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Review

The use of discrete fracture networks for modelling coupled geomechanical and hydrological behaviour of fractured rocks

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ABSTRACT

We present a discussion of the state-of-the-art on the use of discrete fracture networks (DFNs) for modelling geometrical characteristics, geomechanical evolution and hydromechanical (HM) behaviour of natural fracture networks in rock. The DFN models considered include those based on geological mapping, stochastic generation and geomechanical simulation. Different types of continuum, discontinuum and hybrid geomechanical models that integrate DFN information are summarised. Numerical studies aiming at investigating geomechanical effects on fluid flow in DFNs are reviewed. The paper finally provides recommendations for advancing the modelling of coupled HM processes in fractured rocks through more physically-based DFN generation and geomechanical simulation.

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1. Introduction

Fractures such as joints, faults, veins and bedding planes are ubiquitous in crustal rocks. These naturally occurring discontinuities often comprise complex networks and dominate the geomechanical and hydrological behaviour of subsurface rocks [1]. Understanding of the nontrivial effect of fractures is a challenging issue which is relevant to many engineering applications such as underground construction, enhanced geothermal systems, unconventional shale gas production (fracking), groundwater management and radioactive waste disposal [2–4]. The importance of the presence of natural fractures, which can result in heterogeneous stress fields [5] and channelized fluid flow pathways [6] in highly disordered geological formations, has promoted the development of robust fracture network models for numerical simulation of fractured rocks [7].

The first difficulty in modelling fractured rocks is the geometrical representation of complex three-dimensional (3D) discontinuity systems. Natural fractures form under certain mechanically self-organised dynamics, where breakage and fragmentation can occur at all scales [8]. They are subject to in-situ stress fields at depth and can form intricate topologies, such as cross-cutting, abutting, branching, termination, bends, spacing and clustering [9,10]. However, direct observation of the detailed 3D structure of fracture networks deep in the crust is impossible. Field data are usually collected from lower dimensional limited exposures, e.g. one-dimensional (1D) borehole logging and two-dimensional (2D) outcrop mapping [11]. Seismological surveys may be able to locate 3D large-scale structures but the current technology can hardly detect widely-spreading medium and small fractures due to the resolution limit. The description of natural fracture geometries, therefore, has to largely rely on extrapolations, from 1D/2D to 3D and from small samples to the whole study domain. Hence, the question of how to create realistic fracture networks remains an unresolved issue. Often simplifications have to be made by ignoring some details of less importance for the particular questions at hand.

The second fundamental issue in modelling fractured rocks is to solve the fracture and solid mechanics problems of the discontinuous geological media under complex boundary conditions, i.e. the fractured rock mass mechanical response to boundary stresses or displacements. When the spacing of natural fractures is comparable to the scale of interest of the problem to be modelled, the conventional continuum approach may not be adequate to capture some important mechanical behaviour of fractured rocks [12], such as fracturing of intact rocks [13], interaction of multiple fractures [5], and opening, shearing and dilatancy of rough fracture walls [14]. Thus, many computational schemes based on extended continuum, discontinuum, or hybrid continuum-discontinuum methods have been developed to solve a numerical system with fracture geometries explicitly represented.

Another important question is about the hydrological behaviour of fractured rocks under geomechanical conditions. Fractured rocks may deform in response to geological and/or man-made perturbations (e.g. tectonic events, underground excavations), resulting in changes of bulk permeability and fluid migration [2]. The intricacy of such coupled hydromechanical (HM) processes is increased if the presence of natural fractures associated with topological complexities is to be considered [1,15]. The quest for a means of quantifying the influence of in-situ stresses on the permeability of fractured reservoirs has been driven largely by the motivation from petroleum engineering [16]. The understanding of contaminant migration through tectonically strained fractured formations is also crucial for the groundwater community [17] and nuclear waste management [3,4].

The objective of this paper is to review the current state-of-the-art of fracture network models and to provide some discussions and recommendations for HM modelling of fractured rocks. In this context, the issues arising in the aforementioned three key subject areas (i.e. geometry, geomechanics and hydromechanics) will be examined progressively. The paper will present a summary of various approaches used in developing fracture network models that represent natural fracture geometries often with different degrees of simplification, and different numerical frameworks that integrate discrete fracture representations for modelling geomechanical and HM behaviour of fractured rocks. One important focus of this work is to discuss the features or characteristics of a fracture network model needed to properly simulate coupled HM processes in fractured rocks. The rest of the paper is organised as follows. Section 2 reviews the methods of representing natural fracture geometries by geological mapping, stochastic generation or geomechanical simulation. Section 3 provides a brief overview of continuum and discontinuum models that integrate explicit fracture geometries for geomechanical modelling of fractured rocks. A short summary is presented in each of Sections 2 and 3 with a view towards HM modelling. Section 4 summarises the numerical studies of geomechanical effects on fluid flow in fractured rocks and further provides some suggestions on choosing appropriate DFNs and geomechanical models for HM modelling. Finally, outstanding issues are discussed and some concluding remarks are made. It has to be mentioned that this review is focused on HM behaviour of fractured rocks and is not exhaustive. Only limited references are cited for brevity. For more extensive descriptions of fracture network models, the reader is referred to the reviews by Dershowitz and Einstein [18] and Liu et al. [19], and the textbooks by Adler and Thovert [20] and Adler et al. [21]. Extensive reviews of different numerical methods developed in the field of rock mechanics can be found in Jing and Hudson [22], Jing [12], Yuan and Harrison [23], Bobet et al. [24], and Lisjak and Grasselli [25]. More in-depth discussions about stress effects on fluid flow in fractured rocks can be found in Zhang and Sanderson [26], and Rutqvist and Stephansson [2].

2. Representation of natural fracture networks

A "discrete fracture network" (DFN) refers to a computational model that explicitly represents the geometrical properties of each individual fracture (e.g. orientation, size, position, shape and aperture), and the topological relationships between individual fractures and fracture sets. Unlike the conventional definition of DFNs that corresponds to stochastic fracture networks, the term DFN here represents a much broader concept of any explicit fracture network model. A DFN can be generated from geological mapping, stochastic realisation or geomechanical simulation to represent different types of rock fractures including joints, faults, veins and bedding planes.

2.1. Geologically-mapped fracture networks

Fracture patterns can be mapped from the exposure of rock outcrops or man-made excavations (e.g. borehole, quarry, tunnel and roadcut). These geologically-mapped fracture networks were widely used to understand the process of fracture formation [5,27], interpret the history of tectonic stresses [28–30], and derive the statistics and scaling of fracture populations [8,31,32]. However, digitised outcrop analogues (Fig. 1) can also be used to build DFNs for numerical simulations. For example, a series of discrete fracture patterns were mapped from limestone outcrops at the south margin of the Bristol Channel Basin, UK [33]. The traced DFNs were used to study the connectivity [34], multiphase flow