AN ABSTRACT OF THE THESIS OF

Mary Elizabeth Oshnack for the degree of Master of Ocean Engineering in Ocean Engineering presented on March 2, 2010.

Title: Analysis of Wave Forces on Prototype Walls under Tsunami Loading

Abstract approved:

Daniel T. Cox

This thesis is comprised of two manuscripts based on a laboratory experiment conducted to examine realistic wave forcing on a vertical wall subjected to tsunami loading. The first manuscript examined tsunami force and pressure distributions on a rigid wall that was fronted by a small seawall. Six different seawall heights were examined, two of which were exposed to a range of solitary wave heights. The same experiment was done without a seawall for comparison. The measured wave profile contained incident offshore, incident broken, reflected broken, and transmitted wave heights measured using wire resistance and ultrasonic wave gauges. Results showed that small individual seawalls increased reflection of the incoming broken bore front and reduced force on the rigid landward wall. These findings agreed well with published field reconnaissance on small seawalls in Thailand that showed a correlation between seawalls and reduced damage on landward structures.

The second manuscript examined cross-shore variation of tsunami loading as the loading scenario changed from an impulse to a quasi-steady bore. In this study tsunami force and pressure distributions on a rigid wall were determined experimentally in a large scale wave flume, and forces were examined experimentally at three different cross-shore locations. Incident offshore and incident broken wave heights measured using wire resistance and ultrasonic wave gauges, and velocity was measured using acoustic-Doppler velocimeters. Force and pressure profiles were measured using load cells and pressure transducers. At each cross-shore location, the force and pressure profiles showed an impulse peak followed by a period of sustained force. This type of profile was seen for each wave height tested, and as expected as wave height increased the value of the maximum impulse force also increased. By examining force time histories, it was also found that while the hydrostatic pressure distribution accurately depicted the force profile during the period of sustained force it was significantly less reliable during the impact period. It was found that as the rigid wall was moved further offshore the peaks were less
pronounced and the corresponding maximum impulse force values decreased. Thus, as the wall was moved onshore the loading scenario transitioned from impact to a quasi-steady bore-like loading condition. The sustained forces measured experimentally verified the empirical formula for steady state force presented by Iizuka and Matsutomi (2000). This theoretical formula was also presented by both the FEMA Coastal Construction Manual (2000) and the City of Honolulu Building Code (2003) as the “hydrodynamic force.”
An Analysis of Wave Forces on Prototype Walls under Tsunami Loading

by
Mary Elizabeth Oshnack

A THESIS
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degree of

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APPROVED:

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Major Professor, representing Ocean Engineering

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Mary Elizabeth Oshnack, Author
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The staff at the O.H. Hinsdale Wave Research Laboratory at Oregon State University provided invaluable support to the experiment. I’d like to thank Linda Fayler for the calibration of the wave gauges and setup of the data acquisition hardware, and Tim Maddux for training me on the running wavemaker and data acquisition software. Sungwon Shin was essential in checking and calibrating the data as well as spending countless hours running numerical models. I’d also like to acknowledge Jason Killian, Melora Park, Alicia Lyman-Holt, and Adam Ryan for the contributions to this research project.

Finally I’d like to thank my boyfriend, Jordan Berkes for supporting me even when my research became overwhelming and for motivating me to finish my thesis in a timely manner.
CONTRIBUTION OF AUTHORS

John van de Lindt and Francisco Aguiniga were essential to the planning and design of the large-scale experiments. Rakesh Gupta was responsible for the design and fabrication of the wooden prototype walls being tested. Sungwon Shin provided constant assistance with the data analysis and was a major contributor to the second manuscript in writing and running countless numerical simulations for data comparisons. Anne Knight, a calculus teacher from Sweet Home High School participated in the NEES-Research Experience for Teachers (RET) and conducted a small scale experiment in the mini wave flume for comparison to the large-scale data. Francisco Galan participated in the NEES-Research Experience for Undergraduates (REU), and helped to conduct the experiment. Francisco’s preliminary work with force and integrated pressure was also the inspiration for the manuscript titled: “Cross-shore Variation of Tsunami Loads on Vertical Walls: Transition for Impulse Loads to Quasi-Steady Bores.”
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An Analysis Wave Forces on Prototype Walls under Tsunami Loading

Introduction

The current United States’ tsunami evacuation strategy puts large populations at a high risk to nearfield tsunamis, and the Pacific Northwest is particularly vulnerable due to its proximity to the Cascadia Subduction Zone (CSZ). In the next fifty years, there is a 14% chance that a nearfield tsunami could be trigged by the CSZ running from Northern California to Vancouver Island, Canada resulting in a devastating wave similar to that of the December 2004 Indian Ocean tsunami (Groat 2005; USGS 2006). Because this nearfield tsunami would possess higher intensity and a shorter arrival time than far field tsunamis of the recent past, it is of upmost importance that coastal communities are prepared for this new disaster scenario.

The current tsunami evacuation strategy for the continental United States requires that everyone evacuates the inundation zone and does not consider the possibility of vertical evacuation using engineered structures within the zone. Failing to consider vertical evacuation creates panic and disorder among evacuees and thus increases the risk of coastal communities under a nearfield tsunami. Part of our unwillingness to adopt vertical evacuation strategies stems from an inability to estimate the damage level in the inundation area for a range of building types, including reinforced concrete (modern hotel), unreinforced concrete masonry units (older motel, light commercial) and light-frame wood (mostly residential and some commercial) structures.

The experiments of this Master’s Thesis project are part of a larger project funded by the Network for Earthquake Simulation (NEES) division of the United States National Science Foundation (NSF) titled “NEES-houseSmash.” The long-term vision of the NEES-houseSmash project is that building damage level, and, therefore, the debris hazard of collapsed structures and potential for vertical evacuation on survivable structures, can be modeled for large coastal communities by coupling existing hydrodynamic flow models with fragility curves. For the project, we tested prototype-scale wood frame walls under hydrodynamic loads due to tsunami bores to develop a fundamental understanding of the fluid-structure interaction. This work was conducted in the Large Wave Flume adjacent to the NEES Tsunami Wave Basin at the O.H. Hinsdale Wave Research Laboratory at Oregon State University. The experimental consisted of six unique parts with each part having several sub-experiments over the 8-week testing program in 2009. This Master’s thesis will examine two of the six experiments in greater detail. The first
is the effectiveness of a small seawall in reducing tsunami forces measured on a prototype vertical wall, and the second is an analysis of the cross-shore variation of tsunami loads on vertical walls as the wave undergoes a transition from an impulse load to a quasi-steady bore. In other words the second part of the thesis will investigate how tsunami force on a vertical wall changes as it is moved further back onshore away from intense wave action.
EFFECTIVENESS OF SMALL ONSHORE SEAWALL IN REDUCING FORCES INDUCED BY TSUNAMI BORE: LARGE SCALE EXPERIMENTAL STUDY

Mary Elizabeth Oshnack, Francisco Aguniga, Daniel Cox, Rakesh Gupta, and John van de Lindt

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Abstract

Tsunami force and pressure distributions on a rigid wall fronted by a small seawall were determined experimentally in a large-scale wave flume. Six different seawall heights were examined, two of which were exposed to a range of solitary wave heights. The same experiment was done without a seawall for comparison. The measured wave profile contained incident offshore, incident broken, reflected broken, and transmitted wave heights measured using wire resistance and ultrasonic wave gauges. Small individual seawalls increased reflection of the incoming broken bore front and reduced force on the rigid landward wall. These findings agree well with published field reconnaissance on small seawalls in Thailand that showed a correlation between seawalls and reduced damage on landward structures.

