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Importance of stress effects on inputs to fracture network models used for subsurface flow and transport studies

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1. Introduction

Fractured rock masses are composed of intact rock matrix and fractures, with the latter acting as the main pathways for fluid flow. Since the 1980's, flow and transport in such rocks have often been studied by means of the Discrete Fracture Network (DFN) models.[1–4] These models are currently applied in a number of important problems ranging from performance assessment of nuclear waste repositories, environmental remediation of bedrock contamination, to hydraulic fracturing for unconventional oil and gas recovery.[5–10]

For crystalline rocks, in a basic DFN model, fractures are commonly represented by fracture sets of different orientations with different sizes and permeability values. Often these three quantities, orientation, size and permeability, are given in terms of distributions with a mean value and variance. Fractures are rarely located randomly in DFN models. Some larger faults are positioned deterministically, while others, typically smaller faults and joints, are positioned stochastically but conditioned to some mappable variables. In applications, realizations of the DFN model can then be generated for flow and transport calculations. Evaluation of input parameters required for DFN modelling is often based on observations of fractures on tunnel walls or on outcrops, and also on borehole imaging and well testing. In most of such efforts, the hydromechanical effects induced by stresses in the rock are not considered (except for possibly a simple permeability-depth correction), even though *in situ* rock stress conditions can be very different from those near the tunnel walls, surface outcrops and in shallower boreholes.

Coupled hydromechanical (HM) and thermo-hydromechanical (THM) processes have been a subject of intense studies over the last many years.[11–13] More recently, [14] and [15] conducted HM modelling of fracture networks to study the change of fracture apertures and hence their flow permeability due to rock mechanical effects, such as normal stress-induced compression or tension, and shear stress-induced dilation. Effects on the permeability of fractured rock masses and its anisotropy are also explored. These results point to the potential importance of accounting for HM effects when conducting flow and transport studies using the DFN models. The present paper addresses the particular issue of HM effects on the input fracture permeability values and presents results of scoping calculations of the potential errors involved.

More specifically, in this paper the following question is posed; suppose one were interested in flow and transport in a fractured crystalline rock domain at the depth of 1000 m under *in situ* stress conditions. If one were to obtain the permeability values of the fractures to be used in such flow and transport calculations from observations and measurements on a fracture network near tunnel walls and on outcrops, what errors would be introduced if HM effects are ignored? The next section gives the problem definition, followed by a section on our modelling approach and methodology used. Then results are presented and discussed, and the paper is completed with some concluding remarks.

2. Problem definition

To conduct the investigation on a somewhat realistic basis, fracture mapping on an outcrop taken from [16] is used. The fracture pattern on the outcrop shown in Fig. 1 displays multiple fracture sets, fracture intersections, dead-end and curved fractures. From this outcrop map,

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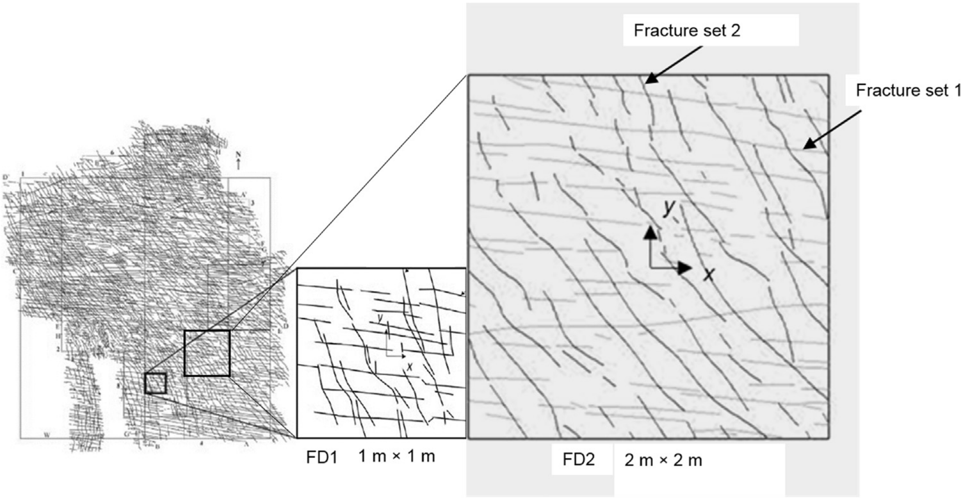

Fig. 1. The outcrop fracture map on the left is extracted from 16. The right side shows the studied domains FD1 and FD2, with the fracture sets 1 and 2.

two fractured rock domain patterns FD1 and FD2, with an area 1 m by 1 m, and 2 m by 2 m, respectively (Fig. 1), are chosen for our study. Two fracture sets can be identified in either domain with Fracture set 1 being sub-horizontal and Fracture set 2 having an angle of approximately 60° with the horizontal direction. Although the ratio between the areas of FD2 and FD1 is 4, the fractures density is similar: the total fracture length is 24.9 m/m^2 and 21.2 m/m^2 in FD1 and FD2, respectively. In this paper we have considered only 2D fracture network systems. The work can be directly extended to 3D DFN models applying available 3D mechanical modelling methods[17] and methods for calculating permeability of 3D fracture networks.[18]

