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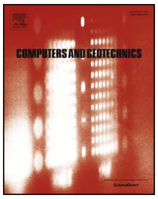

Research Paper

Hydraulic fracturing simulation for heterogeneous granite by discrete element method

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ABSTRACT

In this study, a heterogeneous discrete element model of granite was built considering different mineral contacts, different mineral grains, and the percentages of minerals which were obtained from analysis of the gray-scale values of the rock picture. First, the contacts and grains parameters were fixed by simulating triaxial compression and fracture toughness tests. Then, the permeability of the numerical model was calibrated on constant head tests. Finally, a coupled hydro-mechanical code was used to investigate the hydraulic fracturing under different conditions, considering the influences of permeability, fluid viscosity, fluid injection rate, boundary stress, pre-existing cracks, heterogeneity and weak layer.

1. Introduction

Hydraulic fracturing is an important technology in gas/oil exploitation [1], mining engineering [2], geothermal engineering [3] and in situ stress measurements [4,5]. Generally, this technology, which involves rock damage and fluid flow in cracks, is employed to create desired cracks for improving gas/oil production, reducing mining difficulties, and improving efficiency in the use of geothermal energy. In addition, sealing and safety of gas/CO_2 reservoirs have significant relation to hydraulic fracturing characteristics of the surrounding rocks of the reservoirs [6]. Especially, the understanding of hydraulic fracturing mechanisms in low-permeability rocks such as granite can help engineers efficiently and sustainably exploit geothermal energy.

Numerical simulation technique is a convenient and economical method to investigate hydraulic fracturing mechanism in rocks. Several numerical methods have been developed and adopted by researchers to study the complicated hydraulic fracturing process. For continuum based numerical methods, Pogacnik et al. [3] developed a damage mechanical approach to simulate hydraulic fracturing/shearing around a geothermal injection well. Salimzadeh and Khalili [7] used the extended finite element method which considers a cohesive crack model as fracture criterion to investigate hydraulic fracturing with cohesive crack propagation. Bao et al. [8] proposed a coupled finite element method with condensation technique to simulate hydraulic fracturing. Carrier and Granet [9] studied the problem of fluid-driven fracture propagation in a permeable medium using a cohesive zone model and considering zero-thickness elements for the fracture propagation. Secchi and Schrefler [10] presented a numerical method by continuously updating the mesh around the crack tip to analyze the discrete fractures driven by the fluid pressure. Zhou and Hou [11] integrated a new 3D-model into the software FLAC3D to investigate hydro-mechanical coupling effects of hydraulic fracturing. Kim and Moridis [12] analyzed the vertical fracture propagation induced by hydraulic tensile fracturing for shale gas reservoirs. Abdollahipour et al. [13] systematically studied the hydraulic fracture patterns around a circular wellbore using the displacement discontinuity method. Yang et al. [14] used a finite element code to investigate the hydraulic fracture initiation, propagation and breakdown behavior of circular holes under internal hydraulic pressure. Li et al. [15] proposed a three-dimensional finite element model that considered the coupled effects of seepage, damage, and the stress field to study hydraulic fracturing. In respect to discontinuum based numerical methods which take into account the fluid viscosity and the particle size distribution, Shimizu et al. [16] carried out a series of simulations for hydraulic fracturing in hard rocks by the flow-coupled discrete element method (DEM). Damjanac and Cundall [17] simulated hydraulic fracturing in naturally fractured reservoirs with DEM and exhibited a pattern of hydraulic fractures that evolved in response to both intact rock fracturing and sliding and opening of pre-existing joints. Gerolymatou et al. [18] used DEM to investigate the effect of the orientation and spacing of preexisting

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weakness planes in the process of hydraulic stimulation. Based on DEM, Nasehi and Mortazavi [1] studied the effects of Young's modulus of intact rock, strength parameters of intact rock, and major discontinuities of rock mass on the hydraulic fracture properties in an oil well. Nguyen et al. [19] proposed a meshfree approach which is an extension of the cracking particle method for investigating complex crack patterns in hydraulic fracturing. Zeeb and Konietzky [20] built a DEM model to simulate the hydraulic stimulation of multiple fractures in an anisotropic stress field for an enhanced geothermal system. Wasantha and Konietzky [21] used the DEM to investigate the reactivation mechanism of natural fractures and its subsequent effects on the properties of the reservoir during hydraulic stimulation of naturally fractured reservoirs. Wasantha et al. [22] proposed a DEM scheme to study the geometric nature of hydraulic fracture propagation in naturally fractured reservoirs considering natural fracture properties such as the stiffness and approaching angle, and the distance from wellbore to the natural fracture. Choo et al. [23] proposed a hybrid continuum and discontinuum based numerical model which couples discontinuous deformation analysis blocks with finite element meshes to study hydraulic crack initiation and propagation processes. Yan et al. [24] and Yan and Zheng [25] adopted combined finite-discrete element method with a new coupled hydraulic-mechanical model to simulate hydraulic fracturing. Lisjak et al. [26] proposed a new fully-coupled hydro-mechanical formulation for the finite-discrete element method to investigate the fracturing process in discontinuous porous rock masses.

