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Effects of multilayered porous sediment on earthquake-induced hydrodynamic response in reservoir

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ABSTRACT

Sediment in a reservoir can be inhomogeneous and layered due to the natural sedimentation process, which highly complexes the hydrodynamic response in the reservoir. Based on an extended transmission and reflection matrix (TRM) method developed in this study, an analytical solution to hydrodynamic response of a water-multilayered porous sediment-bedrock system due to SV wave incident from the bedrock is presented. The uniqueness of the method is that it not only can well accommodate porous sediment with multiple layers, but also is convenient to implement compared to global matrix method. Thus the method is able to reasonably reflect the effects of sediment heterogeneity. The analytical solution is effectively verified against the solution proposed by Wang et al. [28]. Comprehensive parametric study is conducted to investigate the effects of sediment heterogeneity and wave characteristics on the hydrodynamic response in reservoir. Resonant frequencies exist and change with incident angle. Sediment heterogeneity highly influences the hydrodynamic response of the system, especially when the sediment is unsaturated. For sediment with relatively low degree of saturation, the sediment heterogeneity in terms of consolidation level significantly affects the hydrodynamic response at higher order resonant frequencies. Sediment can be divided into numerous layers to reflect the sediment heterogeneity with depth. With the increase of frequency, the needed layer number to precisely describe the sediment heterogeneity increases.

1. Introduction

Hydrodynamic pressure acting on dam face during an earthquake is one of the most important issues in earthquake-resistant design of a dam and has been extensively studied in the past half century [1–4]. The developed hydrodynamic force acting on the dam is highly dependent on physical characteristics of boundaries surrounding the reservoir. Sediment deposition generally exists in reservoirs and has been reported all around the world [5]. Sediment not only considerably reduces reservoir capacity, but also significantly affects seismic response of the dam since the sediment absorbs partial energy of hydrodynamic waves (e.g., [6–8]) and the pore water in the sediment also highly influences the hydrodynamic response (e.g., [9]). Therefore, it is essential to study the effects of sediment on earthquake-induced hydrodynamic response in reservoirs.

Chopra and his co-workers (e.g., [6,10,11]), Lotfi et al. [7], Medina et al. [8], Zhao [12], and Hatami [13] were the pioneers to study the effects of sediment on hydrodynamic response. The sediment was idealized as homogeneous elastic or viscoelastic material. The effects of bottom absorption in reservoir on hydrodynamic response of gravity dams to earthquakes have been investigated through different numerical methods, such as finite element method [6,7,10,11], boundary element method [8] and coupled method of finite and infinite elements [12]. Zhao [12] and Hatami [13] investigated the effects of thickness, wave attenuation in the sediment layer, and reflection of waves from the underlying bedrock. Hatami [13] found that excluding the effect of reflected waves from the underlying rock may significantly underestimate the seismic response of the dam.

Idealizing sediment as an elastic or a viscoelastic solid is a simplifying assumption. In fact, sediment is fully or partially saturated, the latter scenario is due to the presence of gases. The theory of wave propagation in porous media was developed by Biot [14,15] and has been the basis of the subsequent work on the dynamic problem of porous media. Cheng [9] was the first to treat reservoir sediment as a two-phase poroelastic medium, and investigated the response of a water-sediment-bedrock system subjected to vertical excitations. The one-dimensional analysis revealed that partially saturated sediment decreases fundamental frequency of the system, and can largely

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increase the maximum hydrodynamic pressure. Further studies of 2D gravity dam-reservoir-sediment interactions were accomplished by Bougacha and Tassoulas [16–19], Chen and Hung [5], Dominguez et al. [20], Du et al. [21], Zhang et al. [22] and Aznarez et al. [23]. Maeso et al. [24], Garcia et al. [25,26] also studied the effects of sediment properties on the dynamic response of arch dams. The results indicated that the effects of sediment on hydrodynamic response of a gravity dam highly depend on compressibility and degree of saturation of the sediment. Wang et al. [27,28] theoretically investigated dynamic coupling of an ideal fluid-porous medium-elastic solid system subjected to SV wave or P wave incidence. The results of the five papers showed that the properties of porous sediment significantly influence the hydrodynamic pressure. It is noteworthy that almost all the sediments were modeled as homogeneous poroelastic medium in the above researches.

