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A dual-functional wave-power plant for wave-energy extraction and shore protection: A wave-flume study

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HIGHLIGHTS

- A dual functional wave-power plant addresses the high cost issue in wave energy utilization.
- The dual functional wave-power plant integrates OWCs into a pile breakwater.
- The dual functional wave-power plant can effectively extract wave energy and protect shore.
- The cost-sharing can make wave-powered electricity economically competitive.

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ABSTRACT

The fundamental roadblock toward commercial-scale wave power operations is cost. The main objective of this work was to address the cost challenge facing wave energy commercialization through cost-sharing with pile breakwaters to be built for shore protection. This was achieved in this study through a dual-functional wave-power plant for generation of wave-power electricity and protection against coastal erosion for sustainable coastal development. The dual-functional wave-power plant was formed by integrating oscillating-water-column (OWC) devices into a pile breakwater, with each pile being an OWC-pile equipped with a power take-off device. The power extraction efficiency and hydrodynamic characteristics of the dual-functional wave-power plant were measured in a wave flume under various wave conditions. An orifice was used at the top of the pneumatic chamber of each OWC-pile to simulate the power take-off device. To evaluate the performance of the power plant in wave power extraction and shore protection, the surface elevation and pressure inside the OWC chamber, as well as the scattered waves, were measured. It was found that comparing to a standalone OWC-pile device with an identical design and geometric characteristics, an OWC-pile in the dual-functional wave-power plant could achieve significantly larger power-extraction efficiency. Comparing to a pile breakwater with the same dimensions, the wave transmission and reflection of the dual-functional wave-power plant were both weaker, especially the wave reflection, which is beneficial for structure safety and shore protection. Based on the Froude's law of similarity and an estimation of the effect of air compressibility at full scale, an evaluation of the performance of a dual-functional wave-power plant at full scale was also provided. The findings of this work promote close collaboration between wave-energy utilization community and the shore-protection community for commercial-scale deployment of wave energy converters and contribute to making wave energy economically competitive.

1. Introduction

With the increase of global energy demand and a rising concern of the environmental consequences of fossil fuel based energy sources, the global need for clean and renewable energy is on the rise over the last decades. Taking Hawaii as an example, the state is surrounded by the Pacific Ocean, and a core strategic goal of its energy policy is to maximize affordable clean energy. The state has determined to achieve 100 percent renewable energy generation by 2045 [1]. The ocean is a tremendous source of renewable energy, and ocean wave energy is one of the four main sources of energy in the ocean: the available ocean wave energy is on the terawatt level [2,3].

Among all Wave-Energy-Conversion (WEC) devices studied so far, Oscillating-Water-Column (OWC) type devices are one of the most

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studied and tested WEC devices. A typical OWC device usually consists of a semi-closed and semi-submerged pneumatic chamber and a power take-off (PTO) system (i.e., a turbine and an electric generator). Incident waves create a fluctuation of the air pressure inside the pneumatic chamber, which forces the air trapped in the chamber to drive a turbine connected to a generator for electricity generation [4].

Experimental, theoretical and numerical studies of OWC devices have been carried out in the past decades. Most of the existing studies are for standalone OWC devices, aiming mainly at improving their conversion efficiencies. Using linear wave theory, Evans [4] found that it was possible to extract wave energy from ocean waves through the resonant interaction between water waves and a pneumatic chamber, and thus laid the foundation to the theories of hydrodynamics of OWC devices. Subsequent theoretical studies considered spatial non-uniformity of the water surface [5] and the compressibility of the air [6] inside the OWC chamber. Most experimental studies on standalone OWC devices focused on the conversion efficiency of various designs. Bingham et al. [7] performed a numerical and laboratory study of a 40-chamber I-beam attenuator in fixed and floating conditions and obtained a good agreement between their experiment and numerical results. Iturrioz et al. [8] studied, experimentally and numerically, a simple shore mounted OWC device with a rectangular pneumatic chamber and showed a good agreement between their experimental results and numerical predictions. Ning et al. [9] studied experimentally the wave energy conversion efficiency, as well as the related hydrodynamics, of a fixed oscillating water column device with a 2D rectangular cross-section under various wave conditions and geometric parameters; their experimental results agreed well with previous numerical results obtained by a nonlinear potential-flow solver [10]. Ning et al. [11] applied the numerical model of Ning et al. [10] to investigate the dynamic wave forces on a 2D rectangular OWC device under various wave conditions and showed a good agreement between the experimental and numerical results. Macfarlane [12] and Vyzikas et al. [13] investigated experimentally how the underwater geometry could affect the energy loss and conversion efficiency of an OWC device. Fleming and Macfarlane [12] carried out 2D PIV experiments that measure the detailed flow field in a 2D rectangular OWC chamber and used it to investigate the energy loss and conversion efficiency of OWC device with different underwater geometries; of all the geometries tested, it was hard to determine a best overall performance, and recommendations were made for future design of geometry. Vyzikas et al. [13] conducted laboratory experiment with and without PTO mechanism for a series of geometric modifications to the classic design of OWC and the U-OWC devices, shape improvement suggestions were made according to the experimental results; they found that adding a slope in the chamber could improve the performance of the U-OWC device, while a small toe protection unit could enhance the performance of a classic OWC device. Prototype tests of OWC devices have also been carried out in Portugal, Norway, China, and India [14,15].

