Mitigating Induced Seismicity Through Active Pressure Management: Simulation Based Studies

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What information is necessary to simulate induced earthquakes?

1. **Fault geometry** and rate-state constitutive parameters
2. **Reservoir characterization**
3. External stressing history
   - Injection history → reservoir model, *in situ* pressure measurement (ground truth)
4. Tectonic driving stress (perhaps neglect this in relatively aseismic regions)
5. Pre-existing shear stress conditions:
   - *In situ* stress measurements - regional average (from global stress maps)
   - Projection of the regional stress tensor (from global stress maps)
   - Randomly generated heterogeneous field (some fractal distribution)
6. Earthquake simulation method
   - RSQSim
7. **Well located seismicity catalog with low magnitude of completeness**
RSQSim
(Rate-State earthquake Simulator)
(Dieterich and Richards-Dinger, 2010; Richards-Dinger and Dieterich, 2012)

- Comprehensive simulation of fault slip phenomena:
  - earthquakes, continuous creep, slow slip events, afterslip
- Implement rate- and state-dependent friction effects
  - Earthquake clustering effects (aftershocks and foreshocks)
- High resolution models of geometrically complex fault systems
  - Up to $10^6$ fault elements
  - Range of earthquake magnitudes $M=3.5$ to $M=8$ (for 1 km$^2$ triangular elements)
- Highly efficient code
  - Good statistical characterizations from long simulations of $10^6$ earthquakes
  - Repeated simulations to explore parameter space
How do we include effects of fluid injection in RSQSim?

- RSQSim itself knows nothing of pore-fluid pressure diffusion, poroelastic effects, etc.
- Must supply external stressing history
- Geomechanical reservoir model
  - Changes in effective normal stress
  - Poroelastic effects
- Not fully coupled – no feedback
  - seismic slip does not affect the permeability structure, etc.
- Preliminary experiments use a simple analytic expression for pore-fluid diffusion (Wang, 2000).
Reservoir Model

\[ \Delta P = \left( \frac{v}{4\phi c(\pi Kt)^{3/2}} \right) \exp \left( -\frac{r^2}{4\kappa t} \right) \]

- Linear diffusion model based on analytical solutions for a point-source in a semi-infinite, isotropic half-space (Wang, 2000).
- Variable injection parameters:
  - Well location(s)
  - Injection Rate
  - Diffusivity \( \kappa = \frac{k}{\eta \phi c} \)

permeability, porosity, compressibility, viscosity
Pre-existing Shear Stress

Correlated fields?

Increasing wavelength

Pattern?
Slip Distribution and Stress

Shorter wavelength

Longer wavelength
Spatial and Temporal Migration of Seismicity

Shorter wavelength

Longer wavelength
Investigate Seismic Response to Various Injection Histories

Closest fault element to well = 1.2 km

Scale by earthquake magnitude

$Q_{\text{ave}} = 0.008 \text{ m}^3/\text{s}$

Linear Diffusion

Constant Injection

Periodic Injection

Distance from Well (km)

Years After Injection
Future Work

1. Reservoir model
   - Finite element simulation
   - Fault and reservoir connectivity
   - Along strike permeability changes
   - Poroelasticity

2. Comparison to field sites
   - Establish working group
   - Collect available data
   - Produce relevant models and compare synthetic/observed catalogs

3. Efficacy of active pressure management at mitigating risk of induced seismicity
   - Co-product and injection
   - Pre-production
   - Fluctuations in injection rate