Available online at www.sciencedirect.com
ScienceDirect
Coastal Engineering 53 (2006) 799 – 815
Coastal Engineering
An International Journal for Coastal, Harbour and Offshore Engineers
www.elsevier.com/locate/coastaleng

Numerical modeling of dynamic responses and mooring forces of submerged floating breakwater

Md. Ataur Rahman, Norimi Mizutani *, Koji Kawasaki

Department of Civil Engineering, Nagoya University, Japan

Received 14 September 2005; received in revised form 22 December 2005; accepted 6 April 2006
Available online 26 May 2006

Abstract

Using the volume of fluid (VOF) method, a numerical model is developed to estimate the nonlinear dynamics of a pontoon type moored submerged breakwater under wave action and the forces acting on the mooring lines, for both the vertical and inclined mooring alignments. The model is developed for a two-dimensional wave field in a vertical plane. The finite displacements of the breakwater such as sway, heave and roll in a very small time step are considered and the numerical grid cells intersected by the breakwater surfaces for changing its position due to wave action are treated using the concept of porous body model. Also, two-dimensional experimental studies are carried out to investigate the performance of the proposed model. The comparison of the computed and measured results reveals that the developed numerical model can reproduce well the dynamics of the floating body and the mooring line forces.

Keywords: Motion response; Mooring force; Submerged floating breakwater; VOF method; Porous body model

1. Introduction

In recent years, the floating breakwater has received wide attention as the concept offers the potential of a less expensive alternative to traditional breakwaters. The knowledge of the forces acting on the breakwater and its mooring lines is required for its structural design. Due to the time varying nature of the environmental loading, such as wind, waves, currents, etc., a dynamic analysis is often required to compute these forces. Dynamic analysis also includes the evaluation of the motion responses of the floating body, such as sway, heave, roll, etc., and the mooring line forces.

Most of the dynamic studies of floating structures are done based on potential flow theory in the frequency domain. The motions of the floating body are assumed to be small so that the body boundary conditions are satisfied very close to the equilibrium position of the body. This is one of the important limitations of these kinds of models when it needs to simulate large-scale motions of the floating body. Moreover, in the frequency domain analysis based on the potential flow theory, the flow is assumed to be irrotational. The dynamic analysis in the frequency domain neglects the transient effects and concentrates on steady-state solution. It cannot simulate the biharmonic or subharmonic motion of the floating body. But from the studies of floating body motion analysis, it is found that there occurs rotational motion as well as vortex forms around the structure during its interaction with waves. This is another important limitation of using potential flow theory in frequency domain.

Various aspects of two and three dimensional problems of wave interaction with submerged, bottom founded, or floating surface-piercing structures have been studied both numerically and experimentally by many investigators. Lau et al. (1990) solved the three-dimensional problem of the dynamics of a moored floating object under the action of regular waves numerically as a boundary value problem by the use of the infinite element method. Sen (1993) developed a numerical method to simulate the motions of two-dimensional floating

* Corresponding author. Fax: +81 52 789 1665.
E-mail addresses: ataur91@yahoo.com (M.A. Rahman), mizutani@civil.nagoya-u.ac.jp (N. Mizutani), kawasaki@civil.nagoya-u.ac.jp (K. Kawasaki).

