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An indirect boundary element method to model the 3-D scattering of elastic waves in a fluid-saturated poroelastic half-space

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ABSTRACT

The indirect boundary element method (IBEM) is extended to solve the scattering of elastic waves by three-dimensional (3-D) subsurface irregularities in a fluid-saturated poroelastic half-space. The Green's functions of inclined circular loads and fluid source in a poroelastic full space are deduced based on Biot's theory. According to the single-layered potential theory, the scattered waves are constructed by using fictitious uniform loads and fluid source distributed on the boundary elements on the scatterer surface, and their magnitudes are determined by the continuity or traction-free boundary conditions. Accuracy verification illustrates that this proposed method can deal with 3-D wave scattering problems in an infinite poroelastic medium conveniently and accurately. Then, the scattering of plane waves by a 3-D canyon is investigated. Numerical results indicate that: the scattering of waves in a poroelastic half-space strongly depends on the incident frequency and incident angle; the 3-D amplification effects both on the displacement and pore pressure appear to be more significant than the corresponding 2-D case; medium porosity of the half space also plays a key role on the wave scattering, especially for obliquely incident waves at the critical angle, and the influence of drainage condition seems to be more considerable for high porosities.

1. Introduction

Scattering of elastic wave by subsurface irregularities such as canyon, cavity, inclusions is an active research topic in many fields such as the geotechnical engineering, earthquake engineering and geophysics etc., which has many crucial applications in seismic (blast) wave analysis, geophysical exploration, nondestructive testing, and soil-structure dynamic interaction analysis, etc. In general, the calculation methods can be divided into the analytical methods and numerical methods. As for the three-dimensional (3-D) model, the analytical methods mainly refer to the spherical wave function expansion methods [23,26,27,38,43,54], etc. The numerical methods mainly include the finite element method [11], the finite difference method [14,16], spectral element method [25], boundary element method (BEM) [17,41,45,47,50,1,7,51,15,18,35], discrete wave number method [24] and other boundary-type or hybrid methods [40,5,52,8], etc..

Note that above mentioned studies are mainly based on the model of single-phased medium. In reality, the rock and soil media are commonly porous and fluid-saturated, especially under the ground water level or in coastal region. According to Biot's theory [4], the propagation of elastic waves in fluid-saturated porous medium is substantially different from that in single-phase medium due to wave-induced interaction between solid and fluid, and some special feature of the attenuation and dispersion of elastic waves has been verified by experiments reviewed by Bouzidi and Schmitt [6]. To improve the quantification of wave motion analysis and to reveal the dynamic characteristics of pore fluid pressure in a poroelastic medium, it is necessary to investigate the scattering of elastic waves by 3-D subsurface irregularities based on fluid-saturated poroelastic model.

As for the 2-D wave scattering problems in a poroelastic medium, until now, a number of studies have been carried out [12,19–22,28,30,31,33,37,46,53,56]. More works can be found in the literature review [49]. However, due to the complexity of scattered wave field in 3-D case, the study on the 3-D scattering of elastic waves in a poroelastic medium based on two-phased model is very limited, especially for the scattering in poroelastic half-space. Zimmerman and Stern [57] presented the analytic solution for the scattering of plane compressional waves by spherical inclusions in a poroelastic full space, and they [58] further developed the BEM solution of 3-D wave scattering problems in a poroelastic medium. Zhao and Han [55] studied the scattering of Rayleigh-waves by a hemispherical saturated alluvial valley by Fourier-Bessel series

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expansion method. Liu et al. [32] investigated the scattering of plane SV waves by spherical inclusions in a poroelastic medium. Ciz and Gurevich [10] investigated the scattering of plane waves by a spherical porous inclusion in a poroelastic medium by series expansion of spherical harmonic functions. Note that Cheng and Detournay [9] presented a unified formulation of various singular integral equations in BEM for the solution of quasi-static, anisotropic poroelasticity; Schanz [48] developed 3-D time domain BEM formulation to wave propagation in poroelastic solid combined with the convolution quadrature method; Ding and Jiang [13] proposed a time domain BEM for the dynamic analysis of saturated porous media subjected to external forces. Yet both of these references did not take the scattering problem into consideration. Note that Ba et al. [2] studied 3-D scattering of obliquely incident plane SV waves by an alluvial valley embedded in a fluid-saturated, poroelastic layered half-space. Liang et al. [29] further presented the diffraction of obliquely incident SH waves by twin infinitely long cylindrical cavities in layered poroelastic half-space. Actually, both of these two references were limited to the 2.5 dimensional case, assuming that the irregularity is infinitely long with a constant cross section but for the obliquely incident waves.

