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Effects of geomechanical changes on the validity of a discrete fracture network representation of a realistic two-dimensional fractured rock

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ABSTRACT

This paper aims to examine the validity of the discrete fracture network (DFN) method in representing a realistic two-dimensional fractured rock in terms of their geomechanical response to in-situ stresses and hydraulic behaviour in a steady state fluid field. First, a real fracture network is extracted from the geological map of an actual rock outcrop, which is termed the analogue fracture network (AFN). Multiple DFN realisations are created using the statistics of the analogue pattern. A conductivity parameter that was found to have a linear relationship with the conductivity of 2D fracture networks is included to further enhance network similarity. A series of numerical experiments are designed with far-field stresses applied at a range of angles to the rock domains and their geomechanical response is modelled using the combined finite-discrete element method (FEMDEM). A geomechanical comparison between the AFN and its DFN equivalents is made based on phenomena such as heterogeneity of fracture-dependent stress contours, sliding between pre-existing fracture walls, coalescence of propagating fractures and variability of aperture distribution. Furthermore, an indirect hydro-mechanical (HM) coupling is applied and the hydraulic behaviour of the porous rock models is investigated using the hybrid finite element-finite volume method (FEFVM). A further comparison is conducted focusing on the hydraulic behaviour of the AFN and DFNs under the effects of geomechanical changes. The results show that although DFNs may represent an AFN quite well for fixed mechanical conditions, such a representation may not be dependable if mechanical changes occur.

1. Introduction

The large proportion of petroleum reserves and natural gas resources remaining in fractured carbonate rock masses [1] continues to incentivise research into fractured reservoirs. Conceptually, a fractured rock mass is composed of two domains: the fracture network with relatively high permeability, and the rock matrix with low permeability. Naturally fractured reservoirs contain numerous discontinuities which greatly influence or even dominate the geomechanical and hydraulic properties of the host media. The construction of computational fracture networks, therefore, is of great importance if fluid flow is to be accurately modelled and oil production reliably predicted.

An analogue fracture network (AFN) obtained from geological outcrop is often used to realistically characterise the geometrical attributes of a naturally fractured system where the fracture geometry in the rock volumes of interest are obscured. Actual rock outcrops and the AFNs produced involve complicated intersections, terminations, bends and segmentations. Many studies have used mapped analogues to investigate the geomechanical and hydraulic behaviour of naturally fractured rock masses. Sanderson and Zhang [2] used 2D natural fracture patterns to investigate the phenomenon of critical stress state where highly localised flow occurs and leads to a sudden increase in network overall hydraulic conductivity. Leckenby et al. [3] studied the estimation approach for the flow heterogeneity in natural fracture systems based on different network attributes (i.e. fracture density, aperture and hydraulic conductance). Davy et al. [4] investigated the scaling effects of flow properties in multi-scale natural fracture systems, which were found dependent on the fracture length distribution and the transmissivity distribution per fracture. Belayneh et al. [5] simulated the dynamic process of oil recovery driven by injected water using two-phase flow numerical modelling method based on a series of natural reservoir analogues exposed along the Bristol Channel. To achieve more accurate modelling of the fluid transport in a fractured rock medium requires more precise representation of fracture networks, realistic characterisation of aperture distribution

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that considers the role of the in-situ stress state as well as crack propagation modifications to an initial fracture patterns to make it more compatible with the in-situ stress of interest [6].

However, complete geometrical description of a naturally fractured rock mass is always difficult due to its three-dimensional nature and limited access to all information [7]. Hence, a discrete fracture network (DFN) is often used to approximate a real faulted or jointed system [8]. A DFN is an artificial fracture pattern which is generated stochastically but conditioned by the statistical data from borehole image interpretation or outcrop observation. The theory of probability and statistics offers numerous tools for analysing various uncertainties involved in limited geological survey data [9]. Statistical analysis of a natural fracture system usually involves the identification of fracture sets [10] and the estimation of different geometrical properties, such as orientation, density and size [7,8,11–13]. A number of DFN approaches have been developed to simulate the topology of complex fracture systems with different emphases. For example, Einstein et al. [14] used a joint system model which incorporates orientation, spacing, fracture length and rock bridge length to analyse the effect of discontinuity persistence on slope stability. Baecher et al. [15] developed a Poisson disk model, in which the location of a fracture is represented by its barycentre with seeding simulated using a Poisson process, while other properties are modelled by Monte Carlo sampling of corresponding probability distribution functions. This Poisson disk model has been continuously developed [8,16] and has become one of the most commonly used DFN approaches to investigate the geomechanical and hydraulic behaviour of fractured rock masses [17–22]. Additional factors may also be included to enhance the accuracy of stochastic realisations such as the average number of intersections per fracture, which can serve as a connectivity index of a fracture network [17,23].

