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Poromechanical response of borehole in excavation disturbed zone

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ABSTRACT

This paper presents time-dependent response of a cylindrical borehole in a poroelastic medium with an excavation disturbed zone. The general solutions are derived based on Biot's theory of poroelasticity by employing Laplace and Fourier transforms. Both shear modulus and permeability coefficient are assumed to be changed from their original values in the disturbed zone. The general solutions are employed to formulate boundary value problems corresponding to a borehole subjected to axisymmetric loading applied at its surface, and contact problems of a rigid cylindrical plug in a borehole. Selected numerical results are presented to portray the influence of poroelastic effects and the excavation disturbed zone.

1. Introduction

Stress analysis of a cylindrical borehole in soils and rocks has important applications in the modeling of several problems in civil engineering and geomechanics such as in situ testing of geological materials, energy and mineral resource explorations, and waste disposal and groundwater discharge. Boundary value problems related to mechanical or fluid loading applied over a segment of borehole surface are useful for investigating the influence of material properties, types of loading and segment length on borehole responses. Analytical solution to a deep cylindrical borehole in an isotropic elastic medium subjected to axisymmetric loading applied to borehole surface was presented in the past [1]. Rajapakse and Gross [2] solved boundary value problems of a borehole in a transversely isotropic elastic medium subjected to axisymmetric traction and contact problem of a rigid cylinder perfectly bonded to a borehole wall. Geomaterials are normally two-phase materials with a solid skeleton and pores, which are filled with fluids (e.g. water or oil), and commonly known as poroelastic materials. The salient features of poroelastic materials under applied loading are time-dependent behaviors due to generation and subsequent dissipation of pore water pressure. Biot [3] developed a general theory of three-dimensional consolidation by adopting Terzaghi's concepts [4]. Rice and Cleary [5] later reformulated Biot's theory in terms of Skempton's pore pressure coefficient [6] and the undrained Poisson's ratio of the bulk material. A comprehensive review of the development of the theory of poroelasticity is given by Detournay and Cheng [7].

Biot's theory of poroelasticity has been widely employed for investigating various problems in geomechanics including those related to cylindrical borehole problems. The poroelastic solution of a borehole in a non-hydrostatic stress field was presented by Detournay and Cheng [8] by assuming a plane strain condition. Plane-strain solution for an inclined borehole was also derived [9]. Rajapakse [10] presented stress analysis of a borehole in a poroelastic medium with incompressible constituents. Abousleiman et al. [11] presented a pseudo-three dimensional solution for an inclined borehole problem. Their solution was later used to assess impacts of poroelastic processes on borehole stability [12,13]. Recently, Abousleiman and Chen [14] presented analytical solutions for an inclined borehole subjected to fluid discharge applied at the surface coupled with three-dimensional far-field in situ stresses.

It is well known that borehole drilling process is a primary factor that causes changes of physical, mechanical and hydraulic properties around the borehole such as, bulk modulus, shear modulus, desaturation and strength. The rock/soil zone, where its properties are changed, is called an excavation disturbed zone (EDZ). The EDZ is one of the most important factors that affect the stability of borehole. Several researchers have studied behaviors of the excavation disturbed zone in the past decade. For example, Sato et al. [15] conducted an excavation disturbance experiment at Tono mine in central Japan to observe the change of rock properties and the width of the EDZ during the drift excavation. Martino and Chandler [16] studied the character and the extent of excavation

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damage at the Underground Research Laboratory (URL) located in Manitoba, Canada. The EDZ investigation was also conducted using seismic measurement techniques at Kiiranavaara mine, Sweden by Malmgren et al. [17]. The influence of hydro-mechanical properties (desaturation and anisotropy) in the EDZ at the Underground Research Laboratory in France was carried out by Shao et al. [18]. In addition, behaviors of the EDZ from an excavation at KAERI underground research tunnel in Korea were studied by Kwon et al. [19,20]. To our knowledge, time-dependent response of a cylindrical borehole in a poroelastic medium with the consideration of excavation disturbed zone has never been considered in the past, although the EDZ could have a significant influence on stresses and pore pressure in the vicinity of borehole.

This paper presents stress analysis of a cylindrical borehole in a poroelastic medium with excavation disturbed zone (EDZ). The general solutions of a poroelastic medium with compressible constituents are derived based on Biot's theory of poroelasticity by employing Laplace and Fourier transforms. Both shear modulus and permeability coefficient are assumed to be changed from their original values in the disturbed zone. In the present study, the EDZ is discretized into a number of infinitely long tubular layers with small thickness and homogeneous properties perfectly bonded together. Boundary value problems, corresponding to a borehole subjected to axisymmetric loading applied at its surface and contact problems involving a borehole containing a rigid cylindrical plug, are formulated. Two extreme hydraulic boundary conditions at the borehole surface, i.e. fully permeable and impermeable surfaces, are considered. Time domain solutions are obtained by employing accurate numerical schemes for Laplace and Fourier inversions. Selected numerical results are presented for radial displacement, hoop stress, pore pressure and fluid discharge to portray the influence of poroelastic effects and the excavation disturbed zone on time-dependent response of the borehole.

