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Solitary, irregular and focused wave impact on coastal bridge deck for different airgaps.

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ABSTRACT

Coastal bridge decks are subjected to wave impact due to the action of extreme wave events like tsunami and storm surges. These events are more frequent in recent years and cause deck upliftment and destruction. Past studies mainly considered regular wave types to represent extreme wave events and the impact force is calculated. The main aim of the present study is to generate a focused wave to simulate an extreme wave condition in the numerical wave tank and to study the impact force on coastal bridge deck. Focused wave and irregular wave of same significant wave height and peak period are generated and comparison is done with solitary wave of same crest height to study the effects of different wave types on impact force. Focused wave height is giving higher impact force when comparing the irregular and solitary wave of same crest height.

Keywords: Focused wave, Air entrapment, Extreme waves, Wave impact.

RESUMEN

Las cubiertas de los puentes costeros están sujetas al impacto de las olas debido a la acción de eventos extremos de olas como tsunamis y marejadas ciclónicas. Estos eventos son más frecuentes en los últimos años y provocan el levantamiento y destrucción de la cubierta. Los estudios anteriores consideraron principalmente tipos de olas regulares para representar eventos de olas extremos y se calcula la fuerza de impacto. El objetivo principal del presente estudio es generar una ola enfocada para simular una condición de ola extrema en el tanque numérico de olas y estudiar la fuerza de impacto en el tablero del puente costero. Se generan una ola enfocada y una ola irregular de la misma altura de ola significativa y período pico y la comparación se hace con una ola solitaria de la misma altura de cresta para estudiar los efectos de diferentes tipos de olas sobre la fuerza de impacto. La altura de la ola enfocada proporciona una mayor fuerza de impacto cuando se compara la ola irregular y la solitaria de la misma altura de la cresta.

Palabras clave: Ola enfocada, Atrapamiento de aire, Olas extremas, Impacto de olas

INTRODUCTION

Coastal bridges are damaged due to tsunami and storm surge across the world, as these events make the waves capable to reach the deck. Numerous experimental and numerical studies have been carried out for developing hydrostatic and hydrodynamic formulations for estimating maximum vertical and horizontal impact forces on coastal decks. Kaplan (1995) derived a simplified formula to estimate wave in deck loading from his experimental results. Hydrostatic formulations were developed by Douglass (2006), McPherson (2008) and AASHTO (2010) for regular stokes and solitary waves for different airgaps. Xu et.al. (2016) conducted numerical studies using solitary wave force on elevated and submerged decks and developed an expanded equation for solitary wave force. The applicability of these theoretical formulations for different wave types needs detailed investigation.

Solitary, Cnoidal and stokes waves are used widely to represent the extreme events and to represent in experimental and numerical studies for studying the impact. Solitary wave impact on flat deck (Seiffert et al., 2014) and deck with girders (Hayatdavoodi et al., 2014) is done both experimentally and numerically considering different parameters. Azadbakht and Yim (2016) studied air entrapment effects using stokes fifth order wave by placing the structure bottom at SWL to obtain the maximum wave load increase due to air entrapment. But this wave types fail to represent the random irregular sea state (Hayatdavoodi et al. 2016).

Solitary waves and regular stokes waves are usually considered for representing extreme wave condition. Hu et al. (2016) used the NewWave concept developed by Ning et.al. (2008, 2009) to study the extreme wave impact on fixed/floating truncated cylinder, providing insight to the non-linear wave structure interaction due to transient wave groups loading on the structure. The applicability of focused wave is tested and proved for deep water (Bihs et.al., 2017) and it is used in intermediate water by Hunt-Raby et.al. (2011) to study the overtopping and runup. Focused wave represents the largest waves in a random sea state and considered as an alternative to irregular waves by saving computational effort.

In the present study, solitary, irregular and focused waves are considered to investigate the extreme wave impact on deck. Prediction of accurate maximum impact force due to extreme events can improve the design basics and parametric equations. Here the objective is to study the wave impact on elevated coastal bridge deck due to solitary, focused and irregular wave for different airgaps. The applicability of focused waves to represent the irregular waves are analyzed.

NUMERICAL MODEL

Numerical investigation is carried out using open source CFD model REEF3D (Bihs et al., 2016) to study the wave load on bridge deck. The incompressible unsteady Reynolds-Averaged Navier-Stokes (URANS) equations (equation 2) along with continuity equation (equation 1) are used to solve the flow dynamics with free surface. The investigations are carried out in a 2D frame work considering x (direction of wave propagation) and z direction (along the depth) as shown in figure 1.

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\nu + \nu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + g_i \qquad (2)$$

where ρ is the fluid density, p is the pressure, u is the velocity over time t, v is the kinematic viscosity, ϑ_t is the eddy viscosity and g the acceleration due to gravity.

The first step to solve the fluid flow problems represented by differential equations is to discretize the convective terms. Finite difference method in terms of conservative finite differences is used in REEF3D for the discretization. The Hamilton-Jacobi formulation of the WENO scheme is employed in the present study. Total Variance Diminishing (TVD) third order Runge-Kutta explicit Scheme is used for the discretization of time dependent terms. To maintain an adequate time step size using explicit methods, a condition called CFL (Courant-Frederick-Lewy) criterion is used. A signed distance function called Level Set function is employed in REEF3D to capture the free surface air water interface (Bihs et al., 2016). The movement of the interface is characterized by convection of the level set function using reinitialization technique.

NUMERICAL WAVE TANK

Numerical wave tank modelled using REEF3D is used to represent the experimental set up. Uniform cartesian staggered grids are used for spatial discretization. For 2D analysis, one mesh size (0.01 m) is considered as width of the wave tank. The physical processes at boundaries are represented using appropriate boundary conditions in the numerical wave tank as shown in Figure 1. Bottom of the numerical wave tank and the deck structure model are solid walls, for which wall boundary condition (BC1) is applied. For BC1, normal velocity is explicitly set to zero. Wave generation is from velocity inlet (BC2) where wave source is given using suitable wave theory. In 2D simulation top and the sides are specified with symmetry boundary condition (BC3). The free surface (air-water interface) is captured using the level set function; an interface capturing technique. The numerical wave tank is validated with experimental results by Moideen et al. (2019).

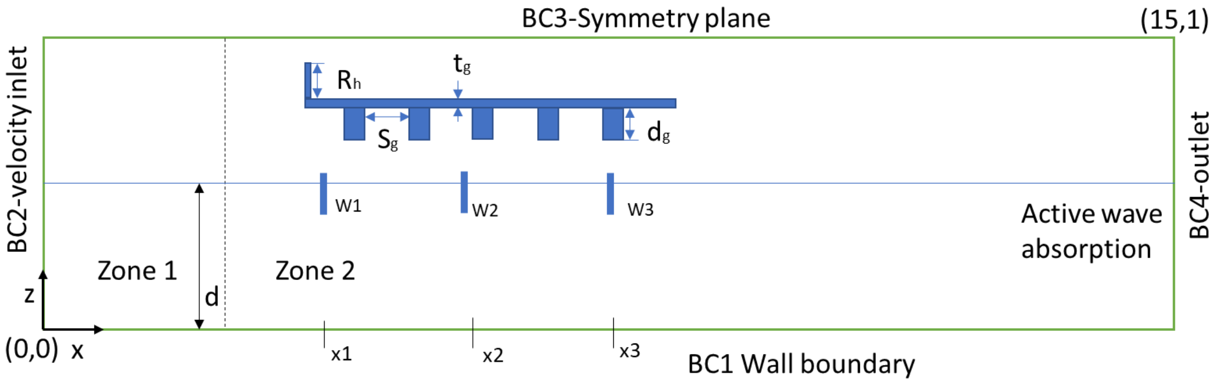
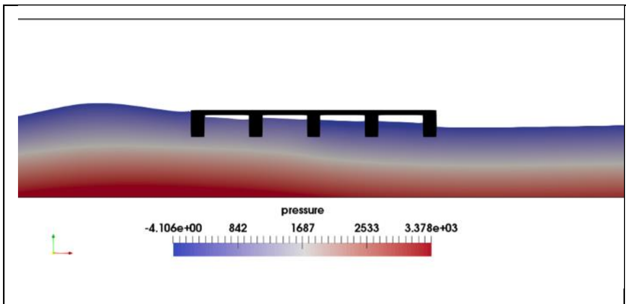


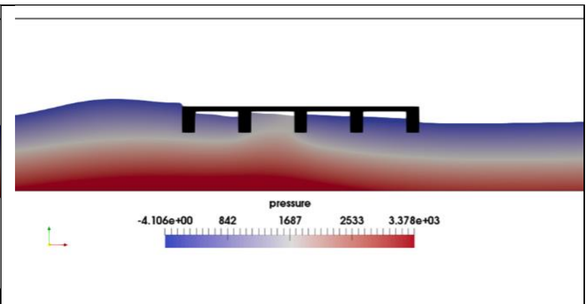
Figure 1: Numerical wave tank with boundary condition

IMPACT ON DECK

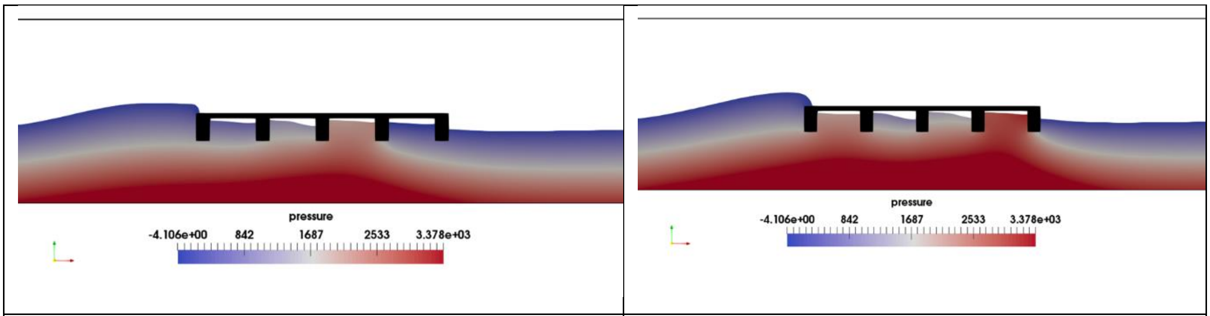
Solitary (Moideen et al., 2019), focused (Moideen et al., 2018) and irregular waves are generated in the numerical wave tank. The pressure distribution at different time steps for wave impact at a normalized airgap, S/d = 0.11 is shown in Figure 2. Figure 2 (i) shows the wave hitting the structure filling up the chambers and in chamber 2 (Figure 2 (ii)) the pressure starts to increase; the pressure increases in chamber 3 (Figure 2 (iii)) at time, *t* = 7.98 s and in the next time step, pressure increases in the first and last chamber leading to rise in the maximum force. After there is a gradual reduction of positive impact force and the water leaves the deck giving rise to slowly varying negative impact force as seen in figure 2 (iv).



(i) t = 7.85 s



(ii) t = 7.9 s



(iii) t = 7.95 s	(iv) t = 8 s

Figure 2: Screen shots of pressure variation inside the chambers of focused wave at an airgap, S = 0.04 m at different time steps (i) t = 7.85 s (ii) t = 7.9 s (iii) t = 7.95 s and (iv) t = 8 s

IRREGULAR WAVE IMPACT ON DECK

Irregular wave is generated in the NWT to study its impact on the costal bridge deck structure. A time domain analysis is done to study the effect of airgap on impact force characteristics. Total simulation time and other parameters for irregular wave generation is chosen based on the study of Aggarwal et al. (2016) in REEF3D. Irregular wave is then generated using Pierson-Moskowitch spectrum with the same significant wave height used to generate focused wave. The spectral density of PM spectrum is given as:

$$S(\omega) = \frac{5}{16} * {H_s}^2 * {\omega_p}^4 * {\omega_i}^{-5} * exp\left(\left(\frac{-5}{4}\right) * \left(\frac{\omega_i}{\omega_p}\right)^{-4}\right)$$

Where ω_p is the peak frequency of the spectrum and ω_i covers the range of frequencies in the spectrum.

Irregular wave with significant wave height, H_s = 0.07 m and T_p = 1.18 s is generated in the numerical wave tank for 500 s. The same deck size, water depth and significant wave height is used at different airgaps. The impact force is then compared with the forces obtained by solitary and focused wave of crest wave height, H_c = 0.07 m. The wave elevation time history (figure 3 (i)) shows the wave elevation for time, t = 50 to 150 s and the individual wave heights reaching height of 0.07 m. The total wave elevation time history is converted to the frequency spectrum (figure 3 (ii)) using FFT and has a peak frequency of 0.75 Hz. The wave is then impacted on the coastal bridge deck placed at normalized airgaps, *S/d* = 0.11, 0.17, 0.23 and 0.29 for different peak periods, T_p = 1.18, 1.5, 2 and 2.5 s for constant wave height.

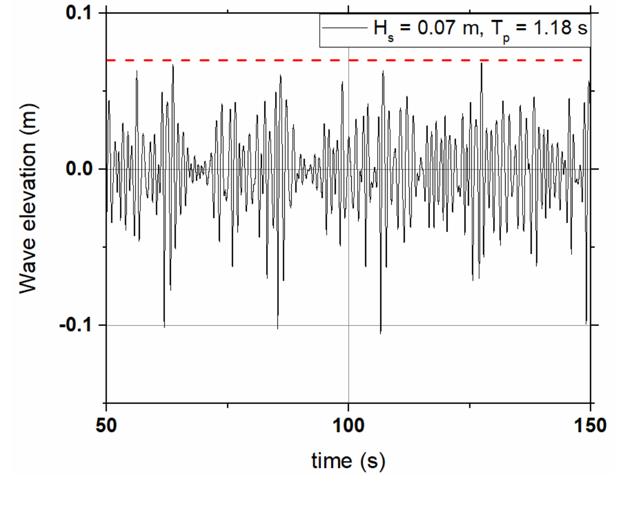
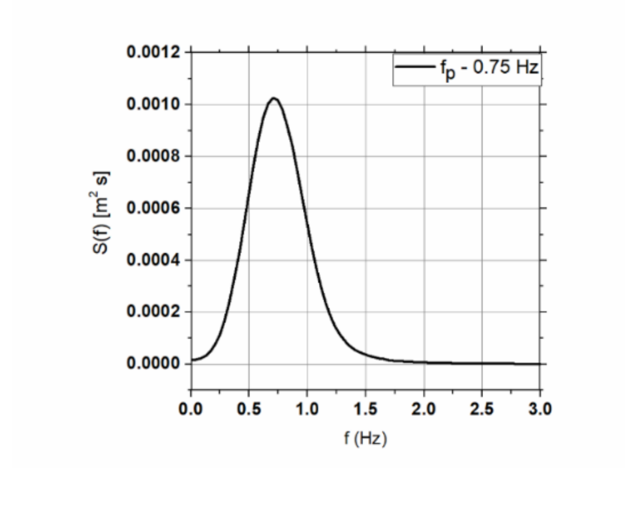
	
(i)	(ii)

Figure 3: (i) Wave elevation time history with significant wave height, H_s = 0.07 m and T_p = 1.18 s. (ii) Wave elevation spectrum plotting spectral density and frequency.

COMPARISON OF VERTICAL IMPACT FORCE

The vertical impact force computed at different airgaps using solitary, focused and irregular wave types is now compared to analyse the interaction of these waves with the coastal bridge deck. The vertical forces at normalized airgaps, *S/d* = -0.06, 0 0.06, 0.11, 0.27 and 0.29 is plotted for wave height, *H* = 0.2*d* at water depth of 0.35 m for solitary wave. The focused and solitary wave is generated using PM spectrum for a significant wave height of H_s = 0.07 m and peak period, T_p = 2.5 sec. All the wave types are then allowed to impact the deck with girders (figure 4) at different airgaps and peak vertical impact force is plotted.

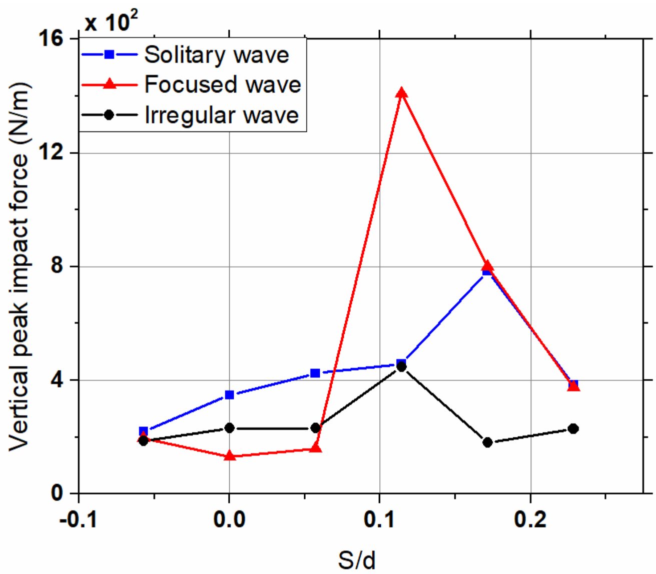


Figure 4: Comparison of peak vertical impact force for different wave types for different airgaps

The peak vertical impact force for submerged condition is almost same for the three wave types and with the increase in normalized airgap, the impact force due to solitary wave is increasing up to *S/d* = 0.17 and then reduces. For the focused wave impact, a sudden increase in the peak is observed at *S/d* = 0.11 and then starts decreasing. Similar pattern is observed in case of irregular wave whereas, the peak at S/d = 0.11 is not higher as that of focused wave and is matching with the peak of solitary wave at that location. It is expected for the irregular wave type to give lower impact force as the maximum wave height above the significant wave height will be less and the peak force is computed as highest one third from a total of 500 s simulation. As the peak impact force for irregular and focused wave show similar profile, focused wave can be used for studying impact force on bridge decks at intermediate water depths instead of irregular waves, saving lot of computational effort. Also, the focused wave can generate an extreme wave incorporating the characteristics of the infield wave spectrum at the location.

CONCLUSION

The vertical impact force on coastal bridge deck is investigated using REEF3D considering different wave types. A detailed parametric study is carried out to analyse the variation of vertical impact force under different scenarios. The following conclusions were drawn from the present study:

- Peak vertical force due to focused wave is 3 times the irregular wave impact but follows the same pattern at different airgaps considered. It shows that the focused wave impact can capture the peak force on the deck and can be used for representing extreme wave by choosing the spectrum matching the real sea state and have less computational time than irregular wave.

Overall, the study includes the numerical modelling of extreme waves using different wave types. Larger wave heights up to breaking is considered where breaking impact on deck of coastal bridge is not considered.

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