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Three-Dimensional, Fully Nonlinear, Combined Eulerian-Lagrangian Numerical Model of Porous Media and Water Waves Interaction

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ABSTRACT

This study proposes a numerical, nonlinear wave model for a 3-dimensional wave field, which can evaluate Lagrangian and Eulerian wave-induced flows and wave deformations around and inside a permeable structure. To achieve stable computations, the model combines a VOF method with a nonreflective wave generator, in addition to the open-boundary treatment based on an added dissipation zone. Also, a numerical scheme is developed to convert the Eulerian velocity into Lagrangian velocity. A laboratory measurement for a rectangular offshore structure including wave-induced flow and wave height distribution was also conducted to investigate the validity of the numerical model. It has been found that the numerical model predicts the wave deformation well, providing a reasonable estimate of the wave-induced flow around the porous media. Also studied further are the effects of media properties, wave specifications and structure length on wave-induced flow, water particle movement and wave deformation. It is concluded that wave period and porosity of structure affect the characteristics of wave-induced flow more than other parameters. Also, a return flow can be seen inside the structure depending on the ratio of structure width to wavelength.

INTRODUCTION

The accurate prediction and estimation of the reflection, transition and deformation of water waves and their interaction with structures are important for design purposes of porous breakwaters like rubble-mound breakwaters in ports and coastal areas.

It is well known that microorganisms live on the surface of the rubble in rubble-mound breakwaters and form biofilm. This biofilm is also understood to contribute to the natural purification of water by biological processes. Thus, the porous structure is expected to have a water purification function due to the microorganisms living in it. Because the sea area inside the basin of a port is usually a semi-closed area, water exchange is not active, and because a river or canal commonly flows into the port, thus transferring nutrients into the basin, water quality is generally not satisfactory in ports.

Recently, coastal and port structures have been expected to have functions besides the wave-controlling ones. Considering the facts mentioned above, a structure such as a perforated caisson breakwater filled with rubble should be a suitable structure for both wave-controlling and water-purification functions. Because the flow inside the structure may affect significantly the function of microorganisms, this flow and its mechanism should be investigated in detail.

Most of the existing research dealing with the interaction of wave and permeable structure focuses on wave deformation. Sollitt and Cross (1972) studied the interaction between linear waves and a porous vertical breakwater. Madsen (1974) simplified their theory for the long-wave condition to decrease the computation time. Both these methods, however, ignore the nonlinear wave deformation and probable occurrence of non-Darcy flow due to the existence of turbulent flow in a permeable structure. Several 2-dimensional numerical models have been developed in this regard by now. Hannoura and McCorquodale (1985) developed a numerical model for the simulation of wave motion in rubble-mound breakwaters in order to check the dynamic stability of the seaward slope under wave attack. They used the modified Navier-Stokes equations for flow in a porous medium, and laboratory records of the wave pressure as a boundary condition for the numerical model. Losada et al. (1998) investigated the wave-induced mean flow in a vertical rubble-mound structure using linearized porous flow equations and second-order waves.

Because most marine structures are constructed in shallow-water regions of seas, the consideration of nonlinear interaction appears necessary. Losada et al. (1995) conducted some experiments to study the wave-induced flow in a porous structure, and they reported that the linearized porous flow equations are not valid in the case of flow inside a structure with considerable porosity.

Regarding the nonlinear models, Sakakiyama et al. (1992) proposed the porous body model for the numerical simulation of nonlinear waves interacting with permeable breakwaters using the finite difference method. Mizutani et al. (1996) developed modified Navier-Stokes equations for flow in a porous medium by comparing the resistance terms in the Navier-Stokes equations with those of Morison-type equations; they proposed a combined BEM-FEM model. This model was developed by Mostafa et al. (1999) to study the nonlinear interactions among waves, composite breakwaters and seabed foundations. However, that model cannot cope with the case of a free surface-piercing porous structure. Further, the model assumes irrotational motion outside the structure, although the vortex at the corner of the structure may be important for the overall flow pattern around the structure in the 3-dimensional case. Van Gent et al. (1995) studied the wave deformation due to a permeable submerged breakwater using a computational procedure, which combined the VOF method with a porous media flow model. This model can be used to deal with 2-dimensional cases and some phenomena which affect

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KEY WORDS: Wave-structure interaction, porous flow, nonlinear wave model, combined Eulerian-Lagrangian numerical model, VOF method, porous body model.