Introduction and Background

Significance of this Study

The December 2004 Indian Ocean Tsunami visited tremendous loss of life and severe damage on coastal communities and infrastructure, reminding the world of the vulnerability of such communities and infrastructure in tsunami occurrence. Prior to this disaster, few research groups specifically studied tsunami force and subsequent structural failure modes, and many findings were based on field reconnaissance or small-scale experimentation rather than large-scale testing. While several experiments have been conducted on wave force on vertical walls, most have, again, been small-scale or considered regular or random waves rather than the unique solitary wave form and bore like loading conditions present during tsunamis. The experiments in this study provide large-scale data for tsunami-induced force and pressure on a stiff aluminum wall. As several field studies have found qualitative correlation between the presence of small seawalls and reduced wave energy, this study provides quantitative data for tsunami loading on a rigid wall fronted by a small seawall. This analysis of the effectiveness of small seawalls in reducing wave force is expected to be valuable in helping protect coastal communities vulnerable to tsunamis.
Literature Review

Numerous studies have covered generation and propagation of tsunamis through the open ocean; however, research on inundation and tsunami impacts on structures is less common. Wave force on vertical walls has long been studied, but most experiments have been small-scale. Theoretical pressure profiles from water-wave impact on walls have been studied in great detail by Peregrine (2003). Several hydraulic model studies have focused on tsunami loading on structures (Ramsden 1996; Thuyathan and Madabhushi 2008; Arikawa, 2008). Ramsden (1996) focused on the impact of translatory waves (bores and dry-bed surges) rather than breaking waves on a vertical wall at a small scale, but his instrumentation did not resolve short-duration shock loads, and the measured force and moment should only be used for design related to sliding and overturning failure, and are not applicable to punching failure. Thuyathan and Madabhushi (2008) studied the effects of appropriate anchoring and increased openings in the front of 1:25 scale coastal housing on tsunami force and pressure. Arikawa (2008) showed mechanisms of failure due to impulsive loading by tsunamis on vertical concrete walls using large-scale hydraulic flume tests.


In addition to theoretical work and laboratory experiments, field reconnaissance has achieved further understanding of tsunami loading. The performance of buildings in Thailand during the 2004 Indian Ocean Tsunami was reported by Lukkunaprasit and Ruangrassamee (2007), Ruangrassamee et al. (2006), Pomonis et al. (2006), and Saatcioglu et al. (2006). For example, hydrodynamic force from the tsunami was found to be much greater than the previously expected wind based design load for coastal buildings. Poor construction practices and inadequate detailing have contributed to structural failures caused by tsunami loading. Lukkunaprasit and Ruangrassamee (2007) noted that low retaining walls -- seawalls 1 m high -- effectively dissipated tsunami energy. One such wall at Patong Beach in Phuket, Thailand, caused a high splash-up of the incoming wave that has been documented by tourist videos and photographs. A photograph of this seawall is shown in Fig. 1, and buildings directly landward of the seawall suffered only modest structural damage. Dalrymple and Kreibel (2005) suggested
that the splash up of the wave deflected part of the wave’s momentum skyward, reducing force on landward structures. Conducting more detailed reconnaissance on the chain of seawalls in Phuket, Dalrymple and Keibel (2005) found that increased damage was observed directly behind pedestrian openings in the seawall chain. Thus, there is a correlation between small seawalls and reduced structural damage.

This paper discusses large-scale experiments on tsunami bores impacting a stiff wall fronted by a small seawall. Section 2 outlines the experimental setup, including flume bathymetry, test specimens and seawalls, and instrumentation. Section 3 explains experimental procedures, including data acquisition and processing and the test matrix and experimental processes. Section 4 presents results, including examples of raw data, data reduction, and comparisons of force as a function of tsunami and seawall height. Section 5 discusses findings, and Section 6 summarizes conclusions.

**Experimental Setup**

**Wave Flume Bathymetry**

These experiments were conducted in the large wave flume (LWF) at the O.H. Hinsdale Wave Research Laboratory at Oregon State University. The 104 m long, 3.66 m wide, 4.57 m deep flume has a piston wavemaker with a 4 m stroke and a maximum speed of 4 m/s able to generate replicable solitary waves. Beginning at the wavemaker, bathymetry consisted of a 29 m flat section, 26 m of impermeable beach on a 1:12 slope, and a horizontal flat section raised on a 2.36 m high false floor called the “reef.” As shown in Fig. 2, the specimen and seawall were located along the reef, which was 30 m long. Given x-locations are based on the wavemaker board in the zero position. Note the typical still water level (SWL) and that, under these conditions, no water coved the reef.

**Test Specimen and Small Seawall**

The specimen to be tested consisted of an aluminum plate and was 2.14 m high and 3.66 m wide - the wave flume width. The aluminum wall was reinforced with ten vertical studs 0.055 m by 0.178 m spaced at 0.393 m (0.350 m on the two ends), and two horizontal studs 0.120 m by 0.205
m. As also shown in Fig. 2, the front of the rigid wall was 81.3 m from the zeroed wavemaker. Fig. 3 shows overall aluminum wall dimensions and stud locations for the LWF. The small seawall was constructed using dimensional Douglas fir boards 3.8 cm high and 23.5 cm wide stacked vertically and bolted to the flume floor. The seawall was 7.2 m landward of the transition from the reef to the beach and 20 m seaward from the aluminum wall.

**Instrumentation**

Ten wire resistance wave gauges and four ultrasonic wave gauges along one side of the flume wall measured variations in instantaneous water surface level. These wave gauges were calibrated at the start of the experiment and when the flume was drained and refilled. From the wavemaker in the zeroed position, wire resistance wave gages 1 to 10 were located at x-locations of 17.6 m, 28.6 m, 35.9 m, 40.6 m, 42.4 m, 44.2 m, 46.1 m, 48.2 m, 50.3 m, and 54.4 m. Ultrasonic wave gage 1 was co-located with wave gage 4 (40.6 m), enabling the calibration of other surface piercing gauges to be corrected for changes due to variation in chlorine from the city water supply. Surface piercing wave gage accuracy was estimated at less than 1% of the full-scale reading for nonbroken waves. A sonic gage seaward (x=58.1 m) and landward (x=65.1 m) of the small seawall estimated incident, reflected, and transmitted wave heights, detailed later. A sonic wave gage was also located on the moveable bridge at 21.5 m from the zeroed wavemaker. The wavemaker was instrumented with sensors to monitor its x position and the water level on the wavemaker board as functions of time. Four acoustic Doppler velocimeters (ADVs) on the side of the flume at x-positions of 43.3 m, 47.0 m, 54.2 m, and 57.9 m collected wave particle velocity for comparison to numerical models, presented elsewhere. Fig. 2 shows the locations of flume instrumentation, where W is a wire resistance wave gage, U a sonic wave gage, and A an acoustic-Doppler velocimeter.

