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Modular Coral Shaped Artificial Reefs acting as Beach Protection Barriers

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Abstract: Beach protection is rapidly turning into a multidisciplinary field in which physical, environmental and socioeconomic aspects acquire similar weights in the design and decision making processes. The final protection strategy (nature-based, engineered ecosystems, soft engineering or ecologically enhanced hard infrastructure) depends on several factors: an accurate diagnosis of the coastal problem, the importance of the human assets to be protected, the level of admissible uncertainty and the desired resilience of the coastal system; none of which can be considered as of lesser importance. In this scenario, it is widely accepted that mimicking nature, in the functioning, the space occupied and even in the shape, is the path to successful coastal defense projects. The present work describes the laboratory testing of a novel prefabricated element intended to imitate the shape, hydrodynamics and ecological performance of coral reefs. The coral shaped elements were designed to replicate the form of the tropical *Acropora palmata*. The results show that these elements dissipate a large amount of energy, mainly by wave breaking and friction; similar in performance to natural reefs. Wave trains equivalent to storm conditions were tested and in several tests the coastline was found to displace seawards. The coastal dune was found to cede sand to the beach as would occur in natural beaches. The overall performance of the barrier is acceptable; it can be considered an efficient and environmentally friendly beach protection alternative.

Keywords: Artificial reef, Coral shaped coastal barriers, Beach protection, Wave energy control, 3D printed reef

1 Introduction

Coral reefs have been proven to be the most effective natural, living coastal protection available (Ferrario et al. 2014). Their richness and robustness has been repeatedly demonstrated, to the point that they are considered amongst the most valuable and protected ecosystems worldwide. Unfortunately, it is not always possible to use coral reefs as a means of coastal protection due to their slow growing rates, fragility and the high costs of reproduction and maintenance, which are not competitive against other coastal engineering measures. As a result, it has been widely accepted that some of the ecosystem services provided by coral reefs can be mimicked with artificial elements or structures. The protective service is that most often required (Silva et al. 2019), although other services, such as habitat provision and ecosystem connectivity are also sought (Schoones et al., 2019). The success in offering these services depends on the geometry, construction material, inner structure complexity and location of the artificial reef. Obviously, the more ecosystem services considered as desirable, the more multidisciplinary becomes the task of designing an artificial reef (Piocha et al. 2018).

Several techniques and strategies for imitating the performance of coral reefs have been developed in the traditional engineering of coastal defense barriers. One of these measures, detached submerged breakwaters, has been used extensively to damp wave energy ('Izzat Na'im et al. 2018) with success in the effective control of wave energy and beach stabilization. Unfortunately, the same cannot be said with regard to other ecosystem services, nor environmental and cumulative impacts. Reports can be found on habitat loss, undesired connectivity, uncontrolled colonization by non-native species and other ecological consequences (Dafforn et al. 2015). Coastal engineers must develop innovative solutions based on a better understanding of the characteristics, cycles and biota dynamics of the marine environment.

Arguably, one of the milestones in coastal protection breakwaters is the use of geometric shapes. While construction viability, costs and certainty in load capacities can be listed among the main reasons to stick to known, manageable shapes, it is evident that in nature straight lines and rigid angles are rarely found. This is the reason the modular elements presented in this paper were developed; a structure made of such elements may mimic nature and become the means to offer artificial barriers capable of providing many ecosystem services, while its resistance makes it a feasible defence strategy. These modular barriers may be constructed in similar time as any other alternative and at a competitive cost.

2 The development of the modular design

Any coastal structure should have the following characteristics: low diversity of materials, easy and relatively rapid construction and robustness to ensure resistance and stability. Consequently, barriers made of robust elements, which offer stability mainly due to their deadweight, have generally been preferred for coastal protection around the world. The development of the coral shaped elements begun with the idea of designing concrete prefabricated modular elements for breakwater construction, these were enhanced to reduce the concrete volume needed and finally the coral shaped were invented. Each development is described next.

