International Journal of Naval Architecture and Ocean Engineering xxx (2017) 1–9

Contents lists available at ScienceDirect

International Journal of Naval Architecture and Ocean Engineering

journal homepage: http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/

Experimental study on multi-level overtopping wave energy convertor under regular wave conditions

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A R T I C L E I N F O

Article history:
Received 9 March 2017
Received in revised form
8 October 2017
Accepted 15 October 2017
Available online xxx

Keywords:
Wave energy conversion
Overtopping device
Multi-level
Experimental study
Sloping angle
Reservoir

A B S T R A C T

A multi-level overtopping wave energy converter was designed according to the large tidal range and small wave heights in China. It consists of two reservoirs with sloping walls at different levels. The reservoirs share a common outflow duct and a low-head axial turbine. The experimental study was carried out in a laboratory wave-flume to investigate the overtopping performance of the device. The depth-gauges were used to measure the variation of the water level in the reservoirs. The data was processed to derive the time-averaged overtopping discharges. It was found that the lower reservoir can store wave waters at the low water level and break the waves which try to climb up to the upper reservoir. The upper sloping angle and the opening width of the lower reservoir both have significant effects on the overtopping discharges, which can provide more information to the design and optimization of this type of device.

1. Introduction

Wave energy is one of the most promising ocean renewable energy resources, which has been developed rapidly in last two decades (Falcao, 2010). As a typical wave energy converting technology, the overtopping Wave Energy Converter (WEC), utilizing the wave overtopping, needs a reservoir at a higher level than the mean water level of the surrounding sea. Waves run up along the sloping ramp and over spill into the reservoir. The stored water is released to the surrounding sea through a duct. The electricity is generated by the low head axial turbine installed in the duct, which realizes the converting process from wave energy to the electrical power. Overtopping devices have demonstrated some advantages and potentials: Extremely unstable wave energy could be converted to relatively stable static energy, which are easier to be utilized; the low head hydro turbine is a mature technique in the hydroelectric engineering.

Sea Power was proposed to be the first overtopping device for wave energy conversion in the world (Kofoed, 2002). Wave Dragon (WD), operating as the world's first grid-connected floating WEC, was developed in Denmark (Cruz). A circular ramp overtopping wave energy converter was proposed for experimental studies (Liu et al., 2017). Other ideals of overtopping WEC have been proposed and are still in the laboratory model testing stage (Kofoed et al., 2002; http://www.jospa.ie). Acting as an onshore plant, TAPCHAN (Tapered Channel), rated to 350 kW, commenced operation in 1985 on the west coast of Norway (Kofoed, 2002). A larger plant with 1.1 MW installed capacity, using the same operation principle as TAPCHAN, was planned to be constructed at Java, Indonesia (Tjugen, 1995). In recent years, a Sea Slot-cone Generator (SSG) overtopping wave energy converter was proposed to collect more wave water under large wave-height conditions (Working Group on Wave Energy Conversion, 2003; Kofoed and Osaland, 2005; Kofoed, 2006).

Wave overtopping has always been one of the hotspot research areas in the costal engineering (Chini and Stansby, 2012). Recent experimental studies have focused on different aspects such as effects of oblique and short crest waves on overtopping behavior (Norgaard et al., 2013), the run-up of solitary waves on a sea wall (Lin, 2012) and the dam-break flows on the steep slope (Xue et al.,

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Peer review under responsibility of Society of Naval Architects of Korea.

https://doi.org/10.1016/j.ijnaoe.2017.10.004

2011). Furthermore, some numerical models based on different methods were developed to simulate the wave motions related to the overtopping such as wave run-up, focus and breaking during the overtopping processes (Tonelli and Petti, 2013; Orszaghova et al., 2014). In addition, uncertainties in experimental and numerical tests are also analyzed for overtopping discharge predictions (Williams et al., 2014; Romano et al., 2015).

Comparing to the WD, the SSG type multi-level device can be coupled with the coastal engineering, such as the breakwater and sea dikes, which will reduce the construction cost significantly (Vicinanza et al., 2012). Furthermore, the combination can convert the traditional passive-energy-absorbing mode of the coastal structures to the initiative-energy-absorbing mode (Vicinanza et al., 2014). The hydrodynamic forces on SSG front faces were experimentally measured (Vicinanza and Frigaard, 2008; Buccino et al., 2012, 2015). The design, reliability and hydraulic performance of SSG have been summarized (Margheritini et al., 2009). The overtopping discharges of the multi-stage overtopping WEC were studied in a numerical wave tank by using the regular waves (Jungrungruengtaworn and Hyun, 2017).

An overtopping wave energy device integrated with the seawall was studied experimentally and numerically for the improvement of overtopping volumes (Tanaka et al., 2015, 2016). A cylinder was used as the running-up ramp for the overtopping WEC and investigated in a laboratory wave flume (Mehmet and Mehmet, 2017). An Overtopping BReakwater for Energy Conversion (OBREC) was proposed and its prototype device has been constructed at the port of Naples (Contestabile et al., 2016, 2017a). The overtopping performance and wave loadings on the slope and vertical walls of OBREC were studied experimentally for its optimal design (Palma et al., 2016; Iuppa et al., 2016; Contestabile et al., 2017b). A numerical wave tank based on the Flow-3D software was employed for the wave overtopping behaviors on the OBREC (Maliki et al., 2017).

