NUMERICAL SIMULATIONS FOR THE DESIGN OF A MULTI-FUNCTIONAL ARTIFICIAL REEF FOR LEIROSA COAST, PORTUGAL

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ABSTRACT

A multi-functional artificial reef (MFAR) is a relatively new kind of coastal structure that can have several functions. The main possible functions are the protection of the local coastline against erosion, increasing the possibilities of local surfing and enhancement of the marine ecosystem in the area. This article elucidates these three functions. For the coast of Leirosa, a small town located in the north western coast of Portugal, a MFAR is a possible solution to protect the local coastline. For the design of the MFAR geometry for the Leirosa coast, some parameters have to be defined, such as the length of the reef slope and the offshore distance of the structure. The use of a numerical model allowed for simulations of the evolution of regular and irregular waves over a variable bathymetry. Several cases have been run for different slopes of the reef and for different offshore distances of the structure, as well as for different dimensions of the crest of the structure. The analysis focused on the influence of the length of the slope on the breaker type and on the characteristic length determination of a broad-crested structure like a MFAR. The results indicate that the depth of the platform has a large influence on the breaker type and no clear differences in the current patterns were found for different distances from the shoreline to the base of a broad-crested structure or from the shoreline to the apex of the structure crest.

Keywords: geotextile sand containers, marine ecosystem enhancement, multi-functional artificial reefs, numerical simulations.

1 INTRODUCTION

Multi-functional artificial reefs (MFARs) are a relatively new kind of coastal structures, that can have several functions. The main possible functions are the protection of the local coastline against erosion, increasing the possibilities of local surfing and enhancement of the marine ecosystem in the area. These three functions are discussed in detail in this article.

A MFAR has two effects with respect to coastal protection. One is, as with any conventional shore-parallel breakwater, to reduce the wave energy that reaches the coast and, consequently, the impact on the base dune system. The other effect is due to the broad crest of a MFAR, which may cause wave rotation as the wave approaches the coast. This wave rotation has two consequences: (i) deflecting and stretching the wave crest, reducing the wave energy; and (ii) aligning the wave to the shore, thereby reducing the wave-driven currents, and thus the sediment transport along the shore.

Increasing the surfing possibilities is another function of a MFAR. Unlike many other sports, for which new recreational facilities may be built to meet increased demand, surfing has previously been confined to a limited number of natural surf sites. By the construction of an artificial reef, surfable waves can be created which increase the possibilities to surf.

Marine ecosystem enhancement is a third possible function of a MFAR. The most appropriate construction materials for these structures are geotextile sand containers. These containers have appeared to provide an excellent substrate for marine flora and the development of a diverse ecosystem [1, 2]. Figure 1 shows, as an example, short algae and seagrasses on shallow containers of the Narrowneck Reef in the Gold Coast of Australia. When the ecosystem on this reef was well developed, a clear zonation between the areas of seagrasses and kelps could be observed. Visually, the macroalgal communities dominated the reef, covering over 70% of the reef surface. However, it was also populated

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Figure 1: Short algae and seagrasses on shallow containers of the Narrowneck Reef [2].

by a variety of other benthos, including coralline algae, sub-massive sponges, ascidians, octocorals (soft corals), hydroids and crinoids (feather starfish), echinoids (sea urchin) and abalone. Observations by the National Marine Science Centre indicated that 'the biological communities associated with Narrowneck Artificial Reef appear to enhance biodiversity and productivity at a local scale and may also contribute to overall regional productivity' [3].

One of the places for which a MFAR could be a good solution as a coastal protection measure is the coastline of Leirosa, a small town located in the north western coast of Portugal. The construction of an underwater effluent outlet damaged the continuity of the existing sand dune system [4, 5]. At present, an implemented temporary solution protects the local coast. This solution consisted of placing geotextile containers filled with sand. However, a more stable measure like a MFAR is needed to provide more secure protection. Moreover, there are no surfable waves in Leirosa to date.

For the design of the MFAR geometry for the Leirosa coast, some parameters have to be defined, such as the length of the reef slope and the offshore distance of the structure. The influence of the length of the slope on the breaker type has not yet been investigated, although much research has been carried out on surfability – the possibility to surf a wave [6, 7]. Breaking waves can be divided into several types: spilling, plunging, collapsing and surging [8]. Henriquez [7] observed that in laboratory experiments with the same incident wave conditions and the same reef bathymetry, the submergence of the reef had an influence on the breaker type. This is probably due to the fact that the wave breaks on another location by which another length of the reef slope has been experienced by the wave. The length of the slope is not a parameter in the Iribarren number, while it seems to have some influence. By simulating a wave flume, the influence of the length of the slope has been investigated.

