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

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Geomechanics of CO$_2$ Storage in Deep Sedimentary Formations

[Rutqvist (2012) Int. J. Geotechnical and Geological Engineering]
Geomechanics of CO$_2$ Storage in Deep Sedimentary Formations

(Rutqvist (2012) Int. J. Geotechnical and Geological Engineering)
Geomechanics of CO$_2$ Storage in Deep Sedimentary Formations

Injection-induced stress, strain and deformation

Unwanted mechanical changes

Localised deformation?

CO$_2$ buoyancy migration?

Seismic?

Fault reactivation?

Reservoir pressure: $\Delta P$  Cooling: $-\Delta T$

Reservoir stress and strain $\Delta\sigma, \varepsilon$

Caprock

Overlying seal

Micro-seismicity

Deformation

Injection well

CO$_2$ plume

Minor faults

Abandoned well

Major Fault

Stress and strain changes beyond area of pressure change

Pressure change far beyond CO$_2$ plume

Butqvist (2012) Int. J. Geotechnical and Geological Engineering
Potential Fault Reactivation and Notable Seismic Events

• An important issue from safety, storage security, and public acceptance perspectives.

• Release of stored energy triggered by the injection.

• Not just limited to seismically active areas, but could also occur within the seismically quiet intraplate crust (Zoback and Gorelick., 2012).

• Undetected minor faults relevant

Outline of Presentation

• Introduction

• Modeling approach

• CO2 injection and fault activation
  - Potential magnitudes?
  - Potential leakage?

• Deep fracture/fault responses at In Salah

• Concluding remarks
Modeling Fault Reactivation and Seismicity

- Anisotropic plasticity model allowing shear (Coulomb) failure along the fault plane
- Shear-induce fault permeability change
- Strain-softening plasticity to represent slip-weakening fault behavior (sudden slip)
- Seismic moment and moment magnitude calculated from Kanamori et al (e.g. $M_0 = \mu A d$)
Simulated CO2 Injection and Fault Activation

- Reactivation at about 7.5 MPa overpressure
- 4 cm fault slip over 0.4 seconds, peak slip 0.6 m/s
- 290 m fault rupture corresponding to $M_w = 2.53$

(Cappa and Rutqvist, GJI, 2012)
Ground Surface Motion at Top of the Fault

- PGA 0.6g at 30-40 Hz
- High frequency acceleration damped for soil

- PGV 30 mm/s at 6-12 Hz
- PGV for one jolt at a lower frequency

(Rutqvist et al., IJGGC, 2014)
**Building Damage and Human Perception**

US Bureau of Mines (USBM) ground vibration criteria for building damage and human-perception limits for vibration

- In this example vibrations could cause cosmetic building damage and clearly felt by humans

Rutqvist et al 2014 (Int. J Greenhouse Gas Control)
Rupture Size of a Notable (Felt) Seismic

TOUGH-FLAC modeling of events triggered by injection (Cappa and Rutqvist, 2011)

Stress ratio = $\sigma_H / \sigma_V = 0.6$, 0.7 or 0.8

- Largest magnitude when fault exposed to the highest shear stress (horizontal/vertical stress ratio = 0.6)
- A notable (felt) event, e.g. magnitude 4, requires a km-sized fault rupture
- What about 2D model simplification?
3D Modeling of Fault Reactivation and Seismicity

- Flow in the third dimension (not confined within 2D plane strain model)
- Longer time for pressure buildup before reactivation $\Rightarrow$ slightly larger magnitude
3D Modeling of Fault Reactivation and Seismicity

- Rupture area elongated along strike of fault
- Large fault area pressurized at rupture ⇒ felt events, e.g. M = 3 - 4
Potential Shear-Induced Permeability and Leakage

Shear slip and stress drop associated with a seismic event:

Zoback and Gorelick (2012)

Rutqvist and Stephansson (2003)
In this simulation example we simulated a seismic event that might be felt but with no upward CO$_2$ leakage

Rinaldi et al 2014 (nt. J Greenhouse Gas Control)
Example of Shear-Permeability Tests on Shale Fractures

Gutierrez et al. (2000)

Under higher stress normal to fracture the permeability decreases with shear (at stress level higher than the uniaxial compressive rock-strength)
The CO₂ injected at a depth of about 1.8 to 1.9 km into a 20 m thick formation of relatively low permeability.

- Nearly one million tonnes CO₂ per year injected from 2004 to 2011 at 3 horizontal injection wells
- Bottom hole pressure limited to below the fracturing gradient ⇒ maximum pressure increase of about 100 bar (160% of hydrostatic)
- 950 m thick caprock with multiple low permeability formations
In Salah Ground Surface uplift 2004-2007 from Satellite (InSAR)

Horizontal CO2 injection wells

Fractures

Stress

Krechba Gas Field

Gas-water contact

Production wells

KB501

KB502

KB503

Rutqvist et al. (2010)
In Salah Ground Surface uplift 2004-2007 from Satellite (InSAR)

Double-lobe uplift

Horizontal CO2 injection wells

KB501

KB502

KB503

Fractures

Stress

Gas-water contact

Production wells

Krechba Gas Field

Rutqvist et al. (2010)
Vasco et al. (GRL, 2010) interpreted observed double-lobe (uplift) response to be caused by a tensile opening feature at the injection zone.
In Salah Deep Fault or Fracture Zone Responses

Rinaldi, Rutqvist (2013) TOUGH-FLAC modeling with simultaneous matching of transient uplift and injection data

Modeling indicates that the fracture zone extends a few hundred meters up from the reservoir (contained within the 900 m thick caprock)
In Salah Deep Fault or Fracture Zone Responses

Injection pressure sufficiently high to induce deep fracture zone opening

Minor faults indicated from 3D seismic (Ringrose et al., 2011)

Theoretically close to critically stressed for shear reactivation (Morris et al., 2011)

However, CO2 injection at In Salah has not resulted in any felt seismic events or substantial strike-slip shear movements (Max magnitude 1.7, (Stork et al. 2014))
Concluding Remarks

- We used numerical modelling to induce reactivation of steeply dipping faults at a high injection pressure in an unfavourable stress regime.

- We simulated events of magnitudes < 4 that would not result in any structural damage, but could likely be felt and cause concern in the local community.

- At In Salah, injection pressure was relatively high indicating minor faults being critically stressed for reactivation, but no felt seismic event has been reported.
Concluding Remarks

- We used numerical modelling to induce reactivation of steeply dipping faults at a high injection pressure in an unfavourable stress regime.

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- At In Salah, injection pressure was relatively high indicating minor faults being critically stressed for reactivation, but no felt seismic event has been reported.

- At future large-scale CO2 operations (much larger than In Salah), it is the large-scale and long-term pressure buildup, associated crustal straining, and potential undetected (minor) faults that might be of greatest concern.
Thank you!

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