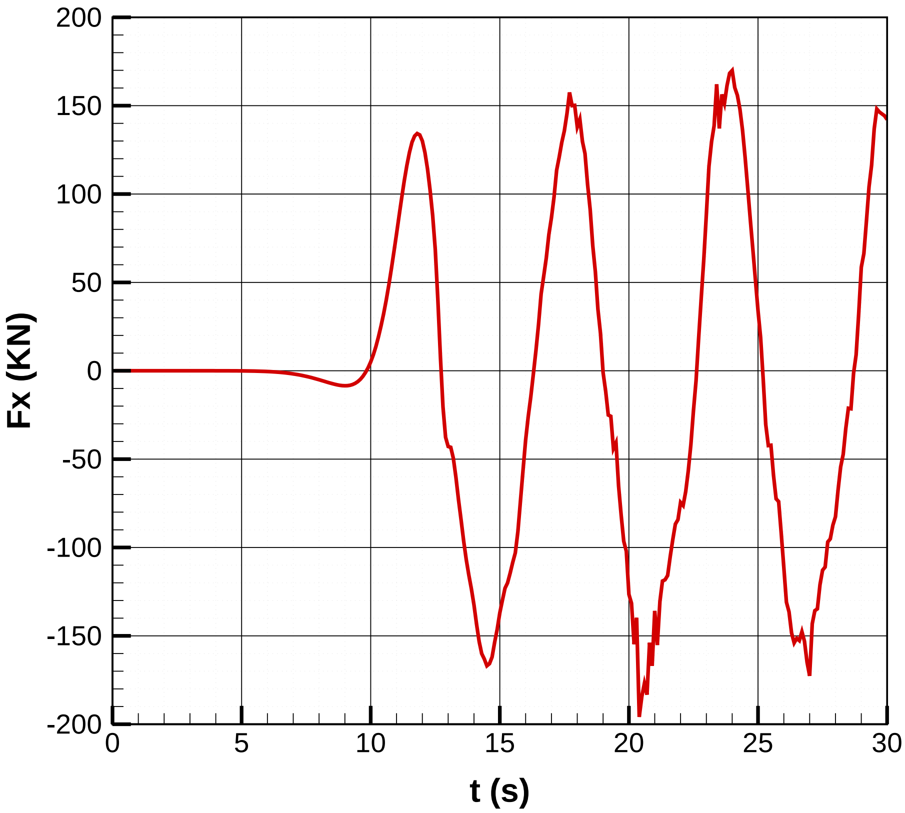

Figure 6: Total horizontal force on Punaluu Stream Bridge, Case I (h = 3.7m) calculated by OpenFOAM.

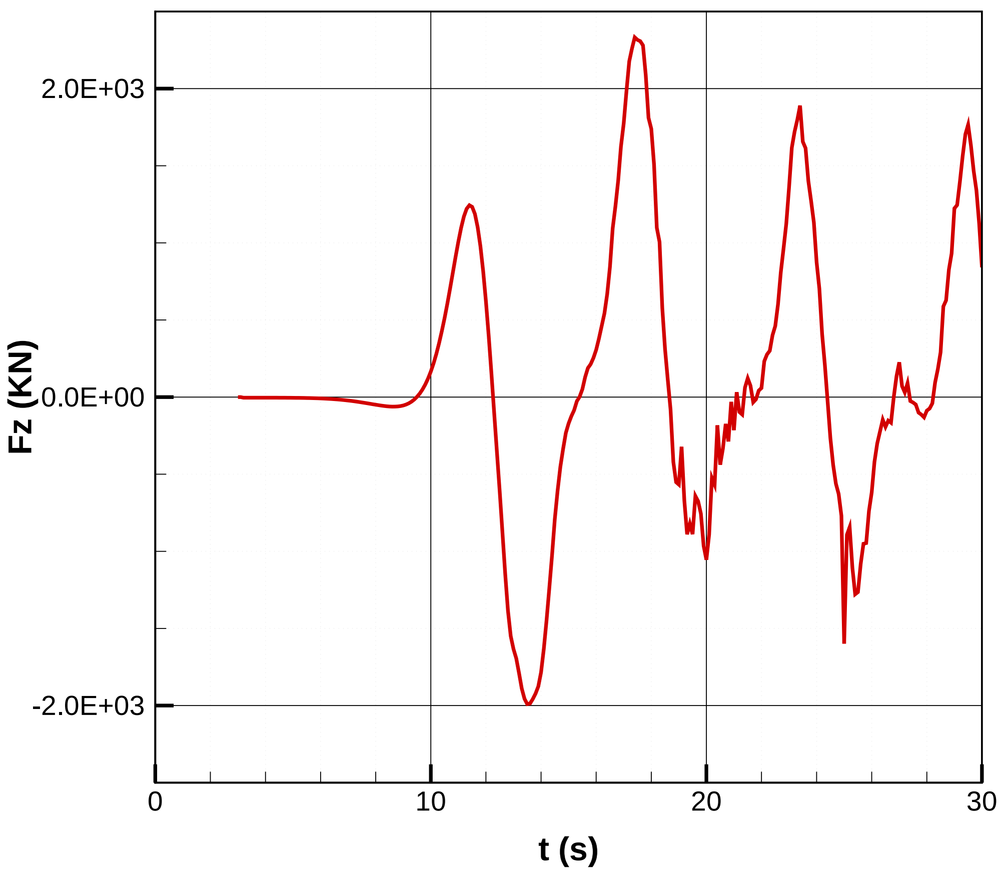

Figure 7: Total vertical force on Punaluu Stream Bridge, Case I ($h = 3.7$m) calculated by OpenFOAM.

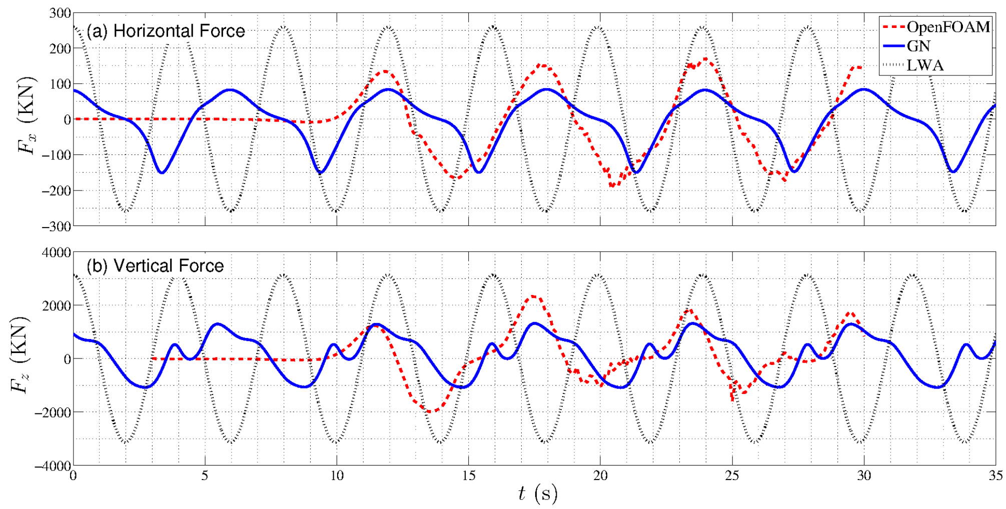

Figure 8: Total (a)horizontal force and (b)vertical force on Punaluu Stream Bridge, Case I ($h = 3.7$m).

5.2 New Makaha Stream Bridge

5.2.1 Bridge Geometry

The deck of the New Makaha Stream Bridge consist of a slab (with no girders), which has a slight slope from the ocean side to the mountain side of the bridge. A schematic of the deck, including maximum water depth, is shown in Fig. 11.

5.2.2 Results

The largest possible water depth at the location of the New Makaha Stream Bridge is such that the deck of the bridge is located on the SWL. Therefore, only one case is considered for this bridge. The wave condition is given in Table 8. Figure 12 shows snapshots of the numerical wave tank in OpenFOAM of interaction of waves with New Makaha Stream Bridge.

Surface elevation recorded at wave gauges upwave and downwave from the bridge are shown in Fig. 13. The waves are generated and propagate smoothly in the wave tank until they collapse on the bridge, which is located on the SWL. Part of the waves are then reflected back towards the wave maker, and a portion of it (very small in this case), is transmitted downwave.

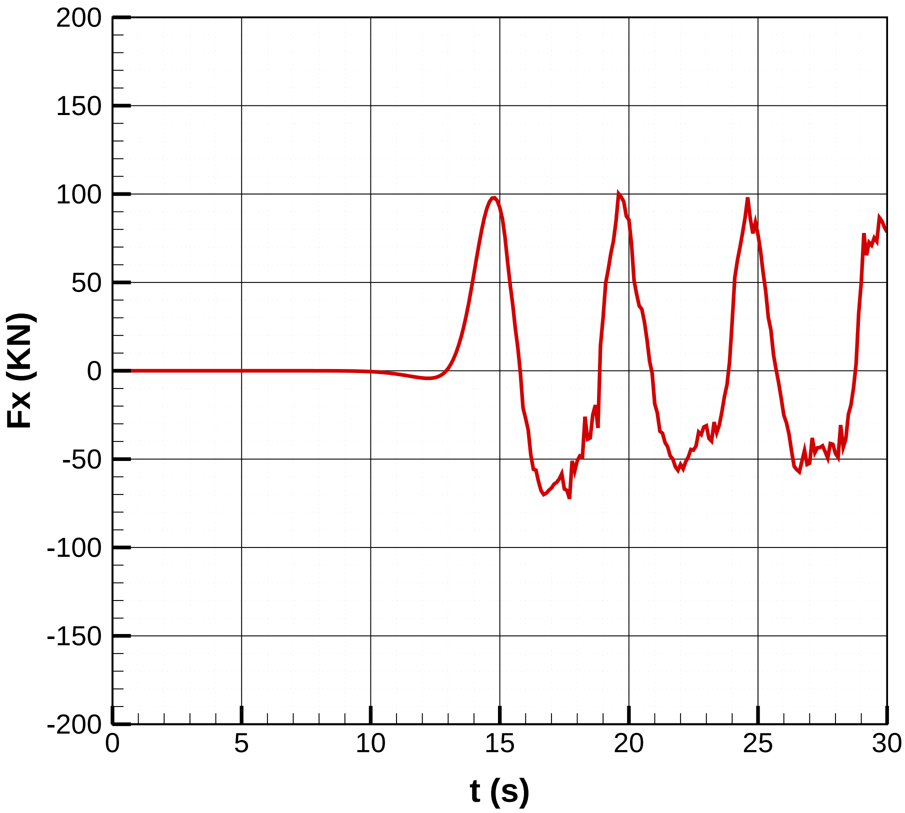

Figure 9: Total horizontal force on Punaluu Stream Bridge, Case II (h = 2.3m) calculated by OpenFOAM.

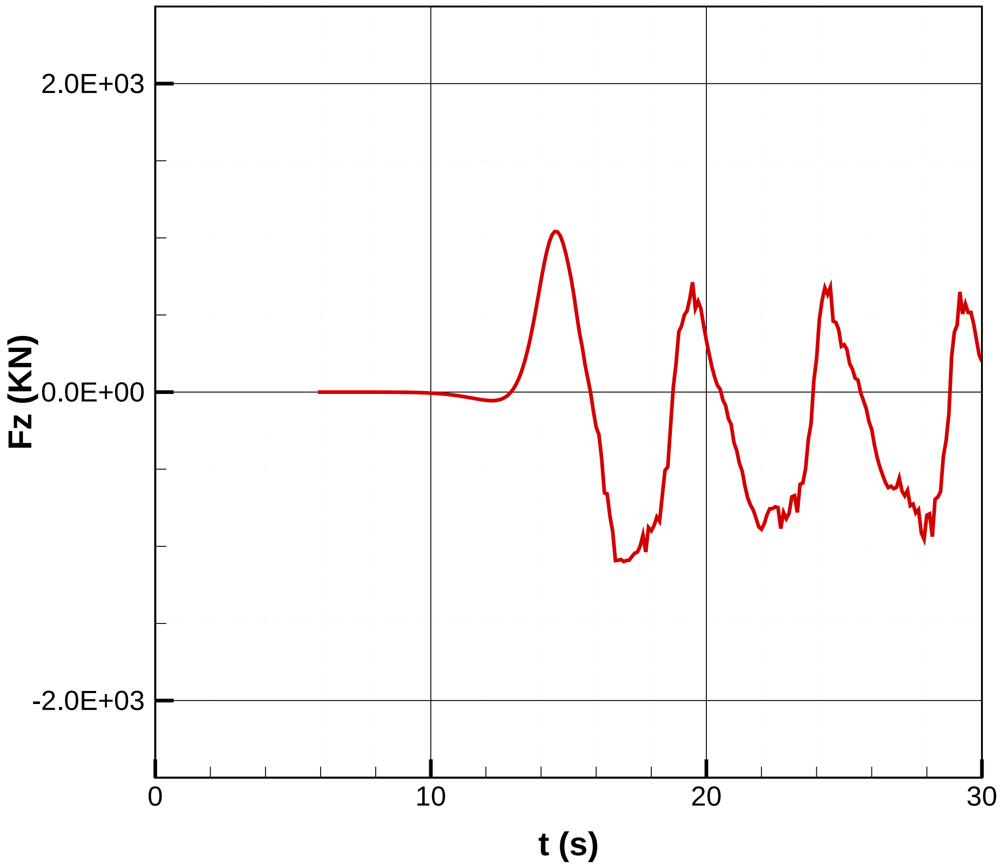

Figure 10: Total vertical force on Punaluu Stream Bridge, Case II ($h = 2.3$m) calculated by OpenFOAM.

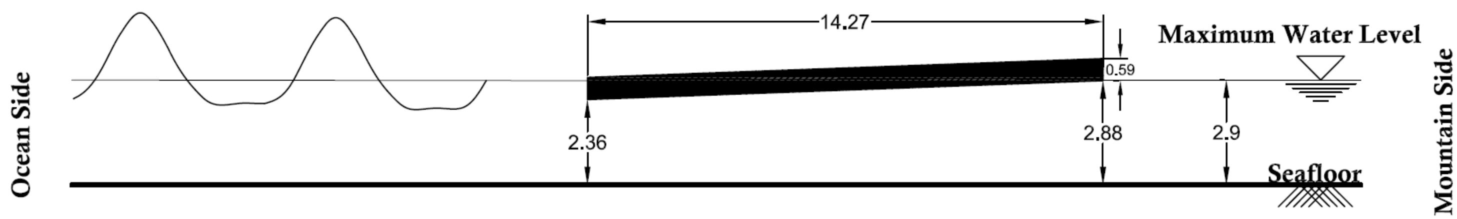

Figure 11: Schematic of the New Makaha Stream Bridge. All dimensions are in meter.

Table 8: Wave condition at the New Makaha Stream Bridge.

h (m)	H (m)	T (s)	λ(m)	Submergence Status
2.9	1.5	5.5	29.88	Deck on the surface

Table 9: Horizontal and Vertical forces on the New Makaha Stream Bridge, calculated by use of the empirical relations and OpenFOAM (see Figs. 14 and 15).

Method	F_x (KN)	F_z (KN)
Douglass	1.37E+02	3.22E+03
McPherson	1.12E+02	3.01E+03
AASHTO	6.50E+01	2.36E+03
OpenFOAM	1.50E+02	1.45E+03

The vertical and horizontal wave forces on the bridge deck calculated by OpenFOAM are shown in Figs. 14 and 15, respectively. Seen in Fig. 14, the horizontal positive force is about three times larger than the horizontal negative force. This is mainly due to the wave breaking and reflection of the wave as it approaches the bridge; only a small portion of the wave passes the trailing edge of the bridge and propagates downwave. This can also be observed in Fig. 13. The magnitude of the uplift force is comparable with the magnitude of the downward force, see Fig. 15, mainly due to the slope of the deck.

The vertical and horizontal forces on the New Makaha Stream Bridge calculated by the empirical relations are given in Table 9. In the calculations of the empirical relations, the deck is assumed to be horizontal with water level at the middle of the deck. The horizontal force estimated by the empirical relations of Douglass and McPherson is in close agreement with the horizontal positive force on the bridge calculated by OpenFOAM. AASHTO underestimates the horizontal forces in this case. The vertical force, however, is overestimated by empirical relations (almost twice larger), with AASHTO's result being the closest one, when compared with the OpenFOAM results.