2.1 Concrete modular elements

A modular element was developed at UNAM coastal laboratory for the construction of coastal protection barriers that satisfied the design criteria of being heavy, easy to place and resistant. The main idea behind its design was to provide an element that can be used to fabricate barriers of any height. Fig. 1 shows images of the modular barrier. Geometrically, the modular elements are a combination of triangular and rectangular prisms; the upper part has a right-angled triangular cross section and is placed on top of a rectangular prism, with two triangular prisms at the sea and leeward sides, respectively. The bottom part of the element fits into the space between two others in a lower layer. In the barrier, the elements are staggered vertically and horizontally, thus enhancing stability.

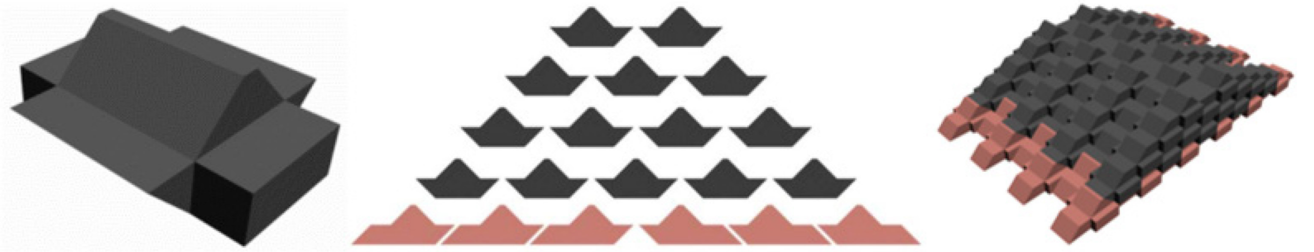

Fig. 1. Images of a single element (left), construction scheme (center) and a 3D view (right) of the modular barrier (Monroy 2013).

The modular barrier has seaward and leeward slopes of close to 2(H):1(V) and a very rough surface, which enhances wave dissipation. The modular barrier was tested in the wave flume at UNAM and gave good results in terms of wave energy control; some sample results for reflection (K_R) and transmission (K_T) coefficients are presented in Fig. 2, where data for two different scale ratios was plotted. Arguably, the main disadvantage of the elements shown in Fig. 1 is the volume of concrete needed to make the barrier; slightly more concrete than that needed for a barrier made of concrete cubes. Thus, the design of the elements was improved.

