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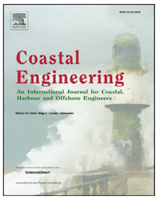

Experimental modeling of horizontal and vertical wave forces on an elevated coastal structure

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ABSTRACT

A large-scale physical model was created in Oregon State University's Large Wave Flume to collect an extensive dataset measuring wave-induced horizontal and vertical forces on an idealized coastal structure. Water depth was held constant while wave conditions included regular, irregular, and transient (tsunami-like) waves with different significant wave heights and peak periods for each test. The elevation of the base of the test specimen with respect to the stillwater depth (air gap) was also varied from at-grade to 0.28 m above the stillwater level to better understand the effects of raising or lowering a nearshore structure on increasing or decreasing the horizontal and vertical wave forces. Results indicate that while both horizontal and vertical forces tend to increase with increasing significant wave height, the maximum and top 0.4% of forces increased disproportionally to other characteristic values such as the mean or top 10%. As expected, the horizontal force increased as the test specimen was more deeply submerged and decreased as the structure was elevated to larger air gaps above the stillwater level. However, this trend was not true for the vertical force, which was maximized when the elevation of the base of the structure was equal to the elevation of the stillwater depth. Small wave heights were characterized by low horizontal to vertical force ratios, highlighting the importance of considering vertical wave forces in addition to horizontal wave forces in the design of coastal structures. The findings and data presented here may be used by city planners, engineers, and numerical modelers, for future analyses, informed coastal design, and numerical benchmarking to work toward enabling more resilient nearcoast structures.

1. Introduction

1.1. Background and literature review

With the population densities in coastal regions being almost three times that of the global average (Nicholls and Small, 2002), coastal communities provide important economic, transport, and recreational services to large numbers of people. However, these coastal communities are vulnerable to damage by extreme events such as tropical cyclones or tsunamis, and studies indicate that the potential destructiveness of tropical cyclones, based on the storm's intensity and total lifetime, has increased over the past 30 years (Emanuel, 2005). The potential damage of these storms is exacerbated in regions characterized by aging infrastructure and structures built according to outdated design standards. For example, recent storms in the United States such as Hurricane Ike (2008) and Hurricane Sandy (2012) generated strong waves and storm surge that caused extensive damage to aging infrastructure in the affected communities. As shown in Fig. 1, waves and surge cause extensive damage to elevated structures through a combination of horizontal and vertical wave and surge-induced forces. While age and deterioration play an important role, structural elevation has been shown to be a critical variable affecting damage and loss. Hurricane Ike caused significant damage to structures located on the Bolivar Peninsula, a narrow region along the Gulf of Mexico located east of Galveston, Texas, USA, in 2008. After the storm, reconnaissance surveys by Kennedy et al. (2011a) identified a sharp distinction between houses that were destroyed or survived with minimal structural damage based on the elevation of the lowest horizontal structural member of a residence with respect to the local storm surge elevation above ground. Likewise, Tomiczek et al. (2014) found much greater destruction rates on the peninsula for pile elevated residences built before the establishment of Flood Insurance Rate Maps (FIRMs) than for newer homes built according to updated

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Fig. 1. Examples of wave and surge-induced damage to elevated coastal structures located in Toms River, New Jersey occurring after Hurricane Sandy (2012). Photographs by Tori Tomiczek.

guidelines. Similarly, many residences that were severely damaged by Hurricane Sandy had been built before the National Flood Insurance Program (NFIP) established base flood elevations (BFEs) for vulnerable areas, while others had been built using construction guidelines that had been published over 25 years prior to the storm (Frantz, 2012).

Recent efforts have been made to retrofit structures or improve coastal protection and damage mitigation plans in coastal communities in order to increase community resilience, defined as the ability to recover quickly after a disaster (NRC, 2012). However, in order to effectively retrofit old structures or design new structures to resist damage due to hurricanes, engineers require an accurate estimation of both the wave climate and the resulting loads. Therefore, the estimation of wave-induced loads on structures has been the subject of many theoretical, experimental, and numerical studies. Bagnold (1939) studied impulsive wave pressures induced by waves on a vertical wall, and noted the importance of the wave's breaking condition (breaking or non-breaking) as well as the effects of trapped air on the recorded impact pressure. Since this work, the shape of the incoming wave has been shown to affect the type of breaking and the maximum pressure on a structure (Cooker and Peregrine, 1995; Peregrine, 2003). Lundgren (1969) characterized wave impact phenomena into ventilated, compression, and hammer shock loads and noted that entrained air may cause overestimation when scaling laboratory pressures to prototype scales according to the Froude Number. Kirkgöz (1995) also characterized the breaking condition as early breaking (with or without air entrainment), late breaking, and perfect breaking, concluding that perfect breaking waves produced the largest impact pressures on a vertical face. Due to the extremely short duration of the force caused by wave impact, additional studies have considered the quasi-hydrostatic forces caused by waves affecting coastal structures. Morison et al. (1950) published a pioneering model to estimate wave forces on small piles as the combination of drag and inertial forces. Based on large-scale experimental measurements of wave impacts on a vertical seawall, Cuomo et al. (2010) developed prediction formulae for impulsive and quasi-hydrostatic wave loads and overturning moments on a vertical seawall based on the incident wavelength, height, and the normalized difference between the water depth at the structure and the water depth at breaking. Seiffert et al. (2014) and Hayatdavoodi et al. (2015) experimentally measured horizontal and vertical forces caused by Cnoidal waves on a flat plate elevated at varied distances above or below the free surface on a 1:35 scale. Additional studies have further investigated horizontal breaking wave-induced pressures and loads on coastal structures of varying geometries (e.g. El Ghamry, 1965; Cuomo et al., 2011; Schoeman, 2012; Wiebe et al., 2014; Tomiczek et al., 2016a).

Many studies have also given attention to the horizontal and vertical wave-induced pressures and forces on bridge superstructures (e.g. French, 1969; Wang, 1970; Broughton and Horn, 1987 Shih and Anastasiou, 1992; Bricker and Nakayama, 2014; Azadbakht and Yim, 2015; Hayatdavoodi and Ertekin, 2015; Wei and Dalrymple, 2016). A review article by Hayatdavoodi and Ertekin (2016) provides a comprehensive review of the state of the art in understanding bridge failure mechanisms and experimental, theoretical, and numerical advances in understanding wave loads on coastal bridge decks. Early experimental work by French (1969) considered the rapidly-varying and slowly-varying wave-induced horizontal and vertical pressures acting on a horizontal platform elevated above the stillwater level and found that the slowly varying positive force was dependent on deck clearance and wave height. Broughton and Horn (1987) performed experiments on a 1:50 scale to measure the horizontal and vertical wave loads on elevated platforms. Based on these experiments they proposed a method for evaluating the impulsive force based on the change in momentum of the wave crest at the moment of impact as a function of the deck geometry, height and length of the wave crest, celerity, and the wave's water particle velocity components. After the damage caused by Hurricane Katrina (2005) to bridges in the Gulf Coast of Mexico, wave loads and effects on bridges became a subject of significant concern (e.g. O'Conner, 2005; FEMA, 2006). Bradner et al. (2011) performed a series of experiments on a 1:5 scale bridge superstructure and found a relationship between force and wave height while noting that the sharp pressure peaks induced by wave impact had a small effect on the horizontal and vertical forces on bridge superstructure, as suggested by Lomonaco et al. (2016).

Based on experimental results, empirical methods for wave force