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Large Scale Experiments on the Effect of Artificial Reef Restoration on Wave-Driven Flooding

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Abstract. This paper presents a new set of experiments conducted at near-prototype scale to investigate the impact of artificial reef flat restoration on wave transformation and runup. The experiments were carried out in the 300m-long Delta Flume, which allowed the representation of the entire fringing reef profile and sandy island at a 1: 3 scale. The reef restoration consisted of rows of complex-shaped roughness elements arranged in different layouts. In total, three configurations were tested under five irregular wave conditions and two water levels. All tests were also repeated on a bare (unrestored) reef flat to assess the impact of the restoration. Preliminary data analysis indicates that the artificial reef restoration reduced significant wave heights by up to 13% near the shore for the high-density restoration configuration and the lowest water level. This reduction in wave height was similar for both the sea-swell and infragravity wave frequency bands. Next steps are to examine how the spectral distribution of the (incident) wave energy is impacted by the reef restoration for the different configurations, relate this to flow observations within the artificial canopy and assess the impact on runup characteristics.

Keywords: Fringing reef · Reef restoration · Wave transformation · Physical modelling

1 Introduction

Atoll islands are often characterized by maximum elevations of only a few meters above mean sea-level making them extremely vulnerable to coastal flooding. Coral degradation decreases the reef roughness and elevation, and thus its ability to dissipate wave energy

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and protect the coast. In this context, coral reef restoration measures, traditionally motivated by ecological reasons, are now brought forward to increase the resilience of coral islands to wave-driven flooding.

Because of costs and operational constraints, reef restorations are typically of limited spatial extent (a few 10s of meters at most in the cross-shore direction). A few studies have investigated how reef restoration design could be optimized for coastal protection [1, 2]. However, these studies often relied on numerical modelling in which the reef restoration was highly schematized [1]. For instance, wave-driven oscillatory flows within and around the (artificial) reef structures were not always represented. This could lead to different responses in terms of wave dissipation but also wave reflection, and thus to modifications of both the total amount of wave energy reaching the coast, the frequency distribution of this energy [3] and the mean water level response [4] which are all key parameters to wave-driven flooding. How the combination of these commonly neglected effects ultimately influences water levels at the reef-fronted beach is still largely unknown, and there is still limited experimental data allowing a quantification of these processes.

Here, we present large-scale experiments recently carried out in a 300 m-long wave flume (Delta Flume, Deltares) to characterize the impact of artificial reef restoration on wave transformation and wave runup. The experiments were conducted at near-prototype scale (geometric scaling factor of 1 on 3), allowing the modeling of the 3D flow around complex-shaped reef structures with minimal scale effects.

2 Experimental Set-Up

2.1 Reef Restoration Test Series

The reef restoration tests were part of a larger experimental program described in [5]. For these experiments, a 60 m-wide sandy island was built behind a 45 m-wide horizontal reef flat (see bed profile in Fig. 2c). The reef restoration tests were part of the so-called hydrodynamic test series, where the sandy island was elevated to prevent overwash and covered by a geotextile to measure runup on a permeable island while limiting morphodynamic changes.

The same wave and water level conditions were repeated with and without artificial reef structures on the reef flat. Five irregular wave conditions (H_s = 0.5–1.5 m and T_p = 5.7–9.5 s) were generated for two different water levels, corresponding to still water depths of 0.33 m and 0.67 m above the reef flat. Additionally, bichromatic wave conditions with fixed wave heights but increasing group periods were generated for the largest water level to study resonance behavior with and without artificial reef structures. The bichromatic cases are not discussed further in this contribution.

2.2 Artificial Reef Configurations

The hydrodynamic conditions were repeated for three configurations of the artificial reef restoration (called S1, S2 and S3 in the following). For S1 and S3, the restored area spread over 10m in cross-flume direction (between x = 136 and x = 146 m, with

x = 0 at the wavemaker, see also Fig. 2c), and consisted exclusively of the 3D printed structures shown in Fig. 1a and 1b. These were 25 cm high concrete structures, with a base diameter of about 35 cm. The only difference between S1 and S3 was the spacing of the reef structures. For the 'low-density' configuration S1, the distance between the centers of the structures in both x- and y-direction was ~70 cm, leading to a total of 91 3D printed structures to cover the 10 m * 5 m area (Fig. 1a). For the 'high-density' configuration S3, the distance between the structures was reduced to ~50 cm from center to center, leading to the installation of 153 structures over the same area (Fig. 1b). The last configuration (S2) is an extension of the low-density configuration S1, with 11 larger structures installed in three additional rows shoreward of the main restoration area (see Fig. 1c).