In fact, sedimentation in reservoir is a complex process varying with sediment production rate, transportation, and deposition. During the sedimentation process, the sediments gradually consolidate and the density generally increases with depth (e.g., [23]). The permeability of the sediments can vary by more than tenfold [29]. Thus, sediment is generally an inhomogeneous material with properties varying with depth. Some efforts have been made to study the effects of layered sediment on the hydrodynamic response of reservoir using finite element method or boundary element method [e.g., 19,23,25,30,31]. To the best of our knowledge, no analytical solution can consider the effects of multilayered porous sediment on earthquake-induced hydrodynamic response in reservoir.

The objective of the present paper lies in two aspects. The first one is to develop an analytical solution to describe wave propagation in a coupling water-multilayered porous sediment-bedrock system due to incident SV wave caused by earthquake. The second one is to investigate the effects of sediment heterogeneity and wave characteristics on the hydrodynamic response in reservoir. The paper is organized as follows. First, the governing equations and general solutions for ideal compressible fluid, poroelastic sediment, and elastic solid are introduced in Section 2. The coupling water-multilayered porous sediment-bedrock system is described in Section 3, including continuity and boundary conditions, and the definitions of reflection and transmission coefficients. In Section 4, an extended TRM method for the coupling system is established. Afterwards, the method is verified using published analysis results in Section 5. Finally, the effects of sediment layering and wave characteristics are comprehensively investigated using the developed method.

2. Governing equations and general solutions

A water-multilayered porous sediment-bedrock system is shown in Fig. 1. Water in the reservoir is retained by a rigid dam. A SV wave is incident from the bottom bedrock and propagates in the multilayered porous sediment with N–2 layers, causing complex hydrodynamic response. θ_{in} is the incident angle. The origin of the coordinates is set at the free face of the top water layer and the z-axis points downward.

The sediment in each layer is assumed to be porous, isotropic and homogeneous. According to the Biot's theory [14], the constitutive equations are

$$\tau_{ij} = \left(\lambda + \frac{Q^2}{R}\right)\delta_{ij} e + 2\mu e_{ij} + Q\delta_{ij}\varepsilon \tag{1}$$

$$\tau = -\phi p = Qe + R\varepsilon \tag{2}$$

where $\tau_{ij} = -\sigma_{ij} - (1-\phi)p\delta_{ij}$ is the solid skeleton stress tensor; σ_{ij} is the effective stress tensor; δ_{ij} is the Kronecker delta; ϕ is the porosity; p is the pore pressure; $\lambda=Re(\lambda)(1+2i\xi)$ and $\mu=Re(\mu)(1+2i\xi)$, where ξ is the damping coefficient, and internal damping of the solid skeleton is introduced using a complex valued Lame constants; Q and R are the Biot constants; τ is the fluid equivalent stress; $e_{ij}=(u_{i,j}+u_{j,i})/2$ is the strain tensor of the solid phase, $\varepsilon_{ij}=(U_{i,j}+U_{j,i})/2$ is the strain tensor of the fluid phase, where u_i and U_i are the solid and fluid displacements, respectively; $e=e_{ii}$ and $\varepsilon=\varepsilon_{ii}$ are the dilatational strain of the solid phase and the fluid phase, respectively.

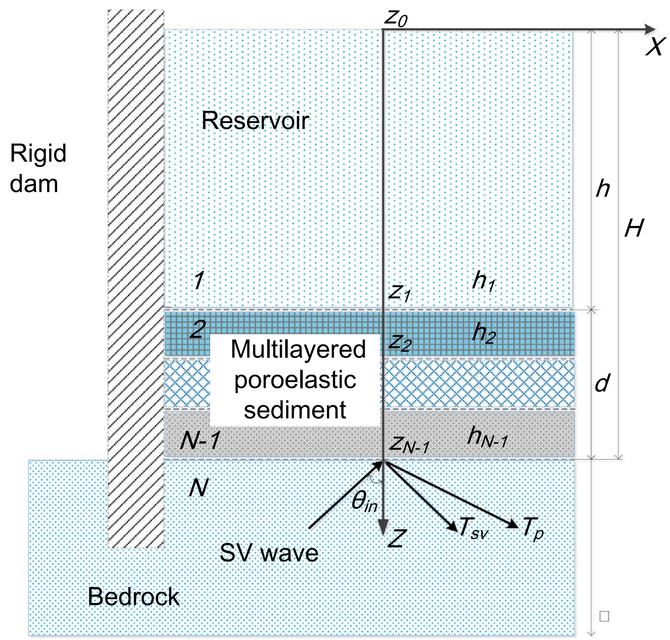

Fig. 1. Water-multilayered porous sediment-bedrock system.

The equilibrium equations in the frequency domain can be written as

$$-\frac{\partial \sigma_{ji}}{\partial x_j} - (1-\phi)\frac{\partial p}{\partial x_i} = -\omega^2(\hat{\rho}_{11}u_i + \hat{\rho}_{12}U_i) \tag{3}$$

$$-\phi\frac{\partial p}{\partial x_i} = -\omega^2(\hat{\rho}_{12}u_i + \hat{\rho}_{22}U_i) \tag{4}$$

where, for simplification, the dissipation terms have been included as part of complex valued densities as follow:

$$\hat{\rho}_{11} = \rho_{11} - ib/\omega;\quad \hat{\rho}_{12} = \rho_{12} + ib/\omega;\quad \hat{\rho}_{22} = \rho_{22} - ib/\omega \tag{5}$$

where $\rho_{11} = (1-\phi)\rho_s + \rho_a$; $\rho_{12} = -\rho_a$; $\rho_{22} = \phi\rho_f + \rho_a$; ρ_s is the solid density; ρ_f is the fluid density; ρ_a is the added apparent density; $\rho=(1-\phi)\rho_s+\phi\rho_f$ is the bulk density; $b=\rho g\phi^2/k$ is the dissipation constant, where k is the hydraulic permeability of the porous medium; ω is the angular wave frequency.

If solid grains are assumed to be incompressible, the Biot constants are given by Mei and Foda [32]; namely, $Q=(1-\phi)K'_f$ and $R=\phi K'_f$, where K'_f is the effective bulk modulus of pore fluid. For a fully saturated porous medium, $K'_f=K_f$, where $K_f=2.0736\times10^9$ N/m^2 is the bulk modulus of the pore water. For a partially saturated porous medium, K'_f is expressed as [33]

$$\frac{1}{K'_f} = \frac{1}{K_f} + \frac{1-S}{p_0} \tag{6}$$

where S is the degree of saturation of the sediment; p_O is the hydrostatic pressure.

Following the method of Jocker et al. [34], Eqs. (1)–(4) can also be expressed in the form of first-order ordinary differential ones in wavenumber-frequency (k_x, ω) domain:

$$\frac{d}{dz}\mathbf{f}(z) = \begin{pmatrix} \mathbf{0} & \mathbf{A}_1 \\ \mathbf{A}_2 & \mathbf{0} \end{pmatrix}\mathbf{f}(z) \tag{7}$$

where $\mathbf{f}(z)$ is the displacement-stress vector for the porous sediment,

$$\mathbf{f}(z) = [u_z, \zeta_z, \sigma_{zx}, \sigma_{zz}, p, u_x]^T \tag{8}$$