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Controls of natural fractures on the texture of hydraulic fractures in rock

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ABSTRACT

Hydraulic fracturing plays an important role in the exploitation of oil, shale gas and coal seam gas resources – all of which contain natural fractures. We systematically explore the role of the pre-existing texture of such natural fractures on the form of the resulting stimulated reservoir volume (SRV). A blocky discrete element model (DEM) coupled with fluid flow is used to explore this response. Numerical predictions for the evolution of fluid pressure and fracture width at the well are compared with first-order analytical approximations of the zero-toughness solution (FMO). We then construct four typical joint system models separately comprising orthogonal, staggered, diagonal and randomly oriented joints and conduct the virtual hydraulic fracturing simulations via DEM. This defines the influence of structure on breakdown pressure and fracture propagation and allows the analysis of the main factors that influence behavior and resulting SRV. Results for the four forms of jointed rock mass show that: (1) the aggregate/mean extension direction of the fractures is always along the direction of the maximum principal stress but significant deviations may result from the pre-existing fractures; (2) there are negative correlations between the maximum fracture aperture with both Poisson ratio and elastic modulus, but the breakdown pressure is only weakly correlated with Poisson ratio and elastic modulus; (3) an increase in injection rate results in a broader fracture process zone extending orthogonal to the principal fracture, and the breakdown pressure and interior fracture aperture also increase; (4) an increase in fluid viscosity makes the fractures more difficult to extend, and the breakdown pressure and interior fracture aperture both increase accordingly.

1. Introduction

Hydraulic fracturing (HF) is widely used as a method for enhancing oil and gas production and in increasing recoverable reserves. Introduced in 1949, hydraulic fracturing has evolved into a standard operating practice, with many treatments completed (Veatch, 1983). Today, HF is used extensively in the petroleum industry to stimulate oil and gas wells to increase their productivity (Adachi et al.,2007; Yuan et al., 2017a,b; Yuan et al., 2018).

During the past few decades, considerable effort has been applied to understand the mechanics of hydraulic fracturing through numerical methods. The Finite Element Method (FEM) and the Boundary Element Method (BEM) have each been used to simulate HFs in complex formations (Papanastasiou, 1997; Vychytil and Horii, 1998). These have included three-dimensional nonlinear fluid-mechanics coupling of FEM to represent staged fracturing processes of a horizontal well in the Daqing Oilfield (Zhang et al., 2010). Coupling algorithms combining FEM and meshless methods have been applied for the simulation of the dynamic propagation of fracturing under either external forces or hydraulic pressure (Wang et al., 2010). In attempts to validate the models, microseismic monitoring has been used to image the extent and nature of hydraulic fractures. One of the major findings of these studies is that the nature of the hydraulic fractures determined by observing the recorded seismicity does not generally agree with that predicted by conventional analytical and numerical models (Al-Busaidi et al., 2005). For this reason, discontinuum-based Distinct Element Methods (DEM) have been applied to the simulation of HF. With these techniques, the continuum is divided into distinct blocks or particles between which fluid can flow. This allows a better representation of hydraulic fracture growth in the rock mass, which may contain multiple pre-existing cracks, joints or flaws.

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DEM has been used to investigate the mechanics of naturally fractured reservoirs subject to a constant rate of fluid injection (Harper and Last, 1990). Moreover, Granular mechanics implementations of DEM have become an effective tool for modeling crack propagation (Potyondy and Cundall, 2004). This method provides a way to simulate the process of crack formation and extension in rock masses when injecting fluid into the borehole, with the simulation results compared to acoustic emission data from experiments (Al-Busaidi et al., 2005). The fluid viscosity and selected particle size distribution exert significant influence on simulations of HF in competent rock when using coupled flow-deformation DEM codes (Shimizu, 2010; Shimizu et al., 2011). An attempt has been made to validate the several proposed methods for shut-in pressure, under various remote stress regimes and various rock properties using DEM (Choi, 2012). PFC^{2D} was used to simulate HF propagation within a coal seam (Wang et al., 2014). The objectives of this study is to investigate mechanisms governing HF propagation in coal seams, propose schemes that may achieve the desired fracturing effects and aid in optimally guiding engineering practice.

Primarily from mine-back experiments and laboratory tests, geologic discontinuities such as joints, faults, and bedding planes are observed to significantly affect the overall geometry of the resulting hydraulic fractures (Warpinski and Teufel, 1987). This can occur by arresting the growth of the fracture, increasing fluid leak off, hindering proppant transport, and in enhancing the creation of multiple fractures. Discrete fracture network (DFN) modeling is an approach for representing and assessing complex fracture growth and associated production prediction through generated fractures coupling with DEM (McLennan et al., 2010; Riahi and Damjanac, 2013). A microscopic numerical system has been used to model the interaction between HFs and natural fractures (Han et al., 2012). Preliminary results obtained using combined finite-discrete element techniques have also been used to study the interaction between fluid driven fractures and natural rock mass discontinuities (Grasselli et al., 2015). *HF Simulato*r (A DEM solution based on a quasi-random lattice of nodes and springs) has been used to represent hydraulic fracturing in jointed rock masses (Damjanac and Cundall, 2016). The effect of natural existing fractures on fluid-driven hydraulic fracture growth is investigated by analyzing the variation of fracture radius, cumulative crack number, and growth rate of porosity versus injection time based on PFC^{2D} (Wang et al., 2017).

In this paper, we use a DEM code (UDEC) to simulate and analyze the characteristics of HF propagation in complex jointed rock masses to codify crack propagation influences of natural fractures. After verification of the first order approximation of the zero-toughness solution of HF, correlations among the initial stress, injection parameters and the performance of fractures induced by HF in naturally fractured media are then all studied.

2. Simulation mechanism of UDEC

It is well known that accommodating the role of discontinuities in rock masses is a challenging task. UDEC is specifically developed to model discontinuous problems. It can accommodate many discontinuities and permits the modelling system to undergo large geometrical change through the use of a contact updating scheme (Fig. 1). In UDEC, the deformation of a fractured rock mass consists of the elastic/plastic deformation of blocks of intact rock, together with the displacements along and across fractures. The motion of a block is characterized by Newton's second law of motion, expressed in central finite difference form with respect to time. Calculations are performed over one timestep in an explicit time-marching algorithm. For deformable blocks, numerical integration of the differential equation of motion is used to determine the incremental displacements at the gridpoints of the triangular constant strain element within the blocks. The incremental displacements are then used to calculate the new stresses within the element through an appropriate constitutive equation (Itasca, 2015).

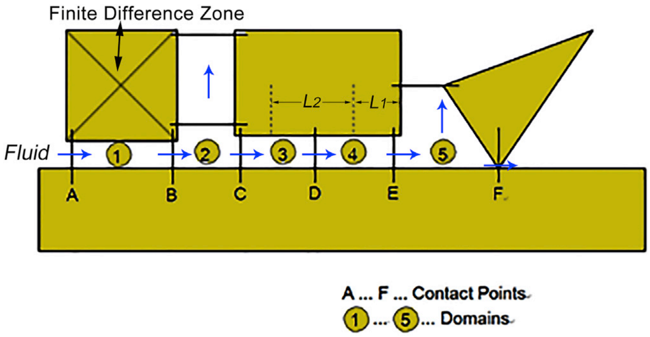

Fig. 1. Contacts, domains and flow between domains between blocks. Modified from Lemos and Lorig (1990).

2.1. Joint behavior model

The data structure only needs two types of contacts to represent a system of blocks: corner-to-corner contacts and edge-to-corner contacts. These are termed "numerical contacts." Physically, however, edge-to-edge contact is important, because it corresponds to the case of a rock joint closed along its entire length. A physical edge-to-edge contact corresponds to a domain with exactly two numerical contacts in its linked-list. The joint is assumed to extend between the two contacts and to be divided in half, with each half-length supporting its own contact stress. Incremental normal and shear displacements are calculated for each point contact and associated length (i.e., L_1 and L_2 in Fig. 1).

Many types of constitutive models for edge-to-edge contact may be contemplated. The basic joint model used in UDEC captures several of the features that are representative of the physical response of joints. In the normal direction, the incremental normal stress and the incremental normal displacement are $\Delta\sigma_n$ and Δu_n respectively, and the stress-displacement relation is assumed to be linear and governed by the stiffness k_n such that

$$\Delta\sigma_n = -k_n \Delta u_n. \tag{1}$$

A more comprehensive displacement-weakening model is also available in UDEC. This model (the continuously yielding joint model) is intended to simulate the intrinsic mechanism of progressive damage of the joint under shear.

There is also a limiting tensile strength $\tau_{\max}$ for the joint. If the tensile strength is exceeded (i.e., if $\sigma_n < -\tau_{\max}$), then $\sigma_n = 0$. Similarly, in shear, the response is controlled by a constant shear stiffness k_s. The shear stress τ_s is limited by a combination of cohesive (C) and frictional (ϕ) strength. Thus, if

$$|\tau_s| \le C + \sigma_n + \tan\phi = \tau_{\max} \tag{2}$$

then

$$\Delta\tau_s = -k_s \Delta u_s^e. \tag{3}$$

Or, if

$$|\tau_s| \ge \tau_{\max} \tag{4}$$

then

$$\tau_s = sign(\Delta u_s)\tau_{\max} \tag{5}$$

where, $\Delta\tau_s$ is the incremental shear stress; Δu_s^e is the elastic component of the incremental shear displacement; and Δu_s is the total incremental shear displacement.