Ocean Engineering 108 (2015) 519–528

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Analytical solution of hurricane wave forces acting on submerged bridge decks

Anxin Guo *, Qinghe Fang, Hui Li

Ministry-of-Education Key Laboratory of Structural Dynamic Behavior and Control, School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China

A R T I C L E I N F O

Article history:
Received 29 December 2014
Accepted 13 August 2015

Keywords:
Analytical solution
Wave force
Hurricane wave
Coastal bridge
Eigenfunction expansion

A B S T R A C T

Hurricane waves are catastrophic disasters that cause damage to coastal bridges with insufficient clearance. This study presents an analytical method to estimate the wave forces acting on a submerged bridge superstructure during a hurricane based on the potential flow approach. The boundary value problem of the submerged bridge deck under wave action is analyzed first, and the mathematical formula for the analytical solution is derived using the eigenfunction matching method. To validate the effectiveness of the analytical model, results are compared to test data from two hydrodynamic experiments on the wave action of bridge decks. Finally, the AASHTO model is discussed, and a simple method for estimating the maximum horizontal and vertical wave forces is proposed. The analysis results indicate that the proposed analytical model can be used effectively for prediction of the maximum wave forces acting on a submerged bridge superstructure during hurricane waves.

1. Introduction

During Hurricane Ivan in 2004 and Hurricane Katrina in 2005, a large number of engineered structures were damaged or destroyed by the combination of storm surge and hurricane waves; costal bridges with insufficient clearance were especially vulnerable. The catastrophic failure of coastal bridges caused serious economic and social losses, and hindered rescue and reconstruction efforts in the affected area due to transport disruptions.

Due to the serious damages to coastal bridges in hurricane events in recent years, some researchers have dedicated themselves to studying the wave-action mechanism and wave force estimation methods of bridge superstructures under storm surge and hurricane wave conditions. Douglass et al. (2006) reviewed the literature on this topic for elevated structures such as docks, horizontal plates and offshore platforms, and proposed a simple but less accurate approach to estimate wave forces, for the sake of interim guidance. The American Association of State Highway and Transportation Officials (AASHTO) also published a guideline for estimating the wave forces acting on coastal bridges, to guide the retrofit and repair of bridges damaged in hurricane events (AASHTO, 2008).

Due to the complexity of the superstructure configuration, a hurricane wave acting on a bridge deck is a complex process. Hydrodynamic experimentation is recognized as a direct and effective method to investigate this problem. Cuomo et al. (2009) conducted a hydrodynamic test on a 1:10 scale bridge model in a wave basin to measure the wave forces. The effects of trapped air were also comprehensively investigated in this study. Bradner et al. (2011) designed a 1:5 scale reinforced concrete model based on the damaged I-10 Bridge over the Escambia Bay in Hurricane Katrina. The characteristics of the wave forces were investigated for structures with different clearances subjected to regular and random waves. Marin (2010) performed a hydrodynamic test on a 1:8 scale model to investigate the wave loads acting on the bridge superstructure. The test data were used to develop coefficients needed for the numerical simulation process, known as the Physics Based Method (PBM), in the AASHTO guideline.

Numerical simulation is another effective approach to studying the fluid-structure interaction problem. Huang and Xiao (2009) employed the incompressible Reynolds averaged Navier–Stokes equations to simulate the wave field characteristics and wave forces on bridge decks. Simulation results from the numerical model were compared with two empirical methods suggested by Bea et al. (1999) and Douglass et al. (2006). The effects of submersion depth on the wave forces acting on the bridge deck were also studied with the same numerical model (Xiao et al., 2010). Jin and Meng (2011) investigated the wave loads exerted on the bridge deck using the commercial software Flow-3D. Comparison between the simulation results and the AASHTO model indicated that the AASHTO model overestimated the vertical wave forces.

* Corresponding author. Tel./fax: +86 451 86283190.
E-mail address: guoanxin@hit.edu.cn (A. Guo).

http://dx.doi.org/10.1016/j.oceaneng.2015.08.018

When a coastal bridge experiences hurricane waves, the wave-structure interaction can be classified into the subaerial, semi-submerged and submerged states according to the clearance between the lower chord of the bridge girders and the storm water level. The wave-structure interaction process has different characteristics because of the existence of the wave impact in the subaerial state and trapped air in the semi-submerged state. Due to the complexity of wave action mechanisms, it is difficult to establish one specific method to cover all of the wave action process in the estimation of the wave force. However, the previous hydrodynamic experiment (Bradner et al., 2011) and numerical simulation (Jin and Meng, 2011) have demonstrated that the maximum wave force is generally applied on the bridge deck in the submerged case. Moreover, some empirical methods for estimating the wave force on bridge decks are also developed based on the submerged state (Jin and Meng, 2011). Therefore, understanding the wave-structure action mechanism and providing an accurate estimation method for the wave force in the submerged state is a first and important step to gain insight into the whole interaction process and to establish a complete method for wave force estimation.

