Modeling Fault Reactivation, Induced Seismicity, and Leakage during Underground CO2 Injection

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GCS considered as feasible solution but…

- Overpressures due to large-scale fluid injection may induce seismic events! (e.g. Basel)
- What is the potential for structural damage and human perception?
- What is the effect of reactivation on leakage (CO$_2$, brine)?
- Can the fault reactivation change the permeability in the fault? Can the fault reactivation compromise the sealing properties of a storage site?
- Does the size of the caprock/storage aquifer have a role?
Importance of Minor versus Major Faults

- Large offset major faults can be detected on the ground surface and by seismic surveys.
- Sequestration site might be designed to stay away from such faults and because they are known they can be closely monitored, modeled and analyzed in terms of avoiding reactivation.

(Cappa and Rutqvist, GRL, 2011a)

- The regional injection-induced (slow) crustal straining and minor (hidden) faults might be of greatest concern at future large scale injection sites (minor faults of unknown location and orientation).
- Both analytical and modeling results show event magnitude ~3.6

(Mazzoldi et al., IJGGC, 2012)
Numerical modeling

• TOUGH-FLAC/ECO2N (2D model)
• Fully hydro-mechanical coupling
• 100 m storage aquifer, bounded by 150 m caprock
• Pre-existing normal fault with dip 80°
• CO₂ injection at -1500 m, 500 m from the fault
• Isothermal with gradient 25°C/km
• Initial hydrostatic linear gradient
• Constant pressure and stress boundary
• Extensional stress regime \( \sigma_H = 0.7 \sigma_V \)

**Stress and strain dependent permeability:**

\[
\phi_{hm} = \phi_0 + \Delta \phi_{fp}
\]

\[
\Delta \phi_{fp} = e_{ftp} + e_{fsp} \tan \psi
\]

\[
K_{hm} = K_0 \left( \frac{a}{c(c \sigma'_{n} + 1)} \right) \sqrt{\frac{\phi_0}{12 \kappa_0}} + \frac{e_{ftp} + e_{fsp} \tan \psi}{\phi_0}
\]

\[
a = K^{-1}
\]

\[
c = \frac{-1 \pm \sqrt{1 + 4 \sigma'_{n0} a \sqrt{\phi_0 / \kappa_0}}}{2 \sigma'_{n0}}
\]

• Damage zone as high permeability zone and Fault core with Ubiquitous-joint model
• Oriented weak plane in a Mohr-Coulomb solid
• Strain-softening model: friction as function of plastic shear strain
SCENARIO 1 after 5 years injection

LEAKAGE:
- CO$_2$ leakage into upper aquifer compared to total injected amount as function of injection rate ($q=2\text{--}100$ kg/s) and initial fault permeability ($\kappa=10^{-16} \text{--} 10^{-14}$ m$^2$)
- High percentage only for high $\kappa$ and $q$, with about 30% in the worst case scenarios
- Fault permeability changes 1-2 orders magnitude

FAULT REACTIVATION:
- Events only for $q > 30$ kg/s ($M\sim2\text{--}3.5$)
- High $q$ requires less time for reactivation, but triggers smaller event
- High $\kappa$, requires more time for reactivation, but trigger bigger events (pressure distribute more along fault)

(Rinaldi et al., IJGGC, 2014)
SCENARIO 2 after 5 years injection

LEAKAGE:
- Reservoir hydraulically smaller
- CO$_2$ leakage as function of injection rate ($q=2$-12 kg/s) and initial fault permeability ($\kappa=10^{-16} – 10^{-14}$ m$^2$)
  - High percentage only for high $\kappa$ and $q$
    (same as Scenario 1)
  - About 10% in the worst case scenarios
  - At low $\kappa$ CO$_2$ into shifted aquifer

FAULT REACTIVATION:
- Higher overpressure compared to Scenario 1, then lower $q$ needed for reactivation (M$\approx$2-3.5)
- Greater magnitude for a lower $q$…
- …or for higher $\kappa$ (when pressurization at critical value for reactivation!)
- Null CO$_2$ leakage for the worst simulated case (M$\approx$3.6).

(Rinaldi et al., IJGGC, 2014)
What about the thickness of the caprock?

**Scenario 1**

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Magnitude</th>
<th>Rupture (m)</th>
<th>Ev. Disp (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 m</td>
<td>3.01</td>
<td>596.03</td>
<td>6.91</td>
</tr>
<tr>
<td>150 m</td>
<td>2.86</td>
<td>467.14</td>
<td>6.26</td>
</tr>
<tr>
<td>50 m</td>
<td>2.71</td>
<td>352.14</td>
<td>5.84</td>
</tr>
</tbody>
</table>

(Rinaldi et al., GHG, 2014)

150 m Caprock
CO₂ leaking ~400 tons
~6.5% of total injected mass

50 m Caprock
CO₂ leaking ~940 tons
~15% of total injected mass
...and aquifer?