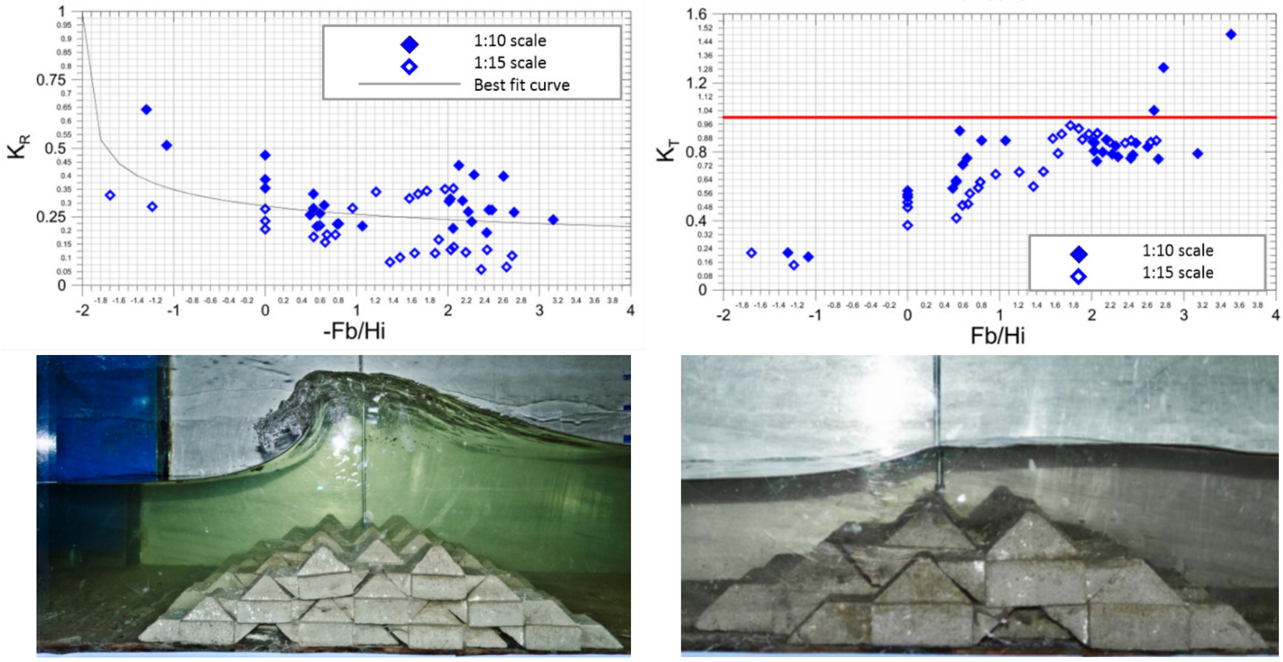

Fig. 2. Reflection (top left) and transmission (top right) coefficients computed from experimental recordings of the modular barrier and images of the barrier during the experiments, scale ratio 1:10 (bottom left) and 1:15 (bottom right) (Monroy, 2013).

The improved design of the modular elements has large voids in the cross and longitudinal directions, as seen in Fig. 3. The barrier has the same advantages as that of the original design, but with a reduction in the volume of concrete needed; less than that required for a traditional cube breakwater (Cardenas et al. 2018).

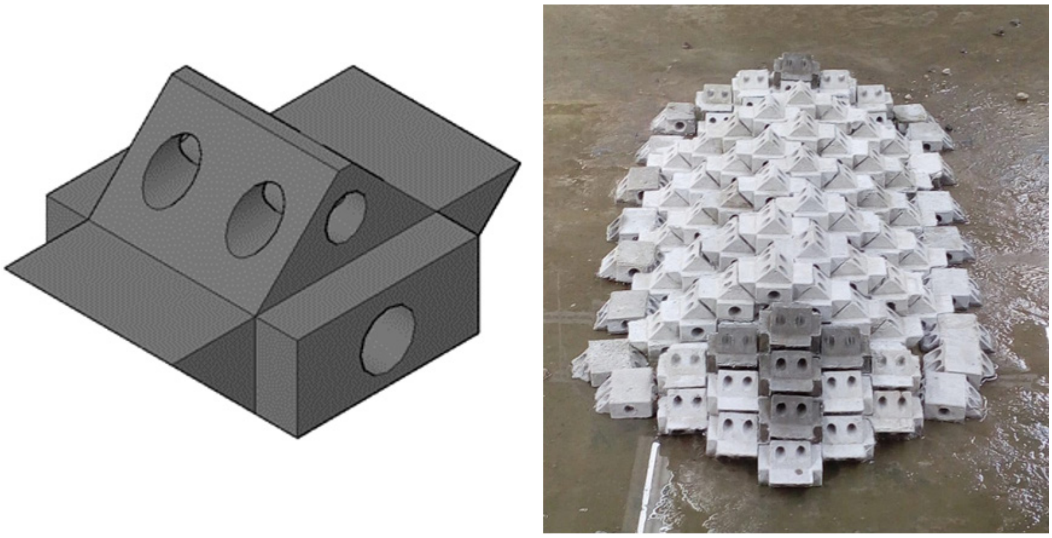

Fig. 3. Images of the improved element (left) and of a modular barrier (right).

The improved modular barrier was tested in a small wave tank under regular waves. Reflection coefficients of around 30 % and transmission coefficients of 15 % for short periods and up to 70 % for longer periods were found. This performance is considered acceptable for any low crested structure, but if the environmental, constructive and cost advantages are considered, the proposed modular barrier is a promising alternative for coastal protection.

