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Performance of an array of oscillating water column devices integrated with an offshore detached breakwater

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ABSTRACT

A systematic experimental investigation on the effect of different spacing between an array of oscillating water column (OWC) devices integrated with offshore detached breakwater (ODBW) in terms of their hydrodynamic performance has been studied. A Froude scale of 1:20 was chosen for integrating five similar devices of OWC to the ODBW (OWCBW) and a series of experiments was carried out in a shallow wave basin. Three different centre to centre spacings, *S*, i.e., one, two, and three times the width of the OWC model were considered. The hydrodynamic performance was studied in terms of non-dimensional lip wall pressure, wave amplification factor, non-dimensional air pressure, capture width, and relative capture width. The OWCBW system with thrice the width of the model spacing exhibits a better performance. The convergence of water waves in front of the OWC devices due to obstruction from rubble mound breakwaters to progressive waves enhances the concentration of energy in front of the array of OWC devices. It facilitates the system to absorb a larger amount of wave power of about 2.2 times the given input power at natural frequency of the system. This confirms that the array of OWC devices exhibits better performance than in isolation.

1. Introduction

Overwhelming worldwide awareness to reduce the use of conventional energy sources such as coal, nuclear, fossil fuels, which lead to rise in sea level and climate change, necessitates methods to be formulated for attenuation of green gas emission. It insists the scientific community to focus on intensive research in developing enhanced renewable energy harnessing methods. Energy from sea waves is one of the most promising sources of renewable energy which is also environment-friendly. In the wave energy conversion process, an interface device i.e., a floating body or an oscillating water within a structure is needed to convert the energy in the waves in the form of kinetic and/or potential energy [Brooke (2003)]. This process is known as the primary conversion process and the device is called as the Wave Energy Converter (WEC). Under the secondary conversion process, stored energy is converted into a useful form of energy. A critical review of the research and development on this topic has been reported by Shaw (1982), Ross (1995), Brooke (2003), Falcão (2010), and Heath (2012). Meticulously examining the sources available, Harris et al. (2004) classifies the WECs based on its working principle as follows: point absorber, terminator, and attenuator. Based on the fundamental concept, during oil crisis date back to late seventies, several attempts through experimental, numerical, analytical, and pilot plant stage studies have been made to optimize the different WECs [Salter (1974); Malmo and Reitan (1985); Henderson (2006); Crom et al. (2009); Vicinanza et al. (2013); Stratigaki et al. (2014); Kamath et al. (2015)]. Among them, terminator type of “Oscillating Water Column (OWC)” device is considered here. The principle of OWC device is similar to an air pump, due to the up and down oscillation of the water column inside the chamber. Suction and expulsion of air would occur in the chamber through an air hole (power take-off (PTO) device) that is connected to a turbine.

In general, the concentration of the population in a coastal belt is many times higher than the inner region and the human activities in the coastal zone have amounted to substantial economic proportions. In view of industrialization, there has been severe beach erosion observed all over the world whenever man-made structures are built along the coast. The coastal protection structures i.e., seawall, groin, offshore detached breakwaters, and artificial beach nourishment are considered by coastal engineers for maintaining the stability and sustainability of the coastal zone. Among the different coastal protection structures, offshore detached breakwaters (ODBW) have been proved to be an efficient coastal protection structure which also maintains the aesthetic view of the beach. The foremost burden in the advancement of OWC WEC technology is the financial aspect in comparison with the

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alternative renewable technologies. The construction of a single OWC device in the ocean would cost an enormous amount. For this reason, a multi-utilitarian system is potential and more feasible. This encompasses the integration of OWC devices with ODBW for coastal defence systems and with harbour formation [Sundar et al. (2010)]. The combined OWC devices with ODBW will minimize the cost of its construction with dual purposes: an energy extracting devices and protecting the coast from erosion. The mutual benefits of avoiding erosion and harnessing energy could be achieved by analysing the performance of OWC devices when it is integrated with breakwaters.

