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Dynamic response of a partially sealed tunnel in porous rock under inner water pressure

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ABSTRACT

In this paper, the dynamic response of the surrounding rock and structure of a tunnel that is subjected to an inner water pressure is investigated by taking hydraulic–mechanical coupling into account. A dimensionless permeable parameter defines the flow capacity of the lining, is introduced by considering the relative permeability of the lining of the tunnel and the surrounding rock. Further more, a dimensionless loading coefficient depending on the porosity of the medium, is introduced to determine approximately the quantity of the inner water pressure supported by the solid and the pore water at the boundary of tunnel. Therefore, the coupling property of partial sealing, porosity of tunnel material and geometry is developed. The analytical solutions of stress, displacement and pore pressure are derived in the Laplace transform domain with and without considering the stiffness of lining. Numerical results in time domain are obtained by Durbin's inverse Laplace transform and are used to analyze the influence of the loading coefficient, permeable parameter, relative stiffness and thickness on stress, displacement and pore pressure in the rock mass. The available result without considering the coupling properties of partial sealing and porosity is only an extreme case of this paper.

1. Introduction

Many underground structures are built in saturated rock material. To study the deformation and stability of such structures, it is obviously necessary to take hydraulic–mechanical coupling into account. Biot's poroelastic theory for both isotropic and anisotropic porous media defined the fundamental for the model of such a coupling (Biot, 1941, 1955). More recent works have been performed to complete and generalize the initial works of Biot (Detournay and Cheng, 1993; Rice and Cleary, 1976), particularly for anisotropic porous media.

A great number of experimental, analytical and numerical research works have been carried out to characterize and model the mechanical behavior of rock. A reformulation of anisotropic and poroelastic equation was presented by Thompson and Willis (Thompson and Willis, 1991) and, the relationships between the macroscopic poroelastic constants and the properties of porous media constituents have been established. To better elucidate the physical meaning of poroelastic constants, Cheng (1997) proposed a comprehensive methodology for the determination of anisotropic poroelastic constants from easily realizable laboratory tests. Detournay and Cheng (1988) were concerned with the analysis of various coupled poroelastic processes triggered by the drilling of a vertical borehole in a saturated formation subjected to a non-hydrostatic in situ stress. Schmitt et al. (1993) presented a time-dependent analytic solution for the pore pressure within a permeable and porous hollow cylinder, and was used to estimate the laboratory experiment results. Analytical and numerical solutions using anisotropic and poroelastic (or poroviscoelastic) theory were also proposed by Abousleiman et al. (1993, 1996) for the model of a generalized Mandel's problem and of an inclined borehole one. All these models deal with the poroelastic and poroviscoelastic behaviour of porous materials with initial constant isotropy and anisotropy. Recently, Liu et al. (2005) analyzed the scattering of plane harmonic wave by a partially permeable cylindrical shell embedded in the poroelastic medium to model the effect of primary wave on the tunnel.

Measurements of poroelastic constants and hydraulic flow parameters of tight rock are important for modeling many geological processes. Bemer et al. (2004) studied the behavior of this clayey rock within the framework of Biot's mechanics of fluid saturated porous solids. Drained and undrained oedometric tests (i.e. uniaxial strain tests) were performed to determine the poroelastic parameters for different stress levels. Hart and Wang (2001) presented a method for determining three independent poroelastic constants: the drained bulk compressibility; the undrained bulk

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compressibility; Skempton's B coefficient, and two hydraulic flow parameters: the hydraulic conductivity and the three-dimensional unconstrained specific storage, from a single test.

The traditional dynamic and static analysis method of a tunnel subjected to inner water pressure is either to idealize the pressure as axisymmetric loading (Xu, 1982; Xie et al., 2004) without considering the porosity of solid, or to idealize the pressure as fluid pressure (Xie et al., 2004; Senjuntichai and Rajapakse, 1993) when the porosity of solid is considered. In which there are only two extreme cases due to the assumption of porosity of the lining and the rock mass. In fact, a part of the inner water pressure is supported by the solid, the others are supported by the pore water at the boundary of tunnel, the proportion is then depended on the area coefficient of pore water related to the porosity of tunnel material and rock. Therefore, the inner water pressure can't be idealized simply as axisymmetric loading or fluid pressure. A dimensionless loading coefficient Γ, which can be used to denote the value of inner water pressure supported by the pore water and the rock material, respectively, was proposed by Liu et al. (2005), and an analysis was carried out.

Since the proportionality constant κ that depends on the porosity of the lining and the rock material was presented by Li (1999) to define the partial permeability property of tunnel and is introduced directly herein, then the coupling property of partial sealing and porosity of the tunnel material and geometry is developed, and the dynamic response of the lining and rock in a partially sealed pressure tunnel is studied in this article. The analytical solution of the interaction of lining and rock is derived in the Durbin (1974) Laplace transform, and by inverting the Laplace transform, numerical results in the time domain are obtained and are used to discuss the influence of the loading coefficient Γ, the porous and geometry constants that indicate the property of the lining and rock on the stress, displacement and pore pressure.

2. Poroelastic model and general solution

The poroelastic theory was firstly introduced by Biot (1941, 1955), and reformulated by Rice and Cleary (1976) in terms of easily identifiable quantities and material constants. Following the Biot's original theory, the basic dynamic variable in the governing equations are the total stress σ_{ij} (note that tension is here negative), the excess pore pressure p, the solid strain e_{ij} and the variation of the fluid content per unit reference volume ξ with the corresponding conjugate kinematic quantities. The constitutive model can be written in terms of these quantities as (Rice and Cleary, 1976):

$$\sigma_{ij} = 2Ge_{ij} + \lambda\delta_{ij}e - \alpha\delta_{ij}p \tag{1}$$

$$p = -\frac{2GB(1+v_u)}{3(1-2v_u)}e + \frac{2GB^2(1-2v)(1+v_u)^2}{9(v_u-v)(1-2v_u)}\xi \tag{2}$$

where σ_{ij} and p denote the increase in total stress components and pore pressure over the initial equilibrium, respectively. λ, G are the Lame constants of rock material; δ_{ij} is the Kronecker symbol; v and v_u (the range of v_u is $v \sim 0.5$) are the drained and undrained Poisson's ratios; B (ranges from 0 to 1) is the Skempton's pore pressure coefficient. The parameters B and v_u can be used to account for the poroelastic coupling of deformation and flow processes; α is the coefficient of Biot effective stress, the realistic range of variation for α is 0–1, the expression of parameter α is

$$\alpha = \frac{3(v_u - v)}{B(1-2v)(1+v_u)} \tag{3}$$

To obtain some limiting cases, the micromechanical parameters should be dealt with, i.e. the upper bounds for B, v_u and α are simultaneously reached for cases in which both the fluid and the solid constituents are incompressible.

Besides the constitutive Eq. (1), the governing equations for poroelasticity consist of the equilibrium equations:

$$\sigma_{ij,j} = 0 \tag{4}$$

Darcy's law

$$-\frac{k_s}{\gamma_w}p_{,i} = q_i \tag{5}$$

and the continuity equation for the fluid phase

$$\frac{\partial \xi}{\partial t} + q_{i,i} = 0 \tag{6}$$

where k_s is the intrinsic permeability of rock; γ_w is the unit weight of the pore water; q_i is the specific discharge.

Let us consider now a pressure tunnel (shown in Fig. 1) embedded in an infinite porous elastic rock with inner and outer radius r_1 and r_2, respectively. Prior to removal of the material, the porous mass is in situ stress state and that the deformation and redistribution of stress induced by the excavation tends to be stable is assumed before a time-dependent inner water pressure $q(t)$ is applied on the surface of the lining. So, the effect of the in situ stress may not be taken into account. Since the lining and the rock are completely in contact, and the thickness of lining ($h = r_2 - r_1$) is so small with respect to the radius of tunnel, there is no need to distinguish whether the loading is applied at $r = r_1$ or $r = r_2$. As a result, the inner water pressure $q(t)$ can be thought of as acting on the interface of lining and rock. In addition, the tunnel is assumed to be long enough that it can be considered as a plane strain axially symmetric problem.

To obtain the solutions of stress, displacement and pore pressure-induced by inner water pressure acting on the surface of the tunnel in an infinite rock, the field quantities have the form $p = p(r,t)$, $\sigma_{ij} = \sigma_{ij}(r,t)$, $u_r = u_r(r,t)$. The diffusion equation can be derived by combining the governing Eqs. (2), (5), and (6):

$$\frac{k_s}{\gamma_w}\left(\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r}\right) = \alpha\frac{\partial e}{\partial t} + \frac{1}{M}\frac{\partial p}{\partial t} \tag{7}$$

where $M = \frac{2GB^2(1-2v)(1+v_u)^2}{9(v_u-v)(1-2v_u)}$, is Biot's modulus.

With the help of Eqs. (1), (2), and (4), the relationship of volumetric strain and excess pore pressure can be obtained

$$\frac{\partial e}{\partial r} = \frac{\alpha}{\lambda + 2G}\frac{\partial p}{\partial r} \tag{8}$$

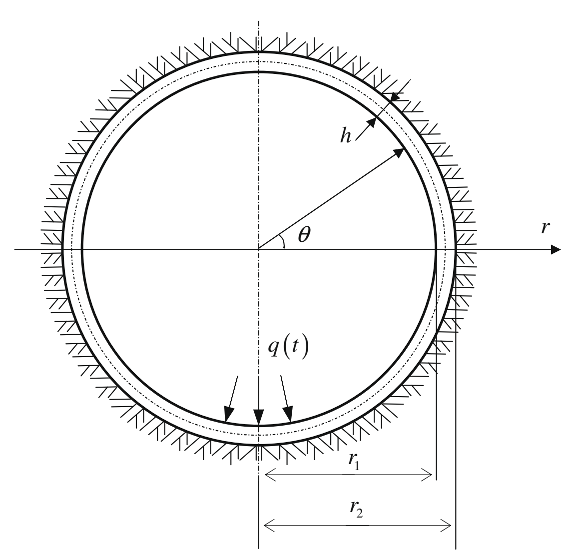

Fig. 1. Geometry of a pressure tunnel.