2.2 *Coral shaped reefs*

As stated before, geometric shapes are not commonly found in nature and although evidence of the colonization of artificial geometric shaped breakwaters exist, reports can be found on the fragility, low

effectiveness and undesirable results of the resulting ecosystems (Airoldi et al. 2015; Ferrario et al. 2016).
The development of coral shaped elements, which better mimic the local substrata and are expected to be colonized quickly and easily. These barriers should develop more resistant and resilient ecosystems which in turn, may be colonized by native biota.

Non-geometric shapes have been previously used in coastal engineering projects, most of them onshore or in the intertidal areas. Strain et al. 2018 presented a classification of these, from small textures and pits, to large structures, such as large elevations and submerged soft structures. The proposal presented here is, to the authors´ knowledge, the first submerged rigid structure to provide a reef-like surface which offers both coastal protection and ecosystem enhancement.

A structure was designed that is similar to *Acropora palmata* coral, which is known as one of the best reef-building species. It has various growing patterns: from large individual branches to finger-like structures and can be found in tropical seas, at depths of up to 30 m.

The coral shaped artificial reef pieces were designed to fit into the modules of the barrier described in section 2.1. Different heights were designed, in order to reproduce the natural distribution of branch length, that is, short branches seawards, longer ones at the crest and the longest branches on the leeward side. The three modular elements are shown in Fig. 4.

Fig. 4. Coral shaped modular elements for artificial reef construction; seaward element (left), crest elements (center), leeward element (right).

The use of the modular barrier underneath the coral shaped elements provides a stable substratum, facilitates the construction of the barrier and retains the benefits described previously. The coral shaped elements were produced by a 3D printer for the laboratory tests. Fig. 5 shows images of the barrier.

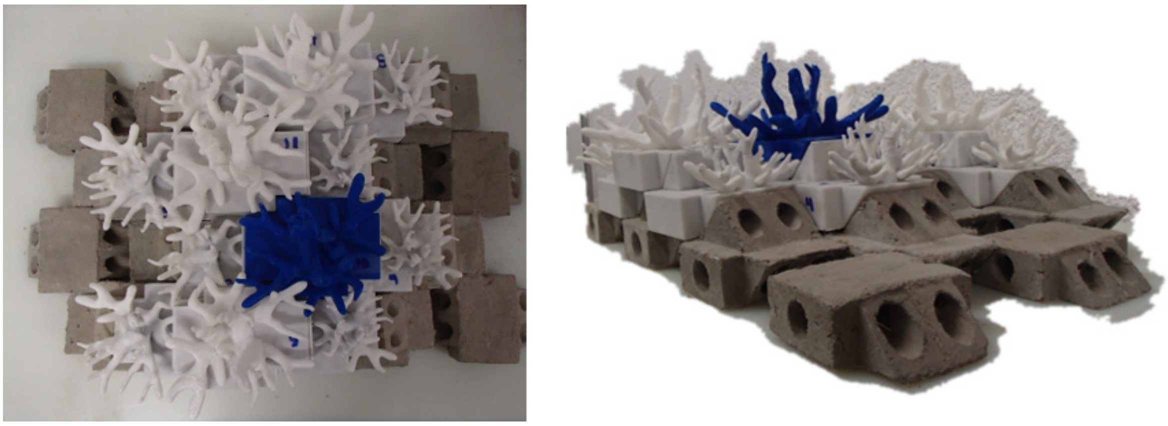

Fig. 5. Coastal protection barrier made of coral shaped reef modular elements.

3 Experimental work

The tests focused on the evaluation of the hydrodynamic and morphological functions of the coral shaped artificial reef were performed in the wave flume of the Ports and Coastal Engineering Laboratory at UNAM, Mexico. There, a piston type wave maker was used to produce Jonswap spectra

($\gamma = 3.3$). This wave maker is equipped with an active re-reflected wave absorber. The flume is 37 m long, 0.8 m wide and 1.2 m deep.

