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Dynamic response of a partially debonded pipeline embedded in a saturated poroelastic medium to harmonic plane waves

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ABSTRACT

A practical model of partially debonded pipeline embedded in a saturated poroelastic medium is proposed, and the dynamic response of this model to harmonic plane waves is theoretical investigated. Biot's poroelastic theory is introduced to describe the dynamic equations of the saturated poroelastic medium, and the potentials obtained from Helmholtz decomposition theorem are expressed by wave function expansion method. The debonding areas around the pipeline are assumed to be filled with water. The disturbed solutions of basic field equations in these areas are expressed in terms of a scalar velocity potential. Different boundary conditions of bonded and debonded areas are adopted, and the expanded coefficients are obtained. An example of one partially debonded area is presented and analyzed. It is found that the stresses in the perfectly bonded and debonded areas show great difference, and the jump of dynamic stress at the connection points between these two areas is great in the case of low frequency. The effect of debonded areas on the dynamic stress under different thicknesses of lining is also examined.

1. Introduction

In the engineering of transporting oil and gas products, pipelines are recognized as the most efficient way, and thousands of kilometers of pipelines have been laid down at various water depths and on all sorts of soil conditions. With the rapid development of offshore oil and gas industry, the mechanical behavior of buried pipelines is attracting more and more interests [1].

Lots of accidents have evidenced that the consequence of pipeline failure is disastrous both economically and environmentally. Therefore, maintaining its structural integrity and reliability is essential to the world's energy requirements. In order to improve the safety performance of the natural gas pipeline supply system, the stress analysis including mechanical damage [2–4] and stress concentration [5] was widely carried out.

It is well known that the soil medium is porous material, which has two phases: the solid phase, referred to as the frame, and the fluid contained within the pores formed by the frame. The microscopic heterogeneity of the saturated medium results in a complex macroscopic physical behavior sensitive to slight variations of fluid content or pipelines under various loadings. These loadings include static [6–7] and dynamics ones.

Under dynamic loadings such as traffic [8], machinery [9], or seismic waves [10], the pipeline–soil interaction is a complicated dynamic contact problem and the investigations on the dynamic response of pipelines and underground structures in soil to seismic waves is of high interest, especially if these facilities are built in areas subjected to strong earthquake activities. To solve this complex problem, the theory of elastic wave propagation in a fluid-saturated poroelastic medium was first formulated and presented by Biot [10].

It has been shown in early researches that there are three kinds of waves in the medium, i.e. the fast waves (P1), the slow waves (P2), and the shear waves (S). In recent years, the scattering of these waves from the inclusions of various shapes has attracted lots of interests. The shapes of the inclusions includes two-dimension (semi-circular cavity [11], cylindrical cavities [12–14], circular pipelines [15], elliptic cylinder [16], lined tunnel [17], and a circular tunnel [18,19]) and three-dimensional scatters (a spherical cavity [20] and a spherical poroelastic inhomogeneity [21]). To analyze the dynamic interaction of the embedded inclusions, the multiple scattering of these three kinds of waves between two circular tunnels [22], and two circular cavities [23] was carried out. By using the boundary element method in the frequency domain, the response of a circular tunnel with and without an elastic concrete liner in an infinite poroelastic medium subjected to harmonic P and SV plane waves was studied [24].

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During the construction of urban transportation or water management facilities in many large cities, pipelines are often buried in soft ground on the coast. The investigations on the wave scattering and dynamic stress around the pipelines are very significant for the safe and economy oil and gas transmitting. Recently, the dynamic response of a circular pipeline in a poroelastic medium has been investigated [15]. Fang et al. extended this work to the dynamic interaction of two fluid-filled circular pipelines in a porous elastic fluid-saturated medium subjected to harmonic plane waves [25].

The preceding review has primarily focused on the inclusions perfectly bonded with the saturated soil, namely, the displacement and stress are continuous at the boundary of inclusions. However, this boundary condition is hypothetical for convenience of computation. In practical engineering application, the inclusions are often partially debonded with the ambient medium, with the consequence of a detrimental effect in the stress transfer between the inclusions and saturated soil. Such a phenomenon, also known as debonding, is crucial for the proper assessment of in-service safety and for the optimal designs. This kind of boundary will bring about complex problem. For the partially debonded inclusions embedded in elastic or viscoelastic medium, the stresses resulting from the debonding areas have been addressed. The scattering of SH waves [26] and P and SV waves [27] by a rigid cylindrical inclusion in elastic matrix was studied by Wang and Wang, and the debonding regions were modeled as multiple arc-shaped interface cracks with non-contacting faces. The case of elliptical inclusions partially debonded with the elastic medium was also investigated by Mathieu function expansion method [28,29], and the resonance around the debonding areas was discussed. Subsequently, the elastic matrix was extended to the viscoelastic medium, and the phase delay between the stress and strain in viscoelastic materials was reflected [30]. In the saturated poroelastic medium, the scattering resulting from three kinds of waves around the partially debonded inclusions will become more complex. The coupling of fluid pressure and stress in the debonding areas may result in significant variation of stress distribution. Up to present time, no one else has dealt with this problem.