0378-3839/$ - see front matter
doi:10.1016/j.coastaleng.2006.04.001

bodies. He proposed the basic algorithm based on a boundary integral formulation and time stepping of the nonlinear free surface constraints in an Eulerian frame of reference. Kawasaki (1999) proposed a numerical model to simulate wave deformation including wave breaking based on a SOLA-VOF code using the VOF technique, which was originally developed by Hirt and Nichols (1981). He developed this method to include a wave generation source method and an added dissipation zone method (Hinatsu, 1992) so that the characteristics of wave breaking due to a submerged breakwater and post-breaking wave deformation can be simulated without the effects of reflected waves from both ends of computational domain and wave generation boundary. Shirakura et al. (2000) developed a 3-D fully nonlinear wave tank to simulate floating bodies interacting with water waves. They used quadratic boundary element method (QBEM) to solve the velocity field and acceleration field taking into account the interaction between the fluid and the floating body motions. Agarwal and Jain (2003a,b) studied the nonlinear coupled dynamic response of offshore spar platforms under regular sea waves. They used a unidirectional regular wave model for computing the incident wave kinematics by Airy's wave theory and forces by Morison's equation. Seah and Yeung (2003) studied the sway and roll hydrodynamics of cylindrical sections. They applied the free-surface random-vortex method (FSRVM) to investigate two types of forced motion problems with the inclusion of viscous effects. Hur and Mizutani (2003) have developed a numerical model, which combine the VOF model and porous body model, to estimate the wave forces acting on a three-dimensional body on a submerged breakwater. They examined wave induced deformation on the permeable submerged structure making use of the porous body model (Sakakiyama and Kajima, 1992) to express the governing equations of fluid motion. In the porous body model, a numerical mesh cell, which is partially occupied by the structure material and partially by fluid and/or air, is treated as porous cell. They have shown two-dimensional numerical evaluation to give good estimation of the wave force associated with the Morison equation. They concluded that the wave force can be calculated by integration of the pressure on the whole surface of the structure obtained by the numerical computation without any empirical coefficients like the drag and inertia coefficients.

The accurate prediction of wave-induced motions of floating structures and the hydrodynamic forces acting on the structure and on its mooring lines are one of the main concerns of coastal and ocean engineering. To predict these motions and forces, a two-dimensional numerical model is proposed here that combines the VOF method and the concept of porous body model to simulate the nonlinear wave deformation including wave breaking. The model can also predict the displacements of the floating body due to wave action. A rectangular shaped pontoon type submerged floating breakwater supported by mooring chain is considered in the model. The SOLA scheme is employed to calculate the pressure and velocities at each time step and the added dissipation zone method is adopted to treat the open boundary (see Sections 2.1 and 2.3). The numerical domain cells cut by the breakwater surfaces, due to its oscillation under wave action, are treated as partially obstacle cells and are solved through the concept of porous body model. The nonlinear phenomena of the wave–breakwater interaction are solved using continuity equation, Navier–Stokes equation and the advection equation of VOF function that represents the fractional volume of fluid in a cell. The dynamics of the floating body and the forces acting on its mooring lines are solved using the equations of motion. The present two-dimensional numerical model developed in this study overcomes the limitations of earlier models, which are developed based on potential flow theory. In this proposed numerical model, the whole numerical domain is divided into uniform size meshes of very small dimensions in both horizontal and vertical directions. The dynamic analysis is done in the time domain by step technique, in which case the transient effects as well as nonlinearities are considered. All of the nonlinear parameters are calculated in each cell using the coupled SOLA-VOF and porous body model. The boundary conditions at the structure surfaces are applied at every time step and it changes with the dynamic interaction between the body and waves. For this reason, it can simulate large-scale motions of the floating body. On the other hand, it can simulate the rotational motion of the flow. So the vortex generated during the interaction can be estimated using this model. It should be noted that the turbulence modelling is not applied in this study. The conventional turbulence models have been chiefly developed for unidirectional internal turbulent flows, while the breaking wave induced turbulence is introduced from the free surface boundary in an oscillatory flow field. Therefore, it is difficult to find a turbulence model that can appropriately reproduce the energy dissipation in the wave breaking process and to give proper boundary conditions for it. The model is capable of simulating both the regular and irregular wave interaction with the body. The simulation for irregular waves is not shown in this paper.

Also, two-dimensional experimental studies are carried out in the laboratory to confirm the validity of the displacements of the body, mooring forces, etc. estimated by the developed numerical model. The details of the numerical and experimental studies are presented in this paper.

2. Numerical model

2.1. Governing equations

2.1.1. Adaptation of porous body model and coupling with VOF

As the floating body oscillates due to the wave action, the position of the floating body always changes. In Fig. 1, different kinds of the numerical domain cells, which develop during the oscillation of the floating body due to wave action, are shown. If the floating body remains fixed in its position against the wave action, four different kinds of cells are obtained: a full cell filled with fluid, an empty cell occupied by air, a surface cell containing both fluid and air, and an