Coastal Structures 2019 - Nils Goseberg, Torsten Schlurmann (eds) - © 2019 Bundesanstalt für Wasserbau
ISBN 978-3-939230-64-9 (Online) - DOI: 10.18451/978-3-939230-64-9_114

Preliminary Assessment of the Impact of a Hybrid Wave Energy Converter in the Stability and Functionality of a Rubble-Mound Breakwater

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Abstract: As environmental and scarcity issues related to the use of fossil fuels become increasingly pressing, renewable energy sources are becoming a competitive and sustainable alternative. As a result, new ways of harvesting clean and renewable energy are being actively pursued, such as wave energy, which remains largely untapped. Conversely, seaports are considerable air polluters and have significant energy needs, therefore benefiting from a more sustainable and environmentally friendly energy mix. Breakwaters in seaports are prime locations to implement wave energy converters, as they are usually directly exposed to highly energetic sea-states. The SE@PORTS project proposes to demonstrate the advantages of merging wave energy converters (WECs) into seaports' breakwaters by researching the integration of a hybrid WEC for two case studies, the Port of Leixões, Portugal, and the Port of Las Palmas, Spain. This paper describes the experimental study carried out at a geometrical scale of 1/50 to assess the energetic performance of a hybrid WEC designed having as reference the extension of the North breakwater of the Port of Leixões and evaluate its impact on the breakwater's effectiveness and structural stability, focusing on the functionality and stability analysis. The modular device combines the overtopping and the oscillating water column principles, and it is estimated that the wave-to-wire efficiency is around 35%. The mean overtopping flow over the structure was quantified and the damage number N_{od} was calculated. The device's estimated annual energy production is promising, although preventive measures must be enforced to mitigate the negative structural impact on the breakwater.

Keywords: Breakwater, Wave Energy, Hybrid WEC, Ports, Physical Modelling

1 Introduction

Changes in the world economy, which include the globalization of both product production and consumption, have deeply affected the dynamics of ports and their importance in the global transport system (Park and De, 2015), namely shipping networks (Wang, 2017). As such, port infrastructures are developing to cope with increasing pressure from the global transportation system, since they are required to receive and shelter berthing ships with increasing draught and capacity as well as to process and expedite goods as efficiently as possible, which requires a complex logistical network for the ports to remain competitive. Consequently, ensuring that all port activities are executed implies a high demand of energy from both infrastructures and equipment.

As core hubs of goods processing and transportation, seaports can have a negative environmental impact on local communities due to their activities. On one hand, the air pollution produced by large berthing ships is responsible for several thousands of annual deaths worldwide. On the other hand, the expansion of port facilities to accommodate berthing ships takes a heavy toll on coastal ecosystems (Wan et al., 2016). Furthermore, being located on the coastline, seaports are particularly vulnerable to the consequences of climate change, mainly due to the mean sea level rise and the occurrence of extreme events and severe wave conditions (Becker et al., 2012). A compromise between economic growth and sustainable development has become a major topic of discussion amongst port authorities, prompting them into action.

Several energy management policies have been proposed by port authorities to deal with the energy demand paradigm in an environmentally sustainable way (Acciaro et al., 2014), including berth scheduling and re-definition of routes as to mitigate fuel consumption and CO_2 emissions (Mansouri et al., 2015), identification of key environmental risks accompanied by supporting methodologies in order to improve the environmental management at ports (Puig et al., 2015) and the introduction of alternative, clean and renewable energy sources. On this latter topic, researches have been striving to develop new energy converter concepts, namely ones capable of harnessing blue energy from the oceans with the intent of supplying port infrastructures with electricity in an environmentally friendly way. One of the approaches currently being studied is the integration of wave energy converters (WECs) into the main protective structures of seaports: breakwaters. Due to their inherent exposure to wave action, breakwaters are prime candidates for this approach, so long as their structural and functional characteristics are not compromised.

There are several technologies for harnessing wave energy, namely Oscillating Water Columns (OWC), Overtopping Wave Energy Converters (OWEC), Wave Activated Bodies (WAB) and flexible membranes. Currently, there are already some full-scale facilities combining harbour protection and wave energy converters, such as the Mutriku OWC (Torre-Enciso et al., 2010), Spain (Fig. 1) which was completed in 2011 and has yielded important information on WEC integration on breakwaters. Another example is the more recent REWEC3 (Arena et al., 2016) in the port of Civitavecchia, Italy (Fig. 2), as well as the OBREC (Iuppa et al., 2016) in the port of Naples, Italy (Fig. 3).

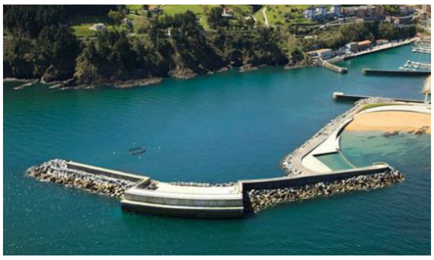

Fig. 1. Mutriku OWC in Spain.

Fig. 2. REWEC3 U-OWC in Italy.

Fig. 3. OBREC OWEC in Italy.

Integrating WECs into breakwaters has some major advantages besides the reduction of air pollution in ports, such as sharing construction costs, access to the devices for maintenance and repairs and connection to the main electrical grid (Falcão, 2010). Therefore, synergies can be created between ports, research organizations and electricity companies that can contribute to the development of wave energy technologies and efficiently bring them to higher Technology Readiness Levels (TRL).

Nevertheless, at the moment there is no information of any fully commercial wave energy converter installed on a harbour breakwater. The current wave energy prices are still not competitive enough when compared with other renewable energy sources, namely solar and wind energy (Mustapa et al., 2017). Therefore, research should be encouraged in order to find solutions to increase efficiencies of WECs and to decrease electricity generation costs. An innovative and attractive solution is a hybrid device combining two types of wave energy harvesting technologies, thus increasing the global energy production and reducing construction costs. For this matter, the SE@PORTS project has investigated a hybrid WEC that combines the OWC and the OWEC technologies. Both technologies have an extensive record of individual studies, although hybrid devices are still uncommon and not as well developed. Having as case studies the ports of Leixões (Portugal) and Las Palmas (Spain), SE@PORTS analyses the advantages of combining both technologies into a single device and may present a breakthrough in wave energy generation.

However, the impact of this hybrid device on the stability and functionality of the breakwater must be thoroughly assessed. Breakwaters have the main purpose of sheltering berthing ships and their functionality should never be compromised, given that security is one of the most important concerns in port activities. Therefore, before any full-scale implementation of the device, a study must be performed aimed at clarifying how its introduction will affect the breakwater into which it is integrated.

This paper describes the physical model tests carried out at the wave tank of the Hydraulics Laboratory of the Hydraulics, Water Resources and Environment Division of the Faculty of Engineering of the University of Porto (FEUP), Portugal, to study the performance of the hybrid WEC module integrated into the proposed 300 m extension of the Leixões North breakwater, on a geometric scale of 1/50. The cross-section of the breakwater extension where the device is integrated is reproduced, as well as the seabed bathymetry in front of the structure, with a complete model scale device integrated into it. The tested wave conditions were defined near the structure at a prototype water depth of 21 m (chart datum – CD) and cover a wide range of wave heights and periods, from frequent to severe wave conditions. The paper aims at giving a preliminary assessment of the device's efficiency and at analysing the effect of the introduction of the WEC into the rubble-mound breakwater in terms of structural stability and mean overtopping flow, which are of the utmost importance for the well-functioning of the port and its activities.

2 Experimental Study

2.1 Case study: Port of Leixões

The Port of Leixões, managed by the Port Authority of Douro, Leixões and Viana do Castelo (APDL), serves as a major hub of shipping trade and goods expedition for the north-western coast of Portugal (latitude 41°11′ north, longitude 8°42′ west), Fig. 4. It is located about 4 km north of the mouth of the Douro River and facing the Atlantic Ocean. As such, the port is subjected to a severe local wave climate and seasonal wind regimes. In fact, during storms, significant wave heights can reach up to 8 m, with the north and south breakwaters serving as the main sheltering structures to the innermost areas of the port. Tides are of the semi-diurnal type, with amplitudes ranging from 2 to 4 m.

Fig. 4. Location (Google Earth, left) and perspective (right) of the Port of Leixões with the current north breakwater structure highlighted, courtesy of APDL.

In order to ensure that the Port of Leixões remains competitive within the global shipping network, the Port Authority has prepared several projects to be developed in the short to medium-term, which should improve the port's capability of receiving and sheltering berthing ships, ranging from containers to cruise ships, as well as its logistical network. One of the key upgrades to the port is the 300 m extension of the north breakwater into deeper waters, as to allow for the berthing of ships with a draught greater than those currently entering the harbour. The preliminary setup of this project is schematized in Fig. 5. The aim of the SE@PORTS project is to design a hybrid OWEC-OWC module concept capable of being integrated into the extension of the north breakwater. Its objective is to provide port infrastructures with electricity from a clean and renewable energy source, thus assisting in meeting, at least in part, its high energy demand and to contribute to the European renewable energy targets. The final solution should be modular and scalable, as well as easily adaptable for integration into other rubble-mound breakwaters anywhere in the world.

In 2017, the Port of Leixões has had a total energetic consumption of 104 GJ, of which 53 GJ is electrical. Its electrical power consumption has increased 2.1% from 2015 to 2016 and another 2.1% from 2016 to 2017, whilst its total energy consumption decreased 0.6% both from 2015 to 2016 as from 2016 to 2017. These variations show a rise in the port's electrical power demand alongside a decrease in the port's total power consumption, suggesting a shift towards electrically powered equipment. Consequently, it should be beneficial to invest in electrical power production inside the port, namely in renewable energy, as its generation prices decrease and become more and more competitive with fossil fuel based electric energy generation (Kåberger, 2018).

The hybrid WEC being studied should be able to contribute to supplying, at least in part, this increasing electrical energy demand.

Fig. 5. Aerial view of the Port of Leixões' North breakwater and schematic of the future extension project (source: APDL).

The preliminary study carried out by the Hydraulics and Water Resources Institute suggested that a 200 to 300 m extension with an orientation of up to 20° relative to the existing breakwater was necessary (Fortes et al., 2017). The results favoured the 300 m long breakwater with a non-aligned orientation relative to the existing breakwater's alignment for better ship manoeuvrability (IHRH, 2013). The National Civil Engineering Laboratory (LNEC) then conducted a study to choose the best solution considering three lengths (200, 250 and 300 m) and two different orientations relative to the existing breakwater (0° and 20°), adding to a total of six different configurations (Pinheiro et al., 2017). The Portuguese engineering consultant company Consulmar designed a provisional solution consisting of a rubble-mound breakwater around 30 m high (from toe to crest) and composed of a *tout-venant* core, two internal rubble-mound layers and protected on the seaward side by a two Antifer blocks thick armour layer of 680 kN Antifer cubes and a toe berm of 800 kN Antifer cubes (two layers), Fig. 6. The water depth reaches about 18 m (CD) near the breakwater's head, whilst it is around 16 m (CD) deep in the 40 m wide section where the device module's integration is being considered.

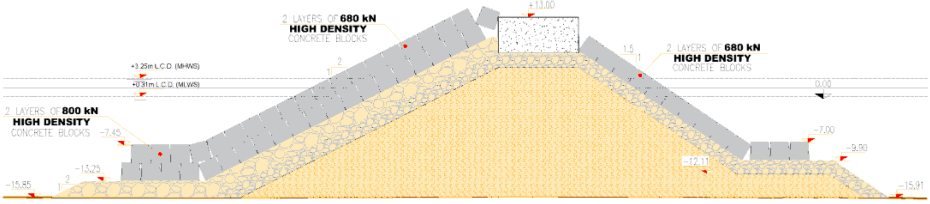

Fig. 6. Provisional cross-section of the North breakwater extension (adapted from Consulmar, 2017).

The general layout of the solution is presented in Fig. 7, with the device's location pointed out in black. As the device is intended to be modular, more modules could be implemented side-by-side to increase power production. Local wave conditions were obtained by propagating offshore wave data to the breakwater's location using the SWAN (Simulating WAves Nearshore) numerical model (Capitão et al., 2017).

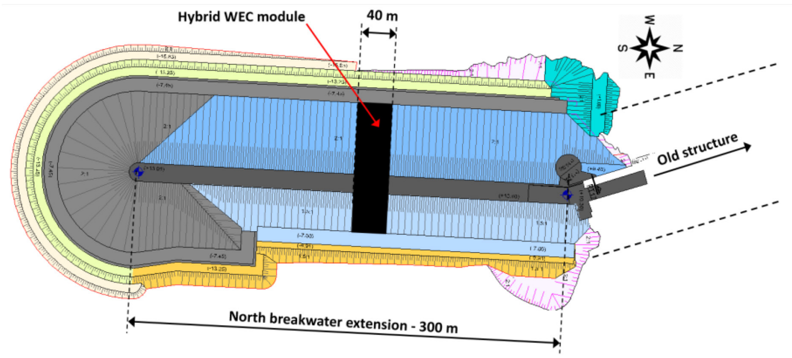

Fig. 7. Provisional layout of the North breakwater extension (adapted from Consulmar, 2017).

The most frequent significant wave heights range from 1 to 2 m, occurring during 49% of an average year and are below 3 m throughout 92% of the time. Also, the most frequent mean wave periods range from 6 to 7 s, occurring during 19% of an average year and are between 4 and 11 s throughout 91% of the time.

2.2 *Equipment, experimental facility and methodology*

The hybrid OWEC-OWC module designed having as reference the future extension of Leixões North breakwater was studied within the wave basin at the Hydraulics Laboratory of the Hydraulics, Water Resources and Environment Division of the Faculty of Engineering of the University of Porto (FEUP), Portugal. It features a 28 m long wave basin, spanning 12 m in width and with a maximum depth of 1.2 m, Fig. 8. The wave basin includes a rubble-mound dissipative beach in order to reduce wave reflections and is equipped with a multi-element piston-type wave generation system capable of reproducing a wide range of sea-states and wave conditions (HR Wallingford, Oxfordshire, UK). Moreover, this wavemaker system has an incorporated dynamic wave absorption system to compensate for wave reflections.

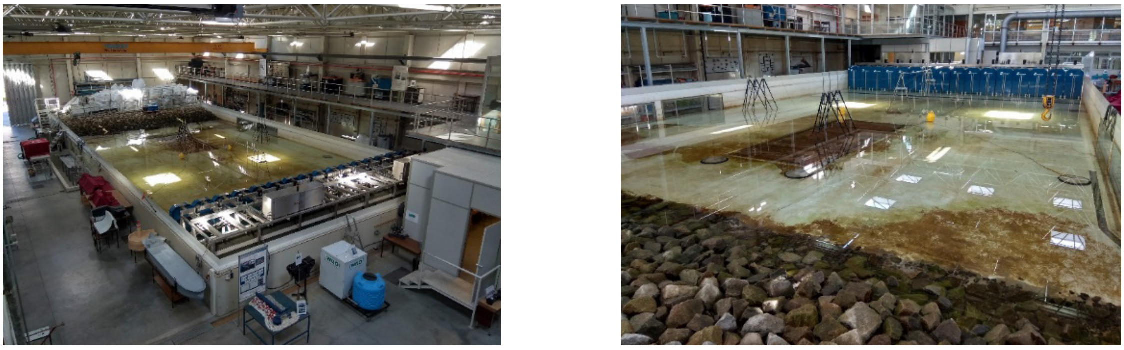

Fig. 8. Perspective of the wave basin in the Hydraulics Laboratory of the Hydraulics, Water Resources and Environment Division (FEUP).

The experimental setup of the study was designed with the intent of minimizing scale effects and also ensuring that all technical obstacles of testing a reduced-scale physical model of the OWEC-OWC solution, given also the physical and practical limitations of the facilities and equipment, would be overcome. To that end, a 1/50 geometrical scale (Froude similarity) was selected, with the experimental study being carried out in 3D within a channel created inside the wave tank using vertical barriers. The experimental domain spanned 14.30 m in length and 0.84 m in width. A single piston-type paddle was responsible for the generation of both regular and irregular long-crested waves.

As seen in Fig. 9, the experimental setup encompassed a total of eleven resistive wave gauges, four of them being deployed in order to carry out a wave reflection analysis, one to measure the free surface elevation near the physical model, one to measure the free surface elevation within the OWC and the remaining five to acquire the time series of the water free surface inside each auxiliary reservoir. These reservoirs were also equipped with hydraulic pumps as to quantify the overtopping volume received from a corresponding OWEC reservoir. To measure the overtopping volume, the pump was connected to a relay system that served as an on/off switch when the water reached an upper and lower limit, respectively. From the time-series of the wave probes inside the reservoirs it was possible to measure the time during which the pump was working (i.e., the water level lowered). Since the pump's flow curve was known, the overtopping volume was calculated by multiplying the pump's flow by the pump's working time. Besides, knowing the water level inside the reservoir at the end of the test, the water volume remaining inside the reservoir was determined and accounted for. Additional equipment includes a pressure sensor inside the OWC, to measure air pressure variations, a photographic camera orthogonally placed above the model to track armour layer and toe berm blocks movements and two video cameras monitoring the wave/structure interaction from above and from the side visualization window.

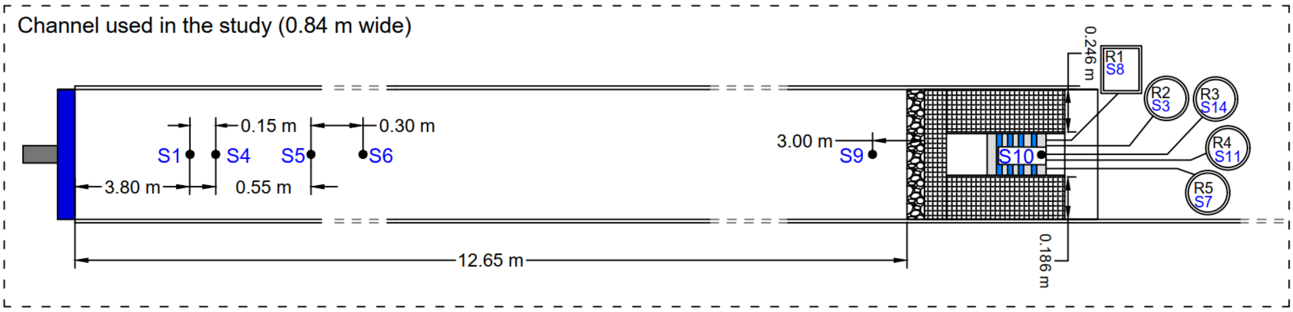

Fig. 9. Schematic of the experimental setup inside the wave basin.

The design of the hybrid OWEC-OWC was optimized through the preliminary application of numerical modelling tools, namely the WOPSim 2.0 software (Meinert et al., 2008) and the ANSYS Fluent CFD code (ANSYS, 2013). This allowed for the optimization of the OWEC's geometry, particularly the crest heights of the OWEC's reservoirs and their dimensions, and the adjustment of the resonance frequency of the OWC component to match the most frequent wave periods in front of the breakwater. As a result, four main overtopping reservoirs were considered for the OWEC component and three different geometries for the water intake channel of the OWC, Fig. 10. Moreover, a reservoir on top of the model captured the volume that overtopped the crest of the structure.

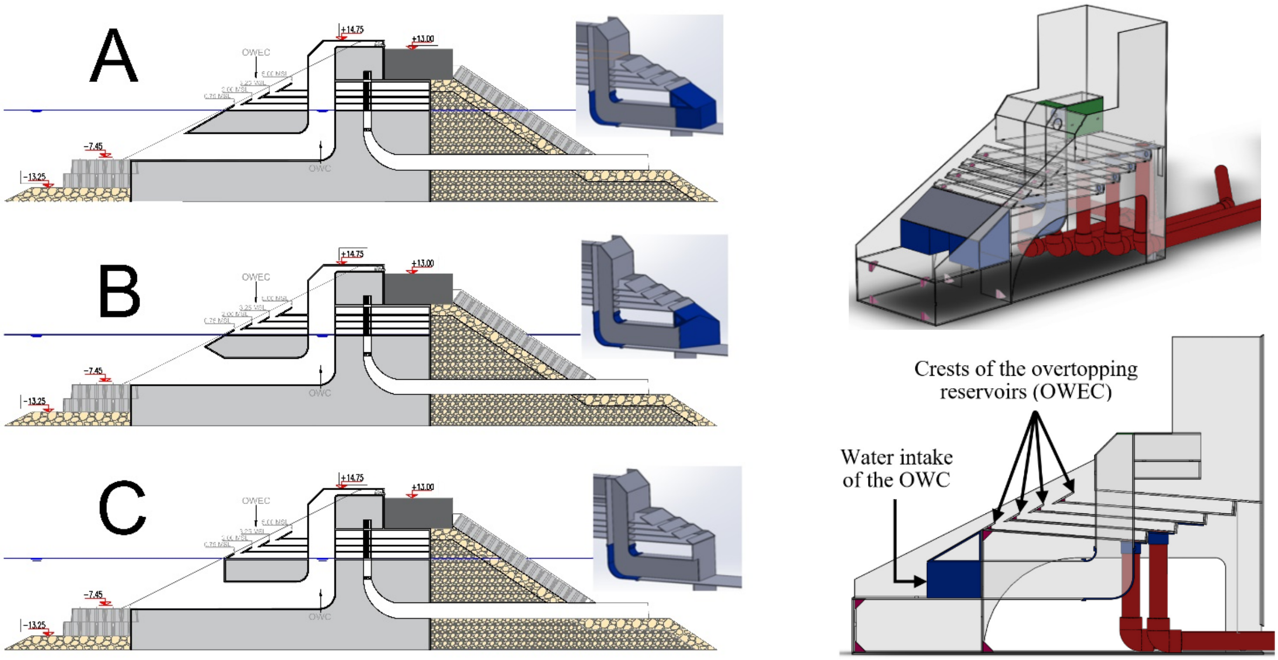

Fig. 10. Geometries A, B and C of the hybrid WEC tested (left), and perspective (upper right) and cross-section (lower right) views of the hybrid device model design for geometry A.

For this experimental study, seven sea-states were judiciously chosen to cover the wave energy resource matrix (scatter diagram) as well as possible, Tab. 1, following the recommendations for the selection of sea-states for the estimation of the annual energy production (AEP), as suggested in

Pecher and Kofoed (2017). The sea-states are characterized by the spectral significant wave height H_{m0} and the peak wave period T_P. The water level variations induced by tides were addressed by considering and testing three representative water levels: the mean sea level (MSL), the mean low water springs (MLWS) and the mean high water springs (MHWS), respectively 1.36 m below and 1.58 m above MSL.

Tab. 1. Sea-states tested for the estimation of the AEP.

Sea States	**H_{m0} (m)**	**T_P (s)**	**Energy contribution (-)**	**Probability of occurrence (-)**	**Water Level**
SS1	1.7	9.0	19.6%	25.6%	MLWS MSL MHWS
SS2	1.9	11.5	24.5%	20.5%	
SS3	2.8	14.1	19.0%	6.2%	
SS4	2.9	16.6	10.5%	2.6%	
SS5	3.7	11.6	13.8%	3.1%	
SS6	1.1	6.8	4.9%	21.0%	
SS7	1.5	13.9	4.6%	5.1%	
		Total:	96.8%	84.1%	

The sea-states considered to test the functionality and structural stability of the WEC-breakwater structure were chosen to take into consideration both the wave climate and the physical limitations imposed by the wave generation system, as well as the water depth, Tab. 2. The maximum wave height was 8.0 m for MLWS and around 9.1 m for MHWS.

Tab. 2. Sea-states tested for the analysis of the breakwater's structural stability and functionality with and without the integrated WEC.

H_{m0} (m)	**T_P (s)**	**Water Level**
6.0	13	MLWS
7.7	16	MLWS
8.0	16	MLWS
6	13	MHWS
7.7	16	MHWS
9.1	16	MHWS

3 Results and Discussion

3.1 Structural and functionality analysis

One of the purposes of the experimental study undertaken was to test the breakwater's functionality and structural stability with the hybrid WEC integrated into it and to compare it with the breakwater's performance without the WEC. This is a critical aspect for the device's suitability for implementation in port's sheltering structures since breakwaters are key elements to achieve calm conditions in the inner parts of ports, thus ensuring safety conditions for port activities, namely for the berthing of ships and the unloading of their cargo.

Hence, the stability of the breakwater was studied by tracking the movement of the armour layer blocks and the toe berm blocks after each test and calculating the damage number N_{od} for each, defined as:

$$N_{od} = \frac{N_{dis}}{W/D_n} \tag{1}$$

where N_{dis} represents the number of units displaced, W the width of the reference section and D_n the nominal diameter of the Antifer blocks (in this case calculated as the equivalent cube length). Fig. 11 presents the N_{od} for each of the significant wave heights tested. The armour layer N_{od} is not displayed because there was not any block movement in the armour layer, neither with nor without the device.

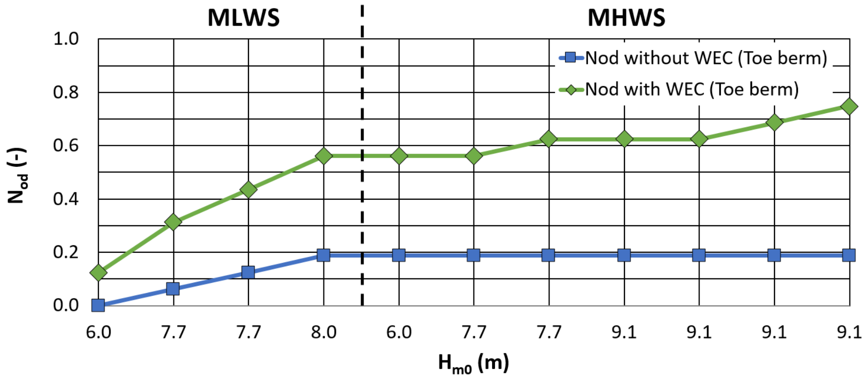

Fig. 11. Comparison of the damage number N_{od}, with and without the WEC.

From the results in Fig. 12, we can see that the toe berm's damage number N_{od} is larger when the hybrid WEC is integrated into the breakwater when compared to the solution not incorporating the device. This suggests that the WEC's integration should be considered when designing the breakwater, as we can see that after the final test (hence observing the cumulative damage), the toe berm's N_{od} is almost four times larger (0.19 against 0.75) when the WEC is included. Also, this difference seems to increase with the significant wave height tested. We can further observe that for the solution that does not incorporate the device, the N_{od} does not increase after the fourth test, which indicates that the toe berm reaches a condition of equilibrium. On the other hand, when including the WEC, there is an increase in the N_{od} up until the very last test, indicating that the damage in the toe berm could further develop if it were submitted to more tests, possibly leading to its failure. More experimental tests should be done in the future to support the obtained conclusions. As reference, the Coastal Engineering Manual (U.S. Army Corps of Engineers, 2002) suggests the following values for the toe berm's N_{od}:

$$N_{od} = \begin{cases} 0.5 & \text{no damage} \\ 2 & \text{acceptable damage} \\ 4 & \text{severe damage} \end{cases}$$

Moreover, the performance of the structure with respect to overtopping was analysed by capturing and quantifying the mean overtopping flow rate over the structure crest, for each experimental test. Fig. 12 summarizes the results obtained for each significant wave height tested, both for the MLWS and MHWS levels.

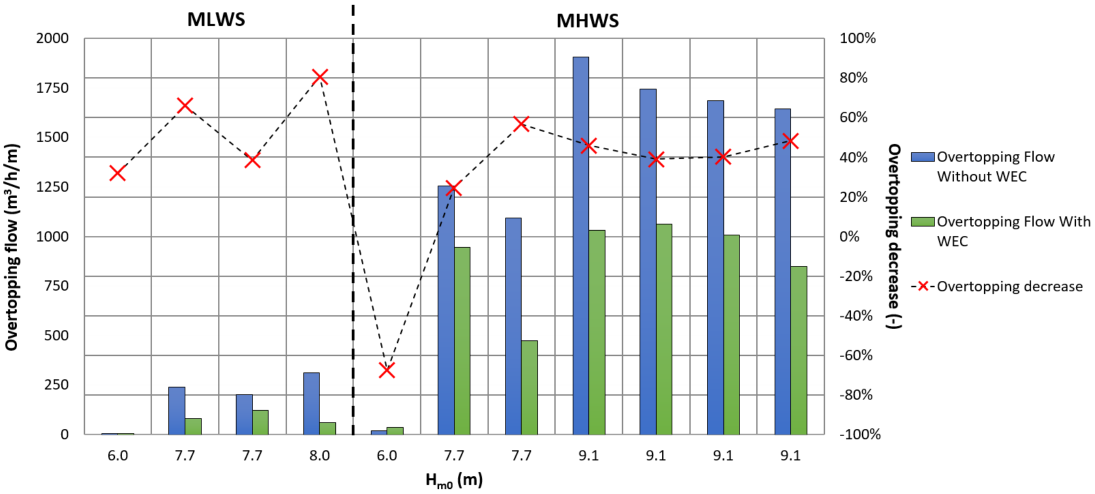

Fig. 12. Comparison with and without WEC of the overtopping flow per metre of width.

The results noticeably show that the overtopping flow of the structure considerably decreases with the integration of the hybrid WEC. The exception is for H_{m0}=6 m (MHWS), when the overtopping flow increases with the WEC's integration. Nonetheless, this was attributed to the uncertainty of wave overtopping prediction, especially for low discharge data (Romano et al., 2015), since it is not coherent with the results from all the other tested conditions. Fig. 13 presents the dimensionless discharge plotted against the dimensionless freeboard and compares it with EurOtop II (EurOtop, 2018) overtopping prediction formula (equation 6.5) for rubble-mound breakwaters with steep slopes (1:2 to 1:4/3) and upper and lower 5% confidence bands. The formula used is as follows:

$$\frac{q}{\sqrt{g\,H_{m0}^{3}}} = 0.09\,e^{-\left(1.5\,\frac{R_c}{H_{m0}\,\gamma_f\,\gamma_\beta}\right)} \tag{2}$$

where q is the mean overtopping discharge, g is the gravitational acceleration, R_c is the crest freeboard, γ_f is the roughness factor and γ_β is the influence factor for oblique wave attack. In this case, following the recommendation in EurOtop for an armour layer of Antifer blocks, $\gamma_f = 0.50$ and $\gamma_\beta = 1$ since only waves perpendicular to the breakwater were considered. However, it should be noted that the value of $\gamma_f = 0.50$ from the EurOtop manual was obtained considering a slope of irregularly placed Antifer blocks, which usually leads to smaller overtopping discharges when compared to a slope with regularly placed blocks, as is the case in this study.

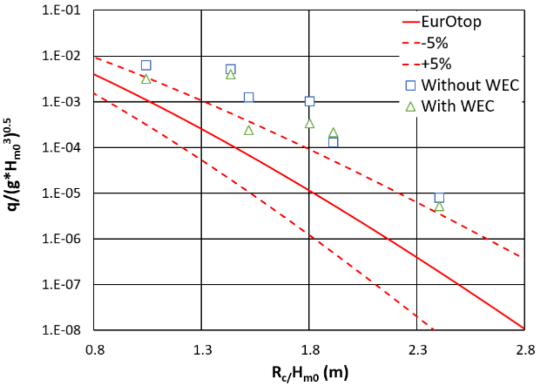

Fig. 13. Wave overtopping data compared with EurOtop II.

