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# Effective poroelastic behavior of a jointed rock

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ABSTRACT

A main characteristic of rock masses is the presence of natural fractures (or joints) at different scales. The effective mechanical behavior of a rock medium is strongly affected by that of the joints, which can be viewed as cracks able to transfer stresses. The purpose of the present paper is to formulate the macroscopic poroelastic behavior for a rock with fluid-saturated joint network. The joints are modeled as interfaces whose behavior is described by means of generalized poroelastic state equations. Particular emphasis is given to the situation of small extension joints for which micromechanics-based expressions of the poroelastic properties are derived. Finally, the accuracy of the micromechanical predictions is assessed by comparison with 2D finite element solutions based on the cohesive model.



## 1. Introduction

It is well-known from observations made at different scales that rock masses generally exhibit discontinuity surfaces of various sizes and orientations, commonly referred to as joints. Since joints represent surfaces of weakness along which sliding can occur and preferential channels for fluid flow, their presence is a fundamental weak component for stability and safety of many rock engineering structures, such as dam foundations, underground caverns, oil wells or toxic waste storage facilities. A comprehensive modeling of a rock mass behavior should thus incorporate a reliable description of the hydromechanical coupling that governs the joint deformation.

Strength, deformation and permeability coupling of rock joints have been widely investigated during the previous decades, leading to numerous experimental works and models. Among the pioneering works, one may quote the contributions due to Goodman (1976) and Bandis et al. (1983). Representative works include references (Barton et al., 1985; Plesha, 1987; Saeb and Amadei, 1992; Ng and Small, 1997; Nguyen and Selvadurai, 1998; Lee et al., 2001; Olsson and Barton, 2001; Indraratna and Ranjith, 2001; Boulon et al., 2002; Bart et al., 2004; Lui et al., 2009), to cite a few.

However, most of the hydromechanical models have focused on the connection between the joint aperture due to applied stresses and the permeability. The effect of fluid pressure on joint deformation have been either neglected or not properly accounted for. Few models have addressed the fully hydromechanical coupling in rock joints (Ng and Small, 1997; Bart et al., 2004; Maghous et al., 2013).

Conceived as a potential alternative to the discrete methods in which the individual joints and the rock matrix are handled separately, the homogenization approach adopts a continuum formulation for the constitutive behavior of the jointed rock material, which is regarded as a homogenized medium. In this context, a recent paper by Maghous et al. (2013) proposed a general micromechanics-based approach to poroelastic behavior of a jointed rock. These authors addressed the particular case of a rock matrix cut by a network of parallel short joints. The main purpose of the present contribution is to extend the previous formulation to the situation of a rock medium containing randomly oriented joints. Emphasis shall be given to derive closed-form expressions for the tensor of homogenized drained moduli, as well as for the effective Biot tensor and modulus. A primary objective of the analysis is to highlight the effect of fluid pressure in the interstitial space of rock short joints on the overall poroelastic properties of the rock mass. Adopting a simplified two-dimensional setting, the accuracy of the micromechanical predictions is assessed by comparison with finite element solutions based on the cohesive model (Needleman, 1987; Xu and Needlman, 1996). It should be emphasized that, unlike the classical model of cracks in which no stresses are transferred across the cracks, the joints are in fact fractures that are able to transfer normal as well as tangential stresses.

## 2. Micromechanics

Let $\Omega$ denote the representative elementary volume (REV) of a homogeneous rock matrix cut by a discrete distribution of short

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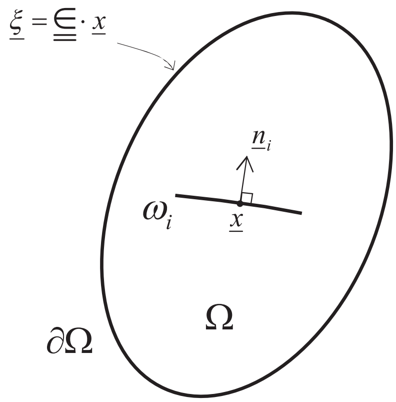


**Fig. 1.** REV of a jointed rock and loading conditions.

joints $\omega = \underset{i}{\cup}\omega_i$ (Fig. 1). Adjective 'short' refers to joints with small extension when compared to the size of the REV. It is noted that short joints are in fact microfractures (or microcracks) that are able to transfer stresses. It is also noted that the concept of REV implies the scale separation between its characteristic length and those of joints, namely the size of short joints.

The rock matrix fills the domain $\Omega\backslash\omega$, where symbol $\backslash$ stands for the set difference. Note that strains and stresses within the rock medium are defined on the rock matrix domain $\Omega\backslash\omega$ only, and not on the whole REV. Throughout the paper, symbol $\langle\cdot\rangle$ denotes the volume average over the rock matrix:

$$\langle\cdot\rangle = \frac{1}{|\Omega|}\int_{\Omega\backslash\omega} .dV \tag{1}$$

At the scale of the REV (microscopic scale), each joint is modeled as an interface $\omega_i$, whose orientation is defined by a normal unit vector $\underline{n}_i$ (see Fig. 1).

### 2.1. Hill's lemma for the jointed medium

The loading applied to the REV is defined by homogeneous strain type boundary conditions on the boundary $\partial\Omega$:

$$\underline{\xi}(\underline{x}) = \underline{\underline{\in}} \cdot \underline{x} \quad \forall \underline{x} \in \partial\Omega \tag{2}$$

where $\underline{\underline{\in}}$ represents the macroscopic strain and $\underline{x}$ is the position vector. Hill's lemma reads in the situation of a jointed medium (e.g., Maghous et al., 2008)

$$\langle\underline{\underline{\sigma}}\rangle : \underline{\underline{\in}} = \langle\underline{\underline{\sigma}} : \underline{\underline{\varepsilon}}\rangle + \frac{1}{|\Omega|}\int_{\omega} \underline{T} \cdot [\underline{\xi}] dS \tag{3}$$

for any statically admissible stress field $\underline{\underline{\sigma}}$ and any kinematically admissible displacement field $\underline{\xi}$. Tensor $\underline{\underline{\varepsilon}}$ represents the linearized strain associated with displacement $\underline{\xi}$ and $[\underline{\xi}]$ is the displacement jump at the joint interface. In the above equation, $\underline{T}$ is the stress vector acting upon the joint.

The strain average rule relating the macroscopic strains to the local strains writes

$$\underline{\underline{\in}} = \langle\underline{\underline{\varepsilon}}\rangle + \frac{1}{|\Omega|}\int_{\omega} [\underline{\xi}] \overset{s}{\otimes} \underline{n} dS \tag{4}$$

where $\underline{n} = \underline{n}_i$ along $\omega_i$ and symbol $\overset{s}{\otimes}$ stands for the symmetric part of dyadic product: $\left(\underline{u}\overset{s}{\otimes}\underline{v}\right)_{ij} = (u_i v_j + v_i u_j)/2$. Identity (4) physically means that the macroscopic strain $\underline{\underline{\in}}$ is the sum of two contributions, namely that of the rock matrix strains and that of the displacement jump along the joints.

### 2.2. Formulation of the poroelastic state equations

We consider the situation where the connected joint network is saturated by a fluid at pressure $p$, which is assumed to be uniform in the REV. The rock matrix is assumed to be linearly elastic with fourth-order stiffness tensor $\mathbb{C}^s$: $\underline{\underline{\sigma}} = \mathbb{C}^s : \underline{\underline{\varepsilon}}$ in $\Omega\backslash\omega$. A poroelastic formulation is adopted for the behavior of the joints in order to account for the effect of the fluid pressure on the relationship between the stress vector acting on the joint and the corresponding relative displacement. The poroelastic state equations for the joints are written in the following form (Bart et al., 2004; Maghous et al., 2013)

$$\begin{cases} \underline{T} = \underline{\underline{\sigma}} \cdot \underline{n} = \underline{\underline{k}} \cdot [\underline{\xi}] + \underline{T}^p \\ \varphi = \dfrac{p}{m} + \alpha[\underline{\xi}] \cdot \underline{n} \end{cases} \quad \text{along } \omega = \underset{i}{\cup}\omega_i \quad (\text{with } \underline{n} = \underline{n}_i \text{ along } \omega_i) \tag{5}$$

where

$$\underline{\underline{k}} = \underline{\underline{k}}^i, \quad \alpha = \alpha_i, \quad m = m_i, \quad \underline{T}^p = -\alpha_i p \underline{n}_i \quad \text{along} \quad \omega_i \tag{6}$$

$\underline{\underline{k}}^i$ is the stiffness of joint $\omega_i$, relating the stress vector to the displacement jump in drained conditions $p = 0$. Scalar $\alpha_i$ has the significance of a Biot coefficient for the joint $\omega_i$ modeled as a generalized porous medium. This means that the displacement jump $[\underline{\xi}]$, which represents the joint deformation, is controlled by the effective stress vector $\underline{T} + \alpha p \underline{n}$. The second state equation in (5) relates the joint pore change per unit joint surface $\varphi$ to the fluid pressure $p$ and the joint displacement jump $[\underline{\xi}]$. Scalar $m_i$ represents the Biot modulus for joint $\omega_i$. Physical interpretation as well

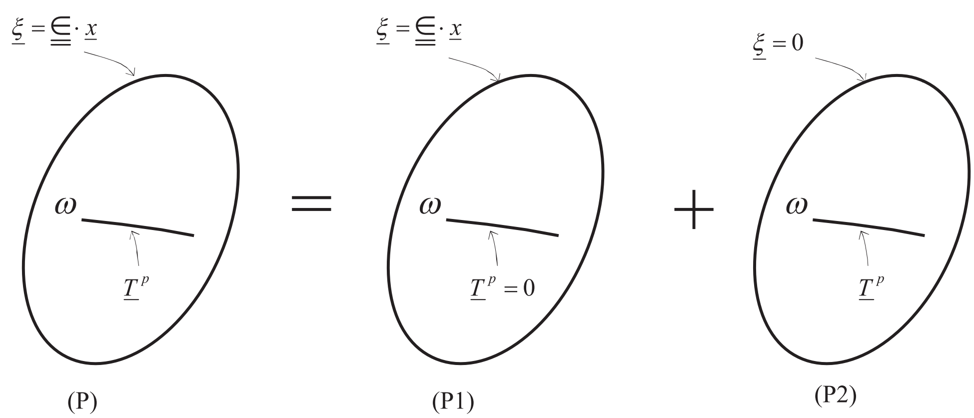


**Fig. 2.** Decomposition of problem (P) into two elementary problems (P1) and (P2).