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Physical modelling of tsunami onshore propagation, peak pressures, and shielding effects in an urban building array

Tori Tomiczek [a,*], Adi Prasetyo [b], Nobuhito Mori [b], Tomohiro Yasuda [c], Andrew Kennedy [a]

[a] University of Notre Dame, 156 Fitzpatrick Hall, Notre Dame, IN 46556, USA
[b] Kyoto University, Disaster Prevention Research Institute, Gokasho, Uji, Kyoto 6110011, Japan
[c] Kansai University, 3-3-35 Yamate-cho, Suita, Osaka 5648680, Japan

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ABSTRACT

Wave experiments were conducted on a 1:20 length scale to measure water surface elevations and extreme pressures on and around idealized structural elements and arrays of structures. Experiments varied offshore wave characteristics and onshore structural configurations. Conditions in which waves broke on or just before the specimen caused maximum impulsive pressures. Pressures measured under nonbreaking wave conditions agreed with predicted values using design equations suggested by the Japanese Cabinet Office; however bare-earth water surface elevation inputs produced nonconservative estimates in breaking wave trials. Shielded structures experienced pressure reductions of 40–70% under breaking wave conditions. Results indicate that shielding elements constructed nearshore may reduce wave-induced damage. This dataset may be used to validate numerical models of tsunami propagation through urban environments.

1. Introduction

1.1. Coastal hazards

Coastal environments offer valuable sources of economy, transportation, and recreation, spurring a high concentration of people to settle near the coastline. The population density of coastal regions 100 km or closer to shore and within 100 m of sea level is over 2.5 times that of the global average, with the majority living in small coastal villages with <1000 people/km^2 (Nicholls and Small, 2002; Small and Nicholls, 2003). However, these communities are vulnerable to coastal hazards including tsunamis and hurricanes. In recent years, the 2004 Indian Ocean Tsunami (e.g. Papadopoulos et al., 2006; Tsuji et al., 2006; Koshimura et al., 2009; Leone et al., 2011) and the 2011 Tohoku Earthquake Tsunami in Japan (e.g. Mimura et al., 2011; Mori et al., 2011, Mori and Takahashi, 2012; Kazama and Noda, 2012; Udo et al., 2012; Kawai et al., 2013) caused extensive damage to coastal areas. Hurricanes and typhoons have also historically caused catastrophic damage and loss of life across the globe. Recent examples include Typhoon Haiyan (e.g. Tajima et al., 2014; Mori et al., 2014), Hurricane Sandy (e.g. Fanelli et al., 2013; Blake et al., 2013), and Hurricane Katrina (e.g. Robertson et al., 2007; van de Lindt et al., 2007). In the United States alone, seven of the ten costliest disasters since 1980 have been caused by hurricanes (Lackey, 2011).

These coastal hazards emphasize the need to understand the fundamental processes causing damage in order to provide increased resilience to hurricane or tsunami events. However, on a local scale, engineers must consider site-specific characteristics to creatively employ hazard-mitigation methods that most effectively defend a particular community. Close to shore, a tsunami will be affected by the local bathymetry and tides, which can increase or decrease tsunami runup and inundation. As tsunamis approach shore, runup processes may be observed as a rushing bore or group of bores; for steeper beachfront slopes, a tsunami may cause a gradual rise and fall of the water level, and in some situations (e.g., the 1946 Aleutian Tsunami), a tsunami may form a collapsing breaker directly at the shoreline (Yeh, 2009). Seawalls, breakwaters, and vegetated dunes successfully or partially protected inland communities off the epicenter in the 2011 Tohoku Earthquake Tsunami and during Hurricane Sandy, while communities in other areas sustained near-complete destruction (Suppasri et al., 2013a; Nandasena et al., 2012; Irish et al., 2014). However, details of hydrodynamic transformation and forces as flows propagate through urban communities are still not well understood at both the research and design levels.

