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Experiments and calculations of cnoidal wave loads on a coastal-bridge deck with girders

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ABSTRACT

Horizontal and vertical forces on a 1:35 scale model of a typical two-lane coastal bridge due to cnoidal wave loads are investigated by conducting an extensive set of laboratory experiments and comparing the resulting data with CFD calculations and existing simplified, design-type equations. The experimental parameters tested cover a wide range of wave and inundation conditions that may occur during a major storm or hurricane. This includes a wave matrix of 40 waves and bridge model elevations covering a range where the top of the bridge is fully submerged below the still-water level (SWL) to where the bottom of the girders are elevated above the SWL. Measurements for surface elevation, vertical and horizontal forces are compared with calculations made by solving Euler's equations using the CFD software *OpenFOAM* with good agreement. Vertical uplift and horizontal positive forces (forces measured in the direction of wave propagation) are compared with the simplified equations using the relations given in Douglass et al. (2006). This set of data provides a valuable benchmark for understanding wave loads on coastal bridges during a storm or hurricane.

1. Introduction

In post-disaster surveys taken after hurricane Katrina, such as in [1], it was found that the major agent of failure of bridges, such as the US90 Bridge over Biloxi Bay, Mississippi, was a combination of sea level rise and increased wave action caused by storm surge. Xiao et al. [2] used a numerical model to calculate wave loading on the Biloxi Bay Bridge during Hurricane Katrina. A time history of wave loading on the bridge calculated for five different storm-surge water depths show the greatest uplift forces occurred when the SWL reached the top of the bridge deck. This led to increased hydrostatic and hydrodynamic forces on the US90 bridge that ultimately led to its failure. This example highlights the need for a better understanding of the mechanisms that cause this and other bridge failures during storm events, and how to prevent this kind of damage in the future.

Recently, Hayatdavoodi [3] and Hayatdavoodi and Ertekin [4,5] developed a model based on the Green–Naghdi (GN) nonlinear shallow water wave equations to calculate the horizontal and vertical wave forces and the overturning moment on a submerged bridge deck (flat plate). Their GN model showed a close agreement with the laboratory experiments of solitary and periodic wave forces on a submerged deck; see also Hayatdavoodi and Ertekin [6] and Hayatdavoodi et al. [7].

Estimations of wave loads on coastal bridges by existing simplified design-type methods, such as AASHTO [8], Douglass et al. [9] and McPherson [10], are mostly suitable as a preliminary guideline and they are primarily applicable only to the cases that the bridge deck is fully above the SWL. The equations given by AASHTO [8] is the only one among these design equations that includes the effect of wave period on the wave-induced loads and is mainly applicable to short waves. Others take into account hydrostatic forces only. The blunt body of bridge structures, the presence of girders and the proximity of coastal bridges to the water surface mean hydrodynamic forces due to wave impact, turbulence, wave breaking, and green-water effects must also be taken into consideration when estimating the forces that act on a bridge.

Existing experimental data covering wave loads on coastal bridges focus mainly on intermediate-water-depth waves and include those by Cuomo et al. [11], Bradner [12], McPherson [10], Marin [13], and Denson [14]. Experimental data covering periodic wave loads on a horizontal flat plate include Bradner [12],

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Marin [13], Brater et al. [15], El Ghamry [16], French [17], Wang [18], Denson [14], Bhat [19], Shih and Anastasiou [20], Tirindelli et al. [21], McPherson [10], and most recently, Seiffert [22], and Hayatdavoodi et al. [7]. Cnoidal waves are of interest as they most closely resemble the wave form seen during a storm or hurricane in rather shallow waters.

In the present study, we conduct experiments on a 1:35 scale model of a typical coastal bridge deck under storm conditions. A wide range of wave parameters and bridge elevations are considered, including two water depths, four wave heights, five wave lengths, four submergence depths and five elevations. The experimental measurements are compared with the simplified equations based on the relations developed by Douglass et al. [9]. Recently, Seiffert et al. [23], Hayatdavoodi et al. [24] and Hayatdavoodi et al. [7] have calculated solitary wave forces on a bridge model with girders and solitary and cnoidal wave forces on a flat plate by solving Euler's equations using the CFD program *OpenFOAM*. In the present paper, we apply the same method to calculating cnoidal wave forces on a bridge model with girders and compare these with the experimental data.

