An Experimental and Analytical Study on Wave-Structure Interaction

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***Abstract*—Coastal regions host significantly higher population densities compared to inland areas, and coastal communities are at risk for damage due to wave forces during hurricane or storm events. To better understand wave-structure interaction for the robust design of coastal structures, a physical model was constructed and tested to measure wave-induced pressures on three vertical walls with varying widths. Forces determined by integrating measured pressures over the face of each wall were compared with existing analytical formulations for determining wave forces on walls. Results indicate that blockage, the term used to account for the ratio of the wall area to the cross-sectional flow area, influences the wave forces experienced by a wall and that this factor is not accounted for in certain contemporary models.**

Keywords: Wave forces, vertical structure, physical modeling, blockage effect

I. INTRODUCTION

As global sea levels continue to rise, near-shore communities are being exposed to more severe coastal hazards, which include flooding and wave-induced forces. The effect that wave forces have on near-coast structures must be understood for these coastal communities to adequately prepare for and mitigate damages due to these coastal flood hazards. In particular, the forces exerted by waves on walls must be understood to ensure that these structural elements can be constructed or retrofitted to withstand design loads.

Models to predict effects of waves on near-coast structures have been researched extensively over the past century. Researchers, such as Hiroi [1], Sainflou [2], Goda [3], and Cuomo et al. [4], have all contributed to the understanding of wave-structure interaction. In particular, Cuomo et al. [4] developed an equation for determining quasi-static wave forces on walls. Equations were developed based on large-scale physical model experiments measuring wave loads on a test wall spanning the entire width of the flume. Still, many previous studies have come to varying conclusions, and existing predictive equations only apply to vertical walls in specific conditions. Building upon these theoretical and experimental findings, a widely-accepted and practical analytical model that can effectively predict wave forces for different environmental conditions would be useful to design and construct robust structures.

This experiment investigates the accuracy of the method proposed by Cuomo et al. [4] in predicting wave forces on walls of varying widths using a reduced-scale physical model. The effect of blockage, which represents the ratio between the projected area of the wall to the cross-sectional flow area of the flume, on the total wave-induced force is also studied. This study focuses on the horizontal blockage effect, which considers only variation of the width of the structure with respect to a constant cross-sectional flow area, and assesses how well this horizontal blockage effect is accounted for in existing analytical equations for predicting wave forces on walls.

II. BACKGROUND

A multitude of studies have investigated wave loads on walls by comparing the theoretical and empirical methods for predicting the forces due to wave-structure interaction. Wave-induced forces can be categorized as either short-duration, high magnitude impact loads or longer-duration, quasi-static "pulsating" loads. Analytical equations are based on trends seen in wave load measurements as well as the understanding of water properties and physics. Owing to their short-duration and variability between repeated trials, impact forces are difficult to measure, and few predictive methods exist that accurately estimate wave impact forces. However, quasi-static loads can be more accurately predicted and are expected to be significant contributors to damage owing to their longer interaction with a structure or component.

Empirical equations for predicting wave loads over the past century have improved based on advances in experimentation and physical understanding of wave-induced pressures. Hiroi [1] used field measurements to develop (1) for predicting the average wave pressure due to breaking waves:

$$P = 1.5\,\rho g H_D \tag{1}$$

where P is wave pressure, 1.5 is a unitless constant, ρ is the water density, g is the acceleration due to gravity, and H_D is the design wave height.

Sainflou [2] developed a Lagrangian analytical solution for non-linear, standing wave-induced pressure on vertical walls. Bagnold [5] experimentally measured wave-induced loads on coastal structures and found that impact pressure varied greatly even for fixed conditions. Minikin [6] developed a predictive method for estimating local impact wave forces caused by waves breaking directly onto a vertical breakwater as shown in (2):

$$F_{h,imp} = \frac{101}{3}\frac{\rho g H_D^2 d}{L_D D}(d + D) \tag{2}$$

where $F_{h,imp}$ is the impact wave force, d is the depth at the toe of the wall, L_D is the design wavelength, and D is the water depth at distance L_D from the wall. Allsop et al. [7] measured wave loads on walls in hydraulic model tests to assess the accuracy of (2) as well as other methods for estimating wave impact loads.