Concerning the second goal, coastal protection, numerical and physical studies were conducted for specific locations of certain reef projects [9]. Besides these studies, a numerical and physical research study was carried out by Ranasinghe *et al.* [10], in which shoreline response to submerged structures was investigated. The conclusion of this study was that the offshore distance of the structure is the parameter responsible for the mode of shoreline response (erosion versus accretion). If the structure is relatively close to the shoreline, two current cells are formed that can lead to erosion. When the structure is relatively further away from the shoreline, four current cells are formed (Fig. 2), of which the two cells close to the shoreline can lead to sedimentation. As a preliminary engineering tool, a predictive empirical relationship between the mode of shoreline response and the offshore distance of the structure was proposed. In this relationship, the characteristic offshore distance of a broad-crested structure like a MFAR was assumed to be the distance between the shoreline and the seaward point of the crest of the reef. However, further study needs to be done in order to investigate the characteristic length.

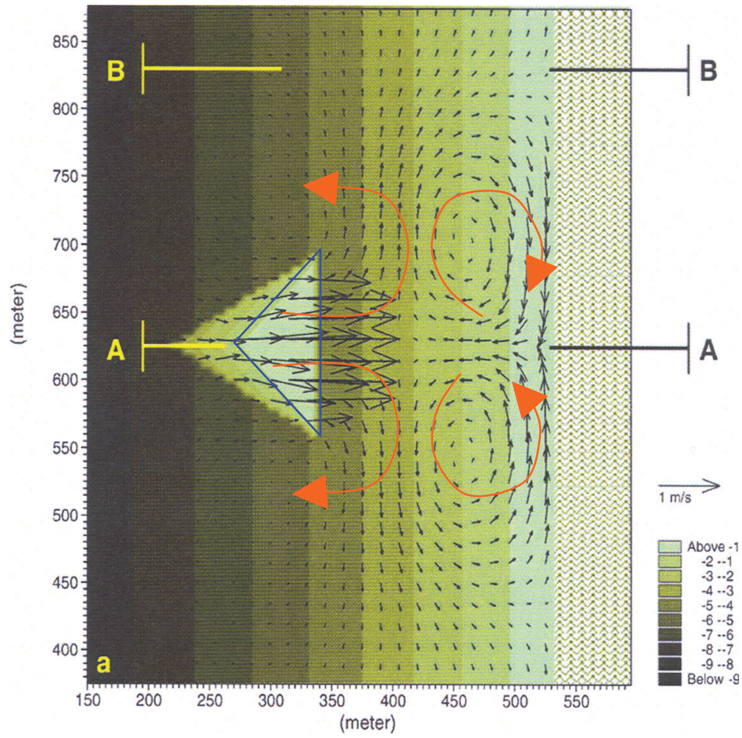

Figure 2: Accretion for distance apex structure coast of 250 m [10].

In this article, the numerical simulations performed to investigate the influence of the length of the reef slope and the offshore distance of the structure on the MFAR functionality are presented.

2 COULWAVE MODEL

For this study, a Boussinesq-type model, COULWAVE [11], was used. The model allows for simulation of the evolution of irregular waves over variable bathymetry. Boussinesq-type models like COULWAVE do not include dissipation due to wave breaking and thus an additive breaking module is necessary. The breaking scheme in COULWAVE is based on a simple eddy viscosity-type model [12]. This simple eddy viscosity formulation is used to simulate the turbulent mixing and dissipation caused by breaking. The mass conservation equation remains unchanged, while, eddy viscosity terms are added at the momentum conservation equation. Comparisons between numerical results and experimental data about wave shoaling, breaking and run-up for both one and two horizontal dimensions showed good agreement for a variety of regular and irregular wave conditions. Unlike 3D Navier–Stokes models, the overturning of the crest of the wave during breaking can never occur in a Boussinesq-type model.

3 INFLUENCE OF THE LENGTH SLOPE ON THE BREAKER PARAMETER

Numerical simulations have been performed with COULWAVE (1DH) to study the influence of the length of the slope on the breaker type. The purpose of these simulations is to analyze the wave

Table 1: Test conditions.

Case	Slope reef	Length slope of the reef at the breaking point	T (s)	H_0 (m)	ξ_0	Depth d (m)
1	1:10	2.0L (= 170 m)	10	1.5	1.0	28.1
2		1.0L (= 98 m)				11.5
3		0.5L (= 34 m)				5.0

conditions near the breaking zone in order to obtain information about the breaker type for the same slope of the bottom and the same wave conditions in deep water considering different lengths of the slope and, consequently, different water depths at the toe of the structure (Table 1).