The specimen had four uniaxial donut-shaped load cells with a capacity of ± 89 kN (± 20 kip). One load cell was installed on each corner of the aluminum wall between a plate on the aluminum wall and a clip bolted to the flume wall specifically to hold the load cell in place. Load cells measured horizontal force on the wall. The specimen also had three pressure transducers (Druck PDCR-830) set horizontal to aluminum plates, which were placed in small holes cut in the wall. Transducers were at 0.22, 0.51, and 0.92 m heights on the wall. Load cells (L1-4) and pressure transducers (P1-3) are shown in Fig. 3.
Experimental Procedures

Data Acquisition and Processing

Data were recorded and stored using National Instruments 64-channel PXI-based real-time data acquisition. Software controlling data acquisition was LabVIEW 8. Hydrodynamic data -- free surface displacement and velocity -- were collected at a sampling rate of 50 Hz. Force and pressure data were collected at a sampling rate of 1000 Hz.

Experimental Processes

As shown in Fig. 2, experiments were conducted with the reef dry, essentially modeling the dry beach common at urban waterfronts. While the wavemaker was zeroed, the water level was set at 2.38 m from the flume bottom, at which depth the water level was aligned with the point at which bathymetry changed from beach to reef. The wavemaker was then fully retracted, decreasing the water level due to the finite flume volume. The still water depth \( D_o \) with the wavemaker retracted was 2.29 m, corresponding to -0.07 m below the reef \( D_R \). The tsunami was modeled as an idealized solitary wave using forward paddle movement typical in these studies. Because of the flume’s finite volume, this produced a still water level +0.03 m above the reef at the end of tests from 40 < \( t < 55 \) s, as can be seen in Fig 4b.

Table 1 summarizes trials. Experiment names and trial numbers correspond to those in the experimental notebook supported under the Network for Earthquake Engineering Simulation (NEES) program of the United States National Science Foundation. The RigidWall_1 experiment is the control group of trials in which force was measured on the aluminum wall with no seawall for protection, Macro_1 is testing of a 0.24 m seawall under a variety of wave heights. Marco_2 is the testing of different seawall heights, detailed below. \( H \) is the desired nominal wave height input to the wavemaker, \( H_2 \) is the wave height measured by offshore wave gauge 2, \( D_S \) is the seawall height and \( D_0 \) and \( D_R \) the still water and reef depth defined above. Experimental data will be made public through the NEES data archive.

Four sets of conditions were run:
Condition 1: A 0.24 m high seawall was placed in the flume as described above. To obtain tsunami force on the specimen under the presence of a 0.24 m seawall as a function of wave
height, nominal heights of 0.40, 0.60, 0.80, 1.00, and 1.20 m were run corresponding to heights measured at wave gauge 2 of 0.39, 0.57, 0.74, 0.91, and 1.06 m, as shown in Table 1. We refer to the measured wave height at wave gauge 2 and provide the nominal wave height in parentheses for reference to file names in the NEES Experimental Notebook (e.g., Baldock et al., 2008).

Condition 2: The seawall height was changed to 0.12 m and the same waves were run.

Condition 3: To better understand force reduction as a function of seawall height, the height of the wall was changed to 0.04, 0.08, 0.16, and 0.20 m by varying the number of wooden boards composing the wall. A $H_2 = 0.74$ m wave ($H=0.8$ m) was run for each wall configuration.

Condition 4: An experiment was conducted under the same conditions with no seawall for comparison. The overall dataset contains 21 runs -- 7 with no seawall, 5 with a high 0.24 m seawall, 5 with a low 0.12 m seawall, and 4 additional runs with varied seawall heights under an $H_2 = 0.74$ m ($H=0.8$ m) wave. The 0.24 m and 0.12 m walls are included in this set of 6 runs for comparison.

**Results**

An example of data collected is shown in Fig. 4 for an experimental run using a wave height of $H_2 = 0.74$ m ($H=0.8$ m) and a seawall height of 0.12 m. Fig. 4 shows the following variables -- (4a) wavemaker displacement (black) and free-surface displacement on the wavemaker (blue); (4b) free surface displacement measured by wire resistance wave gauges 1-5 with a total of 10; (4c) free surface displacement collected by ultrasonic wave gauges -- incident before breaking (blue - wave gauge 1), transmitted over the seawall (red - wave gauge 2), and broken incident/reflected off the seawall (green - wave gauge 3); (4d) velocity measured by ADV 1 and 2 from a total of 4; (4e) force data collected by the four load cells -- L3 and L4 at the bottom of the wall and L1 and L2 at the top; and (4f) pressure data collected by pressure transducers PS 1, PS 2, and PS 3 located at heights of 0.218 m, 0.512 m, and 0.921 m on the wall. Graphs similar to these were made for each run to ensure all instrumentation was operating properly. Note that ADV data were filtered to reduce unwanted noise from air entrainment.

Fig. 5 shows force and pressure time histories for each seawall at a wave height of $H_2 = 0.74$ m ($H=0.8$ m). Total force on the rigid wall was obtained by summing the four load cells, and the pressure transducer at the lowest elevation, P1, gave the pressure time history. As shown in Fig. 4f the two pressure transducers higher on the wall had small or, in many cases, zero readings,
so the lowest pressure transducer was representative of the depicted pressure time history. Note that as seawall height increases, force and pressure peaks decrease. Comparing the 0.24 m seawall (green) and no seawall (blue) force profile shows that maximum force under a 0.24 m seawall is only 35% of force in the absence of the seawall, which reduces total force by 65%. The graph also shows that the force profiles for the 0.20 m and 0.24 m seawalls are absent of the sharp force peaks that are present under smaller seawall heights. Pressure distributions show similar trends. Note the distinction between relatively smooth integrated force measured by load cells, as shown in Fig. 5a, and high localized pressure fluctuation shown in Fig. 5b. Note that as seawall height increases, the time it takes for the wave to impact the wall -- determined by the start of the sharp increase or “heel” in the force time history -- increases similarly, showing that seawalls act to decrease bore speed. This potentially interesting affect requires further study.

In addition to reduced force, seawalls were also found to cause reflection/splash-up of the broken incoming wave’s profile. Fig. 6 shows the unbroken measured height $H_L$ from sonic wave gage 1, the height of the broken bore $H_B$, and the height of the broken bore reflected off of the seawall, $H_R$ (both $H_B$ and $H_R$ were measured by sonic wave gage 3). As expected, the highest seawall caused the greatest reflection -- an $H_R/H_B$, ratio of nearly 1 -- and the height of the reflected wave decreases with seawall height over the range of conditions tested. Fig. 6 also shows the high level of repeatability in wave height measurement. Note the similarity between offshore wave profiles (black lines) even after breaking and the broken bore (colored lines) before hitting the seawall. This high level of repeatability for incident and broken waves lends credibility to reflection measurement. Fig. 7 shows maximum broken incident ($H_B$), broken reflected ($H_R$), and transmitted ($H_T$) waves for 0.12 and 0.24 m seawalls for a range of wave heights. Broken incident wave conditions are very similar regardless of seawall height, this is also shown in Fig. 6, and the height of the broken incident wave increases linearly as offshore wave height $H_2$, measured by wave gauge 2, increases. Note that for the 0.24 m seawall when $H_B$ is less than the height of the seawall, $D_S$, reflection exceeds the incident broken wave height. When $H_B$ is nearly equal to $D_S$, reflection is very close to the incident broken wave height, and when $H_B$ exceeds $D_S$, reflection is less than the broken incident wave height. For the 0.12 m seawall, $H_B$ is greater than $D_S$ for each wave condition, and reflection is less than the broken incident wave height. Fig. 7b shows that the transmitted wave height increases linearly with offshore wave height for both seawalls.

