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Numerical study on the performance of a twin-raft wave energy dissipator in a stilling basin

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ABSTRACT

In this paper, a raft-typed wave energy dissipator is proposed, and a mathematical model for the hydrodynamics of such a dissipator is presented, based on Reynolds-averaged Navier–Stokes equations. The model is validated by a comparison of the numerical results with the results of other investigators. The validated model is then utilized to examine the effect of wave height, wave frequency, damping coefficient, flow velocity on wave energy dissipation ratio and wave transmission coefficient for a hinged twin-raft wave energy dissipator. Our results reveal that the differences in behaviour exhibited by an inviscid fluid and a viscous fluid can be large and vary considerably, depending on the flow velocity.

1. Introduction

Huge waves are caused by water tongues plunging into a stilling basin when floods discharge through high dam spillways, leading to negative impacts on the structural reliability of the stilling basin and the performance of turbines (Zhang et al., 2008). In addition, huge waves generate infra-sound, the mechanism of which was described by Daniels (1953, 1962). The infra-sound from large ocean waves has been observed (Garcés et al., 2003; Le Pichon et al., 2004); its frequency ranges from 1 to 5 Hz, roughly equalling to the natural frequencies of houses/buildings (Crowley and Pinho, 2006). Thus, it is reasonable to consider the infra-sound generated by huge waves in stilling basins as a cause for the tangible vibration of rolling shutter doors and drop lights, etc. in the nearby buildings, which is mentioned by Yin et al. (2014). To the authors' knowledge, though the precise mechanism describing the causes of the nearby buildings vibration has not been proposed, the huge waves generated in the stilling basin should be an essential reason for such vibration. In order to reduce or eliminate the negative effects made by the waves, a measure should be taken to dissipate wave energy in the stilling basin to avoid transferring the energy to the air or the structures around the stilling basin and then triggering the vibration of nearby buildings.

Currently, two methods to reduce or even eliminate waves can be concluded from the description of Sollitt and Cross (1972) and Grilli et al. (1994): reflecting waves and dissipating waves. The former would only make sense when it comes to infinite water areas, for instance, the reflection occurs at breakwaters when waves travel from seas to shore, but once it comes to a finite water area, such as a stilling basin, reflecting waves would fail to reduce or eliminate waves. The latter could be suitable for various water areas and can reduce or even eliminate waves, which could be reflected back at the

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boundaries. This method has been applied in wave tank and wave basin, where the wave energy dissipates at the wave-absorbing beach (Akyildiz, 2002). The traditional means of dissipating wave energy is turbulent dissipation, which usually occurs during wave breaking (Sollitt and Cross, 1972; Grilli et al., 1994; Akyildiz, 2002). Recently, a new scheme of dissipating wave energy based on wave energy conversion method was developed (Chen et al., 2014), capturing wave energy by hinged floating bodies with a damping system and then dissipating the absorbed energy directly into thermal energy. It is noted that, over the past three decades, more and more attention has been paid to floating bodies for dissipating wave energy because they have many advantages over the traditional bottom founded ones, such as little interference of water circulation, suitability for poor foundation, removability and aesthetic acceptability (McCartney, 1985). Thus the performance of these floating bodies has been extensively studied analytically and numerically.

