Poroelastic Models of Stress Diffusion and Fault Re-Activation in Underground Injection

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Outline

Relation of hydrogeology to stress, deformation, and failure
   
   *The “solid” earth exhibits a poroelastic response.*

Underground injection: the petition process and modeling
   
   *Flow and containment*
   *Chemical fate*
   *Mechanical integrity*
   *Modeling plays a central role in the regulatory process.*

Induced earthquakes
   
   *Traditional methods to predict are conservative, inaccurate.*

COMSOL poroelastic models: set-up and results
   
   *Stress diffusion models*
   *Implications for onset of failure*
   *In some scenarios, poroelastic response decreases the perturbation pressure which would trigger seismicity.*

Conclusions
   
   *Poroelastic models provide a more accurate prediction of the onset of seismicity.*
   *These predictions can differ significantly from the traditional methods.*
   *COMSOL provides an effective poroelastic modeling capability.*
Groundwater has been known to be influenced by external forces – including earthquakes -- since Roman times.  

**General**
- Water level in wells correlate with ocean tides
- Water level changes as trains pass
- Water level rise in wells near a pumping well
- Land subsidence following oil/gas extraction

**Earthquake-related**
- Water levels in wells
- Lake Mead filling triggers earthquakes
- Streamflow and spring discharge changes following earthquake
- Changes in mud volcanoes and geysers
- Liquefaction

Earthquakes related to human activity are quite widespread.

**Associated technology**
- Oil/gas extraction
- Secondary recovery
- Waste water injection
- Reservoir-induced
- Geothermal
- Hydraulic fracturing

The two-way coupling between rock matrix and pore fluids (poroelastic response) accounts for the connection between stress and deformation.

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1 e.g., H. F. Wang [2000]; Wang and Manga [2010].

2 from Hitzman [2012]
Siting, construction, and operation of injection wells are regulated by USEPA and by state and local authorities.

“not just a hole in the ground”

Highly engineered structure

Multiple layers of protection

Injectate is separated from USDW by multiple confining layers
For Class I wells, the petition process requires modeling to demonstrate, using accepted methodology and to a reasonable degree of certitude, that injection can be carried out in a manner “protective of human health and the environment.”

Flow and containment

Injectate shall remain confined to the permitted zone for 10,000 years

Chemical fate (alternate demonstration)

Interaction of the injectate with the native fluids in the rock shall render it non-hazardous

Mechanical integrity

Wellbore shall remain mechanically intact
Earthquakes due to failure of pre-existing faults shall not be induced as a result of injection operations
Any other features (solution cavities, …) shall remain stable against collapse
Failure criteria may be mapped into normal stress-shear stress ($\sigma-\tau$) space. A two-dimensional state of stress appears as a circle in this space.

Failed to generate proper diagram.

Predicting the state of stress during and following injection is critical to a reliable seismicity prediction.
The structural integrity analysis for seismicity is composed conceptually of three models.

Darcy’s Law

(reservoir model)

pressure buildup

rock hydrological properties

fluid properties

(poro)elastic Hooke’s Law

rock mechanics model

rock stresses

rock mechanical properties

(Mohr-)Coulomb failure

frictional failure model

failure prediction: Y/N

rock failure properties

background stresses
Model demonstration: inject water into a massive limestone formation at 1500 m depth

We observe for 60 days at

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>Observation Points</th>
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<tbody>
<tr>
<td>0.5</td>
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<tr>
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<tr>
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<td></td>
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<tr>
<td>10</td>
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</tbody>
</table>

Injection schedule: inject @ 1000 psi from day 7 to day 14

\[ p = 1000 \cdot (flc2hs((t - 7 \times 86400),3600)) - flc2hs((t - 14 \times 86400),3600)) [\text{psi}] \]

Physical properties:

<table>
<thead>
<tr>
<th></th>
<th>confining layers</th>
<th>injection layer</th>
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<tbody>
<tr>
<td>density</td>
<td>2750 kg/m³</td>
<td>2750 kg/m³</td>
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<tr>
<td>porosity</td>
<td>0.25</td>
<td>0.25</td>
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<tr>
<td>permeability</td>
<td>1.18E-14 m²</td>
<td>2.90E-11 m²</td>
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<td>Young's modulus</td>
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<td>Poisson's ratio</td>
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<tr>
<td>Biot-Willis coeff.</td>
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</tbody>
</table>

Compare Darcian and poroelastic responses.

A. 2-D planar symm model
B. 2-D axial symm model
Mesh and boundary conditions

flow boundary conditions

no flow

pressure pulse

mechanical boundary conditions

free surface

roller

fixed

2-D model, 15541 DoF
Fluid pressure at injection depth vs time

**planar symmetry**

900 psi near well

Response is instantaneous
Pressure decreases linearly from well to far boundary

900 psi far end

770 psi

Poroelastic

Pressure shows finite build-up and decay, indicating storage
Pressure decreases non-linearly from well to far boundary

Pressure is less than Darcian response at corresponding locations.

**axial symmetry**

290 psi near well

Response is instantaneous
Pressure decreases inversely from well to far boundary

290 psi far end

200 psi

Poroelastic

Pressure shows finite build-up and decay, indicating storage
Pressure varies non-linearly from well to far boundary

Pressure is less than Darcian response at corresponding locations.
Horizontal fluid velocity at injection depth vs time

**planar symmetry**

- **Darcy**
  - Response is instantaneous
  - Velocity is constant from well to far boundary

- **Poroelastic**
  - Horizontal velocity near well goes negative after pumping is shut off, indicating drainage of the rock mass

**axial symmetry**

- **Darcy**
  - Response is instantaneous
  - Velocity drops off from well to far boundary

- **Poroelastic**
  - Velocity shows build-up and decay
  - Velocity varies non-linearly from well to far boundary
  - Horizontal velocity near well goes negative after pumping is shut off, indicating drainage of the rock mass.
  - Effect not as pronounced as in planar symmetry case.
Deformation at injection depth vs time (planar symmetry)

No deformation in Darcy model

Response shows complex build-up and decay
Deformation varies non-linearly from well to far boundary
Horizontal and vertical deformations are about the same
Horizontal deformation near well goes negative for a while after pumping is shut off as water drains

**Planar symmetry**
- 3.2 m poroelastic
- 2.2 m poroelastic

**Axial symmetry**
- 0.55 m poroelastic
- 0.35 m poroelastic
Deformation vs time during injection period in poroelastic model (planar symmetry)

Injection starts on day 7
Injection ends after day 14

Earth deforms during injection
Max deformation occurs at depth and is a few meters in both horizontal and vertical

Post-injection, earth deflates
Some inflation persists even after 60 days
von Mises stress at injection depth vs time (planar symmetry)

No solid framework to stress in Darcy model

Stress shows finite build-up and decay, indicating storage in injection interval
Stress varies non-linearly from well to far boundary

**planar symmetry**

420 psi  poroelastic

**axial symmetry**

85 psi  poroelastic
The “solid” earth exhibits a poroelastic response relating pore pressure, stress, deformation, and failure.

Since models play a central role in the regulatory process governing underground injection, the poroelastic response of reservoir rocks should be included in models for onset of seismicity.

Models using a poroelastic reservoir show that, at least in some scenarios, the perturbation pressure is reduced from that found by traditional methods. This would allow higher injection pressures before onset of seismicity.

COMSOL provides an effective poroelastic modeling capability.

Further validation is needed before this approach can be incorporated into regulations.


H. F. Wang, Theory of Linear Poroelasticity with Applications to Geomechanics and Hydrogeology, Princeton University Press, 2000
Extra Slides
Prior studies of injection-induced seismicity suffer from one or more deficiencies -- all related to stresses in the rock mass. ¹

Used flowing downhole pressure buildup at the well as an indicator of observed critical pressure.

Used “USGS Unaltered Stress Assumption” rather than properly formulated poroelastic model to calculate rock stresses.

Used Mohr-Coulomb Criterion, rather than the more general Coulomb Criterion, to establish the predicted critical pressure.

¹ Miller et al. [2010]
Orientation and magnitude of the background stresses come from well tests.

Breakouts and drilling-induced fractures observed in well logs indicate local stress field orientation.

A hydrofrac test provides the best available estimate of the least horizontal stress.

From Schlumberger’s DSI log, we infer greatest horizontal stress.

From the density log, we estimate the vertical stress, which comes from the “overburden” (gravity acting on mass density).
Rock mechanical data come from specialized wireline well logs, calibrated by lab measurements on selected rock cores…

… to provide a continuous record of rock mechanical properties down the well.