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A study of changes in deep fractured rock permeability due to coupled hydro-mechanical effects

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ABSTRACT

This paper presents a numerical study of the hydro-mechanical behaviour of a fractured rock domain at 1000 m depth below the land surface as a function of different levels of fluid pore pressure. A 2D fractured rock domain is adopted based on data obtained from outcrop mapping, displaying multiple fracture sets, fracture intersections, dead-end and curved fractures. A continuum based numerical model is used to evaluate the effects of compressive boundary stresses, cracking by tension failure in the intact rock and fractures and shear displacement along fractures on its equivalent permeability. Two *in situ* stress boundary conditions are considered: an isotropic case SR1 with the two horizontal boundary compressive stresses having the same magnitude, and an anisotropic case SR2 with the ratio between these compressive stress components set to be 2. In the SR2 case, changes in the local stress and stress ratio distributions due to different fluid pore pressure levels are anisotropic and more significant than in the SR1 case, because of tension failures in the intact rock forming bridges between fractures. These failure regions opened new flow connections between fractures and thereby caused important anisotropic changes in the flow paths, and significant decrease in local gradients of fluid pore pressure. The equivalent permeability increases sharply when the fluid pore pressure is approximately 90% of the magnitude of the minimum stress at the boundaries of the fractured rock domain. Results show that the equivalent permeability of the fractured rock domain is most sensitive to the fractures normal stiffness, the permeability of the tension failure regions and the power-law exponent for permeability change.

1. Introduction

Hydro-mechanical coupling in fractured rock masses is an important issue for many rock mechanics and hydrogeology applications,[1] particularly in the study of hydrogeology of deep formations at the depth of 1 km or more.[2] Fractured rock masses are composed of intact rock materials and fractures, with the latter acting as the main pathways for fluid flow. The fractures usually consist of several fracture sets, fracture intersections, dead-end and curved fractures. Apertures of fractures can change due to rock mechanical effects, such as normal stress-induced compression or tension, and shear stress-induced dilation. Hence, the permeability of fractured rock masses and its anisotropy is stress dependent.[3]

The stresses at various locations over a fractured rock domain are naturally different from the far-field stresses, because of local stress concentrations induced by the existing fractures. There are several measurement techniques to determine *in situ* stresses in rock masses. Depending on the domain of application, the most commonly used stress determination techniques include hydraulic methods, relief methods and jacking methods. More techniques exist, and comprehensive reviews of stress determination methods may be found, for example, in Refs. 4 and 5. Although those techniques enable to determine the far-field stresses, the measurement results can be influenced by various factors, such as local heterogeneities, pre-existing fractures and spatial variability of the rock mass properties. Since the hydro-mechanical behaviour of fractures and the intact rock at any point of interest is dependent on the local stress changes, which in turn depends on the complexity of the near-field fracture pattern, there is a need to understand how these local changes are different from the far-field stresses.

Numerical studies of the coupled hydro-mechanical effects in fractured rock masses have been conducted using different methods, such as discrete and combined continuum–discrete based models.[6–11] Discrete based models, while more realistic for discontinuous media, have the limitation of not considering permeable intact rock and are time consuming for modelling

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hydro-mechanical behaviour of fractured rock domains with curved or dead-end fractures. Continuum based finite difference codes require a representation of discrete fracture behaviour with appropriate hydro-mechanical properties by an elemental cell, but they can have the advantage of being able to model fractures that are sealed and filled with mineral materials and are less time consuming. Furthermore, important phenomena such as changes in the permeability field and flow paths due to tension failure regions in the intact rock between fractures can be included. An important open issue is how much of the conclusions based on continuum based code are valid in understanding the mechanical and hydro-mechanical behaviour of a fractured rock domain which is a discontinuous medium. Continuum based models have been applied to simulate fractures propagation in fractured rocks.[12,13] The stress intensity factors obtained with such modelling are in good agreement with the available analytical solutions. In Ref. 14, a numerical method for fragmentation is presented that combines the finite element method with the impulse-based discrete element method. Results for fracture growth within each three-dimensional fragment are in good agreement with experimental data. A comparison of the results obtained with a continuum and discrete fracture based models on fracture opening and sliding in response to fluid injection in a geothermal reservoir, was made in Ref. 15. The results obtained with the two models were found to be in agreement. In Ref. 16, a comparison between results obtained with a continuum-based model and discrete fracture and discontinuous models, was done. A good agreement was also found for the coupled hydro-mechanical fracture flow.

For our study of coupled hydro-mechanical effects within a fractured rock domain, as a function of different levels of fluid pore pressure, we use an actual observed fracture geometry with multiple fracture sets, fracture intersections, curved and dead-end fractures, obtained by outcrop mapping. The changes in fluid pore fluid pressure could be due to injection wells in the neighbourhood, e.g. during hydraulic stimulation of a reservoir, regional hydrogeological changes, or seismic events. The consideration of such a complex fractured rock domain enables us to study the coupled hydro-mechanical effects with focus on those issues related to the complexity of multiple fractures. Our goal is to draw general conclusions on these effects in complex fractured systems that do not depend on exact details of the complexity.

