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The method of fundamental solution for elastic wave scattering and dynamic stress concentration in a fluid-saturated poroelastic layered half-plane

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ABSTRACT

A meshless method based on the method of fundamental solution (MFS) is developed to solve elastic-wave scattering and dynamic stress concentration in a fluid-saturated poroelastic layered half-plane, by utilizing the line sources of cylindrical P_I, P_{II}, and SV waves in a poroelastic layered half-plane. The numerical accuracy and stability of the MFS is verified by examining the boundary conditions and comparison with other methods. Subsequently, the amplification effects on displacement, surface hoop stress and fluid pore pressure around a cavity in a three-layered poroelastic half-plane are investigated. Numerical results indicate that the scattering characteristics strongly depend on parameters including the incident frequency and angle, soil-layer porosity and boundary drainage condition. The amplification effects of a cavity in the poroelastic layered half-plane appear to be more significant than the corresponding case of a homogenous half-plane. The amplitude of the fluid pore pressure on the surface of the cavity is amplified up to five times that of the free field, which also considerably aggravates the dynamic stress concentration around the cavity.

1. Introduction

Fluid-saturated poroelastic media widely exists in nature in forms such as rock and soil, oil reservoirs and muscle tissue. It is of high theoretical and practical value to study the wave scattering and dynamic stress concentration caused by surficial cavity, crack or inclusion in saturated two-phase media. Thus, in recent decades, the related problems have been intensely examined in earthquake engineering, geophysics, civil engineering and other fields. The saturated poroelastic soil model developed by Biot [1] is the most frequently employed multi-phase elastic media model. According to Biot's theory, the propagation of elastic waves in fluid-saturated porous medium varies substantially from that in single-phase medium owing to wave-induced interaction between the solid and fluid, and certain special feature of the attenuation and dispersion of elastic waves has been verified by experiments reviewed by Bouzidi and Schmitt [3].

In general, the calculation methods for the wave scattering and dynamic concentration can be categorized into analytical methods and numerical methods. The analytical methods mainly refer to wave function expansion methods such as study of the wave scattering in a full poroelastic space ([6,13–16,19,31,36,58]; etc.) and the more complex wave-motion problem for a poroelastic half-plane ([18,22,24,55], etc.). The numerical methods mainly include finite element method ([11,26,44,46,50,51]; etc.), finite difference method ([2,7,17,38,52,57]; etc.), spectral element method ([39]; etc.), boundary element method (BEM) ([5,9,10,35,41,42,59]; etc.), discrete wave number method and other boundary-type or hybrid methods. Other studies are also available in the literature review [4,43].

It is noteworthy that a majority of the above studies are on either a poroelastic full space or poroelastic half-plane. However, actual rock and soil media are generally layered owing to the varying depositional ages. Moreover, owing to the complexity of scattered wave field in layered case, theoretical studies on wave scattering and stress concentration in poroelastic layered medium are relatively few. In this field, Liang et al. [25] developed indirect BEM to solve the scattering of plane SV waves by a canyon in a poroelastic layered half-plane. Furthermore, Ba et al. [56] used indirect BEM to investigate the scattering of obliquely incident plane SV waves by a poroelastic alluvial valley. In theory, compared with BEM, FDM and FEM are capable of addressing wave motion in heterogeneous medium more conveniently; however, for infinite layered poroelastic half-plane, the exact satisfaction of no-reflection boundary conditions is a significant challenge as of yet [11].

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Among the various boundary-type methods, the method of fundamental solution (MFS) reduces the dimension of problem and automatically satisfies the boundary conditions at infinite as well as serves as a meshless method. Owing to the remarkable numerical accuracy and straightforwardness of usage, the MFS (also referred to as special indirect boundary integral equation method) has been widely applied in the field of wave scattering in a single-phase elastic medium ([12,20,30,32,37,47–49,54]; etc.). As for two-phase medium, Rajapakse and Senjuntichai [40] solved the time-harmonic and transient problems related to infinite and semi-infinite poroelastic domains. Liang and Liu [27,28] and Liu et al. [33,34] developed this method to solve the scattering of seismic waves by typical local sites (canyon, cavity, valley) in a fluid-saturated poroelastic half-plane.

As an extension of the work of Liang and Liu [28], this paper further develops the MFS to solve the elastic wave scattering and dynamic stress concentration in a fluid-saturated poroelastic layered half-plane, using the cylindrical P_I, P_{II} and SV line sources for a poroelastic layered half-plane to simulate the scattered wave field. In order to avoid singularities, the fictitious wave sources are placed at a certain distance to the physical boundaries of the scatters. The densities of the fictitious sources are first obtained using the boundary integral equations discretized through boundary collocation points. The meshless characteristic renders the MFS essentially dissimilar from the IBEM used by Liang et al. [25], which requires element discretization of the scatter surface and constructs the scattering waves based on Green's function of inclined distributed loads.

