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A multiscale microstructural model of damage and permeability in fractured solids

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Abstract

Deterioration of mechanical and hydraulic properties of rock masses and subsequent problems are closely related to changes in the stress state, formation of new cracks, and increase of permeability in porous media saturated with freely moving fluids. We describe a coupled approach to model damage induced by hydro-mechanical processes in low permeability solids. We consider the solid as an anisotropic brittle material where deterioration is characterized by the formation of nested microstructures in the form of equi-distant parallel faults characterized by distinct orientation and spacing. The particular geometry of the faults allows for the analytical derivation of the porosity and of the anisotropic permeability of the solid. The approach can be used for a wide range of engineering problems, including the prevention of water or gas outburst in underground mines and the prediction of the integrity of reservoirs for underground CO_2 sequestration or hazardous waste storage.

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1. Introduction

Fractures and discontinuities are among the most important features of geological structures. In natural rock formations, fractures and other types of discontinuities facilitate storage and movement of fluids, representing the

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most efficient conduit for fluid flow [1]. Despite the current availability of fault and fracture mappings in reservoirs, the understanding of the influence of these structures on fluid flow is nowadays not satisfactory, in particular when mechanical coupling is significant. The complexity of fault geometry and topology is an additional issue. In fact, each group or class of faults is characterized by different orientation, spacing, distribution and connectivity, affecting the entrapment of fluids, limiting or enhancing fluid flow in a particular environment [2]. In engineering technology fracture processes are often exploited, for example to improve the production and optimize well stimulation in low permeability reservoirs, to prevent water or gas outburst in underground mines, to predict the integrity of reservoirs for underground CO_2 sequestration or hazardous waste storage, and in various other areas of application [3]. The excavation of underground structures in rock masses induces cracking accompanied, in general, by significant changes in flow and permeability due to the deterioration of geotechnical and hydrogeological properties [4]. Damage induced by mechanical or hydraulic perturbations influences the permeability of the rock mass, with significant effects on the pore pressure distribution. Modifications in the pore pressure, in turn, affect the mechanical response of the material via poro-mechanical coupling.

In this contribution we present a recently developed model of brittle damage of confined rock masses [5], with particular emphasis on the influence of mechanical damage on the evolution of porosity and permeability. The model is based on an explicit micromechanical construction of connected patterns of parallel equi-spaced cracks, or faults. The dry multi-scale brittle damage model was first introduced in [6]. In contrast to the generic deterioration described by abstract damage mechanics, the fracture patterns that form the basis of the theory are explicit: the rock undergoes compatible deformations and remains in static equilibrium down to the micromechanical level. A relevant feature of the model is that the fracture patterns are not arbitrary, but their inception, orientation and spacing follow from energetic consideration. The constitutive model is derived within a thermodynamic framework, assuming the existence of an incremental work of deformation which accounts for reversible and dissipative behaviors of the material.

2. The brittle damage model

2.1. Constitutive equations

The brittle damage model is characterized by nested microstructures, with different length scale L_k and orientation $\mathbf{N}_k$, embedded in a homogeneous matrix. The number of levels of the nested microstructure is not limited in principle, as described in [5] where the finite kinematics version of the model is discussed. For the sake of simplicity, in the following we illustrate only the simplified model obtained through consistent linearization, and we limit the theoretical description to one single family of faults, characterized by the spacing L and the unit normal $\mathbf{N}$ to the plane of the faults.

It is assumed that the kinematics of the damaged material accounts for the deformations of the matrix and for fault opening. According to the small strain assumption, the additive decomposition of the total strain $\boldsymbol{\varepsilon}$ holds

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_m + \boldsymbol{\varepsilon}_f \tag{1}$$

where $\boldsymbol{\varepsilon}_m$ is the deformation of the homogeneous matrix and $\boldsymbol{\varepsilon}_f$ the deformation due to fault activity. By means of simple kinematic considerations (see [7] for the mathematical derivation), the deformation of the faults can be expressed through the fault displacement jump $\boldsymbol{\Delta}$ as (see Fig. 1a):

$$\boldsymbol{\varepsilon}_f = \frac{1}{2L}\left(\boldsymbol{\Delta}\otimes\mathbf{N} + \mathbf{N}\otimes\boldsymbol{\Delta}\right), \tag{2}$$

where $\otimes$ denotes the dyadic product between two vectors. Remarkably, equation (2) shows that, once L and $\mathbf{N}$ are known, there is a one-to-one correspondence between the deformation due to the fault $\boldsymbol{\varepsilon}_f$ and the displacement jump $\boldsymbol{\Delta}$. The behaviour of the matrix is assumed to be linear elastic (defined by Young modulus E and Poisson ratio ν).