Ocean Engineering 158 (2018) 78–98

Contents lists available at ScienceDirect

Ocean Engineering

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

Numerical modeling of non-breaking, impulsive breaking, and broken wave interaction with elevated coastal structures: Laboratory validation and inter-model comparisons

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ARTICLE INFO

Keywords:
Experiment
IHFOAM
ANSYS FLUENT
Validation
Force
Pressure

ABSTRACT

Quantitative CFD model validation and inter-model comparisons between IHFOAM and ANSYS-FLUENT were performed for pressures and forces on an elevated structure using a 1:10 physical model. Non-breaking, impulsive breaking, and broken wave conditions at the structure's location were simulated in IHFOAM and FLUENT. The calculated time series of water surface elevation and horizontal and vertical pressures and forces were compared with the measured data. We introduced the impulse of residual to quantify the variation of the force and pressure time series. Results indicated that the numerical models performed differently depending on the wave conditions, even for the same initial set up. Non-breaking wave simulations showed the best agreement with experimental data for both models, while broken wave trials showed the largest deviations. Bottom pressures and vertical forces were less sensitive to wave breaking conditions. Results indicate that future benchmarking tests for an elevated structure must consider both horizontal and vertical forces due to various wave breaking conditions. The accuracy of simulated wave shoaling and breaking processes played a key role in precisely calculating the forces and pressures on the structure, and it was difficult for the CFD models to simulate the exact wave breaking conditions as the measurements.

1. Introduction

Hurricanes and typhoons generate elevated surge levels and strong waves that can cause extensive damage to buildings and other coastal infrastructure, especially those located in low-lying coastal regions. The history of recorded damage on buildings near the shoreline from past storms indicates that the intensity of storms and resulting damage has increased over the past 30 years (Emanuel, 2005). For example, the United States has been impacted by recent events such as Hurricanes Katrina (2005), Ike (2008), and Sandy (2012). The 2017 Atlantic hurricane season was one of the most active and costliest seasons in recorded history. To withstand the high surge levels and waves induced from hurricanes and typhoons, structures are commonly elevated above grade; this structural design is a common building type in regions of low elevation such as barrier islands on the East Coast and Gulf Coast of the United States. However, the magnitude of damage is exacerbated in regions that are characterized by aging infrastructure and buildings that were built with outdated codes and standards, especially as coastal regions are threatened by increasing storm intensity and global sea level rise (e.g. Mori et al., 2013). Retrofitting a structure is one option to mitigate damage during future storm events and thus increase the resilience of coastal communities. However, to effectively mitigate damage, these techniques require precise predictions of the wave climate and the corresponding wave loads under various storm wave conditions.

Estimation of wave forces on elevated structures is available through analytical solutions or empirical solutions based on physical experimental results. Previous studies have mostly focused on coastal infrastructure such as bridges and jetties rather than residential buildings. Kaplan (1992) and Kaplan et al. (1995) predicted the time history of impact loadings on offshore platforms and the wave impact force from large incident waves based on momentum flux. Cuomo et al. (2007) conducted a 1:25 scale model test of wave forces on exposed jetties and developed new dimensionless predictive solutions. Cuomo et al. (2009) also performed large scale (1:10) experiments on coastal highway bridges

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https://doi.org/10.1016/j.oceaneng.2018.03.088
Received 1 September 2017; Received in revised form 22 January 2018; Accepted 31 March 2018

and determined the dynamics of wave loadings and the effects of openings in bridge decks. Based on this work, they derived predictive methods for both quasi-static and impulsive wave loads. Bradner et al. (2011) investigated a 1:5 scale model of a reinforced concrete type coastal bridge superstructure. They investigated the vertical and horizontal force for an array of wave heights, periods, and water levels and found that the vertical force could be greater than the horizontal force by a factor of four.

Recently, ASCE/SEI (2016) published minimum design standards for buildings as a design guideline for elevated structures, including methodologies to calculate three wave loading types: non-breaking, breaking and broken (Sections 5.4.2 to 5.4.5). FEMA (2011) also published a design manual for residential coastal dwellings, which includes guidance on both horizontal and vertical wave forces, similar to those presented in the ASCE standard. However, those theoretical approaches are limited in their applicability to real, complex, storm wave climates and the corresponding wave forces. Wiebe et al. (2014) proposed an analytical solution to estimate the wave-induced force on an elevated structure by modifying Goda's pressure formulae for a caisson breakwater (Goda, 1974, 2010) to include the effects of various freeboard conditions (air--gap) and wave climates. They concluded that three types of breaking conditions yielded different aspects of horizontal wave force as function of wave height, period and freeboard.

