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Physical and Numerical Modeling of an Innovative Vertical Breakwater for Sustainable Power Generation in Ports: SE@PORTS Project

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Abstract: SE@PORT project aims to improve the overall performance of a single Wave Energy Converter (WEC), developing hybrid systems that combine the use of two technologies over and above individual working principles. An oscillating water column (OWC) and an overtopping converter (OBREC-type in this case) have been designed to be included in Las Palmas harbor vertical breakwater. This work describes the procedure followed to pre-design the WECs integration in the breakwater by means of numerical modelling and laboratory experiments. The hydraulic performance of the WEC is investigated.

Keywords: Breakwater, Wave energy converters, Sustainability, Wave-structure interaction, Laboratory experiments

1 Introduction

Breakwaters are traditionally designed to resist the action of waves and promote the dissipation of wave energy at port entrances, creating security conditions for port activities. Within the new tendencies of the international community to invest in reliable, clean and reasonable energy sources, a new line of work has arisen with the objective of integrating in the breakwaters, devices capable of harvesting energy from the waves (for example: Wave Energy Converters, WECs) and promoting a new use for such structures.

The high potential of breakwaters for the integration of WECs, due to their high exposure to waves, has also raised new issues related to the hydraulic performance of the modified breakwater. Although several examples have already been implemented following different technologies, there are still questions open about their performance. WECs current applications onshore are either based on the oscillating water column (Pico Plant in the Azores Islands, 1995; Mutriku in Spain, 2008; Civitavecchia in Italy, 2012) or on the overtopping principle (TAPCHAN in Norway, 1980; SSG, 2002; OBREC in Naples, 2013). See Vicinanza et al. (2019) for a review of the technologies. These proof-of-concept prototypes, installed in real environments for validation purposes, still lack an integrated, multipurpose-driven assessment aimed at maximizing its technology efficiency, power production, long-term reliability and minimizing visual impacts or the overall construction. Within this framework, is where the Sustainable Energy At sea PORTs (SE@PORT) has been developed.

2 SE@PORTS project

SE@PORTS project has been funded by OCEANERA-NET call (OCEANERA/0003/2016). The main goal of the project has been going beyond real design to improve the overall performance of a single WEC, developing hybrid systems that combine the use of two technologies over and above individual working principles. SE@PORTS has shown great potential to drive innovation in (1) the hybridization of WEC technology, the technological approach followed for integration into port infrastructure is based on the combination of WEC systems that have already proven their value in realistic conditions, especially their combination with overlapping WEC devices (2), the impact on port breakwaters, with particular attention to their stability and functionality, (3) WEC power performance optimization, refers to applying proper converter devices, control strategies and storage systems to maximize the power production performance and its integration into the electrical grid, (4) methodologies and tools for end-users, (5) Advanced WEC energy yield prediction model train, envisioned to increase the knowledge on energy yield and decrease uncertainties, making the assessment of the power generation of such converters for any port considered possible, and (6) overall WEC System Design, including feasibility assessment of the new hybrid systems in a set of specific domains and variables associated with the operation of a WEC, such as reliability performance, maintenance, and cost.

To accomplish SE@PORTS project, it has been necessary to characterize two case studies, including the offshore wave conditions, wave conditions in the vicinity of the breakwaters, and wave energy potential in front of the WECs. Port of Leixões (Porto, Portugal) and Port of Las Palmas (Gran Canaria, Spain) have been analyzed. Several concepts have been numerically studied in order to analyze its hydrodynamic behavior, define the best design for the foundations, combine different approaches of harnessing wave energy, define which PTO is better suited for power generation, establish control strategies to be applied and explore the integration of storage systems.

The integration of high potential, overtopping concepts (TRL3) in breakwaters of large ports has been finally confirmed by means of numerical and physical modelling. In order to improve the system overall performance, hybrid systems combining overtopping with other working principles to harness wave energy has been analyzed to explore the potential of this original approach. Potentiality of WEC's application in SE@PORTS has been economically evaluated also including both the effectiveness and efficiency, considering Lean Principles by apply Lean Design-for-eXcellence (LDfX) tool.

In the first phase of the project, a multi-criteria analysis has been carried out to characterize the viability of the installation of different existing WEC technologies in breakwaters. The following systems have been considered: oscillating water column (OWC), overtopping converters (OBREC), hinged point absorbers or flexible membranes. The result of the analysis concluded that the two most technologically advanced and highly reliable devices to be used are oscillating water column (OWC), and overtopping converters, using in this case an OBREC-type (Vicinanza et al., 2014; Contestabile et al., 2017a; di Lauro et al., 2019). The rest of the project has been developed around these two technologies for dual integration in two breakwater typologies, rubble-mound and vertical breakwaters.

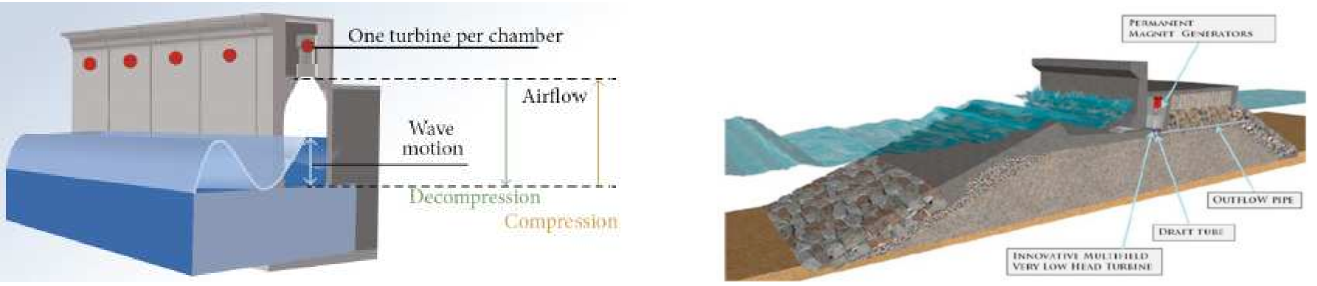


Fig. 1. Conceptual WEC design. Left: oscillating water column (OWC); Right: overtopping converter (OBREC-type).