The wave flume was divided into two sections in order to test two sandy beach profiles simultaneously (D_{50}=0.142 mm): Profile A, with a horizontal berm and a narrow coastal dune (reflective beach) and profile B with no berm and a wider coastal dune (dissipative beach), as plotted in Fig. 6. Details of the shape and characteristics of the profiles can be consulted in Silva et al. 2016.

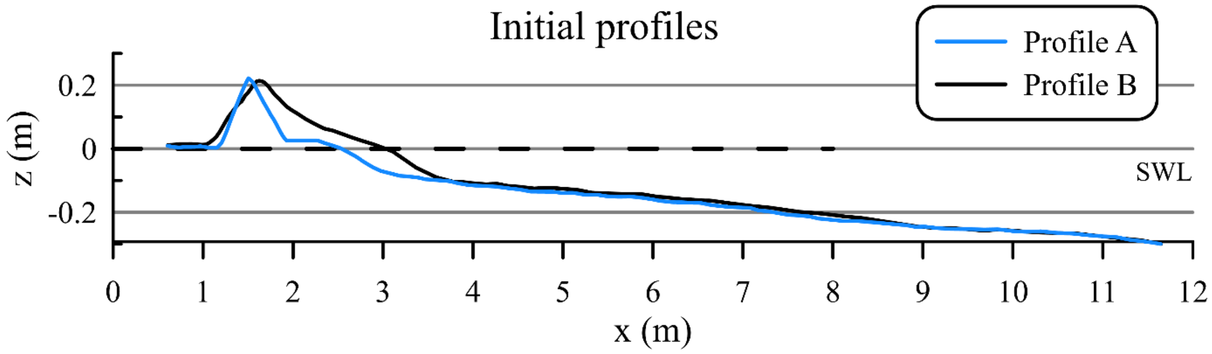

Fig. 6. Experimental beach profiles A and B.

Only storm condition wave trains were run in order to evaluate unfavorable cases in which the breakwater is critically loaded and the beach response can be recorded. Tab. 1 shows a summary of the wave trains used in the experimental program.

Tab. 1. Experimental program.

Wave train	T_p (s)	Hs (m)	h (m)	Structure height (m)	Depth at structure toe (m)
1	0.849	0.05	0.45	0.15	0.30
2	1.118	0.05	0.45	0.15	0.30
3	0.849	0.10	0.45	0.15	0.30
4	1.118	0.10	0.45	0.15	0.30
5	1.118	0.10	0.48	0.15	0.30
6	0.894	0.05	0.45	0.15	0.15
7	1.118	0.05	0.45	0.15	0.15
8	0.894	0.10	0.45	0.15	0.15
9	1.118	0.10	0.45	0.15	0.15
10	1.118	0.10	0.48	0.15	0.15
11	0.849	0.05	0.45	0.30	0.30
12	1.118	0.10	0.45	0.30	0.30
13	1.118	0.10	0.48	0.30	0.30

T_p is the peak period, Hs the significant wave height and h the still water level.

During the tests, the water surface elevation was recorded at 100 Hz by wave gauges placed on the sea- and leeward sides of the protection barrier and Baquerizo's 1995 recommendations for the separation between gauges was followed. The final beach profile was recorded with a topographic automatic level.

4 Results

The hydrodynamic and morphologic performance of the coral shaped modular barrier was analyzed through the reflection, transmission and dissipation of the wave energy and the coastline displacement and sand distribution along the beach profile. Given that the performance of the elements cannot be compared to any existing low crested structure, it is compared to the wave energy dissipation recorded for a natural coral reef barrier, allowing the investigation into how similar the wave damping of the artificial reef is.

4.1 Laboratory results

4.1.1 Hydrodynamic performance

The separation of the incident and reflected spectra was estimated following Baquerizo`s 1995 method, from which the reflection coefficient, K_R, was also computed. The transmitted wave was recorded directly in the wave flume and the transmission coefficient was estimated as:

$$K_T = \frac{Hs_i}{H_T} \tag{1}$$

As a first approach, the energy dissipation coefficient, *D*, was determined following the energy conservation law, that is:

$$K_R^2 + K_T^2 + D^2 = 1 \tag{2}$$

Tab. 2 shows a summary of the hydrodynamic results.

