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A two-step homogenization-based permeability model for deformable fractured rocks with consideration of coupled damage and friction effects

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ABSTRACT

The permeability variation induced by anisotropic damage of rock blocks and nonlinear deformation of fractures is modeled with a two-step homogenization technique for deformable fractured rocks containing arbitrarily-distributed penny-shaped microcracks in rock blocks separated by multiple sets of critically orientated fractures of much large scales. The proposed model accounts for the influences of the microstructural alteration of rock blocks and fractures at the laboratory scale and the development pattern of the fracture system as well as the rock-fracture interaction at the field scale on the permeability of a fractured rock under mechanical loading or excavation condition. The proposed model was first validated by laboratory data of compression tests with permeability measurements on the Beishan granite, coupled shear-flow tests with hydraulic conductivity measurements on a granite fracture and anisotropic strength tests on the Martinsburg slate, with good agreement between the model predictions and the laboratory measurements. Numerical simulations were finally performed to examine the excavation-induced permeability change in the surrounding granitic rock of the Stripa tunnel, demonstrating the importance in considering both the damage of rock blocks and the deformation of fractures for better understanding the excavation-induced permeability change in the surrounding rock near the excavation surface.

1. Introduction

The permeability of fractured rocks is an important hydraulic property for understanding the groundwater flow behaviors in rock aquifers and designing the seepage-proof barriers in various surface and underground engineering practices.[1–5] In most cases, the permeability of a fractured rock is mainly determined by its more water-conductive fracture system and less influenced by the impervious rock blocks cut by the fractures. However, in the deep-seated environment where natural fractures could be well sealed and less extended under high in-situ stress condition,[6] or in the excavation disturbed zone where the rock blocks could be seriously damaged,[7] the contribution of rock blocks to the effective permeability of a fractured rock may be in the same order of magnitude as the contribution of the fracture system and hence could no longer be simply ignored without inducing significant estimation errors.

Groundwater flow essentially occurs in the connected pores and cracks of smaller scales in rock blocks and in the connected discontinuities of much larger scales in the fracture system, and as the geometries (such as the size, opening and connectivity) of the void system change, the flow behaviors in the fractured rocks change accordingly.[1,8–11] Therefore, the permeability of a fractured rock is in nature scale-dependent and deformation-dependent.[1,12–15] At the laboratory scale, the permeability is governed by the throat size and connectivity of pores and cracks of rock samples or the surface geometry and aperture distribution of fracture specimens of tens of centimeters in dimension, and it is commonly formulated as a function of the microcracking-induced damage growth of rocks[9,16–18] or the surface degradation and aperture variation of fractures under mechanical loading.[1,8,19–21] At the field scale, the permeability of a fractured rock is commonly related to the development pattern (e.g. aperture, spacing, connectivity and the number of critically-oriented fracture groups) and aperture variation of its fracture system subjected to mechanical loading or excavation,[1,3,22–24] where the contribution of rock blocks is either ignored or simply regarded as the background permeability of rock matrix.

Both continuum approach-based analytical models[1,8,25–27] and discrete method-based numerical models[24,28–31] have been developed for estimating the permeability of a representative volume element (RVE) of fracture rocks at various scales. The performance of the

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analytical models depends on how the geometries, the connectivity and the variations in micro-/macro-structures of the void system in the fractured rocks are characterized. The geometries of the void system are considered either by directly using the volumetric averaging approach for representing the contribution of voids (e.g. pores, cracks and fractures) to the effective permeability of rocks[8,9,26,32] or by using the homogenization schemes by regarding the voids as inclusions of different size, shape, orientation and spatial distribution.[18,33,34] To characterize the dependence of the permeability on the changes in the void geometries, various equivalent elastic/plastic models[1,8,23,35] and damage models[9,16,18,26] have been developed to account for the compression, friction and damage-induced deformation and propagation of the void system.

Given the different scales of the pores, cracks and fractures ubiquitously present in a fractured rock, two-scale analytical models have also been suggested. For example, Yao et al.[31] conducted a numerical analysis of permeability variation in rocks with dual porosity by using the distributed Voronoi diagram to represent macroscopic fractures and connected pore space of porous rock matrix. Lu et al.[36] modeled the damage-induced permeability variation with a two-scale conceptual model for representing realistic heterogeneous rock material containing micro-fractures. Barthélémy[37] suggested an estimate for the effective permeability of fractured media by superposing the tangential permeability of long fractures and the contribution of microfractures estimated with the self-consistent scheme.

This study examines the permeability variation in deformable crystalline rocks that contain cracks in rock blocks separated by rough fractures of much large scales. As shown in Fig. 1, a two-step homogenization model was adopted to formulate the permeability model, with the first step aiming at formulating the microcracking-induced permeability variation in rock blocks and the surface degradation-induced permeability variation in rough fractures at the laboratory scale. The second step formulates the effective permeability of fractured rocks at the field scale by accounting for the contribution of multiple sets of homogenized planar and parallel fractures embedded in the homogenized rock blocks, in which the interaction between fractures and cracks was considered by relating the damage resistance of cracks to the microstructure tensor introduced by Pietruszczak et al.[38]. As a potential advantage, the proposed model simultaneously accounts for the permeability variation in fractured rocks induced by crack initiation and propagation at the microscopic scale and fracture dilation and asperity degradation at the macroscopic scale. The proposed model was validated against the laboratory data of triaxial compression tests with permeability measurements on the Beishan granite,[39] coupled shear-flow tests on a rock fracture[19] and anisotropic strength tests on the Martinsburg slate,[40] and finally applied to examine the excavation-induced hydraulic conductivity change in the surrounding rock of the Stripa tunnel.[41]