The work presented here is focus only the hydraulic design of the dual WEC system, formed by an Oscillating Water Column (OWC) and a wave overtopping device (OBREC-type device), both integrated in an innovative vertical breakwater. The modified breakwater has been determined considering that it could be potentially installed in Las Palmas Nelson Mandela vertical breakwater.

The paper is organized as follows. First a description of the framework of this work is provided, including a description of the SE@PORTs project and its main goals. Then, the conceptual design of the dual system and the design methodology followed is presented. Next, a description of Las Palmas Port is introduced, including breakwater typology and wave climate. Based on the previous cross-sections, the dual WEC system is described and the laboratory tests are presented. Finally, some conclusions are drawn.

3 Conceptual design and methodology

The innovative breakwater has been designed to integrate two WEC devices, OWC and OBREC, in a vertical breakwater built with concrete caissons. Due to the fact that both devices need to be integrated into the same caisson, the OWC is defined using an L-shaped duct, which is inserted into the body of the caisson. This allows the arrangement of the pool and auxiliary chamber for the OBREC in the superstructure. As can be seen in Fig. 2, the design follows a modular design that considers different elements containing several OWC chambers and a pool placed on top. The design presented in the figure is an example of a tentative design for the breakwater in Las Palmas that could be slightly modified in terms of the number of chambers or the size (length and width) of the upper pool according to the characteristics of the local wave climate. As shown in the figure, the design is integrated in a concrete caisson type vertical breakwater.

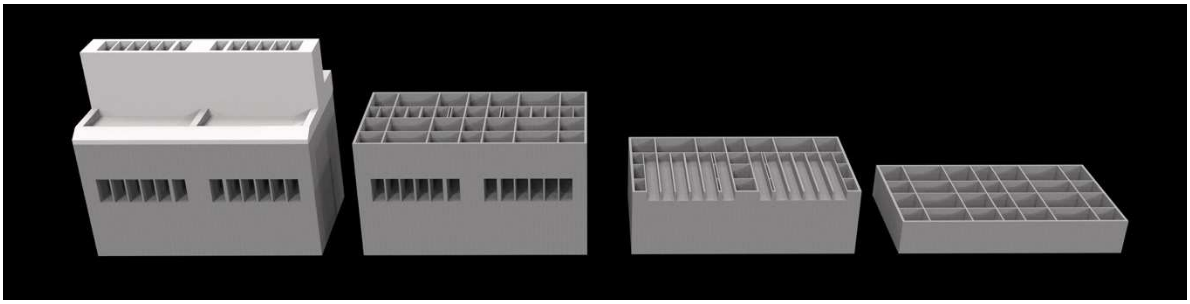


Fig. 2. Innovative vertical breakwater hosting an OWC device and an OBREC device.

Fig. 3 shows a representation of the cross-section of the breakwater where it can be seen how the two WECs are inserted in the same structure. The most important geometrical parameters considered for the definition of the different devices have been represented.

Thus, the following parameters are considered for the OWC (represented in blue in the figure): the depth of the horizontal inlet duct of the OWC (d), the width of the horizontal duct (B1), the horizontal length of this duct (A), the width of the OWC vertical duct (B2). It has been considered that the vertical conduit coincides with one of the cells of the caisson to better proceed with the breakwater construction.

In the case of the OBREC, three geometric parameters have been identified as the most relevant (represented in red in fig. 3): the width of the overtopping pool (Br), the freeboard of the outer ramp of the pool (Rr) and the angle of the ramp (α).

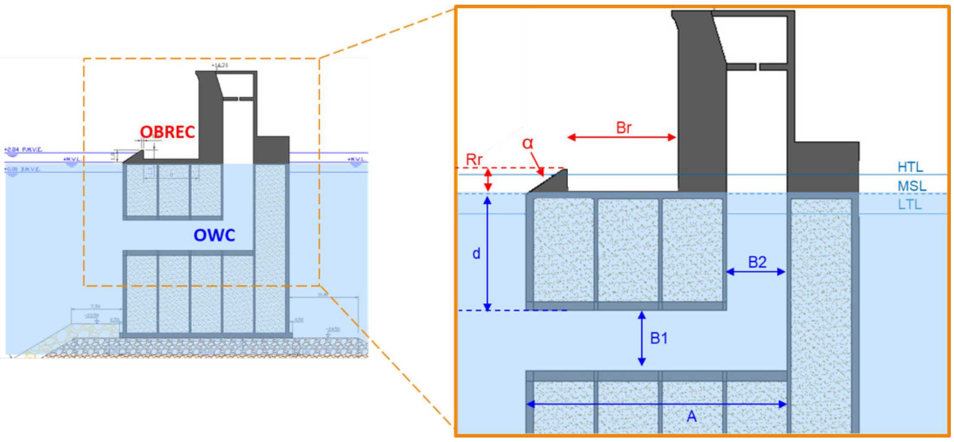


Fig. 3. Cross-section of an innovative vertical breakwater hosting an OWC device and an OBREC device.