Drimer et al. (1992) presented a simplified two-dimension (2-D) model for a long floating breakwater based on the potential flow theory and evaluated its performance. Later, the performance of a dual pontoon floating breakwater connected by a rigid deck was investigated theoretically, based on the 2-D potential flow theory and the assumption of linearised fluid motion (Williams and Abul-Azm, 1997). It was found that the dual breakwater may exhibit better performance than an equivalent single pontoon structure. Williams et al. (2000) carried out a numerical study on the behaviour of a pair of pontoon breakwaters without any connection between them. Based on a three-dimension (3-D) boundary element method (BEM) utilizing Green's theorem and potential flow theory, linearised frequency-domain analysis for the motion of two-hinged rigid barges (Newman, 1994) and the force in the connection (Sun et al., 2011) were presented. The performance of floating breakwater array with various configurations of hinges was compared with the corresponding one of a single rigid breakwater without hinges (Diamantoulaki and Angelides, 2010). It was found that the increasing number of the hinge joints may improve the effectiveness of the floating array. Michailides and Angelides (2012, 2015) conducted a linear analysis for a flexible floating breakwater consisting of a grid of floating modules, which were connected flexibly by connectors and a linear power take-off (PTO) system to produce power. It was found that for that flexible floating breakwater, when the power increases the protection effectiveness of the breakwater decreases. Recently the dynamics of a raft-typed wave energy dissipator, which was connected by a hinge and a linear PTO system, was studied numerically in an inviscid numerical wave tank (NWT) based on a finite volume method (FVM) to solve the Euler equations (Chen et al., 2014). All the above work so far, however, has concentrated on potential flow and linearised wave, and well elucidated the fundamental mechanism of linear wave–structure interaction for interconnected multi-bodies with and without the consideration of a linear damping power take-off system. Less work has been devoted to non-linear wave–structure interaction, even though in many practical applications, viscous fluids generally exhibit non-linear behaviour. Turbulence and wave energy dissipation have not been considered despite being important for the study of wave characteristics before and after the breakers, which are essential parameters for the performance evaluation of breakwaters.

Landrini et al. (1998) built a non-linear viscous numerical wave tank (NWT) to investigate the non-linear interaction between waves and a stationary horizontal cylinder for different Keulegan–Carpenter (KC) number and the effect of viscosity. It was found that the wave-induced loading predicted by the viscous and by the inviscid model coincided for the smaller KC while exhibiting significant discrepancies for the larger value. Meanwhile, Park and Kim (1998) studied the non-linear interaction of waves and currents around a stationary vertical cylinder by building a non-linear viscous NWT, which could consider current, based on a finite-difference scheme and a marker-and-cell (MAC) method. It can be seen that the simulation by the fully non-linear NWT gave much more reliable results than other numerical methods. The results also showed that the hydrodynamic forces tended to increase as current speed increased. Based on a similar viscous wave tank, Yu and Li (2013) presented a numerical study on the hydrodynamic performance of a two-body floating-point absorber (FPA). The results showed that the non-linear forces including viscous drag, wave over-topping force and the impact load when the out-of-water float re-enters the water surface could have significant influence on the response of the FPA system. Li et al. (2013) studied the motion of multi-floating bodies without connectors, as a simplified model of raft-typed wave energy converter (WEC), in a similar viscous NWT. The result showed that the behaviour of multi-floating bodies differed from that of a single floating body as the motions of the bodies decreased along the wave direction. Many efforts have been devoted to the hydrodynamic characteristics of floating WECs whose widths are usually much smaller than wave length (Antonio, 2010; Falnes, 2007; Yu and Li, 2013; Li et al., 2013; Zheng et al., 2015; McNatt and Retzler, 2016). In order to dissipate waves efficiently behind floating structures, either the width of these floating structures in wave crest direction should be much larger than wave length in open waters, or their width is only a little bit smaller than the width of waters, such as the width of a stilling basin.

So far, most of the studies are limited to the dynamic analysis of raft-typed wave energy converters or breakwaters without considering either the combined action of non-linear waves and viscous flows or the effect of PTO damping system. The aim of this paper is to propose a raft-typed wave energy dissipator, and present a mathematical model for the hydrodynamics of such a dissipator, focusing on the wave energy dissipation ratio and wave transmission coefficient over a wide range of wave height, wave period, damping coefficient and flow velocity. The differences in behaviour exhibited by an inviscid fluid and a viscous fluid are also highlighted.

The rest of this paper is organised as follows. In Section 2, a twin-hinged raft wave energy dissipator is first introduced, then a mathematical model for the dynamics of such a dissipator is presented based on the Navier–Stokes equations. Three-dimensional (3-D) numerical investigations into the effect of wave parameters, linear damping, flow velocity and viscosity on the system performance are included in Section 3. Finally conclusions are made in Section 4.