International Journal of Rock Mechanics & Mining Sciences 70 (2014) 593–604

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Computational modelling of crack-induced permeability evolution in granite with dilatant cracks

T.J. Massart [a,*], A.P.S. Selvadurai [b]

[a] Building, Architecture and Town Planing Department CP 194/2, Université Libre de Bruxelles (ULB), Av. F.-D. Roosevelt 50, 1050 Brussels, Belgium
[b] Department of Civil Engineering and Applied Mechanics, McGill University, 817 Sherbrooke Street West, Montreal, Canada H3A 2K6

ARTICLE INFO

Article history:
Received 7 August 2012
Received in revised form
21 April 2014
Accepted 21 June 2014
Available online 21 July 2014

Keywords:
Stress-induced permeability alteration
Computational homogenisation
Multiscale modelling
Dilatant plasticity
Triaxial loading
Fluid transport

ABSTRACT

A computational homogenisation technique is used to investigate the role of fine-scale dilatancy on the stress-induced permeability evolution in a granitic material. A representative volume element incorporating the heterogeneous fabric of the material is combined with a fine-scale interfacial decohesion model to account for microcracking. A material model that incorporates dilatancy is used to assess the influence of dilatant processes at the fine scale on the averaged mechanical behaviour and on permeability evolution, based on the evolving opening of microcracks. The influence of the stress states on the evolution of the spatially averaged permeability obtained from simulations is examined and compared with experimental results available in the literature. It is shown that the dilatancy-dependent permeability evolution can be successfully modelled by the averaging approach.

1. Introduction

The isothermal mechanical behaviour of fluid-saturated porous media is described by Biot's theory of poroelasticity [1]. This theory has been successfully applied to describe many types of geomaterials as illustrated in the reviews presented in [2–6]. It accounts for the coupling between the porous fabric and the fluid saturating the pore space, often with the implicit assumption that the material properties such as porosity and permeability remain unchanged during the coupled interaction. However, it is known that such properties can evolve as a result of mechanical, thermal or chemical actions. A number of experimental contributions have identified the potential effect of stress states at the micromechanical level on the permeability of porous media. Experimental results presented in [7–10] show substantial evolution of permeability in granite and limestone samples associated with microcracking under deviatoric stresses. Such permeability alterations in turn may strongly affect the poromechanical processes that control pore fluid pressure dissipation.

In addition to these experimental procedures, computational approaches have recently been utilised to evaluate the effective properties of heterogeneous porous media [11,12]. Computational homogenisation principles have been employed to evaluate damage-induced permeability alterations [13]. The versatility of this approach is that it enables the incorporation of a variety of micromechanical constitutive laws to investigate the potential influence of various features or phenomena, such as the local fabric of geomaterials, inter- and trans-granular cracking, or pore closure on parameters such as permeability. The effect of damage was investigated in [13] using a phenomenological description of intergranular cracking at the scale of the constituents. In addition to disregarding transgranular cracking and to maintain a purely phenomenological approach, Ref. [13] neglects the effect of plastic dilatancy, which is often considered to be one of the main causes of permeability evolution associated with micro-cracking [14–16].

Dilatancy is a material property that is difficult to evaluate experimentally, which may explain why it usually receives less attention in routine engineering applications [17]. Various authors have investigated dilatancy aspects and its potential dependence on the confining stress and plastic shearing [17–21].

Regarding the effects of microcracking on the average response of rocks, a number of important contributions were published based on approaches of phenomenological and micromechanical nature. The works by Kachanov and co-workers investigated the influence of microcracks on the material behaviour by analysing the effect of frictional cracks on stress-induced anisotropy [22] and on the propagation of secondary cracks together with local dilatancy [23]. Subsequent efforts along these lines focused on characterising computationally the mechanics of crack–microcrack

---

[*] Corresponding author: Tel.: +32 2 650 27 42; fax: +32 2 650 27 89.
E-mail address: thmassar@ulb.ac.be (T.J. Massart).
URL: http://batir.ulb.ac.be (T.J. Massart).

http://dx.doi.org/10.1016/j.ijrmms.2014.06.006
1365-1609/© 2014 Elsevier Ltd. All rights reserved.

interactions [24] and the effects of microcrack interaction on elasticity properties [25]. Other contributions dealt with the potential use of crack interaction features to model crack coalescence [26], and with the validation of the use of the penny-shaped crack effective medium theory for irregular fractures, see [27]. Contributions using such penny-shaped crack approximations were also provided in [28] to investigate the link between macroscopic dilatancy and multiscale friction and, recently, in [29] to incorporate the effect of initial stresses in microcrack-based models. Another significant stream of research for models incorporating cracking effects was proposed by Dragon and co-workers initially based on a micromechanically motivated decomposition in the frame of thermodynamics of irreversible processes, see [30]. This approach was progressively developed, focusing on volumetric dilatancy, pressure sensitivity and stiffness recovery [31]; and on the interaction between initial and cracking-induced anisotropy [32]. The effect of anisotropic damage and unilateral effects on the elastic behaviour was analysed in [33]; subsequent evolutions of the approach were proposed to account for discrete orientations of cracking in the formulation of thermodynamical potentials [34,35].