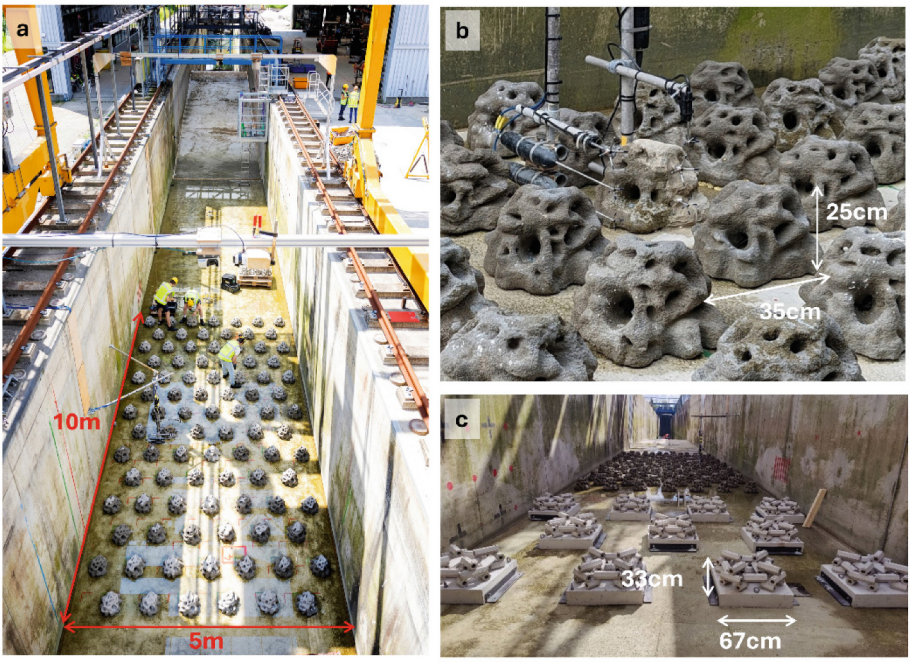


Fig. 1. (a) Top view of the reef restoration S1 (low-density configuration of the 3D printed structures designed and produced by Coastruction); (b) Zoom on the 3D printed reef structures, now deployed in the high-density configuration S3; This picture also shows the 6 acoustic doppler velocimeters deployed to measure the flow between the structures; (c) Configuration S2, where 11 additional, larger, reef structures designed by ReefSystems were added shoreward of the 3D printed structures.

2.3 Instrumentation

Wave transformation and runup was measured by a series of pressure sensors and electromagnetic current meters as well as cameras and line-scanning lidars (see [5] for a detailed

overview of the instrument setup). At 10 locations across the reef profile (including locations right before and right after the restoration), pressure sensors and electromagnetic current meters were collocated and can be used to separate incoming and reflected wave components. Two vertical arrays of 3 Acoustic Doppler Velocimeters were additionally installed during the reef restoration tests to measure the 3D flow between and right above the structures at elevations of 10, 20 and 30 cm (Fig. 1b). These velocimeters were installed around x ≈ 141 m, at the same y-position but about 30 cm apart in x-direction.