**SCENARIO 1**

- **150 m**
  - Magnitude = 2.98
  - Rupture = 526.67 m
  - Ev. Disp = 7.53 cm

- **100 m**
  - Magnitude = 2.86
  - Rupture = 467.14 m
  - Ev. Disp = 6.26 cm

- **50 m**
  - Magnitude = 2.62
  - Rupture = 360 m
  - Ev. Disp = 4.59 cm

(Rinaldi et al., GHG, 2014)

- 100 m AQUIFER
  - CO₂ leaking ~400 tons
  - ~6.5 % of total injected mass

- 50 m AQUIFER
  - CO₂ leaking ~1200 tons
  - ~19.6 % of total injected mass

- 1800.0 days

Image credits: Rinaldi et al., GHG, 2014.
Injection in a multi-caprock, multi-aquifer system

**SCENARIO 1**

Multi-

- **Magnitude**: 2.71
- **Rupture**: 352.14 m
- **Ev. Disp**: 5.97 cm

Single-

- **Magnitude**: 2.86
- **Rupture**: 467.14 m
- **Ev. Disp**: 6.26 cm

*Graphs showing pressure change (MPa) and slip (cm) versus depth (m) for multi-caprock and single caprock scenarios.*

*Graphs illustrating CO₂ leakage with 1800.0 days representation.*

*Graphs indicating CO₂ leakage with approximate masses: Multi-caprock with 181 tons (18% of total injected mass) and single caprock with 400 tons (6.5% of total injected mass).*

*References: Rinaldi et al., GHG, 2014*
Dynamic analysis for SCENARIO 2

- Reactivation at about 10 MPa overpressure
- 4 cm fault slip over 0.4 seconds
- 290 m fault rupture corresponding to $M_w = 2.53$

(Cappa and Rutqvist, GJI, 2012)
Top soil

- PGA 0.6g at 30-40 Hz
- Damping of high frequency acceleration for soil

(Rutqvist et al., IJGGC, 2014)

- PGV 30 mm/s at 6-12 Hz
- PGV for one jolt at a lower frequency
Comparison to Potential Damage Criteria

- US Bureau of Mines (USBM) limits for cosmetic damage in plaster stucco and drywall and human-perception limits for blast vibration (after Bommer et al., 2006).
- Human perception limits are based on steady vibration

Siskind Curve and Human Perception:
Peak velocity 30 mm/s at 6 to 12 Hz
⇒ Some cosmetic damage and perceived as unpleasant by humans (if steady vibration)

(Rutqvist et al., IJGCG, 2014)
Comparison to Potential Damage Criteria

<table>
<thead>
<tr>
<th>PEAK VELOCITY (mm/s)</th>
<th>FREQUENCY (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PERCEPTIBLE</td>
<td>1.1-3.4</td>
</tr>
<tr>
<td>UNPLEASANT</td>
<td>0.1-1.1</td>
</tr>
<tr>
<td>DRYWALL (19.1 mm/s)</td>
<td>0.17-1.4</td>
</tr>
<tr>
<td>PLASTER (12.4 mm/s)</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>INSTRUMENTAL INTENSITY</td>
<td></td>
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</tbody>
</table>

**USGS PGV:**
Peak velocity 3 cm/s
⇒ Light to moderate shaking and none to very light damage

**USGS PGA:**
Peak acceleration 0.6g
⇒ Severe shaking and heavy damage

**Siskind Curve and Human Perception:**
Peak velocity 30 mm/s at 6 to 12 Hz
⇒ Some cosmetic damage and perceived as unpleasant by humans (if steady vibration)

(Rutqvist et al., IJGGC, 2014)
### Comparison to Potential Damage Criteria

<table>
<thead>
<tr>
<th>PEAK ACC. (%g)</th>
<th>Not felt</th>
<th>Weak</th>
<th>Light</th>
<th>Moderate</th>
<th>Strong</th>
<th>Very strong</th>
<th>Severe</th>
<th>Violent</th>
<th>Extreme</th>
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<tr>
<td>&lt; 1.7</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>Very light</td>
<td>Light</td>
<td>Moderate</td>
<td>Moderate/Heavy</td>
<td>Heavy</td>
<td>Very Heavy</td>
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<td>1.7 - 1.4</td>
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<td>3.9 - 9.2</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>PEAK VEL. (mm/s)</th>
<th>0.1 - 1.1</th>
<th>1.1 - 3.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>USBM RI 8507</td>
<td>PLASTER (12.4 mm/s)</td>
<td>DRYWALL (19.1 mm/s)</td>
</tr>
<tr>
<td></td>
<td>PERCEPTIBLE</td>
<td>UNPLEASANT</td>
</tr>
<tr>
<td></td>
<td>(50.8 mm/s)</td>
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</tbody>
</table>

#### USGS PGV:
- Peak velocity 3 cm/s
  - Light to moderate shaking and none to very light damage

#### USGS PGA:
- Peak acceleration 0.6g
  - Severe shaking and heavy damage

#### Siskind Curve and Human Perception:
- Peak velocity 30 mm/s at 6 to 12 Hz
  - Some cosmetic damage and perceived as unpleasant by humans (if steady vibration)

More appropriate to use **PGV** (rather than PGA) and **frequency** for shallow injection-induced events.
Discussion & Conclusion

• Poor correlation between seismic events and leakage:
  ✓ A single event not enough to substantially change permeability along the entire fault length;

• Site characterization is essential:
  ✓ Accounting for multiple caprocks and multiple storage aquifers can reduce both leakage amount and event magnitude

• Low potential for structural damages:
  ✓ Shallow-induced events frequency analysis well within the proposed limits, although could unsettle the local population

• There are some limitations:
  ✓ What will change when considering a full 3D formulation?
  ✓ Slip-weakening model, then single event. Will a series of notable earthquakes compromise the caprock integrity?
Thank You!

Acknowledgment

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