1.2. Previous tsunami and hurricane investigations

Common methods used to evaluate local conditions caused by tsunamis and hurricanes include post-disaster reconnaissance field

* Corresponding author.
E-mail addresses: vtomicze@nd.edu (T. Tomiczek), adi.prasetyo246@yahoo.com (A. Prasetyo), mori@oceanwave.ac.jp (N. Mori), tomo@oceanwave.jp (T. Yasuda), Andrew.B.Kennedy.117@nd.edu (A. Kennedy).

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surveys, numerical modelling, and laboratory experiments. After a tsunami or hurricane, field surveys are useful in assessing damage and measuring runup and high water marks (e.g. Mori et al., 2011). Such surveys have led to the development of empirical fragility models that relate inundation height, structural characteristics, and other hindcast variables to a structure's probability of damage (Suppasri et al., 2012, 2013b; Tomiczek et al., 2014, 2016). However, it is often difficult to estimate water velocities or forces on structures from post-disaster survey data. In addition to on-site surveys, numerical models such as ADCIRC (Luettich et al., 1992), SLOSH (Jelesnianski et al., 1992) for storm surge, SWAN (Holthuijsen et al., 1993) for wave spectral modelling, FUNWAVE (Wei and Kirby, 1995), COULWAVE (Lynett et al., 2008), and NHWAVE (Ma et al., 2012) for phase resolving wave modelling, have been developed to simulate hurricane conditions or tsunami propagation over local topographies. These models require validation and refinement to reliably predict overland wave dissipation. Often, numerical models remove structures and use land-use-based roughness coefficients rather than explicitly modelling the complex wave-structure interaction, leading to errors in model outputs (e.g. Westerink et al., 2008; Dietrich et al., 2012). Therefore, wave models, vulnerability assessments, and damage prediction techniques must be refined to account for wave interaction with individual structures and groups of structures to design resilient coastal communities.

Laboratory experiments are an essential starting point in understanding urban roughness effects on hydrodynamic phenomena. Historical experiments have provided valuable datasets that have been used to validate numerically-simulated water velocities and water surface elevations, as well as to derive empirical Manning's n or roughness coefficients (e.g. Goto and Shuto, 1983; Synolakis, 1987; Briggs et al., 1995; Liu et al., 1995; Chen et al., 2007; Baldock et al., 2009). Goto and Shuto (1983) determined Manning's n values for tsunami flow through various configurations of vertical cylinders; however, Manning's n values for tsunami flow through urban areas and forests have been found to be too small (Bricker et al., 2015). Other tests have focused on tsunami characteristics, as breaking wave solutions differ significantly from the nonlinear shallow water equations for nonbreaking waves. To simulate tsunami profiles during the 2004 Indian Ocean Tsunami that showed breaking initial wave fronts, Baldock et al. (2009) performed experiments to measure water surface elevations, water velocities, and wavemaker displacements for breaking tsunami wave conditions. These experiments were forced using solitary wave conditions at the O.H. Hinsdale Wave Research Laboratory at Oregon State University. Goseberg et al. (2013) presented a thorough review of the state-of-the-art of these and other tsunami generation techniques including that by piston-type paddle, dam break, vertical wave board motion, and pneumatic wave generation, as well as limitations of such models.

