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Coupled continuum modeling of fracture reactivation and induced seismicity during enhanced geothermal operations

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ABSTRACT

We constructed a coupled model to obtain a better understanding of the role of pore pressure changes in causing fracture reactivation and seismicity during enhanced geothermal systems operation (EGS). We implemented constitutive models for fractures in a continuum approach, which is advantageous because of the ease of integration in existing geomechanical codes (FLAC3D), the speed of the calculations and the flexibility of the fracture representation. For modeling the mechanical behavior of the fracture zone the softening ubiquitous joints model was used with random strength properties for the fracture zone. We implemented a hyperbolic deformation with effective stress for the reversible tensile fracture opening (used for fracture permeability), and a linear relationship between plastic shear strain and irreversible fracture opening. The effective permeability of the fracture network was described by a cubic dependence on the fracture aperture. Seismic events were simulated using a dynamic friction angle smaller than the static friction angle, and healing to the static friction angle was allowed after completion of a seismic event. We created a model inspired on the Soultz-sous-Forêts GPK3 injection well, where the granite rock mass is intersected by a dominant fracture zone. The model reproduced reactivation of the fracture zone due to injection of water and we observed the growth of a zone with large directional permeability. The model was used to perform a sensitivity analysis on parameters like in situ stress regime, fracture strength, and frictional weakening. This allowed us to evaluate the trends of their impact on fracture reactivation, including reactivated area, seismic moment and moment magnitudes. A comparison with a Block–Spring model as reported by Baisch et al. (2010) yielded similar results.

The models were applied on the GPK3 stimulation case that was performed in Soultz in 2003. The basic features of the observed seismicity were reproduced. The 3D implementation and the Block–Spring model showed their specific advantages: the Block–Spring model, if calibrated, establishes a fast modeling tool for sensitivity analyses; the FLAC3D implementation allows better understanding as it is based on actual physics.

1. Introduction

Enhanced geothermal operations are intended to stimulate the permeability of a network of natural fractures (Tester et al., 2006). The high pressure of the injected water causes the fractures to deform and to open, thus providing additional injectivity. This deformation of the fractures can be tensile or shearing, dependent on the geomechanical parameters of the fractures and the subsurface. The drawback of the fracture network stimulation can be unwanted seismicity—especially when the fractures deform in a shearing mode (Davis et al., 1993).

A proper description of the processes during enhanced geothermal operations requires a coupling between the geomechanics and the flow behavior in both directions: the reservoir pressurization, due to injection, causes fracture deformation; and the fracture deformation causes injectivity enhancement. Different ways exist to model this coupled behavior of flow and fracture mechanics. Some approaches presented in the literature rely on an explicit modeling of a fracture network (Kohl and Megel, 2007). This can be combined with an iterative coupling between a flow simulator and a geomechanical simulator. A promising model has been presented by Baisch et al. (2010). They presented a Block–Spring model in which a fracture was divided in patches which could fail in shearing mode, which then resulted in stress communication to neighboring patches and possible activation of those. In their model such activation was assumed to result in increased transmissivity of

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the activated patches. The drawback of their model is the engineering correlations used for the geomechanical interaction and for the transmissivity increase, only loosely based on the actual physical mechanism. However, it has been applied successfully to predict seismicity in geothermal injection.

We have chosen to use a coupled model in which we have implemented the required behavior, like Cappa and Rutqvist, based one earlier work of Hsiung et al. (Cappa and Rutqvist, 2011a,b; Hsiung et al., 2005). We have used FLAC3D, an explicit finite-difference simulator developed for engineering mechanics computations.[1] The approach was also applied by Mazzoldi et al. (2012) and Rutqvist et al. (2013). For the slip behavior we applied Zielke's approach of static and dynamic friction angles (Zielke and Arrowsmith, 2008). With the built-in programming language FISH, we have implemented our own constitutive models tailored at the coupled behavior. Both the geomechanical behavior and the flow behavior of the fracture network are treated in the simulator with effective continuous properties. Their constitutive behavior is derived from the specific fracture properties using an upscaling approach. The implementation of the coupling has been used to perform a number of calculations.

We compared our results to predictions using a Block–Spring model based on the work of Baisch et al. (2010). This model is capable to calculate the rupture process much faster than the coupled approach.

We will first describe the coupled physical phenomena and the implementations in FLAC3D and the Block–Spring model. Then we will present the geometry on which we have applied the models, a number of sensitivities and the application to the actual stimulation case in Soultz GPK3 (Dorbath et al., 2009). The paper closes with a number of discussion points and conclusions.

2. Coupled behavior of flow and mechanics

2.1. Flow

Flow in a porous medium is described by Darcy's law and the continuum equation. In a fractured medium, the permeability of the fracture network is calculated using the network properties. We neglected the development of gouge material in the fracture due to damaging of the rock, which is adequate for EGS in granite. For the representation of a single fracture as an aperture w between two parallel plates, the permeability parallel to the fracture can be calculated using basic Poisseuille flow theory (Bear et al., 1993):

$$k_f = \frac{w^2}{12} \quad (1)$$

In reality, the form and roughness of a fracture is spatially variable and the opening varies along the fracture, therefore we used the aperture w as a statistical average and added a constant c_{kf} to the definition to account for fracture roughness. For the continuum equivalent we calculated the effective upscaled permeability of a fracture set in a certain direction by multiplying the single fracture permeability with the part of the system occupied by it, w/L, with L the fracture spacing:

$$k_{||} = c_{kf}\frac{w^3}{12L} \quad (2)$$

This is called the cubic law for the fracture permeability. We took $c_{kf} = 0.1$, and for numerical stability we used a value of 10% of the resulting permeability for the fracture permeability in the perpendicular direction. The permeability tensor for a fracture set in a coordinate system with axes along and perpendicular to the fracture orientation does not have off-diagonal elements. The small distance over which the fluid can flow in the perpendicular direction makes the induced effects of these features negligible.

2.2. Mechanics

We assumed linear elastic behavior for the intact parts of the rock mass–this is described by Hooke's law in combination with the equilibrium equation.

The fractures deform in a different way. There are two modes of fracture deformation: tensile and shear. For the tensile fracture deformation we used the correlations used by Bagheri and Settari (2008), as developed by Bandis et al. (1983). They suggested a hyperbolic deformation between the decrease in aperture, Δw, and the effective normal stress on the fracture plane σ'_n:

$$\Delta w = \frac{a\sigma'_n}{1 + b\sigma'_n} \quad (3)$$

The parameters a and b are constants; $1/a$ signifying the normal stiffness of the fracture at zero normal stress, a/b the maximum value for the fracture closure. We considered the normal deformation of the fracture reversible. The values for a and b are approximately in line with the stiffness of the matrix; the calculation outcome is not very sensitive to their precise values. The treatment given by McDermott and Kolditz (2006) gives a similar behavior.

The shear deformation of the fracture was considered permanent. We used a linear relationship between shear strain $\Delta\gamma$ beyond failure and fracture aperture Δw (Kohl and Megel, 2007):

$$\Delta w = L\Delta\gamma \tan\psi_{dil} \quad (\Delta w < \Delta w_{max}) \quad (4)$$

Here ψ_{dil} is the dilatancy angle of the fracture. The change in fracture aperture was maximized to a value $\Delta w_{max} = 0.45$ mm, in agreement with experimental data.

Shear failure was described by a Mohr–Coulomb failure envelope between effective normal stress σ'_n and shear stress τ, with the cohesion c and the friction angle φ as parameters:

$$\tau = c + \sigma'_n \tan\varphi \quad (5)$$

The initial friction angles were given random values. Slip weakening was implemented as a linear decrease of the friction angle with increasing shear strain (Cappa and Rutqvist, 2011a). With such slip weakening, which is realistic in view of the geological reality and fault rupture models (McClure and Horne, 2011), seismic events of larger magnitudes are expected. After a seismic event, healing could be enabled by letting the friction angle increase to its original value. The concept of healing was inspired by current dynamic seismicity models, such as those using a rate-and-state description for fault friction (Marone, 1998). After healing, the fracture is still present, but the friction angle to be overcome for reactivation has increased again.

The seismic moments M_0 and the moment magnitudes M_w were calculated from the shear displacement in every failing grid block (Aki, 1966; Hanks and Kanamori, 1979). They are given by:

$$M_0 = G \cdot d \cdot A$$
$$M_w = \tfrac{2}{3}\log M_0 - 6.07 \quad (6)$$

in which G is the shear modulus, d the displacement and A the fracture area that is failing. To arrive at interpretable moment magnitudes of events, all simultaneous seismic moments of different grid blocks were summed.

[1] Itasca (2012) FLAC3D 5.0 manual.