Fig. 8 summarizes experimental findings showing measured force, pressure, time for the broken bore to reach the aluminum wall, and the ratio of $H_R$ to $H_B$ as functions of seawall height.
As expected, the largest seawall causes the lowest force and pressure on the aluminum wall by reflecting the greatest percentage of the broken bore. It also takes the longest for the bore front to reach the rigid wall in the presence of the largest seawall. Fig. 9 shows a similar trend in plotting maximum force and percent reflection for 0.12 and 0.24 m seawalls at a variety of wave heights. As expected, force increases with wave height and the highest seawall reduces force the most over the range of wave heights tested. A similar trend was found for pressure (not shown due to space limitations). As shown by Fig. 7 and reaffirmed by Fig. 9, the 0.24 m seawall effectively deflected each wave height. The 0.12 m seawall was also effective, especially at lower wave heights.

**Discussion**

Fig. 5 suggests that higher seawalls (0.20 and 0.24 m) reduce total force so as to eliminate sharp peaks (impulse loading) for a H2= 0.74 m- (H=0.8 m) wave height. Note that the force profile for the 0.12 m seawall in Fig. 5 is somewhat peculiar. Other profiles appear to have a group of high force readings before the peak, while the force profile in the presence of the 0.12 m seawall (red line) appears to rise rapidly to the peak. This slightly skewed profile explains why travel time for the 0.12 m seawall in Fig. 8 is slightly above the linear trend shown by other points. Peak force in the presence of a 0.12m seawall is slightly higher than the peak for a 0.16 m seawall, and the reason for this discrepancy is unknown. Both lower load cells exhibit similar force time histories and replays of the video for this run did not provide any insight. Further experimentation, possibly coupled with numerical investigations, are thus needed to attain conclusive results.

Fig. 7 suggests that the maximum reflection height is governed somewhat by seawall height. For both seawall heights, when the height of the broken incident wave exceeded seawall height heights of transmitted and reflected waves were both less than the height of broken incident waves. For the two cases in which the height of the broken incident wave was less than the seawall height, reflected wave height exceeded broken incident wave height. The relationship that can be drawn from Fig. 7 between waves transmitted by 0.12 and 0.24 m seawalls is somewhat inconclusive. For H2= 0.74 m (H=0.8 m) and H2= 0.90 m (H=1.0 m) wave heights the larger seawall actually enables higher transmitted wave height. This may be related to the details of the hydraulic jumps formed at the base of the seawall and the rate at which the energy is dissipated.
Summary and Conclusions

This study is a first step in further understanding the effectiveness of small-scale seawalls in reducing tsunami wave force. The 0.20 m and 0.24m seawalls most effectively reduced wave force on the rigid wall over the range of conditions tested. Force and pressure time histories for this wave height do not show sharp peaks, indicating that a seawall may effectively reduce impulsive wave force. A further study is required to understand detailed dynamics. A correlation between seawall height and the ratio of broken incident wave height to reflected wave height was also found. Based on the ratio of broken incident wave height to reflected wave height, the 0.24 m seawall effectively reflected wave height. The 0.12 m seawall was also effective (H_r/H_b > 0.50) at smaller wave heights, and H_r/H_b was equal to 0.48 and 0.45 for the largest wave heights of 1.0 and 1.2 m. Using a limited number of wave conditions and seawall configurations we concluded that as seawall height is increased, the reflection of the incoming wave is greater, and force on the onshore structural element is reduced. Force reductions observed in these experiments range from 23% to 84% for offshore waves up to 4 times the seawall height – an observation that holds for both 0.12 and 0.24 m high seawalls over the range of wave heights tested. As suggested by a reviewer, it is important to note that the results of this study are only valid for this particular setup because the distance between the seawall and structure should play a role in determining force on the onshore structural element.

Acknowledgements

This research was supported by the National Science Foundation under Grant No. CMMI-0830378. The tsunami facility is supported in part by the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Program of the United States National Science Foundation under Award Number CMMI-0402490. We thank the O.H. Hinsdale Wave Research Laboratory staff of Tim Maddux, Melora Park, Jason Killian, Sungwon Shin, Alicia Lyman-Holt, and Adam Ryan for its invaluable support. We hereby acknowledge the work of Milo Clauson of Oregon State University, Francisco Galan of San Jose State University, Manuel Guerra of Texas A&M Kingsville, and Sangki Park of Colorado State University for their assistance in conducting experiments.
Figures

Fig.1. Small seawall at Patong Beach, Phuket, Thailand (Photo courtesy of Robert Dalrymple).
Fig. 2. Elevation of wave flume with experimental setup: W is a wire resistance wave gage, U a sonic wave gage, and A an acoustic-Doppler velocimeter.
Fig. 3. Elevation of test specimen with instrumentation: L denotes load cells and P pressure transducers.
Fig. 4. Example time series of data collected during a typical run corresponding to $H_2 = 0.74$ m ($H = 0.80$ m), $D_s = 0.12$ m: (a) wavemaker displacement and free-surface displacement on the wavemaker; (b) free surface profile: wire resistance wave gages 1-5; (c) free surface profile: ultrasonic wave gages; (d) velocity measured by ADV 1, 2; (e) force; and (f) pressure measurements.
Fig. 5(a) Total force and (b) pressure time histories for different seawall combinations at a wave height of $H_2 = 0.74$ m ($H=0.8$ m). Pressure is read from the lowest pressure transducer shown in Fig 3.
Fig 6. Free surface time series measured by ultrasonic wave gages. Numbers in the graph indicated seawall height in meters. Note the high repeatability of measurements shown by the unbroken wave and broken bore. Note the decrease in the reflected bore as seawall height is decreased.
Fig. 7. Incident, reflected, and transmitted bore height as function of offshore wave height. Bore height measured by ultrasonic wave gage 3 (a-red, magenta), and transmitted bore heights by ultrasonic wave gage 2 (b-red, magenta) as functions of offshore wave height measured by resistance wave gage 2. Both cases of broken incident waves were measured by ultrasonic wave gage 1 (a, b-blue, green).
Fig. 8. (a) Force and pressure, (b) travel time, and (c) reflection variations with seawall height for a wave height of $H_2 = 0.74$ m ($H=0.8$ m).
Fig. 9. (a) Maximum force and (b) reflection as a function of measured offshore wave height
### Table 1: Experimental Trials Run During Seawall Experiment

