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SMALL SCALE EXPERIMENTS' ABILITY TO AUGMENT LARGE SCALE LABORATORY TESTING FOR DESIGNING NATURE-BASED AND HYBRID SOLUTIONS FOR COASTAL FLOOD HAZARD MITIGATION

DAN MCMANN[1], JORDAN KECK[2], TORI TOMICZEK[3] PEDRO LOMONACO[4], DAN COX[5], MARGARET LIBBY[6]

1 United States Naval Academy, United States, m244176@usna.edu
2 United States Naval Academy, United States, m243222@usna.edu
3 United States Naval Academy, United States, vjohnson@usna.edu
4 Oregon State University, United States, pedro.lomonaco@oregonstate.edu
5 Oregon State University, United States, dan.cox@oregonstste.edu
6 Oregon State University, United States, libbym@oregonstate.edu

ABSTRACT

Mangroves and other natural coastal defenses have the potential to augment or replace traditional engineered coastal structures in preventing adverse events such as wave overtopping. Natural, or "green" systems may reduce maintenance costs, reduce sediment erosion, and increase biodiversity compared to traditional "gray" infrastructure built from stone and concrete. To effectively inform the design of hybrid green-gray infrastructure, experimental results must be reliable, but testing at 1:1 scale is time-consuming, expensive, and available at only a few facilities worldwide. This study addresses a knowledge gap in defining the nature of the interactions between green and gray coastal defenses with a focus on overtopping and scaling experimental results. This study will compare data from mangrove-related experiments conducted at scales including 1:2 and 1:8 as part of a collaborative effort between Oregon State University (OSU) and the United States Naval Academy (USNA). The study aims to analyze this data and contribute to the joint compilation of a methodology for designing prototype-scale tests from small-scale experiments to identify the relative importance of friction and scaling effects between prototype and small-scale experiments. Testing conducted at USNA as part of this study included a 1:8 scale, 0.61m-wide (2ft.) flume that replicates the conditions of 1:2 scale experiments at Oregon State University. The experimental setup includes a model *Rhizophora* mangrove forest placed in front of a seawall, behind which overtopping is measured as volume per unit length either computed from overtopped water weight or directly measured by overtopped volume. Mangroves are modeled as central trunks with stilt roots, as this study focuses on the effects of the root structures on overtopping. Waves generated for the 1:8 experiments include regular waves with heights between 5cm and 10cm and periods between 1 and 2 seconds, scaled according to Froude similitude. Implications of scaled-up measurements of overtopping are also discussed.

KEYWORDS: Overtopping, *Rhizophora* Mangroves, Scaled Physical Model Experiments, Nature-based Solutions, Froude Similitude.

1 INTRODUCTION

Mangroves, which can be characterized as woody trees able to grow in coastal seawater and marine conditions, have shown potential for significant benefits as augmentations to coastal protection systems. Generally, such systems consider *Rhizophora*, a genus of "true mangroves" that rely on stilt roots adapted to their intertidal environment (Ohira et al., 2012). Such systems have been studied for their ability to attenuate wave heights, and found to have measurable effects on wave decay when tested at full scale (Kelty et al., 2022). Globally, coastal flooding poses an increasing threat as inundation events become increasingly likely and severe with eustatic and relative sea level rise (SLR). Using natural elements such as flora to aid in the defense of coastal infrastructure and human structures may be called "hybrid" engineering due to its incorporation of natural, vegetation-based elements or "green" systems alongside more traditional stone, earthen, and concrete structures, dubbed "gray" systems. Hybrid green-gray systems have the potential to cost-effectively achieve desired protection while providing co-benefits in the form of biodiverse habitats for coastal ecosystems, sediment stabilization, and economically attractive zones for both commercial and subsistence fishing.

