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Reflection and transmission of plane waves at an interface of water/multilayered porous sediment overlying solid substrate

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ABSTRACT

Researches in wave reflection and transmission at water-marine sediment interface have a long history and have received much attention during the past half-century in many scientific fields. A new stable reflectivity method is developed to solve the problem of wave propagation in coupling water-layered porous sediment-solid substrate system. The uniqueness of the method is that it not only has the advantage of traditional TRM method but also is able to accommodate numerous sediment layers with arbitrary thickness for wide range of wave frequency. The method proves to be able to well describe the wave propagation in the fluid-porous sediment-solid substrate system. The wave propagation is significantly influenced by the porous sediment layers, including thickness, layer number, arrangement and sediment properties. In the case of high wave frequency, even thin porous sediment leads to significant energy loss and the reflection coefficient mainly depends on the upper porous sediment layer. The influence of real shear modulus on reflection is substantial for low wave frequency, while the influence of permeability on reflection is significant for medium and high wave frequency. The reflection coefficient is extremely sensitive to the change in frequency within a certain frequency range.

1. Introduction

Researches in wave reflection and transmission at water-marine sediment interface have a long history and have received much attention during the past half-century in many scientific fields, such as marine seismology, geotechnical engineering, acoustics and geophysics (Hamilton, 1970; Bianco and Tommasi, 1995; Fokina and Fokin, 2000; Chotiros et al., 2002; Camin and Isakson, 2006; Madeo and Gavrilyuk, 2010; Zhang et al., 2012; Das and Bora, 2014; Lee and Shin, 2014). Properties of marine sediment have been recognized as a key factor in estimating reflection loss (Vidmar, 1980; Chapman, 1983; Hovem and Kristensen, 1992). Recent research shows that the porous sediment layer has a significant effect on the wave reflection in the overlying water (Wang et al., 2013).

Poroelasticity was first adopted by Biot (1941) to model the coupled deformation-diffusion phenomena of porous solid, and its dynamic effect was then comprehensively studied by Biot (1956a, b). Since then, porous sediment models have received much attention in modeling marine sediment and related research (e.g., Stoll and Kan, 1981; Wu et al., 1990; Santos et al., 1992; Yang, 1999; Williams, 2001; Williams et al., 2001; Denneman et al., 2002; Yang et al., 2002; Cui and Wang, 2003; Ohkawa et al., 2005; Dai and Kuang, 2008; Vashishth and Sharma, 2009; Madeo and Gavrilyuk, 2010). Stoll and Kan (1981), Wu et al. (1990), Santos et al. (1992), Denneman et al. (2002) and Madeo and Gavrilyuk (2010) studied the reflection and transmission of acoustic waves at a water-sediment interface, and the sediment was modeled as a porous medium on the basis of Biot theory. Williams et al. (2001), Yang et al. (2002) and Ohkawa et al. (2005) investigated wave scattering at a fluid/porous sediment interface. Williams (2001) presented a new acoustic propagation model that approximated porous medium as fluid, and the bulk modulus and effective density of the fluid were derived from Biot theory. Cui and Wang (2003) studied the squirt flow effect on reflection and transmission waves based on the Biot-squirt flow model. Dai and Kuang (2008) investigated wave reflection and transmission using a double porosity model.

In the above research, the sediment was modeled as a homogeneous poroelastic half-space. However, the sediment is generally inhomogeneous. For example, the permeability of marine sands can vary by more than tenfold (Davis, 1969). Therefore, great efforts have been made to study the reflection and transmission of acoustic waves in systems of water and inhomogeneous sediment (e.g., Hawker and Foreman, 1978; Holthusen and Vidmar, 1982; Bogy and Gracewski, 1984; Hovem and Kristensen, 1992; Kuo, 1992; Badiey et al., 1994; Ainslie, 1996; Vashishth and Khurana, 2004; Jackson et al., 2010; Wang et al., 2013). Holthusen and Vidmar (1982) investigated the effect of near-surface layering in marine sediment on the plane wave reflection

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coefficient. Kuo (1992) proposed an acoustic wave scattering model for a three-layer system consisting of a solid sediment layer sandwiched by a water half-space and solid substrate. Hawker and Foreman (1978), Ainslie (1996) and Jackson et al. (2010) studied plane wave reflection and transmission in a water-sediment system consisting of layered fluid or solid overlying a semi-infinite solid substrate. These work provides valuable basis for further research.