The wave breaking type with certain wave conditions in deep water can be determined with the help of the offshore Iribarren number, eqn (1):

$$\xi_0 = \frac{tan\ \alpha}{\sqrt{\frac{H_0}{L_0}}}, \tag{1}$$

where tan α is the slope of the bottom, H_0 is the wave height in deep water and L_0 is the wave length in deep water. The values adopted for tan α, H_0 and L_0 in the simulations were based on design conditions for a reef in front of the Leirosa coast. The MFAR was simulated with the geometric conditions shown in Fig. 3. The geometry for cases 2 and 3 is different from that for case 1 in order to prevent instability at the wave source. In fact, the use of a platform is also a possibility in the design of a reef. The simulations have been made using sinusoidal waves.

In this model, the breaking parameters that can be changed are the upwinding parameter (by which the fraction of upwinded differences composing convective terms is determined) and the friction coefficient. In the simulations, the upwind parameter was chosen to be 1 (it can be varied between 0 and 1) and the friction coefficient was set to the default value of 10^{-3}.

In order to make a comparison between the wave characteristics at the breaking point, the location of the beginning of the breaking zone (x_break, see Fig. 3), the reflection coefficient close to the wave source and the wave height as well as the surface elevation at 0.5 m from the beginning of the breaking zone (Fig. 4) were analyzed. A distance of 0.5 m from the beginning of the breaking zone was chosen to obtain the wave signals due to the fact that it is not possible with a Boussinesq-type model like COULWAVE to define the exact wave shape at the breaking point. The reflection coefficient in Table 2 was obtained with the Mansard and Funke method applied considering three gauge positions close to the wave source [13].

It can be seen from Fig. 4 and Table 2 that the wave is more non-linear, before breaking, and that x_break is smaller in case 3 than in cases 2 and 1. The differences in the reflection coefficient are small. From these results, it can be concluded that the depth of the platform in cases 2 and 3 seems to be important. In case 3, the waves experience great modifications, frequently followed by double and even triple decompositions. As a consequence, these modifications lead to a more non-linear wave and a less wave height close to the breaking position. Probably the depth of the platform is in fact the parameter that causes more modifications, namely in the wave shapes, with the same parameters as in eqn (1) and not the length of the slope, although they are related to each other. More tests are

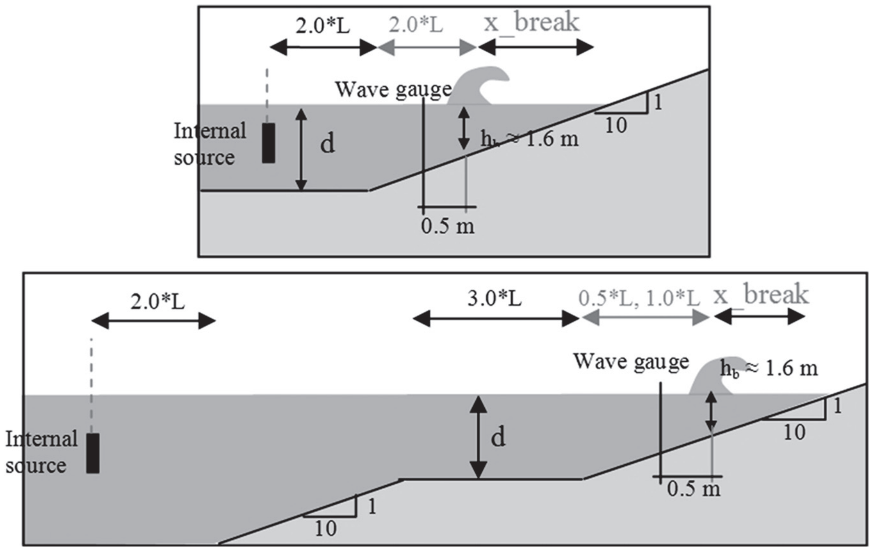

Figure 3: Geometric conditions of the simulations (top: geometry for case 1 (Table 1); bottom: geometry for cases 2 and 3).

