WAVE HEIGHT ATTENUATION AND DAMAGE REDUCTION BY MANGROVE FORESTS: FIELD AND LABORATORY INVESTIGATIONS

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Abstract: Coastal and nearshore communities face increasing coastal flood hazards associated with climate change, leading to overland flow and inundation processes in the natural and built environments. As communities seek to build resilience to address these hazards, natural infrastructure (*e.g.*, emergent vegetation) and hybrid designs have been identified for their potential to attenuate storm-driven waves and associated effects in developed nearshore regions. However, challenges remain in robustly characterizing the performance of natural systems under a range of incident hydrodynamic conditions and in bridging interdisciplinary knowledge gaps needed for successful implementation. This paper synthesizes field and laboratory results investigating the capacity of *Rhizophora mangle* (red mangrove) systems to mitigate wave effects. Results indicate that *R. mangle* forests of moderate cross-shore width have significant effects on wave transformation and load reduction in sheltered inland areas. Opportunities for future interdisciplinary collaborations are also identified.

Introduction

Coastal and nearshore communities face increasing coastal flood hazards (*e.g.,* sea level rise, chronic erosion, storm-driven waves and surge) associated with climate change, leading to overland flow and inundation processes in the natural and built environments. As communities seek to build resilience by proactively addressing these hazards, natural infrastructure (*e.g.,* emergent vegetation) and hybrid designs have been identified for their potential to attenuate storm-driven waves and associated effects in developed nearshore regions. For example, after Hurricane Irma in 2017, Tomiczek et al. (2020a) observed that waterfront structures in the Florida Keys sheltered by red mangroves consistently experienced less damage than structures subject to similar hydrodynamic conditions with other shoreline treatments (*e.g.,* bulkhead, revetment). Other studies have similarly identified that mangroves provided engineering services such as hazard mitigation, damage reduction, or shoreline stabilization during extreme events, including tropical cyclones (Zhang et al. 2012; Krauss et al. 2009) and tsunamis (Alongi 2008; Goda et al. 2019), as well as for ambient conditions, including wind-generated waves (Mazda et al. 1997; Bao 2011; Horstman et al. 2014) and ship-generated wakes (La et al. 2015; Ismail et al. 2017; Tomiczek et al. 2022).

Based on these observations, mangroves have rapidly gained attention as part of several domestic and international initiatives to implement natural infrastructure into conventional (structural) coastal engineering alternatives (Cunniff and Schwartz 2015; Browder et al. 2019; Webb et al. 2019; Bridges et al. 2021; Science for Environmental Policy 2021; UNDRR 2021). Natural infrastructure, also referred to as "natural and nature-based features (NNBF)," "nature-based solutions (NbS)", "Engineering with Nature (EWN)," "Building with Nature," and "green infrastructure," among other terms, leverages landscape features such as dunes, native vegetation, islands, and reefs to not only mitigate flood risk but also provide environmental, social, and economic benefits (*e.g.,* Guannel et al. 2016; Bridges et al. 2021). However, challenges remain in robustly characterizing the performance of natural systems under a range of incident hydrodynamic conditions and in bridging interdisciplinary knowledge gaps needed for successful implementation (Ostrow et al. 2022). This paper will (1) summarize previous field and laboratory studies investigating the capacity of *Rhizophora mangle* (red mangrove) systems to mitigate wave heights; (2) describe field measurements of wave height attenuation by mangroves during overland flow conditions caused by a far field tropical cyclone; and (3) identify opportunities for future interdisciplinary collaborations.

Previous Studies of Engineering Performance of Mangrove Systems

This section presents a summary of previous studies investigating wave interaction with emergent vegetation, focusing on field measurements of wave height attenuation through mangrove forests and physical model studies conducted at reduced- and prototype-scales, as listed in Table 1. A detailed literature review of field, laboratory, and numerical investigations of wave-vegetation interaction and resulting effects on shorelines and the built environment is presented by Tomiczek et al. (2021).

Previous field measurements have evaluated wave height attenuation through a variety of mangrove species, with many studies focusing on the above-ground prop root systems of the *Rhizophoracae* family (Mazda et al. 1997; Bao 2011; Horstman et al. 2014). Mangroves provided significant wave height attenuation for short-period waves; for example, Horstman et al. (2014) reported wave height attenuation rates of 0.012/m. Similar effects were observed in measurements of boat wake transformation through mangrove forests, with reported vessel-generated wake height reductions between 38 – 84% over mangrove cross-shore widths between 4 m and 15 m (La et al. 2015; Ismail et al. 2017; Tomiczek et al. 2022).