In 1974, Goda et al. [3] used test data from an experiment on caisson breakwaters to determine a semi-empirical formula to estimate the wave-induced pressure distribution on the vertical upright section. Tanimoto et al. [8], Takahashi et al. [9], and Takahashi & Hosoyamada [10] improved Goda's initial formula by broadening its scope to fit a wider variety of structures and incident hydrodynamic conditions. Goda [11] later refined these methods and produced what is considered to be the standard of all physically probable prediction methods.

In 1984, Blackmore and Hewson [12] determined that entrained air can affect the forces that waves impart on walls. Until then, the amount of entrained air within a wave had not been considered a factor in wave force estimation. Blackmore and Hewson [12], through empirical evidence, proved that as the proportion of entrained air increases, the wave forces on walls decrease. Although laboratory tests have the capacity to produce waves without entrained air, many coastal structures are affected by breaking waves in which entrained air is a factor. Blackmore and Hewson [12] developed (3) to include the impact that entrained air has on wave pressure:

$$P = \lambda \rho c_{sw}^2 T \tag{3}$$

where P is the average pressure under broken waves, λ is the aeration factor, c_{sw} is the wave celerity in shallow water, and T is the wave period.

After Blackmore and Hewson's [12] work with entrained air, additional experiments were conducted on the effects of breaking waves. Kirkgöz [13] [14] determined that water depth at the wall and the type of wave breaking (early, late, or perfect breaking) affected the total wave-induced force on the wall. Kirkgöz [13] [14] concluded that even small changes in water depth greatly altered impact forces, and large pockets of entrained air (from breaking waves) decreased impact forces.

Kortenhaus et al. [15] and Klammer et al. [16] analyzed data from large-scale experiments to investigate horizontal wave impact and vertical wave uplift loading. In Allsop et al. [17], smaller-scale tests are described in depth. From the wave force and pressure analyses during these experiments, a new set of predictive equations were developed. The new method to predict wave impact forces was recommended by Oumeraci et al. [18] and British standards [19] and is shown in (4):

$$F_{h,imp} = 15\rho g d^2 (H_{si}/d)^{3.134} \tag{4}$$

where H_{si} is the design significant wave height at the toe of the wall and d is the water depth.

The procedure described by Allsop et al. [17] and Oumeraci et al. [18] considered the impact rise time and vertical pressure distribution along the wall. The maximum horizontal impact force and relative maximum wave force, respectively, are given by (5) and (6):

$$F_{h,imp} = F_{h,imp}^{*}\rho g H_b^2 \tag{5}$$

$$F_{h,imp}^{*} = \frac{\theta}{\xi}(1 - \xi \cdot lnP_{\%}) + \mu \tag{6}$$

where $F^{*}_{h,imp}$ is the relative maximum wave force, H_b is the wave height at breaking, $P_{\%}$ is the probability of non-exceedance of impact forces, and θ, ξ, and μ are scale, shape, and location parameters, respectively.

Cuomo et al. [4] performed experiments in a large wave flume in order to quantify the scale effects of wave overtopping of vertical walls and to investigate wave load characteristics on walls. A total of 54 tests were performed with varying structural configurations, water depths, significant wave heights, and mean periods. The pressure distribution on the wall was recorded by eight Druck pressure transducers spaced evenly and vertically. The total horizontal force and overturning moments were considered in the experimental design as well.

