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Hydrodynamic performance of a pile-restrained WEC-type floating breakwater: An experimental study

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In this paper, a system which integrates an oscillating buoy type wave energy converter with a vertical pile-restrained floating breakwater is introduced. A preliminary experimental study on the hydrodynamic performance of the system is carried out in a wave flume under the action of regular waves. A current controller-magnetic powder brake system is used to simulate the power generation system. The design is verified against published results. The power-take off damping characteristics are investigated, and the current controller-magnetic powder brake system can simulate the (approximate) Coulomb damping force very well. The effects of various parameters, including wave period and wave height, dimensions of the system and excitation current, on the hydrodynamic performance are investigated. Results indicate that the power take-off damping force, draft and relative width between the floating breakwater and the wavelength have a significant influence on the hydrodynamic performance of the system. A range can be observed for which the capture width ratio of the system can achieve approximately 24% while transmission coefficient was kept lower than 0.50 with the proper adjustment of power take-off damping force, and the floating breakwater performs in an effective manner. The new concept provides a promising way to utilize wave energy cost-effectively.

1. Introduction

For coastal areas with high tidal range and/or deep water depth, floating breakwaters are frequently used as wave-attenuation structures. Compared with fixed mounted breakwaters (e.g. rubble mound breakwaters, vertical breakwaters and submerged breakwaters), floating breakwaters are favored due to relatively low construction-costs, no requirements on marine geological conditions, low environmental impact, aesthetic considerations and flexibility [31]. Therefore, the utilization of floating breakwaters is increasing in port engineering, artificial beaches and marine aquaculture.

To date, a wide variety of floating breakwaters have been developed. According to the mooring type, floating breakwaters can be classified into two categories: vertical pile-restrained floating breakwaters and tethered floating breakwaters. For the former type, the floating breakwater can only move freely in heave due to the restriction of the vertical pile; by contrast, for the latter type, the floating breakwater can move in several degrees of freedom under the limitations of the mooring system.

From the standpoint of reducing construction-costs and practical engineering applications, floating breakwaters should be as simple and durable as possible [20]. Based on this, floating breakwaters with rectangular cross-sections, which are typically termed box-type floating breakwaters, may be the prime choice of design. For the box-type floating breakwater (including vertical pile-restrained type and tethered type), much theoretical [1,2,13,44], numerical [11,27,29,30] and experimental [25,28,35] work has been performed, although with different emphasis points such as wave transmission, floating body motion, hydroelasticity, wave forces and effects of the mooring line systems.

At the same time, as a consequence of environmental pollution and climate change, extracting energy from renewable energy resources have been a growing area of research in recent years. Ocean wave energy is a huge, largely untapped renewable energy resource, and is becoming potentially attractive for researchers and engineers. Based on the different deployment sites and ways in which energy can be absorbed from the waves, a wide range of wave energy converters (WECs) have been developed. Generally,

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WECs can be classified into three predominant types: oscillating water columns, oscillating bodies and overtopping devices [15]. Detailed information on particular wave energy converters can be obtained from the related company websites or published reviews such as the one by Ref. [26].

The hydrodynamic performance of various of WECs have been investigated theoretically, numerically and experimentally [9]. However, the high construction costs is still a big challenge [10]. Thus, in order to gain necessary confidence and accelerate wave energy developments, more and more developers focus on reducing the construction costs.

Cost-sharing is an effective way to reduce the capital cost of engineering applications, and integrating WECs into breakwaters provides a promising way to realize cost-sharing in wave energy technology. Some researchers have integrated the OWC-type wave energy extraction system into caisson breakwaters [4,6,37]. Vicinanza et al. [40] combined rubble mound breakwaters and WECs in an innovative way. Wave energy is extracted by collecting wave overtopping in a front reservoir, by which turbines are driven in the process of the returning the water to the sea. Orer and Ozdamar [33] investigated the efficiency of a plate wave energy converter. A pulsating flow occurs opposite to the direction of the wave propagation below the plate, which can be used to drive turbines. Observation showed that an efficiency of approximately 60% can be achieved by modifying the structure below the plate. The plate can be used as a breakwater, but detailed information of the transmission coefficient was not provided. He and Huang [21] experimentally investigated the hydrodynamic performance of a pile-supported OWC structure as a breakwater, and showed that pile-supported OWC-type breakwaters have the potential to utilize wave energy. But since the aforementioned breakwater is a fixed structure, the cost of this project will rise with increasing water depth. So far, the idea of integrating wave energy devices with floating breakwaters has not been studied to a large extent. He et al. [22,23] integrated an OWC-type device with a slack-moored floating breakwater and found that the integrated system can broad the frequency range for energy extraction and improve the performance of wave attenuation for longer-period waves at the same time. Michailides and Angelides [32] introduced a new type of flexible floating breakwater (FFB), which represents not only a shore protection structure but also a wave energy device. In this system, wave energy can be captured through the relative motion of adjacent floating modules of FFBs. The hydrodynamic performance of the FFB under power take-off (PTO) damping was investigated based on linear hydroelastic theory. The results showed that it is possible to realize the function of wave energy utilization and desired-level wave attenuation simultaneously. Zanuttigh et al. [42] experimentally investigated the feasibility of using the wave energy converter DEXA as wave attenuation structures, and the results suggested that DEXA can be integrated into coastal protection schemes. Furthermore, Zanuttigh and Angelelli [41] studied the hydrodynamic performance of multiple wave energy converters and affirmed that they can be integrated into coastal protection schemes.

It is understood that there is a correlation between the vertical pile-restrained floating breakwater and the oscillating buoy WECs in terms of working conditions, structural characteristics and applied functions. In this study, we propose a novel integrated system of a vertical pile-restrained floating breakwater which is working under the principle of an oscillating buoy WEC. The integrated system comprises a box-type floating breakwater as base structure, with a PTO system installed above the breakwater without changing the geometry of the original base structure. The working principle is described in the schematic sketch of the integrated system (as is shown in Fig. 1). The heave motion of the

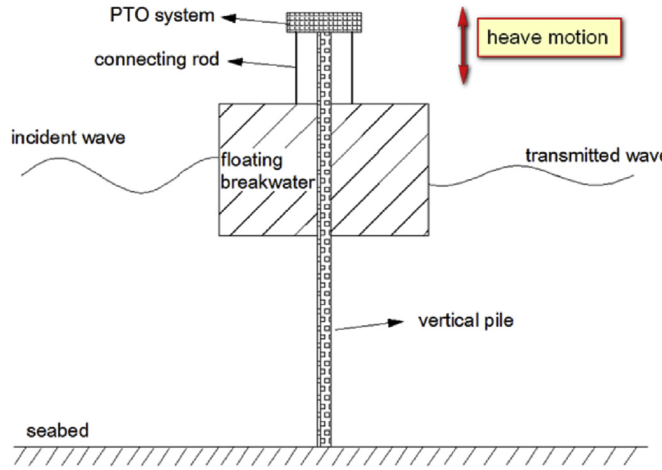

Fig. 1. Schematic sketch of the integrated system.

floating breakwater can be controlled by the PTO system through the transmission mechanism, and the wave energy can be captured in the form of kinetic energy of the heave motion of the floating breakwater by the PTO system. However, the magnitude of the PTO damping force could affect the motion of the floating breakwater, and then modify the transmission coefficient to some extent. So, as a hypothesis, there may exist a configuration, for which the capture width ratio (CWR) and transmission coefficient of the integration system meet a satisfied level.

One of the aims of the presented study is to provide an efficient way to integrate the function of wave energy utilization into a floating breakwater, which may reduce the cost of the development of WECs and also improve the performance of base structures as a breakwater. For a new proposed integrated system, preliminary investigation under regular waves is often needed to examine its performance [21,23,32,33]. So, a parametric study of the hydrodynamic coefficients (including reflection, transmission and dissipation coefficients) and CWR of the proposed integrated system under regular waves is performed. The variations of the hydrodynamic coefficients and CWR as function of the excitation current (i.e. PTO damping force) can be obtained.

The paper is organized as follows. In Section 2, the experimental setup and test procedures are described. In Section 3, the experimental design is studied and verified. In Section 4, the results of the hydrodynamic performance of the integrated system are presented and discussed. Finally, the conclusions are presented in Section 5.

2. Method

2.1. Experimental setup

The experiments were conducted in a wave flume at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, China. The dimensions of the flume were 69 m in length, 2 m in width and 1.8 m in depth. A piston-type unidirectional wave-maker was installed at one end of the flume, and a wave-absorbing beach was located at the other end to reduce the wave reflection. A wall was installed along the longitudinal direction of the wave flume to divide the width of the flume into two parts: of 1.2 m width and 0.8 m width, where the part of 0.8 m width was selected as test section.

Through the use of Froude scaling, a 1:10 model was adopted to build the experimental model. Fig. 2 shows the dimensions of the floating breakwater model. The width *B* was 0.8 m, the height 0.6 m