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Numerical interpretation of transient permeability test in tight rock

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ABSTRACT

Pulse-decay method has been widely used to estimate the fluid transport properties of low-permeability geomaterials. In this context, radial flow transient pulse test is conducted to measure the water permeability of Cobourg limestone hollow cylinder. The proposed method applies hydraulic pulses to the sealed central cavity and then the cavity pressure dissipates as the fluid migrates into the saturated rock matrix. The influence of entrapped air bubbles within the pressurized cavity is crucial to interpreting permeability from transient pulse test. The modeling results indicate that the air inclusions can significantly increase the fluid compressibility and thus delay the hydraulic pulse decay process, which may lead to the underestimation of the rock permeability.

1. Introduction

Permeability has been identified as an important parameter influencing environmental geomechanics problems that deal with groundwater seepage flow (Zhou et al., 2011), deep geological disposal of radioactive nuclear wastes (Delage et al., 2010; Wang et al., 2014), energy extraction from geothermal reservoirs (Tomac and Gutierrez, 2017), and geological sequestration of carbon dioxide (Siriwardane et al., 2016). Considerable laboratory efforts have been devoted to measuring the permeability characteristics of porous geomaterials under different mechanical and environmental conditions (Siriwardane et al., 2009; Chen et al., 2014; Pan et al., 2015; Zhang, 2016).

The pulse-decay method is widely employed to estimate the transport properties of low-permeability rocks (permeability $K < 10^{-18}$ m^2), using either liquid (e.g. water and ethanol) or gas (e.g. nitrogen, argon, and helium) as the permeating fluid (see Table 1). This technique mainly involves the instantaneous pressurization of a fluid volume that is in direct contact with the deformable porous medium and allowing the pore pressure to diffuse through the permeable rock matrix. The decay pattern of the pressure within the fluid-filled pressurization system can be monitored and related to the permeability of the rock quantitatively. The transient test overcomes the difficulties of applying extremely low flow rates and continuing painfully long time required for performing steady-state test on tight rocks.

For hydraulic pulse test, the interpretation of experimental results relies on the numerical analysis of the fluid pressure decay process within pressurized cavity. The coupled hydro-mechanical modeling of hydraulic pulse diffusion through rock matrix should take into consideration the deformability of porous skeleton and the compressibility of permeating fluid. In the conventional mathematical formulation of hydraulic pulse test, it is assumed that both the pressurized cavity and the pore space of the rock matrix are completely saturated with water. However, laboratory experiences show that the air inclusions within the pressurization system cannot be entirely eliminated. The presence of entrapped air bubbles can significantly alter the compressibility of the air–water mixture (Schuurman, 1966; Fredlund, 1976; Nguyen and Selvadurai, 1995; Scherer, 2006), which may influence the transient diffusion of pore water pressure.

Little literature deals with the effects of entrapped air on permeability measurement. Keller and Kamp (1992) presented a method for considering storage due to entrapped air in slug test analysis. They suggested that the air present in the gravel pack or formation surrounding the piezometer intake can increase the storage capacity of the piezometer and thus retard the recovery of water levels due to the high compressibility of air. The delayed hydraulic response may lead to the underestimation of permeability. Scherer (2008) investigated the effects of air inclusions within pore liquid on steady-state permeability test, taking into account the pressure-dependent compressibility of air–water

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Table 1
Selected transient pulse tests on tight rocks.

Research	Rock material	Permeating fluid	Sample geometry	Permeability, K (m^2)
Brace et al. (1968)	Granite	Water/argon	Cylinder	$10^{-21}-10^{-19}$
Neuzil et al. (1981)	Shale	Water	Cylinder	$10^{-19}-10^{-17}$
Bernabé (1986)	Granite	Water	Cylinder	$10^{-21}-10^{-18}$
Escoffier et al. (2005)	Mudstone	Water	Cylinder	$10^{-21}-10^{-20}$
Selvadurai and Jenner (2013)	Limestone	Water	Hollow cylinder	$10^{-22}-10^{-19}$
Pan et al. (2015)	Shale	Helium	Cube	$10^{-21}-10^{-19}$

mixture. The analysis results show that the time required to reach steady flow can be significantly increased by the presence of entrapped air within pore liquid. The general implication of these studies is that the pressurization system should be de-aired and the rock samples should be completely saturated before the permeability tests.

