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Simulation of hydraulic fracturing and its interactions with a pre-existing fracture using displacement discontinuity method

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ABSTRACT

The coupled hydro-mechanical (HM) function has been implemented in the existing fracture mechanics modelling code FRACOD (Fracture Propagation Code) where the Displacement Discontinuity Method (DDM) is used to simulate rock fracturing process. This new advance allows the code to model hydraulic fracturing in the presence of natural fractures. Verification was performed by simulating hydraulic fracturing process against the KGD model of the propagation of a single fracture driven by fluid injection. Numerical results show a good agreement with the analytical solutions and the main features of hydraulic fracturing process in intact rock have been successfully captured. The simulator is used to model the interactions of induced and natural fractures, where the hydraulic fracture shows to divert into only one branch of the pre-existing sealed fracture after the intersection.

1. Introduction

Hydraulic fracturing has been extensively used as a key technique for improving the well productivity of oil and gas reservoirs in a variety of host rocks (Valk and Economides, 1995; Warpinski and Teufel, 1987). Hydraulic fracturing process means the initiation and propagation of artificial fractures in the reservoir by fluid injection, which targets to increase the permeability of the reservoir sequentially. One important emerging application is unconventional gas reservoir engineering such as shale gas stimulation. Due to the application of horizontal drilling and hydraulic fracturing techniques, the production of shale gas experienced a huge increase in U.S. Shale gas provides the largest share of U.S. natural gas production in 2013, representing 40% of total natural gas production (EIA, 2014). Shale gas is the natural gas trapped within shale formation whose natural permeability is extremely low and thus stimulation techniques using hydraulic fracturing are essential to make gas recovery possible and economically viable. Because of ubiquitous natural fractures in the reservoir, understanding the interactions between hydraulically induced fractures and natural ones is important to the success of the stimulation treatment.

Hydraulic fracturing is a complicated coupling process which involves: 1) mechanical deformation induced by the fluid pressure on the fracture surfaces; 2) fluid flow within the fracture; and 3) fracture propagation (Adachi et al., 2007). The geometry of the induced fracture is dominated by the host rock mechanical properties, insitu stress, the applied fracturing fluid properties and local geological features such as natural fractures and bedding planes (Dahi-Taleghani, 2009). The observation suggests that these natural discontinuities can significantly impact the overall patterns of hydraulic fractures and multiple fractures or segments can propagate simultaneously (e.g., Warpinski and Teufel, 1987; Fast et al., 1994; Gale et al., 2007; Jeffrey et al., 2009). Understanding complex hydraulic fracture behaviour in the presence of natural fractures is critical to the optimum stimulation design.

Different hydraulic fracturing models were proposed to explain field observations and to assist operation design. In the most basic hydraulic fracturing theory (Hubbert and Willis, 1957), it is typically assumed that the planar fracture is generated and propagated normal to the minimum principal stress orientation. Two simplified models, Kristonovich-Geertsma-de Klerk (KGD) and Perkins-Kern-Nordgren (PKN) geometry models, were widely accepted and used to predict the shape and size of a hydraulic fracture with given rock and fluid properties and field stresses (Valk and Economides, 1995). Essentially they are two dimensional plane strain solutions applicable in homogeneous isotropic medium (Khristianovich and Zheltov, 1955; Perkins and Kern, 1961; Nordgren, 1972; Geertsma and De Klerk, 1969). Extended KGD and PKN models were used

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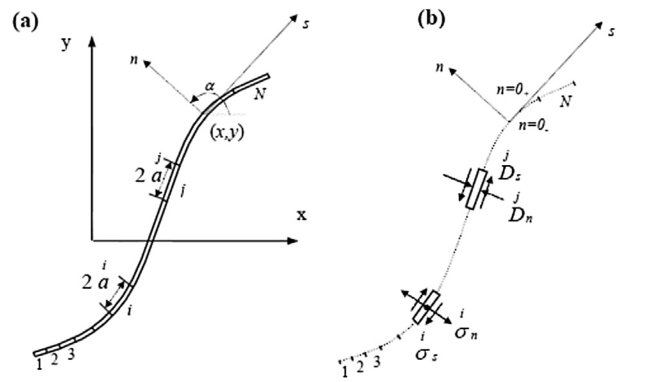

Fig. 1. A curved crack represented by N element displacement discontinuities (CSIRO & FRACOM, 2014). (a) global x-y co-ordinate system and (b) local n-s co-ordinate system.

routinely for treatment designs as recently as the 1990s, and they have been largely replaced by the semi-analytical pseudo-3D (P3D) models (Adachi et al., 2007). The P3D models were developed to adjust for sedimentary layer reservoir conditions in reality.