Transfer matrix method has been widely adopted to study reflection and transmission of plane waves. Bogy and Gracewski (1984) derived the plane wave reflection coefficient for a layered solid half-space based on transfer matrix method (Thomson, 1950; Haskell, 1953). Badiey et al. (1994) applied propagator matrix method for plane wave reflection from anisotropic poroelastic sediment overlying isotropic poroelastic half-space. Using the technique of transfer matrix, Vashishth and Khurana (2004) investigated wave propagation in multilayered anisotropic poroelastic medium sandwiched by a water half-space and solid substrate. Wang et al. (2013) studied reflection and transmission of plane waves at an ocean-floor interface, wherein a porous sediment layer was sandwiched between a homogeneous fluid above and a homogeneous solid substrate below. Lyu et al. (2014) extended the work of Wang et al. (2013) to a coupled fluid-porous sediment-double porosity substrate system. The method used by Wang et al. (2013) and Lyu et al. (2014) has also been applied to the problem of dynamic pressures of coupled fluid-porous sediment-solid substrate system due to P or SV wave incident from solid half-space (Wang et al., 2004; 2009). Generally, the transfer matrix approach (Bogy and Gracewski, 1984; Vashishth and Khurana, 2004) becomes unstable especially when either the overall thickness of the layer or the frequency of the waves becomes very high. An alternative approach (Brouard et al., 1995; Wang et al., 2013; Lyu et al., 2014) is to form a large global matrix, consisting of the general solutions for all the layers. It is very suitable for the cases with several layers (e.g., Wang et al., 2013). However, when there are numerous layers, this method is not only complex to establish the local-to-global mappings, but also rather time consuming because the memory requirement of the method is proportional to the number of layers (Jensen et al., 2011).

The objective of this paper is to propose a stable reflectivity method to solve the problem of wave propagation in a coupling water-layered porous sediment-solid substrate system. Rigorous analytical solution to the system is proposed. The sandwiched sediment is poroelastic material, and the material is homogeneous within each layer. The paper is organized as follows. The governing equations and general solution are introduced in Section 2. The boundary conditions are presented in Section 3. A stable reflectivity method for the coupling system is introduced in Section 4. Transitional R/T matrices are defined for water/porous-sediment interface and porous-sediment/solid-substrate interface, respectively. Combining these R/T matrices with the traditional TRM method, the reflection and transmission coefficients can be obtained incorporating boundary conditions. In Section 5, the method is verified using published analysis results, and a series of parametric studies are conducted based on the stable reflectivity solution in Section 6.

2. Governing equations and general solution

The coupling water-layered porous sediment-solid substrate system is shown in Fig. 1, which consists of a semi-infinite water half-space, poroelastic sediment layers, and a semi-infinite elastic solid substrate. Biot-Stoll theory (Stoll and Kan, 1981) is adopted to describe the porous sediment. Water is modeled as ideal compressible fluid, and elastic solid is modeled as classical single phase solid. The origin of the coordinate system is set at the water/sediment interface, and the z-axis points downward. The incident angle of wave from the water layer is θ_{in}.

The governing equations for the poroelastic sediment layers are given following the physical laws proposed by Biot (1956a, b) and Ding et al. (2013):

(1) Constitutive equations

$$\sigma_{ij} = \lambda\delta_{ij}e + 2\mu e_{ij} - \alpha\delta_{ij}p \quad (1)$$

$$p = M(\zeta - \alpha e) \quad (2)$$

(2) Equilibrium equations

$$\sigma_{ij,j} = \rho\ddot{u}_i + \rho_f\ddot{w}_i \quad (3)$$

(3) Generalized Darcy's law of the fluid phase:

$$\dot{w}_i = -\kappa(p_{,i} + \rho_f\ddot{u}_i + m'\ddot{w}_i) \quad (4)$$

where the subscript following a comma denotes the spatial derivative; the dot above a variable denotes the derivative with respect to time; δ_{ij} is the Kronecker delta; σ_{ij} is the total stress tensor; p is the pore-fluid pressure; $e_{ij} = (u_{i,j} + u_{j,i})/2$ is the strain tensor of the solid phase; $e = e_{ii}$ is the dilatational strain of the solid phase; $\zeta = -w_{i,i}$ is the variation in fluid content; $w_i = \phi(U_i - u_i)$ is the relative displacement vector, where ϕ is the porosity, and u_i and U_i are the solid and fluid displacements, respectively; $p= (1-\emptyset) +p\emptyset p_f$ is the bulk density; p_s is the solid density; p_f is the fluid density; $m' = c\rho_f/\phi$, where $c\geq1$ is the structure factor; λ and μ are drained Lame coefficients; $\alpha$and M are the Biot effective stress coefficient and Biot modulus. The relationships between the above four parameters are expressed as follows (Stoll and Kan, 1981):

$$\lambda = [(K_r - K_b)^2/(D - K_b)] + K_b - 2\mu/3 - \alpha^2 M \quad (5)$$

$$\alpha = (K_r - K_b)/K_r \quad (6)$$

$$M = (K_r)^2/(D - K_b) \quad (7)$$

$$D = K_r[1 + \phi(K_r/K_f - 1)] \quad (8)$$

where K_r is the bulk modulus of the grains; K_f is the bulk modulus of the pore fluid; K_b is the bulk modulus of the frame. K_r and are assumed to be real constants, while $K_b = K_{br}(1 + id_1/\pi)$ and $\mu = \mu_r(1 + id_2/\pi)$ are complex variables to account for the various forms of energy dissipation occurring at the grain contacts. Here, K_1 and K_2 are the bulk and shear logarithmic decrements, respectively.

The permeability coefficient, κ, is defined as the ratio of k to η, where k and η are the intrinsic permeability and the dynamic viscosity of the fluid phase, respectively. It should be noted that some material properties (e.g., η) can be frequency-dependent. According to Biot theory, η should be replaced by a dynamic complex value, $\eta F(\kappa')$, in the high frequency range (Biot, 1956b; Wang et al., 2013), and the expression of $F(\kappa')$ is as follows: