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Exploring Coral Reef Restoration for Wave-Energy Dissipation through Experimental Laboratory Testing

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Abstract: In recent years, there has been an increasing recognition that green, nature-based, infrastructure provided by coastal ecosystems, such as coral reefs, can mitigate the impacts of climatic hazards in an efficient and cost effective manner. Coral reefs act as low-crested, submerged breakwaters reducing wave action and thus providing flood reduction benefits for coastal communities. This paper focuses on using coral reef restoration for coastal resilience purposes. In the absence of universally accepted guidelines for coral reef structures and a lack of direct measures of their effect in wave energy at relevant scales, the study focuses on a series of experiments in the University of Miami's Surge-Structure-Atmosphere-Interaction (SUSTAIN) facility. Preliminary results revealed that wave heights, and thus wave energy, reduce after the coral reef with the decrease being wave-frequency dependent. Current studies focus on a series of tests including parameters related to the wave spectrum as well as the reef characteristics, such as reef length, width, slope and composition, through measurement of the wave height, water velocity and pressure on an auxiliary structure.

Keywords: Shoreline protection, green infrastructure, coral reef structure, wave, wind, experimental testing

1 Introduction

According to National Centers for Environmental Information (NCEI, 2019), the U.S. has sustained 233 weather and climate disasters since 1980 with overall damages/costs exceeding $1.5 trillion. Those events include 29 flooding events, 40 tropical cyclone events and 99 severe storm events, making extreme winds and flooding the main components of the costliest and deadliest natural disasters in recent years. The geographic analysis of these events reveals the Southeastern U.S. and its coastal regions are among the most susceptible areas to such disasters. As average annual temperatures and sea level continue to rise, these areas will likely experience stronger windstorms and more significant coastal flooding events. Therefore, it is of utmost importance to employ efficient and ecofriendly solutions that make coastal infrastructure less prone to weather and climate disasters.

Coral reefs have been shown to mitigate the impacts of climatic hazards in an efficient manner (Ferrario et al. 2014). They protect the shoreline from erosion and flooding by functioning like low-crested breakwaters reducing wave energy through wave-breaking action and friction (Beck et al. 2018). Both effects are linked to their self-generated carbonate structure (i.e. their skeleton). Coral reefs can thus be considered natural, regenerative, and cost-effective breakwaters as restoration has been shown to be cost-effective in comparison to the development of traditional submerged breakwaters (Beck et al. 2018). However, they are typically not accounted for directly in coastal infrastructure as their effects are not always easy to quantify. Consequently, artificial coral reefs unlike typical shoreline-protection structures, such as seawalls and revetments, do not have well-established design guidelines making their implementation even more challenging. The only example of an artificial reef designed and deployed for shoreline protection purposes has been the one recently deployed in the Caribbean island of Grenada (Reguero et al. 2018). Therefore, this paper focuses on the design of experiments for the evaluation of the impact of artificial coral reefs through physical testing in the SUrge STructure Atmosphere Interaction (SUSTAIN) Facility.

2 Coral reefs and waves

In this section, the key design parameters for the use of coral reefs as shoreline protection are discussed. As natural breakwaters, coral reefs must be investigated considering both ecological and engineering aspects. Coral reefs are among the most biologically diverse ecosystems. They are also extremely sensitive to changes in their environment. Therefore, their successful implementation depends on both environmental parameters (i.e. temperature, light, sediment, hydrodynamics, and depth) and physical parameters (i.e. material composition, surface texture, color and chemistry of the substrate, reef profile, size and configuration, stability) that in many cases affect also their wave-energy dissipation capability (Spieler et al. 2001).

