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Wave loads on a coastal bridge deck and the role of entrapped air

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ABSTRACT

Wave loading on a coastal bridge deck due to nonlinear waves during a storm, where air may be fully or partially trapped between the girders, is studied through an extensive set of laboratory experiments. Wave cases tested cover a range of shallow-water to intermediate-water depth waves. A range of model elevations is tested to include conditions where the bridge may be partially inundated, to where the model is fully elevated above the still-water level (SWL). The model is constructed to include different percentages of air-relief openings, to capture a range of cases where no air can escape between the girders, to where all the air can escape and the wave can freely interact with the bottom of the bridge deck. Effects of the compressibility of entrapped air as well as the effects of the model scale are investigated through numerical calculations solving the compressible and incompressible Euler's equations, at both the model and prototype scales, by use of the open source CFD software, OpenFOAM. Along with coastal bridges, this research is applicable to other coastal and offshore structures, such as piers, submerged breakwaters and offshore platforms, in which wave loading or entrapped air is of concern.

1. Introduction

One of the major agents of failure of bridge structures during hurricane events, such as the US90 Bridge over Biloxi Bay that was damaged during Hurricane Katrina, is the increased hydrodynamic and hydrostatic forces caused by the storm surge and waves, as described by Robertson et al. [1] and Chen et al. [2], for example. As the sea level rises, the bridge may become partially or fully inundated and air can become trapped, adding to the increased uplift force. This, combined with increased wave action, can overcome the weight of the bridge and ultimately lead to bridge failure as the structural capacity of the bridge is exceeded.

Estimations of hydrodynamic forces on coastal bridges by analytical methods alone are not practical as the effects of trapped air, wave breaking, turbulence and green-water effects cannot be predicted analytically, in general, and thus, sometimes we must rely on empirical data. The blunt body of bridge structures, the presence of girders and proximity of coastal bridges to the water surface mean that these effects must be taken into consideration when predicting the forces that act on the bridge deck.

Until recently, existing laboratory experiments of wave loads on scaled bridge models focused mainly on periodic waves in deep or intermediate water regions, such as those conducted by Denson [3], McPherson [4], Bradner [5], Marin [6], and Cuomo et al. [7]. With the exception of Cuomo et al. [7], air relief openings were not included in the bridge models. McPherson [4] conducted experiments on a 1:20 scale model of a bridge section with girders and side rail under periodic, intermediate water-depth waves and the resulting solitary wave loads. Bradner [5] conducted experiments on a 1:5 reinforced concrete scale model of the I-10 Bridge over Escambia Bay, Florida, which failed during Hurricane Ivan in 2004. Waves tested were those estimated to have occurred at the U.S. 90 Bridge over Biloxi Bay during Hurricane Katrina in 2005 as presented by Chen et al. [2]. Sheppard and Marin [8] tested a model based on a 1:8 scale of the spans that failed on the I-10 Escambia Bay Bridge during Hurricane Ivan. Intermediate water-depth waves were tested for both elevated and submerged conditions. Cuomo et al. [7] carried out large scale, three-dimensional experiments to study storm-wave loading on a coastal-bridge model. Air-relief slots added to the bridge deck surface were found to reduce the uplift forces. However, with larger wave amplitudes, the slots were found to be not of adequate size to effectively reduce the uplift loads.

Recently, Seiffert et al. [9,12] and Hayatdavoodi et al. [10,11] conducted experiments and did calculations measuring solitary and cnoidal wave loading on a flat plate (see also Hayatdavoodi

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Nomenclature

%ARO	percentage of air relief opening area of air gap area
α	air–water phase fraction
β	isothermal compressibility
ϵ	ratio of the area of air relief opening to the area of the ceiling slab
γ	polytropic index for air
λ	wavelength
$\mathbf{U}$	velocity field
ν	kinematic viscosity
ψ	compressibility factor
ρ	density
a	wave amplitude
A_c	area of air cavity between girders
A_r	area of air relief hole
B	width of the bridge model in the direction parallel to wave propagation
C_a	contraction coefficient
C_v	velocity coefficient
C_ϵ	reduction coefficient
D	initial thickness of trapped air layer
F_x	horizontal force
F_z	vertical force
g	gravity
H	wave height
h	water depth
h_G	water surface elevation in the air cavity in the absence of entrapped air
k_t	thickness of the water mass contributing to wave momentum
L_G	girder spacing (CL to CL)
L_P	length of bridge model in the direction normal to wave propagation
p	pressure
p_0	atmospheric pressure
p_a	absolute pressure of air inside the chamber
p_d	dynamic pressure
$q(t)$	amount of air leakage
r_D	air relief hole diameter
T	wave period
t	time
t_G	girder height
t_P	bridge deck thickness
w_0	maximum vertical velocity of the wave
z^*	distance between the SWL and the bottom of the elevated bridge deck
z_G	distance between the SWL and the bottom of the bridge girders for an elevated bridge deck