The methodology used for the design of the innovative vertical breakwater is based on obtaining the optimum values of the parameters described above, which are adjusted according to the wave climate conditions of each place. In this study, they have been determined for the specific case of the Nelson Mandela breakwater in the port of Las Palmas. In addition to determine the optimum parameters that define the functionality of the devices, an analysis of the breakwater hydraulic stability and its functionality has been made, so that it can continue to fulfil the main function of a classic breakwater: protect a harbor area.

The proposed methodology follows the following steps:

1) *Wave climate site characterization*: Wave climate data for the Nelson Mandela breakwater location, situated in the port of Las Palmas de Gran Canaria (Spain), has been considered.
2) *Definition of the geometric parameters of the innovative vertical breakwater containing an OWC*: geometrical breakwater parameters (see Fig. 3) for the OWC (d, B1 and B2).
3) *Definition of the geometric parameters of the innovative vertical breakwater containing an OBREC*: geometrical breakwater parameters (see Fig. 3) for the OBREC (Rr, α and Br).
4) *Functional analysis of the integration of the two WECs in the innovative vertical breakwater.*
5) *Functional and hydraulic stability analysis of the innovative vertical breakwater containing the dual WEC system.*

In summary, each WEC has been designed individually using numerical models in order to optimize its operation individually. The design of the OWC has been carried out in two steps using NEMOH model first, and IH2VOF model (http://ih2vof.ihcantabria.com) next to include viscous effects. The OBREC device has been defined using the IH2VOF model. In order to represent a realistic PTO for the overtopping device, a new boundary condition which consists in extracting a water flow from the OBREC pool right boundary has been implemented in the IH2VOF model. This water flow is defined each time step as a function of the hydraulic head on the aforementioned pool. Finally, both designs have been tested together numerically in 2D, using the IH2VOF model. The final design has then been experimentally tested to confirm the numerical predictions.

4 Las Palmas harbor vertical breakwater description

The harbor of Las Palmas is located on the northwest coast of Gran Canaria island (Canary Islands, Spain) as shown in Fig. 4 (left). It is geographically protected by a volcanic formation called La Isleta in the north and also from the northwest winds. The harbor has a north-south orientation and has two distinct zones: the Inner Basin and the Outer Basin (the last of which is La Esfinge Basin). The water depth within the basins varies between 3 m and 22 m. The existing infrastructures were designed for a wave height of 50 years return period (Hs = 7.63 m) and a sea level corresponding to a maximum tidal range of 3 m.

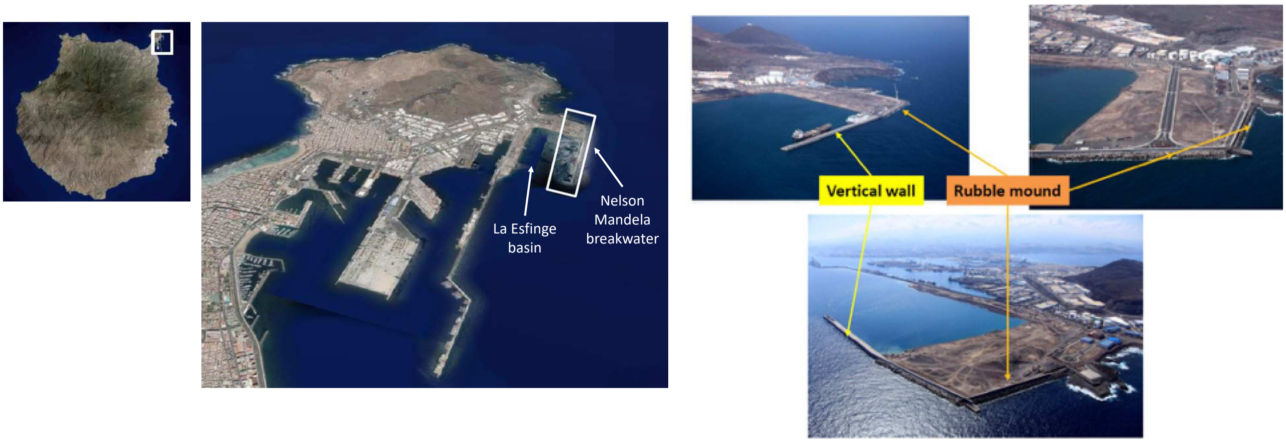


Fig. 4. Left: Site location (Nelson Mandela breakwater in Las Palmas port). Right: Existing cross section typologies at Las Palmas Port (Nelson Mandela breakwater).

The selected site for the dual WEC implementation is the Nelson Mandela breakwater, which is the one that protects La Esfinge basin from the incoming waves (see Fig. 4, right). Nelson Mandela breakwater presents two different typologies: vertical and rubble mound (see Fig. 4, right). For the study case, the vertical cross-section has been used for the design of the new dual device.

Wave climate in the vicinity of the Nelson Mandela breakwater is shown in Fig. 5. On the left figure, the directional rose of significant wave height (Hs) is presented, while in the right figure the Hs histogram is shown.