The interactions between the green and gray elements of green-gray systems currently fall into a knowledge gap. While the effects of mangrove forests on wave height and energy have been documented (Kelty et al., 2022), their direct effects on the reduction of wave overtopping of structures such as seawalls have not. The concentration of high-value vulnerable property along coasts, along with the potential for injury and loss of life associated with overtopping motivate research into quantifying these interactions (Allsop et al. 2008). To address this lack of understanding, one effective way to evaluate a hybrid green-gray system's effectiveness is to reconstruct the system in an idealized physical model to evaluate the relative importance of system parameters in physical processes. When geometrically scaled experiments are designed, they are traditionally scaled according to Froude similitude, which neglects the scaling of effects such as skin friction drag and water viscosity, making Reynolds similitude impossible to maintain. At large enough scales, effects of friction may be assumed small; however, at too-small scales, friction may dominate, leading to unphysical results that cannot be "scaled up" for real-world interpretation. Due to these scaling issues with the Reynolds number inherent to reduced-scale models using Froude number similitude, the only way to achieve no scaling effects is to reconstruct the model at full prototype scale and test in the desired conditions. However, such tests are only viable in large testing facilities which, for most applications, are prohibitively expensive and long in duration as there are few facilities worldwide to conduct these large experiments. Smaller-scale experiments in more accessible flumes can take less time and monetary investment to make mangrove-based solutions easier to implement worldwide. The question that arises is: how do we interpret small-scale experimental results in order to design full-scale systems to be implemented at a project site?

2 METHODOLOGY

This study aims to quantify the scaling relationship between small and large experiments of the hybrid green-gray nature. Such relationships are currently unclear due to the factors that scale with respect to various non-dimensional terms such as Reynolds' number, Froude number, or the geometry of the system. Due to these complex relationships that may not simultaneously be scaled due to limitations such as the viscosity of water, results from small-scale experiments must be carefully interpreted. Empirically defined relationships may provide a more readily interpretable result. In order to evaluate the effects of a geometrically scaled mangrove forest, this study considers overtopping data collected during 1:8 scale experiments in the United States Naval Academy's (USNA) Coastal Basin, which are produced by scaling down 1:2 scale experiments conducted in Oregon State University's (OSU) Large Wave Flume (Libby et al. 2024). This paper presents the methodology for scaling model mangrove dimensions, mangrove forest specifications, tested wave conditions, and data collection methods.

2.1 Physical Experiment Design

In order to create a model mangrove specimen, the mangroves constructed at 1:2 scale by the U.S. Army Corps of Engineers (Bryant et al., 2022), which were used in the overtopping experiments of Libby et al. (2024), were redesigned to 1:8 scale for construction and installation in the Coastal Basin at the USNA's Hydromechanics Laboratory. The nominal dimensions of mangrove trunk diameters, height, root diameters, and highest root height are listed in Table 1. The mangroves reproduce the effects of *Rhizophora* by mimicking the stilt root and trunk morphology following modifications to the parameterization described by Ohira et al. (2013). This parameterization is achieved by creating a "trunk" from a cylinder, commonly a rod or pipe. Holes through which seven root pairs can pass are drilled at 45-degree angle increments. The roots are formed from a more flexible material, cut to specific lengths in order to facilitate a parabolic spreading to the experimental seafloor (Ohira et al., 2013). Libby et al. (2024) and Bryant et al. (2022) utilized PVC pipe and PEX tubing as the trunk and roots, respectively. These specimens used for the 1:8 scale experiments were constructed from 0.015m (3/5-inch) brass rod and 6-gauge (diameter 0.004 m) galvanized steel wire. An example specimen is displayed in Figure 1.

Table 1. Comparison of mangrove model nominal dimensions at 1:2 scale and 1:8 scale

	Trunk Diameter (m)	Trunk Height (m)	Root Diameter (m)	Highest Root Height (m)
Libby et al. (2024); Bryant et al. (2022)	0.0603	1	0.016	0.6732
This study	0.015	0.25	0.004	0.1683

