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Performance-based design methodology for inundated elevated coastal structures subjected to wave load

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ABSTRACT

This paper presents the method and results of a numerical study to develop a performance-based design methodology for elevated coastal structures with a focus on bridges. However, the methodology is applicable to other elevated coastal structures. A combined Eulerian–Lagrangian method for fluid–structure interaction was applied in order to compute forces on elevated coastal structures. The numerical results are in good agreement with test results of a large scale bridge section tested previously at the O.H. Hinsdale Wave Research Laboratory at Oregon State University. Specifically, a 5-m section of a prototype I-10 bridge section was used to demonstrate the fragility approach for performance-based design using four different levels of elevation. By introducing fragility modeling, a variety of design options can be considered consisting of either raising the elevation of the bridge or strengthening the structure itself in order to obtain the desired probability of failure for a specific intensity of hurricane surge and waves.

1. Introduction

As a result of global climate change, many experts anticipate an increase in hurricane disasters along the coastal area of the U.S. with potential implications demonstrated by hurricane Ivan (2004), Katrina (2005) and Ike (2008), and most recently Sandy (2012). Elevated structures are one of the solutions to mitigate the damage and reduce risk to buildings and bridges along the coast by reducing the impact flow of surge and/or waves during hurricanes. In some surveys, structures fail or survive with just 0.5 m (1.6 ft) difference in elevation [1]. The wave impact forces include shear (lateral wave force), uplift from underneath the structure, and over turning moment which all can result in significant damage to many types of structures including highway bridges [2,3]. In addition, coastal and near-coast structures must resist forces due to buoyancy and hydrodynamic drag resulting from currents associated with hurricane surge.

A large body of research exists for wave loading on fixed and floating ocean and coastal structures and was conducted for offshore oil platforms, rubble-mound port structures and vertical caisson (e.g. [4,5]). Early laboratory studies in shallow water wave loading on elevated structures were conducted using small scale hydraulic models under simplified geometry and wave forces [6–9]. These studies focused on predicting the uplift forces including buoyancy, slamming force, drag force as well as inertial force. These forces reflect not only the wave characteristics but also the dynamic response of the structures and often the fluid–structure interaction between the waves and structure. Later in 1999, a series of tests on the offshore oil platforms exposed to hurricane wave-in-deck load [10] in Gulf of Mexico were conducted. Those tests showed that clearance height between still water level and the lower deck of the platform is the critical parameter for designing an elevated structure subjected to waves as one might expect. Other important parameters are the wave height crest and its probability distribution such as the peakedness of the sea state. Some follow up research projects used different probability distributions such as the Rayleigh distribution for the wave crests in deep water [11], wave overtopping [12] or a truncated Weibull distribution for significant wave height (H_s) and peak period (T_p) [13] were also conducted. However, most of the research has focused on deep water waves, and there is less guidance for shallow water impacts, particularly for elevated coastal structures.

A series of wave loading tests were conducted at the O.H. Hinsdale Wave Research Laboratory, Oregon State University to determine quasi-static equations for wave loadings on structures. In 2011, Bradner et al. performed a test on a 1:5 scale concrete bridge superstructure section under hurricane wave loads [14]. Differences between dynamic and static forces have been observed

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experimentally. In 2013, a full scale test of light frame wood shear wall under tsunami load was tested by Linton et al. [15] and confirmed that the transient loading was 2.2 times that of the quasi-static force. The Goda equation [5] is felt by many to present state-of-the-art for predicting the static shear and uplift loading on a vertical caisson. Following this equation, Wiebe et al. [16] developed the Goda pressure formula for horizontal wave loads on elevated structures and validated it with small scale tests.

Laboratory testing is both time consuming and costly and thus many researchers have focused on development of robust computational fluid dynamics (CFD) models that can replicate test results. In a CDF model, Navier Stokes equations are the governing equations and the basic tool for modeling fluid dynamics in both deep and shallow water. In 2010, Bozorgnia et al. [17] used the commercial CFD code STAR CCM+ to apply the finite volume method to solve the governing fluid equations. Using this method, the effect of entrapped air on wave impact and uplift forces on a 2D model of a bridge section was investigated. Recently, Chen et al. [18] used another open source package called OpenFOAM to investigate wave–structure interaction. ABAQUS is a robust general commercial tool that can also be applied to this type of problem. In 2013, Como and Mahmoud [19] used the Eulerian–Lagrangian model in ABAQUS to study the impact loading on light-frame wood walls subjected to tsunami debris.

In order to introduce performance-based design for elevated coastal structures, one may consider fragility curves. Fragilities are conditional probability distributions which represent the conditional probability of the demand exceeding a specific limit state or capacity as a function of one or more hazard intensities. Constructing fragility curves for performance-based design using fragility curves is not a new design concept. In 1996, the Federal Emergency Management Agency (FEMA) funded a large project in performance-based design for buildings subjected to earthquake [20]. The fragility concept was then studied by Rosowsky and Ellingwood [21] for wood frame housing for both wind and earthquake hazard. In earthquake engineering, the hazard intensity can be the spectral acceleration for a specified fundamental period of building. In wind engineering, performance based design for wind turbine tower base connections was introduced recently by Do et al. [22].