Previous reduced-scale physical model studies have been performed to evaluate wave transformation through idealized mangrove forests under constant flow (Zhang et al. 2015; Maza et al. 2017), solitary wave (Strusińska-Correia et al. 2013), transient (Tomiczek et al. 2020b), and sinusoidal and irregular (Chang et al. 2019; Maza et al. 2019) wave conditions. Several of these studies measured wave height attenuation through idealized mangrove forests (Chang et al. 2019; Maza et al. 2019) to calculate an empirical drag coefficient C_D for use in theoretical formulations predicting wave height attenuation through vegetation (*e.g.,* Dalrymple et al. 1984; Mendez and Losada 2004). Often, drag coefficients are presented as a function of the Reynolds number *Re* (Chang et al. 2019; Maza et al. 2019); however, care must be taken when interpreting results owing to scaling effects on the Reynolds number when Froude similitude is maintained.

Recent near-prototype- and prototype-scale physical models of wave interaction with idealized mangrove forests have been constructed to further document wave height attenuation through mangroves and identify possible scaling effects in reduced-scale studies. Bryant et al. (2022) constructed a near-prototype-scale (1:2.1) physical model in the Coastal and Hydraulics Laboratory at the U.S. Army Corps of Engineers Engineer Research and Development Center in Vicksburg, MS, USA to measure wave height transformation through a 15.12 m (model-scale) long mangrove forest under various incident hydrodynamic conditions. The authors reported wave height attenuation through the forest between 13% - 77% across all hydrodynamic conditions, with attenuation generally decreasing as water depth increased. Bulk drag coefficients were computed for regular wave conditions based on Dalrymple et al. (1984) and for random wave conditions based on Mendez and Losada (2004); observed drag coefficients ranged between 0.5 and 2.9, with C_D decreasing for increasing values of both the Reynolds number and Keulegan Carpenter number *KC*. A better fit was obtained for C_D as a function of *KC* than that obtained as a function of *Re* (Bryant et al. 2022).

A prototype-scale (1:1) physical model of wave-mangrove interaction was constructed by Kelty et al. (2021; 2022) and further analyzed by Mitchell (2021) and Lomónaco et al. (2022). The idealized *Rhizophora* specimen was a full-scale replica of that tested by Bryant et al. (2022). An 18 m long idealized forest transect was constructed in the 104 m long Large Wave Flume at Oregon State University in Corvallis, OR, USA. Two cases with different forest densities and a baseline (no mangrove) case were subject to regular and random wave conditions to measure wave height transformation through the forest. Wave height decay rates were found to be dependent on water depth. Greater wave height attenuation was observed for tests with lower water depths, consistent with observations reported by Bryant et al. (2022). Wave height attenuation also increased with increasing forest density, with the higher forest density causing greater wave height attenuation over the hydrodynamic conditions tested.

Kelty et al. (2022) also determined drag coefficients based on the formulations by Dalrymple et al. (1984) and Mendez and Losada (2004); calculated drag coefficients ranged between 0.4 and 3.8. Empirical equations were fitted to experimental data to estimate the drag coefficient as a function of the Reynolds number. The authors compared calculated C_D values with those obtained by previous reduced-scale tests (Chang et al. 2019; Maza et al. 2019) and observed that drag coefficients obtained in reduced-scale tests agreed well with those calculated from the full-scale experiment after the Reynolds number was rescaled according to Froude similitude (*i.e.,* increased by the length scale factor $\lambda^{3/2}$). These results highlight the importance of understanding scale effects for practical implementation of emergent vegetation systems for coastal flood risk management.

Measurements by Kelty et al. (2022) focused on wave transformation through the forest and therefore considered a bathymetry with a dissipative beach leeward of the mangrove forest test section. Mitchell (2021) and Lomónaco et al. (2022) used the same experiment to further consider wave-induced pressures and forces on sheltered inland structures. These studies considered trials for which a vertical test wall was installed inland of the forest for the baseline (no mangrove), low-density, and high-density mangrove configurations. Wave induced pressures were measured along the vertical wall to assess the wave load reduction associated with the mangrove forest. Results indicated that the mangroves significantly reduced measured forces on the test wall, and existing methods for predicting wave loads on vertical walls (*e.g.,* Goda 2010) could be used with the attenuated (transmitted) wave heights to predict the subsequent wave-induced loads (and load reduction) on sheltered coastal structures.