The coupling between microcracking and fluid transport phenomena was also investigated using penny-shaped crack approximations in [36] for permeability alterations; as well as for crack propagation [37]. This methodology was used in [38] to link microdamage and macrodamage tensors to permeability evolution using 2D cuts of 3D representative volume elements (RVEs) containing discrete cracks. Non-evolving discrete fracture networks (DFN) were also used in several contributions. Such approaches were used in [39] to compute permeability tensors from 2D geometrical models for macroscopic fractures. 2D discrete fracture networks were also used in [40,41] to compute equivalent permeability with statistical distributions of fracture lengths and apertures, in [42] with a discussion on the existence of a RVE, and in [43] to analyse equivalent permeability as a function of discrete fracture networks properties. The coupling between the mechanical behaviour and DFN approaches uses discrete element formulations (DEM) as performed in [44] to deduce stress-dependent equivalent permeabilities for 2D RVEs incorporating fracture dilation. DEM was also combined with DFNs to assess stress-induced permeability evolution using 2D models in [45,46], and to compute bounds on 2D permeability for 3D discontinuity networks using constant flux and linear pressure boundary conditions on RVEs [47].

In view of these contributions, there is an interest for an approach that allows investigating the link between the dilatancy parameters postulated at the scale of evolving microcracks and the permeability evolution in rocks at the macroscopic scale. The main objective of this paper is to show that the homogenisation scheme presented in [13] allows for the computational assessment of the dilatancy-dependent permeability evolution in a granitic material, based on the simplest possible dilatant crack formulation at the scale of the heterogenous fabric of the material. Unlike the phenomenological approach used in [13], the coupling between cracking and local permeability evolution will be directly based on the opening of microcracks caused by the externally applied stress state and the local dilatancy. This effort should be considered in a broader context in which computational homogenisation is used as a generic methodology to assess the effect of specific fine scale phenomena and microstructure evolution on average properties, thereby paving the way for the incorporation of other evolving fine scale features, such as crack closure or pore collapse.

The paper is structured as follows: Section 2 will briefly outline the essential aspects of the averaging scheme used to extract the averaged mechanical and transport properties from representative volume elements (RVEs) of an heterogeneous material. The dilatant plastic interface formulation used in the simulations, which is based on the mechanical parameters such as cohesion, tensile strength and their corresponding fracture energies, will be presented in Section 3 . The coupling applied between the local cracking state and the local permeability evolution is also presented in Section 3. These procedures are used in Section 4 to estimate the variation of permeability of a granitic material with the confining pressure and the deviatoric stresses applied in triaxial testing. The results obtained are compared with experimental data on both the mechanical response and the permeability evolution, leading to a detailed assessment of the influence of the fine scale parameters. The results are discussed in Section 5, and concluding remarks are given in Section 6.

2. Computational homogenisation of mechanical and transport properties

Computational homogenisation techniques were initially used in the field of mechanics of materials to extract average properties of heterogeneous materials [48,49]. They allow the identification of the macroscopic constitutive parameters or the investigation of the behaviour of heterogeneous materials by using scale transitions applied to RVEs, based on averaging theorems and laws postulated for constituents of the microstructure. Geomechanical applications of multi-scale techniques have mostly focused on the extraction of average properties of *non-evolving microstructures* for uncoupled mechanical [50,51] and fluid transport [40,41,47] processes in geomaterials. Computational homogenisation was reformulated to allow nested scale computational schemes in which finite element discretisations are used at both the macroscopic and fine scales simultaneously, which avoids the use of a priori postulated macroscopic laws [52]. This methodology was subsequently adapted to model the failure of quasi-brittle materials [53,54], as well as diffusive phenomena such as thermal conductivity [55,56]. In the recent study [13], these techniques were combined to evaluate damage-induced permeability evolutions in a geomaterial. The essential features of this approach are summarised here for completeness. The detailed derivation of the averaging relationships can be found in [13] and references therein.

The homogeneous equivalent mechanical properties of a material with a heterogeneous microstructure can be deduced by applying a loading to an RVE containing the main microstructural features of the material, and solving the corresponding equilibrium problem [52]. When a macroscopic strain $\mathbf{E}$ is applied to an RVE, the displacement of a point inside the RVE can be written as

$$\vec{u}(\vec{x}) = \mathbf{E}\cdot\vec{x} + \vec{u}_f(\vec{x}) \tag{1}$$

where $\vec{x}$ is the position vector within the RVE and $\vec{u}_f$ is a fluctuation field caused by the heterogeneity of the material. Assuming that the fluctuation $\vec{u}_f$ is periodic, one can show that the macroscopic strain is the volume average of the fine-scale strain field $\boldsymbol{\varepsilon}$ resulting from (1)

$$\mathbf{E} = \frac{1}{V}\int_V \varepsilon\, dV \tag{2}$$

Using the Hill–Mandel condition (energy equivalence between the fine-scale and macroscopic descriptions) written as

$$\boldsymbol{\Sigma} : \delta\mathbf{E} = \frac{1}{V}\int_V \boldsymbol{\sigma} : \delta\boldsymbol{\varepsilon}\, dV \tag{3}$$

the macroscopic stress tensor is obtained as the volume average of the microstructural stress tensor, or equivalently by a summation