Coastal Engineering 88 (2014) 210–228

Contents lists available at ScienceDirect

Coastal Engineering

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

Experiments and computations of solitary-wave forces on a coastal-bridge deck. Part II: Deck with girders

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ARTICLE INFO

Article history:
Received 15 September 2013
Received in revised form 19 February 2014
Accepted 19 February 2014
Available online 2 April 2014

Keywords:
Solitary wave
Wave force
Experiments
OpenFOAM
Coastal bridge
Entrapped air pocket
Deck with girders

ABSTRACT

Solitary wave-induced forces on a two-dimensional model of a coastal bridge are investigated by conducting laboratory experiments and performing CFD computations. Experimental parameters included four water depths, five wave amplitudes, four submergence depths and three elevations above the still-water level (SWL), for a total of 118 cases. Submergence depths and elevations are chosen such that the bridge model may be fully submerged, partially inundated or fully elevated above the SWL. Euler's equations are solved by use of the CFD program OpenFOAM to compute the wave forces. It is found that the forces calculated by OpenFOAM are in close agreement with the laboratory measurements in most cases. The effect of formation of entrapped air pockets on the wave forces is studied by including air pressure relief openings on the deck of the model. This paper is a companion to Part I under the same title. The forces on the deck with girders are compared with those on the flat plate (given in Part I) to examine the role of girders on the forces. The solitary wave forces are further studied computationally by changing the number of girders in different submergence depths.

1. Introduction

The 2011 Tohoku tsunami in the Pacific Ocean and the 2004 Indian Ocean tsunami are only two examples of the recent natural disasters, which have claimed more than 280,000 lives, dramatically affected life of several million people, and cost billions of dollars. Part of these massive destructions was the failure of coastal structures, such as coastal bridges. At places where the connecting roads are limited, such as in the Hawaiian Islands, failure of the coastal bridges may become catastrophic due to the first responders not being able to reach certain communities. As reported by Maruyama et al. (2013), most of the damaged coastal bridges remained intact against the great East Japan Earthquake (magnitude of 9 on the Richter scale), but were destroyed by the tsunami wave. Therefore, it is of great interest to improve our understanding of the tsunami wave forces on coastal bridges.

This paper is a continuation of a previous one by Seiffert et al. (2014) under the same title, hereafter referred to as Part I, which contains the solitary wave forces on a simplified model of a bridge deck without girders (flat plate). In Part II (this paper), a bridge model constructed of a deck with girders under the action of a solitary wave is considered. Unlike the works of Thusyanthan and Martinez (2008) and Lau et al. (2011), we do not consider tsunami bore forces, but rather the incident wave is assumed to be a solitary wave. As so, our main objective is confined to the failure of the deck (and attached girders) of the bridges. Piers and foundations may also be at risk during a tsunami event mainly due to current-induced scour and debris impact, see Unjoh (2006). These are not included in the current study.

Existing laboratory experiments of wave loads on scaled bridge models focus mainly on periodic waves in deep or intermediate water regions, such as those conducted by Denson (1978), McPherson (2008), Bradner (2008), Marin and Sheppard (2009), Cuomo et al. (2007) and Cuomo et al. (2009), or on a hydraulic bore, such as those conducted by Lau et al. (2011) and Shoji et al. (2011)). In one study, McPherson (2008) conducted experiments on a 1:20 scale model of a bridge section with girders and side rail under solitary wave loads. The bridge model was kept at a constant height while water depth was varied to simulate both the elevated and submerged conditions. In that work, the guardrail was placed only at the leading edge of the model (into the page direction) and was partially permeable and thus created three-dimensional effects.

Results from a series of experiments measuring solitary wave loads on a 1:35 scale bridge model with girders for both submerged and elevated cases are presented here. By testing a simplified bridge shape and a broad range of water depths, wave amplitudes, submergence depths and elevations, this set of experiments provides both insight into how these parameters affect wave loads, and a valuable range of data for comparison with analytical and numerical models. Furthermore, by testing many of the same cases that were tested on a

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http://dx.doi.org/10.1016/j.coastaleng.2014.02.007
0378-3839/

flat plate in Part I, we are able to assess whether vertical and horizontal forces on a flat plate can accurately predict forces on a bridge model with girders. These results are relevant to coastal bridges exposed to both tsunami wave loads and storm wave loads as storm waves are characterized by long period waves and a solitary wave represent the infinitely long wave-period limit.

Even when attention is confined to a simple bridge model of a box-shaped deck with rectangular girders, difficulties associated with obtaining an analytical solution of the motion of wave plunging over the structure in water of shallow depth are clear. One approach to the problem is that followed by Overbeek and Klabbers (2001), and later by Douglass et al. (2006), in which the entire wave force is estimated hydrostatically by use of some ad-hoc relations.

Our approach to the problem is that of discussed in Part I, namely to calculate the time-dependent pressure around the body by solving Euler's equations subjected to appropriate boundary conditions. The free surface of the wave is captured by a Volume of Fluid (VOF hereafter) method.

During the interaction of breaking waves with a coastal structure, a large amount of air may become trapped, particularly in the case of a bridge model where the volume between girders and deck may become enclosed by the free surface. The wave-induced pressure is significantly influenced by the amount of air and the manner it is trapped. Formation of the enclosed air pockets (or air layers) results in a shock wave force on the structure, with a very high magnitude and short duration. Such phenomenon is discussed by the pioneering work of Bagnold (1939), and later by Mitsuyasu (1966). Bagnold (1939) concluded that the highest pressure in wave–body collision occurs when the air pocket is very thin.