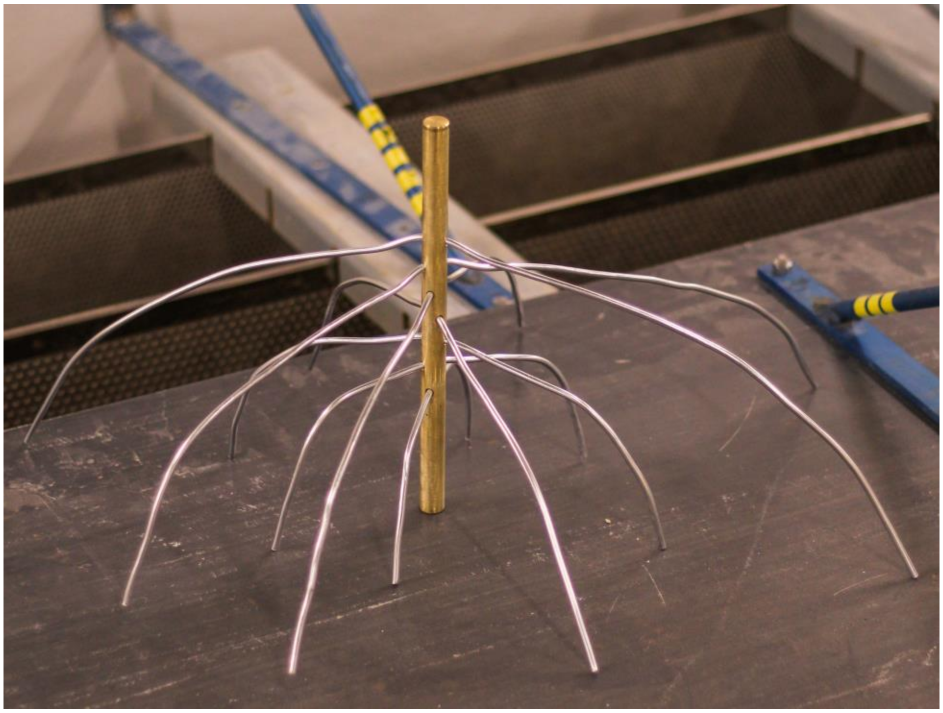

Figure 1. Photograph of a 1:8 scale model mangrove used in USNA experiments made of brass rod of 1.5cm diameter and 6-gauge galvanized steel wire.

The forest density was achieved by machining a baseplate punctured by staggered, equidistant holes 1.5 cm in diameter into a wood bathymetry plate. The density was governed by Equation (1), where N is the density of specimens per square meter and ΔS is the displacement from one hole to the next.

$$N = \frac{2}{\sqrt{3}} \Delta S^{-2} \tag{1}$$

The highest density modelled by Bryant et al. (2022) was 1.42 trees per meter squared at prototype scale. This translated to 90.88 trees per meter squared at 1:8 scale, as density scales with the square of the scaling factor. The resultant spacing of the mangrove models mandates a ΔS of 0.113m. A staggered arrangement has been determined to be an effective wave attenuating arrangement and suitable representation of the random arrangement found in a natural forest (Hashim et al., 2013). Additionally, a staggered arrangement would be among the most likely arrangements of an engineered mangrove system due to the ease of installation and reduction of the likelihood of overcrowding when compared with mangroves arranged in tandem.

The experiments considered configurations including mangroves and a seawall, without other protection features, to isolate the effects of the mangrove forest on overtopping of an otherwise undefended seawall. The density for tested for experiments was reduced from the high-density forest reported by Bryant et al. (2022) by a factor of two to facilitate installation and for comparison with similar tests conducted by Libby et al. (2024), resulting in a density of 45.44 trees per meter squared at model scale. The machined base plate was customized to fit the 0.61m (2ft) wide testing flume and constructed of plywood, then fixed in place opposite a piston-type generator. The forest length was 2.75m. A view of the digitally designed plate and an overhead photograph of the plate installed with the forest are depicted in Figure 2.

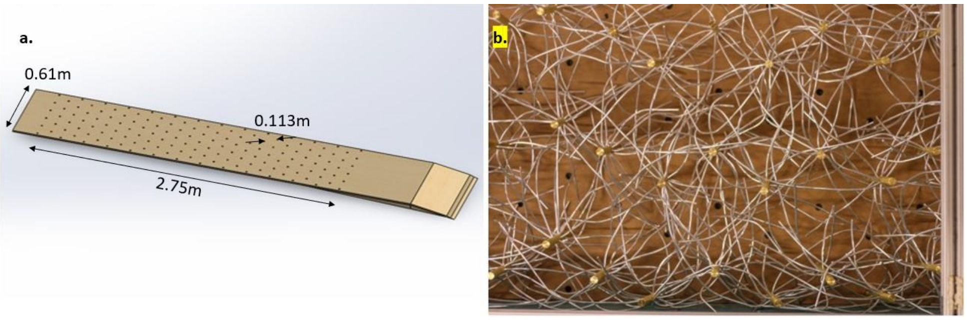

Figure 2. (a) Digitally designed forest-spacing base plate compared with (b) overhead view of the installed base plate with half-density forest.

