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# Effects of submersion depth on wave uplift force acting on Biloxi Bay Bridge decks during Hurricane Katrina

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ABSTRACT

A large portion of the Biloxi Bay Bridge was submerged and destroyed by surface waves and storm surge associated with Hurricane Katrina in 2005. In this paper, the time history of wave forces exerted on the Biloxi Bay Bridge during Hurricane Katrina was investigated by a wave-loading model. The Volume of Fluid (VOF) method was adopted in the model to track the variations of water surface levels. In order to obtain wave parameters and storm-surge elevation at the bridge site during Hurricane Katrina, a storm surge model and a wave propagation model were coupled to hindcast the hydrodynamic conditions. Outputs of the coupled wave–surge models were imported to the wave-loading model to simulate the dynamic wave forces acting on the bridge deck. In order to evaluate the maximum uplift wave force, five different bridge deck elevations submerged at different water depths were investigated. The processes of wave–bridge interaction were simulated by the wave-loading model. The wave profiles, velocity field in the vicinity of the bridge, and dynamic wave forces on the decks were analyzed. Results indicate that the uplift force on the submerged bridge deck span exceeded its own weight under the extreme wave and storm surge conditions during Hurricane Katrina. Moreover, the numerical simulations suggest that the maximum uplift wave force occurred when the storm surge water level reached the top of the bridge deck.



## 1. Introduction

The Biloxi Bay Bridge is located in the state of Mississippi, USA, which carries US Route 90 over Biloxi Bay between Biloxi and Ocean Springs. A large portion of the bridge was completely submerged underwater and severely damaged during Hurricane Katrina in August 2005 (Fig. 1). The Biloxi Bay Bridge was a simply-supported bridge with spans placed on pile caps. Each of the bridge spans consisted of a 0.3-m thick deck and several 1.05-m high girders. The deck was cast integrally with the girders. The deck was 15.85 m long and 10.19 m wide. The bridge had two spans placed side-by-side with east and westbound traffic lanes on opposing sides.

A number of investigators have studied the interaction of waves with marine structures. El Ghamry [8] investigated vertical wave forces exerted on a horizontal deck under the action of periodic waves using small-scale laboratory experiments. The author also used the linearized potential flow theory with a free surface to estimate uplifting wave forces. Wang [22] developed simple rules to estimate the maximum uplift pressures on a pier deck based on the linear wave theory and laboratory tests. It was found in [22] study that the slowly-varying pressure component ranged from one to two times the hydrostatic pressure for a pier above a beach with a 1:14 slope. French [9] investigated the rapidly varying peak uplift pressure and slowly varying uplift pressure on a horizontal pier with positive soffit clearance by theoretical and experiment methods. Tanimoto and Takahashi [20] conducted laboratory experiments to study the horizontal and vertical components of wave forces on a rigid platform due to periodic waves. The total uplift pressure exerted on a horizontal platform was separated into a shock pressure component and a static pressure component. Iradjpanah [12] presented a finite element model to investigate the hydrodynamic effects on a horizontal platform. The flow was assumed to be inviscid and irrotational. Kaplan et al. [15] analyzed the wave impact forces acting on offshore platform deck structures in large incident waves theoretically and experimentally. The authors also investigated the effect of wave heading angles relative to different structural elements. Isaacsion and Bhat [13] conducted an experimental study on the vertical force due to regular, non-breaking waves acting on a rigid horizontal plate located near the water surface. Tirindelli et al. [21] conducted a series of phys-

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Fig. 1. Photograph of US 90 Bridge over Biloxi Bay.

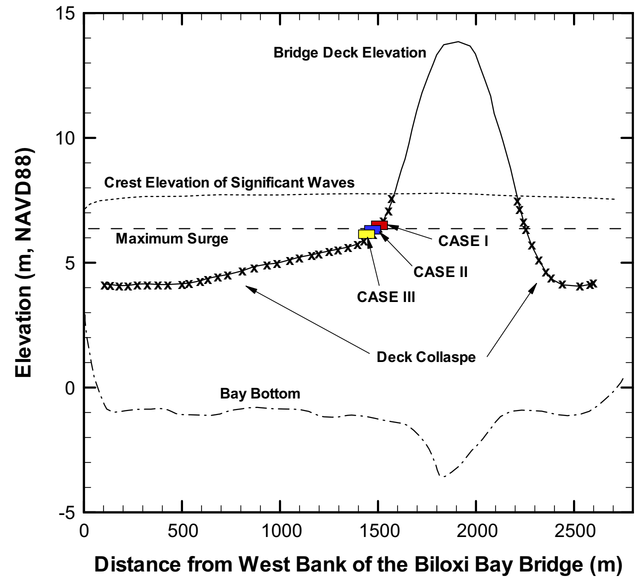


Fig. 2. Elevation view of water levels and bridge finished grade over Biloxi Bay.