Based on these experiments, Cuomo et al. [4] developed equations to model both the impact and quasi-static wave forces on walls. These equations, respectively, are shown in (7) and (8):

$$F_{h,imp(1/250)} = C_r^{1.65}\rho g H_{m0} L(h_s)\left(1 - \frac{h_b - d}{d}\right) \tag{7}$$

$$F_{h,qs+(1/250)} = \alpha \rho g H_{m0}^2 \tag{8}$$

where $F_{h,imp(1/250)}$ is the wave impact force and $F_{h,qs(1/250)}$ is the quasi-static wave force. C_r is the reflection coefficient, 1.65 is an empirical impact coefficient, H_{m0} is the spectral significant wave height, $L(h_s)$ is the wavelength at the toe of the wall, h_b is the breaking depth, and α is an empirical quasi-static coefficient calibrated to 4.8 for the experiments [4]. The quasi-static coefficient is dimensionalized to create the units of Newtons in the equation. The (1/250) subscript indicates that the associated parameter was calculated using an average of the top 0.4% of recorded events in the testing set.

Sipes et al. [20] concluded that the methods proposed by Cuomo et al. [4] and Goda et al. [3] for wave force prediction on walls were more accurate than wave force prediction methods from ASCE7-16 [21] when analytical equations were compared to measured pressures and forces from 1:10 scale experiments by Park et al. [22]. Sipes et al. [20] proposed a blockage coefficient for (8) to account for the finite wall considered in the experiments of Park et al. [22]. Bang et al. [23] determined that (8) was conservative compared to measured forces from reduced-scale experiments performed in the United States Naval Academy's (USNA) Hydromechanics Laboratory, and these equations did not capture the force changes experienced by the walls with varying horizontal blockage.

III. METHODOLOGY

Experiments were conducted in the Sediment Tank in the Coastal Engineering Tank of the USNA Hydromechanics Laboratory. The Sediment Tank is a 1.00 m wide, 10.70 m long flume and uses a vertical wedge wave maker with electric servo-motor ball-screw drive for regular or random wave generation with wave periods ranging from 0.67 s to 2.5 s. A large movable bridge spans the main tank and was used for mounting instrumentation. The wall used for testing was mounted to this bridge structure as depicted in Fig. 1 with its base positioned at-grade. The water depth on the tank can range from 0 m - 0.61 m; a constant depth of 0.48 m was used for this experiment.

Fig. 1. A: View from wave maker showing wave propagation toward wall installed in tank, B: Rear view wall showing method for affixing wall to bridge

A. Wall Design

Three walls with identical heights and varying widths were tested during experiments. The first wall measured the same width as the tank (1.00 m) and had a height of 0.83 m. The other two walls were 0.75 m wide and 0.50 m wide with the same height. A vertical plate with pressure gauges was installed along the centerline of the wall. During testing, each wall was installed 4.70 m away from the wave maker in the center of the 1.00 m wide tank and was positioned at-grade (*i.e.,* with its base at the bottom of the flume). The walls were fixed to the bridge with 8020 beams made of 6105-T5 aluminum and secured with clamps in order to stiffen the wall and minimize deflection.

B. Instrumentation

Wave height measurements were obtained in configuration with no wall, using a single wave gauge positioned 4.70 m away from the wave maker, the same distance away from the wave maker as the wall in subsequent tests. Two trials of each wave condition were performed, and the average of these recorded wave heights was used as the incident wave height for subsequent force prediction. Incident wave heights in all trials were within 4.00 mm of the anticipated value.

Five PicoCoulomB (PCB) Piezotronics pressure sensors and one analog Druck pressure sensor were used to measure the wave pressure on the vertical walls. As shown in Fig. 2, the pressure gauge in the lowest position in the wall was located 0.176 m above the bottom (gauge F, Druck). Each other gauge was spaced 0.076 m apart in a vertical stack along the centerline of each wall.

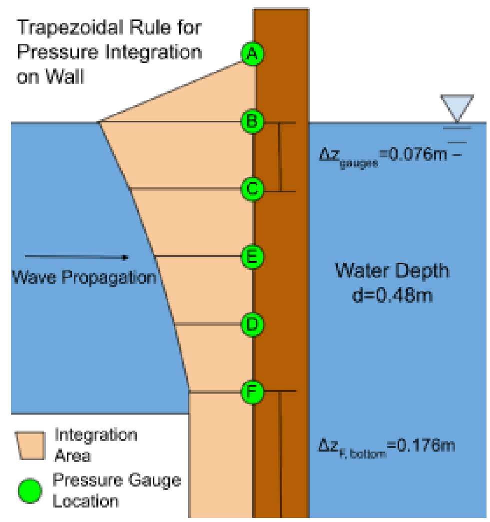

Fig. 2. Profile view of wall showing spacing of pressure gauges and assumption of pressure variation between gauges for force integration

