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# Experimental evaluation of the effect of wave focusing walls on the performance of the Sea-wave Slot-cone Generator

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ABSTRACT

The Sea-wave Slot-cone Generator (SSG) is a multi-level overtopping based wave energy converter that can be installed either nearshore or offshore. The installation in harbor breakwaters and in the shoreline presents several advantages despite the usual exposure to smaller waves than at offshore locations. This work analyzes the effect of wave focusing walls (*i.e.*, wave concentrators) on the performance of isolated SSG units using a physical model built on a geometric scale of 1/40. Seven configurations were defined by changing the opening angle and the crest level of those elements. The use of wave concentrators proved to be advantageous since a wider wave front is captured and the run-up and overtopping phenomena are enhanced on the SSG ramp owing to the wave energy concentration (walls tapering effect). In fact, the total mean power captured increased for all SSG configurations with concentrators in comparison to the base configuration (without concentrators), regardless of the sea state considered. In terms of hydraulic performance, the gain associated to the use of wave concentrators depends on the characteristics of incident waves, being higher for the smaller significant wave heights and the shorter peak wave periods. The hydraulic efficiency, defined as the ratio between the total mean power captured per meter of SSG width and the wave power per meter width of the incident waves, increases with the significant wave height and reduces with the peak wave period in all tested SSG configurations. In addition, in comparison to the base configuration, the hydraulic efficiencies with concentrators were higher for the smaller significant wave heights, but smaller for the other sea conditions. The use of wave concentrators increased the annual energy production approximately to the double. Overall, the application of the SSG technology in breakwaters presents itself as promising considering the characteristics of the wave resource nearshore or even in onshore locations.



## 1. Introduction

The use of renewable energy sources is being stimulated by concerns related to climate change, environmental pollution, security in energy supply, diminishing fossil fuel reserves and volatility of oil markets. Among those clean energy sources, ocean wave energy is one of the most promising ones [4] and it is expected to contribute to attain the ambitious targets that were defined for the share of renewables in the global energetic mix, since the wave power resource available worldwide is estimated in 2.11 TW [5], being of the same order of magnitude of the world's electricity consumption [4].

A wide variety of validated wave energy conversion technologies are already available [7,6,1,23] and some shoreline/nearshore technologies are already in a phase of technological demonstration and approaching a pre-commercial stage (*e.g.*, [28,29]). In addition, studies have been done to assess the wave energy resource and the power performance of selected wave energy converters (WECs) at specific locations [3,30] and helping in the selection of the best technology taking into account local conditions. In spite of that, the variability of the wave resource in several timescales and the harsh marine environment are still important issues, and several challenges exist to ensure the reliability of the developed technologies and to bring the overall costs down to levels that can compete with traditional energy sources. However, the integration of wave energy converters into coastal protection structures [36] and harbor breakwaters [34] introduces new perspectives.

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Overtopping based wave energy converters are known to work by promoting the run-up of incident waves on a sloping wall or ramp, which leads to one or more reservoirs placed at a level higher than the mean water free-surface level of the sea. The potential energy of the stored water is then converted in electrical energy when it goes through low head hydraulic turbines in the way back to the sea. The irregularity of incoming waves is, to some extent, smoothed out by the reservoir capacity, providing a more regular power output to the electric grid. The performance of these WECs is not dependent on resonance with incoming waves, which can be constructed with very large dimensions, either nearshore or offshore. The hydrodynamics of overtopping devices is strongly non-linear [6]; therefore physical model studies are often used in the development and optimization phases of such devices. TAPCHAN [24], Sucking Sea Shaft [12], Power Pyramida [13], Sea-wave Slot-cone Generator [14,15], Wave Dragon [17], Wave Plane [9] and WaveCat [8] are examples of that type of WECs.

The Sea-wave Slot-cone Generator (SSG) has been developed by the WAVEenergy AS company (Stavanger, Norway). The structure of this WEC consists of a number of reservoirs one over each other (above the mean water level) that store temporarily the water of incident waves. Low-head multi-stage hydraulic turbines are then used to convert the potential energy of the stored water into electric power. The SSG technology has been extensively studied in the last ten years in order to optimize its hydraulic performance and maximize the wave power captured (*e.g.*, [14,15]), to address the nature and magnitude of wave loadings [32,2] and to analyze technical problems and economical risks related to the integration of SSG units in traditional coastal and harbor structures [18,22]. Vicinanza et al. [33] present a comprehensive overview of the most important research developments.