It is clear that the overtopping flow is reduced by the introduction of the hybrid WEC device, although all the overtopping discharges are higher than those predicted by the EurOtop formula, most even above the upper 5% confidence band. This difference is considered to be because of the regular placement of the Antifer blocks. However, this reduction on overtopping due to the WEC is a major advantage for port authorities, since wave overtopping is one of the factors leading to structural damage and affects both management and exploitation of port activities (Alises et al., 2014). Fig. 14 shows the reflection coefficient C_r with and without the WEC for the significant wave heights tested.

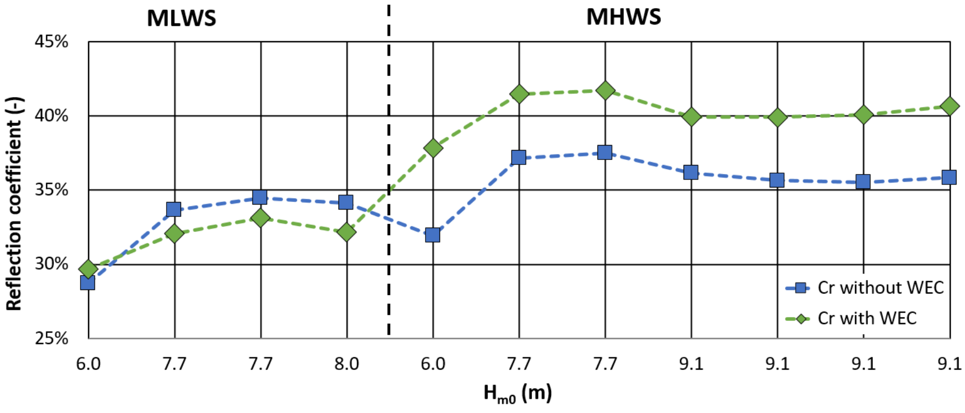

Fig. 14. Comparison with and without WEC of the reflection coefficient C_r.

We can see that the reflection coefficient is practically the same with and without WEC, around 40% or less, although it is slightly higher with the WEC integrated into the breakwater. However, this slight difference should not have a significant impact on the wave conditions in front of the breakwater.

4 Conclusion

An experimental study with a reduced scale physical model of a hybrid OWEC-OWC module, aimed for a possible integration into the future extension of the Port of Leixões' North Breakwater, is presented and discussed. In order to assess if the integration of the hybrid concept into the breakwater structure compromises its functionality or its stability, a thorough analysis was carried out regarding the damage number N_{od}, wave reflection and overtopping volumes over the structure crest. The geometric scale used is within the range of scales (1/30 to 1/50) recommended for the study of rubble-mound breakwaters with respect to stability and overtopping discharges (Hughes, 1993), although equal to its upper limit. The impact of scale effects in the results and conclusions is also minimized since the different models were tested under the same conditions (comparative study), hence laboratory and scale effects impact the results in a similar way. Other aspects were considered to reduce the laboratory effects, *e.g.*, to avoid assessing the damage on the breakwater's armour layer in a small cross section width, the WEC module was moved to one side, leaving a wider cross section (with a sufficient number of blocks) in the other.

The results obtained from the experimental study point towards a decrease in the structural stability as the toe berm's damage number N_{od} increased. Therefore, the incorporation of the hybrid WEC should be considered when designing the armour layer and the toe berm's blocks. On the other hand, the overtopping discharges were considerably reduced by the hybrid module, leading to safer conditions inside the port and potentially fewer inoperative periods during severe sea conditions. The reflection coefficient was not significantly affected, although it was slightly higher with the WEC integrated. Nonetheless, this should not be a critical concern for the breakwater's functionality.

Besides, a preliminary estimate of the device's annual energy production was made. By accounting for the various efficiency terms, following on recommendations from literature (Margheritini, 2009), the annual energy produced by one OWEC-OWC module spanning 20 m in width is estimated at around 920 MWh, corresponding to a 35% wave-to-wire efficiency.

Acknowledgements

This research was funded by the OCEANERA-NET project SE@PORTS – Sustainable Energy at Sea PORTS – with the references OCEANERA/0004/2016 and OCEANERA/0003/2016, under the frame of FCT, the Portuguese Foundation for Science and Technology. It was also funded by PORTOS (EAPA 784/2018), co-financed by the Interreg Atlantic Area Programme through the European Regional Development Fund.

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