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Stress-induced permeability changes in Indiana limestone

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ABSTRACT

This paper examines the influence of triaxial stress states with confining stresses between 5 and 30 MPa, including post-failure, on the alteration of intrinsic permeability of Indiana Limestone. The permeating fluid used in the experiments was distilled/de-aired water. Experimental results are used to develop an empirical state space model of permeability evolution due to the action of maximum and minimum principal stresses imposed on the sample. The developed empirical model is implemented in a computational code to examine the influence of stress-induced permeability alterations on the flow into an unlined cylindrical cavity located in a rock mass subjected to geostatic stresses.

1. Introduction

Permeability of rocks is important to many geoenvironmental endeavors influenced by groundwater movement, including, geologic disposal of hazardous and toxic substances (Gnirk, 1993; Selvadurai and Nguyen, 1996; Tsang et al., 2008), energy resources extraction (Harrison, 1983; Boyer et al., 2006; Osborn et al., 2011), and geological sequestration of greenhouse gases (Lemieux, 2011; Selvadurai, 2013). In the majority of these applications, it is understood that the fluid movement in the geological medium at the field scale is an important consideration. Permeability plays an important role in the management of groundwater resources (Bouwer, 2000; Liu et al., 2008). Globally, it is estimated that between 20% to 25% of the world population depends on water supplies extracted from carbonate rocks (Ford and Williams, 2007) and any groundwater contamination from the sequestration, storage or extraction process could adversely affect the fresh water supply.

In conventional studies involving groundwater movement in geological media it is implicitly assumed that permeability is a property that remains unchanged during the flow and transport processes. However, alterations to the stress state in a geological medium and pore fluid pressure-induced damage to the porous system can cause changes to the permeability at both pore and field scale. It is therefore important to assess the influence of the stress state on the development of permeability of rocks. Such considerations are common when dealing with fractured geological media (Boulon et al., 1993; Selvadurai, 2015). Examples of instances where the permeability can be influenced by the alteration in the stress state due to engineering activities are shown in Fig. 1.

The experiments of Fatt and Davis (1952) and Fatt (1953) described alterations in the permeability of sandstones, with porosities ranging from 15% to 22%, during the application of isotropic compression, where a decay in permeability was attributed to effects such as pore collapse and fabric compaction. Other examples of permeability *reduction* during the application of largely isotropic compression are given by McLatchie et al. (1958) and Wyble (1958). Brace et al. (1968) deal with the permeability changes in Westerly Granite during the application of very high (400 MPa) confining stresses. Permeability reduction with isotropic compression was also observed by Bernaix (1966), Gangi (1978), Kranz et al. (1979), Wright et al. (2002) and Lion et al. (2004). Selvadurai and Głowacki (2008) also observed a permeability reduction with increasing isotropic compression of Indiana Limestone and permeability hysteresis during unloading. With heterogeneous geological media, the external application of isotropic compression can also lead to the development of non-uniform stress states in the internal fabric of the geological medium that can result in an *increase* in permeability. An increase in permeability in the argillaceous Cobourg Limestone under isotropic compression was observed by Selvadurai et al. (2011). The work of Keaney et al. (1998) on sandstones demonstrated that in the "*brittle faulting regime*", under deviatoric compressive stresses, the permeability decreases until failure, after which the increase is controlled by the properties of the fracture. Further examples of permeability evolution in geomaterials are given by Selvadurai (2004) and Selvadurai and Ichikawa (2013).

The change in permeability in the vicinity of excavation damage zones is an important consideration with regard to fluid movement around repositories constructed for the deep geological storage of

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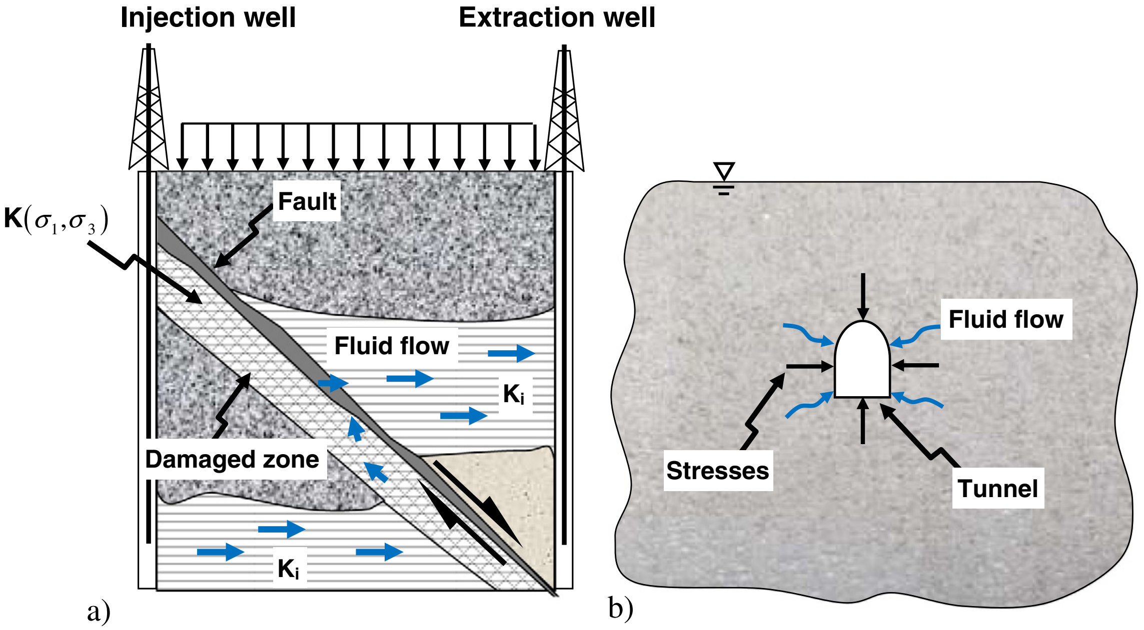

Fig. 1. (a) Hydrocarbon extraction near a fault zone with permeability variations due to stress (Matthäi and Roberts, 1996); (b) Tunnel subjected to geostatic stresses and influx of water.

hazardous materials. Souley et al. (2001) describe the excavation damage-induced increase in permeability, up to four orders of magnitude, in granite from the Canadian Shield. The recent study by Massart and Selvadurai (2012) developed a multi-scale computational approach to relate the permeability evolution to the isotropic and deviatoric stress states where the micro-mechanical processes at the grain-scale incorporate both Coulomb-friction and dilatant friction.

The novelty in this research is that it investigates the evolution of intrinsic permeability with distilled/de-aired water in eleven cylindrical samples of Indiana Limestone when the triaxial stress state is changed, including post failure, using the steady state flow method. Azeemuddin et al. (1995) used an oscillating pulse to estimate the permeability of Indiana Limestone under triaxial compression: at low confining pressures (6.9 MPa); permeability decreased until the initiation of dilatancy, beyond which it increased. At high confining pressures, dilatancy is suppressed and the permeability decrease continues due to pore compression. Leith et al. (1996) tested cores of Salem Limestone subjected to a net radial confining stress of 3.445 MPa and used air injection techniques to determine the absolute and relative permeabilities. They concluded that a large portion of the porosity is intragranular, since the carbonate grains hold static water, which contributes very little to fluid transport. Suri et al. (1997) and Dautriat et al. (2011) reported a reduction in permeability ranging from 25% to 80% for triaxial tests performed on Indiana Limestone and Estaillades Limestone, respectively, at effective confining pressures ranging between 6.9 MPa and 48.3 MPa. Additional research (Selvadurai and Głowacki, 2008; Selvadurai and Selvadurai 2007, 2010 and 2014) has examined the fluid transport properties of Indiana Limestone in either an isotropic stress state or an unstressed state. This research extends the previous ones and culminates in the development of a "*State-Space Permeability Evolution Model*", which provides an analytical result to describe the variation in permeability of the Indiana Limestone in the compressive stress range involving σ_1 and σ_3 for relatively large samples (85 mm in diameter and 170 mm in height). The larger samples used in the current research ensures a more representative volume element that includes more of the defects and effectively includes more microstructural heterogeneities. The state space approach has been successfully applied to examine the thermo-hydro-mechanical behavior of clay barriers proposed for use in nuclear waste management endeavors (Nguyen et al., 2005). The model is implemented in a computational procedure that accounts for stress-dependent permeability evolution and is used to examine the flow into an excavated circular cavity (tunnel) in an elastic geomaterial under geostatic stresses. The influence of the stress-induced permeability alteration on the flow rate to the cavity is estimated.

2. Theoretical background

The fundamental law governing fluid flow through an isotropic porous medium was proposed by Darcy (1856) (see e.g. Harr, 1962; Bear, 1972; Selvadurai, 2000; Ichikawa and Selvadurai, 2012). From Darcy's Law, the fluid flow in a porous medium is governed by the gradient in the reduced Bernoulli potential (hydraulic head) $\varphi(\mathrm{x})$, which consists of the pressure potential (pressure head) $\varphi_P(\mathrm{x})$and the datum potential (elevation head) $\varphi_D(\mathrm{x})$, while the velocity potential is neglected in relation to these. In its general form, Darcy's Law can be written as:

$$\mathbf{v}(\mathbf{x}) = -\frac{K\gamma_w}{\mu}\nabla\varphi(\mathbf{x}) \tag{1}$$

where v(x)is the velocity vector (units L/T) or specific discharge (Darcy's velocity), K is the permeability (units L^2), γ_w is the unit weight of water (units $\mathrm{M/L^2T^2}$), μ is the dynamic viscosity of water (units M/TL), ∇ is the gradient operator and $\boldsymbol{x}$ is a position vector. When permeability is estimated from one-dimensional experiments, where fluid pressures (units $\mathrm{M/T^2L}$) are prescribed at the inlet (p_i) and the outlet (p_o) locations, the permeability (K) can be calculated from the elementary result:

$$\boldsymbol{K} = \frac{\boldsymbol{Q\mu L}}{\boldsymbol{A}(\boldsymbol{p}_\mathrm{i}-\boldsymbol{p}_\mathrm{o})} \tag{2}$$

where $\boldsymbol{Q}$ is the flow rate (units L^3/T), $\boldsymbol{L}$ is the length of the sample (units L) and $\boldsymbol{A}$ is the cross sectional area of the sample perpendicular to the nominal flow direction (units L^2).

3. Materials

The Indiana Limestone was supplied by Les Carrières Ducharme Inc., Québec, in blocks measuring 35 cm × 47 cm × 91 cm. It was quarried