International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 17, No. 2, June 2007, pp. 97–104

Numerical Investigation of Seabed Response Under Waves with Free-surface Water Flow

Xiaofeng Liu and Marcelo H. García
Ven Te Chow Hydrosystems Laboratory, Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

Seabed response caused by waves is investigated numerically with a 3-dimensional coupled solver of fluid flow and consolidation. The free surface is modeled by the Volume of Fluid (VOF) method, and the water wave is generated by the numerical wave maker boundary condition. An iterative numerical scheme is proposed to solve the Biot consolidation equation using the finite volume method (FVM). The coupling between water wave and seabed is through stress and continuity condition on common boundaries. The numerical test shows good agreement with the analytical solution. A 3-D application of seabed response under waves with the presence of the object is also carried out. The current model can also be used at the onset of piping scour.

INTRODUCTION

Liquefaction is one of the most important causes of structure failure. Liquefaction can be caused by either earthquake or waves. Seabed response under waves is very important for the understanding of the liquefaction process, and it is investigated in this paper. In order to understand the process of wave-caused liquefaction, the wave-seabed-structure interaction should be considered; this interaction is important for geotechnical engineers designing offshore engineering projects, such as pipelines, piles and breakwaters. The sinking/floating of objects on the seabed, such as wrecked ships and mines, is also closely related to the seabed response under waves. Many experiments (Sakai et al., 1994; Sumer et al., 1999) and numerical simulations (Magda, 1996; Jeng and Lin, 1999; Gao et al., 2003) have been done to try to understand this complicated process. In addition, many analytical models describe the seabed response and give fairly good results (Yamamoto, 1977; Mei and Foda, 1981; Jeng and Hsu, 1996; Yuhi and Ishida, 2002).

Many numerical models have been developed to solve seabed response under waves, but most of them just assume the wave pressure on the water-bed interface using wave theory (e.g. Jeng and Lin, 1999; Dunn et al., 2006). This is applicable as a 1st-order approximation for many cases if there is only water wave and seabed interaction, but when there is an extra object in the system (such as pile, semi-buried foundation, etc.), the water flow around the object will be highly 3-dimensional, and it is not easy to get an analytical solution from wave theory. Multi-physics numerical models have been widely used to solve a coupled system. The approach in these models is to solve different governing equations on different domains, and to couple the system through a common boundary. This is also the approach used in this paper. To predict the free-surface wave field, 3-D computational fluid dynamics (CFD) models are used. The Volume of Fluid (VOF) method is a popular choice for the free-wave surface (e.g. Lin and Liu, 1998, and Liu et al., 2005). The results from the wave field can be used as a boundary condition for the seabed governing equations. The coupling between wave field and seabed in this paper is a one-way coupling, as the wave is not damped by the porous media. Karunarathna and Lin (2006) studied the wave damping over the porous seabed by modeling the porous media with the spatially averaged Navier-Stokes equation. For 2-way coupling, the boundary condition on the seabed for the fluid solver part should be modified.

The Biot consolidation equations used in this paper to describe the seabed response are traditionally solved via the finite element method (FEM), the most widely used method in stress analysis. But the finite volume method (FVM) is gaining popularity in this area because it is good at treating complicated, coupled and nonlinear differential equations (Jasak and Weller, 2000). Application of FVM in stress analysis can be found in Demidžić et al. (1994, 1997), among many others. An iterative scheme for the Biot consolidation equation using FVM is proposed in this paper. Momentary liquefaction potential due to waves is assessed based on the numerical result of consolidation.

This paper is structured as follows. Governing equations of the coupled system are described first. Then the numerical schemes used in this paper are discussed. Numerical verification and application of the current model are provided. Discussion and conclusion follow.

GOVERNING EQUATIONS

Fig. 1 shows a typical experiment setup for seabed response under waves. Governing equations in different parts of the domain (seabed domain and fluid domain) are listed below. The seabed response is governed by Biot consolidation equations. The fluid flow is governed by Navier-Stokes equations with the k-ε turbulence model.

Biot Consolidation Equations

The governing equation for the poro-elastic seabed 2-phase media is the Biot consolidation equation (Biot, 1941):

$$G\nabla^2\mathbf{v} + \frac{G}{1-2\nu}\nabla(\nabla\cdot\mathbf{v}) = \nabla p \tag{1}$$

$$\frac{k}{\gamma}\nabla^2 p = \frac{n}{K'}\frac{\partial p}{\partial t} + \frac{\partial}{\partial t}(\nabla\cdot\mathbf{v}) \tag{2}$$

Received September 25, 2006; revised manuscript received by the editors January 10, 2007. The original version (prior to the final revised manuscript) was presented at the 7th (2006) ISOPE Pacific/Asia Offshore Mechanics Symposium (ISOPE PACOMS-2006), Dalian, China, September 17–21, 2006.
KEY WORDS: Seabed, wave, consolidation, free surface, CFD, fluid structure interaction, liquefaction.