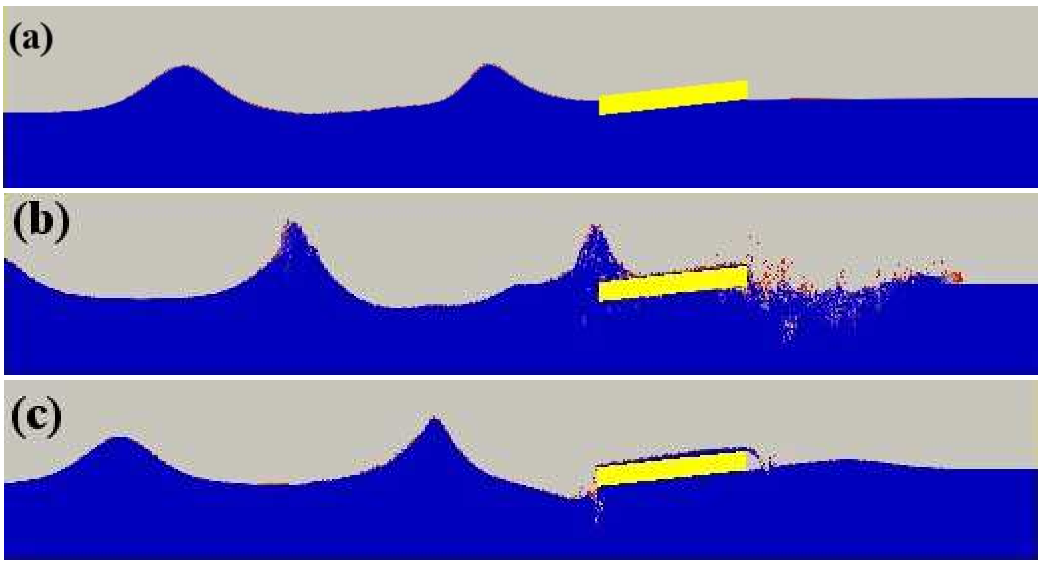

Figure 12: OpenFOAM snapshots of the interaction of surface waves with Makaha Bridge, (a) prior to the interaction of the first wave with the bridge, (b) a wave crest at the leading edge of the bridge and, (c) a wave passing on top of the bridge. Note: For a better display of the wave-bridge interaction, the vertical dimension in this figure is enlarged by a factor of three.

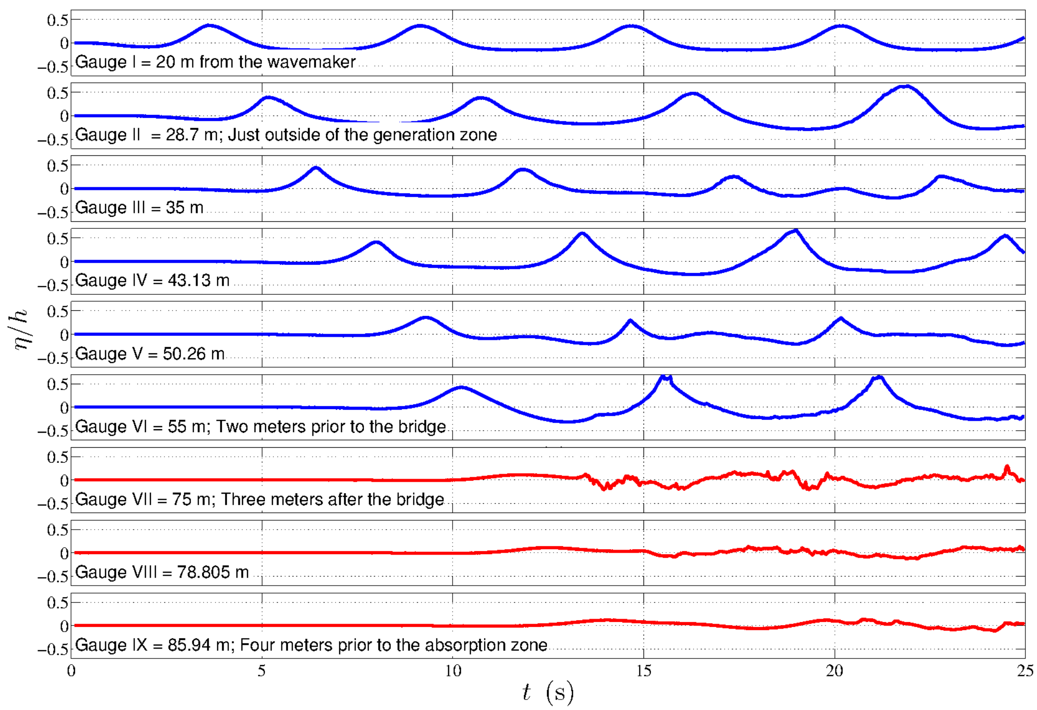

Figure 13: Water Surface Elevation, New Makaha Stream Bridge. The leading edge of the bridge is located at $x = 57$m.

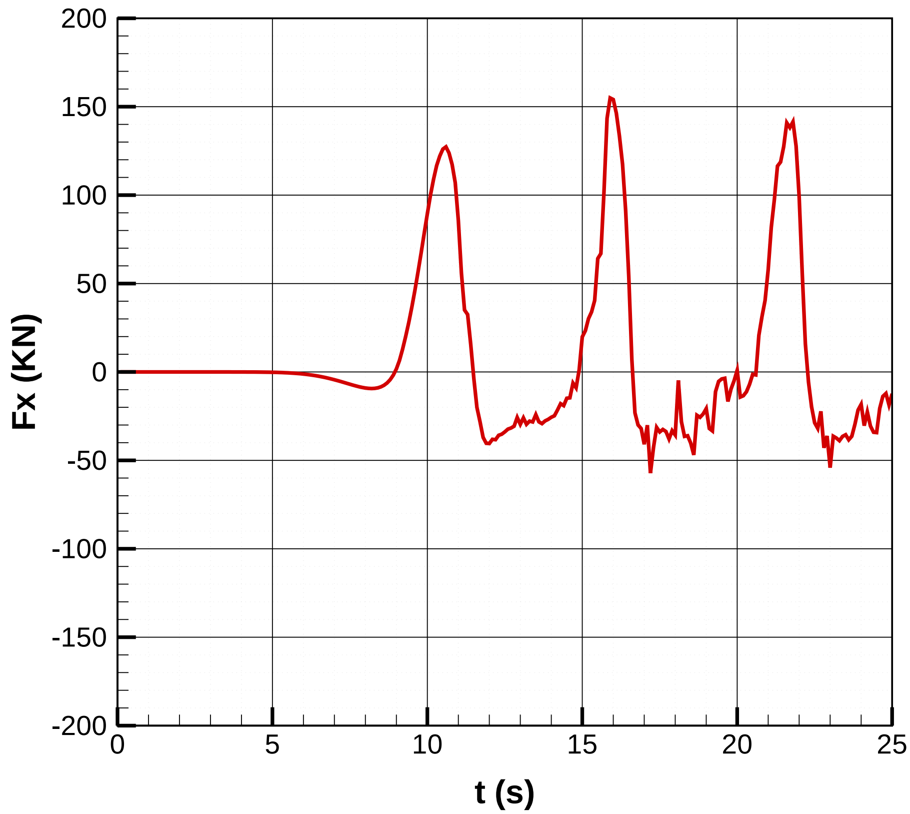

Figure 14: Total horizontal force on New Makaha Stream Bridge calculated by OpenFOAM.

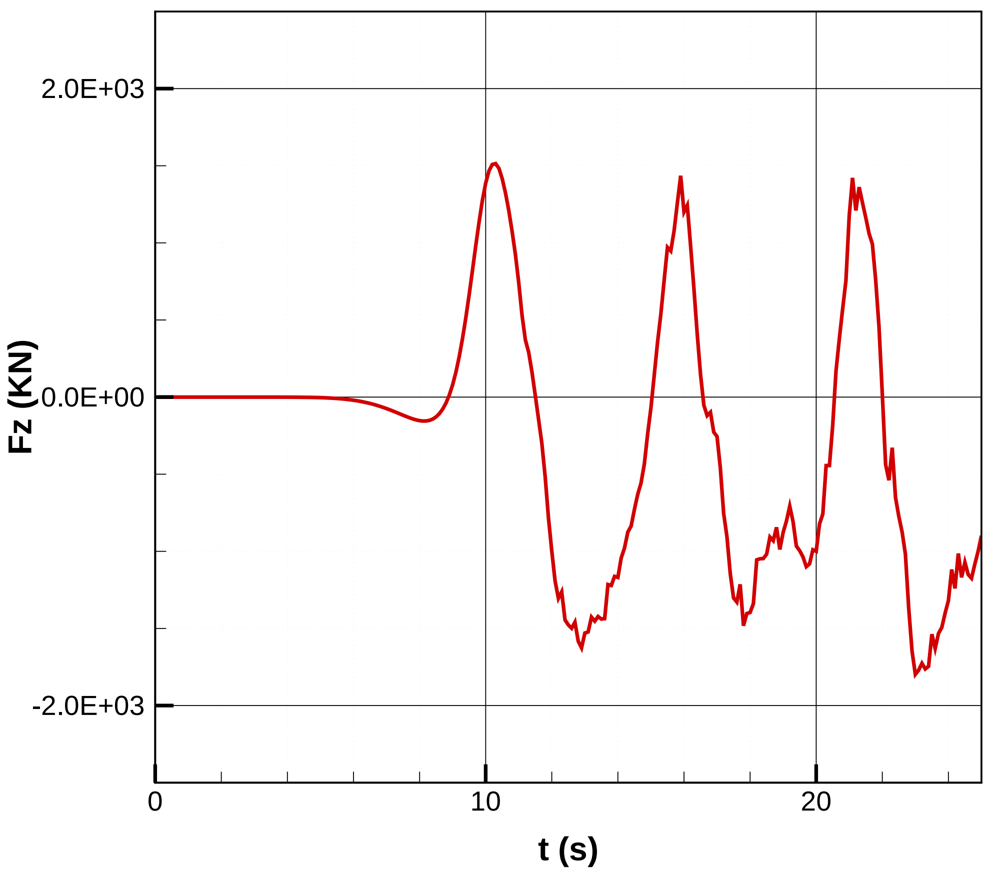

Figure 15: Total vertical force on New Makaha Stream Bridge calculated by OpenFOAM.

5.3 Maili Stream (Maipalaoa) Bridge

5.3.1 Bridge Geometry

The Maipalaoa bridge consists of a slab with 16 girders. A schematic of the bridge is shown in Fig. 16.

5.3.2 Results

The maximum water level at the location of Maipalaoa bridge is such that the bridge may become fully submerged. Therefore, two cases are considered for the Maipalaoa bridge which are given below.

Case I: In this case, $h = 4.9$m (largest possible water depth at the location of the Maipalaoa bridge) and the bridge is fully submerged. A summary of the wave conditions are presented in Table 10. Both the GN and OpenFOAM models are used in this case, and the horizontal and vertical forces on the bridge are shown in Fig. 17. In the GN calculations for this case, submergence depth is defined from the SWL to the middle of the bridge thickness, for which bridge thickness is considered as the thickness of the deck and height of the girders. For this case, calculations of OpenFOAM took about 5 weeks (or 840 hours) on an 8-CPU workstation (Intel Core i7-4770 processors on a PC), while the GN calculations are accomplished in about a minute.

Overall, outstanding agreement between the forces calculated by OpenFOAM and the GN model is observed, given that the bridge is assumed to be a thin plate in the GN calculations. The magnitude of the horizontal positive force calculated by the GN model is slightly smaller than that of the OpenFOAM, see the horizontal force in Fig. 17(a). The vertical uplift force is slightly larger in the GN model compared to the OpenFOAM, see Fig. 17(b). These slight differences are due to the difference of the submergence depth of the bridge with that assumed in the GN model. The horizontal negative force and the vertical downward force of the two models are in very good agreement. The slight phase difference of the horizontal negative force predicted by OpenFOAM and the GN model, is due to the difference in wave propagation on top of the bridge, which is mainly due to the large thickness of the deck and girders ($(t_D + t_G)/h = 0.25$), assumed zero in the GN model.

Case II: In this case, $h = 3.89$m and the water level is in the middle of the bridge deck. The wave condition for this case is given in Table 11. OpenFOAM snapshots of the interaction of surface waves with the bridge

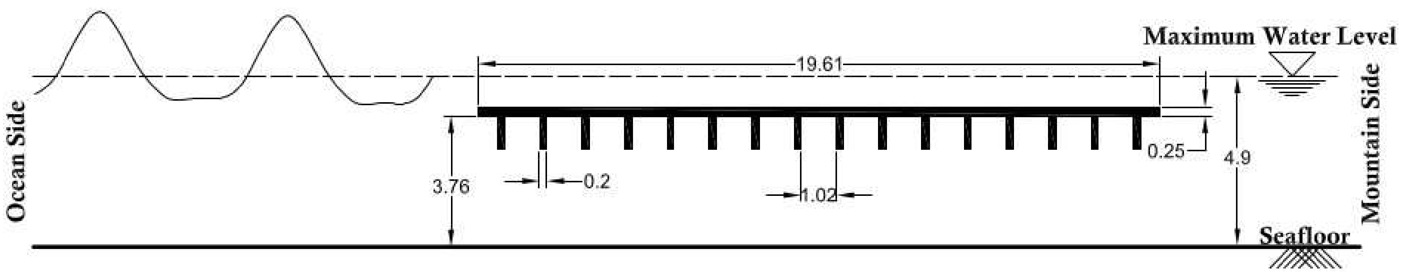

Figure 16: Schematic of the Maipalaoa Bridge. All dimensions are in meter.

Table 10: Maipalaoa Bridge, Case I wave condition.

h (m)	H (m)	T (s)	λ(m)	Submergence Status
4.9	2.7	6.5	44.99	Fully Submerged

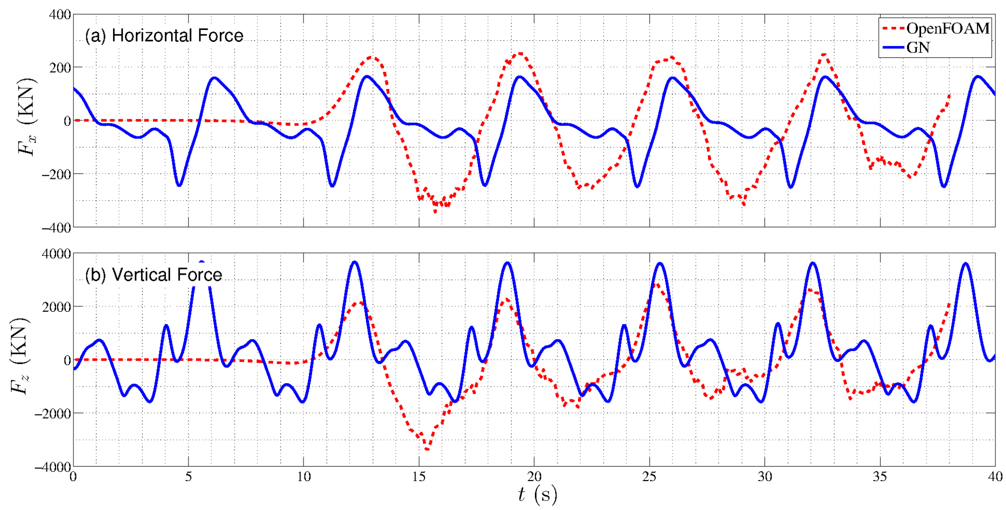

Figure 17: Total (a)horizontal force and (b)vertical and horizontal forces on Maipalaoa Bridge, Case I (h = 4.9m), calculated by OpenFOAM and the GN model.

are shown in Fig. 18. Surface elevation at a series of gauges upwave and a gauge downwave are shown in Fig. 19. Majority of the wave energy is either reflected back towards the wavemaker or dissipates due to the breaking over the bridge. only a small portion is transferred, see the last gauge in Fig. 19.

The horizontal and vertical forces, calculated by OpenFOAM, are shown in Figs. 20 and 21, respectively. The horizontal positive force is about twice larger than the horizontal negative force, see Fig. 20. Also, the vertical downward force is slightly larger than the vertical uplift force, seen in Fig. 21.

In this case, the wave forces on the Maipalaoa bridge are also calculated by use of the empirical relations. In the calculations of the vertical force by McPherson's method, we assume 0% air entrapment between the girders. These forces are presented in Table 12. When compared with the

Table 11: Maipalaoa Bridge, Case II wave condition.

h (m)	H (m)	T (s)	λ(m)	Submergence Status
3.89	2.12	6	37.39	Deck on the surface

Table 12: Horizontal and Vertical forces on Maipalaoa Bridge, Case II, calculated by use of the empirical relations and OpenFOAM (see Figs. 20 and 21).

Method	F_x (KN)	F_z (KN)
Douglass	5.61E+02	4.47E+03
McPherson	4.80E+02	3.28E+03
AASHTO	1.53E+02	7.20E+03
OpenFOAM	2.00E+02	1.5E+03

OpenFOAM results, both Douglass's and McPherson's methods have overestimated the horizontal positive force (about 2.5 times larger), while AASHTO has slightly underestimated the force. The vertical uplift force is overestimated by the empirical relations, with McPherson's result being the closest.