There have been numerous studies on the hydrodynamic optimization of OWC device in isolation subjected to two-dimensional waves [Morris-Thomas et al. (2007); Rezanejad et al. (2013); Wilbert et al. (2013); Kelly et al. (2013); Elhanafi et al. (2016); Ning et al. (2016)]. Moving on to three-dimensional tests, Malmo and Reitan (1985) initially investigated the wave-power absorption by an oscillating water column in a channel using linear wave theory for different boundary conditions in the regions between absorber and channel wall. Their study laid theoretical foundations for the analysis of wave-power stations consisting of an array of such OWC units. Later, Malmo and Reitan (1986a, 1986b) have compared the performance characteristics of OWC device in isolation with that of OWC devices placed in a row and reported that OWC devices in an array were more effective than in isolation. It was inferred by McIver and Evans (1988) using the method of matched asymptotic expansions that the constant load damping of the PTO mechanism for an array of units was able to achieve high performance over a range of wavelengths. Further, it was noticed that the efficiency for obliquely incident waves reduces due to the reduction in the capture width. Whittaker and Stewart (1993) reported that the maximum power output could increase for OWC devices in a row by a scale of two compared to the one in isolation. McIver (1994) found that the benefits of constructive interference for wave energy converters in harnessing energy from heaving motion might considerably be reduced by small changes in the incident wave direction. Through a laboratory model study based on principle of images method on an array of OWC devices, Thiruvenkatasamy and Neelamani (1997) found that efficiency of OWC device increases up to $S/w = 3$ (S = centre to centre spacing between OWC models and w = width of the OWC model) and further increment in S/w results in the decrease of efficiency. Martins-Rivas and Mei (2009a, 2009b) have studied theoretically the wave power extraction from an OWC device at the tip of a breakwater and along a straight coast using method of Eigen function expansions and integral equations, respectively. For a single OWC model installed at the tip of a long and thin breakwater, it was found that the angle of wave incident affects the wave field present outside the structure but not the extracted power. In contrast to this, in the OWC device installed on a cliff coast, it was reported that its performance depends strongly on the angle of wave incidence and the capture length (relative capture width) was doubled due to coastal reflection. Torre-Enciso et al. (2009) presented the three-dimensional experimental study on the performance evaluation of an array of OWC devices integrated with caisson breakwater for the benefit of both harbour formation and energy extraction. It was reported that the integration of OWC devices into breakwater was feasible in view of economical and energy conversion and that certainly led to construction of the Mutriku wave power plant, world's first wave energy commercial project. In extending the analytical theory of Martins-Rivas and Mei (2009a, 2009b), Lovas et al. (2010) studied the hydrodynamic performance of a large circular OWC device installed at the tip of a coastal corner with two special geometries: a convex and a concave corner of right angle. They have introduced a simpler strategy of optimization by assuming that the parameter representing the PTO device could take two different values in high-frequency and low-frequency ranges. It was reported that the optimal efficiency for the considered case can be comparable to the more ideal strategy where the parameter could be controlled for all frequencies. Magagna et al. (2010) have carried out a physical model study on OWC wave pumps and suggested that a limited spacing between the devices show positive effects in its performance and tend to decrease with spacing beyond two times the model dimension. Sundar et al. (2010) presented a comprehensive review on the possible approaches of integrating OWC devices with breakwaters for the harbour formation and coastal defence systems. The interaction between OWC devices and waves is of complex in nature and is more profoundly seen when these devices are arranged in arrays. Nader et al. (2012) investigated the scattered waves around single and multiple OWC devices using a finite element model based on linear wave theory. It was stated that the power capture efficiency of individual devices was highly influenced by presence of neighbouring OWC devices, and that the optimal PTO damping for an isolated OWC might differ from that of an array of devices. Nader et al. (2014) studied the hydrodynamic and energetic performance of a finite array of fixed OWC devices. It was shown that the position of the OWC devices in the array highly influences the inner properties and the interaction between devices, so when determining the optimum device parameters the position of the device in an array should be given more importance to increase the power extraction capacity of the system. By using linearized potential flow theory, Konispoliatis and Mavrakos (2016) have analysed the hydrodynamic performance of an array of floating OWC devices in finite water depth. It was observed that the power capture efficiency has been greatly influenced by the coupling between the number of OWC devices in the array and their position against the wave front. Fleming et al. (2012) and Elhanafi et al. (2016) studied experimentally and numerically the effect of underwater geometry on the performance of an offshore oscillating water column device and reported that the hydrodynamic efficiency of the system can be considerably improved by selecting suitable values for both the submergence ratio of asymmetric lips and the lip thickness. Fleming and Macfarlane (2014) considered in-situ calibration of an orifice separately for both inflow and outflow leads to more accurate flow rate prediction and consequently, better prediction of the power absorbed by the OWC device. Through an experimental study, Vyzikas et al. (2017) examined the performance of OWC devices with a PTO for energy generation and without a PTO as absorbing walls. It was found that with the addition of the slope in front of the U-OWC device, the efficiency of the system improved and the run up in front the structure was lesser in comparison with vertical breakwaters.

The available literature widely pertains to the evaluation of hydrodynamic performance of an array of OWC devices setting into a reflecting wall or as a neighbouring devices with lesser clear spacing. There arises a need to examine its hydrodynamic performance while, being built along with porous structures such as rubble mound breakwaters with dual purposes: an energy extracting devices and protecting the coast from erosion. Ashlin et al. (2016) reported the influence of the chamber bottom profile configuration (i.e., Flat, Circular curve, Slope 1 in 1 and Slope 1 in 5 bottom profiles) through a comprehensive experimental program. It was resolved that the circular curve bottom profile of OWC device is more effective in terms of its hydrodynamic performance, which has been adopted herein. Having realized the multiple benefits of serving as coastal protection measure in addition to harnessing the energy from waves, an experimental study to optimize the centre to centre spacing between five similar devices of OWC while being integrated with ODBW was taken up. While, the experiments were conducted with both normal and oblique wave incidence, results from the normal wave incidence tests are reported here. Similarly, the experiments were conducted with both regular and random wave incidence; results from the regular wave incidence tests alone are reported in this paper. The details of the dimensions of OWC models, wave characteristics, experimental set-up, experimental procedure, results and discussion are reported in this paper.