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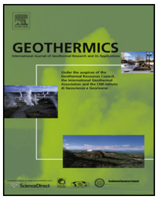

Numerical investigation on optimized stimulation of intact and naturally fractured deep geothermal reservoirs using hydro-mechanical coupled discrete particles joints model

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ABSTRACT

This numerical study investigates hydraulic fracturing and induced seismicity in intact and fractured reservoirs under anisotropic in situ stress using hydro-mechanical coupled discrete particles joints model. A 2 km × 2 km reservoir model with granitic rock and joints properties is constructed. Various injection scenarios are tested which involve continuous and cyclic styles of pressure controlled and flow rate controlled injections. Results are compared which include: spatial and temporal evolution of induced seismic events in relation with fluid pressure distribution, moment magnitudes of the induced events, occurrence of post-shut-in large magnitude events, etc. Several field observations on induced seismicity phenomena are simulated which include creation of new fractures, re-activation of the pre-existing joints, post-shut-in seismicity and large magnitude event with non-double-couple source, Kaiser phenomenon, moment magnitude vs. frequency distribution of the induced events following the Gutenberg-Richter law, etc. Cyclic injection results in larger volume of injected fluid but less number of total events and larger magnitude events; hence less seismic energy radiated by the induced events, slower relaxation of the fluid pressure after shut-in, longer and thinner propagated fractures with larger fluid saturated area. The major conclusions of this study are that the presented modeling is capable of simulating induced seismicity phenomena in Enhanced Geothermal System and fluid injection in fractured reservoirs in cyclic way has potential in mitigating the effects of larger magnitude induced events.

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1. Introduction

Developing an Enhanced Geothermal System (EGS) in deep reservoir requires creation of highly permeable heat exchanger which is usually achieved by fluid injection that results in combination of propagation of new fractures (hydro-fracturing) and induced slip on pre-existing fractures (hydro-shearing) referred to as Mixed-Mechanism stimulation (MMS, McClure and Horne, 2013). Fluid injection causes stress field changes and re-activation of the pre-existing joints and slip of nearby faults which consequently can result in larger magnitude events, e.g. local magnitude of 3.4 event in Basel EGS operation (Kraft et al., 2009). These largest events tend to occur on the fringes, outside the "main cloud" of seismicity and are often observed after well shut-in, making them difficult to control (Mukuhira et al., 2013). The need for developing a solid understanding of the processes underlying the occurrence of post-shut-in seismicity has become an important issue worldwide (Majer et al., 2007). Such phenomena have led to development of numerical tools that are able to simulate fluid injection in rock mass and interactions between injected fluid, rock mass and joints, creation of new fractures and re-activation of pre-existing joints. Appropriate measure for mitigating the effects of large magnitude events and optimizing EGS can be established after reliability of the numerical tools is validated.

In this context, this paper introduces hydro-mechanical coupled discrete particles joints model applied to simulation of hydraulic fracturing and induced seismicity in synthetic reservoirs. Particle Flow Code 2D (PFC^{2D}) (Itasca, 2008) with additionally implemented fluid flow algorithm and seismicity computation algorithm is used. Similar studies have been conducted using PFC^{2D} by Hazzard et al. (2002), Al-Busaidi et al. (2005), Yoon and Jeon (2009), Zhao and Young (2011), Shimizu et al. (2011, but not using PFC^{2D}). Hazzard et al. (2002) simulated a fluid injection test conducted in granitic rock at Soultz-sous-Forêts, France. Al-Busaidi et al. (2005) investigated the initiation and propagation of hydrofractures and the resulting seismic output, by comparing the results from lab-scale

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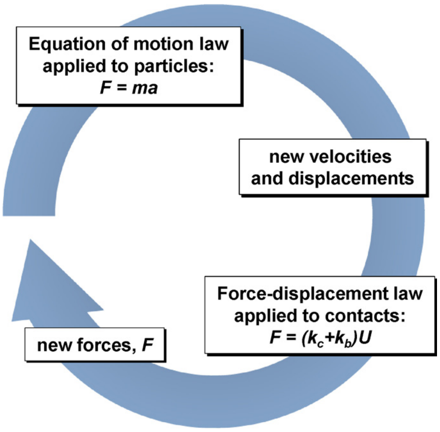

Fig. 1. Calculation cycle in PFC^{2D} (m: particle mass, a: acceleration, k_c: contact stiffness, k_b: bond stiffness, U: particle overlap).

model simulation with the laboratory experiments. Yoon and Jeon (2009) performed numerical modeling of fracturing processes in rocks induced by blast loading. Zhao and Young (2011) investigated interaction between hydraulic fracture and single natural joint. Shimizu et al. (2011) conducted a series of simulations for hydraulic fracturing in competent rock and investigated the influence of the fluid viscosity and the particle size distribution.

This paper presents various fluid injection schemes tested in two different reservoir models – intact and naturally fractured – that have granitic properties. Results are compared which include: (1) spatial and temporal evolution of the induced seismic events in relation with fluid pressure distribution, (2) moment magnitudes of the induced events, (3) occurrence of post-shut-in large magnitude events, etc.