This paper is organized as follows: in Section 2, Biot's theory is first introduced briefly; then, Green's functions for a layered poroelastic half-plane are deduced for the construction of scattered wave field. Subsequently, the implementation procedure of MFS to solve the wave scattering and dynamic stress concentration in a poroelastic layered half-plane is presented. In Section 3, the precision and numerical stability of the MFS is verified by examining the extent of satisfaction of boundary conditions and comparison between the degenerated solutions of single-phased half-plane and the popular solutions. In Section 4, considering the wave scattering and dynamic stress concentration around a cavity as a typical example, the effects of key parameters such as the soil porosity, drainage condition, excitation frequency and incident angle is discussed. Finally, several critical conclusions are presented.

2. Calculation model and the MFS

Fig. 1 illustrates the calculation model for the two-dimensional scattering of elastic waves around scatters of arbitrary shape in a fluid-saturated poroelastic layered half-plane. The medium in each layer is assumed to be poroelastic, isotropic, and homogeneous. Consider elastic waves impinging on the bedrock half-plane at an angle θ_α (P waves) or θ_β (SV waves) to the y-axis. The wave motion around the scatters can be solved by MFS in the following manner: to construct scattered waves (including the reflected and diffracted waves) according to single-layer potential theory, fictitious wave sources including two types of compressional waves and shear waves are introduced in the vicinity of the boundary S, forming fictitious surfaces S_1 and S_2. The magnitudes of the fictitious wave sources can be determined by the boundary integral equations discretized on the boundary collocation points.

2.1. Biot's theory

According to Biot's model (1962), the constitutive relations of a homogeneous poroelastic medium can be expressed as

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

$$p = -\alpha M u_{i,i} - M w_{i,i} \tag{2}$$

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

The wave equations for a homogeneous poroelastic medium can be expressed as follows [1]:

$$\mu u_{i,jj} + (\lambda + \alpha^2 M + \mu)u_{j,ji} + \alpha M w_{j,ji} = \rho\ddot{u}_i + \rho_f \ddot{w}_i \tag{3a}$$

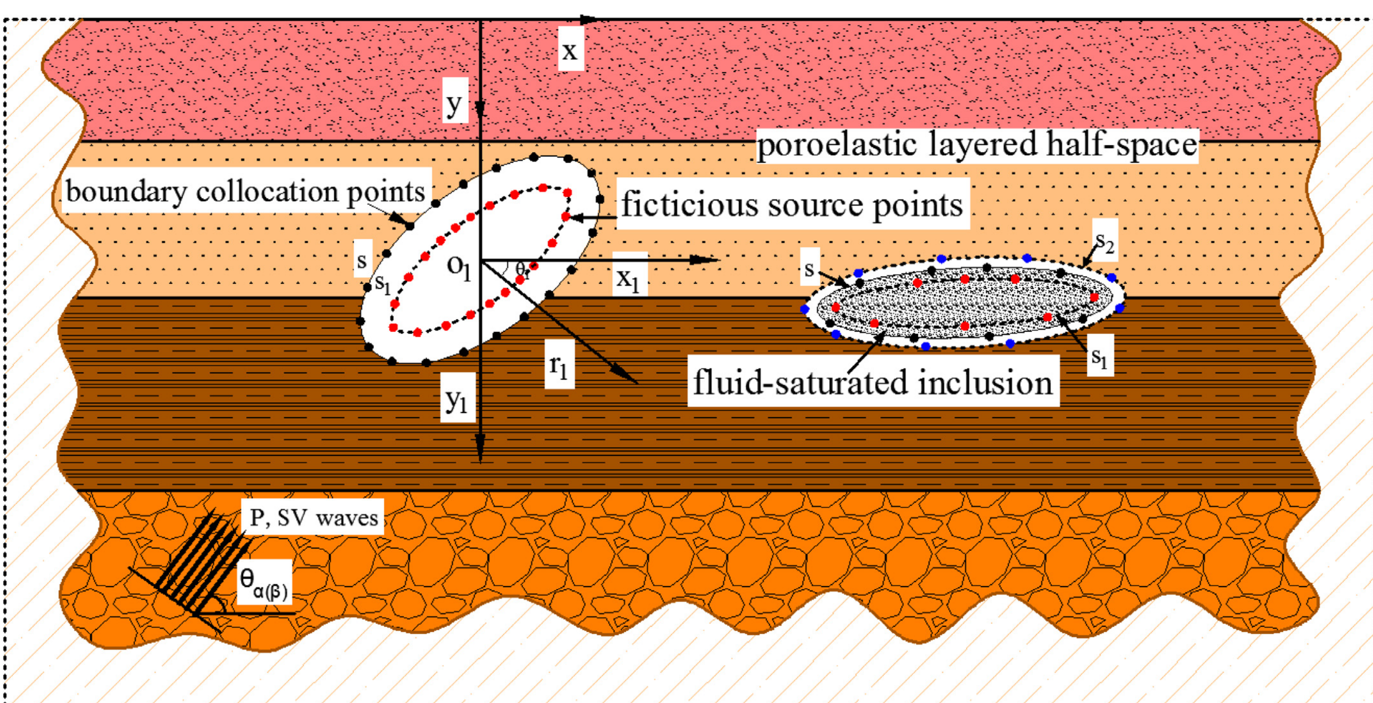

Fig. 1. Calculation model of 2D scatters of arbitrary shape in a saturated poroelastic layered half-plane.