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Experimental and numerical modelling of wave forces on coastal bridge superstructures with box girders, Part I: Regular waves

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ABSTRACT

Hurricane-induced wave forces on a box girder deck for a coastal bridge are investigated by experimental tests and numerical simulations. A series of 70 experiments, which include six types of wave heights, three types of deck elevations, and various water depths, are conducted. The results show that there are five types of submergence coefficients that cover the elevated and submerged conditions for each deck elevation. Following the experiments, a two-dimensional numerical model is utilized to investigate the wave forces on the box girder deck, in which Reynolds-averaged Navier-Stokes equations combined with k-ω turbulence model are applied for wave simulations; the volume of fluid method is used to trace the interface of air and water. This numerical model shows a close agreement with the experimental data in most cases. The laboratory experiment and numerical simulation are different compared to other wave-in-bridge studies in that the box girder superstructure is complex and unique. This study can provide a beneficial tool for estimating hurricane-induced extreme wave forces for this type of coastal bridge superstructure. Regular wave forces on a box girder deck are discussed in Part I of these series of works, while the irregular wave forces will be presented in Part II.

1. Introduction

In the past decades, hurricane-induced storm surges and extreme waves caused devastating damages on coastal structures. Among these, the 2005 hurricane Katrina, slamming the coasts of Alabama, Mississippi, and Louisiana, was one of the costliest natural disasters in U.S. history, which caused extensive damages to infrastructures and coastal structures (Graumann et al., 2005; FEMA, 2006). The cost of rebuilding the coastal bridges damaged in hurricanes Katrina and Ivan was more than $1 billion (Nickas et al., 2005). Coastal bridges are vulnerable to damage under these natural disasters, i.e., hurricanes and typhoons. These extreme conditions often cause the water level to rise, producing huge waves that hit directly on girders, which are only installed at the piers by their own weight or connected by some weak joints. The failure of coastal bridges connecting the roads from islands to the mainland in the Western Pacific Region, may cause traffic paralysis and delayed rescue activities, further aggravating the disaster. The failure mechanisms of coastal bridges under extreme waves still require further studies (Xu and Cai, 2014). Rebuilding of the damaged bridges and retrofitting the existing coastal bridges require an accurate estimation of hurricane-induced wave forces on coastal bridge superstructures. Therefore, it is very important to improve our understanding of hurricane-induced wave forces on these structures.

During the last decades, several investigations on the effects of wave forces on coastal structures have been conducted (Kulin, 1958; French, 1979; McPherson, 2008; Lau et al., 2011; Seiffert et al., 2014a, 2014b; Zhao et al., 2014; Hayatdavoodi et al., 2014; Hayatdavoodi and Ertekin, 2015) to simulate the solitary wave forces on coastal structures. Hayashi (2013) conducted small-scale experiments to investigate the effect of tsunami wave forces on a box girder deck, which is generally applied to expressway bridges. He provided a detailed discussion on the tsunami wave forces on the box girder deck and converted the maximum horizontal wave force and vertical wave force measured in the experiment into values at actual bridge level and compared them with the dead load of the girder of the target bridge. A brief comparison between the wave forces of the box girder and T-type girder was conducted. However, the reason for the differences was not explained in detail. Hayashi (2013) focused on the tsunami wave forces, which are different from the regular wave forces used in this study. Xu and Cai (2015) used the dynamic mesh updating technique to investigate the lateral restraining stiffness effect on solitary wave-induced forces on decks. Istrati et al. (2016) conducted large-scale experiments to study the tsunami-induced wave forces on a bridge. The effects of fluid structure interaction and air-venting on wave forces were considered in their experiments. Xu et al. (2016b) conducted

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a comprehensive study on predicting solitary wave forces on a typical deck using a numerical method. Based on the numerical simulations, they expanded the formula, which was originally proposed by McPherson (2008), to estimate accurately the solitary wave forces on a typical deck with girders. The effect of entrapped air on solitary wave forces on a deck was presented by Seiffert et al. (2016), and they also found that there was a significant reduction in vertical uplift forces when air relief openings were added to the bridge model. Xu et al. (2016d) investigated the wave forces on a typical bridge deck based on a component level assessment and the countermeasure of air-venting holes. Qu et al. (2017) investigated the effect of the opening size of vents and other relevant factors, including the submergence depth of the deck, wave height, water depth, and number of girders, on hydrodynamic loads through a two-dimensional (2D) numerical study. Sarfaraz and Pak (2017) conducted a comprehensive study on tsunami-induced loads on bridge superstructures using smoothed particle hydrodynamics. Furthermore, simple non-dimensional equations were proposed for estimating the tsunami-induced forces and moments on the bridge superstructures in their study. They were mostly focused on solitary wave forces. These experiments mainly focused on coastal structures such as the plate and bridge deck with T-type girders. Among these studies, only Hayashi (2013) investigated the wave effects on a box girder.

