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Numerical simulation of interactions between water waves and inclined-moored submerged floating breakwaters

Wei Peng [a], Kwang-Ho Lee [b,*], Seung-Ho Shin [c], Norimi Mizutani [d]

[a] College of Hydraulic Engineering, Changsha University of Science and Technology, China
[b] Department of Energy Resources and Plant Engineering, Kwandong University, South Korea
[c] Maritime & Ocean Engineering Research Institute, KIOST, South Korea
[d] Department of Civil Engineering, Nagoya University, Japan

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ABSTRACT

This paper studies the interactions of water waves with submerged floating breakwaters moored by inclined tension legs, using a numerical wave tank model proposed by Lee and Mizutani (2009) and based on the Navier–Stokes solver. This model combines a direct-forcing immersed boundary (IB) method, volume of fluid (VOF) method, and the mechanics model of the floating breakwater. The floating breakwaters are free on three degrees of freedoms, namely, surge, heave and pitch. Two floating breakwater shapes, rectangular and circular, are used in the experimental and numerical investigations to validate that the model is capable of treating solid boundaries with complex shapes. The non-breaking and breaking waves are carefully chosen to study the nonlinear interactions between water waves and the submerged floating breakwaters. Comparisons of the computed and measured results reveal a favorable agreement in terms of the free water surface, tension force acting on the mooring line, and dynamics of the floating body. A slight phase discrepancy is found between the offshore and onshore mooring forces in the case of a circular floating breakwater, whereas this phenomenon is not observed in the rectangular case. In addition, fully nonlinear phenomena and viscous process in the flow field such as wave breaking, the boundary layer separation on the interface, vortex formation, and motion can be reproduced and captured accurately using the numerical model.

1. Introduction

Recently, floating structures such as breakwaters, ships, and ocean platforms have attracted favorable attention with the increase in the need for new marinas and with the development of the offshore petroleum industry. Among the numerous types of floating structures, floating breakwaters (FBW) offer designers good alternatives to traditional gravity-type breakwaters and are increasingly being applied in nearshore regions, especially at sites with a large water depth and weak foundation, considering the cost of the construction and maintenance. Moreover, the environmental requirements (for example, aesthetic considerations and water circulation) and multifunction possibilities (for example, cage aquaculture and wave energy converters) advocate the application of such structures. Furthermore, FBWs can significantly diminish wind- or storm-driven waves and boat wakes, which lead to boat or property damage, as well as beach and waterfront erosion. In Japan, various types of FBWs have been proposed and widely applied in coastal and ocean engineering since 1930. The dissipation of wave energy by FBWs mainly depends on the strong non-linear interactions between the incident waves and structures. Therefore, it is important to understand the hydrodynamics of FBWs, not only to efficiently dissipate wave energy but also to ensure the safety of breakwater structures.

Over the years, extensive studies on nonlinear wave-structure interactions have been conducted and numerous conclusions have been made based on hydraulic experiments and numerical simulations. In laboratory experiments, with the aid of the measurement techniques developed in recent years such as laser Doppler velocimetry and particle imaging (or tracking) velocimetry (PIV or PTV), the full-field fluid velocity can be obtained with sufficient resolution and accuracy to study the wave–structure interactions in detail. Dong et al. (1997) measured the flow pattern generated near the bow of a ship model subject to surface waves using the PIV technique. Jung et al. (2005) applied the PIV technique to examine the vortical flow pattern and turbulence characteristics of regular waves propagating over a free-rolling pontoon-type breakwater. Subsequently, the viscous effect on the roll motion of a rectangular structure over various time periods was investigated experimentally by Jung et al. (2006). Earlier numerical studies on the dynamics of floating structures were typically based on the potential flow theory, with the assumptions of a non-viscous effect and irrotational flow. For instance, Yamamoto et al. (1980) developed a numerical model to solve problems involving the wave transformation and motions of elastically moored floating structures based on the direct use of Green's identity formula for a potential function and linear mooring mechanics. Drimer et al. (1992) discussed the performance of a box-

* Corresponding author. Tel.: +82 10 2298 3997.
E-mail address: frog0215@gmail.com (K.-H. Lee).

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type FBW in a finite water depth by using the advantage of a simplified analytical model. Sannasiraj et al. (1998) adopted a two-dimensional finite element model to study the mooring forces and responses of a single floating pontoon-type breakwater in beam waves. Lee and Cho (2003) proposed a numerical model based on an element-free Galerkin method to simulate the wave interactions with a slackly moored pontoon-type FBW. Koo and Kim (2004, 2007) employed a potential-theory-based 2D fully nonlinear numerical wave tank to investigate the nonlinear interactions between water waves and freely floating bodies or stationary surface piercing bodies. Elchahal et al. (2008) applied partial reflecting boundaries to study the interactions of linear water waves with a moored FBW and analyzed the effects of structural parameters such as the draft, width of the floating body, and mooring angle. Bai and Eatock Taylor (2009) used the higher-order boundary element method in conjunction with the domain decomposition method to investigate nonlinear wave interactions with fixed and freely floating flared structures. However, within the framework of potential theory, similar to the researches mentioned above, the nonlinear interactions of waves with obstacles, including flow separation, vortex generation, and shedding, are difficult to determine satisfactorily. In particular, it is difficult to evaluate the pitch motion caused by the viscous damping in the vicinity of a structure using the potential flow theory, although the surge and heave motions are predicted well.

With the substantial advances in computer technology over the past three decades, the latest computers are now capable of carrying out a direct numerical simulation based on the Navier–Stokes (N–S) solver (for example, please see Kothe and Mjolsness (1992), Lin and Liu (1998), Kawasaki (1999), Chang et al. (2001), Hur et al. (2004), Wu and Hu (2006), Su et al. (2007), Young et al. (2007)). Most of the studies listed above only dealt with the interactions between water waves and fixed structures, with very few studies focusing attention on wave-structure problems involving a movable structure. Heinrich (1992) developed a 2D N–S solver to simulate the nonlinear water waves generated by submarine and aerial landslides. A source function was added to the continuity and momentum equations to represent moving boundary effects in that paper. Chen et al. (2002) applied a Reynolds-averaged Navier–Stokes model in conjunction with a chimera domain decomposition approach to simulate large amplitude roll motions in the time domain. Rahman et al. (2006) used a VOF-based numerical model that used a fractional area–volume obstacle representation method to predict the wave deformation and dynamics of tension-leg FBWs. However, these numerical methods still suffered from difficulties because of two issues when treating movable obstacles with complex contours. The first was the high computational cost of the grid generation and re-meshing, especially when the object was moving. The other was the difficulty of fully satisfying the non-slip boundary condition and mass conservation on the surface of a movable solid.

Recently, the immersed boundary method has been widely used to solve fluid-solid problems after it was introduced by Peskin (1972). In the IB method, complex geometries within a Cartesian grid can be replaced by an external force field from the solid boundary acting on the fluid. Deng et al. (2006) developed a new version of IB method, which has a robust ability to deal with arbitrary and complex configurations, and at the same time can keep the overall accuracy of the scheme. A numerical study of the flow around a swimming fish was carried out with relative ease on simple Cartesian meshes. Based on direct momentum forcing on the Eulerian grids, Su et al. (2007) proposed a new IB technique for the simulation of flow interacting with solid boundary. The numerical accuracy and capacity of the technique to model complex flows including the time evolving moving boundary was examined using four test problems both with stationary and moving boundary. Ng (2009) introduced a simple and conservative numerical scheme, where the embedding method (IB + VOF) was implemented in the finite volume framework, to simulate unsteady flow around stationary and moving body. Shen and Chan (2008) combined a discrete direct-forcing IB method and VOF method to study the fluid interaction with submerged structures. The presented methodology was reported to be a good tool for solving many practical problems involving free surfaces and complex boundaries. Lee and Mizutani (2009) presented a numerical wave tank based on a continuous direct-forcing IB method and applied it to predict the wave force acting on a horizontal cylinder. It was reported that the IB method was capable of handling the wave force problems acting on a horizontal cylinder in a general rectangular grid system based on a comparison of the existing experimental data and numerical results. Peng et al. (2012) further applied the model developed by Lee and Mizutani (2009) to simulate the wave transformations caused by interactions with various submerged structures. The results revealed that the proposed model can accurately reproduce and capture the viscous process in the flow field, such as flow separation and vortex generation. Nevertheless, the aforementioned studies focused only on problems involving fixed or forced moving structures (for instance, inline oscillating cylinder or wave maker) interacting with water waves. Their main concern was the influence of the stationary or moving solid on the flow, and almost very few researches attempt to study the problem of interactions between a free floating structure and free surface waves using IB method. However, the external forces from fluid on the structure should be emphasized especially when the structure is free in some freedoms, which may cause complex interaction process, like wave energy transformation, vortex generation and shedding. Jung et al. (2005) also reported that the flow pattern around the free-rolling structure showed distinct features to that reported using a forced oscillatory structure. The main purpose of this study is to investigate the applicability and validity of the numerical model proposed by Lee and Mizutani (2009) in simulating the dynamics of a submerged FBW moored by inclined tension legs. The mechanics model of a FBW is used, taking into account the freedoms of three FBW motions: the surge, heave, and pitch. In the following section, the numerical model is briefly introduced and the laboratory experiment is described. Then, the experimental results are used for validating the numerical model in terms of the free surface profiles, water particle velocity fields, mooring forces, and motions of the floating body. Finally, the conclusions and research prospects are presented.

2. Numerical model

2.1. Governing equations and numerical scheme

In this study, the employed numerical wave tank is based on the N–S solver. The flow of an incompressible viscous fluid, as shown in Fig. 1, is governed by the continuity equation and modified N–S equations:

$$\frac{\partial u_i}{\partial x_i} = Q \tag{1}$$

$$\frac{Du_i}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + 2\nu\frac{\partial D_{ij}}{\partial x_j} - \frac{2\nu}{3}\frac{\partial Q}{\partial x_i} - g_i - \gamma u_i \delta_{i2} + L_i \tag{2}$$

where x_i represents the x or z orthogonal Cartesian coordinate, u_i is the velocity component (u, w) in the i direction, p is the pressure, ρ is the fluid density, t is the time, g is the acceleration due to gravity, ν is the kinematic viscosity coefficient of the water, γ is a wave dissipation factor that is equal to zero except in the sponge zones, δ_{i2} is defined as 0 and 1 in the x and z direction respectively as suggested by Hinatsu (1992), D_{ij} is the velocity stress tensor, and Q is the source term at the source position $x = x_s$, which is defined as $Q = q(z,t)/\Delta x_s$, where Δx_s is the grid width at the source position and q is the flux density of a non-zero value only at the source and gradually increases during the first three wave periods at the start of wave generation (Brorsen and Larsen, 1987). This is expressed by

$$q(z,t) = \begin{cases} \left\{1 - \exp\left(-\frac{2t}{T_i}\right)\right\} 2U_0 \frac{\eta_0 + h}{\eta_s + h}; & t/T_i \le 3 \\ 2U_0 \frac{\eta_0 + h}{\eta_s + h}; & t/T_i > 3 \end{cases} \tag{3}$$