Table 1. Selected Field and Laboratory Investigations of Wave Height Attenuation by Mangroves

Study	Method (Field/ Laboratory)	Reported Performance
Mazda et al. (1997)	Field (Vietnam)	Wave height reduction up to 20% over 100 m transect for 6-yr old mangroves
Bao (2011)	Field (Vietnam)	Exponential decay of wave heights through 32 mangrove forests
Horstman et al. (2014)	Field (Thailand)	Wave attenuation rates up to 0.012/m in forest dominated by *Rhizophora*
La et al. (2015)	Field (Vietnam)	Boat wake reduction of 44% - 56 % over 4 m transect; 70% – 84% over 10 m transect
Ismail et al. (2017)	Field (Malaysia)	Average boat wake height reduction of 63% over 15 m mangrove transect
Tomiczek et al. (2022)	Field (USA)	Average characteristic boat wake height reduction of 38% over 6.8 m transect; 65% over 12.6 m transect
Zhang et al. (2015)	Lab (1:7.5)	Flow velocities, turbulent kinetic energy for unidirectional flow; drag coefficients consistent with field measurements
Maza et al. (2017)	Lab (1:12)	Velocity decrease of up to 50% within mangrove root zone for unidirectional flow
Chang et al. (2019)	Lab (1:7)	Calculated drag coefficient C_D and inertial coefficients C_M based on Morison-type equation for 3D printed idealized forest, related to *KC* and *Re;* observed non-negligible inertial effects.
Strusińska-Correia et al. (2013)	Lab (1:20)	Transmission rates of 20% for solitary wave and tsunami bores.
Maza et al. (2019)	Lab (1:6)	Calculated drag coefficients for regular and irregular wave conditions over a 26 m long forest; C_D range between 0.3 – 2.4
Tomiczek et al. (2020b)	Lab (1:16)	Load reduction by mangrove forests on sheltered inland structures for two cross-shore widths (8.2 m and 19.0 m at prototype scale); force reductions between 11-65%
Bryant et al. (2022)	Lab (1:2.1)	Large-scale physical model; calculated drag coefficients for regular and irregular wave conditions; attenuation rates between 13-77% over the 15.12 m forest; better fit between C_D and *KC* than between C_D and *Re*.
Kelty et al. (2022)	Lab (1:1)	Prototype-scale model of forest of 18-m cross-shore width; wave height decay rates range between 0.004 – 0.021/m, and C_D between 0.4 – 3.8; demonstrated scaling relation for interpreting reduced-scale drag coefficients as a function of *Re*

Field Measurements of Wave Attenuation by *R. Mangle* during Overland Flow Conditions

While the above studies have made significant progress in quantifying the engineering performance of mangrove systems for wave height attenuation and load reduction on sheltered inland structures, questions remain about the applicability of results for flood risk management solutions. Previous physical model studies present an idealization of the mangrove trunk-prop root system; therefore, effects of inherent variability in natural systems (*e.g.,* varying tree ages, stem densities, and mechanical and biological properties) are not well understood. Similarly, a mangrove forest's effects on sediment transport and the resulting effects on wave height attenuation require further investigation. While field studies consider these *in situ* variations, the site-specific nature of field experiments requires additional evidence of mangrove performance over a range of incident environmental conditions ranging from daily to extreme. Therefore, this section presents details and preliminary results of a long-term field campaign on an island near Key West, Florida, USA to measure wind wave transformation through a mangrove transect during overland flow conditions.

Study Location, Instrumentation, and Hurricane Ida

High-frequency pressure gages were positioned along a transect on the southern shoreline of Man Key, an island 12 km west of Key West, FL, USA (Fig. 1). The island is covered by a dense stand of *Rhizophora mangle*. Six RBR*solo*^{3} D pressure gages were positioned in two shore-normal transects: from south to north and from west to east, with shoreline sensors positioned at the southern and western fringes of the mangrove forest, respectively. Here, we focus on measurements from the three sensors installed along the south transect (Fig. 1a).

The sensors recorded temperature and absolute pressure at a frequency of 8 Hz. The sensor at the fringe location (M1) was submerged at the time of deployment; inland sensors were positioned in air at elevations of 0.17 m and 0.19 m above grade at the middle (M2) and rear (M3) positions, respectively, based on accessibility in the mangrove stand and to capture wave transformation during overland flow conditions. Table 2 provides specific details of each sensor's location. An Onset Hobo pressure logger was also positioned in air at a nearby field station on Ballast Key, FL, USA; the logger recorded absolute pressure at a rate of one sample every five minutes and was used to correct for atmospheric pressure fluctuations in wave and inundation data from the RBRs. The sensors recorded continuously from August 16 through October 14, 2021, and experienced moderate overland flow conditions during the passing of far-field storm Hurricane Ida on August 27-28, 2021.

