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Analysis of injection-induced shear slip and fracture propagation in geothermal reservoir stimulation

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ABSTRACT

Permeability enhancement via shear slip is commonly accepted as the main stimulation mechanism. However, the mechanism of permeability increase appears to have been understood to be limited to shear dilation and perceived to exclude the propagation in tensile and shear mode of the natural fractures that experience slip. This has led to the claims of the discovery of a new stimulation mechanism, namely, stimulation via wing crack propagation. The root cause of the misconceptions is likely the inability to model natural fracture propagation and coalescence. However, natural fracture propagation in general and wing cracks in particular are to be viewed as an integral part of the shear slip stimulation mechanism because shear slip increases the stress-intensity at the fracture tips, potentially leading to fracture propagation. In an effort to better illustrate the underlying mechanisms in the geothermal reservoir stimulation process, a displacement discontinuity (DD) model is developed and used to simulate secondary crack propagation associated with natural fracture slip. The model uses Mohr-Coulomb joint (contact) elements and rigorously accounts for fracture propagation. The model is applied to explore the conditions conducive to shear and tensile mode fracture propagation. When natural fractures undergo shear slip due to direct and indirect water injection, out-of-plane wing (tensile) cracks form and propagate at injection pressures below the minimum in-situ stress level and turn toward the maximum in-situ stress direction as they grow longer. It was found in our results that the injection pressure is stabilized at approximately the minimum in-situ stress level. The secondary cracks form as wing cracks and/or shear cracks. The predominance of wing cracks and their lengths and propagation paths were found to be controlled by the relative value of differential and mean stresses, natural fracture length, as well as rock and natural fracture frictional properties. In deeper geothermal reservoir with relatively low differential stress conditions and/or high mean stress levels, the shear crack propagation could play a major role in fracture network formation and permeability enhancement.

1. Introduction

Geothermal energy from EGS is produced by injecting cool water into deep hot rocks and extracting it at higher temperatures. Water injection may cause shearing on critically-stressed natural fractures by reducing the effective normal stress on them. Permeability enhancement through shear slip is a commonly accepted stimulation mechanism (Murphy et al., 1999; Pine and Batchelor, 1984). On the surface, and likely due to the inability to model mixed-mode fracture propagation, this has appeared to exclude the formation of secondary cracks via propagation in tensile and shear modes of the natural fractures that experience slip. But, wing cracks are an essential component of rock failure (Brace and Bombolakis, 1963) and ought to be viewed as a potential contributor to the shear slip stimulation mechanism because shear slip increases the stress-intensity at the fracture tips, potentially leading to fracture propagation (Horii and Nematnasser, 1986; Huang et al., 2013). The processes of slip, propagation, and coalescence of natural fractures have been implicitly and/or explicitly considered as instrumental in Soultz EGS stimulation (Cornet et al., 2007; Evans, 2005; Jung, 2013) and have motivated the development of mixed-mode fracture propagation models for geothermal reservoirs (Huang et al., 2013; Min et al., 2010). The formation of wing-cracks is particularly the case when the natural fractures are subjected to direct water injection as opposed to diffusion from the matrix (Kamali and Ghassemi, 2017). An analytical treatment of the wing crack problem for stimulation was provided by Jung (2013) based on field evidence while focusing exclusively on the possibility of propagation of tensile mode wing cracks. Jeffrey et al. (2015) also considered the problem using a simplified modelling approach concerning the propagation of tensile wing-cracks to confirm the idea of *en echelon* network generation via injection into

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natural fractures. This work established a relationship between the crack length and the injection pressure assuming a uniform pressure inside the fractures without considering the mechanical interaction between the natural fractures. Kamali and Ghassemi (2016a) have explicitly simulated the phenomenon during injection and have shown that shear slip occurs at injection pressures below the minimum in-situ stress and triggers the out-of-plane wing-cracks (Huang et al., 2013; Jung, 2013; Kamali and Ghassemi, 2016a, 2016b; Min et al., 2010). Further propagation and coalescence might be achieved by maintaining the injection at pressures slightly higher than the minimum in-situ stress.

The wing-crack propagation is a well-established concept which is extensively studied in several disciplines such as mining, civil engineering, and rock mechanics (Bobet and Einstein, 1998a; Bombolakis, 1973; Brace and Bombolakis, 1963; Dyskin et al., 2003; Hoek and Bieniawski, 1965; Horii and Nematnasser, 1986; Lehner and Kachanov, 1996; Petit and Barquins, 1988; Shen and Stephansson, 1994; Steif, 1984). These works include experimental, analytical and numerical modelling approaches to the problem of two and three-dimensional cracks under bi-axial compressive stresses. Although these works provide valuable insight into the wing-crack problem, the actual reservoir stress path under injection conditions is not represented in these works. In this work we develop and use a 2D displacement discontinuity model to analyze the response of the closed natural fractures to direct water injection.

2. Model development

Injection into naturally-fractured reservoirs is a coupled process which involves rock and fracture deformation in addition to fluid flow. This section outlines the relevant governing equations which are required to quantify this problem. The numerical implementation and discretization of these equations are described at the end of this section.