It is well known that the hydraulic fracturing process in rocks is significantly affected by the fluid parameters (i.e. viscosity and injection rate), the rocks parameters (i.e. strength, permeability, initial defects and heterogeneity), and the boundary conditions. Although various studies have been carried out in this area, there is still lack of systematic investigations on the effects of these parameters on hydraulic fracturing. The study in this paper presents a heterogeneous discrete element based numerical simulation approach for hydraulic fracturing analysis, considering the influences of the aforementioned parameters; thus, is the innovation of the study. The paper is organised as follows: first, constitutive models of matrix, contacts, and hydro-mechanical coupling are introduced; second, parameters for contacts and grains are calibrated by triaxial compression and fracture toughness tests; third, permeability of the numerical model is calibrated by the constant head tests; finally, considering the influence of permeability, fluid viscosity, fluid injection rate, boundary stress, pre-cracks, heterogeneity and weak layer, the hydraulic fracturing in granite is predicted based on the calibration results.

2. Constitutive models

2.1. Constitutive model for rock matrix and contacts

A two-dimensional Universal Distinct Element Code (UDEC) was adopted to build the numerical model. Therefore, all simulations were performed in two dimensions. The grain-based DEM model (the diameter of the disc is 75 mm) in which different mineral components of biotite, quartz, and feldspar are randomly distributed is formed by about 2000 elastic and unbreakable Voronoi blocks whose equivalent diameter is about 1 mm (as shown in Fig. 1). Hence, the constitutive model of the blocks is elastic and the blocks are unbreakable. Different minerals with corresponding elastic modulus are highlighted by different colors in these Voronoi blocks. Contacts were assigned between the mineral grains to mimic potential breakage of the mineral clumps. Therefore, there were six types of mineral contacts (i.e. biotite/biotite, quartz/quartz, feldspar/feldspar, biotite/quartz, biotite/feldspar, and quartz/feldspar) and one contact type between granite and loading plate (shown in Fig. 1). The contact constitutive behaviour can be described by Eqs. (1) and (2), which is characterized by the Mohr-Coulomb failure criterion with tension cut-off and shear softening. Below the ultimate tensile and shear strength, the stress-displacement relations in normal and shear direction are linearly governed by normal stiffness k_n and shear stiffness k_s, respectively. The damage process associated with unrecoverable deformations and propagation of cracks are realized by breakdown of contacts and relative movement along or across the contacts.

$$\begin{cases} \sigma_n = -k_n u_n \\ if\ \ \sigma_n < -J^T,\ \sigma_n = J_r^T = 0 \end{cases} \tag{1}$$

$$\begin{cases} \tau_s = k_s u_s \\ \tau_{\max} = J^C + \sigma_n \tan\varphi \\ if\ \ |\tau_s| \geqslant \tau_{\max},\ \tau_s = sign(\Delta u_s)\cdot(J_r^C + \sigma_n \tan\varphi_r) \end{cases} \tag{2}$$

where σ_n and τ_s are the normal stress and the shear stress, respectively. k_n and k_s denote normal stiffness and shear stiffness, respectively. u_n and u_s are the normal displacement and the shear displacement, respectively. J^T, J_r^T, J^C, and J_r^C are the tensile strength, the residual tensile strength, the cohesive strength, and the residual cohesive strength, respectively. $\tau_{\max}$ is the shear strength, φ and φ_r are the friction angle and the residual friction angle, respectively. Δu_s is the incremental contact shear displacement.

2.2. Constitutive model for hydro-mechanical coupling

In the numerical model, the blocks (i.e. basic mineral grains) are assumed to be impermeable and the fluid which is assumed to be incompressible can infiltrate only through the contacts (i.e. microcracks). Therefore, hydro-mechanical analysis can be performed as follows. First, the fluid infiltrates into the contacts. Then corresponding fluid pressures are added on the contacts and affect stress and displacement fields around the contacts. Thereafter, apertures of the contacts increase with increasing fluid pressures. Once the failure conditions of the contacts are satisfied, initiation or further propagation of the microcracks will be triggered, resulting in changes of corresponding stress field, displacement field, and fluid pressures in the DEM model. A schematic diagram of the considered fluid flow through the contact, as well as the corresponding crack deformation, is shown in Fig. 2.

During the simulation, the contact network represents the possible flow network due to the assumption that only along the contacts the fluid flow is possible. In Fig. 2a, the node domains 1–10 indicate the intersection points of the flow network and the coloured line between two nodes is the flow path. For example, using the cubic law, the flow rate from domain 4 with pressure P_4 to domain 3 with pressure P_3 can be calculated using Eqs. (3) and (4) [27]:

$$q_{34} = -k_i a^3 \frac{\Delta P}{L_i}[s^2(3{-}2s)] \tag{3}$$

$$\Delta P = P_4 - P_3 + \rho g (y_4 - y_3) \tag{4}$$

where q_{34} is the flow rate, a is the contact hydraulic aperture, k_i is a contact permeability factor (whose theoretical value is $1/12\nu$ in UDEC and μ is the dynamic viscosity of the fluid), ΔP is the pressure difference between domain 3 and domain 4, L_i is the length assigned to the contact between the domains, s is the empirical parameter considering the influence of saturation ($s = 0$ and $s = 1$ mean zero saturation and full saturation of the domains, respectively, $0 \leqslant s \leqslant 1$), ρ is the fluid density, g is the acceleration of gravity, and y_3 and y_4 are the y -coordinates of the domain 3 and 4 centers, respectively.

Eqs. (3) and (4) indicate that the flow can occur at the contact 3–4 due to the gravity even when the fluid pressures are zero in domains 3 and 4. Furthermore, if saturation of domain 4 is zero (i.e. $s = 0$), the flow from domain 4 to domain 3 cannot take place (it means inflow cannot occur from a completely unsaturated domain).

Once flow occurs in the contact, fluid pressure will be induced inside the domain of the contact. During the period of one time step, the new domain pressure can be calculated by the following equation: