PERFORMANCE ENHANCEMENT OF AN OVERTOPPING BASED WAVE ENERGY CONVERTER

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Abstract

The installation of the Sea-wave Slot-cone Generator (SSG) in harbour breakwaters and in the shoreline presents several advantages, in spite of the usual exposure to smaller waves than at offshore locations. This paper analyses the hydraulic performance of the SSG technology and the performance enhancement associated to the use of wave focusing walls (wave concentrators), using a physical model built on a geometric scale of 1/40, tested under the action of wave conditions typical from the Portuguese west coast. The tested SSG configurations were defined by changing the opening angle of the wave concentrators. The use of those elements proved to be advantageous since the total mean power captured increased in relation to the standard configuration, due to the wider wave front captured and the run-up and overtopping enhancement on the SSG ramp, explained by the wave energy concentration. The performance improvement was higher for the smaller significant wave heights and the shorter peak wave periods, since the tapering effect created by the converging walls enables small waves that otherwise could not reach the first reservoir produce overtopping and also increases overtopping discharges in the upper reservoirs. Overall, the application of this extension in breakwaters is very promising.

KEYWORDS: wave energy converter, wave overtopping, physical modelling, concentrators, hydraulic efficiency.

1 INTRODUCTION

A wide variety of concepts to convert wave energy are presently available (Falcão, 2010). Some shoreline/nearshore technologies are already in a phase of technological demonstration and approaching a pre-commercial stage, such as the oscillating water column systems (Brito-Melo et al., 2008) or the Wave Star (Marqués et al., 2010), but several challenges still exist to ensure the reliability of the wave energy conversion technologies and to bring the overall production costs to levels that can compete with traditional and well-established energy production technologies (e.g., onshore wind, large and small scale hydropower), most of them related to the harsh marine environment.

Indeed, wave energy conversion technologies are in an early stage of development and are not yet cost competitive (levelized cost of energy of about 325€/MWh, Astariz et al., 2015). Nevertheless, the integration of wave energy converters into coastal protection structures (Zanuttigh et al., 2010) and harbor breakwaters (Vicinanza et al., 2014) brings new opportunities. Overtopping based wave energy converters, which work by promoting wave run-up on a sloping ramp that leads to one or more reservoirs, are especially suitable to this kind of applications.

The Sea-wave Slot-cone Generator (SSG) is a multi-level overtopping based wave energy converter being developed by the WAVEenergy AS company (Stavanger, Norway). The SSG consists of a number of reservoirs, one over each other (above the mean water level), that store temporarily the water volume resulting from the overtopping of incident waves. Low-head multi-stage hydraulic turbines are used to convert the potential energy of the stored water into electric power.

The installation of the SSG in breakwaters and in the shoreline presents several advantages, despite the usual exposure to smaller waves than at offshore locations, such as sharing structure costs, availability of grid connection and recirculation of water inside the harbor, and improvement of their performance while reducing reflections due to efficient absorption of
energy (Vicinanza et al., 2012). This explains the several studies and projects for pilot installations in several locations worldwide.

The SSG technology has been extensively studied in the last ten years to analyze how wave, tide and structural parameters could affect the mean overtopping discharge, using regular and irregular waves, under either 2D or 3D conditions (Kofoed 2005a, b; Vicinanza and Frigaard, 2008; Margheritini, 2009). The main parameters analyzed were the number of reservoirs, the reservoir crest levels, the ramp slope angle and draught, the front angles, the horizontal distance between the reservoir crests as well as the influence of the wave height and the wave period. Vicinanza et al. (2012) present an overview of the most significant R&D developments.

The integration of wave focusing walls (i.e., wave concentrators) on the SSG technology is proposed as a mean to concentrate the wave energy, and therefore increasing run-up and overtopping phenomena, in shoreline/nearshore locations, where wave energy converters (WEC) are generally exposed to smaller waves. A similar principle is used in floating, offshore WEC of the overtopping type, such as the Wave Dragon (Kofoed et al., 2006) or the WaveCat (Fernandez et al., 2012), but also in the shore based TAPCHAN (Mehlum, 1986).

This paper analyses the effect, with respect to hydraulic performance, of adding wave concentrators to a standard SSG device. The tested SSG configurations were defined by changing the opening angle of the wave focusing walls. Since the hydrodynamics of overtopping based devices is strongly non-linear (Falcão, 2010), physical model studies must be used in the development and optimization phases of such devices.

2 EXPERIMENTAL STUDY

2.1 Experimental facility and equipment

The study was performed at the Hydraulics Laboratory of the Hydraulics, Water Resources and Environment Division of the Faculty of Engineering of the University of Porto (FEUP), Portugal. This experimental facility presents a consistent track record in what concerns the study of offshore, coastal and harbour structures (Taveira-Pinto et al., 2011, Rosa-Santos et al., 2015). The multi-directional wave basin used is 28 m long, 12 m wide and 1.2 m deep, and is equipped with a multi-element piston-type wave generation system (model HR Wallingford, U.K.). A dynamic wave absorption system and a dissipative beach allow controlling wave reflections within the wave basin.

The geometrical scale of 1/40 was selected for this study in accordance with the size of the experimental facility, the prototype dimensions of the SSG device, operational criteria, as well as to ensure that scale effects, due to an incomplete hydraulic similitude, are within acceptable limits. Previous studies of the SSG technology were performed on geometrical scales between 1/15 and 1/66 (Vicinanza et al., 2012).

The experimental equipment used consisted of resistive wave gauges to measure the water free surface elevation and a system designed to measure the wave overtopping volumes, composed of pumps, auxiliary reservoirs and gauge levels.

2.2 SSG physical model

The SSG physical model was designed and built in the INEGI facilities on a geometric scale of 1/40. This model is a reproduction of a SSG device integrated in a harbour breakwater and was designed to allow testing the influence of the wave focusing walls on its hydraulic efficiency.

The physical model is composed of two parts: a structure built with welded steel plates that is the support of the SSG device, built in polycarbonate. The model extends from -17.00 m up to +13.00 m MSL (Mean Sea Level) and is 30 m wide (in prototype dimensions). Because the SSG main structure is only 10.00 m wide, an armour layer made of tetrapods was built on both sides of this central module, reproducing a traditional breakwater and its behaviour in term of wave reflection. Figure 1 presents the central cross section of the model, which includes the SSG structure, and a cross-section intersecting the breakwater armor layer.

The SSG structure was composed of three reservoirs. The reservoirs front openings were 10.00 m long (i.e., the central module width) and 1.20 m wide. The lengths of the reservoirs are presented in Figure 1. The angle of 35° was selected for the overtopping ramp and for all the reservoir’s fronts, to ensure the occurrence of slightly breaking surging waves. The bathymetry was not reproduced in this study since it involves a generic situation and not a particular case-study. The water depth in front of the model was set constant and equal to 17.00 m (flat bottom). Oliveira et al. (2016) presents more details about the construction of the SSG physical model.

The wave focusing walls used are an extension of the SSG vertical side walls, designed to create a tapering effect that increases the incoming wave height due to the wave energy concentration. These wave focusing walls are 12.00 m long (in prototype dimensions), having been developed with three different opening angles (30°, 40° and 50°) and two vertical profiles, to assess which combination results in higher performances, Figure 2. While in profile C2 the concentrators have a constant crest level (+8.00 m MSL) along their length, in profile C3 the crest level is linearly reduced, in accordance with the slope of the approach ramp, maintaining constant the height of the two converging walls.
Figure 1 – SSG physical model: (a) central cross-section showing the SSG module incorporated, (b) cross-section intersecting the lateral modules, with the tetrapods armour layer (prototype dimensions).
The SSG capture width, which corresponds to the span between the extremities of the two wave focusing walls, or to the wave crest width captured by the device, changes with the opening angle: 10.00, 21.60, 25.00 and 28.00 m for the 0°, 30°, 40° and 50° opening angle, respectively.

Figure 3 presents the breakwater structure (supporting structure plus the SSG device on top) and a close view of the SSG physical model (Oliveira et al., 2016).

A flow measurement system was implemented at the rear side of the physical model to measure the amount of water that entered in each individual reservoir (Oliveira et al., 2016). This system was composed by three auxiliary reservoirs, submerged centrifugal pumps and resistive level gauges to control pump operation. The separation of overtopped volumes is justified because the total hydraulic head available is different for each reservoir.

The channel built inside the wave basin for the 2D experimental tests of the breakwater was 0.75 m wide (30 m in prototype dimensions for the 1/40 scale). Figure 4 presents a close view of the physical model setup, showing the location of the wave probes, the SSG structure and the three auxiliary reservoirs (R1, R2 and R3) used to measure the overtopping volumes.
Figure 4 – FEUP wave basin and physical model set-up (values in meters, model dimensions).

A total of eight resistive probes were used (Figure 4) in the experiments: three to monitor the water level inside the auxiliary reservoirs and five to measure the water free surface elevation. From these, four aligned wave gauges were allocated to the determination of the incident wave conditions (S4, S5, S6 and S7). The wave probe S8 was located closer to the model to measure the water surface elevation in front of the structure.

