Slip response to fluid depressurization constrains fault friction

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1) Challenge: Fluid injections in the subsurface promote fault slip

2) A unique fluid-injection experiment on a natural fault

3) BICycle code for simulating seismic & aseismic slip

4) Depressurization allows to distinguish between models

5) Spatial extents of slip vs. pressurized zones depend on residual friction

6) Diverging fault stability with sustained injection

Highlights
- Multiple rate-and-state friction models can replicate the observations of a fluid-injection field experiment during pressurization.
- The depressurization stage provides additional constraints on hydromechanical parameters and points to a high-friction and hence relatively stable fault.
- Fault stability and the extent of the slipping zone relative to the pressurized zone depends on the difference between residual friction and initial stress levels.

Pressure earlier and more slowly would allow to distinguish between models.

2019) produces aseismic slip that outgrows the pressurized zone, slip stays well within the pressurized zone in the high friction state.

FIGURE 1. Seismicity is a concern for many industrial activities involving crustal fluid injections (adapted from Grigoli et al., 2017).

Research Questions
- What controls whether induced fault slip is stable (aseismic) or unstable (seismic)?
- Is the induced slip limited to the pressurized zone?
- Are there observable indicators of the propensity to earthquakes before they happen?
- Can industrial practices be improved to minimize induced seismicity hazard?

FIGURE 2. Fluids were injected into a borehole crossing a natural but inactive fault and the resulting displacement was measured directly at the injection site with a special probe.

FIGURE 3. Pressure and fault slip measured during the field experiment. The grey area indicates the previously unmodeled depressurization stage.

FIGURE 5. (A) Temporal evolution of pore pressure, slip and slip rate for 3 models (solid curves) that reproduce the observations (dotes) during pressurization. (D) Same as (A) but for an improved depressurization: Reducing pressure earlier and more slowly would allow to distinguish between models.

Parameters of 3 qualitatively different models

A fully-dynamic spectral boundary-integral method to simulate fault slip (Lapusta et al., 2000)

\[ \tau_{\text{int}} + F(\delta(x,t)) \frac{dV}{dt} = f(x,t) (\sigma - p(x,t)) \]

Initial stress \[\frac{d\sigma}{dt}\] Stress transfers Radiation damping Friction coeff. Effective normal stress

Radial pore pressure diffusion: \[r = \sqrt{x^2 + r^2}\]

\[ \frac{dp(r,t)}{dt} = \alpha \left( \frac{dp(r,t)}{d\tau} \right) + \frac{1}{r} \frac{d((r, t))}{d\tau} \]

Rate-and-state friction (Dieterich, 2007):

\[ f(V(x,t), \theta(x,t)) = f^* + a \ln \left( \frac{V}{V_l} \right) + b \ln \left( \frac{V}{V_l} \right) \]

Friction coefficient Reference friction Direct effect Evolutionary effect

FIGURE 6. Same as Figures 3 (A), 4 (B) and 5 (C-E) but for a longer injection scenario, with keeping the injection pressure constant past 1400s. The low-friction case produces a runway earthquake much sooner than the intermediate-case, while the earthquake in the higher-friction case - which is consistent with most known information about the fault - self-arrests once out of the pressurized zone.

References


Larcheille, S., Lapusta, N., Ampuero, J-P., Cappa, F. Constraining fault friction and stability with fluid injection field experiments, submitted.

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