C. Testing Conditions

The wave conditions, including wave height *H* and wave period *T*, are shown in Table 1 and were tested for each wall width listed. The blacked-out conditions were outside the capabilities of the wave maker. Three trials were run for each condition to ensure repeatability of the experiments. A total of 54 tests were conducted.

TABLE I. TEST CONDITIONS

Wave Conditions			
Wave Height (m)	**Wave Period (s)**		
0.024	1.00	1.25	1.50
0.048	1.00	1.25	
0.072	1.00		

*wall widths tested: 1.00 m, 0.75 m, 0.50 m

D. Data Analysis

Pressure sensors were zeroed at the beginning of each trial to measure dynamic pressures associated with wave-structure interaction. The peak wave-induced pressures were averaged only after the incident waves were fully formed and before the measured pressures were affected by reflected waves. Outliers were also removed.

A high-pass filter was applied as shown in Figs. 3 and 4 to correct for the drift in the gauges. The high-pass filter differentiated the frequency of the experimental data (the wave) and the frequency within the sensor (*e.g.,* background electricity) that caused the sensor to drift. Fig. 3 depicts the raw data signal (red) and the high-pass filtered signal (blue) to show the noise removed by the high-pass filter. Fig. 4 shows the signal received by the sensor (red) and the signal corrected by the high-pass filter (blue). Once the filter distinguished this difference, the filter removed the sensor frequency and therefore the drift, yielding the stable signal shown in Fig. 4.

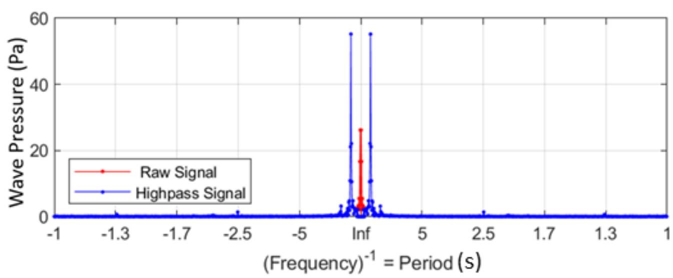

Fig. 3. Fourier transform for pressure gauges signal with high-pass correction for wave conditions $H = 0.024$ m, $T = 1.25$ with a 1.00 m width wall

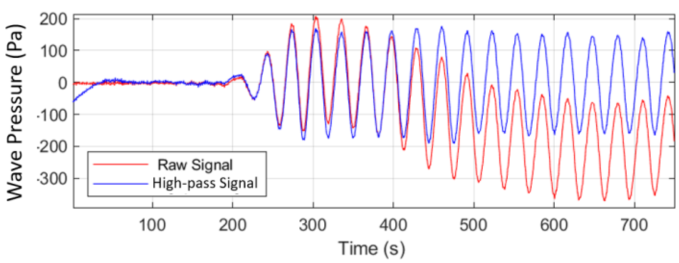

Fig. 4. Time series of wave pressure at Gauge C showing high-pass correction for wave conditions $H = 0.024$ m, $T = 1.25$ with a 1.00 m width wall

Fig. 5 displays the differences in each pressure gauge's measured force after high-pass filter correction. This figure shows the time series of measured pressures recorded at each sensor, with the vertical position of each gauge (A – F) shown in Fig. 2. Pressure gauge time series were integrated vertically over the face of the wall using trapezoidal rule to determine the total force on the wall. This process assumed that measured pressures varied linearly between subsequent gauges and were constant over the width of the test wall. Conservatively, the pressure below the lowest gauge (gauge F) was assumed to be constant from the sensor to the base of the wall. For the wave conditions tested here, pressure measurements at the highest pressure gauge (A) were near-zero; therefore, the pressure was assumed to linearly decrease to zero between Gauge B and Gauge A.