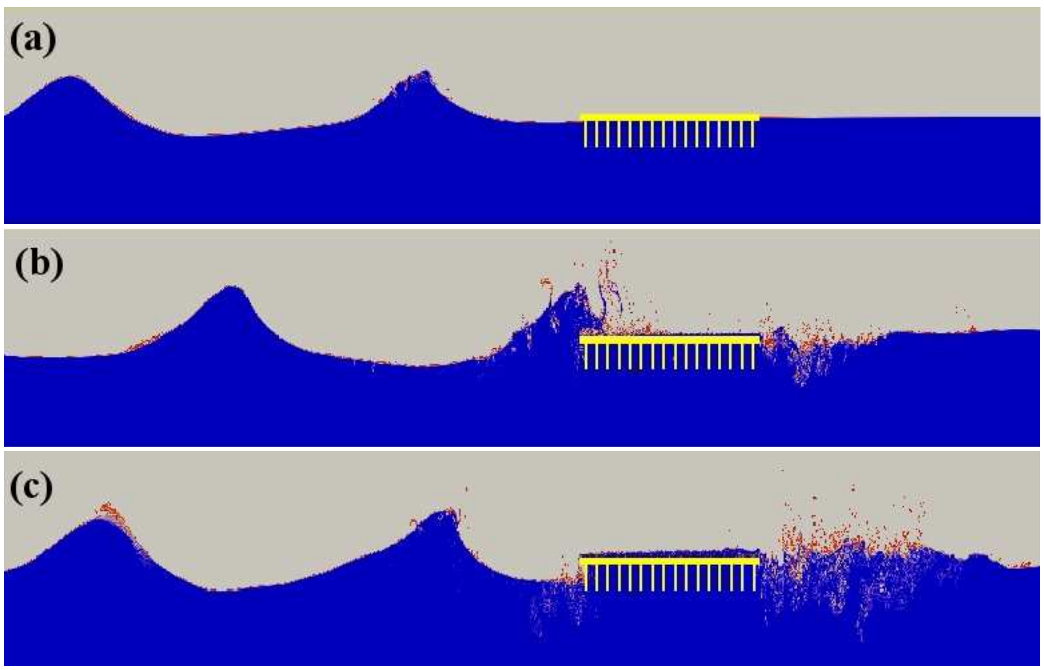

Figure 18: OpenFOAM snapshots of the interaction of surface waves with Maipalaoa Bridge, Case II (h = 3.89m), (a) prior to the interaction of the first wave with the bridge, (b) a wave crest at the leading edge of the bridge and, (c) a wave passing on top of the bridge. Note: For a better display of the wave-bridge interaction, the vertical dimension in this figure is enlarged by a factor of three.

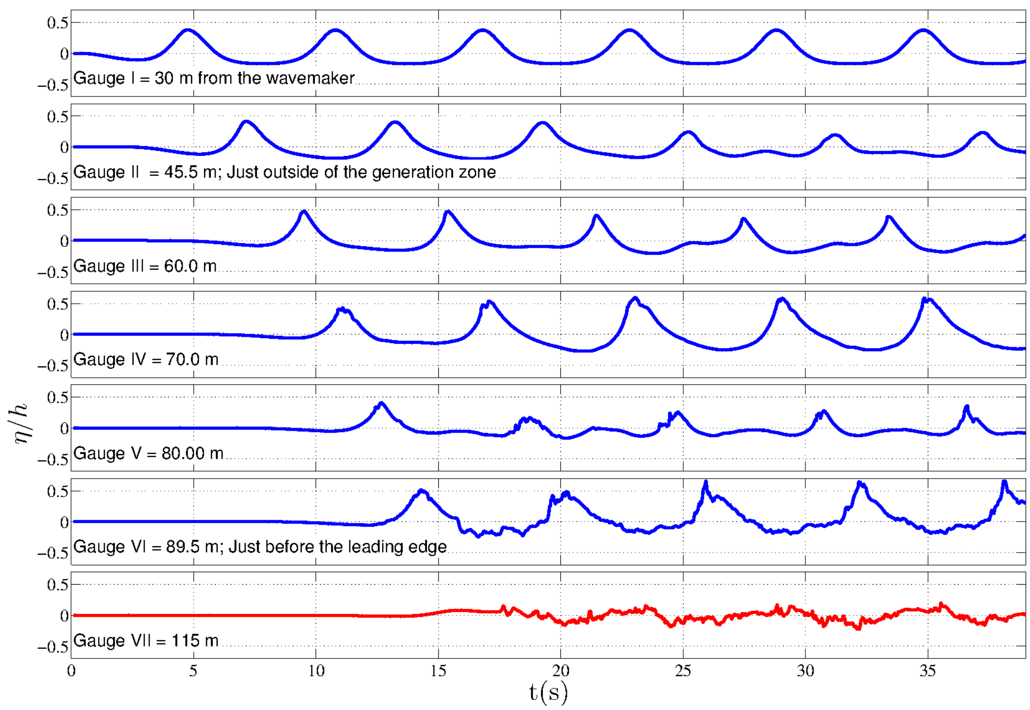

Figure 19: Water Surface Elevation, Maipalaoa Bridge, Case II ($h = 3.89$m). The leading edge of the bridge is located at $x = 90$m.

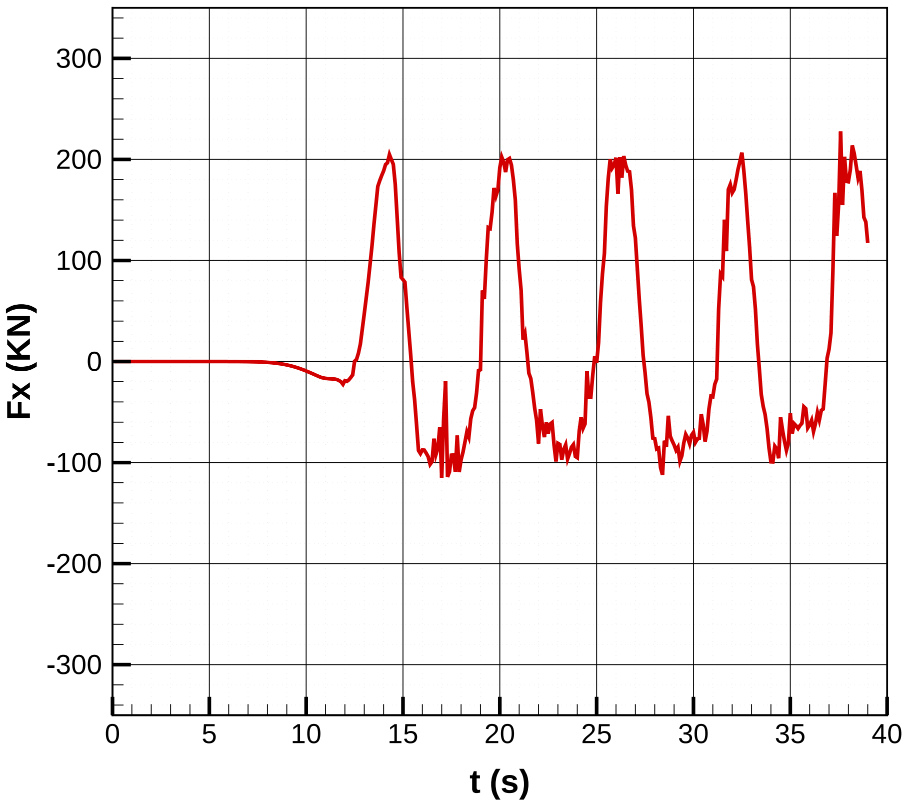

Figure 20: Total horizontal force on Maipalaoa bridge, Case II ($h = 3.89$m).

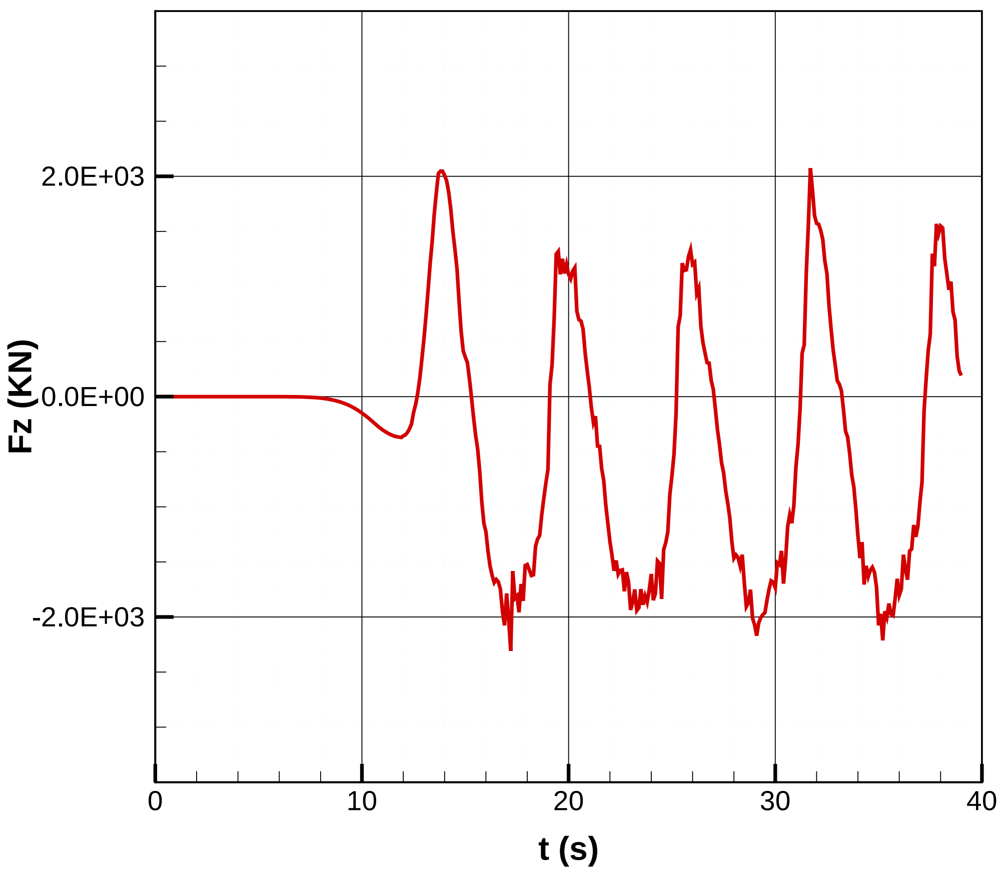

Figure 21: Total vertical force on Maipalaoa bridge, Case II ($h = 3.89$m).

5.4 Kahaluu Stream Bridge

5.4.1 Bridge Geometry

Kahaluu Stream Bridge consists of a deck and eight girders, as shown in Fig. 22.

5.4.2 Results

Three different cases are considered for the Kahaluu Stream bridge. These are given below.

Case I: In this case, $h = 5.7$m (maximum water depth) and the bridge is fully submerged. Wave condition of this case is presented in Table 13. Only OpenFOAM is used for the force calculations in this case. The deck, in this case, is very close to the SWL and therefore, the GN model can not be used due to the wave breaking. Figures 23 show snapshots of the numerical wave tank in OpenFOAM for this case.

Surface elevation at a series of a wave gauges upwave and downwave are shown in Fig. 24. The OpenFOAM horizontal and vertical forces on the bridge are shown in Figs. 25 and 26, respectively. Seen in Fig. 25, the horizontal positive force has almost the same magnitude as the horizontal negative force. The vertical uplift force, however, is very slightly smaller than the vertical downward force, seen in Fig. 26.

Table 13: Kahaluu Stream bridge, Case I wave condition.

h (m)	H (m)	T (s)	λ(m)	Submergence Status
5.7	3.2	7	52.40	Fully Submerged

Case II: In this case, $h = 5.415$m and the water level is in the middle of the bridge deck. Wave condition of this case, at the location of the bridge, is given in Table 14. The horizontal and vertical forces, calculated by OpenFOAM, are shown in Figs. 27 and 28, respectively. The horizontal positive force is about 1.5 times larger than the horizontal negative force in this case, see Fig. 27. On the other hand, the vertical uplift force is slightly smaller than the vertical downward force, seen in Fig. 28.

The forces are also calculated by use of the empirical relations and results are presented in Table 15. In McPherson method, 0% air entrapment is

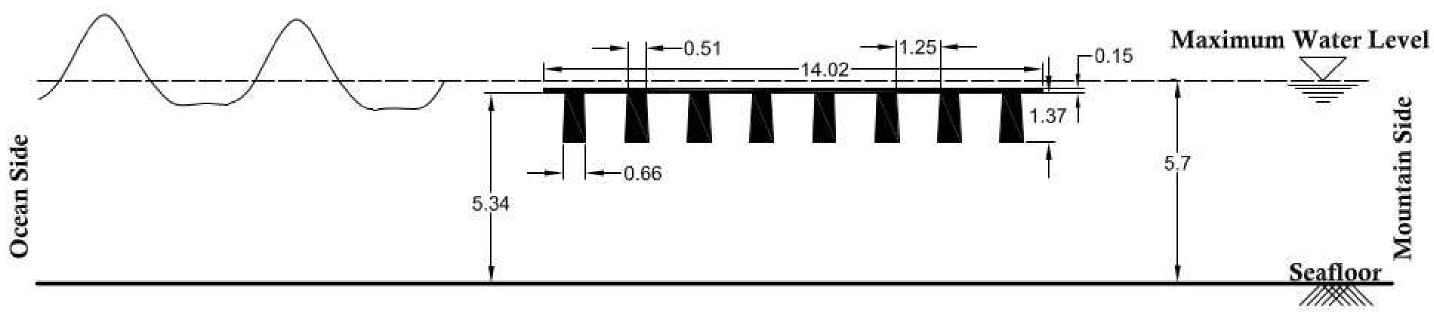

Figure 22: Schematic of Kahaluu Bridge. All dimensions are in meter.

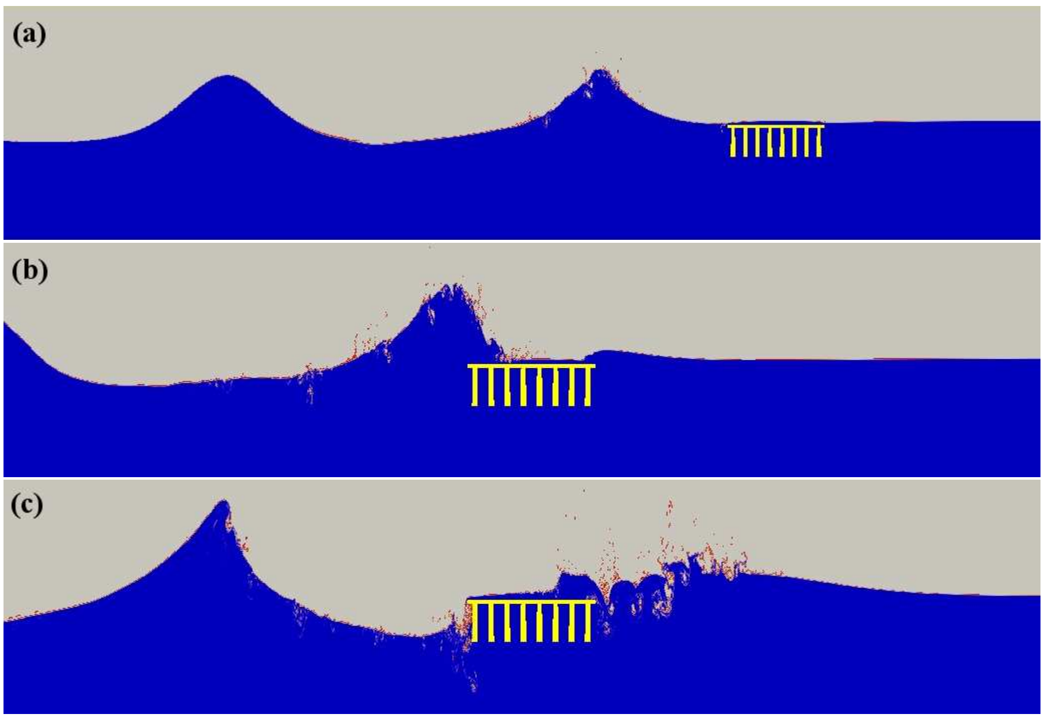

Figure 23: OpenFOAM snapshots of the interaction of surface waves with Kahaluu Stream Bridge, Case I ($h = 5.7$m), (a) prior to the interaction of the first wave with the bridge, (b) a wave crest at the leading edge of the bridge and, (c) a wave passing on top of the bridge. Note: For a better display of the wave-bridge interaction, the vertical dimension in this figure is enlarged by a factor of three.