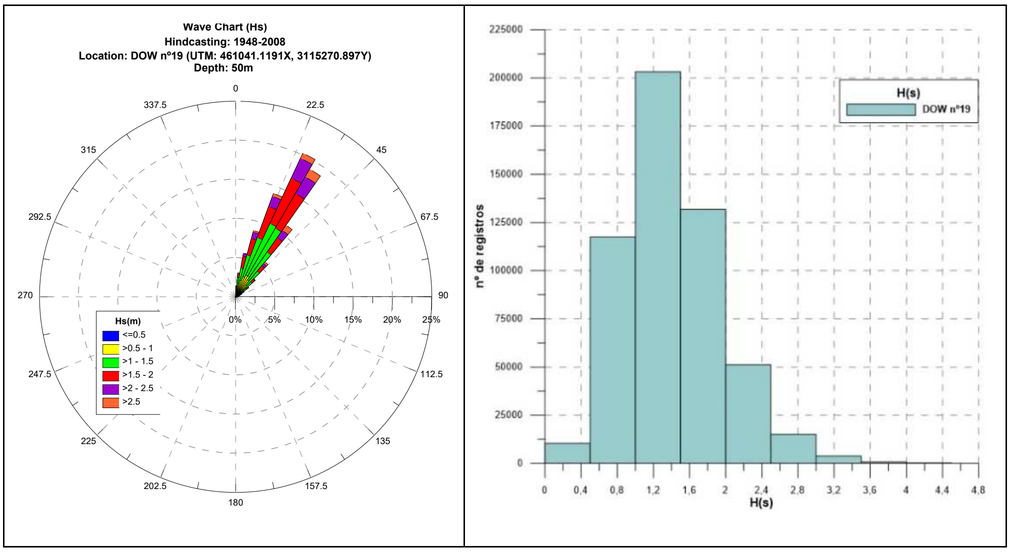
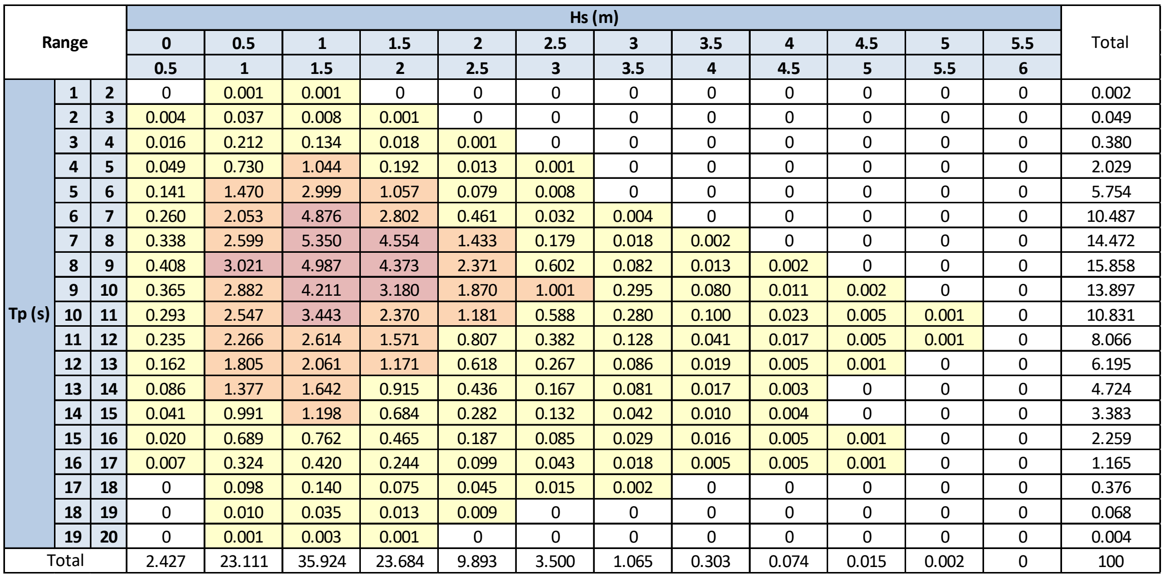


Fig. 5. Wave climate in the vicinity of the Nelson Mandela breakwater.

Regarding the sea level conditions, the tidal range at the Port of Las Palmas is around 3m, being its maximum high tide observed around 3.15m (above harbor datum), and the mean sea level around 1.55m (above harbor datum).

In Fig. 6, the probability of occurrence of sea states (significant wave height, Hs, and peak periods, Tp) in the vicinity of Nelson Mandela breakwater is presented, in which the colors represent the probability of occurrence of a combination of Hs and Tp (yellow represents a low probability while red corresponds to the higher ones). It is observed that Hs presents values ranging from 0.5m to 5.5m, with Tp between 1s and 20s, with most probable wave conditions in the ranges of 0.5-2.5m of Hs and 4-15s of Tp. Based on the presented wave climate, the range of values of Hs and Tp to be numerically and physically tested have been defined.



Range			Hs (m)												Total
			0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	
			0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	
Tp (s)	1	2	0	0.001	0.001	0	0	0	0	0	0	0	0	0	0.002
	2	3	0.004	0.037	0.008	0.001	0	0	0	0	0	0	0	0	0.049
	3	4	0.016	0.212	0.134	0.018	0.001	0	0	0	0	0	0	0	0.380
	4	5	0.049	0.730	1.044	0.192	0.013	0.001	0	0	0	0	0	0	2.029
	5	6	0.141	1.470	2.999	1.057	0.079	0.008	0	0	0	0	0	0	5.754
	6	7	0.260	2.053	4.876	2.802	0.461	0.032	0.004	0	0	0	0	0	10.487
	7	8	0.338	2.599	5.350	4.554	1.433	0.179	0.018	0.002	0	0	0	0	14.472
	8	9	0.408	3.021	4.987	4.373	2.371	0.602	0.082	0.013	0.002	0	0	0	15.858
	9	10	0.365	2.882	4.211	3.180	1.870	1.001	0.295	0.080	0.011	0.002	0	0	13.897
	10	11	0.293	2.547	3.443	2.370	1.181	0.588	0.280	0.100	0.023	0.005	0.001	0	10.831
	11	12	0.235	2.266	2.614	1.571	0.807	0.382	0.128	0.041	0.017	0.005	0.001	0	8.066
	12	13	0.162	1.805	2.061	1.171	0.618	0.267	0.086	0.019	0.005	0.001	0	0	6.195
	13	14	0.086	1.377	1.642	0.915	0.436	0.167	0.081	0.017	0.003	0	0	0	4.724
	14	15	0.041	0.991	1.198	0.684	0.282	0.132	0.042	0.010	0.004	0	0	0	3.383
	15	16	0.020	0.689	0.762	0.465	0.187	0.085	0.029	0.016	0.005	0.001	0	0	2.259
	16	17	0.007	0.324	0.420	0.244	0.099	0.043	0.018	0.005	0.005	0.001	0	0	1.165
	17	18	0	0.098	0.140	0.075	0.045	0.015	0.002	0	0	0	0	0	0.376
	18	19	0	0.010	0.035	0.013	0.009	0	0	0	0	0	0	0	0.068
	19	20	0	0.001	0.003	0.001	0	0	0	0	0	0	0	0	0.004
Total			2.427	23.111	35.924	23.684	9.893	3.500	1.065	0.303	0.074	0.015	0.002	0	100

Fig. 6. Probability of occurrence of wave conditions in the vicinity of the Nelson Mandela breakwater.

5 Dual WEC design

5.1 *OWC design*

A numerical study in the frequency domain (NEMOH) has been used for the design of the OWC. In this frequency domain study, the response of different OWC geometries under the incidence of different regular wave trains has been analyzed, with the final objective of adjusting the device geometry to the target wave climate scenario. The results of this analysis have been subsequently be combined with a parallel analysis carried out for the design of the OBREC, as both will be integrated into the same section of the breakwater. The present analysis is a hydrodynamic analysis that does not involve the pneumatic part of the OWC problem, which represents the power take-off (PTO) system as the first approximation.

An analysis in two steps has been performed. First, only parameter B1 is freely varied in the current analysis. Parameter d, which defines the ridge depth of the horizontal duct, is set at 8.4 m below the port datum according to the wave climate characteristics, and has been defined to avoid the dragging of air from the water under operating conditions. Parameter B2, which defines the width of the OWC vertical duct, is set at 5 m, which is the width of the building cells used in the current caisson of Nelson Mandela's breakwater. Finally, A is found to be ranging between 8 and 20 m, but it is finally fixed at 16.6 m defined on the basis of the OBREC design. Then, three different submerged opening of the OWC (B1) have been considered: 5 m, 8 m and 10 m.

Results for this first analysis are shown in Fig. 7. The excitation force in the OWC submerged entrance (F_{exc}), the added mass (A), the hydrodynamic damping coefficient (B) and the OWC oscillation amplitude in heave (Zowc) have been calculated and compared for different OWC openings.

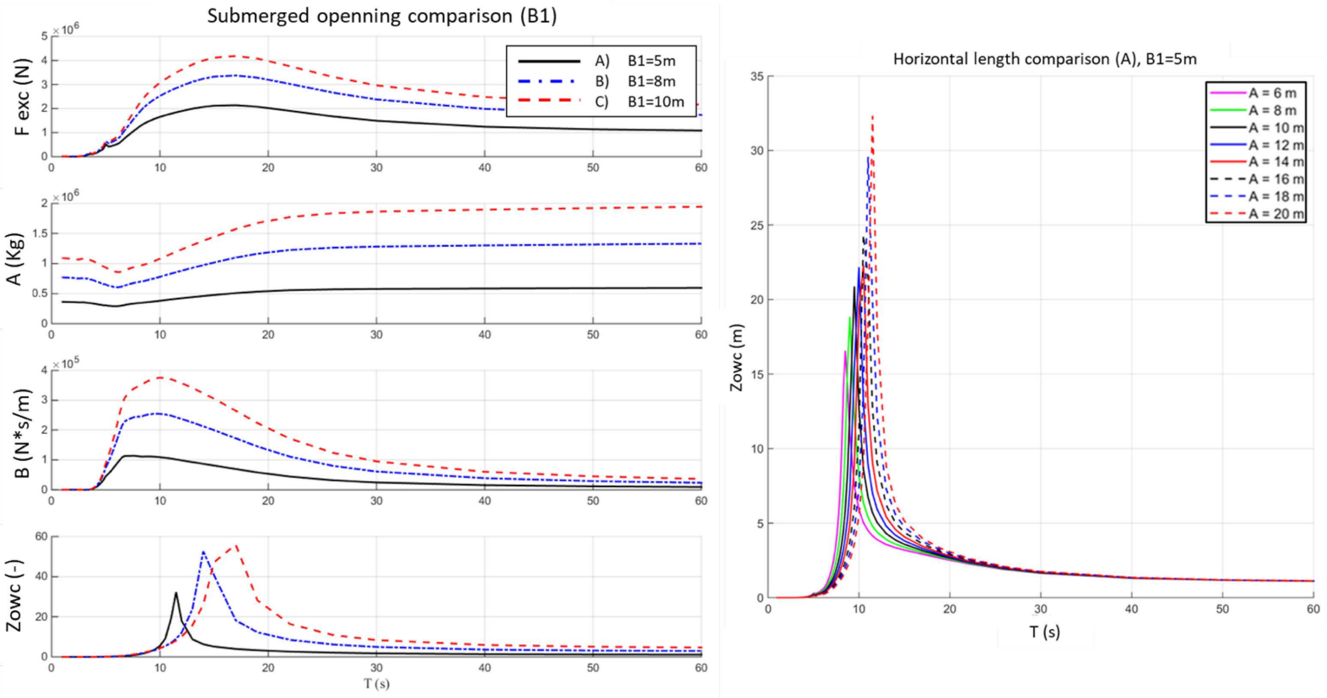


Fig. 7. Left: Comparison for different submerged openings of the OWC. Right: Analysis of the influence of A dimension in the Response Amplitude Operator (RAO) magnitude.