Compared with the analytical method, numerical methods are more robust and flexible for solving practical problems with complicated geometrical and material features. This paper concentrates on extending the indirect boundary element method (IBEM) to investigate the scattering of elastic waves by subsurface irregularities in a poroelastic half-space. The IBEM resolves wave motion problems in the following way. The whole wave field is divided into free field and scattered field firstly. Then, the scattered waves are constructed by using fictitious loads and fluid source distributed on the boundary of the irregularities, and their magnitudes are determined by the continuity or traction-free boundary conditions. Sanchez-Sesma and Luzon [47] and Ortiz-Alemán et al. [42] had successfully used this method to solve the scattering of seismic waves by local sites in single-phased elastic half space. It is illustrated that this method has many advantages such as reducing dimensions of problems, automatic satisfaction of radiation condition, and high calculation precision. Besides, the integral singularity on the loaded element could be accurately addressed. Hence, this IBEM is well suited to accurately simulate 3-D wave scattering in infinite or semi-infinite domain. However, to the best of our knowledge, none has solved the 3-D scattering problem in a poroelastic medium by this method.

The main contribution of this paper is to develop the IBEM to solve the 3-D scattering problem in a poroelastic half space based on the Green's functions of inclined circular loads in a poroelastic full space. In Section 2, the calculation model and Biot's theory is briefly introduced. Then, Section 3 illustrates the formulation and procedure for IBEM solution to scattering of elastic waves by 3-D subsurface irregularities in a poroelastic half space. In Section 4, the Green's functions of inclined circular loads and fluid source are derived based on Biot's theory. In Section 5, the validity of the present method is confirmed through comparison with an available well-known solution. In Section 6, several numerical results are presented for scattering of plane P and SV waves around a 3-D canyon in a poroelastic half space and several fundamental response characteristics are discussed. Finally, some important conclusions are obtained.

2. Calculation model and Biot's theory

The IBEM can be utilized to deal with arbitrary-shaped 3-D subsurface irregularities in a poroelastic half-space, such as 3-D canyon, 3-D cavity and 3-D inclusions. As an example, Fig. 1 shows the scattering of plane P, SV waves by a 3-D canyon in a poroelastic half-space. To construct the scattered waves field, fictitious distributed loads are introduced on the boundary S (the surface of the canyon and nearby horizontal ground). The problem to be studied is the 3-D scattering of plane waves around the canyon of arbitrary shape in a poroelastic half-space, assuming that the material in the half-space is poroelastic, homogeneous and isotropic. For the sake of brevity, in this paper, the IBEM formulation and the numerical analysis are all presented in the frequency domain, while the time-domain results can be easily obtained through Fourier synthesis of frequency-domain solutions.

2.1. Biot's theory

According to Biot's theory [3], the constitutive relations of a homogeneous poroelastic medium can be expressed as

$$\sigma_{ij} = 2\mu\varepsilon_{ij} + \lambda\delta_{ij}e - \alpha\delta_{ij}p; i, j = x, y \tag{1a}$$

$$p = -\alpha M u_{i,i} - M w_{i,i} \tag{1b}$$

where u_i and w_i (i=x, y) denote the displacement of the solid frame and the fluid displacement relative to the solid frame respectively, σ_{ij} is total stress component of the bulk material, ε_{ij} and e are strain components and dilatation of the solid frame, respectively; λ and μ are Lame constants of the bulk material, p is pore pressure, δ_{ij} is Kronecker's delta, α and M are Biot's parameters describing compressibility of the two-phased material, and $0 \le \alpha \le 1$ and $0 \le M \le \infty$.

Correspondingly, the dynamic equations for homogeneous poroelastic medium can be expressed in terms of displacements u_i and w_i as [4]

$$\mu u_{i,jj} + (\lambda + \alpha^2 M + \mu) u_{j,ji} + \alpha M w_{j,ji} = \rho\ddot{u}_i + \rho_f \ddot{w}_i \tag{2a}$$

$$\alpha M u_{j,ji} + M w_{j,ji} = \rho_f \ddot{u}_i + m\ddot{w}_i + b\dot{w}_i \tag{2b}$$

where ρ=$(1-n)\rho_s$+$n\rho_f$, ρ_s and ρ_f are mass density of the solid grain and the pore fluid, respectively, n is porosity of the solid frame; b is a parameter accounting for the internal friction due to the relative motion between the solid frame and the pore fluid, and b=0 if the internal friction is neglected; m is a density-like parameter depending on ρ_f and the geometry of the pores.

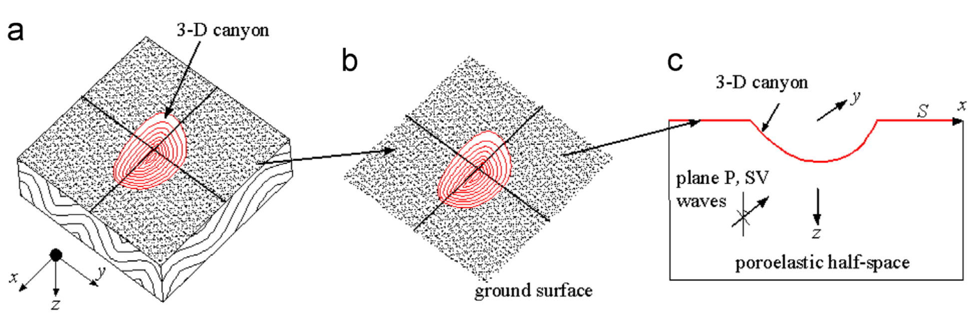

Fig. 1. Scattering of plane waves by a 3-D canyon in a poroelastic half-space.