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A linearized porous brittle damage material model with distributed frictional-cohesive faults

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ABSTRACT

We present a simplified model of damaging porous material, obtained through consistent linearization from a recursive-faulting material model described in (Pandolfi et al. 2016). The brittle damage material model is characterized by special planar micro-structures, consisting of nested families of equi-spaced frictional-cohesive faults in an otherwise elastic matrix material. The linear kinematics model preserves the main microstructural features of the finite kinematics one but offers a far better computational performance. Unlike models commonly employed in geo-mechanical applications, the proposed model contains a small number of parameters, to wit, two elastic moduli, three frictional-cohesive parameters, and three hydraulic response parameters, all of which having clear physical meanings and amenable to direct experimental measurement through standard material tests. The model is validated by comparison to triaxial hydro-mechanical experimental data. Despite the paucity of material constants, the salient aspects of the observed behavior are well captured by the model, qualitatively and quantitatively. As an example of application of the model, we simulate the excavation of a borehole in a rocky embankment.

1. Introduction

Design and analysis of constructions in engineering and earth sciences require careful accounting of the hydromechanical behavior of soils and rocks. Hydraulic properties are fundamental as regards the transport of fluids through rock formations, be it by seepage or through injection, and cannot be disregarded in the evaluation of the long-term stability of structures and geotechnical operations. Technical applications in geomechanics raise a wide range of problems where the hydro-mechanical behavior of rocks plays a significant, or even dominant, role. Typical examples include foundations of civil structures, surface and underground excavations, dam engineering, petroleum engineering, nuclear waste storage, landslide safety assessments, and environmental pollution protection.

The redistribution of the stress induced by underground relaxation may cause short and long-term disturbances in the surrounding rocks. Realistic long-term estimations of groundwater flow are sensitively dependent to natural or damage-induced hydraulic properties of rocks (Kiyama et al., 1996). Localized damage may play an important role on the rate of water flow into tunnels and other underground excavations by significantly increasing the rock mass permeability (Tang et al., 2002; Pardoen et al., 2016). For instance, in nuclear waste disposal the formation of preferential pathways for groundwater flow, with potential transport of radionuclides, may be the result of processes of damage localization in the host rock embankment (Souley et al., 2001). By way of contrast, in problems of interest to the oil and geothermal industry, the increase of the permeability of rocky reservoirs can have beneficial effects in terms of production. Specific techniques, such as hydraulic fracturing, have been developed to artificially increase the permeability of non-conventional reservoirs. At a larger scale, it has been recognized that stress-induced variations in permeability play a fundamental role in the behavior of sedimentary basins, faulted zones, metamorphic terrains, volcanic edifices and in a variety of phenomena related to earthquakes (Simpson et al., 2001; Zoback and Byerlee, 1975; Carrier et al., 2015).

The hydraulic properties of rocks are closely related, and tightly coupled, to their mechanical state. The evolution in time of that mechanical state under general geostatic loading conditions, including the progression of damage by fault formation, shear sliding along faults, fault closure and other rate-limiting processes, induces large variations in the permeability of rocks. Conversely, an increase in permeability facilitates flow into the rock, which in turn alters the state of effective stress and, through it, its mechanical behavior. The physics-based, predictive modeling of this two-way coupling is the

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central and outstanding challenge of the field. Current design and management of geotechnical works and underground constructions depend critically on reliable coupled hydro-mechanical numerical models capable of predicting the dependence of transport properties on the mechanical state of rock and soil formations, and vice versa, both qualitatively and quantitatively (Yuan and Harrison, 2005; Arson and Pereira, 2013; Maleki and Pouya, 2010; Shao et al., 2005).

It has been observed, that rock permeability is greatly altered by the opening or the closure of connected microfractures (Paterson and Wong, 2005). Laboratory studies conducted on compact rocks have provided clear evidence of the dependence of permeability on both porosity and deformation mechanisms. In triaxial compression tests, rock permeability is initially observed to decrease slightly and to experience an abrupt increase following the attainment of a certain level of deviatoric stress (Paterson and Wong, 2005). The initial decrease in permeability owes to the elastic compression of the pores. Following this initial compaction phase, dilatancy is observed following rock failure through brittle faulting or cataclastic processes (Zhu and Wong, 1997). According to microstructural observations, the primary cause of dilatancy is stress-induced microfracture, which increases permeability by widening voids and increasing the connectivity of flow paths (Brace et al., 1968; Zoback and Byerlee, 1975; Brace, 1978; Souley et al., 2001; Ma et al., 2011). Triaxial tests carried out beyond the peak strength reveal a remarkable several-orders-of-magnitude enhancement of the permeability in the post-failure stage, accompanied by a concomitant increase in porosity (Kiyama et al., 1996). Although the correlation between porosity and permeability is not always evident (Zhu and Wong, 1997), a number of tests on sandstones clearly evince a simultaneous post-peak evolution of both permeability and porosity (cf., e. g., the investigations on Darley Dale sandstone in (Mordecai et al., 1970) and on a German Permian sandstone in (Heiland, 2003b)).