2.2 Experimental Wave Conditions

Quantifying the overtopping effects of the 1:8 mangrove forest for comparison with 1:2 scale tests required scaling of waves for direct result comparisons. Regular waves tested by Libby et al. (2024) are scaled to 1:1 scale for reference of the characteristics of full-scale waves. Additionally, these conditions are scaled to 1:8 scale for reference of characteristics in USNA experiments. These three scales of four wave conditions are displayed in Table 2. Waves were scaled geometrically by the scaling factor in wave height and by the square root of the scaling factor in period to maintain the Froude similarity of each wave condition. The wave conditions selected represent typical fetch-limited wave periods and wave heights in an estuarine environment. To observe the difference in overtopping per unit width caused by a mangrove forest and compare the effects of scaling, tests in the USNA Coastal Basin included four normal wave conditions directly scaled from waves considered by Libby et al., 2024. These regular wave conditions are tabulated in Table 2 and were tested in the presence and absence of the forest to quantify the percentage reduction in overtopping due to the mangrove forest. The results were compared with the results of Libby, et al. (2024).

Table 2. Waves tested in the USNA Coastal Basin on 1:8 scaled experiments categorized by period and wave height, compared with 1:2 scale tests conducted by Libby et al. and full-scale waves

	1:1 Scale		1:2 Scale (Libby et al., 2024)		1:8 Scale	
	Period (s)	Wave height (cm)	Period (s)	Wave height (cm)	Period (s)	Wave Height (cm)
Wave Condition 1	4.24	48	3	24	1.5	6.0
Wave Condition 2	4.24	54	3	27	1.5	6.8
Wave Condition 3	4.24	60	3	30	1.5	7.5
Wave Condition 4	5.66	48	4	24	2	6.0

2.3 Experimental Procedure and Data Collection

Experimental procedure consisted of running waves through the mangrove forest while measuring the overtopping per unit seawall length. The entire configuration consisted of a vertical seawall, representing the protected gray infrastructure landward of the mangrove forest, which is preceded by a gently sloping (1/20) seafloor. For consistency with the experiments of Libby et al. (2024), the freeboard measurement between the crest of the seawall and the stillwater level was kept constant at 0.025 m. for all trials, giving a constant depth of 0.19 m. within the vegetation. A profile view of the experimental configuration is depicted in Figure 3, not drawn to scale.

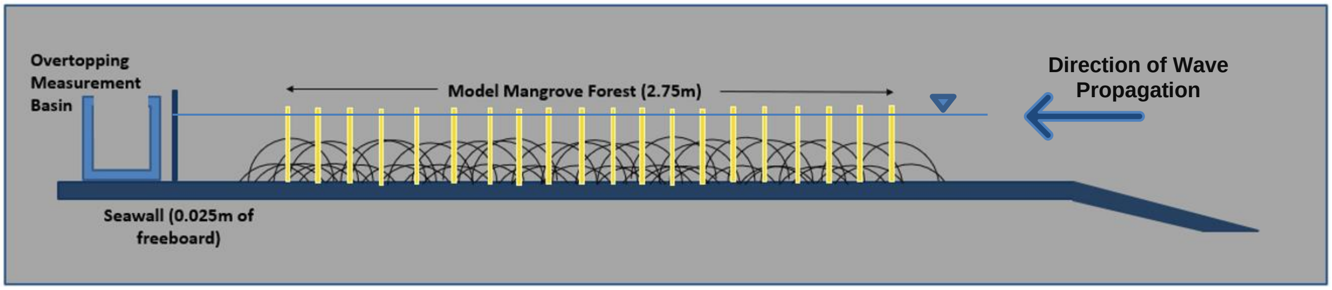

Figure 3. Profile diagram of experiments (not to scale).