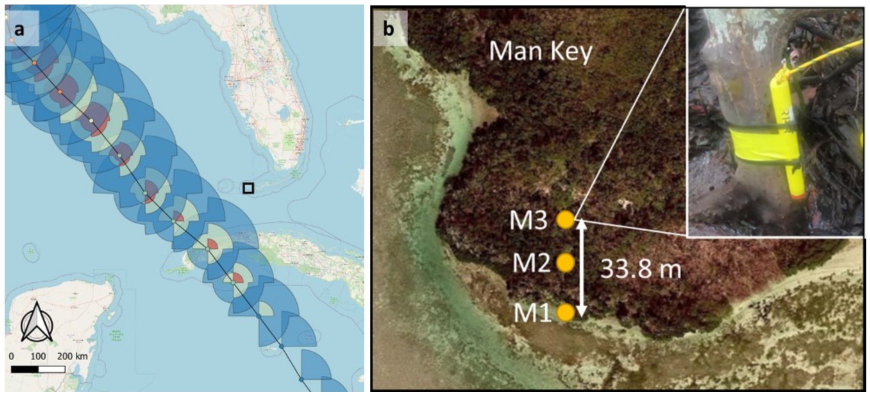

Fig. 1. (a) Gulf of Mexico showing study location (black box) and track of Hurricane Ida (data from NHC 2022). Shaded areas show radii of (blue) tropical storm force (17.5 m/s (34 kt)), (green) 25.7 m/s (50 kt), and (red) hurricane force (32.9 m/s (64 kt)) winds; points are colored by hurricane classification on the Saffir Simpson Hurricane Wind Scale: tropical storm (blue); 1 (blue-green); 2 (yellow-green); and 4 (orange); (b) Detail image of southwest Man Key, showing locations of fringe, middle, and rear sensors on the south transect and photograph of inland sensor deployment (inset).

Table 2. Instrumentation locations

Location	Distance from Fringe (m)	Elevation above Ground (m)
Fringe South (M1)	0	0.19
Mid South (M2)	22.2	0.15
Rear South (M3)	33.8	0.17

Hurricane Ida formed from a combination of weather systems in the tropics and reached tropical storm status on August 26, 2021 at 1800 UTC (Beven et al. 2022). The system made two landfalls in in Cuba the following day as a Category 1 hurricane on the Safir Simpson Hurricane Wind Scale. The storm rapidly intensified between August 28 and 29, 2021 as it traversed northwest through the Gulf of Mexico, reaching Category 4 status at 0600 UTC on August 29, 2021. The storm made landfall at Port Fourchon, Louisiana, as a Category 4 storm, with a central pressure of 93.1 kPa and sustained wind speeds of 66.9 m/s (130 kt). The storm's winds, storm surge, and rainfall caused flooding and damages amounting to $75 billion USD in the United States (Beven et al. 2022). Although the hurricane's wind field remained offshore of Man Key (Fig. 1a), the island experienced overland flow conditions from August 27-28, 2021.

Wave Transformation through Mangrove Transects

Data were analyzed to assess wave-vegetation interaction during overland flow conditions, which occurred during the passing of Hurricane Ida from August 27-28, 2021. Recorded absolute pressures were processed by subtracting atmospheric pressure and converted to water depths, and wave heights were determined by correcting for dynamic wave pressure attenuation with water depth, based on the periods obtained via zero-upcrossing analysis of the uncorrected signal.

Owing to the far field nature of the storm, conditions at the study location were relatively mild, with peak inundation depths reaching 0.51 m and generally small incident wave heights (O~0.05 m). These incident waves were significantly dissipated across the 33.8 m transect through the mangrove stand. Time-domain transmission coefficients, calculated as the ratio between the significant wave height $H_{1/3}$ measured at the as the fringe location (M1) to that measured at the rear location (M3), were generally consistent and ranged between 0.65 and 0.79 over the storm's inundation duration on Man Key. These calculations suggest that for the wave conditions measured here, incident wave heights were reduced by 22% to 35% over the mangrove transect.

In addition to time-domain analysis, spectral analysis of the storm wave spectra was performed for the signals at locations M1, M2, and M3. Results are shown in Fig. 2, which plots the spectral energy density against the dominant frequency for the storm at the fringe (M1), middle (M2), and rear (M3) locations. As shown by the figure, the spectral energy density decreases from the fringe to the middle to the rear locations, indicating wave attenuation by the mangrove forest. Greater attenuation is observed for shorter-period waves (T_p O~1s), suggesting that short period waves may experience greater attenuation through a given mangrove forest, similar to observations in previous studies (Kelty et al. 2022).

