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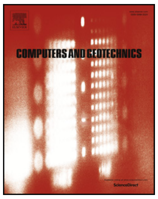

Research Paper

Numerical study of interaction between a hydraulic fracture and a weak plane using the bonded-particle model based on moment tensors

Qi Zhang, Xiao-Ping Zhang*, Pei-Qi Ji

The Key Laboratory of Safety for Geotechnical and Structural Engineering of Hubei Province, School of Civil Engineering, Wuhan University, Wuhan 430072, China

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ABSTRACT

To better investigate hydraulic fracturing in tight reservoirs, interaction modes between a hydraulic fracture and a weak plane are studied with acoustic emission (AE) based on moment tensor under different differential stresses ($\Delta\sigma$) and approaching angles (β). Failure nature of hydraulic fracture is mainly tensile based on moment tensors except that the hydraulic fracture propagates into weak plane. At $\beta = 30^\circ$, the hydraulic fracture is arrested by the weak plane. The failure nature of weak plane changes from 'Shear' ($\Delta\sigma = 10$, 7 and 5 MPa) to 'Tensile' ($\Delta\sigma = 3$ MPa). At $\beta = 60^\circ$, the hydraulic fracture branches into weak plane as crossing, the nature of which is 'Shear' as differential stress decreases from 10 MPa to 5 MPa. At $\beta = 90^\circ$, the hydraulic fracture crosses the weak plane perpendicularly.

1. Introduction

The world is entering a 'golden age of gas', with the exploitation of unconventional resources (tight gas, shale gas and coalbed methane, etc.) expected to influence regional and global gas markets [1]. The gas resource size and production cost are the two key preconditions for its development [2]. Compared with conventional resources, the production of unconventional resources is relatively low due to the unconventional reservoirs are generally with low porosity and permeability. Hydraulic fracturing treatments can enhance production of unconventional resources remarkably by creating complex fractures in the naturally fractured reservoirs. Hydraulic fracturing is a method using pressurized fluid to fracture underground formations, which was initially introduced for oil industry in 1948 [3].

To study the fracture initiation, propagation and interaction during hydraulic fracturing, many laboratory experiments were performed under different confining stress conditions, flow rates, fluid viscosities, sizes and orientations of pre-existing fractures [4–8]. Fan and Zhang [9] used laboratory experiments to study the evolution of hydraulic fracture networks in naturally fractured formations with specimens containing two groups of orthogonal cemented fractures. Strength and geometry of pre-existing fracture have a significant influence on the mode of the interaction with hydraulic fracture [5,10–12]. Three types of interaction between pre-existing fracture and hydraulic fracture were observed including (1) crossing, (2) arrest by opening and dilating the fracture and (3) arrest by shear slippage of the fracture with no dilation and fluid flow along the fracture. Horizontal differential stress and geometry (strike and dip) of pre-existing fracture are the two major factors that affect the interaction modes. Lee et al. [69] ingeniously performed an experiment study, Semi-Circular Bend tests on Marcellus Shale core samples containing calcite-filled natural fractures (veins), to investigate the influence of weak planes on hydraulic fracture propagation. The results indicated that the approach angle of the induced fracture to the veins and the thickness of the veins have a strong influence on hydraulic fracture propagation. Some field studies [13–18] indicated that hydraulic fracture encountering the natural fractures may enhance fluid leak-off, fracture offsets and multiples, high net pressure and pre-mature screen-out.

Due to the complexity and non-visibility of hydraulic fracture site, numerical simulation is widely used to study the reservoir fracturing reconstruction and mechanism of hydraulic fracture. Sesetty and Ghassemi [19] used boundary element and finite difference based method to model interaction of hydraulic fracture and pre-existing fractures. Zhou and Hou [20] used the FLAC3D to simulate hydraulic fracture propagation under 3D stress state, which not only considered the propagation of a single fracture, but also its influence on the adjacent rock formations and the neighboring fractures. Universal distinct element code (UDEC) was applied to study seismic energy release [21] and the effect of fracture geometries and stress on shut-in pressure during hydraulic fracturing [22]. Particle flow code (PFC) [23] is extensively used to model hydraulic fracturing based on the bonded-particle model (BPM). Hazzard et al. [24] initially used this method to

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* Corresponding author.
E-mail address: jxhkzhang@163.com (X.-P. Zhang).

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simulate fluid injection into a granite reservoir. Al-Busaidi et al. [25] introduced the development and application of the BPM to study the mechanics of fracture initiation and propagation during hydraulic fracturing. The simulation results were consistent with those of laboratory experiments. Zhao and Young [26] used the BPM coupled with micro-seismic monitoring technique to study the interaction between hydraulic fractures and pre-existing fractures, which indicated that the model can realistically simulate hydraulic fracturing by comparing with the geometry of hydraulic fractures and seismic source information from both laboratory experiments and field observations. Shimizu et al. [33] and Wang et al. [27,28] used the BPM to study the effect of particle size distribution, fluid viscosity and injection parameters on fracture types and propagation. Zhou et al. [29,30] developed the model to investigate the effect of the confining stress ratio, injection rate and fluid viscosity on fracture propagation in laminated reservoir rocks. Yoon et al. [31,32] adopted the model coupled acoustic emission technique to investigate the stress shadow that accumulated as the fracturing stages advanced from toe to heel and fluid injection, induced seismicity, and triggering of fault rupture in jointed rocks. Lee et al. [70] investigated the interaction of propagating tensile fractures with calcite-filled veins in Marcellus shale using Semi-Circular Bend tests in the PFC3D, which discussed the effect of vein properties, e.g. approach angle, thickness, strength, stiffness, penetration length, on fracture diversion.