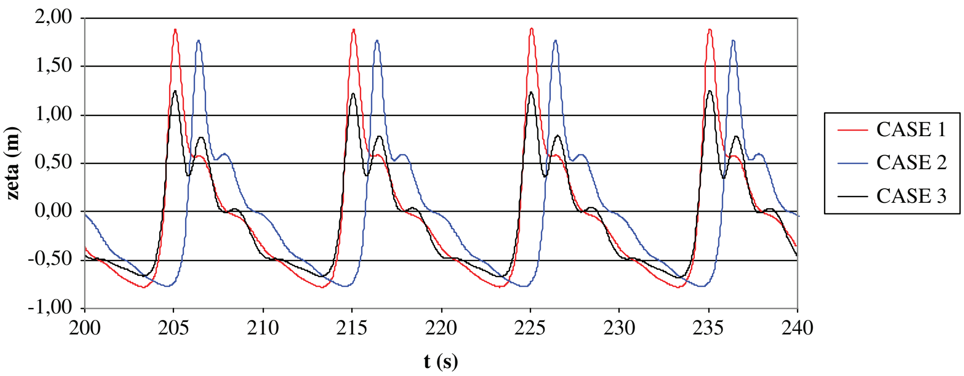

Figure 4: Surface elevations 0.5 m from the beginning of the breaking zone for the three cases.

Table 2: Breaking location and surface elevation at the breaking point.

Case	x_break	*H* at x_break (m)	Reflection coefficient
1	25.6	2.7	0.06
2	25.6	2.6	0.10
3	17.5	2.2	0.08

necessary to obtain a deep insight to this parameter. The length of the slope of a reef is an important parameter in the design of a MFAR regarding the wave shape, but naturally the choice of the length of the slope also depends on the bathymetry of the bottom. If a platform is part of the reef design, its depth is also important concerning refraction on the reef.

4 CHARACTERISTIC LENGTH OF BROAD-CRESTED STRUCTURES

Numerical simulations have been done with COULWAVE (2DH) to study the characteristic length of a broad-crested submerged structure. Ranasinghe *et al.* [10] proposed a predictive empirical relationship between the mode of shoreline response and the offshore distance of the structure. Shoreline accretion can be expected when S_a/SZW > 1.5, while shoreline erosion can be expected when S_a/SZW < 1, regardless of the wave direction. S_a is the distance of the apex of the structure crest from the undisturbed shoreline and SZW is the natural surf zone width. The purpose of the numerical simulations is to see if S_a or the distance from the shoreline to the base of the structure is the correct characteristic length to predict the response of the shoreline.

Figure 5 shows the geometric conditions that were used in the simulations. The reef half nose angle is 45° and the slope of the reef is 1:12, as in the simulations of Ranasinghe *et al.* [10]. Table 3 shows the test conditions. The distances S and S_a in Table 3 are illustrated in Fig. 5. All three cases have a reef half nose angle of 45° in order to have the same refraction on the reef slopes. As in Section 3, the

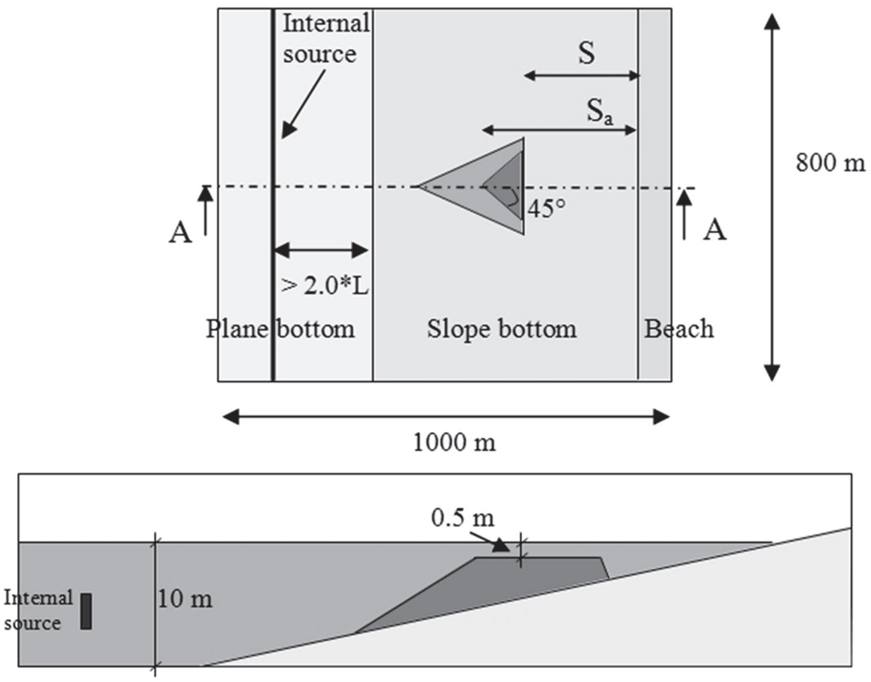

Figure 5: Geometric conditions of simulations (top: plan view; bottom: cross-section A–A).

Table 3: Test conditions.