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References


CROSS-SHORE VARIATION OF TSUNAMI LOADS ON VERTICAL WALLS: TRANSITION FROM IMPULSE LOADS TO QUASI-STeady BORES

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Abstract

Tsunami force and pressure distributions on a rigid wall were determined experimentally in a large scale wave flume. Forces were examined experimentally at three different cross-shore locations. Incident offshore and incident broken wave heights measured using wire resistance and ultrasonic wave gages, and velocity was measured using acoustic-Doppler velocimeters. The force and pressure profiles were measured using load cells and pressure transducers. At each cross-shore location, the force and pressure profiles showed an impulse peak followed by a period of sustained force. This type of profile was seen for each wave height tested. As wave height increased the maximum impulse force also increased. By comparing the force time histories with the integrated pressure distribution, it was also found that the hydrostatic pressure distribution accurately depicted the force profile during the period of sustained force. The integrated pressure distribution was significantly larger than the forces measured by the load cell owing to the dynamic effects of the large wall. It was found that as the wall was moved further from the still water shoreline, the peaks were less pronounced and the corresponding maximum impulse force decreased. Thus, as the wall was moved onshore the loading scenario transitioned from impact to a quasi-steady bore-like loading condition. The sustained forces measured experimentally agreed well with the empirical formula for steady state force presented by Iizuka and Matsutomi (2000). This theoretical formula was also presented by both the FEMA Coastal Construction Manual (2000) and the City of Honolulu Building Code (2003) as the “hydrodynamic force.”

Introduction and Background

The December 2004 Indian Ocean Tsunami plagued coastal communities with loss of life and severe damages to coastal infrastructure. This disaster has renewed attention paid to the vulnerability of coastal communities to tsunami hazards and tsunami forces and loading. Previous to this disaster, few research groups have specifically investigated tsunami forces and subsequent structural failure modes, and many of their findings were based on field reconnaissance or small scale experimentation rather than large scale testing. While there have been several experiments investigating wave forces on vertical walls, most have been at a small
scale or considered regular or random waves, rather than the unique solitary wave form and bore like loading conditions present during a tsunami.

While there have been numerous studies on the generation and propagation of tsunamis across the ocean, research on inundation and tsunami impacts on structures is less common. Wave forces on vertical walls have also been the subject of research for many years; however, most experiments have been conducted at a small scale (Ramsden 1996; Thusyanthan and Madabhushi 2008). Ramsden (1996) focused on the impact of translatory waves (bores and dry-bed surges) rather than breaking waves on a vertical wall at a small scale. However, the instrumentation used in his study did not resolve short-duration shock loads, and the measured forces and moments should only be used for designs related to sliding and overturning failures and are not applicable to punching failures. Also at a small scale, Thusyanthan and Madabhushi (2008) investigated the effects of proper anchoring and increased openings in the front of 1:25 scale model coastal houses on tsunami force and pressure. Arikawa (2008) showed the mechanisms of failure due to impulsive loading by tsunamis on vertical concrete walls using large-scale hydraulic flume tests.

This study also used speed and wave profile of the inundated tsunami to qualitatively divide surge front tsunami force into three types: overflow, bore, and breaking. In the case of overflow the flooding velocity is low. Flow under type 2 is much quicker and the inundated tsunami carries out soliton fission, or becomes a bore. Type 3 was described as the case where the tsunami breaks in front of the structure, which occurs when structures are near the coastline. Arikawa (2008) stated that if the height of the inundated tsunami is the same then the maximum force will increase as the surge front transitions from the overflow type to the breaking type. However, the author also stated that it is unclear as to how much greater the breaking force is and as to where the boundary line between the different inundation types lies.

Yeh et al. (2005) developed design guidelines for buildings subjected to tsunami loading by conducting a detailed analysis of tsunami forces and compiling equations from the following design codes which currently address loads under flooding and wave situations: The City and County of Honolulu Building Code (CCH 2003), The Uniform Building Code (UBC 1997), The International Building Code (IBC 2000), The American Society of Civil Engineers Committee 7, (ASCE 2006), and the Federal Emergency Management Agency Coastal Construction Manual (FEMA 2000).

In addition to theoretical work and laboratory experiments a further understanding of tsunami loading has also been achieved through field reconnaissance. The performance of
buildings in Thailand during the 2004 Indian Ocean Tsunami has been reported by Lukkunaprasit and Ruangrassamee (2007), Ruangrassamee et al. (2006), Pomonis et al. (2006), and Saatcioglu et al. (2006). It has been found that the hydrodynamic forces from the tsunami was much larger than previously expected based wind design loads for coastal building, for example. Poor construction practice and inadequate detailing have also contributed to structural failures caused by tsunami loading.

The Journal of Disaster Research has also recently released a special issue (Volume 4, Number 6, December 2009) addressing tsunami effects on buildings and infrastructure. The special issue contained 14 papers, and those described below are of particular relevance to this paper. Arikawa (2009) experimentally investigated the structural performance of wooden and concrete walls using a large-scale laboratory tank in Japan. Oshnack et al. (2009) used a similar large wave flume in the United States to show the effectiveness of small seawalls in reducing tsunami forces on a vertical wall. The issue also contained a section focused on tsunami force on 3-D structures with papers by Arnason et al. (2009), Fujima et al. (2009), and Lukkunaprasit et al. (2009). Van de Lindt et al. (2009) examined tsunami loading on light-frame wood buildings, and Matsutomi summarized his previous research on impact force by driftwood. Yim and Zhang (2009) numerically simulated tsunami impact on a vertical cylinder.

This paper describes a large-scale experiment conducted at Oregon State University’s O.H. Hinsdale Wave Research Laboratory for tsunami bores impacting a rigid wall at three cross-shore locations and uses essentially the same setup described in Oshnack et al. (2009). Section 2 gives an overview of the experimental setup, including the flume bathymetry, test specimen, and instrumentation. Section 3 explains the experimental and numerical modeling procedures, including the data acquisition and processing and details of the test matrix and experimental process. Section 4 provides the results, including examples of the raw data, data reduction, and comparisons of the force as a function of tsunami height and that vertical wall’s distance from the shoreline and provides a discussion of the findings, Section 5 discusses a small-scale experimental comparison and future work to be carried out, and Section 6 concludes the paper.
Experimental Setup

Wave Flume Bathymetry

This experiment was conducted in the Large Wave Flume (LWF) at the O.H. Hinsdale Wave Research Laboratory at Oregon State University. The flume was 104 m long, 3.66 m wide, and 4.57 m deep. It is equipped with a piston-type wavemaker with 4 m stroke and maximum speed of 4 m/s, capable of generating repeatable solitary waves. Beginning at the wavemaker, the bathymetry was comprised of a 29 m flat section, followed by 26 m of impermeable beach at a 1:12 slope, followed by a horizontal flat section raised on a 2.36 m high false floor. For consistency with other experiments and nomenclature used at the Hinsdale Wave Research Laboratory, this elevated flat section will be referred to from hereafter as the “reef”. The specimen was moved to three different cross-shore locations along the 30 m long reef. Fig. 1 shows the overall dimensions of the wave flume and the three x-locations of the test specimen. The x-locations given are based on the wavemaker board in the zero position (fully retracted). This figure also shows a typical still water level (SWL). Under these conditions there is no water on the reef.