The methods used for numerical time-domain studies related to OWC devices can generally be categorized into two types: non-linear potential solvers and computational fluid dynamics (CFD) models. Koo and Kim [16] used a nonlinear potential solver to study the performance and motion responses of OWC devices in wave fields; their solver was based on a fully non-linear boundary element method combined with a mixed Eulerian–Lagrangian method. Using a time-domain higher-order boundary element method (HOBEM), Ning et al. [10] developed a 2D fully non-linear numerical wave flume to study the performance of a fixed OWC device; their numerical wave flume was validated against the experimental results reported in Ning et al. [9,11]. Computational fluid dynamics (CFD) models, which solve Navier–-Stokes equations and various turbulence closures, are computationally costly, but can capture viscous phenomena such as viscous dissipation and generation of vorticity. Zhang et al. [17] developed a numerical method based on a two-phase level set and immersed boundary method and Navier–Stokes equation using FLUENT software, and the model validation against the existing experimental results showed a satisfactory agreement in terms of the oscillation of the free surface inside the chamber and the power extraction efficiency. To study the influence of OWC chamber geometry and turbine characteristics on OWC device performance, an aerodynamic model for the air pressure inside the OWC chamber was included in the CFD simulation of Teixeira et al. [18]. Iturrioz et al. [8] and Simonetti et al. [19] used the open source C++ CFD library OpenFOAM®to study hydrodynamics and wave-energy conversion of OWC devices and highlighted the capability of OpenFOAM®to accurately simulate important physical processes involved in the energy conversion of OWC devices. More recently, Elhanafi et al. [20,21] used the CFD software package StarCCM®to investigate hydrodynamics and energy conversion of two OWC devices with 2D rectangular OWC chambers (a tension-leg type floating-moored OWC device and a fixed OWC device with different lip shapes) and yielded good agreements with the measured energy conversion and motion responses.

Even though power from ocean waves can potentially make a significant contribution as a renewable energy source, a host of challenges, including high costs incurred in using the current technologies to generate electricity [22], have made the electricity generated by wave energy devices economically less competitive. These challenges include reducing construction and operation costs, increasing reliability, being suitable for a wide range of wave conditions, and minimizing potential environmental impacts. For example, while a WEC device must be optimized to the local prevailing wave conditions, its structure must withstand local extreme events, which will significantly increase the construction and maintenance costs of wave-power plants. To make wave energy economically competitive, innovative concepts to reduce costs are crucial in order to overcome the cost hurdle associated with wave energy utilization. Combining wave extraction with shore protection is one potential route to take.

Even though several studies have proposed the concept of integrating WECs with caisson or rubble mound or vertical wall breakwaters, these studies do not focus on shore protection and minimizing potential environmental impacts on coastal water quality. For example, the prototype project that integrated an overtopping-type WEC with a rubble mound breakwater at the port of Naples in Italy [23,24] was not designed for shore protection; Yueh and Chuang [25] proposed an integration of a piston-type porous wave energy converter into a vertical wall breakwater, but vertical walls do not allow water exchange across the breakwater and thus may have potential negative environmental impacts. Integration of OWCs with caisson breakwaters have been reported by several authors. Martins-Rivas and Mei [26] and Henriques et al. [27] studied the integration of a single OWC at the tip of a vertical wall, focusing on the influence of the vertical breakwater on the power-extraction efficiency of the OWC device. A wave power plant consisting of 16 OWC-chambers built into a caisson breakwater was constructed at the port of Mutriku, Spain [28]. Boccotti [29], Boccotti et al. [30] and Boccotti [31] studied theoretically and experimentally a caisson breakwater with a U-OWC device with its power take-off modeled as a small opening; they showed that by properly optimizing the design of the caisson breakwater-OWC system, the efficiency of the U-OWC device could be greatly improved. A prototype caisson breakwater with a U-OWC was later constructed in the Mediterranean Sea in REWEC3 project [32] at the harbor of Civitavecchia, Italy. Because of the large hydrodynamic loads, caisson breakwaters are usually constructed in relatively shallow water on rubble mound foundations with armor layers. Various sources of wave energy dissipation inevitably reduce the amount of energy that can reach the OWC devices embodied in the caisson [33]. Moreover, as an impermeable structure, a caisson type OWC-breakwater does not allow water, marine life and sediment exchange across it, which may potentially introduce high ecological footprint.

Most of the coastal structures that have been considered in the aforementioned studies are constructed either onshore or inside the surf