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Numerical investigation of the interaction between an inverse T-type fixed/floating breakwater and regular/irregular waves

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ABSTRACT

This paper presents a numerical analysis of nonlinear interaction between inverse T-type free surface breakwater and regular/irregular waves using a zonal hybrid RANS/laminar method based on an improved mesh updating strategy, which divides the whole computation domain into several parts to avoid low quality mesh elements caused by the large-scale movement. Each mesh zone is specified with different degrees of motion freedom. In the stationary zone where the flow is less influenced by the body motion, the flow is assumed to be laminar to avoid energy loss during the wave propagation. The RANS turbulence model applies only to the moving zones that move with specified motion components (sway/heave/pitch). The zonal hybrid RANS/laminar method is validated by comparison with the experimental data measured under a regular wave with period $T_w = 1.0$ s and amplitude $A = 0.0192$ m. The simulated motion responses, especially the sway motion amplitudes, of the floating breakwater are agree well with the experimental measurements. The motion responses and the energy-dissipating performances of the fixed/floating inverse T-type-type breakwater under regular/irregular waves are further investigated.

1. Introduction

The interaction between waves and free surface breakwaters has been extensively studied in the past two decades (Losada et al., 1996; Neelamani and Wave, 2002a, b; Li and Lin, 2012; Lara et al., 2012). Compared with submerged breakwaters, the free surface breakwater is located near the free surface where the water particle amplitudes and velocities are maximized. The barriers are connected to the sea bottom by pile/jacket structures (fixed breakwaters) or mooring cables (floating breakwaters) (Teh, 2013). Generally, fixed breakwaters perform better but cost much more than floating breakwaters. Koutandos et al. compared the hydrodynamic behaviour of the fixed and the heave motion breakwater using a Boussinesq Model. In their study, the hydrodynamic components of the pressure on the fixed breakwater are much higher than the floating breakwater, though the mean vertical force is in the same range (Koutandos et al., 2004, 2005). Shao and Gotoh simulated the interaction between progressive waves and a floating (or fixed) curtain-wall type breakwater using the SPH-LES model. The wave dissipation efficiency of the fixed curtain wall is observed to be four times higher than the floating one, while the horizontal mooring force acting on the floating curtain wall is only 10% of the fixed one (Shao and Gotoh, 2004). Furthermore, for pneumatic breakwaters, a floating breakwater follows the vertical motion of the incident waves, such that the resulting volume-change pneumatic damping effect is less significant compared with the fixed barrier (Koo et al., 2006).

The inverse T(⊥)-type breakwater is the most common free surface breakwaters. Usually, wave energy can be dissipated effectively by the wave breaking over the top of the horizontal plates (Patarapanich, 1984; Koutandos et al., 2005) or the wave reflection due to vertical plates (Reddy and Neelamani, 1992). Neelamani and Rajendran combined a horizontal plate and a vertical plate into a T-type or a ⊥-type (or written as inverse T-type) fixed free surface breakwater with the addition of wave breaking and reflection (Neelamani and Wave, 2002a, 2002b). Later, wave interaction with a ⊥-type floating breakwater has been investigated by Zhao and Hu using a constrained interpolation profile (CIP) -based Cartesian grid method (Zhao et al., 2012). Numerous types of free surface breakwaters have been proposed in the past (Koraim, 2013), and they are reviewed and classified into four categories: solid-type, plate-type, caisson-type and multipart-type (Teh, 2013). Both T-type breakwater and ⊥-type breakwaters are plate-type breakwaters. Compared with the other types of the free surface breakwaters, the plate-type breakwater has no advantage in wave attenuation and wave reflection. However, because of its low cost, it is still widely used in engineering.

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Numerous laboratory experiments have been carried out to investigate the interaction between waves and free surface structures, e.g., fixed plate-type breakwaters (Neelamani and Wave, 2002a, b), fixed U-type breakwaters (Günaydına and Kabdaşlı, 2004), heave motion solid-type breakwaters (Koutandos et al., 2005; Alizadeh et al., 2014), and free motion ⊥-type breakwaters with spring constraints in the horizontal direction (Changhong and Kashiwagi, 2009). Based on the laboratory measurements, numerical methods have been widely used to understand the nonlinear interaction between waves and floating structures in the past decades. There are two difficulties when simulating the flow dynamics around the free surface floating body. The primary difficulty is the free surface tracking, and the secondary difficulty lies in how to capture the moving body.

Compared with the submerged breakwater, the free surface breakwater allows water circulation beneath the structures, and the wave transmission, reflection and dissipation characteristics of fixed/floating free surface breakwaters are influenced by the complex turbulent flow around the breakwater.

The fully nonlinear potential theory (FNPT) model, based on the potential theory, has been improved to investigate the two-way fully nonlinear interactions of waves with a submerged horizontal cylinder (Guerber et al., 2012). Nevertheless, the convection potential flow method assumes an irrotational flow and cannot handle the complex nonlinear free surface deformation (Guyenne and Grilli, 2006; Yan and Ma, 2007). Improved numerical methods are proposed to solve the nonlinear Naiver-Stokes equations, and the free surface is modeled using a grid based method, e.g., Volume of Fraction (VOF), or the meshless method, e.g., Smooth Particle Hydrodynamics (SPH) (Monaghan, 1992).