2.1. Governing equations of elasticity

The solution of an elastic body deformation must satisfy the governing equations for a given set of stress/displacement boundary conditions. The formulation of elasticity problems relies on the stress tensor partial differential equations and strain-displacement equations. The solution is then completed through a constitutive equation relating the stresses to the strains. Assuming static equilibrium, isotropic and homogenous body, and linear elasticity, the constitutive equation is given as (Timoshenko and Goodier, 1970):

$$\varepsilon_{ij} = \frac{1}{E}[(1+\nu)\sigma_{ij} - \nu\sigma_{kk}\delta_{ij}] \tag{1}$$

Where ε_{ij} are the strain tensor components, σ_{ij} are the stress tensor components, E is the Young's modulus, ν is the Poisson's ratio, δ_{ij} is the Dirac delta function, and σ_{kk} represents summation over normal stress components.

2.2. Numerical methodology

To model fractures, the displacement discontinuity method (DDM) used in this work. The DDM (Crouch and Starfield, 1983) which is an indirect Boundary Element Method (BEM) is proved to be a powerful tool in coupled natural fracture and fluid flow analysis (Asgian, 1988; Farmahini-Farahani and Ghassemi, 2016; Ghassemi and Tao, 2016; Safari and Ghassemi, 2015, 2016; Tao et al., 2011; Verde and Ghassemi, 2015), and simulation of hydraulic fracturing (Ghassemi and Roegiers, 1996; Kumar and Ghassemi, 2016; Sesetty and Ghassemi, 2015; Vandamme and Curran, 1989). A two-dimensional displacement discontinuity model is therefore developed and used to calculate fracture normal and shear displacements along the natural fractures. Displacement discontinuities are defined (Figure 1) as the difference between the displacements of the negative and the positive sides of a DD element (Crouch and Starfield, 1983) and is calculated as follows:

$$D_i = u_i(x, 0_-) - u_i(x, 0_+) \quad i = x, y \tag{2}$$

Where u_i is the displacement vector in the local coordinate of the crack element. For a rock containing N displacement discontinuity elements, the original DD formulation (Crouch and Starfield, 1983) is modified to account for contact elements and fluid pressure as follows:

$$\overset{i}{\sigma_n^\infty} + \sum_{j=1}^{N} \overset{ij}{A}_{ns} \overset{j}{D}_s + \sum_{j=1}^{N} (\overset{ij}{A}_{nn} - \delta_{ij}K_n)\overset{j}{D}_n - p_i = 0 \tag{3}$$

$$\overset{i}{\sigma_s^\infty} + \sum_{j=1}^{N} (\overset{ij}{A}_{ss} - \delta_{ij}K_s)\overset{j}{D}_s + \sum_{j=1}^{N} \overset{ij}{A}_{sn} \overset{j}{D}_n = 0 \tag{4}$$

Where σ_n^∞ and σ_s^∞ are the far field normal and shear stresses acting on crack elements, p_i is the fluid pressure at element i, K_s and K_n are the shear and normal stiffness, and $\overset{ij}{A}_{kl}$ is the influence coefficient relating the normal (shear) stress of element i to the normal (shear) DD of element j. These influence coefficients reflect the mechanical interaction between the crack elements. The details of elastic kernel computation is summarized in Appendix A (Crouch and Starfield, 1983).

2.3. Contact elements constitutive equations

The closed natural fractures are represented by contact displacement discontinuity elements (Asgian, 1988; Tao et al., 2011). The contact elements are considered mechanically-closed as long as their effective normal stress is compressive. Despite mechanical closure, contact elements may be hydraulically open and therefore transmit the injected fluid (Safari and Ghassemi, 2015, 2016). The normal (shear) displacements of the contact elements are related to their normal (shear) stress using normal (shear) stiffness as follows (Goodman et al., 1968):

$$\sigma_n' = K_n D_n \tag{5}$$

$$\sigma_s = K_s D_s \tag{6}$$

Where σ_n' is the effective normal stress, σ_s is the shear stress, K_n and K_s are the normal and shear stiffness, D_n and D_s are the normal and shear displacement discontinuities along the crack surfaces. It should be emphasized that these equations hold only when the contact elements are mechanically-closed. The shear and normal stiffness are zero for open cracks.

2.4. Friction law and inelastic shear slip

Natural fractures are likely to experience shear slip as a result of normal stress reduction due to injection. Therefore, a proper friction law should be used to capture the full range of elastic and inelastic fracture deformation in the transverse direction. Mohr-Coulomb criterion is imposed on the contact elements to identify the state of contact in the transverse direction as follows:

$$|\sigma_s| \le c + \sigma_n' \tan\phi \tag{7}$$

Where c and φ are the natural fracture's cohesion and friction angle which differ from that of the intact rock. Two distinct modes of contact are then defined based this criterion; *stick* mode, which implies that the contact element deforms elastically and *slip* mode, which occurs when the shear stress reaches the shear strength of a particular element. It is worth noting that the shear stiffness drops to zero for the elements in the *slip* mode. The contact elements are allowed to switch between the stick and slip mode from one time step to another. Once the contact status is identified, the boundary conditions are specified accordingly; for elements in the stick mode, the original set of coupled equations (Eq.3,4, and 12) are used whereas for elements in the slip mode the