To initiate our calculation, let us assume that initially FD1 and FD2 are located at a depth of 7.5 km. This depth corresponds to a residual or irreducible permeability. By assuming a vertical gradient of 0.027 MPa/m, the magnitude of the vertical stress component or the stress normal to the plane of fracture network (σ_N) will be 200 MPa. The horizontal stresses in the plane of the fractured rock domains, σ_H and σ_h, respectively, are assumed to have the same magnitude as the stress σ_N. At these high stresses, all the fractures are then assumed to have a residual permeability of 4.5×10^{-16} m^2 (which is the value for a fracture square element with side of 0.005 m, see below). Using this as a starting point, we simulate simultaneously the release of horizontal and normal stresses and calculate fracture permeability values under five loading cases that differ from each other in the magnitude of σ_H and σ_h and the ratio *SR* between σ_H and σ_h. The choice of 7.5 km as the starting point with residual fracture permeability is somewhat arbitrary. We have repeated the calculations reported in this paper with a starting point of 5 km. The results and conclusions are similar with those using 7.5 km as the starting point, showing insensitivity to this selected value.

In Table 1, Loading 1 represents an outcrop case, in which σ_N is set to zero and σ_H and σ_h are assumed to have the same value of 1 MPa. Loadings 2 and 3 are cases where the fracture network is found on the wall of a tunnel at 1000 m depth, for which σ_N is zero and σ_H along the axis of the tunnel is 27 MPa. The stress σ_h in the direction tangential to the curved tunnel wall can have a range of values from compression to tension dependent on whether its location is at the spring line or ceiling of the tunnel. For our scoping studies, we assume σ_h to have values of 2.7 and 54 MPa for Loading 2 and 3 respectively. Loadings 4 and 5 both correspond to an *in situ* case at a depth of 1000 m within the rock mass, in which σ_N is 27 MPa, σ_H and σ_h are 27 MPa ($SR = 1$) for Loading 4 and σ_H is 54 MPa and σ_h is 27 MPa ($SR = 2$) for Loading 5. For all the loading cases, stresses are applied normal to the boundaries of the fracture domain FD1 or FD2, which are free to move. No shear stresses are considered at the boundaries, but they are accounted for within the fractured rock domain.

Table 1
Boundary loading stresses: σ_N is the stress normal to the plane of the fracture network; σ_H is the horizontal stress in the plane of the fractured rock domains; σ_h is also a stress in the plane of the fractured rock domain that is perpendicular to σ_H; SR is the ratio between σ_H and σ_h.

Loading case		σ_N (MPa)	σ_H (MPa)	σ_h (MPa)	*SR*
1	Outcrop	0	1	1	1
2	Tunnel-wall I	0	27	2.7	10
3	Tunnel-wall II	0	27	54	0.5
4	*In situ* I	27	27	27	1
5	*In situ* II	27	54	27	2

Loadings 4 and 5, with *SR* equal to 1 or 2, are the possible *in situ* cases of relevance for calculations of flow and solute transport in fracture network models for various practical applications, such as performance assessment of underground nuclear waste repositories or solute transport in contaminated fractured bedrock. To get input values of fracture permeability for such fracture network calculations, often measurements are made on the outcrop corresponding to Loading 1, or on tunnel wall, corresponding to Loadings 2 and 3 cases. These cases, however, have very different stress boundary conditions. The focus of this paper is to discuss potential errors involved if the different stress conditions in these cases are ignored.

3. Numerical approach

3.1. Finite-difference numerical model

A 2D finite-difference model is developed in FLAC3D[17] to study permeability changes and stresses normal and parallel to each of the fractures in the network. The models are square regions with 1 m and 2 m side, respectively for fractured rock domains FD1 and FD2. The mesh consists of 40,000 and 160,000 elements 0.5 cm on each side, for FD1 and FD2, respectively. The mesh used to study the behaviour of the fractured rock domain is shown in Fig. 2.

Necessary model parameters are listed in Table 2. No flow occurs in the intact rock and fractures. The model is executed in a plane strain analysis. For the intact rock, an elastic model is used, in which the mechanical properties (elastic modulus E_R, Poisson's ratio ν_R) are extracted from 14.

The two sets of fractures have the same mechanical and initial hydraulic properties. The shear stress-displacement fracture behaviour is modelled by a Mohr-Coulomb model with a tension cut-off. The mechanical properties of the fractures (friction angle ϕ_F, dilation angle ψ_F, cohesion c_F, fractures aperture b_h) are extracted from 14. The Poisson's ratio ν_F value is assumed to be 0.2. The fracture normal stiffness k_n is