Assessing uncertainty of time-lapse seismic response due to geomechanical deformation

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Acknowledgements:
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Outline

• Context
• Multi-physics solution
• Time-lapse seismics/geomechanics
• Overburden imaging
• Valhall example
• Geomechanics and uncertainty
• Way forward
Context

Sleipner
- Negligible pressure effect
- High porosity/high permeability

Snohvit/In Salah
- Pressure effect
- Snohvit – compartmentalisation
- In Salah - ?
e.g., microseismicity – static velocity model
e.g., microseismicity – non-static velocity model

Static velocity model

Event location MTMI

True dynamic velocity model
Multi-physics: porous deformable media

- Change in pore pressure ($\Delta P$)
  \[
  \begin{align*}
  \Delta V &= V - P \\
  \Delta H &= H - P
  \end{align*}
  \]

- Leads to change in horizontal total stress

- Difficult to predict stress evolution

Dynamic view (syn- and post-production)
Multi-physics: porous deformable media

- Integration (hydro-mechanics):
- Coupled fluid-flow/geomechanics
  - Fully-coupled
  - One-way coupling (flow to geomechanics)
  - Two-way coupling

\[ \Delta P, \Delta S_i, \Delta k, \varnothing, c \]

Petroleum Production

Stress changes

Reservoir property changes

Geophysical attributes

4D Seismsics Microseismics
Rock physics transforms

- Stress dependent velocities

**rock physics model**

- Intrinsic anisotropy
- Static to dynamic conversion
- Nonlinear stress dependence
- Fluid effects
- Frequency effects
- Effects of fractures

**Implement geophysical model** (see Kendall et al., 2007)

**Not implemented yet, but exploring options** such as Guyer et al. (1995)

**Implement microstructural analytic nonlinear mode** (see Verdon et al., 2008)

- Low frequency
- Gassmann’s equation (see Brown & Kvarning, 1975)

- Squirtflow model (see Chapman et al., 2002)

**Implement fracture induced excess compliance and anisotropy** (see Hall, 2000, for review)
Rock physics

Reservoir model with high fault transmissibility

Shapiro 2003

Tod 2002
Seismic monitoring

Acquisition (instrument) geometry

A. OBS with azimuths

B. OBS with midpoints

C. Offset Distribution

D. Azimuth Distribution
Time-lapse or 4D seismic

- Change in:
  - Saturation
  - Pressure/stress
  - Mechanical properties

Baseline model

Baseline - Monitor 1

Baseline - Monitor 2

P-wave velocity change for true earth model
Time-lapse or 4D seismic

- What is measured:
  - Time differences
  - Amplitude differences
  - “Devil is in the detail”
Time-lapse or 4D seismic

- Extract time-lapse amplitude changes

Estimated P-wave reflection amplitude (strength) changes using full-offset seismic data

Estimated P-wave reflection amplitude (strength) changes using near-offset seismic data
Time-lapse or 4D seismic

- Extract time-lapse velocity changes

P-wave velocity change for true earth model

Estimated P-wave velocity change using full-offset seismic data

Estimated P-wave velocity change using near-offset seismic data
Time-lapse or 4D seismic

- Tau-p pre-stack approach
Vertical displacements predicted vs measured

- Subsidence evolution recorded at seafloor
- From PO-035105 document
  - QP (524204,6237070)
  - North (522181,6242020)
  - South (527011,6231800)

Horizontal surfaces
Isosurfaces of vertical displacement

Vertical division of the domain for parallel analysis
AVOA modelling

- Map reflection coefficients and fast P-wave direction
  - Using layer-matrix approach
  - Elasticity between chosen layers
Microseismicity:

- Valhall reservoir
- Geomechanics and microseismicity
Recap

• Likely not all CCS sites will be like Sleipner
• Large scale projects:
  – Not always ideal porosity/permeability
  – Injection rates and volumes
  – Fluid-rock (e.g., geochemical) alterations
• Must be capable of monitoring strains and overburden effects
  – Monitor seal integrity
  – Evaluate CO$_2$ containment
Challenges, uncertainties & way forward

• Rock physics transforms
  – Models for multiphase fluids, patchy saturation, attenuation, anisotropy, plasticity
  – More data (e.g., shallower depths – overburden)
  – Calibration with in-situ data (not only core samples)
  – Scaling (static measurements to dynamic measurements) – significant knowledge gaps, but can apply site specific empirical relationships

• Hydro-mechanical models:
  – Calibration/history match fluid-flow and geomechanical simulation models
  – Systematic approach to model building (i.e. geometry & meshing)
  – Constitutive models from rock and petro-physics with up-scaling
  – Uncertainty of model parameters and geophysical/seismic attributes
Energy Leeds
Valhall reservoir, North Sea

- ELFEN-VIP one-way coupling
  - Hexahedra mesh (6 million elements)
  - Cap plasticity, non-associated flow rule, water weakening SR3 adjusted to Valhall model (ISAMGEO PO-035105)
  - Soft coupled to 500,000 grid VIP model
  - VIP pore pressure output monthly

- Pore pressure used by Elfen as applied load
- ELFEN solved in parallel (4 domains)
- 3 element groups are mapped (VIP-Elfen)
  - Reservoir Tor
  - Reservoir Hod
  - Reservoir faults
### Elastic/Elasto-plastic properties

<table>
<thead>
<tr>
<th>Layer</th>
<th>$E_1$ (MPa)</th>
<th>$E_2$ (MPa)</th>
<th>$v_{xx}$</th>
<th>$v_{yy}$</th>
<th>$G_{xx}$</th>
<th>$G_{yy}$</th>
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<td>1</td>
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<td>240</td>
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<td>10</td>
<td>65</td>
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<td>0.15</td>
<td>15</td>
<td>66</td>
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<tr>
<td>3</td>
<td>Intra mediolaterite</td>
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<td>240</td>
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<tr>
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<tr>
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<tr>
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*ENERGY*
Microseismicity:

- Weyburn CCS pilot
- Geomechanics and microseismicity

[Diagram showing overburden fracture potential after different stages: production, CO\textsubscript{2} injection, shut-off]