2.3 Test programme

Seven different configurations of concentrators were tested to analyse the influence of the wave focusing walls on the SSG hydraulic performance. Nevertheless, this paper only presents the results obtained for four of them, which include the standard SSG model (without concentrators) and the three configurations that result from the combination of vertical profile C3 (the most favorable one) with the three concentrators’ opening angles (Figure 2 and Table 1). Oliveira et al. (2016) showed that there were no significant differences between profiles C2 and C3 in terms of SSG hydraulic performance and concluded that profile C2 was expected to have higher construction costs, due to its larger size and the higher robustness required to withstand the expected higher wave loadings.

Table 1 – Characteristics of the tested wave focusing walls.

<table>
<thead>
<tr>
<th>ID</th>
<th>Opening angle (°)</th>
<th>Vertical profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>00C1</td>
<td>0</td>
<td>C1</td>
</tr>
<tr>
<td>30C3</td>
<td>30</td>
<td>C3</td>
</tr>
<tr>
<td>40C3</td>
<td>40</td>
<td>C3</td>
</tr>
<tr>
<td>50C3</td>
<td>50</td>
<td>C3</td>
</tr>
</tbody>
</table>

Representative wave conditions for the mouth of Douro River, Porto, Portugal (Henriques et al., 2013), were selected to realistically simulate an application of a SSG device. The experimental tests were carried out with regular and irregular long crested waves; however only the results for irregular waves are presented. The irregular sea states were characterized by a JONSWAP spectrum (peak enhancement factor of 3.3) and generated by the filtered white noise technique. Each test was 20 min long (approximately two hours in prototype). The same temporal sequence of waves was used in the tests carried out for each peak wave period so as to allow a comparative analysis of the results. The test plan and the measured (effective) significant wave heights, \( H_{Sreal} \), are presented in Table 2 in prototype values.

Table 2 – Irregular wave conditions (prototype values).

<table>
<thead>
<tr>
<th>#</th>
<th>ID</th>
<th>Significant wave height - ( H_S ) (m)</th>
<th>Peak wave period - ( T_P ) (s)</th>
<th>( H_{Sreal} ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I1</td>
<td>9.2</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>I2</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>I3</td>
<td>16.1</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>I4</td>
<td>9.2</td>
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<tr>
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<td>I5</td>
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<td></td>
</tr>
<tr>
<td>6</td>
<td>I6</td>
<td>16.1</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>I7</td>
<td>9.2</td>
<td>3.3</td>
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<tr>
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<tr>
<td>9</td>
<td>I9</td>
<td>16.1</td>
<td>2.9</td>
<td></td>
</tr>
</tbody>
</table>

Three representative significant wave heights and three peak wave periods were selected, which combined resulted in 9 sea states. Those sea states combined with four SSG configurations produced 36 different test conditions. The overtopped water volume for each individual SSG reservoir and the wave conditions were measured. The position of the wave probes was presented in Figure 4.
3 HYDRAULIC EFFICIENCY AND ABSORBED POWER

The overtopped volume collected by each individual reservoir was calculated multiplying the operation time of the associated pump by the average flow rate of each pump. The mean overtopping flow rate was estimated by dividing the overtopped volume by the duration of the experimental test (Oliveira et al., 2016).

The mean power at the entrance of each SSG reservoir is calculated by,

\[ P_{R,j} = \rho \ g \ q_{ov,j} \ R_{c,j} \]  

(1)

where \( P_{R,j} \) represents the mean power at the entrance of the reservoir \( j \), \( \rho \) the sea water density, \( g \) the acceleration of gravity, \( q_{ov,j} \) the mean overtopping flow for the reservoir \( j \) and \( R_{c,j} \) the crest height of reservoir \( j \) measured from the mean water level. The total mean power for a particular test is obtained by summing the mean power at the entrance of the \( n \) reservoirs.

The hydraulic efficiency is defined as the ratio between the total power available at the entrance of the SSG reservoirs and the wave-power of the incoming waves contained in a wave front with the width of the device, which depends on the SSG side walls’ opening angle. The wave-power level, i.e., the transport of energy per unit width of the progressing wave front, was calculated based on the estimated wave spectra and taking into account the water depth in the wave basin.

In order to support a comparative analysis of the different configurations of wave concentrators, a new parameter was defined, which relates the total mean power captured by each SSG configuration with the situation without concentrators,

\[ G_{\varphi} = \frac{P_{T,\varphi}}{P_{T,00C1}} - 1 \]  

(2)

where \( G_{\varphi} \) represents the gain in terms of hydraulic performance for configuration \( \varphi \) (expressed in percentage), \( P_{T,\varphi} \) the total mean power for configuration \( \varphi \) and \( P_{T,00C1} \) the total mean power for the configuration without wave concentrators.