Test	S_a (m)	S (m)	T (s)	Initial L (m)	Initial H (m)	Initial depth (m)
1 (a)	250	200	10.0	92.4	1.5	10.0
2 (b)	300	200				
3 (c)	250	150				

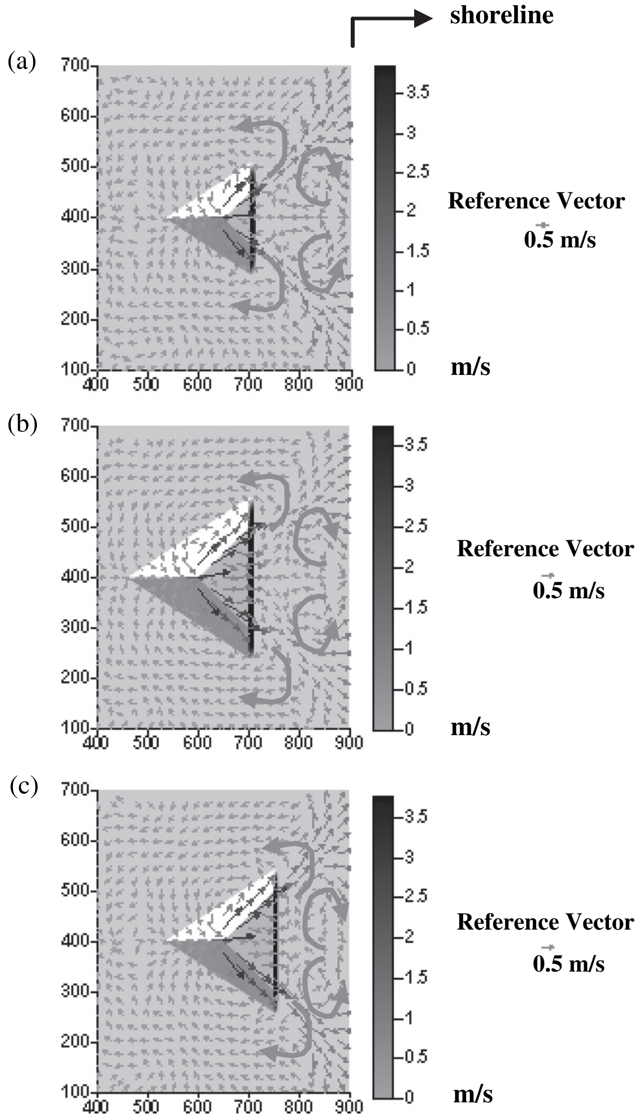

Figure 6: Mean current field around reef for test 1 (a), test 2 (b) and test 3 (c). (The three scale bars belong to the narrow current arrows, not to the wide current cell arrows.)

simulations have been made using sinusoidal waves. The results are analyzed in terms of the mean current field. Figure 6 shows the mean current field obtained around the reef for the three cases.

From Fig. 6 it can be seen that case 1, which is similar to the case of Ranasinghe *et al.* [10] (Fig. 2), gives the four expected current cells. From cases 1, 2 and 3, it can be concluded that the mean current patterns are quite similar, with four cells backward from the structure.

From these simulations, no conclusion can be drawn if the distance from the shoreline to the base of the structure is a better or worse parameter for the characteristic length than the distance from the shoreline to the apex of the structure crest. It has to be mentioned that the nose angle of the reef is 45° in all cases, and so the structure is wider in cases 2 and 3 than in case 1, which can also be of influence. More simulations need to be done in order to obtain more insight in the influence of S and S_a on the formation of current cells.

5 CONCLUSIONS

Multi-functional artificial surfing reefs, which are broad crested structures, are getting more popular, as they can provide for both coastal protection and surfing amenity and enhancement of the environmental value. In order to define a multi-functional artificial reef for Leirosa, in the northern coast of Portugal, numerical simulations (1DH and 2DH) were undertaken. The main goal of this study was to investigate the influence of the slope of an artificial reef on the breaker parameter and to investigate the offshore characteristic length of a broad crested structure with which the mode of the response of the shoreline can be predicted.

Results indicate that the depth of a platform has a large influence on the breaker type. More simulations have to be done in order to obtain more insight in the influence of the length of the slope and the depth of the platform on the breaker type. These simulations should preferably be made with a 3D Navier Stokes model, so the wave shape at the breaking point can be analyzed.

Results of the second part of simulations show no clear difference between different distances from the base of a broad-crested structure to the shoreline and from the shoreline to the apex of the structure crest. No conclusion can be drawn if the distance from the shoreline to the base of the structure is a better or worse parameter for the characteristic length than the distance from the shoreline to the apex of the structure crest. More simulations with more variations in both distances have to be conducted to obtain more insight in the characteristic length of a broad crested structure.

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