Revisiting the Basel-1 hydraulic stimulation with a 3D coupled hydro-mechanical model.

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On the 2nd of December, 2006, the Basel-1 well was hydraulically stimulated with the ultimate goal of sufficiently increasing reservoir transmissivity and reaching economical geothermal energy fluxes. Over six days, 11,500 cubic meters of water were injected into an inclined 371-meter-long open-hole section of the well, which extended to a depth of 5 kilometers. As seismic activity began to rise, reaching up to 200 events per hour, the injection rate was reduced, and eventually, the well was temporarily shut down for five hours. Despite these interventions, an earthquake of ML 3.4 occurred (and was felt in the city of Basel) just before the wellhead pressure was fully released. Given this large seismic event, the project was ultimately abandoned. Over the years, the Basel hydraulic stimulation and its associated seismicity have been extensively studied. Experts have investigated various aspects including stress levels, and hydraulic and micro-seismic data. Although numerous numerical models have been developed, none have yet managed to accurately and comprehensively reproduce both the measured pressure and the spatiotemporal microseismicity migration.

In this study, we aim to reproduce both the well pressure record and the microseismicity migration using a 3D fully coupled hydro-mechanical solver developed at the Geo-Energy Laboratory in EPFL (Ciadro & Lecampio, 2023; Sáez & Lecampion 2023, 2024). Our model integrates changes in permeability, interface spring nonlinearity, and slip-induced dilation. We assume that the microseismic activity tracks the propagation of the otherwise aseismic macroscopic frictional rupture and use the exact injection schedule in our simulations.

Utilizing a seismic catalog containing 3,511 located events, we focus initially on the largest cluster of 2,435 events, divided into six groups based on waveform correlation, arrival time, and location. We begin with the simpler model of the largest group of events (red group) that evidently intersects the borehole and was activated first. We model the microseismicity propagation of the red group as a single axisymmetric slipping patch propagating aseismically in pure shear mode along a planar interface. We constrain the initial hydraulic properties of the injection zone from the pre-stimulation hydraulic test; stress field from studies (Valley & Evans, 2019; Dahrabou et al., 2022) and rock properties from measurements for the Basel granite (Valley & Evans, 2019). Maximum horizontal stress, as well as peak and residual friction, maximum peak dilatancy, characteristic distance for reaching the critical state, and nonlinear interface spring remain quite uncertain. We vary these parameters in the expected range to reproduce both the pressure record and the microseismicity migration of the red group of events. We show that the first abrupt pressure drops can be captured by a simple linear relation of dilatancy with slip. In contrast, the late-time pressure response can be reproduced accounting for the nonlinearity of joint closure as a stress function (Barton-Bandis model).

Building on our initial model, we extended our analysis to include all seismic events by integrating the fracture planes assigned to the different seismicity clustered groups. Starting with the parameters from our model of the red group, we developed a more complex 3D fracture network model. Here, we adjusted the planes' orientations slightly (within the microseismic localization uncertainties) to better predict when each would become active and how aseismic slip would spread along these pre-existing fractures.

Our results show that the fully coupled axisymmetric model initially restricted to a single plane, accounting for linearly weakening friction, variable dilatancy, permeability, and interface springs nonlinearity can reproduce both the pressure record and capture the migration of the observed micro-seismicity of the red group. By incorporating additional fracture planes into the model to simulate aseismic slip propagation tracking the seismic front across the remaining planes, we effectively capture not only the activation times but also the broader seismic behavior of the reservoir.

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