ical model studies to measure the wave-induced loading on a model of an open-piled jetty structure. These measurements gave a series of force and pressure data on selected structural elements of the model jetty, covering a wide range of wave conditions and deck geometries. Douglass et al. [7] provided a synthesis of existing knowledge related to hurricane wave forces on highway bridge superstructures. Based on pre-existing laboratory experimental data, Douglass et al. [7] proposed a simple empirical equation for estimating wave loads on bridge decks. In response to the devastation of the 2004 and 2005 hurricane seasons, a number of new physical experiments on wave forces on bridge decks with realistic configuration similar to the damaged bridges on the Gulf Coast have been reported in the coastal engineering literature [2].

Recently, Huang and Xiao [10] used a numerical model based on the VOF method to simulate wave forces exerted on the Escambia Bay Bridge, Florida, which was severely damaged during Hurricane Ivan (2004). They have obtained and analyzed the time history of uplifting and horizontal wave forces acting on the bridge deck under extreme wave and storm surge conditions. For the wave and water elevation conditions presented in Huang and Xiao [10], the bridge deck bottom was above the maximum surge height. However, in the case of Hurricane Katrina (2005), a large portion of the Biloxi Bay Bridge was completely submerged in the water. Chen et al. [3] analyzed wave forces on the un-submerged decks of the Biloxi Bay Bridge. Although most of the wave energy is concentrated near the water surface, how the wave forces vary with the depth of submergence for the fully submerged decks of the Biloxi Bay Bridge is unclear. Would the wave forces of submerged bridge deck be smaller than those of emergent or partially submerged decks? The objective of the study is to seek answers to those questions.

In this study, numerical computations are carried out to improve our understanding of the wave impact on bridge decks with varying submersion depths. A wave-loading model based on the Reynolds-Averaged Navier–Stokes (RANS) equation is employed. The experimental data of uplift force on a horizontal plate [9] is used to validate the numerical model. Following the validation, the model is applied to the simulation of the dynamic wave loads acting on the full-scaled decks of the Biloxi Bay Bridge during Hurricane Katrina. Both the process of wave–bridge interaction and the uplift and horizontal components of the wave force exerted on bridge decks are investigated.

Based on the numerical results, the variations of uplift force with the submersion depth of bridge decks are also analyzed. Fig. 2 shows the elevation view of the bay bottom, the maximum surge water level, the crest elevation of the significant waves, the bridge finished grade, and the locations of the collapsed bridge spans over Biloxi Bay. In order to investigate the effect of submersion depth on wave forces, bridge decks at three different elevations related to the surge height were selected: Case I: emergent (where the deck or girder bottom is at the surge water surface), Case II: half submerged (where half of the deck or girder height is below the surge water surface), and Case III: fully submerged (where the deck top or finished grade is at the surge water surface), as shown in Fig. 2. Water depth is fixed at the maximum surge condition in Hurricane Katrina.

Because the bridge deck is simply supported, a comparison between uplift force and the weight of the bridge deck would provide the needed information to determine the cause of the deck damage. Also the percentage variations of wave forces at different bridge elevations could be useful in assessing the potential risk of coastal bridges exposed to storm surge and wave attacks.

## 2. Storm surge and waves in Biloxi Bay during hurricane katrina

Tide and wave gauge data are not available in the vicinity of the bridge at Hurricane Katrina's landfall. In order to obtain the reliable information on waves and water levels at the bridge site during Hurricane Katrina for numerical simulations of dynamic wave forces using the wave–bridge interaction model, large-scale, well tested numerical models have to be employed. By coupling the ADvanced CIRCulation (ADCIRC) surge model and the Simulation of WAves in Nearshore areas (SWAN) wave prediction model, Chen et al. [3] have hindcasted the storm surge and wind waves generated by Hurricane Katrina on the northeastern Gulf of Mexico, including Biloxi Bay, Mississippi. They have found the combination of strong winds, shallow water depth, and funneling effect of the coastal geometry resulted in the record high surge elevations of Hurricane Katrina. In particular, the extremely shallow water depth of an ancient Mississippi River Delta played a significant role in the extremely high surge in that region.

Chen et al. [3] set up the surge model using the bathymetry and topographic data with 3-s resolution from the Coastal Relief Digital Elevation Model of the NOAA National Geophysical Data Center (NGDC). The dry-land boundary was extended from the 0 m contour to the 10 m contour above the Surge Sea Level (SSL) in order to simulate the flooding. For the tide elevation boundary condition, the study used the records of the tide gauge at three different stations near the offshore open boundary of the regional-scale model;