As an alternative method, Computational Fluid Dynamics (CFD) models have been widely developed and applied to estimate wave induced pressures and forces; advances in recent years have been supported by an increase in computation power, which allows more detailed calculations of the complex hydrodynamics associated with wave action. However, the performance of CFD models must be validated or verified through detailed comparisons with benchmark tests (e.g. analytic solutions or physical experiments), and difficulties of pressure and force calculations and their sensitivity to wave conditions were well reported by previous studies (e.g. Mokrani and Abadie, 2016). In case of the wave pressure (forces) on elevated structure, many recent numerical studies have been performed with bridge decks (Xiao and Huang, 2008; Jin and Meng, 2011; Hayatdavoodi et al., 2014, 2015; Seiffert et al., 2015; Wu et al., 2016) and validated through the scaled physical experimental results. They mostly utilized solitary or cnoidal waves with constant depth conditions for simple wave climate and focused on analyzing wave loads on coastal bridge decks. Recently, Do et al. (2016) used the results of a 1:5 scale bridge experiment (Linton et al., 2012) to validate the ANSYS FLUENT model (ANSYS, 2013). They then applied the model setup to a vertical wall using a solitary wave.

Generally, differences in wave impacts result from the three breaking types (non-breaking, breaking, and broken waves). Wave breaking is highly dependent on the wave characteristics (e.g. wave height, period, and surge levels), bathymetric and topographic conditions (e.g. cross-shore beach profile, foreshore slope, and presence or absence of offshore sandbars and dunes). Geometric conditions of the infrastructure (e.g. community layout, beach hardening) are also important. In particular, the air gap, or the distance from the water level to the lowest chord of the structure, can significantly affect the magnitude of the wave impact force on the elevated structure (e.g. Wiebe et al., 2014; Park et al., 2017). Impulsive breaking waves (wave slamming) induce the highest horizontal forces on vertical walls (e.g. Bea et al., 1999; Linton et al., 2012); however, it is reported that the breaking wave itself could be separated into three phases such as early breaking, late breaking, and perfect breaking (Kirkgöz, 1995). Each phase creates a wave impact force of different magnitude. Therefore, it is still a challenging task to model the various types of wave deformations over a sloping beach and to calculate the consequent wave pressure distributions and forces on elevated structures for various types of wave breaking conditions.

The goals of the present paper are to: (1) validate two CFD models (IHFOAM and FLUENT) with a scaled (1:10) experimental dataset of waves impacting an elevated structure (Park et al., 2017) with a range of surge levels, wave conditions, and air gaps; and (2) quantify the performance of the two models for the wave induced horizontal and vertical forces (pressures) on the elevated structure. We compare the performance and sensitivity of the two CFD model results conditioned on the three different wave impact conditions: non-breaking, breaking, and broken. In particular, we compare the time-series of the water surface elevations over the compound slope, as well as the front and bottom pressures and vertical and horizontal force components on the elevated structure, which was positioned on a flat region slightly inland of the compound slope. Section 2 introduces the overall setup of the experiment and dataset utilized in model validation including detailed instrumentation and test conditions. Section 3 introduces the two CFD models (IHFOAM and FLUENT) and details of each CFD model setup. Section 4 presents an overview of the two CFD model results, including the detailed validation process. Section 5 discusses the quantitative comparison of the two CFD models and the sensitivity of each model to different mesh size conditions in calculations of the water surface elevation, pressure, and force. Finally, Section 6 discusses the major conclusions of this work.

2. Experimental design

The physical model tests were conducted at the Large Wave Flume (LWF) at Oregon State University's Hinsdale Wave Research Laboratory (HWRL) and are described in detail in Park et al. (2017). The tests are summarized here to provide a context for the numerical modeling in this work. The experiment was designed to measure wave-induced pressures, horizontal forces, and vertical forces separately on an elevated coastal structure. Experiments were performed with a constant water depth and bathymetry while varying the significant wave height and peak period for each test. Three different wave conditions were tested including regular (periodic), irregular (random), and transient (tsunami-like) waves, and the specimen was elevated to different air-gap conditions to measure the horizontal and vertical wave forces on the structure. The model-data validations use the regular waves only.

2.1. Experimental setup

A profile-view sketch of the LWF including bathymetric conditions and wave gage locations is presented in Fig. 1. The length, width and

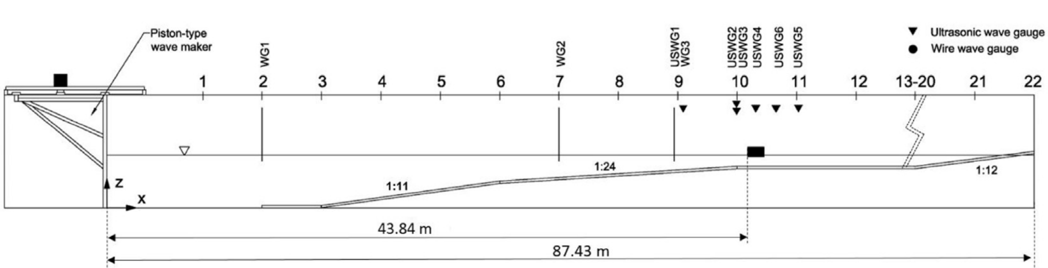

Fig. 1. Profile view of the Large Wave Flume (LWF).