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Effects of asperity distribution on fluid flow and induced seismicity during deep geothermal exploitation

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Abstract

This work investigates the injection-induced seismic response of a heterogeneous fault plane, featuring low-permeability asperities embedded into a high-permeability damage zone. We simulate the pressure evolution with a hydrogeological simulator, accounting for the heterogeneous fault plane. Seismicity occurs then on the asperities, represented as unstable patches reactivating by means of the Mohr-Coulomb criterion. The hydrological and seismic modules are implicitly coupled to account for effects of asperity reactivation on the permeability. Results show that permeability changes may cause at a later time a change in seismicity propagation. We also investigated such effects by varying the density of asperities.

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1. Introduction

Many induced earthquake sequences could be seen as the rupture of brittle asperities along a fault zone, in response to fluid pressure changes generated by an injection at depth. Furthermore, the relocation of seismicity often shows that these brittle patches only cluster on particular regions of the fault zone, indicating that the remaining regions are either creeping or not activated during the injection. This clustering behavior may indicate heterogeneous permeability conditions within the fault zone. This work tries to explain some features often observed in deep geothermal activities, during which a fault zone is stimulated to enhance fluid circulation. One known example that accounts for seismicity during deep geothermal operations is the case of St. Gallen, Switzerland [1]. Although in St. Gallen the fault zone was not really stimulated for proper geothermal operation, and the seismicity rate only largely increased following some well operations [2], a characteristic pattern was observed in the propagation of seismicity. In an initial phase, during which an event of magnitude 3.5 was triggered, the seismicity propagated at a rate of 1000 m/day towards SW. In a second phase, seismicity was also observed to propagate towards NE along the fault zone [3]. In this work, we aim at investigating the response of a heterogeneous fault to injection activities. The heterogenous fault plane features

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brittle asperities with low permeability embedded in a higher permeability and ductile matrix. We first simulate the fluid flow and pressure evolution with the TOUGH2 numerical simulator [4], which accounts for the heterogeneous permeability caused by the presence of a given distribution of asperities. In order to get the seismicity associated with the simulated injection, we modeled in a second step the fault as a planar frictional interface, where brittle asperities are represented as unstable patches that can reactivate following a Mohr-Coulomb criterion. This coupled modeling approach allows to compute the seismicity generated by a localized fluid injection, and to investigate how a cloud of induced earthquakes propagates along a fault. Furthermore, we investigate the effects of permeability changes due to seismic reactivation. In this second case, the hydrogeological and first-order mechanical models are implicitly coupled to account for effects of shear displacement on the permeability changes. Such permeability changes, may cause at a later stage of post injection a change in seismicity propagation. Finally we analyze how the density of the asperities may alter such propagation of the seismic cloud.

Nomenclature

κ asperity (fault core) permeability [m^2]
κ_0 initial asperity (fault core) permeability [m^2]
C constant value for slip-permeability relationship [-]
n exponent factor for slip-permeability relationship [-]
$d*$ critical slip for change in permeability [m]
Δd event slip derived from scalar seismic moment [m]
M_0 scalar seismic moment, derived from seed event magnitude [N·m]
M_w seed event magnitude [-]
$\Delta\tau$ stress drop associated with seed event magnitude [Pa]
μ coefficient of friction [-]
σ_H maximum horizontal stress [Pa]
σ_h minimum horizontal stress [Pa]
σ_V vertical stress [Pa]

2. Model setup

A modified version of the code TOUGH2-SEED [5] was implemented to study the effects of seismicity in a heterogeneous fault plane. TOUGH2-SEED couples the capabilities of the geothermal simulator TOUGH2 [4] with a stochastic-geomechanical model [6]. On one side, TOUGH2 allows the simulation of multiphase, multicomponent fluid flow and heat through porous media. On the other side, the stochastic model, so-called "seed model", accounts for reactivation of potential hypocenters (seeds). The main difference here is that the single "seed" represents an asperity, which also corresponds to a low permeability patch on the fault plane.

We simulate a 2D fault plane stimulated by fluid injection, which lasts for 15 days and it is followed by a 15-day post-injection period. Injection occurs at 4000 m depth, with a rate of 6 kg/s, which results in an overpressure of about 40 MPa in the worst-case scenario, given the 2D approximation. In literature, a fault zone is generally considered as embedded in a host rock and composed of a highly fractured damage zone and a lower permeability central core [7]. Such fault core is generally modeled as a continuous, low-permeability region, but here we assume the fault core as heterogeneous with low and high permeability patches. The low permeability ones represent the so-called asperities: unstable patches that can reactivate. A schematic view of the model as well as the values of permeabilities for the different domains are shown in Figure 1.

Initial pore pressure follows a hydrostatic gradient, while stresses at seed are randomly assigned with average value following an extensional stress regime ($\sigma_H = \sigma_h = 0.8\sigma_V$). The seeds are assumed to be optimally oriented for reactivation. Reactivation on a given seed occurs if the Mohr-Coulomb criterion is satisfied, assuming a coefficient of friction $\mu = 0.6$. When reactivation occurs on a seed, magnitude is randomly assigned assuming a b-value depending on the stress condition at the given seed [6]. In order to account for multiple failures of the same seed, we consider a