In the above literatures, the interaction modes between a hydraulic fracture and a pre-existing fracture are widely studied by numerical simulations and experimental studies. A pre-existing fracture generally refers to an interface with certain friction and zero cohesion. So slippage may occur along the fracture. In the lab test, pre-existing fracture can be created by cutting an intact specimen [6] or inserting paper/tape in a modeled specimen [7]. If a fracture is sealed with weak materials in a certain width, the fracture acts as weak plane and reactivates during hydraulic fracture treatments, which cannot be considered as a fracture with zero cohesion [30]. However, many researchers still used pre-existing fracture to denote a weak plane with certain cohesion and friction. For example, Blanton [34] used hydrostone to simulate a pre-fracture with coefficient of friction of 0.75 and cohesion of 3.15 MPa. Zhou et al. [5] created three types of pre-fractures by paper cast in cement, rice paper, printer paper and wrapping paper with friction coefficients of 0.38, 0.89 and 1.21, respectively and with the same cohesion of 3.2 MPa. Dehghan et al. [12] also used a printer paper to simulate a pre-existing fracture with coefficient of friction and cohesion of 0.89 and 3.2 MPa, respectively. In the BPM, Zhao [35]and Nagaso et al. [8] simulated pre-existing fracture by setting the bond strengths of the pre-existing fracture half times those of intact rocks. In our opinion, if a fracture has certain cohesion along the interface, the fracture acts as a weak plane and the term ‘pre-existing fracture’ cannot be used. In the present study, for a fracture without cohesion, it is considered as a pre-existing fracture. If a fracture has cohesion, the term ‘weak plane’ is used.

Although many experimental and numerical studies have been conducted to investigate the interaction between a pre-existing fracture/weak plane and a hydraulic fracture, most of them focused on pre-existing fracture/weak plane geometry (dip and strike), fluid injection rate and fluid viscosity. The failure nature of fracturing and interaction, which affects the permeability of reservoir after fracturing treatment, is not well understood. To contribute to this field of research, a square model containing a weak plane is modeled at laboratory scale based on the BPM, in which the bond strength of weak plane is 0.25 times that of host rock. A ratio of moment tensor, which can indicate the force applying at the source, is used to determine the failure nature of the hydraulic fracture and weak plane, namely ‘Tensile’, ‘Shear’, and ‘Compaction’. The ‘Compaction’ mode of failure means compression or implosion, implying the failure source mainly with an implosion component. For a better understanding of the effect of micro-parameters in the BPM, a series of Darcy tests are primarily conducted to discuss the effect of initial contact force (F_0) on macro-permeability of a model. In this way, a reasonable approach determining fracturing parameters and better understanding of the mechanism of hydraulic fracture are presented.

2. Fluid flow modeling in the BPM

2.1. Bonded-particle model

The bonded-particle model (BPM), as a discrete element method, was initially introduced by Cundall [36] and developed by Cundall and Strack [37]. Potyondy et al. [38] and Zhang et al. [39,68] had described the principle of the BPM in detail. The model simulates the movement and interaction of solid materials represented by bonded non-uniform sized circular or spherical particles in two-dimension or three-dimension. The properties of simulated materials are generally determined by the stiffness and strength micro-parameters of the particles and bonds. Two types of the BPMs, contact bond model and parallel bond model, are available in the commercial software PFC. Both types can be considered as cements jointing two adjacent particles. The contact bond cement acts only at contact point and can only transmit normal and shear forces. The parallel bond cement acts at cross-section lying between two particles and can transmit both force and moment, which is a more realistic bond model for rock or rock-like material [38,40–42]. Previous studies [39,43–45] indicate that the BPM has capability to reproduce crack initiation, propagation and coalescence in rock-like material containing single flaw, two parallel flaws and non-parallel flaws.

2.2. Fluid-mechanical coupled

In the present study, a commercially-available BPM in the PFC from Itasca Consulting Group [23] is used. For the fluid-mechanical simulation in the BPM, each particle contact is considered as a ‘pipe’ (fluid flow channel) as shown in Fig. 1. A series of enclosed ‘domain’ (green polygons) are created by drawing lines between the centers of all contact particles. These small domains connected up by the pipes store fluid pressure.

For a pipe with aperture (w), length (L) and unit depth (in 2D), the rate of volumetric flow (Q) is governed by Poiseuille equation [25,46]

$$Q = \frac{w^3}{12\mu}\frac{\Delta P}{L} \tag{1}$$

where L and ΔP are pipe length and fluid pressure difference between two adjacent domains, respectively, μ is fluid viscosity and w is aperture. Pipe length is considered as the sum of the radii of the adjacent particles in contact. During fluid calculation, the fluid pressures stored in domains are updated and applied to the surrounding particles as equivalent body force. The change in fluid pressure (ΔP_d) within each domain is calculated from the sum of flow volume ($\sum Q$) in each time step (Δt), the domain deformation (ΔV_d) caused by mechanical force, the apparent volume of the domain (V_d) and the fluid bulk modulus (K_f), which is given as:

$$\Delta P_d = \frac{K_f}{V_d}\left(\sum Q\Delta t - \Delta V_d\right) \tag{2}$$

Fluid pressure applies to the surrounding particles causing particle movement and deformation of domain volume, which modifies the contact force and affects fluid flow by altering the pipe apertures. When a bond is broken (open contact), the fluid pressures stored in two different domains are assumed to be equal to the average pressure of two domains. For the just touching particles (normal contact force equal to 0), a residual aperture (w_0) is assumed. As compressive normal force at a contact increases, the aperture is related to the force: