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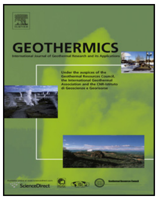

Initiation and propagation of fracture shearing during hydraulic stimulation in enhanced geothermal system

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ABSTRACT

This paper develops a generic model to estimate the location of shearing onset, the required pressure, and the overall shearing growth direction during the hydraulic stimulation in Enhanced Geothermal System, for which massive volume of fluid is injected into the fractured rockmass through a long open hole section. General studies on the effects of the stress condition on the shearing initiation and propagation captured some basic features related to the observed induced seismicity. Upward growth of shearing prevails for most stress conditions and a dense fluid favors downward shearing. Performed case studies demonstrate the developed method is potentially applicable to provide first order assessment of shearing initiation and propagation during hydraulic stimulation in a fractured EGS reservoir.

1. Introduction

Geothermal energy has become an increasingly attractive alternative as a CO2-emission-free, base-load renewable energy source (DiPippo, 2012). In particular, the Enhanced Geothermal System (EGS) provides inspiring prospects in terms of producing large quantities of energy for power generation from deep underground rocks that exist at drillable depths in many parts of the world. It is estimated that utilizing only 2% of the total thermal energy stored in the reservoir between depths of 3 km and 10 km in US territory, which is considered to be a conservative recoverable EGS resource, would be sufficient to provide the US primary energy needs for 2800 years (MIT, 2006). The MIT report defined EGS as the extraction of economical amount of heat from low permeability and/or porosity geothermal resources that are initially not in commercial interests and require engineering enhancement or stimulation. Actually, there is no universal definition of EGS and it should date back to the early 1970s when Los Alamos National Laboratories initiated the Hot Dry Rock (HDR) project at Fenton Hill. In general, the EGS concept involves drilling boreholes to depths where the temperature condition is sufficient for commercial interest and then artificially enhancing or creating the permeability of the reservoir to allow the heat to be extracted efficiently by circulating fluid/steam through injection and production wells. Since the HDR concept was initially proposed in the early 1970s, more than ten EGS/HDR projects have been or are being developed and tested in the world. A systematic review of the existing EGS projects worldwide was provided e.g., in Breede et al. (2013), which shows EGS is still on a learning curve.

Because of the low porosity of a rock matrix and the poor connectivity of natural fracture systems, the natural permeability is generally too low and thus has to be improved artificially. This is commonly accomplished by the technique of hydraulic stimulation, where a massive volume of fluid is pumped into the target formation for making active hydraulic linkages between two or more boreholes through the rock joint network with enhanced permeability (Genter et al., 2010). There are two basic mechanisms of permeability improvement by injection (1) hydrofracturing, which creates new fractures or reopens pre-existing fractures, and (2) hydroshearing, that is the slip of pre-existing fractures associated with shear dilation. Most EGS projects involve pumping fluid at high pressures to enhance permeability through hydraulic fracturing (mode I crack), hydro-shearing (mode II crack), and combination of both (Zang et al., 2014). At an early stage, the concept of hydrofracturing was adopted and designed, similar to the technique used for hydrofracturing treatments for hydrocarbon production. The concept at this stage was called ‘Hot Dry Rock’. The accumulated field observations revealed that deep rocks are naturally fractured and many seismic events were detected when the injection pressure was much lower than the magnitude of minimum principal stress, σ_3. It was realized that the hydroshearing of fractures and faults is

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Nomenclature

g	Acceleration of gravity
h	Depth below surface
k	Ratio of maximum principle stress to minimum one
k_c	Coefficient associated with frictional angle used for P_{cm} computation
k_{cf}	Critical pressure for shearing equal to σ_3 in normalized form
k_{cm}	Minimum critical pressure used to slide the most optimally oriented joint in normalized form
k_{co}	Cut-off critical pressure for defining the range of orientations with high tendency for shearing in normalized form
k_H, k_h	Ratios of maximum and minimum horizontal stresses to vertical one, respectively
k_{pp}, k_{pc}	Injection pressure and critical pressure for shearing in normalized form
k_1, k_2, k_3	Ratios of σ_1, σ_2, and σ_3 to vertical principle stress, respectively
l	Direction cosine between joint normal and maximum principle stress
m	Direction cosine between joint normal and intermediate principle stress
n	Direction cosine between joint normal and minimum principle stress
P_c	Critical pressure required for shearing
$P_c{}'$	Gradient of critical pressure for shearing
P_{cf}	Critical pressure for shearing equal to σ_3
P_{cm}	Minimum critical pressure used to slide the most optimally oriented joint
P_p	Applied injection pressure at depth
$P_p{}'$	Gradient of injection pressure
P_{st}	Hydrostatic fluid column pressure
P_{wh}	Wellhead pressure
S_v, S_{Hmax}, S_{hmin}	Vertical, maximum horizontal and minimum horizontal principle stresses, respectively
α	Coefficient used to estimate the cut-off critical pressureP_{co}
γ	Coefficient of critical pressure gradient
γ_σ, γ_τ	Coefficients of normal and shear stress gradients, respectively
μ	Joint frictional coefficient
ρ_r	Overburden rock density
ρ_w	Density of injection fluid
σ	Resolved normal stress on the joint plane
σ'	Gradient of normal stress
σ_1, σ_2, σ_3	Maximum, intermediate and minimum principle stresses, respectively
σ_1^e, σ_2^e, σ_3^e	Effective maximum, intermediate and minimum principle stresses, respectively
τ	Resolved shear stress on the joint plane
τ'	Gradient of shear stress
τ_f	Shear strength of single rock joint
φ	Joint frictional angle

the primary mechanism of permeability enhancement. However, there is poor knowledge with respect to the essential details of this shearing process, which are vital for understanding the reservoir permeability evolution and managing the induced seismicity (IS). We realize that there are several distinctive features of EGS stimulation compared with common hydraulic treatments in the hydrocarbon field: (1) an EGS well is usually completed with a long open section with interval of tens to hundreds of meters; (2) the application of an isolation packer is very limited; (3) a large fluid volume is injected into a naturally fractured reservoir with the expectation to form a stimulated region with discrete fracture networks; and (4) a deviated well design with a varying well trajectory can be adopted for favorable heat extraction. In this regard, the pressure accumulates along the whole open hole section during fluid injection. It is essential to estimate the location of shearing onset, the required pressure, and the shear slip growth direction because these will determine the volume of the geothermal heat exchanger and the design of the hydraulic stimulation for the desired connectivity between wells.

Numerous previous studies are related to the methodology and applications for characterizing the fracture and fault slip caused by hydraulic injections. Ito and Hayashi (2003) presented a procedure to estimate the orientations of critically stressed fractures which are the potential flow pathways, and addressed the effects of in situ stress. The slip tendency concept, which is defined as the ratio of the resolved shear stress to resolved normal stress acting on a fracture plane (Morris et al., 1996), was applied to investigate the potential for fracture slip and dilation in a deep geothermal reservoir at the Groß Schönebeck site in the Northeast German Basin (Moeck et al., 2009). Meller et al. (2012) proposed an approach for estimating the shearing probability of the fractures based on statistical analyses of the fracture distribution, orientation and clusters, and applied this to the case of the Soultz EGS project. Pine and Batchelor (1984) presented a theoretical basis to explain the downward growth of micro-seismicity during hydraulic injections at the Rosemanowes EGS site, in which two dimensional explicit equations were provided by considering the shear slip on vertical joints that are aligned most critically with respect to the anisotropic strike slip faulting stress condition. This specific study on the downward migration of induced seismicity in the Rosemanowes project led us to the development of a generic model which can be applicable for various stress conditions and joint orientations.

In this paper, we develop generic models, based on the hydroshearing concept, to estimate the location of the shearing onset, the required injection pressure, and the overall shearing growth direction during EGS hydraulic stimulation. The proposed models are applied to general studies on the effects of the stress condition on shearing initiation and propagation. The models are also applied to the selected field stimulation tests in major EGS projects in order to validate its usefulness.

2. Shearing initiation and propagation in EGS hydraulic stimulation

We adopt the Coulomb failure criterion as follows to define the shear strength of a single rock joint.

$$\tau_f = \mu\sigma \tag{1}$$

where τ_f is the shear strength, σ is the resolved normal stress on the joint and μ is the frictional coefficient, which is also the tangent of the friction angle φ.

It should be highlighted that we neglect the cohesion of fracture at significant depth (Zoback et al., 2003) because the fracture cohesive strength contributes little compared to the compressive field stresses at a depth of several kilometers in an EGS reservoir.

From the geomechanical point of view, the elevated fluid pressure due to hydraulic injection weakens the shear strength of rock joints. The hydroshearing of a specific fracture occurs when the applied injection pressure is sufficient to reduce its shear strength to the resolved shear stress τ on the joint plane. We use the Mohr diagram and the movement of stress circles, as shown in Fig. 1, to demonstrate such a physical process. A leftward shift of the stress circles corresponds to a reduction of the effective stress by fluid