This paper presents a two-dimensional finite-difference model, developed in FLAC3D,[17] to study the coupled hydro-mechanical effects of the considered fractured rock domain. We study hydro-mechanical effects as a result of different levels of fluid pore pressure under constant external load, including the effects of tension in the intact rock and fractures and shear displacement in the fractures. The main objectives of the paper are to (1) analyse tension failure regions in the intact rock and fractures caused by different levels of fluid pore pressure, (2) evaluate the changes in the stress field induced by the occurrence of failure regions, (3) evaluate the changes in the fluid pore pressure field and flow paths, induced by changes in the stress field and (4) evaluate the changes in the equivalent permeability and permeability anisotropy.

A sensitivity analysis is made to study the influence of the tensile strength of the fractures, the fractures normal stiffness, the permeability of the tension failure regions and the power-law exponent of the relation used to calculate changes in permeability. The paper is completed with discussion and some concluding remarks.

2. Problem definition and selection of fracture rock pattern from outcrop maps

A fractured rock domain pattern for carbonate reservoir was obtained by using surface outcrop information.[18] Two sets of fractures are identified from outcrop mapping, with different orientations. The fracture sets 1 and 2 are sub-horizontal and sub-vertical, respectively. In our study, the original pattern was modified. Some fractures endings were extrapolated till the outcrop boundaries to ensure that flow occurs in two orthogonal directions, between two opposite boundaries. An area 1 m by 1 m (Fig. 1) is taken to carry out the stress-dependent permeability analysis as a function of fluid pore pressure. The plane of the fractured rock domain pattern is horizontal and the origin of the x and y-axis system is placed in the centre of the studied region.

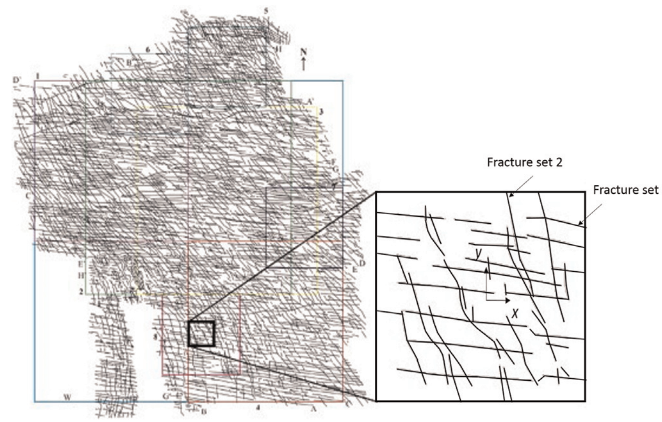

Fig. 1. Fractured rock domain pattern obtained by surface outcrop information. The inset shows the studied domain, with the fracture sets 1 and 2 (adapted from Ref. 18).

The presented fractured rock domain contains straight and curved fractures, fracture intersections, dead-end fractures and fracture tips adjacent to other fractures. Let us now assume that this outcrop is located at 1000 m depth with an equilibrium stress state resulting from the *in situ* stresses and the fluid pore pressure at this depth. This forms the basis for a numerical study of the hydro-mechanical behaviour of the fractured rock domain with different levels of fluid pore pressure.

3. Numerical approach

3.1. Finite-difference numerical model

A 2D finite-difference model was developed in FLAC3D[17] to study the hydro-mechanical behaviour of the fractured rock domain. The model is a square region with 1 m side. The mesh consists of 40000 square elements which 0.5 cm side (Fig. 2). The two sets of fractures have the same hydraulic and mechanical properties. Necessary model parameters are listed in Table 1. The model is executed in a plane strain analysis. For the intact rock, a Mohr–Coulomb model with tension cut-off was used, in which the mechanical properties (elastic modulus E_R, Poisson's ratio ν_R, cohesion c_R, friction angle ϕ_R, tensile strength σ_{tR}) are characteristic of limestone rocks.[19,20] The tensile strength σ_{tR} of the intact rock influences the fractures development, but similar results to those presented in this paper can also be obtained by changing the values of the different fluid pore pressure levels. The cohesion c_R influences the occurrence of shear failure in the intact rock. For a 30 MPa cohesion (see Table 1), shear failure does not occur in the intact rock and tension failure is the dominant mechanism. For small values of c_R, (e.g. 5 MPa) it was found that shear failure occurs in the intact rock and is more prevalent than tension failure, but the shear displacements and consequent changes in permeability are much smaller than those in the fractures. The other mechanical parameters were found not to influence significantly