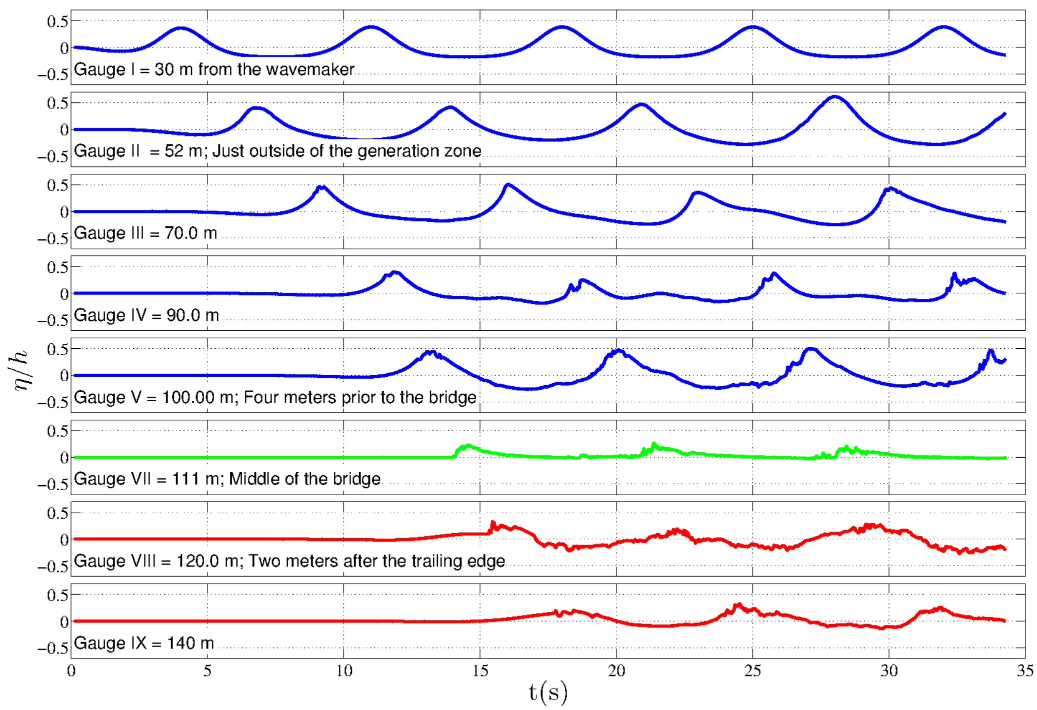

Figure 24: Water Surface Elevation, Kahaluu Stream Bridge, Case I. The leading edge of the bridge is located at $x = 104$m.

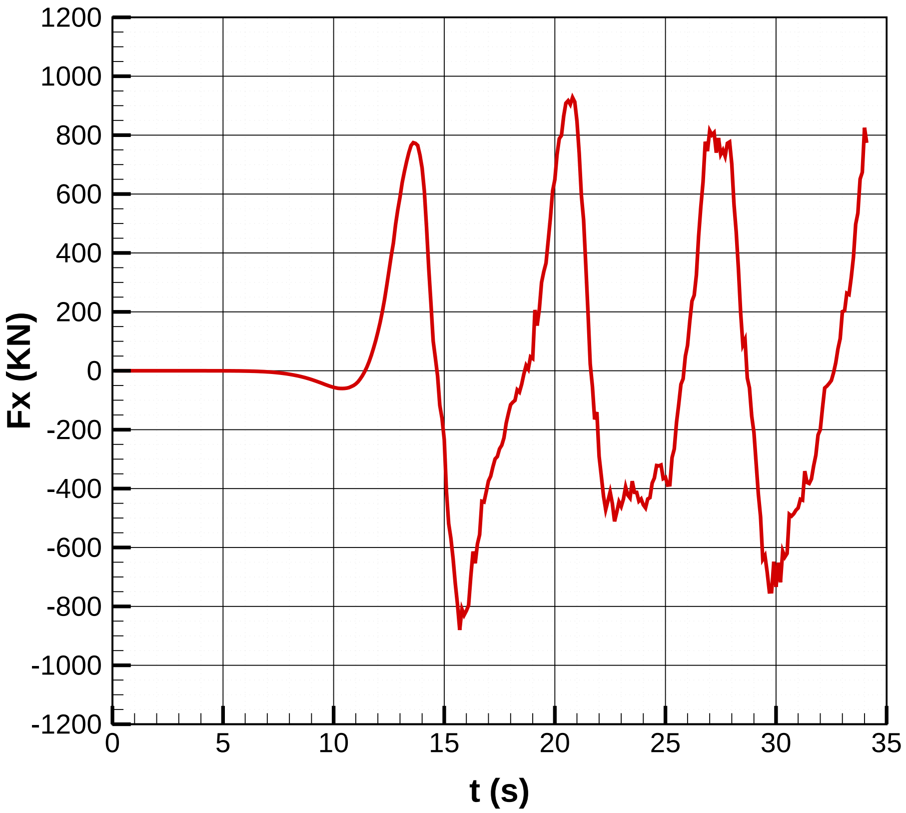

Figure 25: Total horizontal force on Kahaluu Stream Bridge, Case I (h = 5.7m), calculated by OpenFOAM.

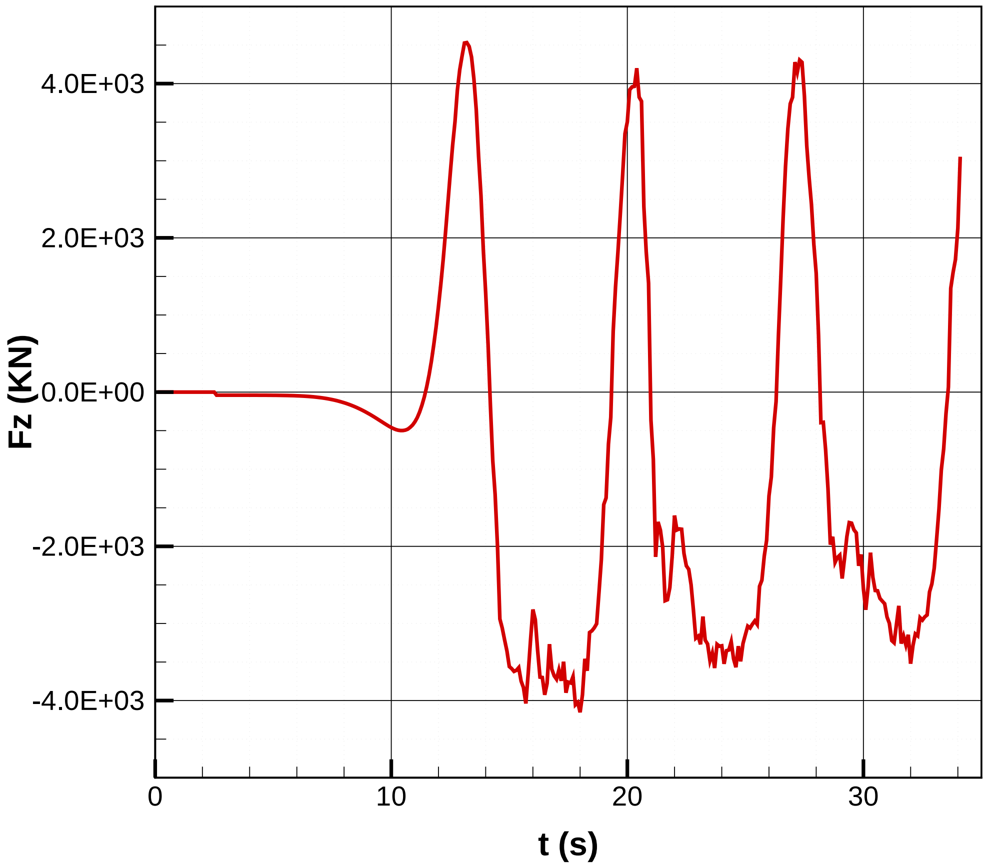

Figure 26: Total vertical force on Kahaluu Stream Bridge, Case I ($h = 5.7$m), calculated by OpenFOAM.

Table 14: Kahaluu Stream bridge, Case II wave condition.

h (m)	H (m)	T (s)	λ(m)	Submergence Status
5.415	3.0	6.5	46.41	Deck on the SWL

Table 15: Horizontal and Vertical forces on Kahaluu Stream Bridge, Case II, calculated by use of the empirical relations and OpenFOAM (see Figs. 27 and 28).

Method	F_x (KN)	F_z (KN)
Douglass	5.30E+02	9.56E+03
McPherson	4.80E+02	3.28E+03
AASHTO	5.32E+02	2.38E+04
OpenFOAM	8.00E+02	3.00E+03

considered. The horizontal positive force is underestimated by all methods, when compared to OpenFOAM results, with AASHTO giving the closest results. The vertical force of McPherson is in very close agreement with the OpenFOAM results, while Douglass and AASHTO overestimate the force.

Case III: In this case, $h = 4.655$m and water level is as high as half of the bridge girders. The wave condition of this case is shown in Table 16. The OpenFOAM horizontal and vertical forces on the bridge are shown in Figs. 29 and 30, respectively. The horizontal force mainly consists of a positive force (in the direction of wave propagation); the negative force is negligible in comparison to the positive force, see Fig. 29. The vertical uplift force, seen in Fig. 30, is larger than the vertical downward force. We note that in the two-dimensional OpenFOAM calculations of this case, the air above the SWL and in between the girders remains there throughout the calculations. This, modifies the wave forces on the deck, see Hayatdavoodi et al. (2014*b*) for more information.

The wave-induced forces on the Kahaluu Stream Bridge of Case III, calculated by the empirical relations are given in Table 17. When compared with the OpenFOAM results, the horizontal force is underestimated by Douglass and AASHTO, but very closely predicted by the McPherson empirical

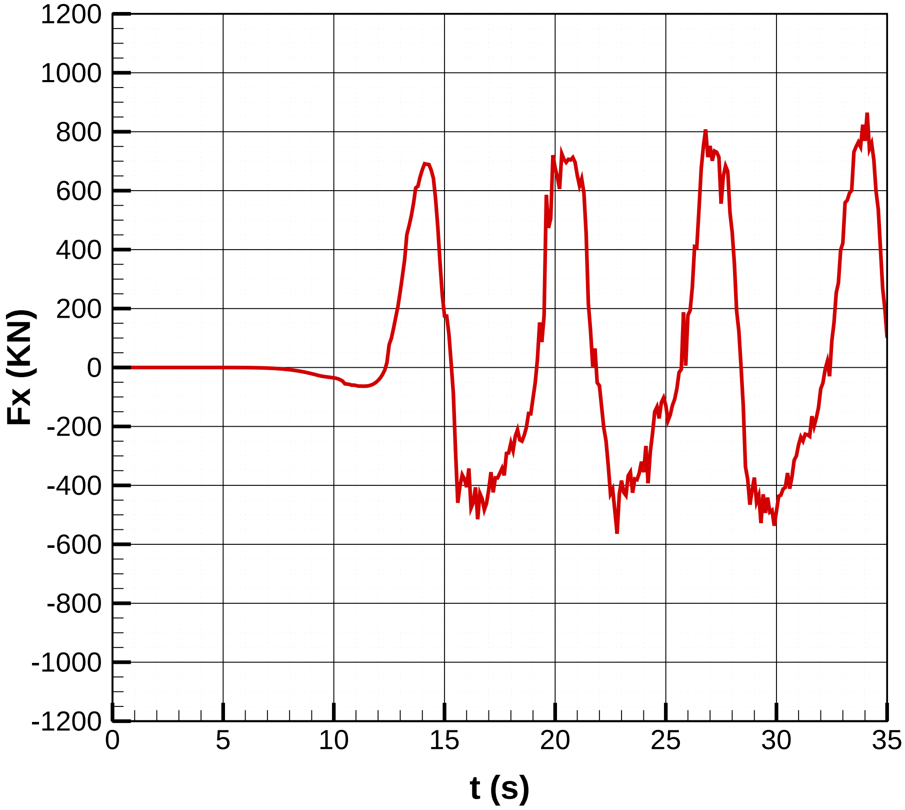

Figure 27: Total horizontal force on Kahaluu Stream Bridge, Case II ($h =$ 5.415m), calculated by OpenFOAM.

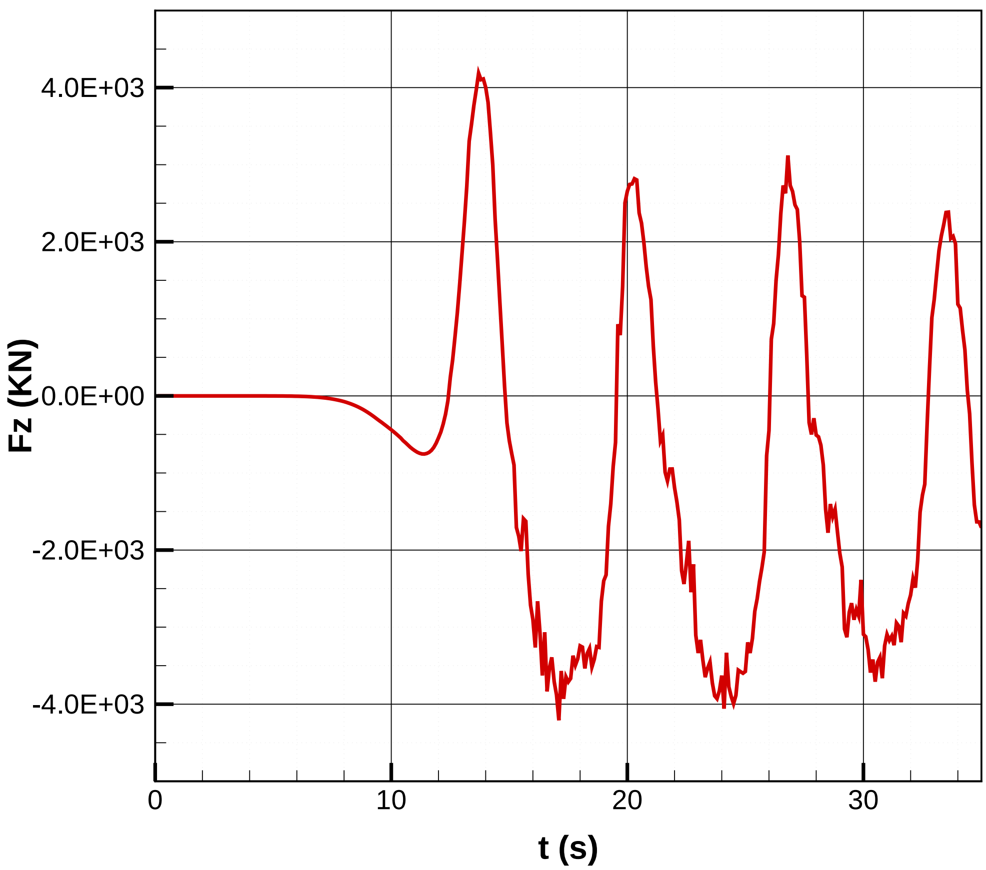

Figure 28: Total vertical force on Kahaluu Stream Bridge, Case II (h = 5.415m), calculated by OpenFOAM.

Table 16: Kahaluu Stream bridge, Case III wave condition.

h (m)	H (m)	T (s)	λ(m)	Submergence Status
4.6550	2.62	6.0	39.76	Girders halfway in water

Table 17: Horizontal and Vertical forces on Kahaluu Stream Bridge, Case III, calculated by use of the empirical relations and OpenFOAM (see Figs. 29 and 30).

Method	F_x (KN)	F_z (KN)
Douglass	3.40E+02	5.23E+03
McPherson	9.82E+02	5.02E+03
AASHTO	7.22E+02	1.05E+04
OpenFOAM	1.00E+03	4.0E+03

relation. This is partially due to the air entrapment in OpenFOAM calculations. The vertical uplift force is slightly overestimated by the empirical relations, with McPherson's relation giving the closest result.

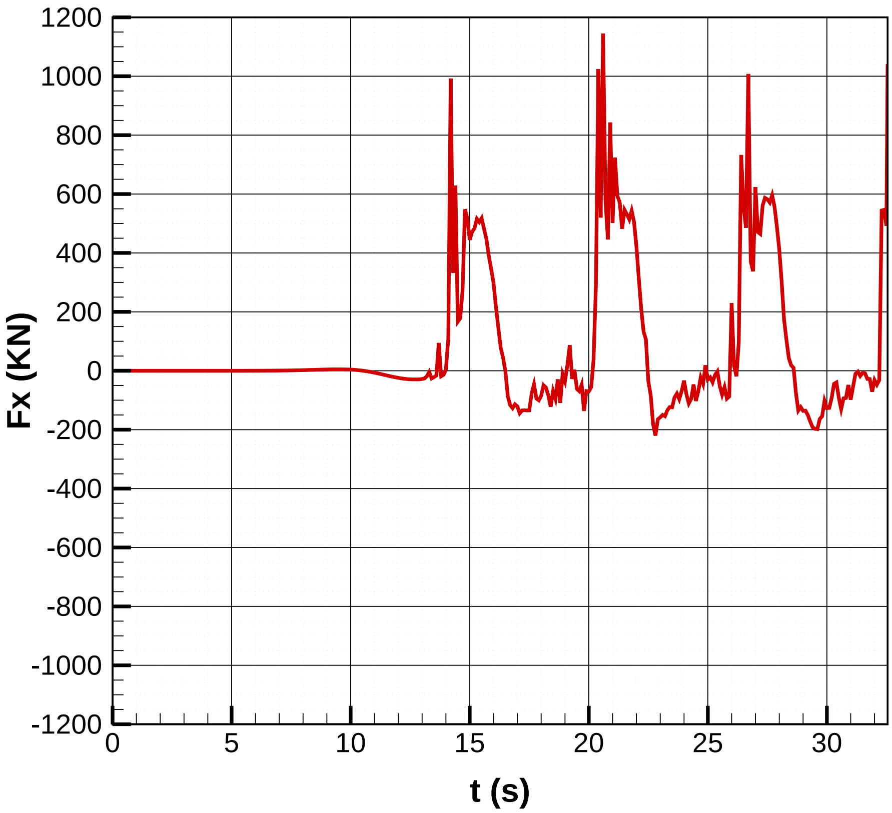

Figure 29: Total horizontal force on Kahaluu Stream Bridge, Case III ($h =$ 4.655m), calculated by OpenFOAM.

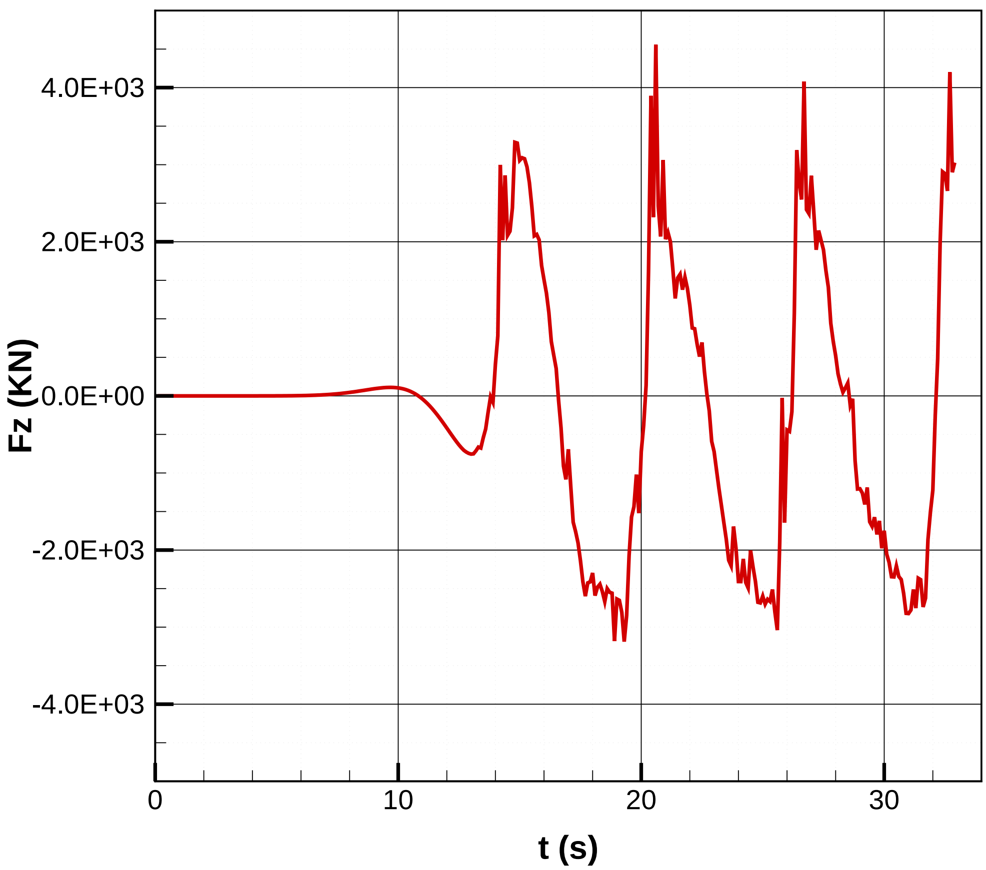

Figure 30: Total vertical force on Kahaluu Stream Bridge, Case III (h = 4.655m), calculated by OpenFOAM.

6 Concluding Remarks

The horizontal and vertical wave-induced forces on decks of four selected bridges on the Island of Oahu are studied by use of several theoretical and empirical approaches. Multiple storm cases (water depth and wave condition) are assumed for each of the bridges. A summary of the results of all the model used here, for all the cases studied, is give in Table 18. It is found that the maximum forces always occur when the water level is the largest (deepest water-depth cases). Those cases that result in the maximum forces (calculated by OpenFOAM), along with the corresponding empirical relations and the GN results are summarized in Table 19.

In all the cases studied here, the total vertical force is significantly larger than the total horizontal force on the bridge. All the theoretical and empirical relations are in agreement about this.

For the elevated cases (bridge deck on or above the SWL), it appears that the horizontal force is underestimated by the empirical relations (compared with the OpenFOAM results), when the deck only consists of a slab (with no girders). For these cases, and for similar bridges to those studied here, it is recommended to use the conservative value of the coefficients of the empirical relations. For a deck with girders, closer results are observed (when compared with OpenFOAM results), and AASHTO appears to give the most accurate results among these three empirical relations.

The vertical forces on a slab (with no girders) are overestimated by the empirical relations, when compared with the OpenFOAM results. For the case of deck with girders, the vertical uplift force seems to be best estimated by McPherson's relation.

For a fully submerged deck (with or without girders), the GN results are observed to be in very close agreement with the OpenFOAM calculations, for both the horizontal and vertical forces. Therefore, given that the computational cost of the GN model is significantly less than that of OpenFOAM, the GN model can safely be used for force calculation on submerged bridges, whether the deck is only a slab or it includes girders.

Table 18: Summary of the calculated wave forces on the selected bridges for all the cases considered here. The following abbreviations are used to refer to the equations; OF: OpenFOAM; GN: The GN Equations; DO:Douglass Equations; Mc:McPherson Equations; AA:AASHTO equations. NA means that the equations are not applicable to this specific case.

		F_x (KN)					F_z (KN)				
Bridge Name	Case	OF	GN	DO	Mc	AA	OF	GN	DO	Mc	AA
Punaluu Bridge	Case I	1.5E+2	1.0E+2	NA	NA	NA	1.9E+3	1.5E+3	NA	NA	NA
	Case II	1.00E+02	NA	4.17E+01	3.38E+01	1.06E+01	7.00E+02	NA	2.35E+03	1.91E+03	3.32E+03
Makaha Stream	Single Case	1.4E+2	NA	1.37E+2	1.12E+2	6.5E+1	1.4E+3	NA	3.22E+3	3.01E+3	2.36E+3
Maipalaoa Bridge	Case I	2.5E+2	1.7E+2	NA	NA	NA	3.0E+3	3.60E+3	NA	NA	NA
	Case II	2.00E+02	NA	5.61E+02	4.80E+02	1.53E+02	1.5E+03	NA	4.47E+03	3.28E+03	7.20E+03
Kahaluu Stream	Case I	0.85E+2	NA	NA	NA	NA	4.2E+3	NA	NA	NA	NA
	Case II	8.00E+02	NA	5.30E+02	4.80E+02	5.32E+02	3.00E+03	NA	9.56E+03	3.28E+03	2.38E+04
	Case III	1.00E+03	NA	3.40E+02	9.82E+02	7.22E+02	4.0E+03	NA	5.23E+03	5.02E+03	1.05E+04

Table 19: Summary of the maximum wave forces on the selected bridges. NA means that the equations are not applicable to this specific case.

	Bridge Name	Punaluu Bridge	Makaha Stream	Maipalaoa Bridge	Kahaluu Stream
Wave Condition	h (m)	3.7	2.9	4.9	5.7
	H (m)	2.0	1.5	2.7	3.2
	H/h	0.54	0.52	0.55	0.56
	λ (m)	36.70	29.88	44.99	52.40
	λ/h	9.9	10.3	9.2	9.2
	T (s)	6.0	5.5	6.5	7.0
F_x (KN)	OpenFOAM	1.5E+2	1.4E+2	2.5E+2	0.85E+2
	GN	1.0E+2	NA	1.7E+2	NA
	Douglass	NA	1.37E+2	NA	NA
	McPherson	NA	1.12E+2	NA	NA
	AASHTO	NA	6.5E+1	NA	NA
F_z (KN)	OpenFOAM	1.9E+3	1.4E+3	3.0E+3	4.2E+3
	GN	1.5E+3	NA	3.60E+3	NA
	Douglass	NA	3.22E+3	NA	NA
	McPherson	NA	3.01E+3	NA	NA
	AASHTO	NA	2.36E+3	NA	NA

7 Acknowledgement

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9 APPENDIX A: Force Calculations by use of the Douglass et al. (2006) Method

New Makaha Stream Bridge

Wave forces calculated by use of ***Douglass et al. (2006)*** *empirical relations.*

Vertical Force Equation:

$$F_v = c_{v-va} * F_v^*$$
$$F_v^* = \gamma * (\Delta z_v) * A_v$$

Horizontal Force Equation:

$$F_h = [1 + C_r * (N-1)] * c_{h-va} * F_h^*$$
$$F_h^* = \gamma * (\Delta z_h) * A_h$$

Constant Coefficients:

Cr	0.4	
Cv-va	1	Nonconserv.
Ch-va	1	Nonconserv.
ρ	1025	kg/m^3
g	9.81	m/s^2
γ	10055.25	kg/(m^2 s^2)

Bridge Dimensions and Wave Condition:

Water Depth	2.9	m
Wave Height/Water Depth	0.517	
Wave Height	1.500	m
Wave above the SWL, Percent (/100)	0.7	
Max. Surface Elevation	1.050	m
Elevation of the deck (SWL to bottom of the deck)	0	m
Dz Vertical Force	1.050	m
Dz Horizontal Force	1.050	
Deck Width	14.27	m
Deck Length	21.34	m
Deck Thickness	0.61	m
Deck Area (Av); Vertical Force	304.522	m^2
Deck Area (Ah); Horizontal Force	13.017	m^2
Number of Girders	1	

Force Calculations:

Fz=	3.22E+03	KN
Fx=	1.37E+02	KN

New South Punaluu Stream Bridge; Case II

Wave forces calculated by use of ***Douglass et al. (2006)*** *empirical relations.*

Vertical Force Equation:

$$F_v = c_{v-va} * F_v^*$$
$$F_v^* = \gamma * (\Delta z_v) * A_v$$

Horizontal Force Equation:

$$F_h = [1 + C_r * (N - 1)] * c_{h-va} * F_h^*$$
$$F_h^* = \gamma * (\Delta z_h) * A_h$$

Constant Coefficients:

Cr	0.4	
Cv-va	1	Nonconserv.
Ch-va	1	Nonconserv.
ρ	1025	kg/m^3
g	9.81	m/s^2
γ	10055.25	kg/(m^2 s^2)

Bridge Dimensions and Wave Condition:

Water Depth	2.3	m
Wave Height/Water Depth	0.539	
Wave Height	1.240	m
Wave above the SWL, Percent	0.7	
Max. Surface Elevation	0.868	m
Elevation of the deck (SWL to bottom of the deck)	0	m
Dz Vertical Force	0.868	m
Dz Horizontal Force	0.868	
Deck Width	15.24	m
Deck Length	17.69	m
Deck Thickness	0.27	m
Deck Area (Av); Vertical Force	269.596	m^2
Deck Area (Ah); Horizontal Force	4.776	m^2
Number of Girders	1	

Force Calculations:

Fz=	2.35E+03	KN
Fx=	4.17E+01	KN

Kahaluu Bridge; Case II

Wave forces calculated by use of ***Douglass et al. (2006)*** *empirical relations.*

Vertical Force Equation:

$$F_v = c_{v-va} * F_v^*$$
$$F_v^* = \gamma * (\Delta z_v) * A_v$$

Horizontal Force Equation:

$$F_h = [1 + C_r * (N - 1)] * c_{h-va} * F_h^*$$
$$F_h^* = \gamma * (\Delta z_h) * A_h$$

Constant Coefficients:

Cr	0.4	
Cv-va	1	Nonconserv.
Ch-va	1	Nonconserv.
ρ	1025	kg/m^3
g	9.81	m/s^2
γ	10055.25	kg/(m^2 s^2)

Bridge Dimensions and Wave Condition:

Water Depth	5.415	m
Wave Height/Water Depth	0.554	
Wave Height	3.000	m
Wave above the SWL, Percent (/100)	0.7	
Max. Surface Elevation	2.100	m
Elevation of the deck (SWL to bottom of the deck)	0	m
Dz Vertical Force	2.100	m
Dz Horizontal Force	2.860	
Deck Width	14.02	m
Deck Length	32.31	m
Deck Thickness	0.15	m
Deck Area (Av); Vertical Force	452.986	m^2
Deck Area (Ah); Horizontal Force	4.847	m^2
Number of Girders	8	
Girder height	1.37	m

Force Calculations:

Fz=	9.56E+03	KN
Fx=	5.30E+02	KN

Kahaluu Bridge; Case III

*Wave forces calculated by use of **Douglass et al. (2006)** empirical relations.*

Vertical Force Equation:

$$F_v = c_{v-va} * F_v^*$$
$$F_v^* = \gamma * (\Delta z_v) * A_v$$

Horizontal Force Equation:

$$F_h = [1 + C_r * (N - 1)] * c_{h-va} * F_h^*$$
$$F_h^* = \gamma * (\Delta z_h) * A_h$$

Constant Coefficients:

Cr	0.4	
Cv-va	1	Nonconserv.
Ch-va	1	Nonconserv.
ρ	1025	kg/m^3
g	9.81	m/s^2
γ	10055.25	kg/(m^2 s^2)

Bridge Dimensions and Wave Condition:

Water Depth	4.655	m
Wave Height/Water Depth	0.563	
Wave Height	2.620	m
Wave above the SWL, Percent (/100)	0.7	
Max. Surface Elevation	1.834	m
Elevation of the deck (SWL to bottom of the deck)	0.685	m
Dz Vertical Force	1.149	m
Dz Horizontal Force	1.834	
Deck Width	14.02	m
Deck Length	32.31	m
Deck Thickness	0.15	m
Deck Area (Av); Vertical Force	452.986	m^2
Deck Area (Ah); Horizontal Force	4.847	m^2
Number of Girders	8	
Girder height	1.37	m

Force Calculations:

Fz=	5.23E+03	KN
Fx=	3.40E+02	KN

Maipalaoa Bridge; Case II

Wave forces calculated by use of ***Douglass et al. (2006)*** *empirical relations.*

Vertical Force Equation:

$$F_v = c_{v-va} * F_v^*$$
$$F_v^* = \gamma * (\Delta z_v) * A_v$$

Horizontal Force Equation:

$$F_h = [1 + C_r * (N - 1)] * c_{h-va} * F_h^*$$
$$F_h^* = \gamma * (\Delta z_h) * A_h$$

Constant Coefficients:

Cr	0.4	
Cv-va	1	Nonconserv.
Ch-va	1	Nonconserv.
ρ	1025	kg/m^3
g	9.81	m/s^2
γ	10055.25	kg/(m^2 s^2)

Bridge Dimensions and Wave Condition:

Water Depth	3.89	m
Wave Height/Water Depth	0.545	
Wave Height	2.120	m
Wave above the SWL, Percent (/100)	0.7	
Max. Surface Elevation	1.484	m
Elevation of the deck (SWL to bottom of the deck)	0	m
Dz Vertical Force	1.484	m
Dz Horizontal Force	2.089	
Deck Width	19.61	m
Deck Length	15.26	m
Deck Thickness	0.25	m
Deck Area (Av); Vertical Force	299.249	m^2
Deck Area (Ah); Horizontal Force	3.815	m^2
Number of Girders	16	
Girder height	0.96	m

Force Calculations:

Fz=	4.47E+03	KN
Fx=	5.61E+02	KN

10 APPENDIX B: Force Calculations by use of the McPherson (2008) Method

New Makaha Stream Bridge

Wave forces calculated by use of ***McPherson (2006)*** *empirical relations.*

Vertical Force Equation:

- $F_{Total} = F_{Hydrostatic} + F_{Bridge} + F_{AirEntrapment}$

- $F_{Hydrostatic} = \gamma \delta_z A - F_w$

If $h \le h\_model$

$$F_w = \frac{1}{2}\gamma \delta A$$

- $F_{Bridge} = \gamma Vol_{Bridge}$
- $F_{AirEntrapment} = (n-1)0.5\gamma \delta_G A_G$