The influence of coral reefs on waves can be calculated using linear wave theory (Beck et al. 2018). Consider the conservation of wave energy given by Eq. (1):

$$\frac{\partial E_w C_g}{\partial x} = -\left(D_b + D_f + D_v\right) \tag{1}$$

where E_w is the wave energy density and $\mathrm{C_g}$ is the wave group phase speed. The terms on the right side of Eq. (1) are related to the dissipation of wave flux energy through wave breaking (D_b), bottom friction (D_f), and the presence of vegetation in the water column (D_v). In this study, the influence of vegetation is neglected. Wave breaking (D_b) and bottom friction (D_f) are given by Eq. (2) and (3) following Thornton and Guza (1983):

$$D_b = \frac{3\sqrt{\pi}}{16}\rho g \frac{B^3 . f_p}{\gamma^4 h^5} H^7 \tag{2}$$

$$D_f = \frac{f_w}{16\sqrt{\pi}}\left(\frac{\sigma}{sinh(kh)}\right)^3 H^3 \tag{3}$$

where ρ is the water density, g is the gravity acceleration, k is the wave number, σ is the angular wave frequency and f_p is the peak frequency. Common values, 1.0 and 0.78, can be considered for the breaking coefficient B and breaker index γ, respectively, while the bottom friction factor f_w varies from 0.1 to 0.2 depending on the texture following Sheppard et al. (2005). The change in wave height can thus be calculated using linear wave theory:

$$E = \frac{1}{8}\rho g H^2 \tag{4}$$

Key parameters for the wave dissipating performance of coral reefs as a shoreline protection system are thus the water depth, wave height, wave frequency and coral cover.

Another important parameter is wave set-up: the increase in the mean water level due to the presence of breaking waves. It is a significant component in determining the water level, wave generated flow and sediment transportation that are important in the formation and continuing existence of the reefs. According to the experimental studies by Gourlay et al. (1996a, b) the increase in mean water level caused by wave set-up on coral reef can be determined by:

$$\bar{\eta}_r = \frac{3}{64\pi} K_p \frac{g^{\frac{1}{2}} H_0^2 T}{(\bar{\eta}_r + h_r)^{\frac{3}{2}}} \left[1 - K_R^2 - 4\pi K_r^2 \frac{1}{T}\sqrt{\frac{(\bar{\eta}_r + h_r)}{g}}\right] \tag{5}$$

where $\bar{\eta}_r$ is the mean wave set-up on reef-top, K_p is the reef profile shape factor, H_0 is the off reef wave height, T is the wave period, h_r is the still water depth on reef-top, K_R is the reflection coefficient, K_r is the reef-top transmission coefficient that is determined by the friction effect of corals on the top-reef. Eq. (5) is the result of experimental tests on a series of predefined reef profiles without the consideration of friction. More recently, Beck et al. (2018) studied the flood-damage reductions by evaluating the impact of coral reefs on waves by employing linear wave theory and empirical friction values. However, no study was found to evaluate the influence of key environmental and physical parameters in the wave-energy dissipation capability of coral reefs.

3 Design of experiments

Although significant research has been conducted on the wave-energy dissipation from coral reefs and their protection to the built environment and coastal infrastructure (van Zanten et al. 2014), direct measures of the reduction in wave energy by coral reefs are largely lacking at relevant scales. Therefore, the influence of key parameters related to the wave spectrum as well as the reef characteristics is investigated through a series of experimental tests defined in SUrge STructure Atmosphere Interaction (SUSTAIN) Facility (Fig. 1) at the University of Miami. SUSTAIN is a wind-wave tank that can generate directionally varying waves using a 12-paddle system combined with direct wind forces simulating hurricane conditions up to Category 5 on the Saffir-Simpson scale. With a tank size of 21m.-L × 6m.-W × 2m.- H, SUSTAIN allows physical testing of shoreline protection systems at relevant scales in a controlled environment.