The final aim of this design is to define an OWC geometry which is suitably tuned to the climate scenario in the target location, where the most frequent peak period is between 8.5 and 9 seconds. Fig. 7 (left) shows that the resonant period of the OWC decreases with B1 dimension, obtaining a resonant period of 11.5 seconds for the minimum aperture analyzed (B1=5 m).

The second step of the design is accomplished fixing B1 to 5 m and varying A, the dimension of the OWC chamber. The same analysis that has been previously carried out for B1, has been repeated for different values of A (6, 8, 10, 12, 14, 16, 18 and 20 m). Fig. 7 (right) shows the Response Amplitude Operator (RAO) obtained for the alternatives considered. The bigger is the RAO, the higher is the air compression/expansion and then, the greater is the power production This figure shows that A dimensions of 8-16 m lead to the most suitable resonance periods (8.5-10.5s).

Considering construction aspects in the existing caisson in Las Palmas, and considering the presence of the OBREC reservoir , A=16.6 m has been defined as the most suitable value, resonant for 10.5 s, which is also inside the most probable periods (red cells in Fig. 6). These results need to be combined with the results obtained in the OBREC device analysis to determine the final design of the dual device.

5.2 *OBREC design*

OBREC design has been carried out to obtain the width of the overtopping pool (Br), the freeboard of the outer ramp of the pool (Rr) and the angle of the ramp (α).

The first approach for the OBREC definition consists on a functional characterization of the main geometric parameters: the ramp angle, the position (height) of the beginning of the ramp and the crest ramp. The first two parameters will have an effect on the wave run-up, and therefore on the overtopping flow that will enter on the OBREC pool and will be susceptible of being turbined (the greater the wave overtopping, the greater the produced energy).

Taking this consideration into account, wave run-up analysis has been performed to define the optimum ramp angle and crest ramp. The wave run-up is a variable that depends on the wave conditions (wave height H, and wave period T), the water depth (h), the position of the beginning of the ramp with respect to the mean sea level (d) and the ramp angle (α), as shown in Fig. 8.

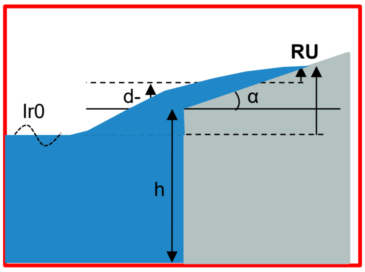


Fig. 8. OBREC: Ramp parameters used in the conceptual design.

Wave run-up can be expressed as a function of the different parameters:

$$Ru = f\,(H, T, h, d, \alpha)$$

Since it is a conceptual design, no breaking is expected, so the run-up will not depend on the water depth. In addition, wave parameters can be defined together by the Iribarren number (Ir0). Wave run-up expression then becomes:

$$Ru = f\,(Ir0, d, \alpha)$$

Based on this expression, the objective was to simulate with IH2VOF model (Losada et al., 2008; Lara et al., 2009) several combinations of d-α values to characterize the wave run-up and obtain the optimum values of d and α. The simulated conditions are:

- Regular waves
- H = 3 m
- h= 10 m (no wave breaking)
- α = [25, 35, 45] (º) (α = 34º is considered an standard value in the literature)
- d/H = [-1, -0.5, -0.3, 0, 0.3, 0.5, 1] (m). Positive values of d mean that the start of the ramp is below the mean sea level.
- Ir0 = [1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5]

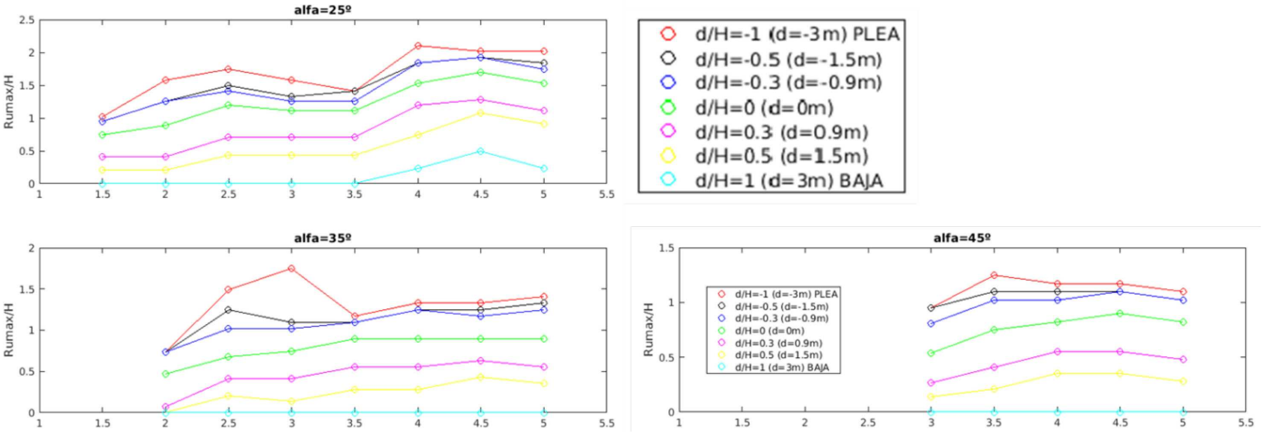


Fig. 9. OBREC: Run-up analysis.