In this context, the permeability of Cobourg limestone is measured by radial flow hydraulic pulse test. The pressurization system is completely sealed with Marine epoxy to avoid any possible pressure leakage. Vacuum suction is applied to the central cylindrical cavity for removing entrapped air bubbles. Pressure pulses in the range of 200 –700 kPa have been applied to the inner cylindrical cavity. The proposed finite difference algorithm is capable of simulating the transient diffusion of pore water pressure through the saturated rock matrix as well as considering the influences of entrapped air bubbles within the pressurized cavity. This method introduces the pressure-dependent compressibility of the air–water mixture into the numerical analysis. Special attention will be given to the interpretation of transient tests under different pressure levels and variable air fractions.

2. Radial flow hydraulic pulse test

The geometric configuration of a typical rock sample utilized for radial flow permeability test is shown in Fig. 1. The rock cylinder contains an inner cavity with diameter of $2a$, outer diameter of $2b$ and height of H. The hydraulic pulse is applied to the inner cylindrical cavity and allowed to diffuse through the tight rock matrix. The gradual dissipation of the cavity pressure can be recorded and then interpreted by either analytical or numerical modeling.

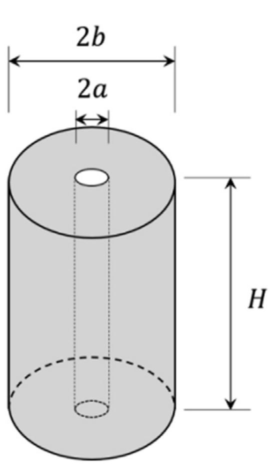

Fig. 1. Geometry of rock sample.

2.1. Analytical modeling

According to Darcy's law, the fluid velocity within a hydraulically isotropic rock can be expressed in the form of

$$\boldsymbol{v} = -\frac{K}{\mu}\nabla p(\boldsymbol{x},t) \tag{1}$$

where $p(\boldsymbol{x},t)$ represents the pore water pressure distribution at time t, $\boldsymbol{x}$ indicates the space coordinates within rock matrix, μ is the dynamic viscosity of water, and K denotes the intrinsic permeability of the rock.

The mass conservation law for a deformable porous medium saturated with a compressible fluid states that

$$S\frac{\partial p(\boldsymbol{x},t)}{\partial t} + \nabla\cdot(\boldsymbol{v}) = 0 \tag{2}$$

where $S = nC_{\rm w} + C_{\rm eff}$ gives the specific storage of the porous medium, n is the rock porosity, $C_{\rm w}$ represents the compressibility of the pore water, and $C_{\rm eff}$ denotes the effective compressibility of the porous skeleton.

Considering the experimental arrangement for radial flow permeability test, the governing equation for the transient diffusion of hydraulic pulse through the cylindrical water-saturated rock is expressed as (Selvadurai and Carnaffan, 1997; Selvadurai and Jenner, 2013):

$$\left[\frac{K}{\mu\left(nC_{\rm w} + C_{\rm eff}\right)}\right]\nabla^2 p(r,t) = \frac{\partial p(r,t)}{\partial t} \tag{3}$$

where

$$\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} \tag{4}$$

Eq. (4) is the radially symmetric form of Laplace's operator in the cylindrical polar coordinate system.

In order to obtain an analytical solution for the hydraulic pulse decay, it is assumed that the pressurized central cavity ($r = a$) is located in an extremely large porous medium ($r \to +\infty$). Previous analysis shows that the difference between semi-infinite and finite cylinders for short-duration pulse tests of typical low-permeability materials is marginal (Selvadurai and Carnaffan, 1997). Thus, for zero-maintained pressure at the remotely located outer boundary, we have

$$p(+\infty,t) = 0 \tag{5}$$

The kinematic constraint for the pressurized fluid within the cavity requires that the rate at which water moves from the pressurized cavity into the porous medium, as expressed by Darcy's law applied to the fluid–rock interface, must be identical to the volume expansion rate of the cavity fluid resulting from hydraulic pulse decay, which is written as

$$2\pi aH\frac{K}{\mu}\left(\frac{\partial p}{\partial r}\right)\bigg|_{r=a} = V_{\rm w}C_{\rm w}\left(\frac{\partial p}{\partial t}\right)\bigg|_{r=a} \tag{6}$$

where $V_{\rm w}$ is the volume of the pressurized fluid within the central cavity.

The initial conditions for the transient pulse test are specified as

$$p(r,0) = \begin{cases} p_0 & (r = a) \\ 0 & (r > a) \end{cases} \tag{7}$$