Ocean Engineering 111 (2016) 279–291

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Comparative study of hydrodynamic performances of breakwaters with double-layered perforated walls attached to ring-shaped very large floating structures

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ARTICLE INFO

Article history:
Received 10 November 2014
Accepted 13 November 2015
Available online 1 December 2015

Keywords:
Very large floating structure
Breakwater
Wave attenuation
Motion response
Mooring force

ABSTRACT

A very large ring-shaped structure composed of spar-type modules is proposed as an intermediate base for supporting deepwater oil exploitation. One of the features of the structure is the attachment of a double-layered perforated-wall breakwater, which reduces the wave energy inside the harbour. To establish the hydrodynamics of the complex structure, the characteristics of the breakwater were experimentally investigated using six different configurations. The transfer functions of the waves inside the harbour were found to have multiple peaks, which were produced by the interaction of the transmitted waves with the diffracted waves. The incident wave amplitude was also observed to significantly affect the wave energy dissipation of the breakwater for short waves, whereas the effect was small for long waves. The wave loss coefficients, wave run-up, mooring force, and surge motion were all observed to increase significantly with decreasing porosity. However, the vertical motions were quite small owing to the low natural frequencies, and they were negligibly affected by the porosity. By quantitative estimation of the effects of the porosity, it was found that the low-frequency horizontal motion, mooring force, and wave attenuation were the critical factors to be considered in the design of a breakwater attached to floating structures.

1. Introduction

The concept of a very large floating structure (VLFS) such as a pontoon-type mega-float and semisubmersible-type mobile offshore base (MOB) has attracted considerable interest in the field of coastal and ocean engineering over the last few decades, and many relevant studies have been reported (McAllister, 1997; Palo, 2005; Suzuki, 2005; Watanabe et al., 2004). The pontoon-type VLFS has a simple flat-box structure that appears like a giant plate floating on the water. Owing to the significant hydroelastic response often induced by waves in open seas, the pontoon-type VLFS is generally suitable for use in calm waters associated with sheltered coastal formations such as harbours. The semisubmersible-type VLFS, on the other hand, has low waterline-area columns that support the long deck and submerged pontoons used to maintain buoyancy, to minimise the effects of waves and to reduce the wave-induced motion response. This type of VLFS is thus regarded as being more suitable for deepwater in open seas with harsh environmental conditions.

In addition to the two typical types of VLFSs mentioned above, engineers and researchers have proposed new concepts and configurations of VLFSs that can be used for diverse purposes such as an airport, a storage facility, an offshore renewable energy base, and habitation. Kashiwagi (2000) investigated a VLFS with many columns that support a flexible upper deck, and developed a hierarchical interaction theory for evaluating the diffraction and radiation forces. Rognaas et al. (2001) described the idea of a single-hull MOB consisting of an 890 m central concrete core and long steel cantilever extensions that provide the required deck length. They concluded that fatigue was not a problem of the concrete hull, which has a design life of 100 years. Pinkster and Meevers Scholte (2001) reported the interesting concept of a VLFS partially supported by air cushions, which enabled substantial reduction of the wave-induced moments and structural loads compared to a conventional hull of the same dimensions. Watanabe et al. (2006) investigated a uniform circular VLFS, which was modelled as a flat plate with free edges floating in finite water depth. The coupled fluid–structure interaction problem was solved theoretically using

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http://dx.doi.org/10.1016/j.oceaneng.2015.11.007
0029-8018/

the modal expansion method in the frequency-domain. Accurate analytical solutions of the deflections and stress resultants were obtained and used as benchmarks for validating the results of the numerical methods employed in the hydroelastic analysis of the pontoon-type VLFS of a general planform shape. Manabe et al. (2008) reported feasibility studies conducted on a sailing-type offshore wind-farm VLFS moored in deep water. The kilometre-sized VLFS consisted of many wind turbines, wing-shaped struts, and slender semisubmersible-type hulls. As the key novelty associated with the concept, the mobility of the VLFS could maximise the generated power to find appropriate breezing conditions but to avoid heavy storms such as a typhoon. Tay et al. (2009) investigated the hydroelastic responses and hydrodynamic interactions of two large floating fuel storage modules placed side-by-side in the presence of floating breakwaters. The storage modules were modelled as plates.

A conceptual design of a ring-shaped VLFS, referred to as an ultra large floating system (ULFS), was recently reported (Liu et al., 2012). The VLFS consists of eight deep-draft spar-type modules that form a ring-shaped structure for use as an intermediate base in deep and ultra-deep water oil exploitation. The purposes of the structure include habitation, supplies storage and transfer, equipment maintenance, work boat shelter, and other logistic support for offshore oil exploitation. The design features include the application of a double-layered perforated-wall breakwater, which is used to reduce the wave energy inside the encircled harbour.