Test Specimen

The specimen to be tested was representative of an infinitely rigid wall and is the same specimen used in the experiments by Oshnack et al. (2009). The specimen was made of aluminum and measured 2.14 m high and 3.66 m wide (the width of the wave flume). The aluminum wall was reinforced with ten vertical studs (0.055 m by 0.178 m) spaced at 0.393 m (0.350 m on the two ends), and two horizontal studs (0.120 m by 0.205 m). As shown by Fig. 1, the front face of the rigid wall was located at 7.03 m, 14.63 m, and 29.02 m from the zeroed wavemaker. Fig. 2 shows the overall dimensions and stud locations for the aluminum wall with respect to the LWF.

Instrumentation

As in the experiment by Oshnack et al. (2009) ten wire resistance wave gages and four ultrasonic wave gages were mounted along one side of the flume wall to measure variations in the
instantaneous water surface level. These wave gages were calibrated at the start of the experiment and when the flume was drained and refilled. From the wavemaker in the zeroed position, wire resistance wave gages 1 to 10 were located at respective x-positions of 17.6 m, 28.6 m, 35.9 m, 40.6 m, 42.4 m, 44.2 m, 46.1 m, 48.2 m, 50.3 m, and 54.4 m. Ultrasonic wave gage 1 was co-located with wave gage 4 (40.6 m). This enabled the calibration of the other surface piercing gages to be corrected for changes due to variation in the chlorine from the city water supply. Using this method, accuracy of the surface piercing wave gages (TS-30S1) was estimated to be less than 1% of the full scale reading for the non-broken waves. Ultrasonic wave gage 2 and 3 were located at x-positions of 54.4 m and 58.1 m. There was also a sonic wave gage located on the moveable bridge located at 21.5 m. The wavemaker was instrumented with sensors to monitor its x position and the water level on the wavemaker board as functions of time. Four acoustic-Doppler velocimeters (ADVs) were also mounted along the side of the flume at x-positions of 43.3 m, 47.0 m, 54.2 m, and 57.9 m. ADVs (Nortek Vectrino) collected wave particle velocities for comparison to numerical models. The locations for all of the above flume instrumentation are shown in Fig. 1 and listed in Table 1.

The specimen was equipped with four uni-axial donut-shaped load cells with a capacity of ± 20 kip (± 89 kN). There was one load cell on each corner of the aluminum wall. They were mounted between a plate on the aluminum wall and a clip bolted to the flume wall specifically designed to hold the load cell in place. In this arrangement, the load cells measured horizontal forces on the wall. The specimen was also instrumented with three pressure transducers (Druck PDCR-830). The pressure transducers were mounted horizontally to aluminum plates, which were placed into small holes cut in the wall. The transducers were located at heights of 0.22 m, 0.51 m, and 0.92 m on the wall. The locations of load cells and pressure transducers are shown by Fig. 2 and listed in Table 2.

**Experimental Procedure**

**Data Acquisition and Processing**

All data were recorded and stored using a National Instruments 64-channel PXI-based real-time data acquisition system. The software used to control the data acquisition process was LabVIEW 8. Hydrodynamic data (free surface displacement and velocity) were collected with a sampling rate of 50 Hz. Force and pressure data were collected with a sampling rate of 1000 Hz.
Experimental Process

As indicated in Fig. 1, this experiment was conducted with a dry water depth on the reef to model the dry portion of the beach that would be common in an urban waterfront area. While the wavemaker was in the zero position, the water level was set to 2.38 m from the bottom of the flume. At this depth, the water level was aligned with the point where the bathymetry changed from beach to reef. The wavemaker was then retracted, causing a decrease in the water level due to the finite volume of the flume. The still water depth with the wavemaker in the retracted position was approximately 2.29 m, from hereafter referred to as $D_o$, which corresponds to -0.07 m below the reef ($D_R$). The tsunami was modeled as an idealized solitary wave using the forward motion of the paddle, as is typical for these types of studies. Because of the finite volume of the flume, this produced a still water level approximately +0.03 m above the reef at the end of the tests as can be seen in the second panel of Fig. 3 from $40 < t < 55$ s.

A summary of all trials run is shown in Table 3. The experiment names and trial numbers correspond to those in the experimental notebook supported under the Network for Earthquake Engineering Simulation (NEES) program of the National Science Foundation. For each experiment the rigid wall was moved to a new x-location along the reef while keeping the water depth constant. The experiments “RigidWall_1,” “RigidWall_2,” and “RigidWall_4” respectively refer to specimen locations of 7.03 m, 14.6 m, and 29.0 m from the start of the reef. This x-location is represented by the variable “x” in Table 1. In Table 1 $H$ refers to the target (nominal) wave height input into the wavemaker, $H_2$ refers to the wave height measured by wave gage 2, and $D_o$ and $D_R$ are the still water and reef depths as defined above. The experimental data will be made public through the NEES data archive (e.g., Baldock et al., 2008).

The goal of the experiments was to obtain the temporal and spatial variation of tsunami force on the specimen as a function of wave height at three given x-locations. For the first experiment, RigidWall_1 (x=7.03), nominal wave heights ranged from 0.40 m to 1.2 m, and the target wave height, $H$ was incremented by 0.10 m on every trial. Corresponding wave heights measured at wave gage 2 are reported in Table 1. Hereafter in this paper, we refer to the measured wave height at wave gage 2 and provide the nominal wave height in parenthesis for reference to the file names in the NEES Experimental Notebook (e.g., Oshnack et al. 2009). The same target wave heights were run for RigidWall_2 (x=14.6 m) and RigidWall_4 (x=29.0 m), where the specimen was located further from the shoreline. There was less impact and minimal splashing of
water out of the flume at these locations. This allowed additional wave heights up to $H_2=1.24$ m ($H=1.40$ m) for the experiments where the specimen was located at $x$-locations of 14.6 and 29.0 m as shown in Table 3.

**Results and Discussion**

An example of data collected is shown in Fig. 3 for an experimental run using a wave height of $H_2=1.07$ m ($H=1.2$ m). Fig. 3 shows the following variables: (3a) wavemaker displacement (black) and free-surface displacement on the wavemaker (blue); (3b) free surface displacement measured by wire resistance wave gages 1-5 with a total of 10; (3c) free surface displacement collected by ultrasonic wave gages, including incident before breaking (blue-wave gauge 1), and broken incident/reflected off the specimen (red-wave gauge 2, green-wave gauge 3); (3d) velocity measured by onshore ADV’s 1 and 2 from a total of 4; (3e) force data collected by the four load cells – L2 and L4 at the bottom of the wall and L1 and L3 at the top; and (3f) pressure data collected by pressure transducers PS 1, PS 2, and PS 3 located at heights of 0.218 m, 0.512 m, and 0.921 m on the wall. Graphs similar to these were made for each run to ensure all instrumentation was operating properly. Note that ADV data were filtered to reduce unwanted noise due to air entrainment.