In a recent study (Pandolfi et al., 2016), we presented a recursive microfracture model of brittle damage in rocks undergoing finite deformations under geostatic conditions. The model, conceived as the extension to permeable media of a dry faulting model (Pandolfi et al., 2006), is predicated on the direct construction of an explicit damage microstructure in the form of nested parallel faults in an otherwise undamaged matrix. The presence of such nested faults allows for stress relaxation under geostatic stress conditions. Indeed, it is shown in (Pandolfi et al., 2006) that the nested or recursive faulting pattern is capable of relaxing all the deviatoric stresses in the rock. In addition, the explicit geometry of the microstructures enables the analytical evaluation of permeability, thus establishing a direct relation between damage and the hydraulic properties of the rock. The original recursive faulting model was developed in finite kinematics (Pandolfi et al., 2006) and validated by comparison to experimental data pertaining to the mechanical response of confined ceramics under dynamical loading (Chen and Ravichandran, 1996).

In many engineering applications in the fields of petroleum engineering and underground excavations that are of interest in the present study, however, the observed deformation of rocks under high confinement is small in general. Therefore, the behavior of compressed rocks can often be well described in a small-strain or linearized kinematics framework. In the present study, we specialize the hydromechanical recursive faulting model of (Pandolfi et al., 2016) to linearized kinematics. Specifically, we consider small-strain kinematics and assume linear elasticity for the matrix. The linearized model greatly outperforms the finite kinematic model in numerical simulations and facilitates the application of fully coupled codes to large-scale field problems. In addition, we extend the validation studies presented in (Pandolfi et al., 2016) by comparing the model against data from experimental tests on Inada granite, Darley Dale sandstone, and Flechtinger sandstone. The model is again remarkable in its ability to capture the salient trends in the experimental data with a minimum of adjustable parameters. Finally, the suitability of the linearized kinematics model for full-field simulations is exemplified by means of an example of application concerned with borehole excavation.

The paper is organized as follows. In Section 2 we describe the linearized brittle-damage model in terms of kinematics of faults, cohesive behavior of the faults in opening, frictional behavior of the faults in sliding, pressure-dependent fault inception, and recursion. In Section 3 we obtain the analytical expressions of the porosity and permeability of the fractured material. In Section 4 we present a parametric analysis and experimental validation of the model. In Section 5 we present the borehole excavation example of application. Finally, in Section 6, we conclude by summarizing the findings of the study and giving a critical appraisal of its strengths and weakness.

2. Distributed damage by confined recursive faulting

The brittle damage model is characterized by the presence of particular microstructures, consisting of nested families of equi-spaced frictional-cohesive faults (or recursive faults) bounding otherwise elastic material of the matrix, see Fig. 1. The model was developed originally in finite kinematics (Pandolfi et al., 2006); a porous version has been presented in (Pandolfi et al., 2016). Here we present a linearized version of the model that is able to preserve the good qualities of the original one. According to the classic approach in soil and rock mechanics, the constitutive equations are stated in terms of effective stresses. Unlikely the standard notation used in geomechanics, tensile stresses and strains are considered here to be positive, except for the numerical examples and applications where we switch to the soil mechanics convention of positive compressive stresses and strains.

2.1. Kinematics of faults

We begin by considering the case of an existing single family of parallel fault planes, with orientation defined by a normal $\boldsymbol{N}$ and spacing L. A material vector $d\boldsymbol{x}$, short on the scale of the macroscopic deformations but much longer than the spacing L, spans two material points P and Q in the reference configuration. The number n of faults traversed by the vectoris

$$n = \frac{1}{L}\, d\boldsymbol{x} \cdot \boldsymbol{N} \tag{1}$$

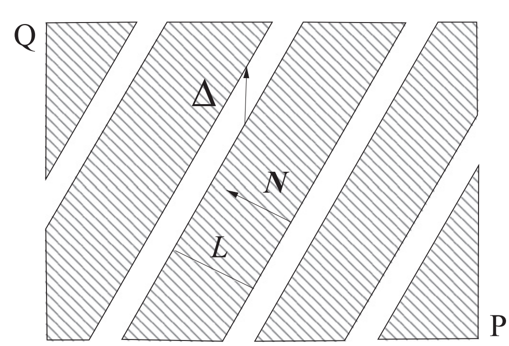

Fig. 1. Schematic of the assumed kinematics of deformation between two points P and Q, showing elastic blocks of matrix material bounded by opening parallel faults.