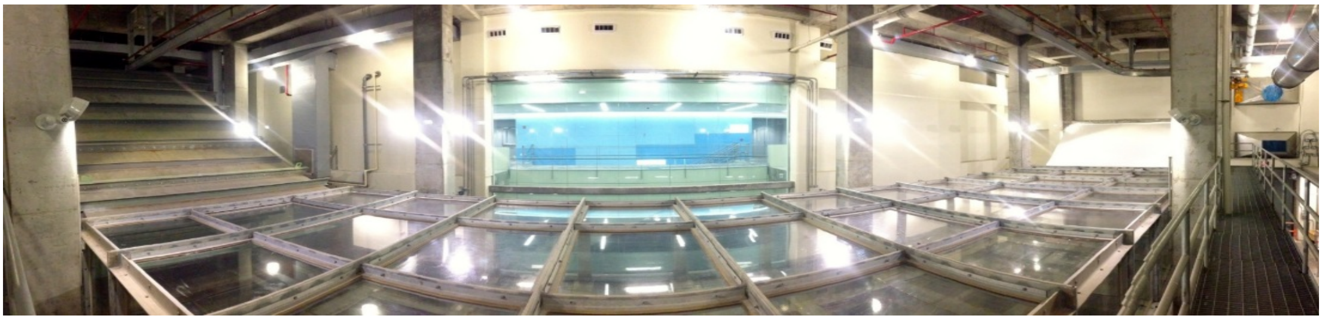

Fig. 1. Panoramic photo of the SUSTAIN tank which has dimensions 21m.-L × 6m.-W × 2m.- H.

Experimental tests for this study are divided into two phases. The first phase was exploratory and focused on the impact of coral friction against wave actions through the testing of a corral array composed of coral (Acropora) skeletons. The tests were thus conducted in the absence of shoaling and wave breaking. The parameters considered in these preliminary tests included the water depths of 52.5cm, 74cm, and 80cm, two orientations for the staghorn corals (parallel or perpendicular to the direction of the waves), wave amplitudes of 3.57cm, 6.29cm, 7.38cm, and 8.56cm, and frequencies of 0.5Hz, 0.8Hz, and 1.0Hz. The influence of the coral thicket on the waves was evaluated through measurements of the wave height via UDM sensors and vertical wire wave gauges (Fig. 2). It was found that in most cases, wave heights, and consequently wave energy, reduced after the coral reef (Fig. 3). However, when the wave amplitude was low, the influence of friction on the waves was negligible as the interaction between waves and corals was minor. A similar trend was observed for the water depth as wave attenuation was higher when the water depth was lower implying a stronger interaction between water particle excursion and the corals. The configuration of corals perpendicular to the wave direction was found more effective compared with the parallel configuration. In few cases, the reef appeared to function as a shallower depth producing shoaling as opposed to friction dissipation that requires further investigation.

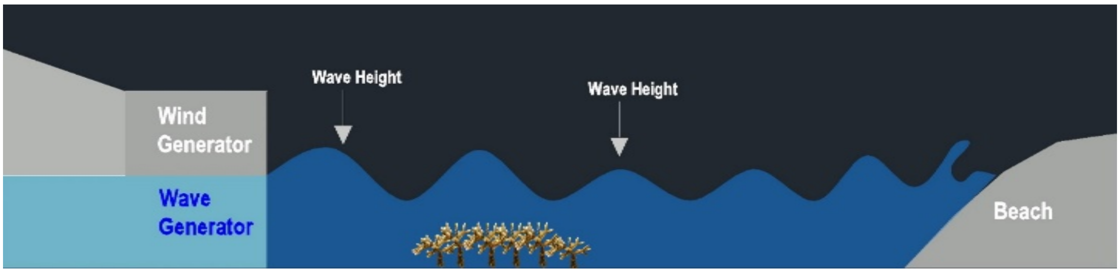

Fig. 2. Illustration of the test set-up for the evaluation of the effect of coral friction on the waves (figure not in scale).