Tab. 2. Hydrodynamic results (energy reflection, transmission and dissipation coefficients).

	Profile A			Profile B		
Wave train	K_R	K_T	*D*	*KR*	K_T	*D*
1	0.58	0.51	0.63	0.61	0.57	0.54
2	0.39	0.84	0.35	0.47	0.76	0.43
3	0.35	0.74	0.57	0.33	0.68	0.64
4	0.38	0.82	0.41	0.37	0.60	0.70
5	0.35	0.85	0.36	0.43	0.84	0.30
6	0.42	0.31	0.85	0.54	0.39	0.73
7	0.35	0.74	0.56	0.38	0.79	0.46
8	0.40	0.27	0.87	0.57	0.38	0.71
9	0.31	0.52	0.79	0.41	0.63	0.64
10	0.40	0.27	0.87	0.45	0.54	0.70
11	0.32	0.16	0.93	0.58	0.34	0.73
12	0.18	0.16	0.96	0.34	0.36	0.86
13	0.37	0.13	0.91	0.45	0.25	0.85

In general, the results presented in Tab. 2 follow the expected trends. That is, energy dissipation is inversely proportional to wave energy (wave height and period) and to the distance from the coast. Also, the hydrodynamic performance of the coral shaped barrier shows strong dependence on wave breaking given that, for some cases, the energy dissipation is greater for higher waves (i.e., breaking waves). This is also true for the tests with the still water level representing storm surge; if waves break the dissipation is larger and vice versa.

Regarding the geometry of the barrier, the higher and more robust the structure, the higher the dissipation. This is irrespective of the modular elements, given that the reflection is not greater than for any other geometry. The dissipation of surface waves produced by the artificial reef is therefore promising.

The performance for the reflective and the dissipative profiles was similar, with the exception of a few tests in which the dissipative character of profile B enhanced the performance of the barrier. This is in agreement with results in nature, as coral reefs are generally found near dissipative beaches. In turn, the wave energy dissipation, in most of the tests, is greater for profile A.

4.1.2 Morphological performance

One way to examine the beach response to specific wave conditions is observing the displacement of the coastline. It is well known among coastal engineers that a coastline retreat does not necessarily means beach erosion, but it is still an important parameter, due to the perception of the public that a reduction in the dry beach shows an unhealthy, unstable beach. Fig. 7 shows the horizontal displacements of the coastline for all the tests performed. It can be seen that both profiles show the same direction of coast line displacement for almost all the wave trains, with the exception of tests 4, 9 and 12 in which profile A gains dry beach and profile B loses it. The landward displacement of the coastline for tests 5, 10 and 13 is as expected, given the intensity of the storm. The same response is found for test 1 which is surprising. In general, it can be stated that the coastal dune-berm system in profile A is the more prone to cede sediment to the beach, making it more resistant. Overall, the protection of the coral shaped barrier is evident.