Fig. 4a shows a force time history for the specimen at each cross-shore location at a wave height of $H_2=1.07$ m ($H=1.2$ m). Total force on the rigid wall was obtained by summing the four load cells (maximum total force is listed in Table 3). Note that as the wall is moved from $x=7.0$ m to $x=14.6$ m the peak impulse forces were reduced by a factor of two, and they were reduced by a factor of 3 as the wall was moved from $x=7.0$ m to $x=29.0$ m. Fig. 4b shows a pressure time history from PS 1, the pressure transducer located at the lowest height on the wall. The other two pressure transducers showed similar histories, but at a much smaller scale: this is shown by Fig. 3f. A total pressure was calculated by plotting pressure transducer height vs. instantaneous pressure (as recorded by each sensor) and using a best-fit line to determine the maximum pressure that would be present at the base of the wall. Multiplying the area under that triangle by the width of the wall resulted in a force based on the integrated pressure. Fig. 5 shows this “integrated pressure” force (red dots) compared to the corresponding force-time history measured by the load cells (blue line) for each cross-shore location. It is evident that the integrated pressure values agree well with the force-time history measured by the load cells during the period of
sustained force (33 to 39 s in Fig 5a). The integrated pressure is significantly larger than the force-time history measured by the load cells during the impact pressure (31.5 to 32.5 s in Fig 5a) due to the dynamics of the “rigid” wall. During the experiment, the vibration of the large wall could be felt during impact, thus it is reasonable to assume that mass of the wall times this acceleration accounts for much of the discrepancy although the acceleration was not directly measured for this experiment. Similar to the work presented here, Arikawa (2008) divided observed force time history into two regimes: an impulsive bore pressure and a sustainable pressure and noted that Iizuka and Matsutomi (2000) have proposed an empirical formula for force in the state of steady flow (Eq 1).

\[
F_{H} = \frac{1}{2} \rho C_D u^2 h_f B_h
\]

(1)

where \(F_{H}\) is the horizontal sustainable force of a structure, \(u\) is the velocity of inundated tsunami, \(C_D\) is the drag coefficient (=1.1 to 2.0), \(h_f\) is the inundated tsunami height in front of a structure, and \(B_h\) is the width of the structure. Since \(u\) is proportional to the square root of the height of inundated tsunami, \(F_{H}\) is proportional to a square of the inundated height. The results of this equation are shown in Fig. 5 (vertical green line) for each cross-shore location. The midpoint of the range of theoretical values was determined by using the wave height measured by ultrasonic wave gauge 3 for \(h_f\), the square root of \(gh_f\) as the velocity (\(u\)), and 1.5 as \(C_D\). Yeh et al. (2005) used Eq. 1 to represent hydrodynamic force and recommend a \(C_D\) value of 1.5 for wall sections. The lower and upper limits of the theoretical range were determined by using \(C_D\) values of 1.0 and 2.0. Fig. 6 shows wave height (upper panels) and velocity (lower panels) measurements recorded by the co-located instruments: ultrasonic wave gage 3 and ADV 4. There are gaps in the ADV data due to filtering of unwanted noise from air entrainment. Therefore, the square root of \(gh_f\) (also plotted in Fig. 6-lower panels) was used to represent velocity. However, a maximum ADV velocity of 2.85 m/s is apparent in the lower panels of Fig 6b and 6c, and Fig 5 (green *) shows the theoretical force calculated by using this velocity. Note that the theoretical force from the ADV velocity is within the upper limit of the theoretical values obtained by varying the drag coefficient. FEMA CCM and CCH suggest using Eq. 2, based on Dames & Moore (1980) to determine the flood velocity \(u\) in the surge depth \(d_s\) (\(d_s\) is equivalent to \(h_f\) in this analysis).

\[
u = 2\sqrt{gd_s}
\]

(2)
The theoretical force calculated by using this velocity is also shown in Fig 5 (green circle). Note that these theoretical force values are much greater than the range predicted by Iizuka & Matsutomi and in the x-locations with less severe impact forces (x=14.6 m and x=29.0 m), the theoretical force actually predicts the impulse force rather than the sustained force.

Fig. 7 shows force on the specimen as a function of cross-shore position. Note that at x=7.1 m the integrated pressure over-predicts the force measured by the load cell by a factor of 2.1 for the impulse regime. However, as the wall was moved further back onto shore, the impulse integrated pressure was greater by factors of 2.2 and 1.6 for wall locations of 14.6 m and 29.0 m, respectively. For the sustained regime the integrated pressure was about 1.4 times greater than the load cell measurement and regardless of cross-shore location. The points in Fig. 7 were determined by taking the average of the boxed points in Fig. 5 for the impulse region and the average of the points where the theoretical line is drawn for the sustained region. Fig. 8 was created in similar manner to Fig. 7, using a range of wave heights for a fixed cross-shore location (x=29.0 m-the furthest from the shoreline). Once again for the region of sustained force, the integrated pressure was about 1.2 times greater than the load cell measurement for the range of wave heights tested. However, as the wave heights and the impact increased the integrated pressure was 1.2 to 1.8 times greater than the load cell measurement for the impulse region. Thus, the greatest differential between the integrated pressure and the force measured by the load cell was when the wall was closest to the shore and experienced the largest impulse forces.

When the wall was located at the cross-shore position closest to the still water shore line (x=7.1 m) the forces were the greatest, and the force peaks were the sharpest (shown by Fig. 4). As the wall was moved landward from the still water shore line, the peak of the impact force peaks were less sharp and the impact forces decreased. However, the quasi-steady forces were nearly constant. Fig. 9 shows that this trend held true over the range of wave heights tested in this experiment. The error bars in Fig. 9 were based on the standard deviation of 25 points before and after the peak impulse force. In other words, the force profiles with the most drastic peaks had the largest error bars. In our experiment, the sharpest force peaks occurred when the wall was located at x=7.1 m under the largest wave heights.
Small Scale Testing

Of the three flow regimes presented by Arikawa, this experiment focused on the bore-like loadings at all three locations. However, the impulsive loading could be seen to exist at the location nearest to the still water shoreline (x=7.1 m) and all three locations exhibited some unsteady affects. It is still unclear where the boundary between flow regimes types lies, and it is difficult to classify them quantitatively. In attempt for a more quantitative analysis the authors have conducted a small-scale experiment in flume 4.88 m long, 0.10 m wide, and 0.30 m deep. The bathymetry was similar to that of the large scale experiment and the water depth was held constant at 0.14 m. The rigid wall was moved to 16 cross-shore locations, and a 0.05 m wave was run at each location. For this experiment data were collected at 200 Hz. Fig. 10 shows the normalized results of this experiment combined with the large-scale data shown in Fig. 9. Force data were normalized by a linear force scale $F_1$ as done by Ramsden (1996)

$$F_1 = \frac{1}{2} \gamma b (2H + h_w)^2$$

Where $\gamma$ is the weight of water per unit volume, $b$ is the width of the wall, $H$ is offshore wave height, and $h_w$ is the water depth at the wall. Cross-shore distance was normalized by dividing by water depth. Fig. 10 shows an exponential decay as the wall is moved further onto the reef, while this is an interesting find these results are preliminary and warrant further investigation. Thus, a numerical model of the experiment using a time-dependent numerical model will be carried out to provide credibility to the preliminary findings.

