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Numerical simulation of earthquake excited dam-reservoirs with irregular geometries using an immersed boundary method

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ABSTRACT

In this work, a ghost-cell immersed boundary method is proposed for the hydrodynamic response of earthquake excited dam-reservoirs. The numerical method employs a second order accurate two-step projection algorithm including compressibility effects in pressure field due to earthquake. The effects of reservoir bottom absorption are treated by introducing damping terms into the momentum equations. Hydrodynamic response of earthquake excited dam with a sloping face is simulated to demonstrate the accuracy of the present numerical method. Numerical results compared with previous numerical and analytical solutions show that the present immersed boundary method can accurately compute the hydrodynamic forces on inclined and curved dam faces including the effects of water compressibility and reservoir bottom absorption for the possibility of resonance. The proposed numerical method was shown to have significant advantages in computational time and memory usage for the hydrodynamic simulation of large dam-reservoirs with arbitrary geometries. Hydrodynamic forces on a double curvature arch dam subjected to real earthquake induced ground motion are also simulated to demonstrate the capability of the method.

1. Introduction

Prediction of hydrodynamic effects that occur on dam faces during earthquake is an important issue for a dam designer. There can be a significant change in pressure field near the dam body due to compressibility effects during the earthquake. The first rigorous analysis in earthquake excited dam-reservoir problem was reported by Westergaard [1] neglecting compressibility effects. Chopra [2] presented analytical formulas for hydrodynamic response of dam-reservoirs subjected to harmonic and arbitrary ground motions including compressibility effects. Aydin and Demirel [3] reported that the acoustic pressure equation solution gives satisfactory results for the pressure field unless the contributions from the free-surface waves become significant at low reservoir depths. These studies are based on the idealized dam-reservoir geometry assumption with vertical dam face and horizontal reservoir bottom.

Analytical studies are available in the literature for hydrodynamic response of dam-reservoirs with various reservoir shapes. Chwang and Housner [4] proposed momentum balance method and exact method [5] based on two-dimensional potential flow theory to determine hydrodynamic pressures and forces on sloping dams. They reported that their solution gives the same result with Westergaard's solution for the vertical dam face. Liu [6] suggested analytical solutions for the onset hydrodynamic pressures acting on the surface of a rigid dam for the cases where the inclined upstream dam face has a constant slope and the reservoir has a triangular shape and reported that analytical results are in good agreement with experimental data of Zangar [7]. Compressibility effects are important in dam-reservoir analysis when the excitation frequency is near the value of natural frequency of the reservoir [2,3]. Tsai [8] presented a semi-analytical solution for hydrodynamic pressures on dams with arbitrary upstream face considering water compressibility effects. Aviles and Li [9] developed an analytical-numerical solution for hydrodynamic pressures on rigid dams with non-vertical upstream faces including the effects of both compressibility and viscosity of water. Analytical solutions developed for earthquake excited dam-reservoirs are valid for specified dam-reservoir geometries such as triangular reservoir geometry and constant sloped dam face.

Numerical studies are available in the literature [10–12] for the hydrodynamic analysis of earthquake excited dam-reservoirs with inclined and curved dam faces. These studies use boundary mapping techniques which may reduce the accuracy of the numerical solution near the complex boundaries. Therefore, an accurate and efficient numerical model is needed for the hydrodynamic response of earthquake excited dam-reservoirs with complex boundaries including the effects of water compressibility and reservoir bottom absorption due to earthquake shocks.

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Accurate computation of hydrodynamic response of large bodies with complex geometries is a challenging problem in engineering. The first possible choice is to adopt boundary-fitted or unstructured grids for the treatment of complex boundaries. Numerical solutions of governing equations on boundary-fitted and unstructured grids require high computational memory and time. However, finite volume discretization of governing equations on boundary conforming grids is more complicated to solve flow equations than the standard discretization schemes based on rectangular grids. Meshing of the computational domain is in general cumbersome and time consuming for boundary conforming grids. However, as the solid body moves and the free-surface deforms rapidly, boundary conforming grid must be regenerated at every time step in a boundary-fitted method which requires extra amount of CPU time. Accurate computation of nonlinear interaction of water and structures with complex geometries on structured grid is possible with the development in cut cell methods and immersed boundary methods (IBMs) in recent years. Numerical discretization scheme is modified in cut-cells due to irregular shapes of cells near the solid boundaries. In the IBMs, an external force field is added to the Navier–Stokes equations on the immersed boundary cells to impose no-slip boundary conditions. Temporal discretization of the governing equations remains unchanged near the irregular solid boundaries in IBMs.

IBMs are classified in two categories named as ‘continuous forcing’ [13,14] and ‘discrete forcing’ methods [15–17] depending on whether the forcing terms will be applied before the discretization of governing equations or not. Interpolation of forcing terms in immersed boundary points is a major issue in IBMs. Many different techniques have been developed to interpolate the velocities on the forcing points depending on the internal treatment of the solid body. Fadlun et al. [15] have discussed several methods for the flow conditions inside the solid body and they concluded that the external flow is independent of the internal conditions. The first possible choice is to leave the interior of the body free to develop a flow. In this approach, momentum and pressure equations are solved for all computational nodes including internal points and there is no need to apply a pressure boundary condition on the point of interest which is close to an immersed boundary. In this category, Balaras [16] developed a second order accurate IBM based on the interpolation of velocities on the immersed boundary points from the nearby velocities along the interface normal. The second approach, so-called ghost-cell IBMs, consists of solving momentum equations for only fluid points [17]. A pressure boundary condition is applied at the irregular cells in this approach since momentum equations and pressure equation are not solved inside the solid body [18].

This paper describes the implementation of IBM using discrete forcing concept to compute the hydrodynamic forces on earthquake excited dams with arbitrary geometries. A well-known ghost-cell IBM is modified by the introduction of acoustic velocity definition in order to include the compressibility effects due to earthquake shocks. Reservoir bottom absorption effects are simulated by using a numerical method proposed in this study. The numerical method and computer code are used to determine the hydrodynamic behavior of earthquake excited dam-reservoirs with different geometries for both incompressible and compressible cases. To demonstrate the applicability of the numerical method for the cases in which the compressibility and absorption effects are prominent, hydrodynamic response of a dam-reservoir system is also presented for the resonance case. To the best of author's knowledge, it has not been implemented an IBM to the hydrodynamic simulation of earthquake excited dam-reservoirs including the effects of water compressibility and reservoir bottom absorption due to earthquake shocks.

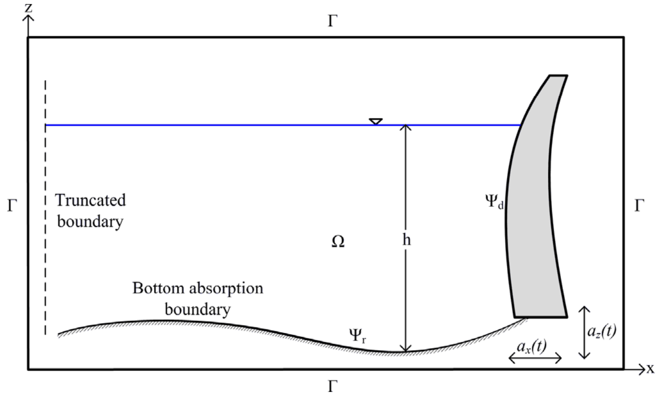

Fig. 1. Definition sketch of the dam-reservoir system subjected to earthquake.

2. Governing equations

In this study, a two-dimensional dam-reservoir system subjected to horizontal and vertical ground accelerations is considered as shown in Fig. 1. The Navier-Stokes equations are written for two-dimensional flows in the reservoir

$$\rho\left(\frac{\partial(u+u_0)}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{1}$$

$$\rho\left(\frac{\partial(w+w_0)}{\partial t}+u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}\right)=-\rho g-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{2}$$

where u and w are horizontal and vertical velocity components in x and z space coordinates, respectively, t is time, p is pressure, ρ is density, μ is viscosity, u_0 and w_0 are horizontal and vertical ground velocities during earthquake, respectively. Ground velocities are included in the momentum equations to represent earthquake excitations assuming that the computational domain and the coordinate system are moved with the ground. The spatial derivatives of density in compressible continuity equation are negligible in dam-reservoir hydrodynamics [3], finally an equation of state is applied to represent the density variations with pressure through the definition of acoustic velocity

$$-\frac{1}{\rho a^2}\frac{\partial p}{\partial t}=\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z} \tag{3}$$

where a (=1438 m/s) is acoustic velocity in water. Dam body is assumed to be rigid throughout this study and reservoir bottom absorption effects are considered using a novel numerical method which will be described in Section 3.3.2.

3. Numerical solution

3.1. Finite volume discretization of governing equations

A two-step projection method is used for the numerical solution of the governing equations [19]. The numerical method is a two-step time splitting and a fully explicit method. In two-step time splitting numerical scheme first a tentative velocity field, which is not divergence-free, can be obtained for the fluid domain Ω

$$\frac{u^*-u^n}{\Delta t}=\frac{3}{2}H(u^n)-\frac{1}{2}H(u^{n-1})+\frac{1}{\rho}\frac{\partial p^n}{\partial x}-a_x^{n+1}+f_x^{n+1} \tag{4}$$

$$\frac{w^*-w^n}{\Delta t}=\frac{3}{2}H(w^n)-\frac{1}{2}H(w^{n-1})+\frac{1}{\rho}\frac{\partial p^n}{\partial z}-a_z^{n+1}+f_z^{n+1} \tag{5}$$

where u^* and w^* are the tentative velocities, Δt is time step, a_x^{n+1} and a_z^{n+1} are horizontal and vertical ground accelerations at $n+1$ time level, H is spatial operator containing the convective, diffusive