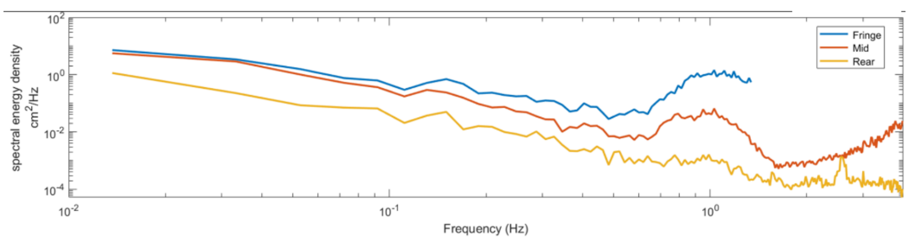

Fig. 2. Spectral energy density vs. wave frequency at the fringe (blue), middle (red), and rear (yellow) locations for the south transect on Man Key.

Discussion and Opportunities for Trans-Disciplinary Collaboration

While the results presented here are promising and further confirm previous studies showing wave height attenuation by mangrove forests, further work is necessary to understand wave interaction with and dissipation through vegetation. Additional field measurements are required to robustly quantity the performance of mangrove systems under more extreme environmental conditions. Future work may consider wave transmission over the duration of an event's inundation duration to confirm the decrease in wave height attenuation for higher water levels with respect to the mangrove's above-ground root system observed by Kelty et al. (2022) and Bryant et al. (2022).

To confidently leverage nature-based infrastructure in a coastal adaptation portfolio, the interaction of natural elements (*e.g.,* mangroves or marsh grasses) with structural elements (*e.g.,* revetments or bulkheads) must be better understood, as well as the combined performance of multi-tiered solutions. Future work will measure the individual and combined performance of hybrid vegetation-structural systems in mitigating overtopping hazards through large scale experimentation. Large-scale physical modeling allows control of wave and inundation conditions to assess the effects of changing incident hydrodynamic parameters on system performance. Potential consequences of incorporating emergent vegetation in coastal engineering designs, such as effects on sediment transport, erosion or accretion, or nearshore currents, must be explored through laboratory, field, and numerical efforts. Field and laboratory results may be used to validate computational fluid dynamics models for extrapolation to a wider range of hydrodynamic and future conditions. Collaborative efforts through initiatives such as Nearshore Extreme Events Reconnaissance (NEER) and Structural Extreme Events Reconnaissance (StEER) seek to provide field data during and after extreme events that may be used to further understand the performance of vegetation during these events and resulting impacts to the built environment. Multi-institutional and multi-agency experiments (Cialone et al. 2019) and collaborative efforts can provide the breadth of data needed to provide a holistic understanding of a system's performance and effects on coastlines, environments, and local populations.

Trans-disciplinary efforts are required to successfully implement natural infrastructure and hybrid systems for coastal adaptation. Furthermore, robust engineering guidance through manuals of practice, design guidelines, and standards is essential to increase the implementation and success of nature-based systems. Designs must consider the ecological requirements, variability, and limitations of natural infrastructure as well as the engineering performance to ensure that a proposed site is an appropriate location for implementation of mangroves or other vegetation systems. Ostrow et al. (2023) describe a performance-based design methodology for emergent vegetation, which incorporates the inherent uncertainties in an emergent vegetation system into the engineered design, including how emergent vegetation changes over its design lifetime in response to natural growth or decay both during and post-storm. These guidance documents and manuals of practice are needed to quantify uncertainties in the use of natural infrastructure for engineered coastal solutions consistent with conventional practice to increase acceptance among practitioners (Ostrow et al, 2022). Expertise from engineering, ecology, economics, and social science fields, among others, is required to develop guidance that fully characterizes the ability of mangroves and other natural infrastructure to provide engineering, ecological, and economic benefits. Support and engagement of local stakeholders is also necessary to ensure the success of a project.

Conclusions

This paper describes results of field and laboratory measurements investigating wave attenuation through mangrove forests. Field measurements during overland flow conditions on a mangrove island in the Gulf of Mexico near Key West, FL, USA are also presented. While additional work is necessary to confidently characterize and implement these systems, existing evidence shows promise in mangroves and other natural infrastructure for mitigating coastal flood hazards and providing environmental and societal benefits. Characterizing, designing, and successfully implementing these systems provides opportunities for trans-disciplinary collaborations and future studies.

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