Summary and Conclusions

A large-scale experiment was conducted to gain a further understanding of tsunami force as a function of cross-shore distance. It was found that the force-time history exhibited a sharp impulsive peak followed by a sustained force. Integrated pressure accurately depicted the force profile measured by the load cells during the period of sustained force. However, the impact force was much more difficult to model, and the integrated pressure over-predicted the force profile measured by the load cells during the impulse period due to the dynamic affects of the large wall. When the force peaks were less sharp (either a smaller wave, or a cross-shore
location further from wave breaking) the integrated pressure and measured force profiles agreed more closely. An exponential decay in force was found as the wall was moved further onshore and the incoming wave transitioned from an impulsive load to a quasi-steady bore. However, this finding warrants further investigation, and a numerical simulation will be carried out to confirm or refute these results. For this experiment, the measured sustained force values corresponded to the theoretical force values of Iizuka and Matsutomi (2000).

Acknowledgements

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Figures

Fig. 1. Elevation view of wave flume with experimental setup.
Fig. 2. Elevation view of test specimen with instrumentation.
Fig. 3. Example time series of data collected during a typical run where $H_2=1.07$ m ($H=1.2$ m) and $x=7.0$ m: (a) wavemaker displacement and free-surface displacement on the wavemaker; (b) free surface profile: wire resistance wave gages 1-5; (c) free surface profile: ultrasonic wave gages; (d) velocity measured by ADV 1, 2; (4e) force; and (4f) pressure measurements.
Fig. 4 Total force (a) and pressure (b) time histories for different cross-shore locations under a nominal wave height of 1.2 m ($H_2=1.07$ m). Pressure reading was taken from lowest pressure transducer, P1 shown in Fig. 2.
Fig. 5. Variation between load cell and force derived from integrated pressure readings at (a) x=7.1 m, (b) x=14.6 m, and (c) x=29.0 m. Theory of Iizuka et al. (2000) is also plotted for each location (green line) with a lower limit $C_d=1.0$ and an upper limit $C_d=2.0$. The * and circle symbols represent the force calculated from the maximum velocity measured by the ADV, and velocity suggested by FEMA (2000) respectively.
Fig. 6 Broken bore height and velocity at (a) $x=7.1$ m, (b) $x=14.9$ m, (c) $x=29.0$ m. The broken bore height was measured by sonic 3 (upper panels) and velocity was measured by ADV 4 (lower panels).
Fig. 7. Maximum force as a function of cross-shore distance for $H_2=1.07$ m ($H=1.2$ m). This plot shows the difference between impulse load-load cell (blue, solid, circle), impulse load-integrated pressure (red, dash, x), sustained load- load cell (cyan, solid, square), and sustained load- integrated pressure (green, dash, star). These values were determined from averaging the boxed points in Fig. 5.
Fig. 8. Maximum force as a function of wave height for $x=29.0$ m. This figure shows the difference between impulse load-load cell (blue, solid, circle), impulse load-integrated pressure (red, dash, x), sustained load-load cell (cyan, solid, square), and sustained load-integrated pressure (green, dash, star).
Fig 9. Maximum force as a function of cross-shore distance for a variety of wave heights. Error bars were determined by taking the standard deviation of 25 points before and after the maximum force. Note that the largest waves at the closest x-location show greater deviations between the measurements. This can be attributed to sharp peaks in the force time history.
Fig 10. Maximum force as a function of cross-shore distance with small-scale data (black squares). Normalized results from Fig. 9 are plotted for $H=1.2$ (green), $H=1.0$ (cyan), $H=0.8$ (red), and $H=0.4$ (blue).
## Tables

Table 1: Wave Gage and ADV locations

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<th>Instr.</th>
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<th>Comment/Location</th>
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* x-position is measured from zeroed wavemaker
Table 2: Load Cell and Pressure Transducer Locations

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z-location is from base of test specimen
x-location is measured from zeroed wavemaker
y-location is measured from center of flume

locations listed are for the first cross-shore location x= (7.03 m)
y and z locations held constant as wall is moved to 14.6 and 29.0 m
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References


Conclusion

A set of large-scale experiments was conducted in the Large Wave Flume at Oregon State University’s Hinsdale Wave Research Laboratory. It is important to note that the experimental results are only applicable to the described experimental setups and the range of wave conditions tested. Under these limited conditions it was found the both a small seawall and re-locating the test specimen further onshore effectively reduced tsunami force.

The seawall experiment described in the first manuscript was the first step in further understanding the effectiveness of small-scale seawalls in reducing tsunami wave force. The 0.20 m and 0.24m seawalls most effectively reduced wave force on the rigid wall over the range of conditions tested, and sharp peaks became less pronounced as seawall height increased. A correlation between seawall height and the ratio of broken incident wave height to reflected wave height was also found. Using a limited number of wave conditions and seawall configurations we concluded that as seawall height is increased, the reflection of the incoming wave is greater, and force on the onshore structural element is reduced. Force reductions observed in these experiments range from 23% to 84% for offshore waves up to 4 times the seawall height. As suggested by a reviewer, it is important to note that the results of this study are only valid for this particular setup because the distance between the seawall and structure should play a role in determining force on the onshore structural element.

The second manuscript describes an experiment conducted to gain a further understanding of tsunami force as a function of cross-shore distance. It was found that the force-time history exhibited a sharp impulsive peak followed by a sustained force. Integrated pressure accurately depicted the force profile measured by the load cells during the period of sustained force. However, the impact force was much more difficult to model, and the integrated pressure over-predicted the force profile measured by the load cells during the impulse period. When the force peaks were less sharp (either a smaller wave, or a cross-shore location further from wave breaking) the integrated pressure and measured force profiles agreed more closely. An exponential decay in force was found as the wall was moved further onshore and the incoming wave transitioned from an impulsive load to a quasi-steady bore. However, this finding warranted further investigation, and a numerical simulation will be carried out to confirm the
results. For this experiment, the measured sustained force values corresponded to the theoretical force values of Iizuka and Matsutomi (2000).

Both experiments exhibited similar force-time histories: a sharp impulse peak was followed by a period of sustained force. For both experiments the mitigation measure (small seawall and cross-shore offset) reduced or eliminated the sharp peaks in the force-time history. Thus the maximum force and most extreme loading condition was reduced through the addition of a small seawall in front of the structural element or by moving the structural element further offshore, away from the breaking tsunami front.

If shared with coastal planners and policy-makers, these results of this study can have a direct impact on society. Small seawalls are easy to construct and the experiment as well as published field reconnaissance found that they caused a skyward deflection of the incoming wave and reduced forces on the landward structural element. If a small seawall isn’t practical force can also be reduced by practicing construction further from the shoreline. However, the difference between different impact regimes is still unclear and it is difficult to quantify exactly where the safest place for construction is. Thus, further investigation is needed to obtain more quantitative results. This will be done through a numerical simulation. Each of the described experiments was the first step in examining how a mitigation measure reduces tsunami force.

**Bibliography**

The following sources are referenced in the introduction. All other references are noted at the conclusion of each individual manuscript.