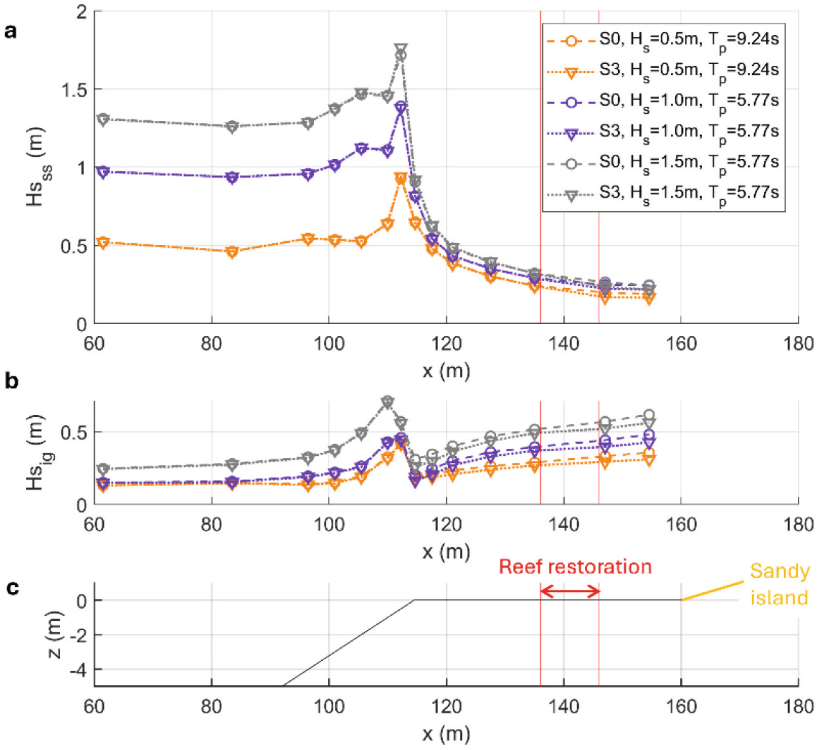


Fig. 2. Cross-shore evolution of the sea-swell significant wave height (a) and infragravity wave height (b) for 3 irregular wave conditions (one color per wave condition) for a still water depth of 33 cm above the reef flat. Both results without reef structures (circles) and with reef structures in the high-density configuration S3 (triangles) are plotted; (c) bathymetric profile with the 10m-long restoration area indicated in red.

3 First Results

Figure 2 presents a first quantification of the effect of reef restoration for the high-density configuration S3. The figure compares the cross-shore evolution of the significant wave height obtained from the pressure sensors for 3 irregular wave conditions, with and without artificial reef structures. Note that, as a first step in the analysis, the total wave height is examined, i.e. including both the incident and reflected components. The cases

shown in Fig. 2 correspond to the lowest water level considered in the reef restoration experiment. The still water depth above the reef flat was then 33 cm, leading to mean water depths larger than 45 cm above the restoration for all wave conditions due to setup, such that the structures (and the ADVs) were always fully submerged.

Overall, the figure shows a relatively small but consistent effect of the reef restoration on the significant wave height evolution, for both the sea-swell frequency band (defined as $f > f_p/2$, where f_p is the offshore peak frequency) and the infragravity wave band (defined as $f < f_p/2$). For the sea-swell wave height (Fig. 2a), differences between the bare (S0) and restored (S3) reef appear for $x > 136$ m, i.e. at the sensors located shoreward of the restoration area. For the infragravity waves, the significant wave heights start differing on the outer reef already ($x > 120$ m). This is likely a result of the significant long wave reflection at the beach but needs to be investigated after decomposition of the signals between incident and reflected wave components. The reduction rate for the sea-swell significant wave height at $x = 154.5$ m, calculated as the relative difference between the measured wave height with and without restoration, ranges between 10 and 13% for the different wave conditions considered. A similar reduction rate is observed for the infragravity wave heights at the same location (9–13%). Increasing the still water depth above the reef flat to 67 cm leads to a decrease by roughly two of the wave height reduction rates (not shown).

4 Conclusion

In this paper, we presented a unique dataset allowing a systematic quantification of the effect of a localized reef flat restoration on wave transformation and runup at the back-reef beach. The experiments were performed in large-scale laboratory facilities, in which the reef profile was schematized at near-prototype scale (1: 3), significantly limiting scale effects in the representation of the interaction between (wave-induced) flow and the complex-shaped reef structures. The newly collected data can be used to improve our fundamental understanding of the interaction between waves and roughness elements, and guide further numerical model development.

Preliminary analysis of the data revealed that the significant wave height was reduced by up to 13% near the beach for the high-density configuration of the reef restoration, and that this reduction in wave height was of similar magnitude for both the sea-swell and infragravity waves. The next steps are to extend the analysis to the other reef restoration configurations and to examine how the spectral distribution of the (incident and reflected) energy is impacted by the reef restoration in these different cases. The observed spectral dissipation will furthermore be linked to flow characteristics within the artificial reef canopy. Finally, the impact on run-up will be quantified and the consequences for island evolution and coastal protection designs investigated.

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