Horizontal Force Equation:

- $F_{Total} = F_{Hydrostatic\_Front} + F_{Hydrostatic\_Back}$

If $\eta_{max} < h_{deck}$

$F_{Hydrostatic\_Front} = 0.5 * (\eta_{max} + h - h_{girders}) H_{bridge} L_{bridge} \gamma$

If $SWL > h_{girders}$

$F_{Hydrostatic\_back} = 0.5(h - h_{girder})^2 L_{bridge} \gamma$

Constant Values:

ρ	1025	kg/m^3
g	9.81	m/s^2
γ	10055.25	kg/(m^2 s^2)

Bridge Dimensions and Wave Condition:

Water Depth	2.9	m
Wave Height/Water Depth	0.517	
Wave Height	1.500	m
Wave above the SWL, Percent (/100)	0.7	
Max. Surface Elevation	1.050	m
Elevation of the top of the deck (SWL to top of the deck)	0.305	m
Deck Width	14.27	m
Deck Length	21.34	m
Deck Thickness	0.61	m
Deck Area; Vertical Force	304.522	m^2
Deck Area; Horizontal Force	13.0174	m^2
Number of Girders	0	
h deck (seafloor to deck bottom)	2.5	m
h girder (seafloor to girder bottom)	2.5	m
D z Vertical Force	0.745	m
D z Horizontal Force	0.745	m

Vertical Force Calculations:

F w=	1140610	N
F Hydro=	1140610	N
F Bridge=	1867846	N
F Air=	0	N
Fz=	**3.01E+03**	KN

Horizontal Force Calculations:

F front=	94897.53	N
F back=	17166.32	N
Fx=	**1.12E+02**	KN

New South Punaluu Stream Bridge; Case II

Wave forces calculated by use of ***McPherson (2006)*** *empirical relations.*

Vertical Force Equation:

- $F_{Total} = F_{Hydrostatic} + F_{Bridge} + F_{AirEntrapment}$

- $F_{Hydrostatic} = \gamma\delta_z A - F_w$

If $h \leq h\_model$

$$F_w = \frac{1}{2}\gamma\delta A$$

- $F_{Bridge} = \gamma Vol_{Bridge}$
- $F_{AirEntrapment} = (n-1)0.5\gamma\delta_G A_G$

Horizontal Force Equation:

- $F_{Total} = F_{Hydrostatic\_Front} + F_{Hydrostatic\_Back}$

If $\eta_{max} < h_{deck}$

$F_{Hydrostatic\_Front} = 0.5 * (\eta_{max} + h - h_{girders})H_{bridge}L_{bridge}\gamma$

If $SWL > h_{girders}$

$F_{Hydrostatic\_back} = 0.5(h - h_{girder})^2 L_{bridge}\gamma$

Constant Values:

ρ	1025	kg/m^3
g	9.81	m/s^2
γ	10055.25	kg/(m^2 s^2)

Bridge Dimensions and Wave Condition:

Water Depth	2.3	m
Wave Height/Water Depth	0.53913	
Wave Height	1.240	m
Wave above the SWL, Percent (/100)	0.7	
Max. Surface Elevation	0.868	m
Elevation of the top of the deck (SWL to top of the deck)	0	m
Deck Width	15.24	m
Deck Length	17.69	m
Deck Thickness	0.27	m
Deck Area; Vertical Force	269.596	m^2
Deck Area; Horizontal Force	4.7763	m^2
Number of Girders	0	
h deck (seafloor to deck bottom)	2.03	m
h girder (seafloor to girder bottom)	2.03	m
D z Vertical Force	0.868	m
D z Horizontal Force	0.868	m

Vertical Force Calculations:

F w=	1176508	N
F Hydro=	1176508	N
F Bridge=	731929.8	N
F Air=	0	N
Fz=	**1.91E+03**	KN

Horizontal Force Calculations:

F front=	27327.28	N
F back=	6483.63	N
Fx=	**3.38E+01**	KN

<u>Kahaluu Bridge; Case II</u>

Wave forces calculated by use of ***<u>McPherson (2006)</u>*** *empirical relations.*

Vertical Force Equation:

- $F_{Total} = F_{Hydrostatic} + F_{Bridge} + F_{AirEntrapment}$
- $F_{Hydrostatic} = \gamma \delta_z A - F_w$

  If $h \leq h\_model$

  $F_w = \frac{1}{2} \gamma \delta A$
- $F_{Bridge} = \gamma Vol_{Bridge}$
- $F_{AirEntrapment} = (n-1) 0.5 \gamma \delta_G A_G$

Horizontal Force Equation:

- $F_{Total} = F_{Hydrostatic\_Front} + F_{Hydrostatic\_Back}$

If $\eta_{max} < h_{deck}$

$F_{Hydrostatic\_Front} = 0.5 * (\eta_{max} + h - h_{girders}) H_{bridge} L_{bridge} \gamma$

If $SWL > h_{girders}$

$F_{Hydrostatic\_back} = 0.5 (h - h_{girder})^2 L_{bridge} \gamma$

Constant Values:

ρ	1025	kg/m^3
g	9.81	m/s^2
γ	10055.25	kg/(m^2 s^2)

Bridge Dimensions and Wave Condition:

Water Depth	5.415	m
Wave Height/Water Depth	0.554	
Wave Height	3.000	m
Wave above the SWL, Percent (/100)	0.7	
Max. Surface Elevation	2.100	m
Elevation of the top of the deck (SWL to top of the deck)	0.075	m
Deck Width	14.02	m
Deck Length	32.31	m
Deck Thickness	0.15	m
Deck Area; Vertical Force	452.986	m^2
Deck Area; Horizontal Force	4.8465	m^2
Number of Girders	8	
h deck (seafloor to deck bottom)	5.34	m
h girder (seafloor to girder bottom)	3.97	m
Girder height	1.37	m
Girder width	0.58	m
D z Vertical Force	2.025	m
D z Horizontal Force	2.710	m

Vertical Force Calculations:

F w=	4611682	N
F Hydro=	4611682	N
F Bridge=	2748463	N
F Air=	0	N
Fz=	**7.36E+03**	KN

Horizontal Force Calculations:

F front=	1412310	N
F back=	339184.1	N
Fx=	**1.75E+03**	KN

Kahaluu Bridge; Case III

Wave forces calculated by use of ***McPherson (2006)*** *empirical relations.*

Vertical Force Equation:

- $F_{Total} = F_{Hydrostatic} + F_{Bridge} + F_{AirEntrapment}$

- $F_{Hydrostatic} = \gamma \delta_z A - F_w$

If $h \leq h\_model$

$$F_w = \frac{1}{2}\gamma \delta A$$

- $F_{Bridge} = \gamma Vol_{Bridge}$
- $F_{AirEntrapment} = (n-1) 0.5 \gamma \delta_G A_G$

Horizontal Force Equation:

- $F_{Total} = F_{Hydrostatic\_Front} + F_{Hydrostatic\_Back}$

If $\eta_{max} < h_{deck}$

$F_{Hydrostatic\_Front} = 0.5 * (\eta_{max} + h - h_{girders}) H_{bridge} L_{bridge} \gamma$

If $SWL > h_{girders}$

$F_{Hydrostatic\_back} = 0.5(h - h_{girder})^2 L_{bridge} \gamma$

Constant Values:

ρ	1025	kg/m^3
g	9.81	m/s^2
γ	10055.25	kg/(m^2 s^2)

Bridge Dimensions and Wave Condition:

Water Depth	4.655	m
Wave Height/Water Depth	0.563	
Wave Height	2.620	m
Wave above the SWL, Percent (/100)	0.7	
Max. Surface Elevation	1.834	m
Elevation of the top of the deck (SWL to top of the deck)	0.835	m
Deck Width	14.02	m
Deck Length	32.31	m
Deck Thickness	0.15	m
Deck Area; Vertical Force	452.986	m^2
Deck Area; Horizontal Force	4.8465	m^2
Number of Girders	8	
h deck (seafloor to deck bottom)	5.34	m
h girder (seafloor to girder bottom)	3.97	m
Girder height	1.37	m
Girder width	0.58	m
D z Vertical Force	0.999	m
D z Horizontal Force	1.684	m

Vertical Force Calculations:

F w=	2275170	N
F Hydro=	2275170	N
F Bridge=	2748463	N
F Air=	0	N
Fz=	**5.02E+03**	KN

Horizontal Force Calculations:

F front=	905676.3	N
F back=	76222.11	N
Fx=	**9.82E+02**	KN

Maipalaoa Bridge; Case II

Wave forces calculated by use of ***McPherson (2006)*** *empirical relations.*

Vertical Force Equation:

- $F_{Total} = F_{Hydrostatic} + F_{Bridge} + F_{AirEntrapment}$

- $F_{Hydrostatic} = \gamma \delta_g A - F_w$

If $h \leq h\_model$

$$F_w = \frac{1}{2}\gamma \delta A$$

- $F_{Bridge} = \gamma Vol_{Bridge}$
- $F_{AirEntrapment} = (n-1)0.5\gamma \delta_G A_G$

Horizontal Force Equation:

- $F_{Total} = F_{Hydrostatic\_Front} + F_{Hydrostatic\_Back}$

If $\eta_{max} < h_{deck}$

$F_{Hydrostatic\_Front} = 0.5 * (\eta_{max} + h - h_{girders}) H_{bridge} L_{bridge} \gamma$

If $SWL > h_{girders}$

$F_{Hydrostatic\_back} = 0.5(h - h_{girder})^2 L_{bridge} \gamma$

Constant Values:

ρ	1025	kg/m^3
g	9.81	m/s^2
γ	10055.25	kg/(m^2 s^2)

Bridge Dimensions and Wave Condition:

Water Depth	3.89	m
Wave Height/Water Depth	0.545	
Wave Height	2.120	m
Wave above the SWL, Percent (/100)	0.7	
Max. Surface Elevation	1.484	m
Elevation of the top of the deck (SWL to top of the deck)	0.12	m
Deck Width	19.61	m
Deck Length	15.26	m
Deck Thickness	0.25	m
Deck Area; Vertical Force	299.249	m^2
Deck Area; Horizontal Force	3.815	m^2
Number of Girders	16	
h deck (seafloor to deck bottom)	3.76	m
h girder (seafloor to girder bottom)	2.8	m
Girder height	0.96	m
Girder width	0.2	m
D z Vertical Force	1.364	m
D z Horizontal Force	1.844	m

Vertical Force Calculations:

F w=	2052151	N
F Hydro=	2052151	N
F Bridge=	1223632	N
F Air=	0	N
Fz=	**3.28E+03**	KN

Horizontal Force Calculations:

F front=	388784.9	N
F back=	91152.88	N
Fx=	**4.80E+02**	KN

11 APPENDIX C: Force Calculations by use of the AASHTO (2008) Method

New Makaha Stream Bridge

Wave forces calculated by use of ***AASHTO*** *empirical relations.*

Constant Coefficients:

specific weight water =	0.064	kip/cubic ft
g =	32.2	ft/sec^2

♦ **Wave Calculations:**

● **Bridge Properties:**

Bridge Deck Width =	46.83	ft	Water Depth =	9.51	ft
Bridge Deck Length =	70.00	ft	Water surface to bot. of girder =	-1.31	ft
Girder to Girder Width =	46.83	ft	Height of girder =	0.00	ft
Deck Thickness =	2.00	ft	Height of railing =	0.00	ft
Av =	3278.33	sq ft	Elevation to bot. of girder =	8.20	ft
N =	0	girders	Elevation to bot. of deck =	8.20	ft

● **Wave Condition**		
Tp =	5.50	sec
Hmax =	4.92	ft
Wave Length (λ) =	98.03	ft
η max =	3.44	ft

■ **Maximum Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO Sec 6.1.2.2)*

● **Maximum Quasi-Static Vertical Force:** *(AASHTO Sec 6.1.2.2.1)*

○ **Determination of Fv-max parameters:** *(eq 6.1.2.2.1-1)*

W_hat =	75.20	ft				
W_hat / W =	1.61		>	0.15	Therefore W_hat = W_hat	
W_hat =	75.20	ft				
η max - Zc =	4.76		>	db =	2.00	ft

β =	1.00					
				λ =	98.03	ft
x =	0.0501887			Hmax =	4.92	ft
				ηmax =	3.44	ft
y =	0.7670732			W =	46.83	ft
				W* =	46.83	ft

For Slab Spans: *(eq 6.1.2.2.1 b)*

				ds =	9.51	ft
b0 =	-0.2364	b4 =	-0.00082	Zc =	-1.31	ft
b1 =	30.88	b5 =	1.3972	dg=	0.00	ft
b2 =	0.053	b6 =	21.4	r =	0.00	ft
b3 =	-38.86			db =	2.00	ft

Tapped Air Factor:

A_air = 0.0046755
B_air = 0.5056779

(η max - Zc) / dg = #DIV/0! #DIV/0! 1
%Air = variable

However, the bridge is not a girder type bridge therefore:

%Air = 0

TAF = 1 > 1 (O.K.)
TAF = 1

Quasi-Static Vertical Force: *(eq 6.1.2.2.1-1)*

Fv-max = 7.5898086 kip/ft

Length of Bridge = 70.00 ft
Fv-max Total = 531.29 kips 265.64 tons

- **Associated Vertical Slamming Force:** *(AASHTO Sec 6.1.2.2.2)*

B = -1.3019071

Zc / η max = -0.3815331 < 0
A = 0.0259152

Vertical Slamming Force: *(eq 6.1.2.2.2-1)*

Fs = 1.9740319 kip/ft

Length of Bridge =	70.00	ft		
Fs Total =	138.18	kips	69.09	tons

- **<u>Associated Horizontal Quasi-Static Wave Force:</u>** *(AASHTO Sec 6.1.2.2.3)*

  *Note: Girders used on the New Makaha #3A Bridge are similar to 36 in Adjacent Box Girders)

<u>From Table 6.1.2.2.3-1:</u> *(for Box Girders)*

a0 =	-0.0304	a5 =	0.0025
a1 =	1.4247	a6 =	0.0403
a2 =	-1.1168	a7 =	0.5503
a3 =	0.3455	a8 =	-0.3612
a4 =	-0.048		

x = 2.379

y = 0.0501887

<u>Horizontal Quasi-Static Wave Force:</u> (*eq 6.1.2.2.3)*

Fh-av = 0.1302662 kip/ft

Length of Bridge =	70.00	ft		
Fh-av Total =	9.12	kips	4.56	tons

- **<u>Associated Moment about the Trailing Edge Due to the Quasi-static and Slamming Forces:</u>** *(AASHTO Sec 6.1.2.2.4)*

<u>For Slab Spans:</u>

a_m =	0.8148	ft
b_m =	-0.0387	ft
c_m =	-0.0049	ft
W' =	0.00	ft
W* =	46.83	ft

<u>Associated Moment about Trailing Edge:</u> *(eq 6.1.2.2.4-1)*

Mt-av = 61.80 (kip/ft)-ft

Length of Bridge =	70.00	ft		
Mt-av Total =	4325.96	kip-ft	2162.98	tons-ft

● **Resulting Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.2)*

Fv-max Total =	531.29	kips	*(Quasi-Static Vertical Force)*
Fs Total =	138.18	kips	*(Vertical Slamming Force)*
Fh-av Total =	9.12	kips	*(Quasi-Static Horizontal Force)*
Mt-av =	4325.96	kip-ft	*(Associated Moment about Trailing Edge)*

● **Resulting Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.2)*

Fv-max Total =	2.36E+03	KN	*(Quasi-Static Vertical Force)*
Fs Total =	6.15E+02	KN	*(Vertical Slamming Force)*
Fh-av Total =	4.06E+01	KN	*(Quasi-Static Horizontal Force)*

■ **Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO Sec 6.1.2.3)*

● **Maximum Horizontal Wave Force:** *(AASHTO Sec 6.1.2.3.1)*

ω check: *(eq 6.1.2.3.1-3 or eq 6.1.2.3.1-4)*

check = 86.61 > W = 46.83 ft Use eq 6.1.2.3.1-4 for omega

ω = 46.83 ft

Reference Horizontal Force: *(eq 6.1.2.3.1-2)*

F*h-max = 0.99 kip/ft

Horizontal Wave Force: *(eq 6.1.2.3.1-1)*

Fh-max = 0.2086972 kip/ft

Length of Bridge = 70.00 ft

Fh-max Total = 14.61 kip 7.30 tons

● **Associated Quasi-Static Vertical Force:** *(AASHTO Sec 6.1.2.3.2)*

α check: *(eq 6.1.2.3.2-3 or eq 6.1.2.3.2-4)*

check = 28.92 < W = 46.83 ft Use eq 6.1.2.3.2-3 for alpha

α = 28.92 ft

Reference Vertical Force: *(eq 6.1.2.3.2-2)*
F*v-ah = 8.81 kip/ft

Quasi-Static Vertical Wave Force: *(eq 6.1.2.3.2-1)*
Fv-ah = 4.1845358 kip/ft

Length of Bridge = 70.00 ft
Fv-ah Total = 292.92 kip 146.46 tons

• **Associated Vertical Slamming Forces:** *(AASHTO Sec 6.1.2.3.3)*
*Note: Slamming force is calculated using the same method as AASHTO sec 6.1.2.2.2)