In the trapped-air problem, the shock wave forces may be combined with the impulsive forces due to breaking waves on the structure, making it a difficult problem for theoretical solutions. Entrapped air and bubbles behave differently in fresh water than in sea water, and in addition, the air compression process cannot fully be scaled (see Bullock et al., 2001), adding to the complexities associated with laboratory experiments of the problem. Takahashi et al. (1985) developed a theoretical method, based on laboratory experiments and assuming adiabatic air compression, and estimated air pressure entrapped in a chamber above the still-water level (SWL) with a small air leakage opening. McPherson (2008) discussed the problem of entrapment of air pockets between girders of a coastal bridge, but only considered the hydrostatic force (due to the added buoyancy) effect of the enclosed air. Bozorgnia et al. (2010) studied the role of entrapped air pockets in between the girders of a model of I-10 bridge across Mobil Bay, USA, and concluded that the enclosed air increases the vertical solitary wave force on the structure. However, no information on the role of entrapped air pockets on pressure distribution below the deck and in between the girders was provided. What portion of the air is able to leave the chamber as the maximum uplift force occurred has also remained unclear due to the very small air pressure relief openings (1% of the deck width).

The wave induced forces measured in the laboratory experiments are given in Sections 2–3. Following the laboratory data presented, comparisons of computed wave loads for two water depths are presented in Section 4. The remainder of the paper is concerned with the studies of the role of the girders and entrapped air pockets on the wave forces. All of the cases studied here are in two dimensions. Maximum and minimum values of the vertical ($\boldsymbol{F}_z$) and horizontal ($\boldsymbol{F}_x$) forces are normalized in two-dimensional forms as

$$\overline{F}_z = \frac{\|\boldsymbol{F_z}\|}{L_P}, \tag{1}$$

$$\overline{F}_x = \frac{\|\boldsymbol{F_x}\|}{L_P(t_P + t_G)}, \tag{2}$$

where L_P is the bridge length (into the page), and t_P and t_G are the deck thickness and girder height, respectively. Therefore, the two-dimensional horizontal force, or average pressure, has the unit of N/m^2, while the vertical force is given in N/m. Such normalization of the forces is consistent with the Part I paper, and allows us to make a direct comparison of the forces on a bridge deck with girders with those of a flat plate. Note that $\overline{F}_x$ represents the net average pressure on the projected area of the bridge.

Similar to the Part I paper, in presenting the results in this paper, uplift and downward vertical forces refer to the maximum and minimum vertical forces, respectively. Horizontal positive and horizontal negative forces indicate the maximum and minimum horizontal forces, respectively. These are shown in Fig. 14.

2. Experimental design

Experiments are conducted in a wave flume located at the University of Hawaii's Hydraulics Laboratory of the Civil and Environmental Engineering department. Dimensions of the bridge model and corresponding prototype bridge are given in Table 1. The prototype bridge in this case is based on a typical 2-lane coastal bridge commonly found in island communities. The deck and six girders are constructed of clear acrylic and the model is attached to an aerodynamically shaped aluminum strut as seen in Fig. 1. A schematic of the model (along with the flat plate model) is given in Fig. 2. Further details on facilities, instrumentation, setup and wave generation can be found in the Part I (Seiffert et al., 2014).

A total of 118 cases were tested including water depths of $h =$ 0.143 m, 0.114 m, 0.086 m and 0.071 m, non-dimensional submergence depths of $z/h = 0$, 0.2, 0.3 and 0.4 (where submergence depth z is measured from the SWL to the top of the submerged model deck), non-dimensional elevations of $z^*/h = 0.06$, 0.1, 0.3 (where z^* is measured from the SWL to the bottom of the elevated model deck), and non-dimensional wave amplitudes of $a/h = 0.1$, 0.2, 0.3, 0.4 and 0.5. Note that for the water depth of 0.143 m, the case of $a/h = 0.5$ was not tested due to limitations of the wavemaker. Also note that, for water depths of $h = 0.086$ m and 0.071 m, not all submergence depths were tested as the height of the model and water depth did not allow for the deeper submergence depths.

The range of submergence depths was chosen such that the model was very close to the tank bottom, to where the surface of the model is even with the still water level. Elevations were chosen to cover a range where the bottom of the bridge deck is just above the SWL to where the bottom of the girders is fully elevated above the SWL.

3. Experimental results and discussion

Measurements for surface elevation and wave amplitude taken at the model location without the model present are given in Part I. Table 2 shows measurements for wave amplitude versus input wave amplitude for each water depth. As repeatability errors for these waves were found to be less than $\pm 5\%$, these values are used in calculations and in plotting the force results in both Part I and II of this series of papers.

Force measurements for elevated cases were sampled at 1000 Hz and for submerged cases at 100 Hz. The higher sampling rate for

Table 1
Properties of the model test specimen and corresponding prototype bridge.

Parameter	Model (1:35)		Prototype (1:1)	
Span length (L_P)	14.923 cm	5–7/8 in	5.215 m	17.135 ft
Width (B)	30.480 cm	12 in	10.668 m	35.000 ft
Girder height (t_G)	3.810 cm	1–1/2 in	1.33 m	4.375 ft
Girder spacing (CL to CL)	5.080 cm	2 in	1.785 m	5.833 ft
Girder width	1.588 cm	5/8 in	0.560 m	1.823 ft
Deck thickness (t_P)	1.270 cm	1/2 in	0.455 m	1.458 ft