140 IH2VOF numerical simulations have been performed (several simulations had to be discarded for being out of the generation range), using meshes with a vertical resolution of 0.03 m and horizontal resolution of 0.06 m. The output of the simulations in terms of dimensionless wave run-up (Ru/H) as a function of the Iribarren number, are presented in Fig. 9. It is observed that decreasing the d value, Ru value increases. Taking this into account and that the wide tidal range, it has been decided to define the toe of the ramp at the mean sea level (d=0 m) to be working at both levels.

Regarding the value of the ramp angle (α), wave run-up increases when the value of α decreases. The value of α must ensure also that the reservoir has a minimum water depth (this depth is the difference between the mean sea level and the crest ramp). If the value of α is very low, the reservoir depth is also low, so the available water to be turbined would be low too. Finally, based on these results it has been decided to define the value of α close to 35º, so in the end, the standard value considered in the literature (α=34º) was fixed.

5.3 Conclusions of the OWC and OBREC analysis

A conceptual design for each of the technologies to be integrated in a vertical breakwater, OBREC and OWC, has been performed. Based on this conceptual design, an optimum geometry for both devices considering Las Palmas Port wave climate has been defined.

In the case of the OWC, although the optimum geometry for this marine climate suggested that the column should have a horizontal dimension of A between 8 and 16 m to maximize the energy production, the need for space due to the integration of the OBREC does not allow it. Then, it has been decided to increase the value of A to leave space for the OBREC reservoir, despite the reduction in the energy production. The final values of the OWC dimensions are presented in Table 1 (see scheme in Fig. 3).

Tab. 1. OWC and OBREC dimensions.

OWC		OBREC	
Dimension	(m)	Dimension	
d	8.4	Br	8.0 m
B1	5.0	Rr	1.6 m
B2	5.0	α	34 º
A	16.6		

As for the OBREC device and after characterizing its functional behavior and the behavior of the breakwater itself in terms of functionality (wave reflection and wave overflow) and stability (wave loading), the dimensions of the device have been defined as shown in Table 1 (see scheme in Fig. 3).

6 Laboratory experiments

Laboratory experiments have been carried out in the wave flume of the University of Cantabria. It is 68.5 m long, 2 m wide and 2 m high. During the tests, 4 different configurations of the vertical breakwater have been tested (see Fig. 10): A1: conventional caisson; A2: caisson with OWC; A3: caisson with OBREC; A4: caisson with OWC and OBREC). In order to reduce time and costs, it has been decided to divide the wave channel longitudinally and test two 1/35 scale model configurations at the same time (A1-A2 and A3-A4). Two types of tests have been performed during the experiments: one for the operational characterization of the devices, and the other for the stability and functionality of the breakwater. Regular and irregular waves have been generated, with significant wave heights between 2 and 10 m, and peak wave periods between 7.5 and 18 s (prototype values) considering the wave climate of the study case and the design wave conditions for Nelson Mandela breakwater.

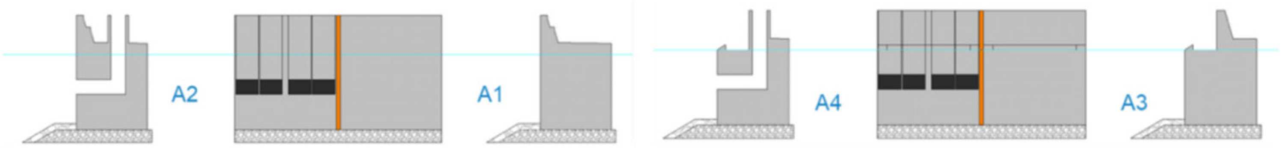


Fig. 10. Tested model cross-sections.

Free surface measurements along the wave flume and inside the OWCs have been obtained, which have subsequently been used to validate the numerical model of the dual WEC. With respect to the OBREC device behavior, free surface and wave overtopping time series have been measured in the reservoir, as well as the overtopping volumes that flow to the overtopping tanks thought the pipes. Based on this data, an estimation of the generated power is made. Then, pressure gauges have been placed in the reservoir to control the water level inside it, and overtopping tanks (including a free surface measurement inside them) have been placed behind the model, connected to the reservoir through several pipes, to control de overtopping discharge time series during each test. Based on the free surface measurements along the wave flume, and performing and incident-reflected analysis, reflection coefficients have been obtained. Results show (see Fig. 11) that the reflection coefficient of the breakwater, which is usually around 0.9 for conventional vertical breakwaters (cross section A1, black line), reduces its value up to 0.7-0.8 due to the presence of the OBREC reservoir (cross sections A3, pink line). Additionally, it is observed that this reflection coefficient is also considerably reduced (up to 0.3) when the incoming wave period coincides with its resonant period (cross sections A2 and A4, yellow and blue line respectively) because of the big amount of water that is flowing inside the OWC.