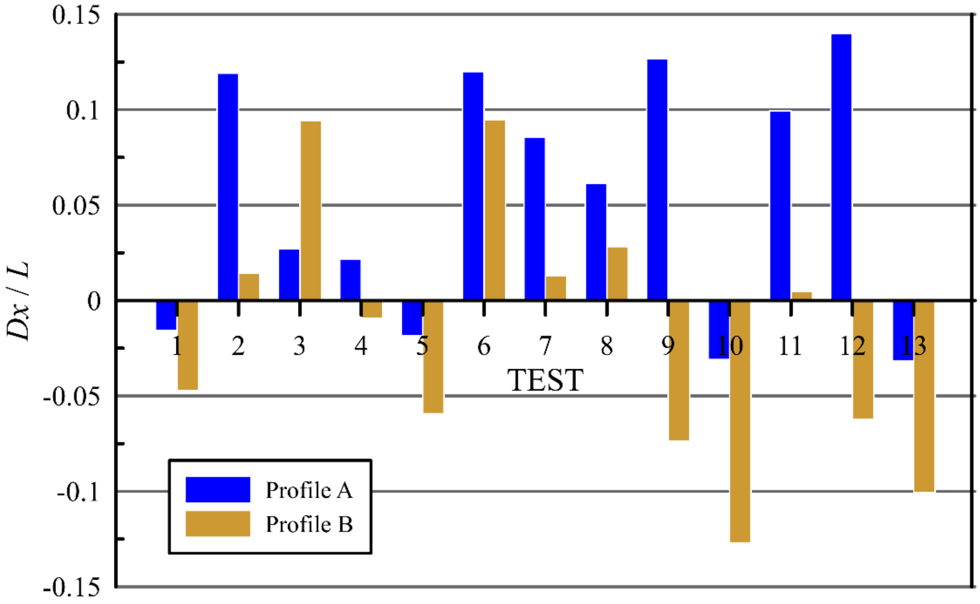

Fig. 7. Coastline vertical displacements for all tests. Positive values mean displacement seawards and vice versa.

The sand distribution along the beach profile also illustrates the performance of the artificial reef. In all the tests with the coral shaped barrier far from the coast, the energy dissipation favoured the creation of a submerged sand bar, which enhances beach stability. In the tests in which the coral shaped barrier was close to the coast, the sand taken from the coastal dune was deposited at the leeward toe of the coral shaped barrier. The result is a very short profile in which the berm of profile A was replaced by a homogeneous slope similar to that of profile B. This means that if the coral shaped barrier is close enough to the coast, the final shape of the beach profile does not depend on the initial shape.

In general, with the exception of the tests representing a heavy storm, the profiles protected by the action of the organic-shaped barrier were seen to be stable and the protection provided by the proposed structure is similar to that of other coastal protection alternatives.

4.2 Comparison to natural reef measurements

The most useful evaluation of the performance of the coral shaped reef is its comparison against a natural reef. To do so, data for the Limones coral reef in the Mexican Caribbean was used (Mariño-Tapia et al. 2015).

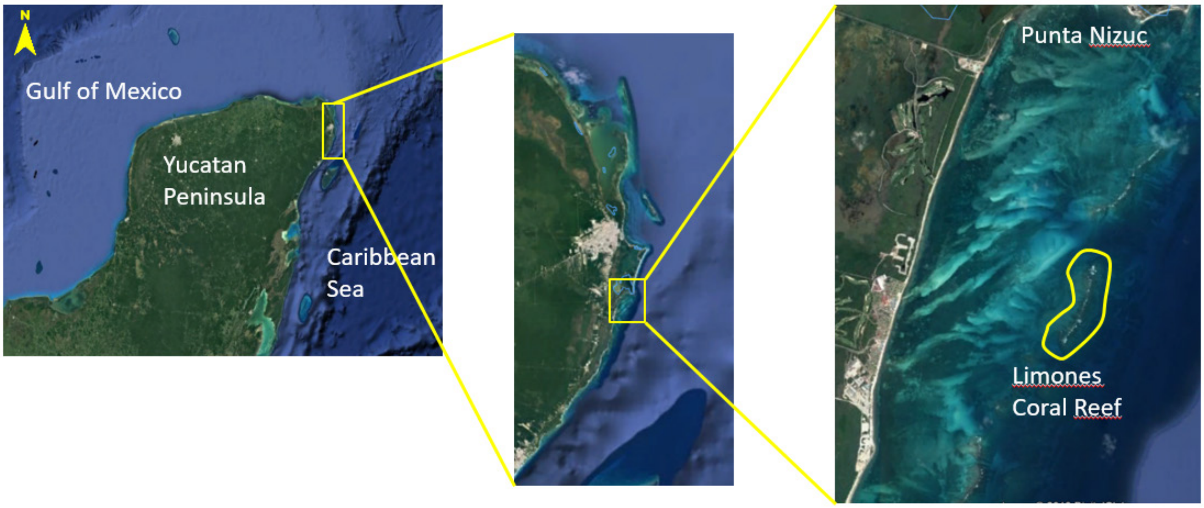

Fig. 8. Location of the Limones coral reef on the Mexican Caribbean.

Fig. 8 shows the location of the reef, known to be the best conserved in all the Caribbean.

The performance comparison focused on the wave energy dissipation due the presence of the reef. Following Lowe at al. 2005 and Rogers et al. 2015, the energy dissipation can be estimated as the gradient, in the wave propagation direction, of the energy flux spectra. The latter is defined in eq. (3).

$$F_x = EC_g = \rho g \int S_{pp} \left[\frac{\cos kh}{\rho g \cos kh}\right] C_g df \tag{3}$$

where ρ is the water density, S_{pp} the energy density spectra and C_g the group celerity. Fig. 9 shows the crest and backreef energy flux spectra recorded at Limones Reef.

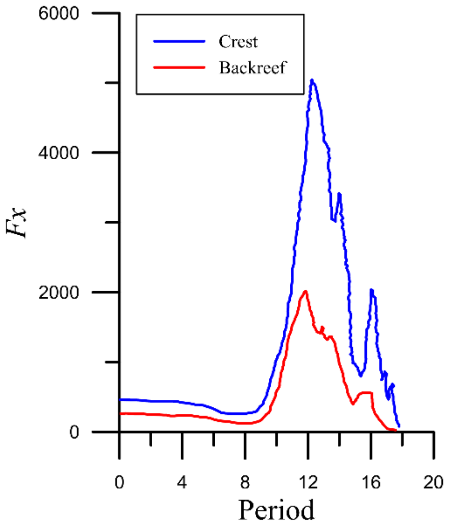

Fig. 9. Energy flux spectra recorded at Limones Coral Reef.

The spatial gradient of the incident and transmitted energy fluxes (area below the spectra) gives the percentage of the energy dissipation, around 75 %.

Following a similar procedure, the incident and transmitted energy flux spectra as well as the energy dissipation ratios were estimated for all the coral shaped structure tests. Tab. 3 shows the results obtained.

Tab. 3. Wave energy dissipation ratios for the coral shaped structure.

Wave train	Profile A	Profile B
2	0.87	0.88
3	0.92	0.98
5	0.76	0.84
6	0.83	0.73
7	0.97	0.95
9	0.83	0.72
10	0.99	0.98
11	0.59	0.38
12	0.92	0.93
13	0.99	0.92

From Tab. 3 it is evident that the energy dissipation due to the coral shaped reef falls within the range of a healthy natural reef, while for several tests, the dissipation is greater. A few tests were not included in Tab 3 because the transmitted energy was higher than the incident energy. This means that a high percentage of waves did not break and high energy was found beyond the structure. In turn, these tests correspond to those in which the coastline retreated the most.

Given that the coral shaped modular structure showed energy control similar to natural reefs, that its protection and hydrodynamic performances are acceptable and that it has been designed to mimic the shape and conditions of natural habitats, it can be stated that this barrier is a feasible alternative for ecological coastal engineering practice.

Conclusions

Coastal engineering has found a great ally in ecosystem based coastal management (Silva et al. 2017). While the environmental worries of traditional engineering practice are undeniable and have been largely documented, coastal protection alternatives can be enhanced through a better understanding of ecological issues such as colonization, connectivity, habitat characteristics and hydrodynamic interaction.

In this work a modular element structure was proposed under the hypothesis that mimicking nature with coral shaped artificial reefs is the path to eco-friendly solutions to coastal problems such as erosion and biodiversity loss. The barriers constructed with these elements facilitate wave energy dissipation by bottom friction, wave breaking and interstitial friction. It is thus envisaged that this type of structure can provide habitat provision services which may be attractive to native biota.

The laboratory results showed acceptable energy dissipation values and the response of a sandy beach profile to the presence of the coral shaped structure that can be considered as tending to stability even under the action of storm waves.

Finally, the performance of the proposed solution was compared to the wave energy control recorded in a natural coral reef, finding similar results and even a higher damping. This ought to be weighted with the fact that laboratory conditions are totally controlled.

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