Vertical Slamming Force: *(eq 6.1.2.2.2-1)*
Fs = 1.9740319 kip/ft

Length of Bridge = 70.00 ft
Fs Total = 138.18 kips 69.09 tons

• **Associated Moment About Trailing Edge:** *(AASHTO Sec 6.1.2.3.4)*

Reference Moment: *(eq 6.1.2.3.4-2)*
M*t-ah = 192.70156 (kip/ft)-ft

Associated Moment about Trailing Edge: *(eq 6.1.2.3.4-1)*
Mt-ah = 104.86674 (kip/ft)-ft

Length of Bridge = 70.00 ft
Mt-ah Total = 7340.67 kip-ft 3670.34 ton-ft

• **Resulting Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.3)*

Fh-max Total =	14.61	kips	*(Maximum Horizontal Wave Force)*
Fv-ah Total =	292.92	kips	*(Quasi-Static Vertical Force)*
Fs Total =	138.18	kips	*(Vertical Slamming Force)*

Mt-ah Total =	7340.67	kip-ft	*(Associated Moment about Trailing Edge)*

• **<u>Resulting Maximum Horizontal Wave Force and Associated Forces and Moments:</u>** *(AASHTO sec 6.1.2.3)*

Fh-max Total =	6.50E+01	KN	*(Maximum Horizontal Wave Force)*
Fv-ah Total =	1.30E+03	KN	*(Quasi-Static Vertical Force)*
Fs Total =	6.15E+02	KN	*(Vertical Slamming Force)*

New South Punaluu Bridge; Case II

Wave forces calculated by use of ***AASHTO*** *empirical relations.*

Constant Coefficients:

specific weight water =	0.064	kip/cubic ft
g =	32.2	ft/sec^2

♦ **Wave Calculations:**

● **Bridge Properties:**

Bridge Deck Width =	50.00	ft	Water Depth =	7.55	ft
Bridge Deck Length =	58.03	ft	Water surface to bot. of girder =	-0.88	ft
Girder to Girder Width =	58.03	ft	Height of girder =	0.00	ft
Deck Thickness =	0.88	ft	Height of railing =	0.00	ft
Av =	2901.50	sq ft	Elevation to bot. of girder =	6.67	ft
N =	0	girders	Elevation to bot. of deck =	6.67	ft

● Wave Condition		
Tp =	5.00	sec
Hmax =	4.07	ft
Wave Length (λ) =	80.38	ft
η max =	2.85	ft

■ **Maximum Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO Sec 6.1.2.2)*

● **Maximum Quasi-Static Vertical Force:** *(AASHTO Sec 6.1.2.2.1)*

○ **Determination of Fv-max parameters:** *(eq 6.1.2.2.1-1)*

W_hat =	57.57	ft					
W_hat / W =	1.15		>	0.15	Therefore W_hat = W_hat		
W_hat =	57.57	ft					
η max - Zc =	3.73		>	db =	0.88	ft	
β =	4.26						
					λ =	80.38	ft
x =	0.050634486				Hmax =	4.07	ft

ηmax =	2.85	ft
W =	50.00	ft
W* =	58.03	ft
ds =	7.55	ft
Zc =	-0.88	ft
dg=	0.00	ft
r =	0.00	ft
db =	0.88	ft

y = 0.716216216

For Girder Spans: *(eq 6.1.2.2.1 a)*

b0 =	-0.588	b4 =	-0.0003
b1 =	56.7	b5 =	-0.608
b2 =	0.0454	b6 =	1.56
b3 =	-193.6		

Tapped Air Factor:

A_air = 0.005506814

B_air = 0.410222466

(η max - Zc) / dg = #DIV/0! #DIV/0! 1

%Air = 100.00

However, we assume that the bridge is not a girder type bridge therefore:

%Air = 0

TAF = 0.410222466 < 1 (O.K.)

TAF = 0.410222466

Quasi-Static Vertical Force: *(eq 6.1.2.2.1-1)*

Fv-max = 12.85154505 kip/ft

Length of Bridge = 58.03 ft

Fv-max Total = 745.78 kips 372.89 tons

● **Associated Vertical Slamming Force:** *(AASHTO Sec 6.1.2.2.2)*

B = -1.29595279

Zc / η max = -0.30888031 < 0

A = 0.026997683

Vertical Slamming Force: *(eq 6.1.2.2.2-1)*

Fs = 1.36669493 kip/ft

Length of Bridge = 58.03 ft

Fs Total =	79.31	kips	39.65	tons

- **Associated Horizontal Quasi-Static Wave Force:** *(AASHTO Sec 6.1.2.2.3)*

*Note: Girders used on the New South Punaluu Bridge are similar to the AASHTO Type III)

From Table 6.1.2.2.3-1: *(for AASHTO Type III Girder)*

a0 =	-0.0938	a5 =	0.0054
a1 =	1.6197	a6 =	0.019
a2 =	-1.4792	a7 =	0.6044
a3 =	0.5367	a8 =	-0.283
a4 =	-0.0877		

x = 4.261714286

y = 0.050634486

Horizontal Quasi-Static Wave Force: (*eq 6.1.2.2.3)*

Fh-av = 0.041082889 kip/ft

Length of Bridge =	58.03	ft		
Fh-av Total =	2.38	kips	1.19	tons

- **Associated Moment about the Trailing Edge Due to the Quasi-static and Slamming Forces:** *(AASHTO Sec 6.1.2.2.4)*

For Girder Spans:

a_m =	0.9150625	ft
b_m =	-0.08663375	ft
c_m =	-0.00330475	ft
W' =	-8.03	ft
W* =	58.03	ft

Associated Moment about Trailing Edge: *(eq 6.1.2.2.4-1)*

Mt-av = -20.43 (kip/ft)-ft

Length of Bridge =	58.03	ft		
Mt-av Total =	-1185.33	kip-ft	-592.66	tons-ft

● **Resulting Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.2)*

Fv-max Total =	745.78	kips	*(Quasi-Static Vertical Force)*
Fs Total =	79.31	kips	*(Vertical Slamming Force)*
Fh-av Total =	2.38	kips	*(Quasi-Static Horizontal Force)*
Mt-av =	-1185.33	kip-ft	*(Associated Moment about Trailing Edge)*

● **Resulting Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.2)*

Fv-max Total =	3.32E+03	KN	*(Quasi-Static Vertical Force)*
Fs Total =	3.53E+02	KN	*(Vertical Slamming Force)*
Fh-av Total =	1.06E+01	KN	*(Quasi-Static Horizontal Force)*

■ **Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO Sec 6.1.2.3)*

● **Maximum Horizontal Wave Force:** *(AASHTO Sec 6.1.2.3.1)*

ω check: *(eq 6.1.2.3.1-3 or eq 6.1.2.3.1-4)*

check = 68.97 > W = 50.00 ft Use eq 6.1.2.3.1-4 for omega

ω = 50.00 ft

Reference Horizontal Force: *(eq 6.1.2.3.1-2)*

F*h-max = 0.46 kip/ft

Horizontal Wave Force: *(eq 6.1.2.3.1-1)*

Fh-max = 0.019706412 kip/ft

Length of Bridge = 58.03 ft

Fh-max Total = 1.14 kip 0.57 tons

● **Associated Quasi-Static Vertical Force:** *(AASHTO Sec 6.1.2.3.2)*

α check: *(eq 6.1.2.3.2-3 or eq 6.1.2.3.2-4)*

check = 22.14 < W = 50.00 ft Use eq 6.1.2.3.2-3 for alpha

α = 22.14 ft

Reference Vertical Force: *(eq 6.1.2.3.2-2)*

F*v-ah =	5.28	kip/ft

Quasi-Static Vertical Wave Force: *(eq 6.1.2.3.2-1)*

Fv-ah =	0.466050195	kip/ft

Length of Bridge =	58.03	ft		
Fv-ah Total =	27.04	kip	13.52	tons

● **Associated Vertical Slamming Forces:** *(AASHTO Sec 6.1.2.3.3)*

*Note: Slamming force is calculated using the same method as AASHTO sec 6.1.2.2.2)

Vertical Slamming Force: *(eq 6.1.2.2.2-1)*

Fs =	1.36669493	kip/ft

Length of Bridge =	58.03	ft		
Fs Total =	79.31	kips	39.65	tons

● **Associated Moment About Trailing Edge:** *(AASHTO Sec 6.1.2.3.4)*

Reference Moment: *(eq 6.1.2.3.4-2)*

M*t-ah =	61.1087473	(kip/ft)-ft

Associated Moment about Trailing Edge: *(eq 6.1.2.3.4-1)*

Mt-ah =	19.2916688	(kip/ft)-ft

Length of Bridge =	58.03	ft		
Mt-ah Total =	1119.50	kip-ft	559.75	ton-ft

● **Resulting Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.3)*

Fh-max Total =	1.14	kips	*(Maximum Horizontal Wave Force)*
Fv-ah Total =	27.04	kips	*(Quasi-Static Vertical Force)*
Fs Total =	79.31	kips	*(Vertical Slamming Force)*

Mt-ah Total =	1119.50	kip-ft	*(Associated Moment about Trailing Edge)*

• **Resulting Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.3)*

Fh-max Total =	5.09E+00	KN	*(Maximum Horizontal Wave Force)*
Fv-ah Total =	1.20E+02	KN	*(Quasi-Static Vertical Force)*
Fs Total =	3.53E+02	KN	*(Vertical Slamming Force)*

Kahaluu Bridge; Case II

Wave forces calculated by use of ***AASHTO*** *empirical relations.*

Constant Coefficients:

specific weight water =	0.064	kip/cubic ft
g =	32.2	ft/sec^2

♦ **Wave Calculations:**

● **Bridge Properties:**

Bridge Deck Width =	46.00	ft	Water Depth =	17.76	ft
Bridge Deck Length =	106.00	ft	Water surface to bot. of girder =	-4.73	ft
Girder to Girder Width =	42.60	ft	Height of girder =	4.50	ft
Deck Thickness =	0.50	ft	Height of railing =	0.00	ft
Av =	4876.00	sq ft	Elevation to bot. of girder =	13.03	ft
N =	8	girders	Elevation to bot. of deck =	17.53	ft

● **Wave Condition**		
Tp =	6.50	sec
Hmax =	9.84	ft
Wave Length (λ) =	152.26	ft
η max =	6.89	ft

■ **Maximum Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO Sec 6.1.2.2)*

● **Maximum Quasi-Static Vertical Force:** *(AASHTO Sec 6.1.2.2.1)*

○ **Determination of Fv-max parameters:** *(eq 6.1.2.2.1-1)*

W_hat =	149.32	ft				
W_hat / W =	3.25		>	0.15	Therefore W_hat = W_hat	
W_hat =	149.32	ft				
η max - Zc =	11.62		>	db =	5.00	ft
β =	2.32					

λ = 152.26 ft

x =	0.0646263			Hmax =	9.84	ft
				ηmax =	6.89	ft
y =	0.9806911			W =	46.00	ft
				W* =	42.60	ft

For Girder Spans: *(eq 6.1.2.2.1 a)*

b0 =	-1.038	b4 =	-0.00057	ds =	17.76	ft
b1 =	55.89	b5 =	0.22	Zc =	-4.73	ft
b2 =	0.058	b6 =	11.01	dg=	4.50	ft
b3 =	-192.5416			r =	0.00	ft
				db =	5.00	ft

Tapped Air Factor:

A_air = 0.0016821
B_air = 1.0268486

(η max - Zc) / dg = 2.5817778 > 1
%Air = 100.00

However, diaphragm of bridge extends to the bottom of the girders at abutments, therefore:
%Air = 100

TAF = 1.1950583 > 1 (N.G.) set TAF = 1
TAF = 1

Quasi-Static Vertical Force: *(eq 6.1.2.2.1-1)*

Fv-max = 50.38325 kip/ft

Length of Bridge = 106.00 ft
Fv-max Total = 5340.62 kips 2670.31 tons

- **Associated Vertical Slamming Force:** *(AASHTO Sec 6.1.2.2.2)*

B = -1.2509583

Zc / η max = -0.6867015 < 0
A = 0.0213681

Vertical Slamming Force: *(eq 6.1.2.2.2-1)*

Fs = 4.0744169 kip/ft

Length of Bridge = 106.00 ft

Fs Total = 431.89 kips 215.94 tons

- **<u>Associated Horizontal Quasi-Static Wave Force:</u>** *(AASHTO Sec 6.1.2.2.3)*
  *Note: Girders used on the Kahaluu Bridge are AASHTO Type IV)

<u>From Table 6.1.2.2.3-1:</u> *(for AASHTO Type IV Girder)*

a0 =	-0.0911	a5 =	0.0048
a1 =	1.5445	a6 =	0.0113
a2 =	-1.4684	a7 =	0.6785
a3 =	0.54	a8 =	-0.2661
a4 =	-0.0861		

x = 2.3236

y = 0.0646263

<u>Horizontal Quasi-Static Wave Force:</u> (*eq 6.1.2.2.3)*
Fh-av = 0.4761304 kip/ft

Length of Bridge = 106.00 ft
Fh-av Total = 50.47 kips 25.23 tons

- **<u>Associated Moment about the Trailing Edge Due to the Quasi-static and Slamming Forces:</u>** *(AASHTO Sec 6.1.2.2.4)*

<u>For Girder Spans:</u>

a_m = 0.8635 ft
b_m = -0.05945 ft
c_m = -0.00427 ft
W' = 3.40 ft
W* = 42.60 ft

<u>Associated Moment about Trailing Edge:</u> *(eq 6.1.2.2.4-1)*
Mt-av = 220.04 (kip/ft)-ft

Length of Bridge = 106.00 ft
Mt-av Total = 23323.84 kip-ft 11661.92 tons-ft

- **<u>Resulting Quasi-Static Vertical Force and Associated Forces and Moments:</u>** *(AASHTO sec 6.1.2.2)*

Fv-max Total =	5340.62	kips	*(Quasi-Static Vertical Force)*
Fs Total =	431.89	kips	*(Vertical Slamming Force)*
Fh-av Total =	50.47	kips	*(Quasi-Static Horizontal Force)*
Mt-av =	23323.84	kip-ft	*(Associated Moment about Trailing Edge)*

● **Resulting Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.2)*

Fv-max Total =	2.38E+04	KN	*(Quasi-Static Vertical Force)*
Fs Total =	1.92E+03	KN	*(Vertical Slamming Force)*
Fh-av Total =	2.25E+02	KN	*(Quasi-Static Horizontal Force)*

■ **Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO Sec 6.1.2.3)*

● **Maximum Horizontal Wave Force:** *(AASHTO Sec 6.1.2.3.1)*

ω check: *(eq 6.1.2.3.1-3 or eq 6.1.2.3.1-4)*

check = 150.79 > W = 46.00 ft Use eq 6.1.2.3.1-4 for omega

ω = 46.00 ft

Reference Horizontal Force: *(eq 6.1.2.3.1-2)*

F*h-max = 3.31 kip/ft

Horizontal Wave Force: *(eq 6.1.2.3.1-1)*

Fh-max = 1.1282913 kip/ft

Length of Bridge = 106.00 ft

Fh-max Total = 119.60 kip 59.80 tons

● **Associated Quasi-Static Vertical Force:** *(AASHTO Sec 6.1.2.3.2)*

α check: *(eq 6.1.2.3.2-3 or eq 6.1.2.3.2-4)*

check = 57.43 > W = 46.00 ft Use eq 6.1.2.3.2-4 for alpha

α = 57.43 ft

Reference Vertical Force: *(eq 6.1.2.3.2-2)*

F*v-ah = 42.70 kip/ft

Quasi-Static Vertical Wave Force: *(eq 6.1.2.3.2-1)*

Fv-ah = 19.215896 kip/ft

Length of Bridge = 106.00 ft

Fv-ah Total = 2036.88 kip 1018.44 tons

- **Associated Vertical Slamming Forces:** *(AASHTO Sec 6.1.2.3.3)*

*Note: Slamming force is calculated using the same method as AASHTO sec 6.1.2.2.2)