Main objectives of this numerical study are (i) to examine if the presented numerical method is capable of reproducing the typically observed induced seismicity phenomena in EGS and (ii) to test two injection schemes – continuous and cyclic injections – and to see how the induced event clouds differ in terms of number of induced events, magnitude distribution, post-shut-in seismicity, occurrence of induced events in relation to fluid pressure distribution in intact and fractured reservoirs, etc. and finally (iii) to provide insights for how one can make use of soft stimulation to mitigate the effects of large magnitude induced seismicity and at the same time optimize the reservoir.

2. Methodology

2.1. Particle Flow Code 2D (PFC^{2D})

PFC^{2D} is a two-dimensional distinct element geomechanical modeling software (Itasca, 2008). The material simulated, in this case a reservoir rock mass, is modeled as an aggregate of circular particles bonded at their contacting points with finite thickness of cementing around the contact with the Mohr–Coulomb strength parameters (Table 1, Itasca, 2012 – enhanced parallel bond model). Under an applied load, the bonds can break in Mode I (tensile) or Mode II (shear). The calculation cycle in PFC^{2D} is a time stepping algorithm that requires repeated application of the law of motion applied to each particle and a linear force displacement law applied to each contact (Fig. 1). For more detail, we refer to Potyondy and Cundall (2004).

2.2. Fluid flow algorithm

Flow of viscous fluid in bonded particle assembly and fluid pressure and volume driven breakages of bonds in Mode I and Mode II are simulated. Original concept of fluid flow algorithm is proposed by Cundall (unpublished technical note, 2000), which was later modified by Hazzard et al. (2002).

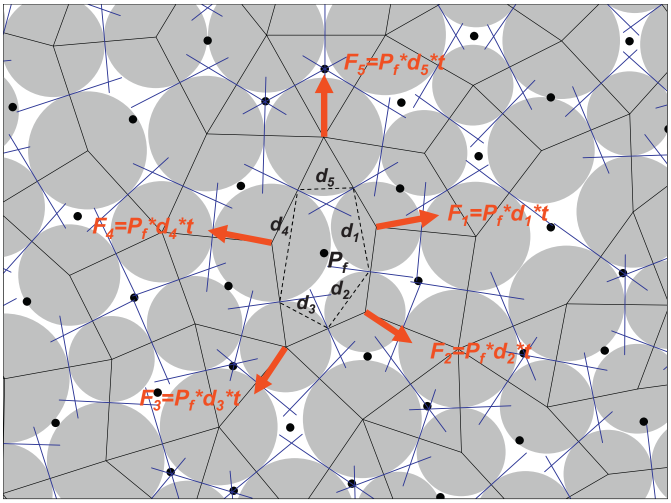

Fig. 2. Pore network model. Flow channels (blue lines at the particle contacts) are connecting two neighboring pore spaces bounded by polygons. Black dots at the polygon centers are virtual pores where pressure (P_f) is stored. Red arrows are resultant forces applied to the particles surrounding the pore space due to the pore fluid pressure P_f. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fluid flow is simulated by assuming that each particle bonded contact is a flow channel (Fig. 2, blue lines) and these channels connect up pore spaces (Fig. 2, polygons) that can store pressure. Pressure driven flow of viscous fluid between the two pore spaces is governed by Cubic law (Table 1) assuming that the flow is laminar between two smooth parallel plates.

$$q = \frac{e^3 \Delta P_f}{12\eta L} \tag{1}$$

where, e is hydraulic aperture, ΔP_f is fluid pressure difference between the two neighboring pores, L is flow channel length, η is fluid dynamic viscosity (Table 1).

Hydraulic aperture e, of the flow channel at a particle contact (Fig. 2, blue lines) changes as a function of normal stress, σ_n. We used experimentally derived e vs. σ_n relation from Hökmark et al. (2010).

$$e = e_{\inf} + (e_0 - e_{\inf})\exp(-0.15\sigma_n) \tag{2}$$

where, $e_{\inf}$ is hydraulic aperture at infinite normal stress, e_0 is hydraulic aperture at zero normal stress, σ_n is effective normal stress at the particle contact.

Fluid pressure increase per time step in a pore space (ΔP_f, Fig. 2) is computed from the fluid bulk modulus (K_f), volume of pore space (V_d), sum of flow volume (q, entering and leaving the pore space) and volume change of pore space (ΔV_d) due to mechanical loading, which is neglected in this study due to its minor effect. The equation used is shown below.

$$\Delta P_f = \frac{K_f}{V_d}\left(\sum q\Delta t - \Delta V_d\right) \tag{3}$$

The fluid exerts pressure on the surrounding particles causing deformations. This force term (F) is a production of fluid pressure (P_f), the length d (Fig. 2) and unit thickness (1 m) in out-of-plane direction. The resulting force term (F) is then applied to the particles from which law of motion computes the particle velocity and displacement which subsequently changes the stress states at the surrounding contacts which in turn changes the hydraulic aperture and thereby flow field.

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