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Technical Note

Discrete element modeling of cyclic rate fluid injection at multiple locations in naturally fractured reservoirs

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1. Introduction

The capabilities to access geothermal resources depend on the complexity of the specific geothermal reservoir conditions. In high-enthalpy systems, which are often steam dominated, energy conversion of extracted heat to electricity can be obtained at economically feasible costs. These resources are referred to as conventional geothermal systems, but they are limited in most countries. However, there are larger amounts of heat in place in alternative environments to cover the heat demand for centuries, but the initial productivity of these systems is too low to be profitable. These kinds of system are commonly called Enhanced Geothermal Systems (EGS), which have to be developed to economically extract circulating fluid [1]. The general EGS concept involves different tracks for enlarging access to heat at depth by improving exploration methods, drilling and reservoir assessment technology for deep geothermal resources, and the stimulation of low permeability reservoirs to develop an appropriate subsurface heat exchanger [2]. Most of these available non-conventional geothermal resources are located in basement rock formations, also referred to as petrothermal environments, where hydraulic fracturing is required to obtain sufficient flow rates [1]. In this context drilling horizontal sections of the wellbore is an option to perform multi-stage hydraulic fracturing in a series of consecutive operations. This is particularly useful in formations which do not have sufficient permeability to produce economically with a vertical well.

Hydraulic stimulations are often associated with the occurrence of induced seismicity, which could be felt at the surface and ultimately stop a geothermal project like in the Basel case [3]. Hence it is crucial to develop a strategy for hydraulic stimulations that involves concepts which reduce the probability of occurrence of felt seismic events in such environments while enhancing permeability by means of a fatigue treatment design [4].

This paper aims at testing of cyclic rate injection to multiple locations in a naturally fractured reservoir and examine if cyclic treatment exhibits advantages over constant rate fluid injection in a setting where hydraulic fracturing is performed at multiple locations in a sequence. Effect of fluid injection rate history on the shape of induced event clouds, occurrence of larger magnitude induced seismicity, energy ratio between hydraulic energy and radiated seismic energy and permeability enhancement are investigated. We conclude with addressing advantages of cyclic treatment for reservoir stimulation. This consideration of cyclic injection refers back to a geothermal stimulation treatment performed at an Enhanced Geothermal System in Germany [5].

2. Discrete element fracture model

2.1. Model generation and parameters

The numerical simulator used is Particle Flow Code 2D (PFC2D) [6,7]. For simulation of hydraulic fracturing, discrete element fracture network model is introduced where hydro-mechanical coupling logic is implemented. In this study, geological medium of low permeability, e.g. shale gas play or hot dry rock reservoir, is represented by an assembly of circular rigid particles. Particles making contacts are bonded with finite strength at their contacts and finite volume of cementation around the contacts to enable the bond to resist mode I, mode II and rotational loadings. Breakage of a bond can have two modes of failure, mode I tensile and mode II shear, which is governed by the Mohr–Coulomb failure criterion using the enhanced parallel bond model [8].

The generated reservoir model is 3 km and 2 km long in the minimum and maximum horizontal in situ stress directions, respectively

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(Fig. 1). The model is set longer in x-direction (3 km) as three injection points are contained with 500 m spacing between them. The model has 1 m thickness in the out-of-plane direction. The 6 km^2 space is packed with disks of which the diameters are in 20–30 m range, resulting in 11,243 particles. The chosen particle diameter range is comparable to that used in similar studies using PFC [9] (average particle diameter = 19.7 m) and using Block-Spring model [10] where fracture zone consists of individual blocks (slip patches) of 20 m side length. Bond strength at the particle contacts follow the Mohr–Coulomb parameters listed in Table 1. Mechanical properties of the rock matrix are taken from various literatures where crystalline granite rocks are investigated: Soultz granite, France [11] and Aue granite, Germany [12]. Although they originate from different locations, it is assumed that they are representative of crystalline granitic rock mass and selected in this study as parameters for the generic model.

Three sets of pre-existing fractures are embedded and represented by collection of smooth joints, of which the parameters are listed in Table 1. Length scales and number of fracture sets and fractures per set are arbitrarily selected. Orientation distributions of the fracture sets are taken from the field observations in Soultz, France [13,14]. The spatial distribution of the fractures shown in Fig. 1 is chosen among many cases of fracture network realization, but intentionally selected to have diverse zones of areal density. Fracture density is the highest around the injection point 1 and less at injection points 2 and 3. Presence of such diverse zones of fracture density is thought to be more representative of a naturally fractured reservoir. The generated fracture fabric is overlaid on to the bonded particle assembly. Those particle contacts located along the fracture fabric are switched to smooth joint contacts. Bonding attributes at the smooth joint contact follow the Mohr–Coulomb criterion which enables two modes of failures: mode I tensile and mode II shear. It should be noted that the mechanical properties of the fractures are generic, but assumed to be representative of the pre-existing joints/fractures in the crystalline granitic rock mass.