Vertical Slamming Force: *(eq 6.1.2.2.2-1)*

Fs = 4.0744169 kip/ft

Length of Bridge = 106.00 ft

Fs Total = 431.89 kips 215.94 tons

- **Associated Moment About Trailing Edge:** *(AASHTO Sec 6.1.2.3.4)*

Reference Moment: *(eq 6.1.2.3.4-2)*

M*t-ah = 719.87772 (kip/ft)-ft

Associated Moment about Trailing Edge: *(eq 6.1.2.3.4-1)*

Mt-ah = 400.04321 (kip/ft)-ft

Length of Bridge = 106.00 ft

Mt-ah Total = 42404.58 kip-ft 21202.29 ton-ft

- **Resulting Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.3)*

Fh-max Total =	119.60	kips	*(Maximum Horizontal Wave Force)*
Fv-ah Total =	2036.88	kips	*(Quasi-Static Vertical Force)*
Fs Total =	431.89	kips	*(Vertical Slamming Force)*
Mt-ah Total =	42404.58	kip-ft	*(Associated Moment about Trailing Edge)*

• **Resulting Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.3)*

Fh-max Total =	5.32E+02	KN	*(Maximum Horizontal Wave Force)*
Fv-ah Total =	9.06E+03	KN	*(Quasi-Static Vertical Force)*
Fs Total =	1.92E+03	KN	*(Vertical Slamming Force)*

Kahaluu Bridge; Case III

*Wave forces calculated by use of **AASHTO** empirical relations.*

Constant Coefficients:

specific weight water =	0.064	kip/cubic ft
g =	32.2	ft/sec^2

♦ **Wave Calculations:**

● **Bridge Properties:**

Bridge Deck Width =	46.00	ft	Water Depth =	15.27	ft
Bridge Deck Length =	106.00	ft	Water surface to bot. of girder =	-2.25	ft
Girder to Girder Width =	42.60	ft	Height of girder =	4.50	ft
Deck Thickness =	0.50	ft	Height of railing =	0.00	ft
Av =	4876.00	sq ft	Elevation to bot. of girder =	13.02	ft
N =	8	girders	Elevation to bot. of deck =	17.52	ft

● **Wave Condition**		
Tp =	6.00	sec
Hmax =	8.60	ft
Wave Length (λ) =	130.45	ft
η max =	6.02	ft

■ **Maximum Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO Sec 6.1.2.2)*

● **Maximum Quasi-Static Vertical Force:** *(AASHTO Sec 6.1.2.2.1)*

○ **Determination of Fv-max parameters:** *(eq 6.1.2.2.1-1)*

W_hat =	99.35	ft				
W_hat / W =	2.16		>	0.15	Therefore W_hat = W_hat	
W_hat =	99.35	ft				
η max - Zc =	8.27		>	db =	5.00	ft
β =	1.65					

				λ =	130.45	ft
x =	0.0659256			Hmax =	8.60	ft
				ηmax =	6.02	ft
y =	0.7616279			W =	46.00	ft
				W* =	42.60	ft

For Girder Spans: *(eq 6.1.2.2.1 a)*

b0 =	-1.038	b4 =	-0.00057	ds =	15.27	ft
b1 =	55.89	b5 =	0.22	Zc =	-2.25	ft
b2 =	0.058	b6 =	11.01	dg=	4.50	ft
b3 =	-192.5416			r =	0.00	ft
				db =	5.00	ft

Tapped Air Factor:

A_air = 0.0043014
B_air = 0.5650465

(η max - Zc) / dg = 1.8377778 > 1
%Air = 100.00

However, diaphragm of bridge extends to the bottom of the girders at abutments, therefore:

%Air = 100

TAF = 0.9951867 < 1 (O.K.)
TAF = 0.9951867

Quasi-Static Vertical Force: *(eq 6.1.2.2.1-1)*

Fv-max = 22.347105 kip/ft

Length of Bridge = 106.00 ft
Fv-max Total = 2368.79 kips 1184.40 tons

● **Associated Vertical Slamming Force:** *(AASHTO Sec 6.1.2.2.2)*

B = -1.301602

Zc / η max = -0.3737542 < 0
A = 0.0260311

Vertical Slamming Force: *(eq 6.1.2.2.2-1)*

Fs = 4.2441431 kip/ft

Length of Bridge =	106.00	ft		
Fs Total =	449.88	kips	224.94	tons

- **Associated Horizontal Quasi-Static Wave Force:** *(AASHTO Sec 6.1.2.2.3)*
  *Note: Girders used on the Kahaluu Bridge are AASHTO Type IV)

From Table 6.1.2.2.3-1: *(for AASHTO Type IV Girder)*

a0 =	-0.0911	a5 =	0.0048
a1 =	1.5445	a6 =	0.0113
a2 =	-1.4684	a7 =	0.6785
a3 =	0.54	a8 =	-0.2661
a4 =	-0.0861		

x = 1.654

y = 0.0659256

Horizontal Quasi-Static Wave Force: (*eq 6.1.2.2.3)*

Fh-av = 0.7586112 kip/ft

Length of Bridge =	106.00	ft		
Fh-av Total =	80.41	kips	40.21	tons

- **Associated Moment about the Trailing Edge Due to the Quasi-static and Slamming Forces:** *(AASHTO Sec 6.1.2.2.4)*

For Girder Spans:

a_m =	0.8635	ft
b_m =	-0.05945	ft
c_m =	-0.00427	ft
W' =	3.40	ft
W* =	42.60	ft

Associated Moment about Trailing Edge: *(eq 6.1.2.2.4-1)*

Mt-av = 170.80 (kip/ft)-ft

Length of Bridge =	106.00	ft		
Mt-av Total =	18104.99	kip-ft	9052.49	tons-ft

● **Resulting Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.2)*

Fv-max Total =	2368.79	kips	*(Quasi-Static Vertical Force)*
Fs Total =	449.88	kips	*(Vertical Slamming Force)*
Fh-av Total =	80.41	kips	*(Quasi-Static Horizontal Force)*
Mt-av =	18104.99	kip-ft	*(Associated Moment about Trailing Edge)*

● **Resulting Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.2)*

Fv-max Total =	1.05E+04	KN	*(Quasi-Static Vertical Force)*
Fs Total =	2.00E+03	KN	*(Vertical Slamming Force)*
Fh-av Total =	3.58E+02	KN	*(Quasi-Static Horizontal Force)*

■ **Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO Sec 6.1.2.3)*

● **Maximum Horizontal Wave Force:** *(AASHTO Sec 6.1.2.3.1)*

ω check: *(eq 6.1.2.3.1-3 or eq 6.1.2.3.1-4)*

check = 114.90 > W = 46.00 ft Use eq 6.1.2.3.1-4 for omega

ω = 46.00 ft

Reference Horizontal Force: *(eq 6.1.2.3.1-2)*

F*h-max = 3.33 kip/ft

Horizontal Wave Force: *(eq 6.1.2.3.1-1)*

Fh-max = 1.5314363 kip/ft

Length of Bridge = 106.00 ft

Fh-max Total = 162.33 kip 81.17 tons

● **Associated Quasi-Static Vertical Force:** *(AASHTO Sec 6.1.2.3.2)*

α check: *(eq 6.1.2.3.2-3 or eq 6.1.2.3.2-4)*

check = 38.21 < W = 46.00 ft Use eq 6.1.2.3.2-3 for alpha

α = 38.21 ft

Reference Vertical Force: *(eq 6.1.2.3.2-2)*
F*v-ah = 20.23 kip/ft

Quasi-Static Vertical Wave Force: *(eq 6.1.2.3.2-1)*
Fv-ah = 12.273529 kip/ft

Length of Bridge = 106.00 ft
Fv-ah Total = 1300.99 kip 650.50 tons

- **Associated Vertical Slamming Forces:** *(AASHTO Sec 6.1.2.3.3)*

*Note: Slamming force is calculated using the same method as AASHTO sec 6.1.2.2.2)

Vertical Slamming Force: *(eq 6.1.2.2.2-1)*
Fs = 4.2441431 kip/ft

Length of Bridge = 106.00 ft
Fs Total = 449.88 kips 224.94 tons

- **Associated Moment About Trailing Edge:** *(AASHTO Sec 6.1.2.3.4)*

Reference Moment: *(eq 6.1.2.3.4-2)*
M*t-ah = 514.19913 (kip/ft)-ft

Associated Moment about Trailing Edge: *(eq 6.1.2.3.4-1)*
Mt-ah = 380.6237 (kip/ft)-ft

Length of Bridge = 106.00 ft
Mt-ah Total = 40346.11 kip-ft 20173.06 ton-ft

- **Resulting Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.3)*

Fh-max Total =	162.33	kips	*(Maximum Horizontal Wave Force)*
Fv-ah Total =	1300.99	kips	*(Quasi-Static Vertical Force)*
Fs Total =	449.88	kips	*(Vertical Slamming Force)*

Mt-ah Total =	40346.11	kip-ft	*(Associated Moment about Trailing Edge)*

● **Resulting Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.3)*

Fh-max Total =	7.22E+02	KN	*(Maximum Horizontal Wave Force)*
Fv-ah Total =	5.79E+03	KN	*(Quasi-Static Vertical Force)*
Fs Total =	2.00E+03	KN	*(Vertical Slamming Force)*

Maipalaoa Bridge:

Method For Estimating Wave Forces on Bridge Superstructures

Constant Coefficients:

specific weight water =	0.064	kip/cubic ft
g =	32.2	ft/sec^2

♦ **Wave Calculations:**

● **Bridge Properties:**

Bridge Deck Width =	64.33	ft	Water Depth =	12.76	ft
Bridge Deck Length =	50.05	ft	Water surface to bot. of girder =	-3.57	ft
Girder to Girder Width =	60.69	ft	Height of girder =	3.15	ft
Deck Thickness =	0.83	ft	Height of railing =	0.00	ft
Av =	3219.88	sq ft	Elevation to bot. of girder =	9.19	ft
N =	16	girders	Elevation to bot. of deck =	12.34	ft

● Wave Condition		
Tp =	6.00	sec
Hmax =	6.70	ft
Wave Length (λ) =	122.67	ft
η max =	4.69	ft

■ **Maximum Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO Sec 6.1.2.2)*

● **Maximum Quasi-Static Vertical Force:** *(AASHTO Sec 6.1.2.2.1)*

○ **Determination of Fv-max parameters:** *(eq 6.1.2.2.1-1)*

W_hat =	126.70	ft				
W_hat / W =	1.97		>	0.15	Therefore W_hat = W_hat	
W_hat =	126.70	ft				
η max - Zc =	8.26		>	db =	3.98	ft
β =	2.08					
				λ =	122.67	ft
x =	0.05461808			Hmax =	6.70	ft

ηmax =	4.69	ft	
W =	64.33	ft	
W* =	60.69	ft	
ds =	12.76	ft	
Zc =	-3.57	ft	
dg=	3.15	ft	
r =	0.00	ft	
db =	3.98	ft	

y = 1.03283582

For Girder Spans: *(eq 6.1.2.2.1 a)*

b0 =	-0.903	b4 =	-0.00049
b1 =	56.133	b5 =	-0.0284
b2 =	0.05422	b6 =	8.175
b3 =	-192.85912		

Tapped Air Factor:

A_air = 0.00176267

B_air = 0.95907769

(η max - Zc) / dg = 2.62222222 > 1

%Air = -162.22

However, diaphragm of bridge extends to the bottom of the girders at abutments, therefore:

%Air = 100

TAF = 1.13534499 > 1 (N.G.) set TAF = 1

TAF = 1

Quasi-Static Vertical Force: *(eq 6.1.2.2.1-1)*

Fv-max = 32.3199359 kip/ft

Length of Bridge =	50.05	ft		
Fv-max Total =	1617.61	kips	808.81	tons

- **Associated Vertical Slamming Force:** *(AASHTO Sec 6.1.2.2.2)*

B = -1.2198895

Zc / η max = -0.761194 < 0

A = 0.02025821

Vertical Slamming Force: *(eq 6.1.2.2.2-1)*

Fs = 2.01948486 kip/ft

Length of Bridge =	50.05	ft		
Fs Total =	101.08	kips	50.54	tons

• **Associated Horizontal Quasi-Static Wave Force:** *(AASHTO Sec 6.1.2.2.3)*

*Note: Girders used on the Maipalaoa Bridge are similar to AASHTO Type III girders)

From Table 6.1.2.2.3-1: *(for AASHTO Type III)*

a0 =	-0.0938	a5 =	0.0054
a1 =	1.6197	a6 =	0.019
a2 =	-1.4792	a7 =	0.6044
a3 =	0.5367	a8 =	-0.283
a4 =	-0.0877		

x = 2.07537688

y = 0.05461808

Horizontal Quasi-Static Wave Force: (*eq 6.1.2.2.3)*

Fh-av = 0.28787475 kip/ft

Length of Bridge =	50.05	ft		
Fh-av Total =	14.41	kips	7.20	tons

• **Associated Moment about the Trailing Edge Due to the Quasi-static and Slamming Forces:** *(AASHTO Sec 6.1.2.2.4)*

For Girder Spans:

a_m =	0.87625	ft
b_m =	-0.0661718	ft
c_m =	-0.0040313	ft
W' =	3.64	ft
W* =	60.69	ft

Associated Moment about Trailing Edge: *(eq 6.1.2.2.4-1)*

Mt-av = 162.11 (kip/ft)-ft

Length of Bridge =	50.05	ft		
Mt-av Total =	8113.85	kip-ft	4056.93	tons-ft

• **Resulting Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.2)*

Fv-max Total =	1617.61	kips	*(Quasi-Static Vertical Force)*
Fs Total =	101.08	kips	*(Vertical Slamming Force)*
Fh-av Total =	14.41	kips	*(Quasi-Static Horizontal Force)*
Mt-av =	8113.85	kip-ft	*(Associated Moment about Trailing Edge)*

• **Resulting Quasi-Static Vertical Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.2)*

Fv-max Total =	7.20E+03	KN	*(Quasi-Static Vertical Force)*
Fs Total =	4.50E+02	KN	*(Vertical Slamming Force)*
Fh-av Total =	6.41E+01	KN	*(Quasi-Static Horizontal Force)*

■ **Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO Sec 6.1.2.3)*

• **Maximum Horizontal Wave Force:** *(AASHTO Sec 6.1.2.3.1)*

ω check: *(eq 6.1.2.3.1-3 or eq 6.1.2.3.1-4)*

check = 124.68 > W = 64.33 ft Use eq 6.1.2.3.1-4 for omega

ω = 64.33 ft

Reference Horizontal Force: *(eq 6.1.2.3.1-2)*

F*h-max = 2.96 kip/ft

Horizontal Wave Force: *(eq 6.1.2.3.1-1)*

Fh-max = 0.68634503 kip/ft

Length of Bridge = 50.05 ft

Fh-max Total = 34.35 kip 17.18 tons

• **Associated Quasi-Static Vertical Force:** *(AASHTO Sec 6.1.2.3.2)*

α check: *(eq 6.1.2.3.2-3 or eq 6.1.2.3.2-4)*

check = 48.73 < W = 64.33 ft Use eq 6.1.2.3.2-3 for alpha

α = 48.73 ft

Reference Vertical Force: *(eq 6.1.2.3.2-2)*

F*v-ah = 25.76 kip/ft

Quasi-Static Vertical Wave Force: *(eq 6.1.2.3.2-1)*
Fv-ah = 12.5207692 kip/ft

Length of Bridge = 50.05 ft
Fv-ah Total = 626.66 kip 313.33 tons

● **Associated Vertical Slamming Forces:** *(AASHTO Sec 6.1.2.3.3)*
*Note: Slamming force is calculated using the same method as AASHTO sec 6.1.2.2.2)

Vertical Slamming Force: *(eq 6.1.2.2.2-1)*
Fs = 2.01948486 kip/ft

Length of Bridge = 50.05 ft
Fs Total = 101.08 kips 50.54 tons

● **Associated Moment About Trailing Edge:** *(AASHTO Sec 6.1.2.3.4)*

Reference Moment: *(eq 6.1.2.3.4-2)*
M*t-ah = 626.346994 (kip/ft)-ft

Associated Moment about Trailing Edge: *(eq 6.1.2.3.4-1)*
Mt-ah = 384.18316 (kip/ft)-ft

Length of Bridge = 50.05 ft
Mt-ah Total = 19228.37 kip-ft 9614.18 ton-ft

● **Resulting Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.3)*

Fh-max Total =	34.35	kips	*(Maximum Horizontal Wave Force)*
Fv-ah Total =	626.66	kips	*(Quasi-Static Vertical Force)*
Fs Total =	101.08	kips	*(Vertical Slamming Force)*
Mt-ah Total =	19228.37	kip-ft	*(Associated Moment about Trailing Edge)*

● **Resulting Maximum Horizontal Wave Force and Associated Forces and Moments:** *(AASHTO sec 6.1.2.3)*

Fh-max Total =	1.53E+02	KN	*(Maximum Horizontal Wave Force)*
Fv-ah Total =	2.79E+03	KN	*(Quasi-Static Vertical Force)*
Fs Total =	4.50E+02	KN	*(Vertical Slamming Force)*