A plastic bucket was used as a basin to capture the mass of overtopped water, which flows through a cut-out portion of the bucket, which was securely fastened to the seawall using vise grips. The rectangular notch in the bucket's lip was cut to 29 cm, the value used to determine the overtopping per unit width of seawall. This basin apparatus is shown in Figure 4. Each wave condition consisted of a total of 50 waves, divided into sets of five or ten based on relative overtopped volume to avoid complete inundation of the overtopping basin, as well as to limit wave reflection in the Coastal Basin to maintain. Together, these factors would otherwise inhibit a reliable, manageable volume of overtopping to be measured for each wave set. Upon completion of each wave set, the mass of overtopped water was measured on a scale.

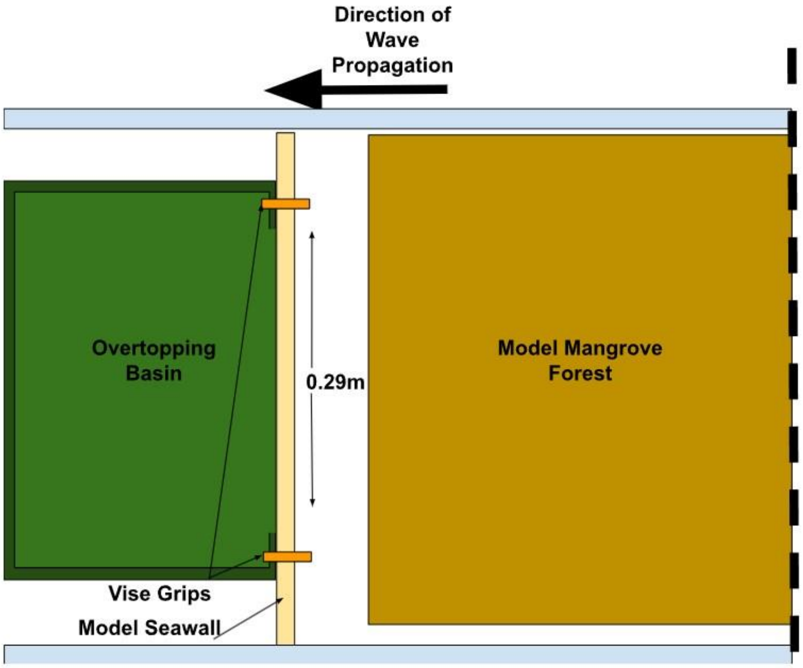

Figure 4. Planview diagram of overtopping basin fixed to model seawall with vise grips in flume.

3 RESULTS AND DISCUSSION

In order to gain the volume of overtopped water for analysis, the recorded mass is adjusted for the basin mass and averaged. Wave overtopping experimentation gathered the overtopped mass data from the four wave conditions directly similar to conditions tested at Libby et al. (2024). The mass of overtopped water measured from each experimental condition is recorded in Table 3 where the constant 1.06 kg of mass provided by the bucket has been subtracted from the measured mass and the individual mass results have been averaged and normalized to a mass per wave value. This calculation is shown by Equation 2, where O_{Avg} is the average overtopping mass per wave in kg, m is the overtopped mass for a given wave condition and forest configuration, n is the number of sets run at that condition and configuration, and n_w is the number of waves in each set for the given condition and configuration.

$$O_{Avg} = \frac{\frac{\sum m - 1.06}{n}}{n_w} \text{(kg/wave)} \tag{2}$$

With no mangrove forest present, testing Wave 3 with a period of 1.5 s and a wave height of 7.6 cm resulted in complete inundation and surpassing of the basin's capacity with five-wave sets, which made testing inviable for this condition.