The irregular waves were employed in most previous experiments and the overtopping discharges in a long term were recorded to evaluate and optimize the performance of the SSG. Due to the characteristics of irregular waves, it is hard to evaluate the wave overtopping behaviors over the devices. On the other hand, the numerical simulations of the overtopping performance of the WECs were carried out by using the regular waves.

Inspired by filling this gap between experimental and numerical studies, a laboratory test was conducted in this study. A Multi-Level Overtopping-type Wave energy converter (MLOW) was designed to operate in a large tidal range. The regular waves were employed to demonstrate the detailed phenomena of wave run-up and overtopping under various wave conditions. The overtopping discharges were also recorded and processed for the analysis of the contributions of different combinations of wave height & period to the overtopping performance. Effects of the upper sloping angle and the opening width of the lower reservoir on the overtopping discharges of two reservoirs at different water levels were also tested and analyzed.

2. Conceptual design of MLOW

Because of the sheltered effects of the island-chain, the density of wave energy in North China is only one-tenth of that in Europe. On the other hand, the tidal difference around the coastal area in China is usually 3–4 m. According to the typical sea conditions and design code of the breakwater in China (Ministry of Transport of the People's Republic of China, 2012), a conceptual design of MLOW was carried out, and the schematics are shown in Fig. 1.

MLOW has a discrete slope and two reservoirs at different water-levels. The upper and lower reservoirs reserve the incident wave water at the High-Water-Level (HWL) and Low-Water-Level (LWL), respectively. The two reservoirs share a common outflow-tube installed with a low-head axial-flow water turbine for electricity generation. The outlets at the bottom of two reservoirs can be automatically opened and closed by recognizing the water levels (Liu et al., 2014). If possible, the guide vanes also can be installed on the slope to focus the incoming waves and absorb more overtopping water.

3. Experimental set-up

3.1. Experiment design

Fig. 2 illustrates the MLOW experimental model. The schematic of MLOW model is presented in Fig. 2 (a). The widths of two reservoirs O_U and O_L are reduced for saving cost of material, and the volumes of two reservoirs are large enough for filling incident wave waters. The heights of the upper and lower reservoirs are $H_U = 450$ mm and $H_L = 350$ mm, respectively. The height of the wave wall on the back is $H_W = 250$ mm. The angles of the two reservoir's sloping walls are defined as α and β, respectively. Following the previous study's suggestion (Kofoed and Osaland, 2005), O_U and β are fixed at 200 mm and 30°, respectively. *Ls* is the horizontal projected length of the lower slope. The components of the physical model made of acrylic plates are shown in Fig. 2 (b). The variations of testing shape parameters including the sloping angle and open width of reservoirs can be realized by assembling and modify the components easily.

The physical model tests were carried out in the wave flume located in the Ocean University of China. The width and length of the flume are 0.6 m and 30 m, respectively. The motions of piston-paddles are controlled by an AC servo motor through the ball screws to generate desired waves at one end of the flume. Fig. 3 presents the deployment of MLOW model in the flume. As shown in Fig. 3 (a), the model was put at the opposite end of the wave

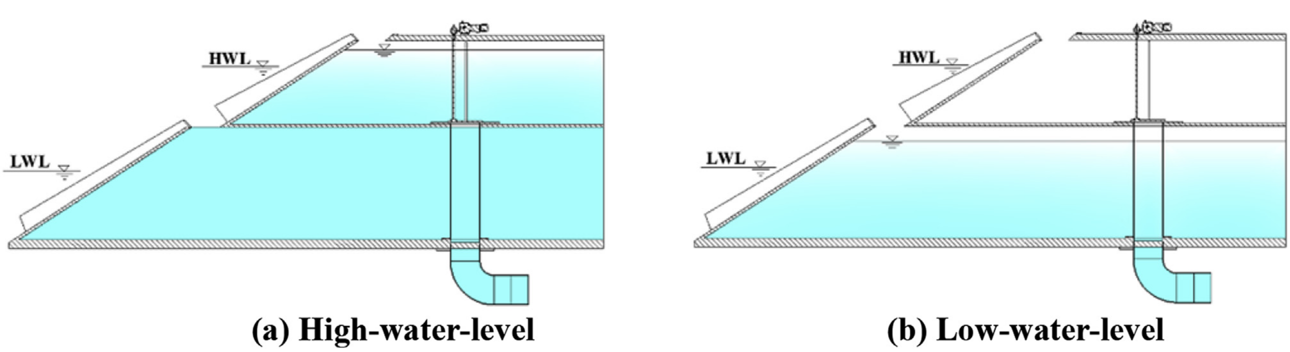

Fig. 1. Schematic of MLOW.

Please cite this article in press as: Liu, Z., et al., Experimental study on multi-level overtopping wave energy convertor under regular wave conditions, International Journal of Naval Architecture and Ocean Engineering (2017), https://doi.org/10.1016/j.ijnaoe.2017.10.004