Model comparison for geomechanical simulation of large-scale CO$_2$ storage

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Building Confidence in Models for Large-scale CO$_2$ Storage

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Challenges of CCS scale-up

- CCS must be scaled up significantly to meet EU emissions targets
- IEA Road Map = 12.2 Gt stored by 2050 → 400 Mt/y!

**Small scale ~ 1 Mt/y**

Safe storage capabilities demonstrated

**Large scale ~ 10-100 Mt/y**

Higher overpressures
Greater stress on caprock
Higher risk for leakage
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Most important question for large-scale storage: How to determine safe operating pressure?
Utsira case study

What is **practically achievable** storage capacity?
- **Prevent leakage** by maintaining a safe pressure both during and after injection

**Two-step approach:**
1. Simple analytical model
2. Large-scale simulations

Kirby et al. 2001

15 Gt storage capacity
Closed system
\[ dV = V_f (\beta_w + \alpha_B/\phi) \, dp \]

Zhou et al.

Compressible sand

Max dp 15 bar

\( \Delta p_{max} \) (bar)

CO\(_2\) mass (Mt)

5 Gt storage in south Utsira

8.3 Gt storage ~50% NPD
Pressure and deformation are more important for capacity than CO₂ trapping

VE model is a simple model that takes only 5 minutes to solve for large-scale, long-term injection
How confident are we in our models?

Large-scale simulations depend on simulation technology that can reliably predict overpressure and deformation.

What really needs to be modeled?
Model comparison

• Several efforts towards model comparison for CO₂ storage
• Models generally compare well when expected
• Simpler models often do quite well
• Intensive effort to communicate data and compile results
• Uncertainty from different interpretation of problem/data


Class et al. (2009) A benchmark study on problems related to CO₂ storage in geologic formations, *Comp. Geosci.*

Nordbotten et al. (2013) Uncertainties in practical simulation of CO₂ storage. *I&GCC.*
Model comparison

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Very little in the way of model comparison for geomechanical processes in CO₂ storage

- Nordbotten et al. (2013) Uncertainties in practical simulation of CO₂ storage, *IJGCC.*
Model comparison objective

• Compare model predictions of overpressure and elastic deformation during high-volume CO₂ injection
• Understand how models of different complexity compare for the same problem
• Identify flow/mechanical processes that have greatest impact on large-scale deformation
• Caveat—study does not address plastic deformation that occur near wellbores or due to activation of faults and fractures.
Benchmark Participants

COMSOL Multiphysics
- **Flow** – Multi-phase, vertical equilibrium (2D in reservoir)
- **Mechanics** – 3D linear poroelasticity, 2D in reservoir

VESA Model
- **Flow** – Multi-phase, vertical equilibrium (2D in reservoir)
- **Mechanics** – Analytical uniaxial deformation

Classic Hydromechanics
- **Flow** – Single-phase flow (3D)
- **Mechanics** – 3D linear poroelasticity (Fixed stress split)
### Utsira case study

**Material Property** | **Value**
--- | ---
**Overburden**<sup>†</sup> |  
Permeability | 1 nanoDarcy  
Porosity | 20%  
Young’s modulus | 0.25 GPa  
Poisson ratio | 0.25  
**Sand**<sup>†</sup> |  
Permeability | 1 Darcy  
Porosity | 35%  
Bulk Compressibility | 3.5 GPa<sup>−1</sup>  
Young’s modulus* | 0.24 GPa  
Poisson ratio | 0.25  
**Underburden** |  
Permeability | 1 nanoDarcy  
Porosity | 20%  
Young’s modulus | 2.5 GPa  
Poisson ratio | 0.25

- Massive lateral scale
- Use measured data
- Single well injection in Sleipner for 25 years
Simulation scenarios

- Diffuse brine leakage
  - Yes
  - No

- Sand compressibility
  - Soft sand (measured)
  - Stiff sandstone

- Injection rate (Mt/y)
  - 1
  - 10
  - 100

Yes

No
Simulation scenarios

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  - No

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  - 1
  - 10
  - 100
Increasing complexity

Model to model

Modeling choices

Modeling choices

Modeling choices

Modeling choices
Increasing complexity

Water vs Water

Water vs Diffuse leakage

Water vs CO₂

CO₂ vs CO₂

CO₂ vs variable CO₂

Model to model

Model to model
Fully-coupled 1-phase flow
Very small differences in pressure of <1%

Overall <5% difference but higher around injection cell
Water vs Water

Water vs Diffuse leakage

Water vs CO₂

CO₂ vs CO₂

CO₂ vs variable CO₂

Model to model
Fully-coupled 2-phase

Overpressure

Uplift

Simple VE 2p flow
Water vs Water

Water vs Diffuse leakage

Water vs CO₂

CO₂ vs CO₂

CO₂ vs variable CO₂

Modeling choices
CO$_2$ vs water injection

Fully-coupled 1-phase

Simple VE 2p flow

CO$_2$ vs water >> model differences
Water vs Water

Water vs Diffuse leakage

Water vs CO₂

CO₂ vs CO₂

CO₂ vs variable CO₂

Model choices
Simple VE 2p flow

Overpressure

Uplift

CO₂ compressibility and viscosity impacts are significant
Increasing injection rate =
Increasing impact of injected fluid properties
• Models compare well when expected

• Upscaled/analytical geomechanical models are more efficient than classical poroelastic modeling

• Take caution for higher overpressures
  – CO₂ properties have high impact
  – Diffuse brine leakage becomes increasingly important

• Equivalent volume injection of water is only comparable with CO₂ inj for low overpressures
Outlook

- High confidence for relatively simple mechanical systems
- Smeaheia is not structurally simple—faulted, heterogeneous
- What is safe pressure for very large-scale injection in faulted systems
- How do models of fault seal and stability compare?
*Protection of Caprock Integrity for Large-scale CO2 Storage, NFR CLIMIT project no. 233736

**Objective:** Understand the impact of **flow, geomechanics, flow and chemistry** on:

- Injectivity
- Storage capacity
- Risk of CO₂ leakage.

**Website:**
www.protect.b.uib.no