Recent tests have further investigated wave propagation through urban environments (e.g. van de Lindt et al., 2009; Cox et al., 2008; Goseberg and Schlurmann, 2012; Goseberg, 2013). Measurements by Thomas et al. (2015) and Irish et al. (2014) found that macro-roughness elements, defined herein as groupings or arrays of large scale obstacles like buildings, seawalls, or forested areas, lead to increased protection in wake areas where waves are reflected and flow is diverted. However, structures in narrow regions are subject to flow amplification and increased hydrodynamic forces. Experiments on scale models of real cities have also been used to validate numerical models. Cox et al. (2008) generated a dataset of tsunami flow over and around a 1:50 idealization of Seaside, Oregon and showed that both the COULWAVE (Lynett et al., 2002) and STOC-IC (Tomita et al., 2006; Tomita and Honda, 2009) numerical models were able to capture many features of flow. Park et al. (2013) compared these data with predictions of water velocity, free surface elevation, and momentum flux from the COULWAVE model (Lynett et al., 2002). Few physical models have further addressed the role of shielding in reducing tsunami-induced run-up and pressures on inland structures. Goseberg (2013) analyzed effects of beachfront developments on reducing the maximum run-up of sinusoidal waves, while the effects of low-height mitigation walls on forces induced by tsunami bores were evaluated by Al-Faesly et al. (2012). Thomas and Cox (2012) extended the work of Oshnack et al. (2009) to show that small seawalls generally reduced the maximum tsunami load on a specimen, although local pressures were sometimes increased. Thomas and Cox (2012) developed empirical formulas for predicting reduction factors for the maximum tsunami force based on the incident tsunami and in-situ seawall characteristics.

1.3. Remaining questions and experimental scope

While the abovementioned tests have been useful and indicate progress toward robustly and accurately modelling wave-structure interaction, all were performed with idealizations of the tsunami wave profile. Many experiments have modelled tsunamis using solitary waves (e.g. Cox et al., 2008; Thomas and Cox, 2012; Park et al., 2013); however, Madsen et al. (2008) showed that solitary waves may not be suitable representations of real-world mega tsunamis due to upscaling discrepancies in wavelengths and periods between model and prototype. Recent works are using alternative methods of wave generation to creatively address the issue of modelling tsunamis in the laboratory (e.g. Rossetto et al., 2011; Goseberg, 2013). For example, Rossetto et al. (2011) validated a pneumatic tsunami generator that is capable of creating solitary waves and leading-depression N-waves with large wavelengths; the wavemaker was able to reproduce a time record of the 2004 Indian Ocean Tsunami off the coast of Thailand. Goseberg et al. (2013) used a novel pump-driven wave maker that produced prolonged sinusoidal and leading-depression N waves with periods of 15–120 s, thus resulting in more realistic prototype tsunami durations. Experimental results compared well with outputs from a numerical model time series of a tsunami water surface elevation in 30 m depth. Bremm et al. (2015) similarly used this volumetric wavemaker to investigate the drag and inertial forces on an aluminum specimen caused by long, leading-depression waves. These waves show better agreement between model and prototype time scales; however, they still simplify the tsunami profile. Water surface measurements recorded by GPS buoys during the 2011 Tohoku Earthquake Tsunami showed complex profiles consisting of waves with shorter periods and sharp peaks embedded in a longer time scale water level rise (Kawai et al., 2012, 2013). Laboratory experiments simulating complex wave conditions may thus provide a clearer understanding of tsunami propagation in the presence of macro-roughness elements. The goal of the current experiment was to generate complex offshore wave conditions involving combinations of short- and long-period waves to characterize the effects of incident wave characteristics in changing hydrodynamic phenomena around varying structural configurations. Benchmark data was collected at Kyoto University on a 1:20 length scale physical model to address this question.

The remainder of this work is organized as follows: Section 2 describes the hydraulic flume, instrumentation, and experimental program. Results are presented in Section 3, and the effects of incident wave conditions and macro-roughness elements on changing the maximum pressure on an idealized structure are described. Section 3 also characterizes the tsunami waveforms recorded by GPS buoys during the 2011 Tohoku Earthquake Tsunami and compares those to waves created in the current experiment. Finally, Section 4 addresses successes and limitations of the hydraulic flume and areas for future research before highlighting major conclusions and offering engineering recommendations for damage mitigation.

2. Instrumentation and experimental conditions

2.1. Hydraulic wave flume

Experiments were conducted at Kyoto University's Hybrid Tsunami Open Flume in Ujigawa Laboratory (HyTOFU), which has dimensions