2. Formulation of a coupled damage-friction model

Consider a RVE of a fractured rock, Ω, that contains arbitrarily-distributed penny-shaped cracks in rock blocks separated by multiple sets of parallel fractures, as shown in Fig. 1. The initial size of cracks is regarded to be equal to the average grain size at millimeter scale, and the critical crack length for coalescence is about 2–5 times of the initial length.[17] The trace length of fractures typically ranges from centimeters to tens of meters, with the first-order asperity being at centimeter to meter scales and the second-order asperity at millimeter to centimeter scales.[42]

Let $\dot{\boldsymbol{\Sigma}}$ be the uniform macroscopic incremental stress field prescribed on the boundary of the RVE. The increment of microscopic stress $\dot{\boldsymbol{\sigma}}(x)$ in Ω can then be related to the increment of macroscopic stress $\dot{\boldsymbol{\Sigma}}$ by introducing a fourth-order concentration tensor $B(\boldsymbol{x})$:

$$\dot{\boldsymbol{\sigma}}(\boldsymbol{x}) = B(\boldsymbol{x}) : \dot{\boldsymbol{\Sigma}}, \ \forall\ \boldsymbol{x} \in \Omega \tag{1}$$

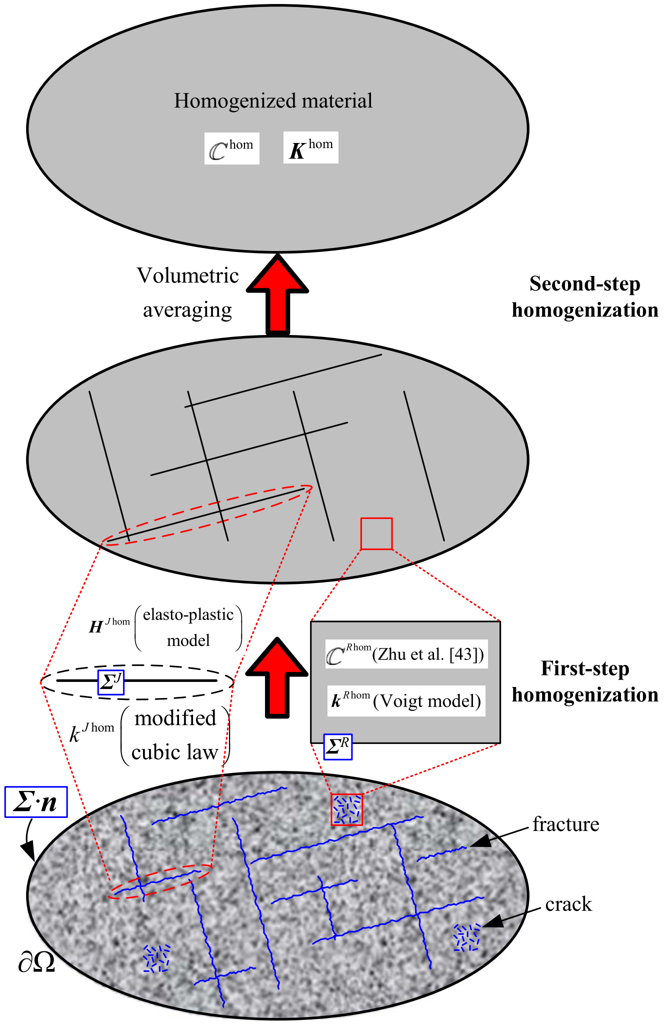

Fig. 1. Illustration of a two-step homogenization technique for fractured rocks.

By the stress average rule $\langle\dot{\boldsymbol{\sigma}}\rangle_\Omega = \dot{\boldsymbol{\Sigma}}$, there is $\langle B\rangle_\Omega = I$, in which $\langle\cdot\rangle_\Omega$ denotes the volumetric average on Ω and I is the fourth-order identity tensor. Affected by the mechanical and geometrical properties of fractured rocks, however, the expression of $B(x)$ in Eq. (1) is generally hard to be specified. For simplicity, this study uses the average stress increment of rock blocks $\dot{\boldsymbol{\Sigma}}^R$ and that of the Jth set of fractures $\dot{\boldsymbol{\Sigma}}^J$ for further development:

$$\begin{cases} \dot{\boldsymbol{\Sigma}}^J = B^J : \dot{\boldsymbol{\Sigma}} \\ \dot{\boldsymbol{\Sigma}}^R = \frac{1}{f_R}(I - \sum_J f_J B^J) : \dot{\boldsymbol{\Sigma}} \end{cases} \tag{2}$$

where B^J is the stress concentration tensor of the Jth set of fractures, and f_R and f_J are the volume fraction of rock blocks and the Jth set of fractures, respectively, with $f_R + \sum_J f_J = 1$. Given that the volume fraction of fractures is usually negligible compared with rock blocks (i.e. $f_J \to 0$ and $f_R \to 1$), one approximately obtains $\dot{\boldsymbol{\Sigma}}^R = \dot{\boldsymbol{\Sigma}}$ and this relation is used in the following derivation.

2.1. A two-step homogenization procedure

2.1.1. The first-step homogenization

At the first-step homogenization, the macroscopic mechanical responses of rock blocks and fractures are, respectively, characterized by taking into account their microstructural features. The rock blocks are assumed to be composed of n_c sets of penny-shaped cracks embedded in a homogeneous elastic solid matrix (Fig. 1). The rth set of cracks of unit normal $\boldsymbol{n}^r$ is characterized by three internal variables,