2.2. Criticality of stress states at the pre-existing fractures

The 6 km^2 reservoir section is assumed to be at 4 km target depth, at which the in situ horizontal stresses are 75 MPa and 60 MPa for the maximum and minimum stresses, respectively [15, Eq.1(b) and (c)]. Displacement of the four boundary walls is servo-controlled in order to achieve the target initial stress field. During the loading of the model by the boundary walls, embedded discrete fractures (smooth joint bonded contacts) fail as their strength parameters are low compared to the applied differential stresses (15 MPa) and maximum shear stress (7.5 MPa). The failed smooth joint contacts act as pre-existing fractures in the reservoir located at the target depth and activated by the applied far-field in situ stresses. These failed contacts are shown in Fig. 1 and marked by different colors, i.e. mode I tensile in blue, mode II shear failure in pink. Servo-controlled loading on the model by the boundary walls is done in a quasi-static condition in order to minimize the shock that bond cracking brings into the model. Normal and shear stresses at the smooth joints are plotted in Fig. 2 which correspond to the state after the in situ stresses are applied and the model is in equilibrium. Red line is the Mohr–Coulomb failure envelope which defines failure of the smooth joint bonded contacts. Data points located above the envelope represent the smooth joints which failed under the given in situ stresses, whereas points located below remained bonded.

2.3. Fluid flow algorithm

To simulate fluid injection and migration in the reservoir, fluid flow algorithm is implemented via *FISH* coding script of PFC2D [6]. The algorithm simulates flow of viscous fluid through the flow channels located at the particle contacts, driven by the pressure difference between neighboring pore spaces. Cubic law is used for the flow rule assuming that the flow is laminar between two parallel plates having smooth surface and uniform hydraulic aperture that changes with effective normal stress, i.e. compressive normal contact force, f_n (N), divided by flow channel length, l (m), and unit thickness (1 m) in the out-of-plane direction.

Relation between the hydraulic aperture and the effective normal stress at the flow channel follows negative exponential decay function in [16,17]

$$e = e_{inf} + (e_0 - e_{inf})\exp(-a\sigma_n) \tag{1}$$

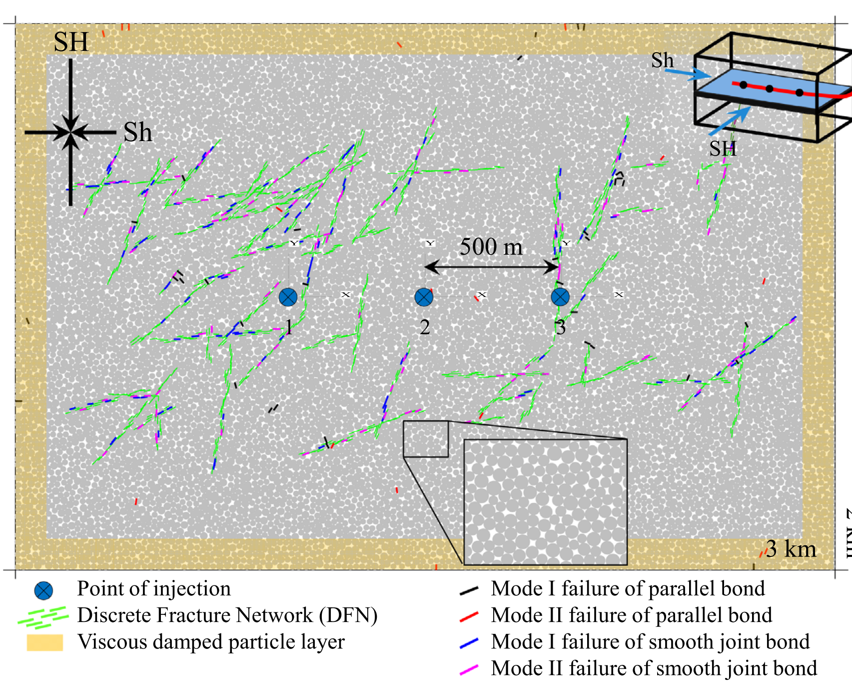

Fig. 1. Fractured reservoir model subjected to differential in situ stresses. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)