2. Experimental design

2.1. Setup

Experiments are performed in a two-dimensional wave flume housed in the Department of Civil and Environmental Engineering's Hydraulics Lab at the University of Hawaii at Manoa. The flume measures 9.14 m in length, 15.24 cm in width and 15.5 cm in height and parabolic shaped wave absorbers, with a length of 72 cm at the base, are placed at each end of the flume to absorb wave reflections. Waves are generated using a piston-type wavemaker with paddle motion dictated by a time–displacement series entered into the LabView software. Non-linear shallow water cnoidal waves are generated following the solution for paddle displacement based on the surface elevation, by a method outlined in [25]. For these experiments, we use the solution of the Level I GN equations for surface elevation of a cnoidal wave, given by Sun [26] and Ertekin and Becker [27]. Further details on cnoidal wave generation and examples of measured surface elevation during experiments can be found in [22,7].

Surface elevation is measured using three capacitance-type wave gauges with a spatial resolution of 0.1 mm and a sampling rate of 71 Hz. Horizontal force is calculated by adding measurements of three 44.5 N load cells at each time step and vertical force is measured directly using one 44.5 N load cell. The load cells have a resolution of 0.022 N and sampling rate of 100 Hz for submerged cases and 1000 Hz for elevated cases. The lower sampling rate was deemed sufficient for submerged cases as the absence of air means the model only experiences long-duration forces and no short-duration impact forces typical with the presence of air. Therefore, the 100 Hz sample rate is able to sufficiently capture the maximum and minimum force peaks for both horizontal and vertical forces when the model is submerged. Air and water temperature remained constant at 20 °C.

The bridge model has a scale of 1:35 and is representative of a typical two-lane coastal bridge located in an island community. Dimensions for the bridge model can be found in Figs. 1 and 2, and model dimensions and corresponding prototype dimensions can be found in Table 1. The model is attached to an aerodynamically shaped vertical aluminum strut which is attached to a rigid support structure by the three horizontal load cells (two at a distance of 43.2 cm and one at 68.6 cm above the model) and one vertical load cell (at a distance of 77.0 cm above the model), shown in Fig. 2.

The model is placed in the flume at a distance of 2.62 m from the wavemaker and 5.22 m from the downwave end of the flume, shown in Fig. 3. Wave gauges are positioned at two plate widths (WG1) and one plate width (WG2) upwave of the leading edge of the model and two plate widths downwave of the trailing edge of the model (WG3). Measurements for surface elevation taken during experiments are used for comparison with numerical calculations. Further details on the model specimen can be found in [24,28] and details on the laboratory experimental setup can be found in [29,7].

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

Parameter	Model(1:35)		Prototype(1:1)	
Span length (L_P)[a]	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

[a] Constraint by flume width.

2.2. Test procedure

The experimental testing procedure includes five wave lengths, four wave heights, and two water depths to cover a range of nonlinear shallow-water waves to shallower intermediate-water waves suitable to characterization by cnoidal wave theory as suggested by, for example Figure 4.17 in [30,31]. Additionally, most of the waves studied have an Ursell number >40, following the stricter definition for a cnoidal wave, given in [32]. A table of water depths, input wave heights, wave lengths and wave periods and corresponding prototype conditions are given in Table 2. Each wave parameter was tested for a range of non-dimensional submergence depths z/h, where z is measured from the SWL to the top of the bridge deck, and elevations z^*/h, where z^* is measured from the SWL to the bottom of the bridge deck to cover a range where the top of the model deck is fully submerged below the SWL to where the bottom of the deck and the bottom of girders are fully elevated above the SWL (see Fig. 1). The coordinate z_G measures the distance from the SWL to the bottom of the girders and is positive if the bottom of the girders are elevated above the SWL and is negative if any portion of the girders are submerged. For water depth $h = 0.071$ m, the model was positioned at non-dimensional submergence depths of $z/h = 0.0$, and 0.2 and elevations of $z^*/h = 0.06$, 0.1, 0.3, 0.35, and 0.55, and for water depth $h = 0.114$ m, the model was positioned at submergence depths of $z/h = 0.0$, 0.2, 0.3, and 0.4 and elevations of $z^*/h = 0.06$, 0.1, and 0.35.

The same wave conditions and submergence depths and elevations were tested on the strut alone to determine the contribution of the strut to horizontal forces. Average measured horizontal forces on the strut in the direction of wave propagation (positive) and opposite the direction of wave propagation (negative) are subtracted from the measured forces on the model and the strut taken during experiments to get the final horizontal positive and negative forces.

2.3. Experimental measurements

Wave force measurements are taken such that the initial wave has already propagated past the model but has not yet been reflected back to the model, leaving 2–3 waves for analysis. Each case (one water depth, one wave length, one wave height and one submergence depth or elevation) is repeated 3 times giving 6–9 measurements for each case. The maxima and minima peak force measurements for vertical and horizontal forces are removed and the remaining measurements are averaged. To insure repeatability,