Experiments and numerical simulations involving periodic wave forces on coastal bridges were also conducted by many researchers. Wang (1970) conducted a laboratory experiment to investigate the validity of his prediction rules, for estimating the maximum uplift wave forces induced by various incident waves on a flat plate. He indicated that the magnitude of impulse force is huge and engineers should pay close attention to it. Shih and Anastasiou (1992) showed the important features associated with this type of loading for the first time by conducting a series of laboratory experiments that covered regular and irregular wave conditions. They also used these experimental data to improve the formula that is used to estimate the uplift wave forces on the bottom of the decks in shallow and intermediate water depths. Takaki (2001) proposed the optimal inclination of a submerged plate under a breakwater based on the maker and cell method and laboratory experiments. Douglass et al. (2004) reviewed existing methods to estimate wave forces on highway bridge superstructures and other coastal structures. They found that existing methods were inadequate for estimating the wave forces on bridge decks. A modified empirical equation for estimating the wave forces on bridge decks was proposed by Douglass et al. (2006) based on laboratory experiments. AASHTO (2008) proposed parametric equations for calculating the wave forces on coastal bridges based on numerous experimental tests. McPherson (2008) proposed a new method to calculate the horizontal and vertical forces on typical U.S. bridges based on large-scale wave basin experiments and existing theoretical methods. Bradner (2008) conducted 1:5 large-scale experiments to investigate realistic wave forces on the I-10 bridge. The roller and rail system were used in their experiments to simulate the dynamic response of the bridge structure. Sheppard and Marin (2009) conducted a comprehensive study of the wave forces on the I-10 Escambia Bay Bridge through wave tank tests, and a theoretical wave force model with drag and inertia coefficients had been proposed for estimating the wave forces on coastal bridges. Cuomo et al. (2009) conducted large-scale experiments to investigate the dynamics of coastal bridges and the effect of openings in the bridge deck on wave forces. The wave forces on eight 1:30 scale bridge models with various deck clearances were investigated by Henry (2011). Bradner et al. (2011) conducted unique 1:5 scale experiments with consideration of the stiffness of the horizontal support system, which can better examine the dynamic properties of a bridge system. Furthermore, the relationship between the wave forces on the superstructure and the hydraulic parameters were also presented in their study. Rey and Touboul (2011) conducted laboratory experiments to investigate the relevance of a linear theory that describe the efficiency of wave breaking, and the forces and moments on a horizontal plate.

More recently, Sheppard et al. (2015) proposed a wave and surge atlas, which is presented in a geographic information system to compute surge/wave loads on bridge superstructures. Seiffert et al. (2015) conducted 1:35 scale laboratory experiments to measure nonlinear wave forces on a typical two-lane coastal bridge under various conditions. In their work, different waves and several locations of decks covering fully submerged, partially submerged and above still water level (SWL) were selected. The experimental data were compared with computational fluid dynamics (CFD) simulation results and those of the empirical equation proposed by Douglass et al. (2006). Guo et al. (2015) performed hydrodynamic experiments to investigate the wave forces on the superstructure of coastal highway bridges. They found that the slamming component of the wave force is not noticeable in the horizontal direction and the total vertical force can be taken as twice the quasi-static vertical force. The horizontal and vertical forces on a horizontal plate in shallow water were studied through laboratory experiments by Hayatdavoodi et al. (2015b). Two water depths, five wavelengths, and six plate elevations were chosen in their experiment to investigate the wave forces on the plate under cnoidal waves. A series of excellent works was conducted by Hayatdavoodi (2013), Hayatdavoodi and Ertekin (2012, 2014, 2015), Hayatdavoodi et al. (2015a) and Xu and Cai (2017), which greatly contributed to the understanding of extreme periodic wave-induced forces on coastal bridges. Almost all of the above studies were focused on the horizontal plate or the typical bridge deck. However, none of them focused on the box girder deck so far, which is widely used in the construction of long-span coastal bridges.

This study presents a series of experiments involving periodic regular waves acting on a box girder deck under various wave characteristics and water depths, and under submerged and elevated conditions. The complex shape of the superstructure and simple wave form make these experiments useful for designing superstructures. Moreover, it is beneficial to apply the results of this study for bridges in the Western Pacific Region, where box girders are used.

For the numerical simulations, the Reynolds-averaged Navier-Stokes (RANS) equations are utilized to describe the mean flow motion, and the volume of fluid (VOF) method is used to trace the free surface of water. This approach was also adopted by Xiao et al. (2010), who proposed a wave-loading model based on the RANS equations which was used to simulate the wave forces on the Biloxi Bay Bridge under hurricane Katrina-induced waves. Jin and Meng (2011) used the software Flow-3D to investigate the wave loads on bridge structures. Xu et al. (2016a) also used the RANS equations with the shear stress transport k-ω turbulence model to simulate the deck-wave interaction. Similar works were also conducted by Hayatdavoodi et al. (2015b) to simulate the wave propagation, wave breaking and wave impact on coastal bridges.

The setup of the laboratory experiment is described in Section 2. The results of regular waves are presented in Section 3. In Section 4, comparisons between the experimental data and numerical results are presented. Then, the hurricane-induced wave forces on the T-type girder deck with similar size as the box girder deck are calculated by numerical simulations. Furthermore, a method for estimating the maximum wave forces on a box girder deck is proposed. We close this study by elaborating the conclusions drawn from the experimental data and comparisons.

2. Experimental set-up

2.1. Experimental facility

Experiments were conducted at Tianjin Port Engineering Institute Ltd., Tianjin, China. The wave flume is 68 m in length, 1 m in width and 1.6 m in height. Periodic waves are generated on the left side of the flume by a wave generator without reflection, which was purchased from Mitsui Shipbuilding Co., Ltd. The wave generator can eliminate the influence of reflection of incident waves by using an active wave absorbing method. The wave machine generates waves that combine the incident wave and eliminating wave, which is used to eliminate the reflection