2. Governing equations and general solutions

Consider an infinite cylindrical borehole of radius a in a poroelastic medium with an excavation disturbed zone of length d subjected to axisymmetric loading as shown in Fig. 1. Let u_i and w_i denote the displacement of the solid matrix and the fluid displacement relative to the displacement of the solid matrix in the i-direction ($i = r, z$) respectively. The constitutive relations of a poroelastic material can be expressed as [3]

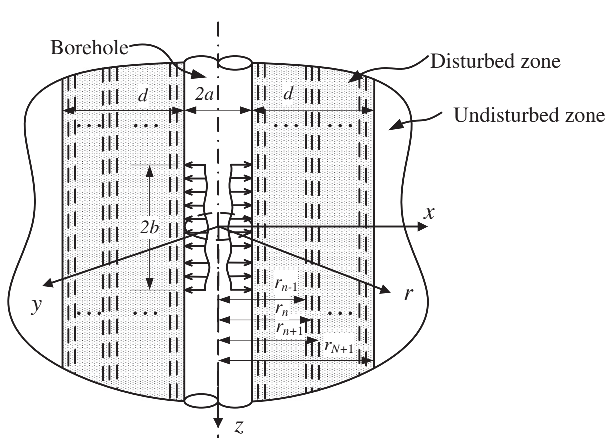

Fig. 1. A cylindrical borehole in a poroelastic medium with excavation disturbed zone.

$$\sigma_{rr} = 2\mu\left(\frac{\partial u_r}{\partial r} + \frac{\nu}{1-2\nu}\varepsilon\right) - bp; \quad \sigma_{\theta\theta} = 2\mu\left(\frac{u_r}{r} + \frac{\nu}{1-2\nu}\varepsilon\right) - bp, \tag{1}$$

$$\sigma_{zz} = 2\mu\left(\frac{\partial u_z}{\partial z} + \frac{\nu}{1-2\nu}\varepsilon\right) - bp; \quad \sigma_{rz} = \mu\left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r}\right), \tag{2}$$

$$p = -\frac{2\mu B(1+\nu_u)}{3(1-2\nu_u)}\varepsilon + \frac{2\mu B(1+\nu_u)}{3b(1-2\nu_u)}\zeta \tag{3}$$

In the above equations, σ_{rr}, $\sigma_{\theta\theta}$, σ_{zz}, and σ_{rz} denote the total stress components of the bulk material; p is the excess pore fluid pressure (suction is considered negative); ε is the dilatation of the solid matrix; μ, ν, ν_u and B denote shear modulus, drained and undrained Poisson's ratios, and the Skempton's pore pressure coefficient [6] respectively; and ζ denotes the variation of fluid volume per unit reference volume defined as $\zeta = -[(\partial w_r/\partial r) + (w_r/r) + (\partial w_z/\partial z)]$. In addition, the parameter b is defined as $b = [3(\nu_u - \nu)]/[B(1-2\nu)(1+\nu_u)]$.

The fluid discharge in the i-direction ($i = r, z$), denoted by q_i, is defined as

$$q_i = -\kappa\frac{\partial p}{\partial i} \tag{4}$$

where κ denotes permeability coefficient.

The Laplace transform of a function $f(r, z, t)$ with respect to time variable t and its inverse transform are defined as [21]

$$\tilde{f}(r,z,s) = \int_0^\infty f(r,z,t)e^{-st}dt; \quad f(r,z,t) = \frac{1}{2\pi i}\int_{\beta-i\infty}^{\beta+i\infty}\tilde{f}(r,z,s)e^{st}ds \tag{5}$$

where s is the Laplace transform parameter. In addition, the Fourier transform of $\tilde{f}(r,z,s)$ with respect to the z coordinate and the inverse relationship are defined as [21]

$$\bar{f}(r,\xi,s) = \int_{-\infty}^{\infty}\tilde{f}(r,z,s)e^{-i\xi z}dz; \quad \tilde{f}(r,z,s) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\bar{f}(r,\xi,s)e^{i\xi z}d\xi \tag{6}$$

where ξ denotes the Fourier transform parameter.

It is convenient to nondimensionalize all quantities including the coordinates with respect to the length and time by selecting the radius of borehole "a" as a unit length and "a^2/c" as a unit of time respectively where $c = [2\mu\kappa B^2(1-\nu)(1+\nu_u)^2]/[9(1-\nu_u)(\nu_u-\nu)]$. All variables will be replaced by appropriate nondimensional variables, but the previous notations will be adopted for convenience.

It can be shown that the general solutions for axisymmetric deformations of a poroelastic medium in the Laplace–Fourier transform space can be expressed in the following matrix form.

$$\mathbf{u}(r,\xi,s) = \mathbf{R}(r,\xi,s)\mathbf{C}(\xi,s) \tag{7}$$

$$\mathbf{f}(r,\xi,s) = \mathbf{S}(r,\xi,s)\mathbf{C}(\xi,s) \tag{8}$$

where

$$\mathbf{u}(r,\xi,s) = [\bar{u}_r \quad \bar{u}_z \quad \bar{p}]^{\mathrm{T}}; \quad \mathbf{f}(r,\xi,s) = [\bar{\sigma}_{rr} \quad \bar{\sigma}_{rz} \quad \bar{w}_r]^{\mathrm{T}} \tag{9}$$

and

$$\mathbf{C}(\xi,s) = [A \quad B \quad C \quad D \quad E \quad F]^{\mathrm{T}} \tag{10}$$

Derivation of the general solutions are presented in the Appendix together with the elements of the matrices $\mathbf{R}$ and $\mathbf{S}$. The arbitrary functions $A(\xi,s)$ to $F(\xi,s)$ in $\mathbf{C}(\xi,s)$ are determined by applying appropriate boundary and/or continuity conditions. In the ensuing section, the general solutions are employed to establish an exact stiffness matrix scheme to study time-dependent response of a borehole in a poroelastic medium with excavation disturbed zone.