In coastal engineering practice, various types of fixed and floating breakwaters are used to protect harbours, coastline, offshore structures, and moored vessels against wave impacts. Such breakwaters include perforated-wall breakwaters (Liu et al., 2008), spar-buoy breakwater fences (Liang et al., 2004), flexible porous membrane barriers (Suresh Kumar et al., 2007), truss breakwaters (Uzaki et al., 2011), pneumatic floating breakwaters (He et al., 2012), mat-shaped floating breakwaters (Loukogeorgaki et al., 2012), and submerged flat plate breakwaters (Lalli et al., 2012). As an example of the application of the pontoon-type VLFS, oscillating-water-column-type breakwaters have been installed near a VLFS to reduce the wave-induced hydroelastic response and enable the use of the VLFS in open sea (Hong et al., 2006; Maeda et al., 2001).

The perforated-wall breakwater, which was initially proposed by Jarlan (1961), has been widely used in coastal engineering. The interaction of the water waves with the perforated-wall breakwaters has been comprehensively investigated and various novel configurations have been proposed and applied in practice to meet practical engineering requirements (Isaacson et al., 2000; Li et al., 2003; Liu et al., 2007; Suh et al., 2006; Tao et al., 2009a, 2009b; Williams et al., 2000). These studies mainly focused on the characteristics of the various configurations of the perforated walls, such as their number, orientation (vertical or transverse), perforation (null or partial), and chamber (empty or rock-filled). The effect of the porosity on the vertical porous plates have also been investigated, and methods were recommended for estimating the linearised resistance coefficient and inertial coefficient based on physical model experiments (Li et al., 2006).

Furthermore, studies have been conducted on perforated breakwaters attached to fixed vertical structures. For example, Wu et al. (1998) investigated wave reflection by a vertical wall with a horizontal submerged porous plate. They showed that, although the plate increased the complexity of the phenomenon, it also effectively reduced the reflection coefficient and wave run-up when a suitable porosity was applied. Wu and Chwang (2002) also investigated wave diffraction by a vertical circular cylinder with a thin porous ring-shaped plate, and found that both the waves near the cylinder and the horizontal wave forces were decreased.

However, there have been very limited studies on a perforated-wall breakwater attached to a floating structure. Owing to the complex wave-wave and wave-structure interactions, the breakwater tends to significantly affect the hydrodynamic performance of the floating structure, including the wave diffraction, transmission, energy dissipation, wave run-up, motion response, and mooring forces.

There are four fundamental considerations in the design of a floating breakwater (Hegde et al., 2008), namely buoyancy and floating stability, wave transmission, mooring forces, and structural design of the breakwater unit. In the case of a breakwater attached to a floating structure, the fundamental design considerations are wave attenuation, wave run-up, motion response, mooring forces, and structural design of the breakwater unit. All these design considerations constitute significant hydrodynamic issues and their highly complex interrelationship within the intricate configuration of a perforated-wall breakwater attached to a ring-shaped VLFS warrants further investigation. A comparative experimental study was conducted to investigate the hydrodynamic performance of a perforated-wall breakwater attached to a ring-shaped VLFS in deepwater. Spectral and statistical analyses were conducted on the wave energy attenuation, wave run-ups, motion responses, and mooring forces. The frequency-dependent characteristics as well as the effects of the porosities and incident waves were examined in detail.

2. Experimental setup and procedure

The experiments were performed in the Deepwater Offshore Basin at Shanghai Jiao Tong University in China. The basin is 50 m long, 40 m wide, and has a maximum depth of 10 m. A large-area movable floor allows flexible modelling of water depths between 0 m and 10 m. A secondary movable floor in the deep pit, which has a diameter of 5 m, further enables the modelling of water depths of 10–40 m. Various environments can be modelled, including collinear and non-collinear waves, currents and winds, which are simulated using two multi-flap wave generators, a deepwater global current generation system, and an axial wind fan matrix, respectively. The capabilities of the facility include the generation of significant wave heights of up to 0.3 m, surface current velocities of up to 0.4 m/s, and wind speeds of up to 10 m/s. This study utilised the Froude scaling law, which means the similarity of the gravitational force and inertia force was satisfied. This was because of the dominance of these forces over the viscous force in the behaviour of large-volume structures in ocean waves.

2.1. Model of ring-shaped VLFS

A comparative study was conducted using a model of a conceptual ring-shaped VLFS of circumference of 1256 m and with a full-scale deep-draft of 150 m. Fig. 1 shows the physical model inside the basin (linear scale ratio of 1:80) and its cross section. The model consisted of eight deep-draft spar-type modules with rigidly fixed connectors. The models of the modules were constructed using materials including wood, Plexiglas, and metal-weight elements to achieve the geometrical and mass properties with sufficient accuracy. Table 1 lists the major full-scale and model scale parameters of the VLFS. As can be observed, the model was very large, having a circumference of 15.7 m, draft of 1.875 m, and weight of 2477 kg.

The ring-shaped VLFS formed an inside leeward harbour that could be used to shelter service vessels in open sea. An innovatively designed double-layered perforated-wall breakwater of height 1.062 m (model scale) was vertically attached to the VLFS model