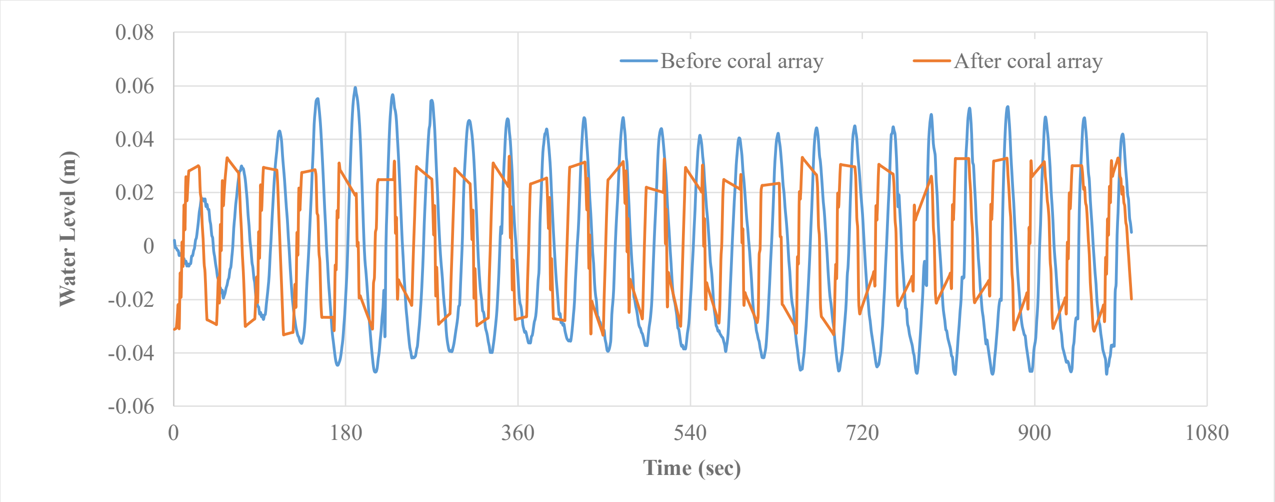

Fig. 3. Wave height measurement under the influence of a corral array (wave amplitude 6cm in water depth 52cm).

The second phase of testing reflects a parametric study of all key parameters on three configurations: a) corals only; b) breakwater only; and c) corals on breakwater. Configurations a) and b) allow the investigation of the effects of friction and wave breaking independently, while configuration c) focuses on their interaction. In addition to the parameters considered in the first phase, coral reef related parameters, such as coral composition, and reef characteristics, such as reef slope, are also considered. Furthermore, both periodic and JONSWAP waves as well as wind action are considered. Moreover, for the study to be transferable to a variety of conditions, outputs are defined as dimensionless ratios (Tab. 1).

Tab. 1. Dimensionless output ratios considered in the coral reef testing.

Ratio	Parameter definition	Reasoning
H_w/L	H_w: wave height L: wave length	Complete description of the wave action
h_r/L	h_r: still water depth over horizontal reef-top L: wave length	Simulation of the effect of waves at different depths
h_r/h_c	h_r: still water depth over horizontal reef-top h_c: average coral height	Simulation of the effect of corals at different depths
w_c/L	w_c: coral bed width L: wave length	Simulation of the effect of coral reef width on different waves

The experimental set-up includes thus a breakwater structure along with the corals and measurements of wave height via UDM sensors and vertical wire wave gauges are combined with measurements of pressure sensors and water velocity using two Acoustic Doppler Current Profilers (Fig. 4). Preliminary testing with measurements of wave height across the reef structure without and with corals showed a difference in the energy dissipation in the presence of the corals (Fig. 5-6). Although the energy dissipation is comparable, the interaction and the mechanisms that control it require further investigation.

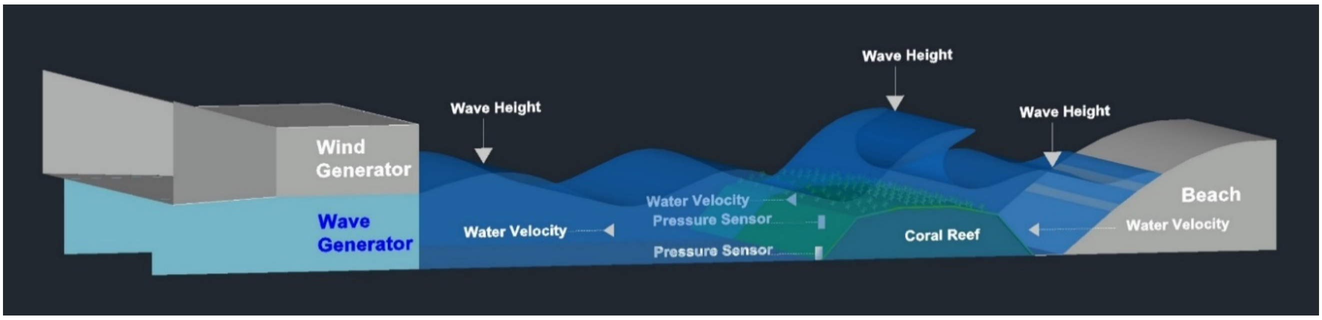

Fig. 4. Illustration of the experimental set-up for phase two testing considering coral reef structure (figure not in scale).