Floating free surface breakwaters undergo large-scale motion under strong wave forces, and the floating body motion response makes it more complex to simulate the disturbed wave flow. Compared with the convectional grid based method, the meshless method has a comparative advantage in the fluid structure interaction (FSI) problem. However, the development of the meshless method is still in its infancy. Most of the widely used CFD (computational fluid dynamics) tools are based on the grid methods and solve the FSI problem using the dynamic mesh. Coupled with the popular turbulence model, RNG $k-\varepsilon$ model, a 2-D wave tank model is built to predict the wave impact on a fixed floating body (Li and Lin, 2012). For a floating body, a constrained interpolation profile (CIP)-based Cartesian grid method is further developed to model the nonlinear interactions between waves and a 2-D ⊥-type floating structure without the turbulence model (Zhao and Hu, 2012; Zhao et al., 2012). The simulated heave and pitch motion of the floating body are in good accordance with the experimental data, while the sway motion is not very well predicted (Zhao et al., 2012; Chen et al., 2016b). One disadvantage of the grid based method is that the large scale body movement may lead to the unexpected mesh distortion.

In this study, the interactions between a ⊥-type floating breakwater and regular/irregular waves are simulated using a zonal hybrid RANS/laminar method which is based on an improved mesh update method, which avoids mesh distortion due to the large-scale motion of the floating body. In this method, the whole computation domain is divided into several zones, and each zone follows different motion components (sway/heave/pitch) (X et al., 2016, Chen et al., 2016a, b). If the mesh zone is far from the moving body, flow in this zone is less affected by the moving body, and it is set up as a stationary zone. The turbulence model is turned off in the stationary zone to avoid the energy loss during wave propagating due to the low width-length ratio of computation cells near the free surface. The Scale Adaptive Simulation (SAS) turbulence model (Menter and Egorov, 2010) applies only to the moving zones, which are specified with different degrees of motion freedom. Interactions between the ⊥-type fixed/floating breakwater and regular/irregular waves are simulated, validated and compared.

2. Numerical method

2.1. Mathematical model.ing

Our attention is restricted to the two-dimension incompressible and viscous flow, which is governed by the continuity and momentum balance equations as follows,

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = 0, \tag{1}$$

$$\frac{\partial \rho\mathbf{u}}{\partial t} + \nabla\cdot(\rho\mathbf{u}\mathbf{u}) = -\nabla\cdot p + \nabla\cdot(\mu_{eff}(\nabla\mathbf{u} + \nabla\mathbf{u}^T)), \tag{2}$$

where ρ, p and $\mathbf{u}$ denote the fluid density, pressure and fluid velocity, respectively. Effective viscosity $\mu_{eff} = \mu + \mu_t$ is the sum of the molecular viscosity and the turbulent eddy viscosity. The governing equations are resolved under the Reynolds-averaged Navier-Stokes (RANS) framework. In the present study, the turbulence is modeled using the scale-adaptive simulation (SAS) model (Menter and Egorov, 2010), which is based on the Shear-stress transport (SST) model (Menter, 1994, 1996). The SST model has advantages of both $k-\omega$ model and $k-\varepsilon$ model. In the region away from the wall, it behaves like the $k-\varepsilon$ model. In the region near the wall, the advantage of the SST model lies in its ability to controls the level of turbulence viscosity. However, the SST model produces too large of length scales for transient problem such that it may overestimate the turbulent viscosity. To avoid this problem, the SAS model is developed to allow a more realistic flow field (Menter and Egorov, 2010). In the SAS model, the value of turbulent kinetic energy k and turbulent eddy frequency ω are resolved using the following transport equations:

$$\frac{\partial \rho k}{\partial t} + \nabla\cdot(\rho\mathbf{u}k) = \nabla\cdot[(\mu + \sigma_k\mu_t)\nabla k] + P_k - D_k, \tag{3}$$

$$\frac{\partial \rho\omega}{\partial t} + \nabla\cdot(\rho\mathbf{u}\omega) = \nabla\cdot[(\mu + \sigma_\omega\mu_t)\nabla\omega] + P_\omega - D_\omega + CD_{SST} + Q_{SAS}. \tag{4}$$

The turbulent viscosity is defined as

$$\mu_t = \frac{\alpha_1\rho k}{max(a_1\omega, SF_2)}, \tag{5}$$

where S is the magnitude of the shear strain rate, F_2 is the blending function, and the constant a_1=0.31, $beta' = 0.09$. The source term are calculated via

$$P_k = \mu_t\nabla\mathbf{u}\cdot(\nabla\mathbf{u} + \nabla\mathbf{u}^T), \qquad D_k = \beta'\rho k\omega \tag{6}$$

$$P_\omega = \frac{\alpha}{\nu_t}P_k, \quad D_\omega = \beta\rho\omega^2, \quad CD_{SST} = (1 - F_1)\frac{2\rho}{\sigma_{\omega 2}\omega}\nabla k\cdot\nabla\omega. \tag{7}$$

The value of the blending function, F_1 and F_2, are approximately constant in the near wall region, and tends to be zero further away from the wall.

$$F_1 = \tanh(\arg_1^4),\ \arg_1{=}\min\left[\max\left(\frac{\sqrt{k}}{\beta\omega d_1}, \frac{500\mu}{\rho\omega d_1^2}\right), \frac{4\rho\sigma_{\omega 2}k}{CD_{SST}d_1^2}\right] \tag{8}$$

$$F_2 = \tanh(arg_2^4),\ \arg_2{=}\max\left(2\frac{\sqrt{k}}{\rho\omega d_1}, \frac{500\mu}{\rho\omega d_1^2}\right). \tag{9}$$

The coefficients α, β, σ_k and σ_ω are calculated as follows:

$$C = F_1C_1 + (1 - F_1)C_2 \tag{11}$$

$$\alpha_1 = 0.556, \quad \beta_1 = 0.0750, \sigma_{k1} = 0.85, \sigma_{\omega 1} = 0.500 \tag{12}$$

$$\alpha_2 = 0.440, \quad \beta_2 = 0.0828, \sigma_{k2} = 1.00, \sigma_{\omega 2} = 0.856.$$

The source term Q_{SAS} in the ω-equation is specifically defined for the SAS model.