Repeating earthquake behavior due to fluid circulation through tough-biem simulation.

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REPEATING EARTHQUAKE BEHAVIOR DUE TO FLUID CIRCULATION THROUGH TOUGH-BIEM SIMULATION

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ABSTRACT

We carry out TOUGH-BIEM simulations for modeling fault slip behavior triggered by fluid circulation in a geothermal context. The TOUGH2 code is used for modeling the pore pressure evolution within a fault and then a boundary integral equation method is applied for simulating fault slip, including aseismic slip on the entire fault plane and fast slip on seismogenic asperities. It is assumed that Coulomb friction and a slip-strengthening-then-weakening friction govern the fault slip. The pore pressure change due to injection is increasing logarithmically (fast at the beginning and later slow) so that the induced aseismic slip is fast at the beginning and slows down later. The fault slip on the asperities are periodic, and its recurrence depends on the previous aseismic slip in surrounding fault areas. When the two asperities are separated, their behavior is independent. When they are close each other, the recurrence timing of each asperity is disturbed. This feature is consistent with repeating earthquakes observed associated with geothermal stimulation experiments. The configuration of this study is simple for our demonstration, but the combination of TOUGH2-BIEM simulation would allow for studies of complex seismic fault behavior in different geological applications of fluid injections.

INTRODUCTION

Repeating earthquakes have been found from seismological analyses in the context of induced seismicity such as geothermal injection (Bourouis & Bernard, 2007) and these are indicators to assess fault reactivation due to the pore pressure change. The seismogenic models of natural earthquakes proposed for plate interfaces is applicable for studying the occurrence of induced seismicity along fault planes. The variety of seismic behaviors in subductions strongly depend on the fault rheology and high-pressure fluid existence (e.g. Lay et al., 2012; Ide, 2014; Saffer & Wallace, 2015).

In geomechanics, fault reactivation and induced seismicity have been modeled through hydro-mechanical coupling in geothermal injection and geological storage of CO_2 (e.g. Rutqvist et al., 2002; Baisch et al., 2010; Rutqvist, 2012). In this context, the TOUGH2 code has been used with many geomechanical modeling tools (review in Rutqvist, 2017). In particular, TOUGH-FLAC (Rutqvist et al., 2014) allows modeling an entire process of an induced earthquake on a fault including dynamic rupture propagation and ground shaking. In this study, we present a combination of TOUGH2 with BIEM, a code based on the boundary integral equation method.. BIEM is generic name of boundary element approach, especially based on theoretical integral equation of linear elasticity and is applied on dynamic rupture propagation and quasi-static faulting process on faults in 2D anti-/in-plane and 3D model domains (e.g. Aochi & Fukuyama, 2002). BIEM is usually more convenient than any volumetric methods (finite difference and finite element methods) and flexible to treat the boundary condition on the fault elements. In this study, we demonstrate a fluid injection in a vertical fault core zone in 3D in which the fault plane (thin fault core) is a 2D plane for faulting. We study how the pore pressure change activates the aseismic shear fault slip and how this aseismic slip loads small seismogenic asperities in analogous with observations at a geothermal site.

MODEL AND METHOD

In order to study this behavior, we combine TOUGH2 (EOS1) simulations (Pruess et al., 1999) of fluid flow along a fault segment with a boundary integral equation method (BIEM; Smai & Aochi, 2017; Aochi & Ide, 2017) simulating earthquake faulting under quasi-static equilibrium. According to the Soultz-sous-Forêt, East France, geothermal case presented by Evans et al. (2005) and Bourouis & Bernard (2007), we prepare a planar, vertical fault segment of 100 m x 100 m at depth containing seismogenic asperities.

For TOUGH2 simulations, we consider that the fault segment is homogeneous related to hydro – thermal parameters, over a large fault core of 500 m x 500 m with a width of 0.04 m (Figure 1). An injection profile of step-like increase from 0.04 l/s to 6 l/s over a few days is given. In the field experience of Soultz-sous-Forêt, the pore pressure change does not increase proportionally with the injection rate and is saturated gradually. This is probably because the injected fluid circulates somewhere else other than the fault core of or the fault core is more permeable when pore pressure is high. This may be modelled by permeability variation such that permeability becomes higher as the pore pressure increases (e.g. Douglas & Aochi, 2014). In this study, permeability is variable according to the reservoir pressure (e.g. Miller et al., 2004). The two of the outer boundaries have drained (constant pressure) conditions in order to avoid too much pressure on the modeled fault region.

The pore pressure change simulated by TOUGH2 drives the BIEM simulation. As shown in Figure 1, the fault domain is divided into three areas: (A) a background domain that is not reactivated by pore pressure and therefore experience no seismic slip, (B) an aseismic area out of seismogenic asperities activated by pore pressure with slip governed by Coulomb friction and (C) seismogenic asperities with slip governed by a non-linear, cycling friction law. Letting the pore pressure change, shear stress change and fault slip ΔP, $\Delta\tau$, and Δw, respectively, we write the boundary conditions of the three areas as follows:

$$\begin{cases} \Delta w = 0 \text{ (A)} \\ \Delta\tau = -\mu\,\Delta P \text{ (B)} \\ \Delta\tau = \tau_b \left(\frac{\Delta w}{w_c}\right)^2 \exp\left(1 - \left(\frac{\Delta w}{w_c}\right)^2\right) \text{ (C)} \end{cases} \quad (1)$$

where μ is Coulomb friction coefficient, τ_b is asperity strength, and w_c is characteristic displacement. Area C governed by slip-strengthening-then-weakening friction corresponds to seismogenic asperities which may repeat under continuous loading (Aochi & Ide, 2017). For our first attempt, we prepare only two asperities of size of 5 m and 10 m radius to demonstrate their seismic periodicity and interaction. The characteristic displacement, w_c in Equation C is scale-dependent

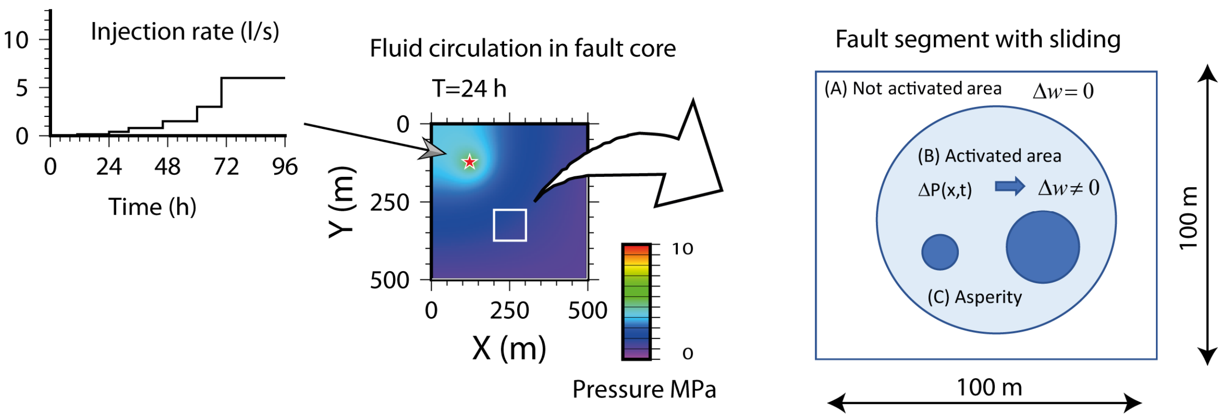

Figure 1. Schematic illustration of TOUGH2-BIEM simulations of fluid driven faulting process. (left) An example of injection profile. (center) A model,500 m x 500 m with a width of 0.04 m, is prepared for TOUGH2 hydro-thermal simulation. The star represents an injection point and the square corresponds to a fault segment for BIEM faulting process modeling. (right) Three fault state conditions (A to C) in the BIEM simulation. Pore pressure change activates area B and the shear stress accumulates on area C.

Table 1. Model parameters.

Parameter	Quantity & Unit
Initial Temperature	275°
Initial Pore Pressure	27.5 MPa
Porosity	0.5
Medium density	2650 kg/m^3
Permeability	10^{-14} m^2 - 3.6 x 10^{-12} m^2

Parameter	Quantity & Unit
Young's modulus	50 GPa
Frictional coefficient	0.6
Fault strength	0.4 MPa
Characteristic displacement	0.5, 1.0 mm
Radius of asperity	5, 10 m