The potential flow approach is a classic method to analyze the wave properties and wave force for structures under gravity waves, such as elastic floating plates (Wu et al., 1995), a group of submerged horizontal plates (Wang and Shen, 1999), and two layers of horizontal thick plates (Liu et al., 2009). Specifically, Mei and Black (1969) and Black et al. (1971) have investigated the scattering phenomenon and the wave force acting on submerged rectangular objects using the potential flow approach. When a bridge deck is submerged in water in hurricane events, the wave force problem is similar to that of the submerged rectangular objects, and the potential flow approach may be extended to solve this practical engineering problem.

This paper presents an analytical solution for the estimation of the wave force acting on submerged bridge decks. First, the mathematic formulas for the boundary value problem are derived, and the eigenfunction expansion method is used to determine the analytical solution. Next, the analytical model is validated using the hydrodynamic test data of 1:5 scale and 1:10 scale bridge deck models. Finally, this method is adopted to analyze the wave force on two typical bridge decks that are widely used in practical engineering, and the simulation results are compared with those of the AASHTO model. Finally, a simple method for estimating the maximum vertical and horizontal wave forces is proposed for designing and retrofitting these types of coastal structures located in areas vulnerable to hurricanes.

2. Mathematical formulation and analytical solution

2.1. Assumptions

The beam and slab combination is the most common section shape in existing coastal bridges. The superstructure of this type of bridge generally consists of several precast, prestressed concrete girders and a cast-in-situ concrete slab. The neighboring girders are always connected by the diaphragm to enhance the integral rigidity. Many damaged coastal bridges, such as the US-90 highway bridge at Biloxi Bay and the I-10 Twin Span crossing Lake Pontchartrain, have this section shape. The potential flow approach is adopted in this study to establish the analytical model. The methodology is developed based on the following assumptions:

(1) The wave is assumed to be an inviscid, incompressible and irrotational fluid.
(2) The superstructure is assumed to be a rigid body, fixed with the cap beam. The effects of the dynamic responses of the structure on wave forces are not addressed in this study.
(3) The incident waves are monochromatic and propagated perpendicular to the superstructure. As a result, the wave action on the bridge superstructure can be simplified to a two-dimensional problem. From the prior study of the researchers, the wave force acting on the bridge decks reach their maximum values when the wave propagated perpendicular to the superstructure. Therefore, it is reasonable to estimate the maximum hurricane-induced wave force in this case.
(4) The effects of the diaphragm, the local shape of the girders and the bridge substructure are assumed to be small, so that the girders can be simplified into rectangular shapes. The proposed model is only validated for the bridge deck with T- and I-shape girders in the follows. For the bridge superstructure with box girders, further investigation should be conducted to validate the accuracy of the proposed model by using the corresponding experimental data.

2.2. Boundary value problem

Using the above assumptions, the schematic diagram of the defined problem is shown in Fig. 1. In this analytical model, the coordinate origin is set at the center of the bridge deck, and the x-axis in the rectangular system (x, z) is assumed to overlap with the still water level (SWL). As shown in the figure, the whole space domain can be divided into J subdomains, including the offshore open subdomain Ω_1, onshore open subdomain Ω_J, and interior subdomains Ω_j $(j = 2, 3, \cdots, \mathrm{J}-1)$ covered by the superstructure according to the boundary of the slab and girders.

With the ideal fluid assumption, the velocity potential

$$\Phi(x, z, t) = \phi(x, z)e^{-i\omega t} \tag{1}$$

satisfies the continuous equation

$$\frac{\partial^2 \phi(x,z)}{\partial x^2} + \frac{\partial^2 \phi(x,z)}{\partial z^2} = 0 \tag{2}$$

The spatial component of the velocity potential, $\phi(x, z)$, must also satisfy the following boundary conditions:

(1) Free surface condition at the external free domains

$$\frac{\partial \phi}{\partial z} - \frac{\omega^2}{g}\phi = 0 \quad \text{for} \quad x \le B_1 \ \text{ or } \ x \geqslant B_{J-1}, z = 0 \tag{3}$$

in which g is the gravity acceleration.

(2) Non-penetrating condition on the seabed

$$\frac{\partial \phi}{\partial z} = 0 \quad \text{for} \quad z = -d \tag{4}$$

(3) Impermeable conditions on the bottom and lateral surfaces of both girders and the slab

$$\frac{\partial \phi}{\partial z} = 0 \quad \text{on the bottom surfaces of the slab and girders} \tag{5}$$

$$\frac{\partial \phi}{\partial x} = 0 \quad \textit{on the lateral surfaces of the slab and girders} \tag{6}$$

According to the division of the subdomains, the velocity potential can be denoted as ϕ_1 and ϕ_J for the external subdomains Ω_1 and Ω_J, respectively, and ϕ_j for the interior subdomain Ω_j. At the interfaces of the adjacent domains, the velocity potentials and horizontal velocities should also satisfy the following continuity conditions:

$$\phi_j = \phi_{j+1} \quad (j = 1, 2, \cdots, \mathrm{J}-1) \tag{7}$$