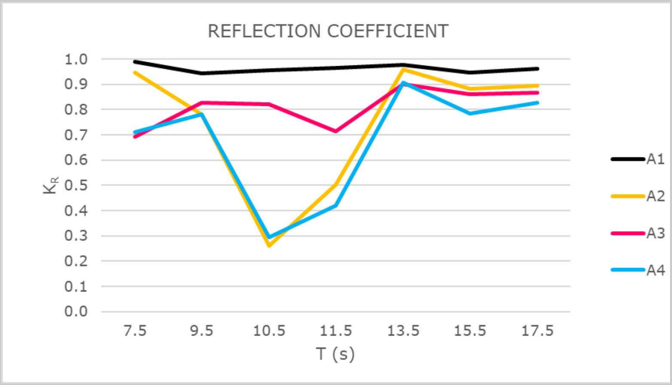


Fig. 11. Reflection coefficient.

Regarding the OBREC device, in order to ensure a hydraulic load inside the OBREC pool to ensure the proper operation of the future turbine, it is needed that the OBREC pool water level keeps almost constant and the hydraulic load being the maximum one. Then, another goal of these tests was to ensure that the OBREC reservoir was almost full during each test, as shown in Fig. 12 (left). This figure shows in its upper graph the free surface in front of the breakwater. In the lower graph, the free surface inside the reservoir is presented and it is observed how the reservoir is empty at the beginning of the test, then gets full when waves starts to overtop, and keeps constant during the whole test.

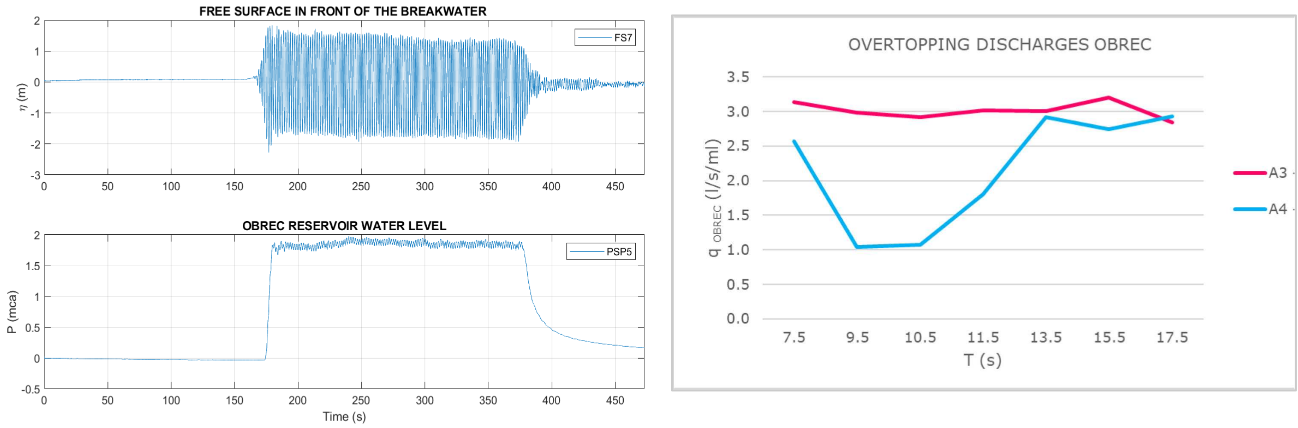


Fig. 12. Left: Free surface in front of the breakwater and inside the OBREC reservoir during a regular wave test (H=4 m, T=10.5s). Right: Wave Overtopping discharges in the OBREC (regular tests, H=4 m).

With respect to the amount of water obtained from each test, the wave overtopping volumes time series on each tank has been obtained by measuring the free surface inside the tank, and based on that, the overtopping discharge time series has been obtained. The result from this analysis is presented in Fig. 12 (right), in which the mean wave overtopping discharge for several regular tests (H=4 m) is presented. These values show that, as observed in the reflection coefficient analysis, in presence of the OWC (cross-section A4, blue line), the overtopping discharges considerably reduces when the incident wave period coincides with the OWC resonant period.

7 Conclusions

A pre-design of a dual WEC integrated in a vertical breakwater has been presented. The analysis has been performed following a hybrid methodology in which numerical and physical modeling have been combined to design the WECs based only on their hydraulic performance.

Based on the WECs state-of-the-art, two already proven technologies have been selected for its integration in the breakwater: the oscillating water column (OWC) and the overtopping converters (using in this case an OBREC-type).

The study case is the breakwater Nelson Mandela of Las Palmas Port (Canary Islands, Spain), which presents a vertical breakwater typology.

At a first stage, a numerical analysis has been performed to define a conceptual design for each of the technologies (OWC and OBREC). Two-dimensional numerical models IH2VOF and NEMOH have been used to characterize and design de OBREC and OWC respectively.

From this analysis, the dimensions of the integrated OBREC and OWC devices have been defined, and the characterization of the breakwater overall behavior has been analyzed.

Based on the numerical modeling, at a second stage, a physical test campaign has been performed using the designed dual WEC system geometry. Within this set of experiments, several regular wave conditions have been studied. Free surface, wave overtopping and pressure measurements have been obtained. This analysis has shown that regarding the functionality of the breakwater, the presence of both OWC and OBREC considerably reduces the refection coefficients of the breakwater, then improving its functionality. With respect to the OBREC device operation, it has been proven that the OBREC reservoir keeps almost full during most of the tests, which is important to ensure the hydraulic head for the turbine and then the corresponding future power production. It has been also obtained the mean wave overtopping discharge for each physical test. It has been observed that discharges are reduced due to the presence of the OWC when the incident wave period coincides with the OWC resonant period.

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