Because of the complexity of hydraulic fracturing process, not to mention the impacts of pre-existing fractures and their interactions with induced fractures, analytical and experimental tools can be used with limited capabilities and, therefore, numerical methods have been the feasible alternatives. In recent years, considerable efforts have been devoted to the numerical simulations of hydraulic fracturing in the presence of natural fractures and they can address the coupling between rock mechanical response and fluid dynamics. Dahi-Taleghani (2009) developed an Extended Finite Element (EFEM) model to consider the interactions between induced and natural fractures, and later applied it to simulate multistranded hydraulic fracture propagation problems (Dahi-Taleghani and Olson, 2011). Xu et al., (2015) used a Finite Element Method (FEM) model which considers the coupling of fluid flow during element damage evolution to investigate hydraulic fracturing behaviour. Kresse et al. (2013) presented an unconventional fracture model (UFM) to simulate hydraulic fracture interaction in complex naturally fractured formations, where the stress shadow from fracture branches is computed based on an enhanced 2D Displacement Discontinuity Method (DDM). Zhang and Jeffrey (2006), Zhang et al. (2007, 2009) developed a Boundary Element Method (BEM) simulator for modelling hydraulic fracture problems, and performed investigations with respect to the roles of natural fractures and bedding planes in fluid-driven fracture growth using models with simple geometries. Besides the above mentioned models based on continuum approaches, the application of Discrete Element Method (DEM) is increasingly popular (Potyondy, 2015). Zangeneh et al. (2014) presented a series of UDEC, a DEM based 2D code, simulations investigating the influence of natural fractures on hydraulic fracture propagation, where a Voronoi tessellation scheme is used to add the necessary degrees of freedom to model the hydraulic fracture path. Yoon et al. (2014) carried out PFC, a particle DEM code, simulations on hydraulic fracturing and induced seismicity in naturally fractured deep geothermal reservoirs. In a recent article by Damjanac and Cundall (2016), they provided a comprehensive summary on the application of distinct element methods to simulate hydraulic fracturing in naturally fractured reservoirs. Nevertheless, it is still challenging to model the real site scale problems with sufficient details for the prediction of hydraulic fracture behaviour for field treatments.

The FRACOD (Fracture Propagation Code) was initially developed in 1990s to model the explicit fracturing processes of brittle materials (fracture initiation, propagation and coalescence) in plane strain conditions using a modified G-criterion (Shen and Stephansson, 1993). Consistent efforts have been made to enrich its capabilities for dealing with complex coupled thermo-hydro-mechanical processes (e.g., Shen, 2014) and modelling fracture propagation in anisotropic rock mass (Shen et al., 2015). Numerous applications have also been conducted (Shen et al., 2014).

This paper starts with the new development of FRACOD focusing on the coupled hydro-mechanical (HM) process simulation. This new advance enables FRACOD to model hydraulic fracturing in the presence of natural fractures, where simulating hydraulic fracture initiation and propagation and accounting for the interactions between induced and natural fractures are essential. Code verification is presented by simulating the KGD model of the propagation of a single fracture driven by hydraulic injection. Finally, the demonstration example which involves the interaction between hydraulic and pre-existing fractures is presented.

2. Theoretical background of FRACOD

The FRACOD code utilizes the DDM method and is essentially a BEM program where the fracture mechanics theory and a modified G-criterion of fracture propagation are incorporated to simulate explicit fracturing process.

2.1. Numerical implementation of displacement discontinuity method in FRACOD

The displacement discontinuity is defined as the difference of the displacement between two sides of a line segment. The DDM method implementation relies on the solutions of the problem of a constant displacement discontinuity over a line segment in an infinite elastic body, which was initially addressed by Crouch (1976) and Crouch and Starfiield (1983). In favour of numerical implementation, the solution can be rewritten as Eq. (1). The normal and shear components of the stress (σ_n and σ_s) and displacement (u_n and u_s) at a specific location, caused by a displacement discontinuity, are explicitly presented.

$$\begin{aligned}\sigma_s &= A_{ss}D_s + A_{sn}D_n\\ \sigma_n &= A_{ns}D_s + A_{nn}D_n\\ u_s &= B_{ss}D_s + B_{sn}D_n\\ u_n &= B_{ns}D_s + B_{nn}D_n\end{aligned} \tag{1}$$

where D_s and D_n are the shear and normal components of the displacement discontinuity on the line segment. A_{ss}, A_{sn}, A_{ns} and A_{nn} are boundary influence coefficients for the stress, while B_{ss}, B_{sn}, B_{ns} and B_{nn} are boundary influence coefficients for the displacement. These coefficients are components of the stress or displacement of a specific location due to a constant unit displacement discontinuity. They are used mainly for concise presentation and their full form expressions are provided in the code manual (CSIRO & FRACOM, 2014).

The code approximates a curved crack by straight line segments joined end by end (Fig. 1) and a sufficient number of line segments

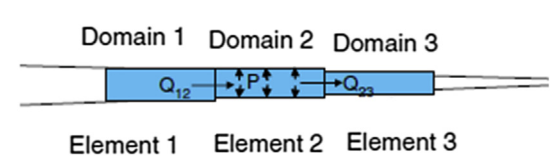

Fig. 2. Diagram of flow system simulated in FRACOD (by courtesy of CSIRO and FRACOM, 2014).