4 RESULTS AND DISCUSSION

The hydraulic performance of the SSG technology for different wave conditions and the performance enhancement associated to the use of wave-focusing walls (i.e., wave concentrators) can be analysed based on the results presented in Figure 5. In general, the total mean power captured by the SSG model increases with the significant wave height and reduces with the peak wave period, regardless the opening angle of the wave focusing walls.

Figure 5 – Total mean power captured for the different opening angles of the wave focusing walls: (a) \( T_P = 9.2 \) s; (b) \( T_P = 11.5 \) s and (c) \( T_P = 16.1 \) s.
It is clear that the use of wave concentrators enhances the hydraulic performance of the SSG device, but the increase of the total mean power resulting from their use depends on the tested sea state. Indeed, those elements concentrate the wave energy, leading to an increase of the significant wave heights over the SSG front ramp, which potentiates wave run-up and results in higher overtopping discharges, especially during sea states characterized by small significant wave heights. Figure 6 presents the mean overtopping discharges for each SSG reservoir and wave conditions presented in Table 2, allowing the comparison between the standard SSG configuration and the alternatives with wave focusing walls. It is clear that the mean overtopping discharges are higher in the models with concentrators and that the increase of overtopping discharges (relative to the standard SSG model) is higher in the upper reservoir. This is an important outcome, since the upper reservoir has the higher hydraulic head and therefore affects significantly the total captured power.

Figure 6 – Mean overtopping flow rates for the lower (a), intermediate (b) and upper reservoirs (c): standard SSG model (00C1) versus alternatives with wave focusing walls (in prototype).

The mean gains in terms of hydraulic performance (Equation 2) are presented in Figure 7. It can be observed that for a fixed significant wave height, the lower the peak wave period, the greater the improvements resulting from the use of wave concentrators. On the other hand, for fixed peak wave periods, the larger the significant wave height, the smaller the gain caused by the use of concentrators. For a peak wave period of 9.2 s (lowest), the mean gain ranges from 89% for the highest significant wave height up to 1017% for the lowest significant wave height, while for a peak wave period of 16.1 s (highest) the mean gain ranges from about 46% for the highest significant wave heights up to 229% for the lowest significant wave height.
In the present study, the hydraulic efficiencies determined for the configuration 00C1 (*i.e.*, SSG without concentrators) were below 20% (Oliveira *et al.*, 2016), *i.e.*, the standard SSG model presented smaller efficiencies than the typical values presented in the literature. Oliveira *et al.* (2016) explained that the geometry of the tested SSG model was not optimized for the conditions simulated (*e.g.*, front ramp angle, reservoirs crest level, among others), because the goal of the work was only to analyze the influence of the wave focusing walls on the SSG hydraulic performance. The authors also concluded that the configurations with concentrators (30C3, 40C3 and 50C3) presented better hydraulic efficiencies for the sea states with the smaller significant wave heights, while the configuration without concentrators presented higher efficiencies for the sea states with larger significant wave heights. On one hand, the total mean power absorbed is higher when wave concentrators are used. On the other hand, the capture width increases with the use of concentrators and their opening angle, which has an important effect on the hydraulic efficiency, since the total mean power captured has to be divided by the power contained in a wave front with the width of the device. The configuration 40C3 was considered as the one with the better overall performance for the conditions tested in the study.

5 CONCLUSIONS

The effect of using wave focusing walls on the performance of the Sea-wave Slot-cone Generator was analysed based on the results of an experimental study carried out on a geometric scale of 1/40 using *Froude* similitude. The SSG physical model was incorporated in a breakwater and tested under the action of sea states selected from the resource characterization available at the mouth of Douro River, Porto, Portugal.

It was concluded that: the total mean power captured by the SSG device increases with the wave height and reduces with the peak wave period, regardless the opening angle of the wave focusing walls; all models with concentrators presented mean overtopping flow rates higher than the standard one, due to the tapering effect created by the converging walls. This effect increases locally the wave height and therefore: (*i*) waves that otherwise could not reach the crest level of the first reservoir produce overtopping; (*ii*) larger waves increased producing higher overtopping discharges in the upper reservoirs, which have the larger hydraulic heads.

The effectiveness of the wave concentrators depends on the characteristics of the tested sea states. The increase of the total mean power captured was higher for the smaller significant wave heights and the shorter wave periods.

The design of a SSG structure for a particular site should take into account, not only the usual design variables, but also the eventual installation of wave focusing walls and their opening angle. Overall, the application of the SSG technology in breakwaters presents itself as very promising considering the characteristics of the wave resource nearshore or in onshore locations.
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