Permeability tensor of three-dimensional fractured porous rocks as a function of fracture pattern growth

Adriana Paluszny, Robin N. Thomas, Robert W. Zimmerman
Imperial College London

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Summary

The permeability tensor of a fractured rock is computed numerically for a set of geomechanically realistic three-dimensional discrete fracture patterns. These patterns are generated with a finite element-based discrete fracture propagation simulator, in which deformation and flow are numerically computed. These detailed multi-fracture growth simulations study permeability as a function of the interaction of fractures and the mechanical effects of pattern evolution on the distribution of apertures in response to *in situ* stresses.

Introduction

Continuum mechanics methods allow to define a rock matrix that has a volumetric variation of properties, and contains fractures as embedded discontinuities defined within the continuum. In all of these approaches, the volume is assumed to be discretised by a surface mesh in 2D, or a volume mesh in 3D. Two distinct numerical approaches can be used to model fractures within a continuum: (1) Non-geometric methods, in which the fracture is represented as a material property of the mesh, including localised damage and plastic models; (2) Geometric methods, in which each fracture is represented explicitly, and has a volumetric or surface domain that is distinct from the rock matrix. In the latter, specific properties can be directly assigned to the fracture, such as friction and cohesion, and processes such as fluid flow and frictional sliding can be directly examined. In geometric methods, discrete fractures are represented as lines, surfaces, or volumes, and have a distinct domain, which is assumed to be independent of the rock matrix definition. Here we present an example of the application of a geometric method for multiple fracture growth simulation in 3D to the computation of the effective permeability of a fractured mass as a function of density. In this particular case density is a function of growth, as opposed to a function of amount of fractures.

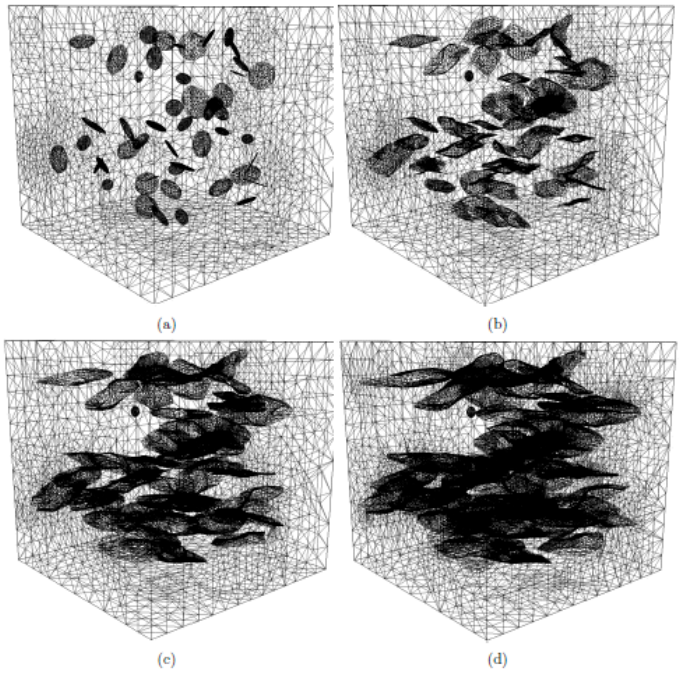

Figure 1: Modelling fracture growth and interaction in response to changes of the *in situ* stresses.

Geomechanical Fracture Growth

Patterns are generated with a finite element-based discrete fracture propagation simulator [1], in which deformation is numerically computed based on measurable material properties, such as Young's modulus and Poisson's ratio, using unstructured tetrahedral meshes. Stress intensity factors are computed using the interaction integral [2]. Growth is computed by applying the Paris law for extension of growth for a low crack velocity exponent (stable growth), and the angle of propagation is computed using the Richard criterion. Compression is resolved using a gap-based Augmented Lagrangian approach [3]. The matrix is assumed to be linear elastic, homogeneous and isotropic. In this approach, fracture geometry is stored independently from the mesh, and so fracture growth is not restricted to conform to an existing mesh, or constrained by the mesh. An example of a fifty-fracture pattern grown under tension is shown in Figure 1. Fractures are represented discretely using surfaces and curves, and are represented as a discontinuity in the flow field, which allows to model the flow within fractures independently of, and in combination with, flow within the matrix. This method has been applied in three dimensions to the analysis of fracture interaction [4], single [5] and multiple [6] hydraulic fracturing within a poro-elastic medium, and the analysis of thermo-hydro-mechanical effects of geothermal production on fracture aperture distribution [7].

Permeability Tensor

The permeability tensor of a fractured rock is computed numerically for a set of geomechanically realistic three-dimensional discrete fracture patterns. The finite element method is used to compute the coupled deformation and flow in the system, taking into account the deformation of the porous material, the fracture surface geometry and topology, and the fluid flow through the discontinuities. The permeability tensor of the medium is computed by applying a pressure gradient and assuming Darcy flow, and by assuming laminar flow within the fractures [8]. The method does not assume, but rather computes the principal directions of permeability of the fractured medium. Thus, permeability is not a scalar but a tensor that characterises the medium. The rock matrix is assumed to be orders of magnitude less permeable that the fractures.

Results

Fracture apertures, which control the macro-scale permeability, are responsive to the deformation of the fracture surface, which results in the variation of flow within each individual fracture as well as across the pattern. Multiple mechanisms, in addition to fracture network topology and connectivity, strongly affect the enhancement or reduction of permeability during fracture growth and intersection. In order to investigate these effects, these detailed multi-fracture growth simulations study permeability as a function of the interaction of fractures and the mechanical effects of pattern evolution on the distribution of aperture distributions in response to *in situ* stresses.

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