Table 3. Average overtopping per wave in given conditions and configuration

Wave Condition	Mangrove Forest Configuration	
	With Forest (kg/wave)	No Forest (kg/wave)
Wave Condition 1 (T=1.5s, H=6.0cm)	1.081	1.604
Wave Condition 2 (T=1.5s, H=6.8cm)	1.431	2.191
Wave Condition 3 (T=1.5s, H=7.5cm)	1.795	N/A
Wave Condition 4 (T=2s, H=6.0cm)	1.416	1.860

3.1 Analysis of overtopping data

The overtopped mass per wave can be further analyzed to produce a volumetric overtopping value per unit width of seawall given the set width of the slit in the basin. Additionally, the percent difference between the with-forest and no-forest configurations is calculated to quantify the effect of mangrove forests on overtopping. These values are tabulated in Table 5 and were developed from Equations 3 and 4, where Q is the overtopped volume per unit length per wave, ρ is the density of water, 998 kg/m^3, and w is the width of the notch in the basin. The percent difference in Q is calculated by Equation 4 where $Q_{mangroves}$ represents the overtopping rate with the mangrove forest and Q_{absc} represents the overtopping rate in the absence of a mangrove forest.

$$Q = \frac{O_{Avg}/\rho}{w}\ (\mathrm{m^3/m/wave}) \tag{3}$$

$$\%Difference = \frac{Q_{absc} - Q_{mangrove}}{Q_{absc}} * 100 \tag{4}$$

Table 5. Overtopping per unit length per wave and percent difference caused by presence of a mangrove forest, hypothetical direct scaling values are added for comparison

Wave Condition	Q (1:8)		%Difference	Q (1:2)		Q (1:1)	
	With Forest (m^3/m/wave)	No Forest (m^3/m/wave)		With Forest (m^3/m/wave)	No Forest (m^3/m/wave)	With Forest (m^3/m/wave)	No Forest (m^3/m/wave)
1	0.00374	0.00554	32.49	0.0150	0.0222	0.0299	0.0443
2	0.00494	0.00757	34.74	0.0198	0.0303	0.0395	0.0606
4	0.00489	0.00643	23.95	0.0196	0.0257	0.0391	0.0514

This table depicts a standardized measurement of overtopping by volume per width per wave and the reduction associated with a half-density mangrove forest at 1:8 scale. In these tests, the mangrove forest reduced volumetric overtopping by an average of 30.39%, with results ranging from a 23.95 – 34.74% reduction in overtopping. The hypothetical values extrapolated for a 1:2 and 1:1 scale experiment represent the expected overtopping in the field and in large scale laboratory experiments if overtopping volume per unit length per wave is consistent with Froude number scaling. Under wave condition 2, scaled to 1:1 scale, the predicted mangrove forest overtopping reduction would be 430 cubic meters per meter given that 20,377 normal waves of period 4.24 seconds occur in a daylong period. A comparison with the results of Libby et al. (2024) on the percentage of overtopping reduction will provide insight on the scaling effects present in the small-scale experiment. Given a forest of a scaled density and cross-shore width, percent difference acts as a metric for normalizing the change in overtopping changes with scale as the independent variable. Comparison with more scaled experiments offers the potential for an empirical curve of overtopping scaling.

4 CONCLUSIONS AND FUTURE WORK

Sea level rise, increasingly common extreme weather events, and the sustainability of current coastal protection solutions all drive the need for the further development of systems that mitigate impacts of coastal flood hazards and promote resilience of nearshore communities and ecosystems. It is important to understand limitations of small-scale laboratory experiments because the results of laboratory experiments can inform design guidance for engineered features. Engineering with mangroves lacks the depth of knowledge to make small-scale tests reliable enough for full scale design and implementation and has a risk of poor translation of effects of the performance of these systems. This uncertainty is due to enhanced effects of friction at reduced scales. Advancing the collective knowledge of the effects of engineered natural systems by providing guidance and mechanisms for appropriately scaling up results of reduced-scale studies informs best practices for coastal protection and increases the potential resiliency of coastal projects in a world of rising sea levels and extreme weather. Future tests will seek to form an empirical model for scaling overtopping reduction through a mangrove forest. This effort involves analyzing data from conditions 1:2 experiments by Libby et al. (2024) and designing similar experimental configurations at multiple scales (*e.g.,* 1:1, 1:2, 1:8, 1:12, and 1:16) in collaboration with other universities and facilities including OSU, Hanyang University, and USACE. By comparing overtopping reduction percentage across scaled experiments, future work can develop a n improved understanding of the processes relevant to reduced-scale physical models will improve initial design feedback and reduce the time and monetary costs of testing at near-prototype scales.

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