In this paper, a procedure for performance-based design of an elevated coastal structure for hurricane waves using the fragility methodology is introduced. The ABAQUS model was validated based on existing laboratory test data. A series of numerical simulations using an Eulerian–Lagrangian formulation for a variety of combinations of significant wave height and peak wave period were conducted. Then, fragilities for four different bridge designs (elevation and inundation level) were developed. The procedure to select a combination of bridge elevation and bridge strength/capacity using fragilities to achieve the desired performance level (in this case failure probability) is then illustrated.

For a complete performance-based design methodology, a hazard intensity would be incorporated. However, only fragility curves which present the conditional probability of failure have been developed in this study for illustrative purposes. In other words, only probability of failure for a given sea state, i.e. one intensity or return period in this case was introduced. A combination of different distributions of wave height and surge levels with fragility curves and hazard intensity could be developed if one wished to consider multiple combinations of hazard intensity and performance level in the PBD.

2. Basic fluid/structure interaction model

The governing equations for fluid dynamics for a viscous incompressible fluid in an Eulerian reference frame, $x = (x_1, x_2, x_3)$ can be written as [23]

$$\frac{\partial v_i}{\partial x_i} = 0 \tag{1}$$

$$\rho_o\left(\frac{\partial v_i}{\partial t} + v_j\frac{\partial v_i}{\partial x_j}\right) = \frac{\partial}{\partial x_j}\left[-P\delta_{ij} + \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)\right] + \rho_o g_i \tag{2}$$

where $v = v(x, t)$ is the velocity of the fluid flow, ρ_o is fluid density, P is fluid pressure, δ_{ij} is Kronecker delta ($\delta_{ij} = 1$ if $i \neq j$ and $\delta_{ij} = 0$, otherwise); μ is the viscous coefficient, and g_i is gravity in the ith direction.

While the equation for fluid dynamics with large deformations can be written in an Eulerian frame work which gives the flow velocity as a function of position x and time t, small deformations are typically written in a Lagrangian reference. In the Lagrangian form, the motion of a body is described by a function of time t and the reference point, X as $x = x(X, t)$. The relation between Eulerian and Lagrangian form is $v(x(X,t),t) = \frac{\partial x}{\partial t}(X,t)$ [24]. The coupled fluid/structure model in ABAQUS used in this study uses this formulation to model the structure with a Lagrangian formulation, the fluid with a Eulerian formulation with the underlying assumption that the water can be modeled as a viscous and incompressible Newtonian fluid [25]. A linear equation of state represented in the Hugoniot form [26] was also employed to determine pressure as a function of fluid density and internal energy per unit mass. Three parameters are required to define the water using this representation, namely density (1030 kg/m^3 for sea water), the speed of sound in water (1500 m/s), and the dynamic viscosity (0.001 kg/m/s at 20 °C). The Eulerian–Lagrangian general contact approach [25] was applied for this analysis with the assumption of zero friction tangential to surfaces.

3. Numerical model validation using existing wave tank data

3.1. Tsunami loads on a wood-frame wall at full scale test

Numerous experiments have been conducted in the 2-D wave flume at Oregon State University. One such test that was used for shear force validation of the ABAQUS model is the full scale light-frame wood wall test under tsunami loads tested by Linton et al. [15]. The unprocessed data was compared to those from the undamaged test of 2×6 stud wall with stud spacing of 40.6 cm subjected to offshore wave height of 0.30 m. The tsunami loading was modeled as a single wave running up to the dry and flat shore line and hitting the transverse wall. Fig. 1 presents a solid model of the numerical simulation of the wave flume with a light-frame wood wall.

Only three locations were used for validating the numerical model (Fig. 1). The offshore wave height at location 1 was measured by wire resistance wave gauge while onshore wave at location 2 was measured with an ultrasonic wave gauge. Wave particle velocity was measured by acoustic-doppler velocimeter at 0.09 m above the reef at location 2. The wall was equipped with 4 load cells at each corner to collect the horizontal forces on the wall. Finally, a linear variable differential transformer was used at middle of the bottom of the wall (location 3) to measure the wall displacement.

The numerical simulations were simplified slightly for computational efficiency with the idea that a large number of simulations would be needed to develop fragilities eventually. The transverse light-frame wood wall, as shown in Fig. 1a, has dimension of 2.24×3.58 m and consisted of 2×6 studs sheathed with 13 mm plywood. This wall was modeled as a flat wood wall with an equivalent thickness of 65 mm to have the same stiffness as the wall with 2×6 studs and plywood sheathing. The wall was modeled with shell elements with regular dimensions of approximately 0.3 m. Load cells were modeled as fix supports at the four corners as shown in Fig. 1b.