and Ertekin [13]), and bridge model with girders, respectively, for both partially and fully inundated conditions. A solitary wave is of interest as it is the theoretically infinite-length limit of a cnoidal wave, and cnoidal waves are of interest as they are highly nonlinear shallow-water waves with long periods, typical of waves that occur during a storm near the coast. Laboratory measurements for surface elevation, vertical and horizontal forces were compared with those calculated by solving incompressible Euler's equations with good agreement.

In the experiments on the bridge model with girders presented in Hayatdavoodi et al. [10] and Seiffert et al. [12], no air is trapped between the girders and the wave can freely interact with the bridge deck. This study includes some experimental measurements for cnoidal wave loads on an elevated bridge model with girders presented in Seiffert et al. [12], and compares these measurements where no air is trapped between the girders with measurements taken for four additional conditions where air is trapped between the girders and different percentages of air relief openings are added. These new experiments allow us to study the effect of entrapped air and the addition of air relief openings on the forces acting on the bridge with girders.

Seiffert et al. [14] conducted systematic experiments measuring solitary wave forces on a bridge model with different percentages of air-relief openings. The results suggest that even if the bridge deck is elevated above the wave crest, without having adequately sized air-relief openings, the bridge will experience large uplift forces due to entrapped air. Furthermore, it was found that the relief of entrapped air through air-relief openings has the effect of slowing and modifying the wave as it propagates over the model. In this study, periodic nonlinear (cnoidal) wave loads are measured on the bridge model with different percentages of air-relief openings. Additionally in this study, numerical calculations of solitary wave loads on a bridge deck with air trapped between the girders are done by solving compressible Euler's equations at both the model and prototype scales to determine the effects of compressibility and scale on the wave-induced forces.

Bozorgnia [15] calculated forces on a 1:5 scale model and prototype scale of the Escambia Bay Bridge damaged during Hurricane Ivan by solving the compressible Euler's equations. Calculations were compared with and without air vents on the deck surface, and it was concluded that venting significantly damps out wave energy and reduces uplift forces such that damage to the bridge could have been prevented. Bozorgnia [15] also found that forces calculated at the model scale, then scaled to prototype scale using the Froude scaling agreed well with the forces calculated at the prototype scale, even when the effect of air entrapment is considered. Calculations were also made using Reynolds-Averaged Navier–Stokes (RANS) equations and compared with calculations made using compressible Euler's equations with good agreement, supporting the assumption that effects of viscosity for these cases are negligible.

Current methods of simplified nature for predicting wave loads on coastal bridges include Douglass et al. [16], McPherson [4] and AASHTO [17]. These methods are acceptable as a preliminary guideline but may not be suitable for partially submerged bridges and have not been verified for cases involving cnoidal waves. Additionally, they rely on hydrostatic forces or coefficients estimated from experimental data for shorter-period waves under a small range of conditions. A more robust approach to determine periodic wave loads on coastal bridges involving both the numerical and experimental approaches is necessary to understand the role of air entrapment. This is the main goal of this work. We also study compressibility of air on the wave loads, as well as whether the model-scale force data can be extrapolated to the prototype under certain conditions. This part of the study is done through numerical calculations by solving Euler's equations.

2. Experimental design

2.1. Setup

Laboratory experiments are performed at the University of Hawaii at Manoa's Hydraulics Laboratory in the Department of Civil and Environmental Engineering. The wave flume has dimensions of 9.14 m length, 15.24 cm width and 15.5 cm height. Air and water temperature remain constant in the lab at 20 °C. Waves are generated using a piston-type wavemaker and motion of the wavemaker is controlled by a time–velocity–displacement series entered into the LabView software. The nonlinear cnoidal waves are generated