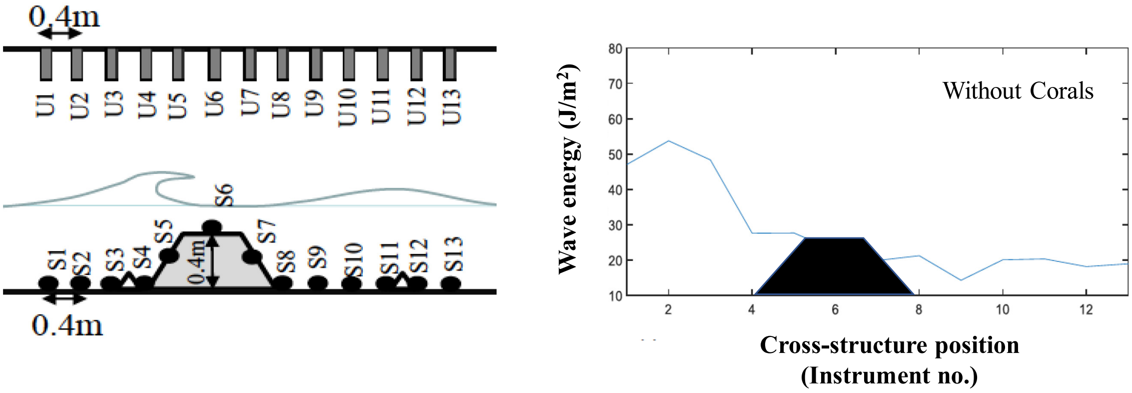

Fig. 5. Wave-energy dissipation across the coral reef without corals on the breakwater structure.

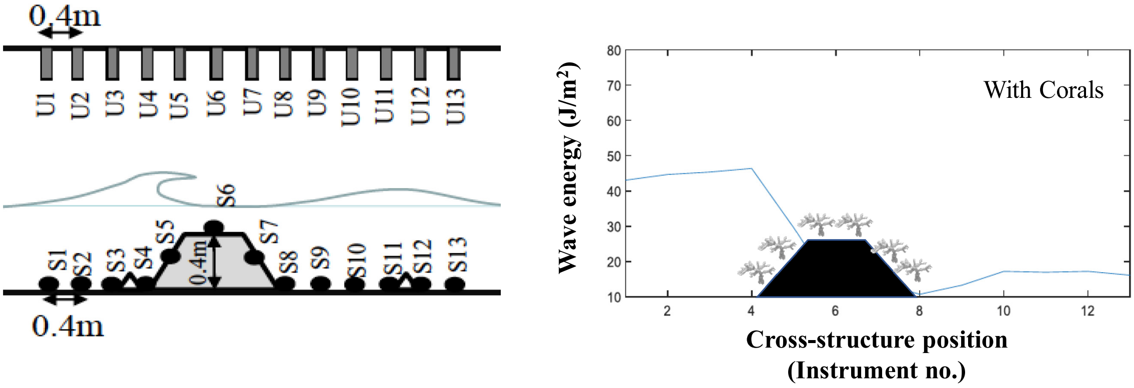

Fig. 6. Wave-energy dissipation across the coral reef with corals on the breakwater structure.

4 Discussion

In the absence of design guidelines for green/gray coastal infrastructure and with direct measures of wave-energy dissipation by coral reefs lacking at relevant scales, this paper explores an experimental testing in the SUrge STructure Atmosphere Interaction (SUSTAIN) Facility to study the effects of environmental and physical parameters in the wave-energy dissipation by coral reefs. The proposed experiments, combined with auxiliary studies on material biocompatibility, can bridge the gap between engineering and ecological knowledge by quantifying the effect of the environmental and physical parameters on wave-energy dissipation enabling the use of coral restoration for coastal resilience.

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