RESULTS

Figure 2 shows an example of simulation results. The pore pressure change calculated from the TOUGH2 simulation is uniformly given on the fault segment. Considering the well-head pressure of about 8 MPa observed in the experiment (Evans et al., 2005), a change of about 3 MPa on the fault segment at about 200 m distance should be reasonable. The sliding area includes all of area B,including two asperities (area C), defined in Figure 1. Asperities respond with a stick-slip behavior , including stress accumulation and release a few times during this injection. Note that the background shear stress (area B) continues decreasing as the pore pressure increases, while shear stress on seismic asperities (area C) is constrained between 0 and 0.4 MPa according to Equation (1). Regardless of the assumed friction, the stress accumulation is faster on smaller patches than larger ones (Aochi & Ide, 2017). The small asperity (5 m radius), which repeats three times, roughly correspond to an area of magnitude 0.

In the case where the two asperities are close enough or superposed, the periodic behavior becomes irregular due to the interaction. Sliding on the small asperity may trigger (make the recurrence earlier) the large one, or fast slip on the small one may be less visible according to the state of the surrounding stress field.

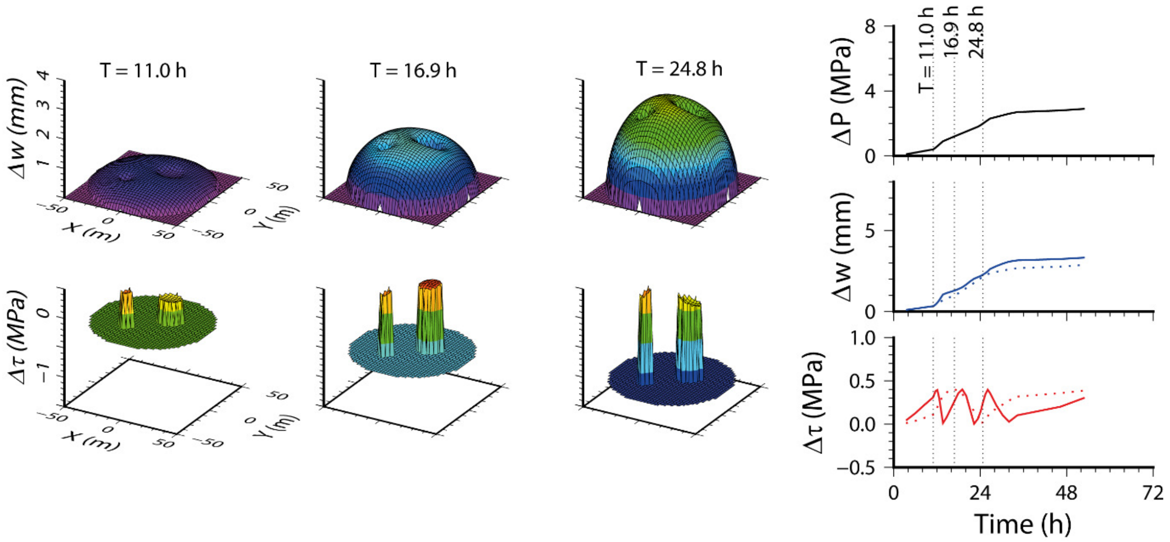

Figure 2. Snapshots of fault slip and shear stress change on the fault segment at three different times. Pore pressure change (ΔP), fault slip (Δw) and shear stress change ($\Delta\tau$) are shown on the right. Schematic illustration of TOUGH2-BIEM simulations of fluid driven faulting process. (left). Solid and broken lines correspond to small and large asperities of radius 5 m and 10 m, respectively.

CONCLUSION AND PERSPECTIVE

This paper demonstrates the TOUGH2-BIEM simulator through simulations of stick-slip fault activation behavior, including aseismic and seismic slip. The stick-slip fault behavior is generated by aseismic slip that is activated by an internal pore pressure change due to injection. The simulation shows the occurrence of repeating stick-slip behavior on the fault segment, which is more frequently during the first 24 hours. The assumed governing equation (Equation (1)) is simple enough to test the framework of the simulation and to qualitatively demonstrate the fault activation behavior. It will be worth testing different relations, especially strong rate-dependent frictions. Systematic, parametric studies will allow us to compare the statistics of the repeating earthquake behaviors (their spatio-temporal patterns) to understand the physical relation governing the fault activation and the parameters as well as the hydraulic configuration surrounding the faults. The current study is applied on the stimulation test of deep geothermal experiment at a rather short time scale, but the framework is also applicable to other geological storage problems considering longer time scales.

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