The objective of this paper is to develop a practical model of partially debonded pipeline embedded in a saturated poroelastic medium, and the dynamic response to harmonic plane waves is theoretically investigated. This work is structured as follows. In Section 2, the governing equations and general solutions of poroelastic medium, isotropic elastic material, and the filled fluid around the partially debonded pipeline are given. In Section 3, the analytical solutions in different regions in the case of perfectly bonded areas are expanded. The solutions of different regions in the case of perfectly bonded areas are presented in Section 4. To obtain the expanded coefficients, the boundary conditions around the partially debonded pipeline are illustrated in Section 5. Some numerical examples and analyses are given in Section 6. In Section 7, the concluding remarks are presented.

2. Governing equations and general solutions

A partially debonded circular pipeline filled with fluid is embedded in saturated poroelastic medium, as depicted in Fig. 1. It is assumed that the incident fast or slow wave propagates in the saturated poroelastic medium. The plane wave has a direction perpendicular to the axis of the lining, and the incident angle between the incident direction and the x axis is α. Three parts are divided in this model: saturated poroelastic medium, lining, and fluid medium. The inner and outer radii are denoted by a_1 and a_2, respectively. Several debonding areas exist at the interface of the pipeline. These areas are denoted by $\theta_{2i-1}-\theta_{2i}$ $(i=1,2,3,\ldots)$.

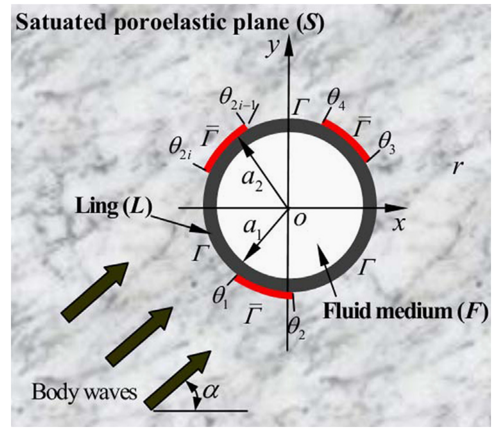

Fig. 1. The partially debonded pipeline embedded in saturated poroelastic medium and incident waves.

The properties of saturated medium are characterized by the physical parameters, such as Lamé constants λ_M, μ_M, and the densities of porous medium, solid skeleton, and pore fluid (ρ_M, ρ_S, ρ_F). It is assumed that the lining is an elastic medium with properties characterized by λ_L, μ_L and ρ_L.

2.1. General solutions of poroelastic medium

In Biot's model, the saturated poroelastic medium is assumed as a macroscopically homogeneous and isotropic two-component solid/fluid system with the same macroscopic bulk properties as the actual porous material. The (coupled) constitutive relations for the saturated poroelastic medium can be expressed as [10]

$$\sigma_{ij}=(\lambda_M e-\beta P_f)\delta_{ij}+2\mu_M\varepsilon_{ij}, \tag{1}$$

$$P_f=M(\xi-\beta e), \tag{2}$$

$$e=u_{i,i},\quad \xi=-w_{i,i},\quad i,j=x,y, \tag{3}$$

where σ_{ij} are the total stress components of the bulk material, ε_{ij} and e are, respectively, the strain component and dilatation of the solid matrix, u_i and w_i are the average solid displacement and the infiltration displacement of the pore fluid, ξ is the bulk the variation of fluid content per unit reference volume, β and M are Biot's parameters, P_f represents the excess pore pressure, and δ_{ij} is the Kronecker delta.

The governing equations of the solid medium and the interstitial liquid with dissipation taken into account can be expressed, in terms of displacements u_i and w_i, as [13,15,23]

$$\mu_M u_{i,jj}+(\lambda_M+\alpha^2 M+\mu_M)u_{j,ji}+\alpha M w_{j,ji}=\rho_M\ddot{u}_i+\rho_F\ddot{w}_i, \tag{4}$$

$$\alpha M u_{j,ji}+M w_{j,ji}=\rho_F\ddot{u}_i+\frac{\rho_F}{n}\ddot{w}_i+\frac{\eta}{\kappa}\dot{w}_i, \tag{5}$$

where $\rho_M=(1-n_0)\rho_S+n_0\rho_F$, n_0 is the porosity of the porous medium, κ and η are the permeability and the fluid viscosity, respectively. A superimposed dot denotes the derivative with respect to time t.

To solve Eqs. (4) and (5), Helmholtz decomposition theorem is used. For the plane strain problem, two scalar potentials φ_f, φ_s and one vector potential ψ are introduced. Helmholtz equations can be expressed as

$$\nabla^2\varphi_{f,s}+k_{f,s}^2\varphi_{f,s}=0, \tag{6}$$

$$\nabla^2\psi+k_t^2\psi=0, \tag{7}$$

where k_f, k_s, and k_t denote the complex wave numbers of the fast