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Hydro-mechanical description of fractured porous media based on microporomechanics

R.G. Wan*, M. Eghbalian

Civil Engineering Department, Schulich School of Engineering, University of Calgary, AB, Canada

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ABSTRACT

The fracture behaviour of cemented materials such as rock consisting of randomly distributed microcracks is addressed within a coupled physics and Hydro-Mechanical (HM) framework. Average-field theory is used to formulate a continuum description of such heterogeneous material based on observed microscale physical mechanisms in the fully saturated case. A representative elementary volume (REV) of the medium is considered over which governing field variables for both solid and liquid phases, including the underlying constitutive relations, are averaged based on a detailed description of the microstructure. Hence, coupled fluid flow and deformation mechanisms of an effective homogeneous porous medium can be ultimately described based on the micromechanical properties of both solid and fluid phases. The presence of heterogeneities in the form of distributed microcracks is described using an anisotropic formulation and considering a one-way coupled problem wherein fluid pressures impact on stress and strain fields, but not vice versa. The macroscopic behaviour is then described by relating the relevant macroscale quantities together using a suitable homogenization scheme. It is shown through various numerical examples that the model captures most of the salient underlying physics of HM behaviour of fractured porous medium due to the microporomechanical approach adopted in this study.

1. Introduction

Porous media with microfractures are special cases of dual porosity systems that encompass a wide range of natural or damaged geomaterials such as soils, rocks and some cement-based materials. Investigating the behaviour of such materials has been the subject of many researches in the past few decades. The study of porous media is important because of their ability to store and transmit fluids, especially extremely low permeability rocks in tight gas reservoirs with a permeability of less than 0.1 milliDarcies (Sonntag et al., 2014). It is known that rocks are comprised of a porous matrix which is randomly dispersed with microcracks in their natural state. They also often constitute cavities at a wide range of length scales—from less than 5% to as high as 40% of their volume (Tan and Konietzky, 2014). These cavities have different shapes, sizes and orientations depending on the type of rock. As the low permeability of rock formations hinders the production process by limiting the oil and gas flow rate, research works have been directed towards developing a better understanding of the HM behaviour of rocks as a fractured porous media in order to optimize the Hydraulic Fracturing (HF) process for enhancing the oil and gas recovery.

Most of the developed phenomenological poroelastic models are based on the pioneering work of Maurice A. Biot (1905–1985) in 1941, who extended Hooke's law to isotropic poroelastic solids. He later developed the model for the anisotropic case. Since then, various methods have been proposed to derive the macroscopic poroelastic behaviour of saturated porous medium based on micromechanics. A comprehensive review of these methods is presented in Xie et al. (2013). However, it is known that both the emergence and growth of microcracks have a dominant affect on the HM behaviour of porous materials. A few of the phenomenological and micromechanical constitutive equations of the cracked material can be found in the works of Fanella and Krajcinovic (1988); Halm and Dragon (1996); Nemat-Nasser and Obata (1988); Prat and Bažant (1997) where only the mechanical behaviour is treated. A comprehensive discussion on the effective mechanical characterization of single porosity media containing different shapes of cavities (crack, vugs, etc.) in two and three dimensions based on micromechanics is presented by Nemat-Nasser and Hori (1993). These models neglect the effect of HM coupling on the behaviour of fractured medium. However, we know that the role of fluid flow on the mechanical behaviour of cracked porous materials is of vital importance. It is only through the coupling of fluid

* Corresponding author.
E-mail address: wan@ucalgary.ca (R.G. Wan).

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flow with deformation equations using a robust strategy that we can study the effect of hydraulic loading on fracture behaviour, and hence changes in HM properties of porous media. In this regard, the HM description of single porosity media was investigated in detail for three dimensional cavities by Dormieux et al. (2006). Also, a combination of experimental observations and micromechanics is used in the semi-empirical model proposed by Shao et al. (2005) where an anisotropic damage parameter is coupled within the poroelastic governing equations, the evolution of which is controlled by a phenomenological equation based on Linear Elastic Fracture Mechanics (LEFM).

Generally speaking, the mechanical behaviour of materials can be studied at three different length scales. We herein recall that the engineering scale is called macroscale, while the mesoscale (material point level) is an intermediate length scale where local variations in loads and/or compositions take place. Finally, the microscale is where the interaction of the various constituents are accounted for. Bridging between these scales is possible through either the so-called *Localization* scheme, which is the transfer from macroscale to microscale, or *Homogenization*, where a reverse transfer occurs. To facilitate the solution of boundary value problems involving the hydromechanics of porous materials, it is ideal to develop a framework capable of describing the effective behaviour of such systems at the macroscale rather than dealing with complex multiphasic phenomena occurring at the microscale involving coupled physics. In this regard, multiscale modelling of materials which involves predicting the macroscopic response based on the underlying microscale behaviour, has been the subject of many researches in the past few decades. It is an important tool used to derive the effective properties of bodies including microfractures. Various computational (either analytical or numerical) techniques have been developed and used in the literature to derive the homogenized effective properties of microheterogeneous materials.

Computational homogenization methods include both analytical and numerical calculations. In the latter approach, a specific phenomenological form is usually assumed for the homogenized material behaviour and numerical analysis results are fitted to it to obtain the macroscopic properties (see e.g. Van der Sluis et al., 1999; Smit et al., 1999; Mchugh et al., 1993). However, in the case of large deformations and nonlinear behaviour of materials, the form of the macroscopic governing equations is difficult to guess. To overcome this difficulty, multiscale numerical homogenization methods have been proposed, in which brute force numerical simulations play the role of constitutive equations (see e.g. Kouznetsova et al., 2001). Although numerical techniques allow us to account for complex microstructures and the effect of various microstructural features, the computational effort is usually very high and they cannot be implemented in standard simulation software in contrast to their analytical counterparts. Moreover, it is difficult to model realistically the actual microstructure of the heterogeneous material and some simplified model should be advocated.

On the other hand, apart from bounding methods which provide the upper and lower bounds (like Voigt and Reuss bounds) for the overall properties (e.g. Suquet and Ponte Castaneda, 1998; Willis, 1981), two basic analytical approaches have been introduced in the literature for obtaining the overall response: (1) the average-field theory (mean-field theory), and (2) the homogenization theory. Homogenization theory assumes a periodic microstructure and utilizes the multiscale asymptotic expansion method to upscale the microscale fields (see e.g. Benoussan et al., 1978; Sanchez-Palencia, 1980). On the other hand, the average-field theory defines the macrofields as the volume average of the microscale fields. A comprehensive overview of the above two analytical approaches and different averaging schemes for the average-field theory can be found in the works of Aboudi et al. (2012); Nemat-Nasser and Hori (1993).

In this paper, we work out a novel continuum description of HM coupling in a saturated fractured rock with an arbitrary distribution of strong kinematic discontinuities, representative of a class of dual porosity media. The analysis is carried out in the context of average-field theory and based on observed microscale phenomena. A representative elementary volume (REV) of the medium is investigated to obtain the macroscopic constitutive equations governing the HM behaviour resulting from the interaction of both solid and fluid phases. The procedure considers a detailed description of the microstructure through a two-stage homogenization process. Fig. 1 shows the hierarchy of scales dealt with in such a process. The left figure is related to a typical triaxial test on sedimentary rock samples at the scale of 10 mm. The middle figure is a Scanning Electron Microscopy (SEM) image of microcracks and pores at 50 μm scale (mesoscale) that can be attributed to one material point within the macroscopic sample. The idealized picture of the porous matrix/microcracks assembly is given in the bottom figure. Finally, the right figure depicts the nanoscopic image (200 nm scale) of the porous matrix where the geometry and arrangement of nanopores can be identified. We should mention that the above-mentioned figures do not belong to the same sample or material, but originate from different kinds of sedimentary rocks gathered here solely to illustrate the hierachical nature of the scales.

The paper is presented in three main parts. In the first part, the HM behaviour of the intact rock (matrix) is recovered based on the work of Dormieux et al. (2006). Herein, a random distribution of nanopores has been considered, leading to an isotropic behaviour of the matrix. In the second part, we investigate the effect of distributed strong discontinuities on the overall behaviour of the fractured rock, especially, by invoking Biot's coefficient as a tensorial quantity. It is the microcracks at the mesoscale that confer various anisotropies to material behaviour. Very few material parameters are involved in the proposed model, which are basically the mechanical parameters intrinsic to the microconstituents of the porous material. Finally, in the third part, the robustness of the proposed formulation is studied through various illustrative examples comparing the results of the current work with numerical simulations reported in the literature.

2. Hydro-poroelasticity of the intact rock

As introduced in Section 1, the analytical homogenization process seeks for a macroscopic homogeneous description of a microheterogeneous material point of the medium through either an averaging procedure or a perturbation method. A schematic structure of such a micromechanical framework is illustrated in Fig. 2. According to the average-field theory, details of the macroscopic state at a given material point can be worked out by probing into an underlying microscale state as a boundary value problem (BVP) defined over the REV. The solution of this so-called microscopic BVP indeed captures features of microscale heterogeneities and their interactions. The average-field treatment advocates a one-to-one relationship between the variables in the microscale and macroscale problems through a simple volume averaging rule. Furthermore, the input to the microscale BVP is the macroscale state subset applied as loading and boundary conditions. A *Localization* step then follows in order to solve the BVP by exploiting the microscale behavioural equations of individual heterogeneities, including interface conditions between them. Finally, the macroscopic response subset is determined as a simple volume average of the corresponding microscale field through the so-called *Homogenization* stage.