Numerical simulation can be conducted on a geologically conditioned DFN model to estimate the mechanical and hydraulic properties of a fractured rock mass. Min et al. [19] analysed the hydro-mechanical behaviour of fractured rock masses by conducting a series of numerical experiments on a DFN realisation. Several geological phenomena were observed in the fractured region, such as flow concentration caused by shear dilation, sensitivity of permeability in different in-situ stress ratios and anisotropy induced by differential stresses. Leung and Zimmerman [20] investigated the macroscopic conductivity of two-dimensional DFNs by assuming matrix to be impervious and calculating the flow through fractures. A number of fracture networks were generated with centres seeded homogeneously, orientations assigned uniformly and lengths constrained by a lognormal or power–law distribution. A conductivity parameter η was proposed to incorporate the information of both length and connectivity. Based on the numerical simulations, a significant linear relationship was found between the normalised conductivity of fracture networks and the proposed conductivity parameter.

The potential for stochastic network simulation processes to provide poor representations of real systems of fractures is a widely-recognised disadvantage of the DFN approach. Odling [24] compared a natural fracture pattern with ten random realisations with fractures simulated by spatially distributed line segments. The clusters formed by interconnected fractures were identified. The natural pattern was found to possess fewer clusters but the dominant cluster had a larger occupation than that of the stochastic patterns. Any such differences in connectivity point towards possible limitations if the DFN method and stochastic realisations are used to calculate the permeability of a natural system. Belayneh et al. [25] investigated the permeability difference between an outcrop-based deterministic analogue and several stochastic realisations created from statistical parameters based on data from scanlines and window samples. The hydraulic properties of these DFNs vary dramatically between two limiting cases in which fluid transport is dominated either by fractures or by permeable matrix. In their research, a reported positive correlation between aperture and fracture length is the only means by which aperture variation is introduced. However, fracture aperture evolution in response to in-situ stress is much more complicated than this simple relation or other correlation models, such as lognormal distribution [26], power–law distribution [27], linear aperture–length correlation [28,29] and sublinear aperture–length correlation [30,31]. In reality, aperture distribution is significantly influenced by the specific geomechanical condition where the fractured rock is located. Some fractures with unfavourable orientation for closure or critical orientation for shear can become the major pathways for fluid migration while other fractures may contribute little [2,6,19]. Geomechanical modelling is therefore considered to be of great importance if the hydraulic properties of fractured rock masses are to be accurately evaluated. The semi-analytical solution proposed by Pollard and Segall [28] and Cruikshank et al. [32] permits the incorporation of linear elastic fracture mechanics to deduce fracture opening and shear dilation under in-situ stresses for flow simulation [33,34]. Olson [30] further modified the analytical solution by linking it with critical stress intensity factor and obtained a square root aperture-to-length relationship. However, the analytical solution is based on the assumption that fractures are poorly-interconnected and straight, which oversimplifies natural fracture systems involving complicated intersection, bending, and arresting. Furthermore, the analytical solution proposed applies to the aperture at the critical state for crack propagation, which is not the general state of interest. Accurate characterisation of fracture behaviour requires systematic geomechanical modelling of fractured rocks which can simulate well-interconnected fracture system, capture the deformability and interaction of matrix blocks and also incorporate fracture propagation when appropriate, to obtain realistic stress distributions [6].

The objective of this study is to examine the validity of using the DFN method to estimate the hydraulic properties of a naturally fractured rock mass in a geomechanically stressed condition and to further recognise the important factors influencing the quality of DFN representations. The methodology for numerical modelling employed in this research is presented in the following section, including description of the approaches for modelling solids and fluids in fractured porous media as well as mechanism of indirect hydro-mechanical coupling. A 2D analogue pattern is first extracted from an outcrop map and its statistical parameters in several important respects are calculated. Multiple DFN realisations are created stochastically but conditioned by the outcrop statistics and a conductivity parameter. Both types of fractured reservoir models are discretised into triangular elements using the unstructured mesh technique. A geomechanical comparison is conducted with biaxial effective stresses applied to the fracture patterns at a range of angles, while a further hydraulic comparison is performed using steady state flow simulation through the deformed models under a fluid pressure differential. Discussion is presented on the effects of geomechanical changes, how they induce aperture variability and influence the hydraulic behaviour of a fractured rock mass, and conclusions drawn.

2. Methodology

The combined finite-discrete element method (FEMDEM), pioneered by Munjiza [35], is a numerical method capable of computing a discontinuum system consisting of numerous deformable discrete bodies, which are discretised into a number of finite elements. Further development was accomplished by Xiang et al. [36,37] for 3D solid modelling. A Virtual Geoscience Workbench (VGW) was launched under the collaboration project between