This multi-level overtopping WEC can be installed either nearshore or offshore. Its shoreline and breakwater applications present important advantages, such as sharing structure costs, availability of grid connection and recirculation of water inside the harbor, improvement of their performance while reducing reflections due to efficient absorption of energy [33]. This explains the studies and plans for pilot installations at the island of Kvitsøy, Norway [16,19,20], the port of Hanstholm, Denmark [22] and the port of Garibaldi (Oregon, USA). The integration of SSG units in breakwaters has already been studied (preliminary studies) for other locations to assess the cost of the structure and compare it to traditional breakwater solutions such as in the renovation of the harbor in Plentzia (Bask Country, Spain), Swakopmund (Namibia) and Sines (Portugal) [18,33].

The SSG efficiency depends, primarily, on the amount of overtopping water that enters the reservoirs. Therefore, extensive experimental work has been performed at the Hydraulic and Coastal Engineering Laboratory of the Department of Civil Engineering of Aalborg University, Denmark, 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. 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 (*e.g.*, [14,15,18,33]).

One often mentioned drawback of shoreline/nearshore WECs is their exposure to smaller wave power levels than offshore devices, although this could be partially compensated by a proper selection of their installation site, due to the natural energy concentration associated to wave refraction. Nevertheless, this positive effect can also be enhanced artificially by the use of wave focusing walls that could work as wave energy concentrators. A similar principle is used in floating, offshore WECs of the overtopping type, such as the Wave Dragon that uses two custom designed wing reflectors (*e.g.*, [17,25]) or the WaveCat, composed of two convergent hulls linked at the stern by a hinge that form an wedge in the plan view [8], but also in TAPCHAN, in which a fixed-geometry, variable-width open-channel is applied to transport water to an on-shore water reservoir [24].

The use of wave focusing walls may not only increase the significant wave height considerably (and therefore the energy captured during mild wave conditions), but also the overtopping discharges in the upper reservoirs, which have the higher hydraulic head. In this case, the SSG performance would be positively affected by these two effects. In addition, if adjustable wave focusing walls are incorporated, the hydraulic performance of isolated SSG devices could be less affected by 3D phenomena (*e.g.*, spreading and directionality), which may result in a reduction of 50% of the hydraulic efficiency estimated in 2D studies, especially for devices with a low width to depth ratio, as pointed out by Margheritini et al. [19,21].

The importance of geometry control on the performance of overtopping based WECs has been demonstrated previously. Victor et al. [35] analyzed the effect of adapting the slope geometry of a SSG device (slope angle and crest freeboard) to the variable wave characteristics at the deployment site and concluded that the overall hydraulic efficiency and overall hydraulic power increase in comparison to a fixed slope geometry.

This paper analyzes the influence of wave focusing walls on the performance of an isolated SSG unit. Those elements are called concentrators since they concentrate the energy of incident waves, increasing run-up and overtopping phenomena. The experimental work was carried out in the Hydraulics Laboratory of the Hydraulics, Water Resources and Environment Division of the Faculty of Engineering of the University of Porto, Portugal. The SSG physical model was designed and built in the INEGI facilities on a geometric scale of 1/40. Seven configurations of concentrators were defined by changing the opening angle and the crest level of the wave focusing walls. The use of concentrators proved to be advantageous for the overall performance of the SSG.

## 2. Experimental study

### 2.1. Experimental facility and equipment

The physical model study was carried out at the Hydraulics Laboratory of the Hydraulics, Water Resources and Environment Division (SHRHA) 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 maritime structures such as harbor breakwaters [31], moored floating structures [27] and wave energy converters [26]. The multi-directional wave basin used is 28 m long, 12 m wide and 1.2 m deep. Waves were generated with a multi-element piston-type wave generation system, controlled by a wave synthesizer software and equipped with a dynamic wave absorption system (HR Wallingford, UK). A dissipative rubble beach was installed at the opposite end of the wave basin to minimize the reflection of incident waves.

In a physical model of an overtopping based WEC it is essential to reproduce properly the wave overtopping and the wave breaking phenomena, minimizing scale effects that could limit the validity of the results. The preceding studies of the SSG technology were performed for geometrical scales between 1/15 and 1/66 [33]. 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 and economic criteria as well as the desired quality of the experimental results. Vicinanza et al. [33], states that in this kind of studies scale effects are not expected to be significant, even for a geometric scale of 1/66, since SSG devices are usually designed to promote slightly breaking surging waves on its front ramp and there is only a little amount of air involved in this