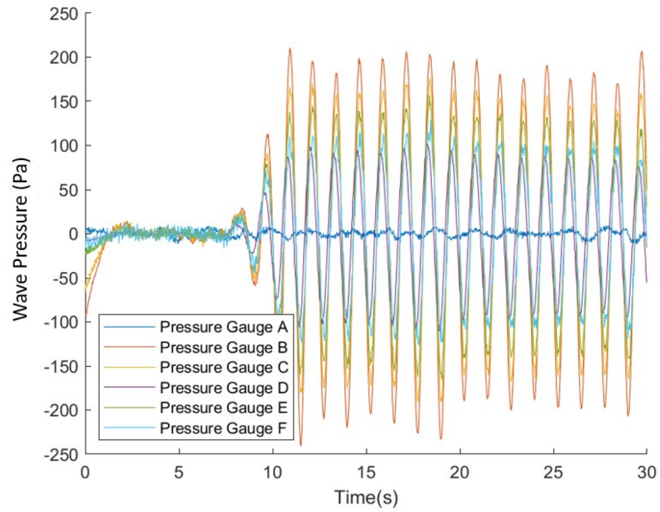

Fig. 5. Time series of measured pressures on 1.00 m width test wall for wave conditions $H = 0.024$ m, $T = 1.25$ s

IV. RESULTS AND DISCUSSION

The integrated wave forces for the three walls are plotted against the incident wave heights in Fig. 6 and compared to theoretical quasi-static wave force values obtained from (8). The standard deviation of each force value is indicated by the error bars in Fig. 6. Measured forces are larger than predicted forces for all wall widths tested except for the 0.5 m wall at the largest wave height. Wave forces decrease as a function of wall width for a given wave height, indicating that for these tests, wave forces increase as the horizontal blockage approaches 1 (*i.e.,* as the wall width approaches the flume width).

Fig. 6 suggests that measured wave forces were generally under-predicted by (8) [4]. Differences in measured and predicted forces could be a result of the different facility and wave conditions for which the empirical coefficient α was calibrated to 4.8 by Cuomo et al. [4]. This coefficient may be dependent upon various factors such as the wall location, flume characteristics (*e.g.*, bottom roughness, dimensions), and incident wave conditions (*e.g.*, wave height, period, water depth). Also, the rectangular approximation used to estimate the wave force from the lowest pressure gauge (F) to the bottom of the tank, is a conservative approximation that may lead to higher force estimations for the wave-induced forces on the wall.

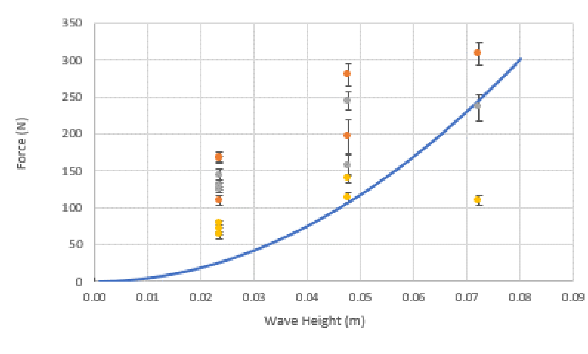

Fig. 6. Experimental and theoretical wave forces vs. wave height

The relationship between wave force ratio (F_{Bm}/F_{1m}) and wave steepness (H/L) is shown in Fig. 7. The wave force ratio represents the ratio of the force experienced by the wall with a width of less than or equal to 1 m to the force experienced by the wall with width equal to 1 m (*i.e.*, spanning the full-width of the testing tank). Wave steepness represents the ratio of the wave height to the wave length. Fig. 7 indicates the dependence of measured wave forces on different wave conditions and wall geometries. The wave force ratios are generally consistent for the different wave steepness values considered in experiments and decrease as the wall width is decreased. These results suggest that the force reduction for a reduced-width wall compared to the full-width wall is proportional to the decrease in wall width for the geometries tested here. Additional testing over a broader range of wave conditions is required to determine the generality and applicability of these observed trends.

In coastal engineering design, it is important to provide conservative estimations of wave-induced forces to ensure the safety of designed structures. Based on these experiments, the equation (8) proposed by Cuomo et al. [4] using the existing empirical coefficient of 4.8 results in wave force predictions that are not conservative. The experiments by Cuomo et al. [4] tested waves with larger wave heights and larger periods than those tested in this project. Cuomo et al. [4] considered wave periods ranging from 1.97 s to 3.8 s and wave heights ranging from 0.22 m to 0.63 m, compared to these experiments, which tested wave periods ranging from 1.0 s to 1.5 s and wave heights ranging from 0.024 m to 0.072 m. Therefore, a different empirical coefficient than that used by Cuomo et al. [4] may be more applicable for waves interacting with structures in these conditions.

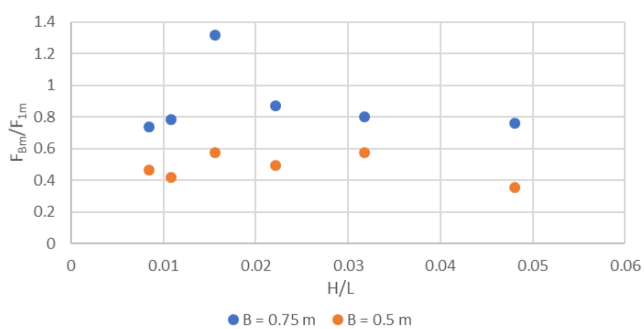

Fig. 7. Wave force ratio vs. wave steepness

The effect of the wall width on the wave force ratio is shown in Fig. 8. Since the tank width is constant and the wall is at-grade, a reduction in wall width can be interpreted as a reduction in blockage. Fig. 8 displays a linear relationship between the wall width and the wave force averaged across all conditions. The linear relationship with a slope of 1.07 [1/m] shows that wave force increases as wall width increases, as may be expected. Therefore, blockage has an effect on wave forces on walls and should be considered when predicting wave force values. This coefficient may be particularly important when considering urban areas with high building densities where significant blockage and flow channeling are expected.

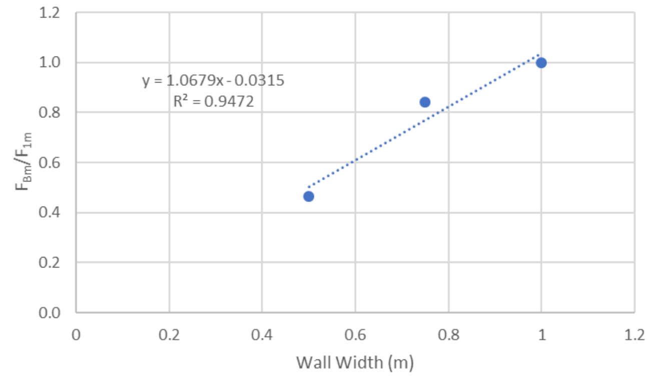

Fig. 8. Average wave force vs. wall width across all wave conditions

V. CONCLUSIONS AND FUTURE WORK

This study experimentally measured the wave-induced quasi-static forces on walls of varying widths and compared measurements with predictions by a well-known analytical equation. The experimental measurements exceeded predicted values, indicating that the method presented by Cuomo et al. [4] requires a calibrated coefficient for force estimation. The measured wave-induced forces increased linearly as wall widths increased. Additional tests should be performed to determine and verify a blockage coefficient based on the ratio of the wall area to the flow area. This coefficient could be applied to (8) or other wave prediction methods to improve the fit between measured and predicted force values.

This study only varied wall width for a structure positioned at-grade; thus the blockage relationships presented only consider horizontal effects. Future studies may consider the effects of vertical blockage, for example when a structure is elevated above grade. Future experiments could also consider the effects of wave period on the magnitude of the peak wave force. Overall, this work advances the understanding of the wave-structure interaction in the coastal environment. Future testing will allow for further advances in coastal structure design, construction, and safety.

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