Integrated Seismics and Hydro-mechanics

The Impact of Geomechanics on Predicted Seismic Attributes for CO$_2$ Injection and Storage

Doug Angus, UKCCSC Geomechanics Workshop, Liverpool, 6-7 September, 2012
(collaborators: Tom Lynch, Quentin Fisher, James Verdon, Alan Baird and Noel Gourmelen)
Outline

• Terminology & basic concepts
• State-of-the-art in integrated geophysics, geomechanics and petroleum engineering
• Multi-disciplinary approach (e.g. integration)
• Results and examples
  • Conceptual models
  • Case studies
    • Off-shore – Valhall reservoir North Sea
    • On-shore – Tight-gas reservoir
    • On-shore pilot CCS – In Salah Algeria

• Challenges
Basic concepts (as how I interpret it):

- Fluid-flow (injection programmes)
  - Saturation, pressure, permeability (Eclipse, Tempest, VIP)
- Geomechanics (well design, seal integrity)
  - Stress, strain (Abacus, Diana, Elfen, FLAC/UDEC)
- Rock physics and petro-physics
  - Link mechanical and fluid properties to geophysical attributes
- Geophysics (seismics)
  - Image structure, fluid volumes and stress/strain state
Effective stress concept:

- Change in pore pressure ($\Delta P$)
  - Effective stresses ($\Delta \sigma^v$)
  - Total stresses ($\Delta \sigma$)

\[
\Delta \sigma^v' = \Delta \sigma^v - \alpha \Delta P \\
\Delta \sigma_H' = \Delta \sigma_H - \alpha \Delta P
\]

- Assumed that total vertical stress is constant
  - Weight of the overburden
  - Assumption fails when stress arching develops

- Change in pore pressure often leads to change in horizontal total stress
- So it can be difficult to predict stress evolution

Herwanger (2007)
- Multidisciplinary approach needed
  - Geomechanics
  - Petroleum engineering
  - Geophysics

- State-of-the-art
  - Susan Minkoff / Rick Dean
  - Some examples of current groups
    - Rutqvist-Vasco (Lawrence Berkeley)
    - Herwanger-Koutsabeloulis (Schlumberger)
    - Settari (University of Calgary)
  - Leeds funded projects
    - IPEGG
    - GESER
    - PETGAS
    - FRACGAS

Synthetic seismic

Coupled geomechanical – production simulation models
Geomechanics:

- Deformation (strains) and stresses

Kato (2010)
Petro-physics:

- Relative Permeability $k_r$
- Gas Saturation $S_g$
- CO2 - Host
- Brine - Host
- CO2 - Fault
- Brine - Fault

Tueckmantel (2010)
Rock physics:
- Seismic attributes (e.g., travel-time, Ai, Q, anisotropy)
- Acoustic properties: $V_P$, $V_S$, density and Q
- Reservoir properties (e.g., porosity, saturation, pressure, stress)
- Impact of microstructure/fluid on stress dependence

Calibration

Prediction

Brine saturated

$e^2$ saturated

$e^2$ dry

$e^2$ saturated

$e^2$ dry

$B_{N}/B_{T}$ saturated

$B_{N}/B_{T}$ dry

$\alpha_i$ saturated

$\alpha_i$ dry

$CO_2$/Brine saturated

Angus et al. (in review)
Integration (hydro-mechanics):

- Coupled fluid-flow/geomechanics
  - Fully-coupled
  - One-way coupling (flow to geomechanics)
  - Two-way coupling

Geophysical attributes:

- Reservoir property changes
- Geophysical attributes
  - 4D Seismics
  - Microseismics

- Petroleum Production
  - Stress changes
  - \( \Delta P_p \)
  - \( \Delta S_i \)
  - \( \Delta k, \emptyset, c \)
Simple conceptual reservoir models

- Aspect ratio reservoir models
- Two-fault reservoir models
Microseismic predictions

- Poro-elastoplastic
  - Matrix failure and pre-existing faults
- Poro-elastic
  - Fracture potential or Mohr-Coulomb
2 Fault reservoir model

\[ V_p \text{ initial (m/s)} \]

\[ V_p \text{ final (m/s)} \]

\[ \Delta V_p \text{ (fraction)} \]

Angus et al. (2011)
Geomechanics
- Overrides mechanical properties
- Updates pore volume
- $\Delta \approx 35\%$ to $40\%$ between coupled simulations
- $\Delta \approx 10\%$ to $25\%$ between uncoupled and coupled simulations
CiPEG

Anisotropic ray tracing (ATRAK)

Seismic Geomechanics (velocity predictions)

4D seismic attributes (reflection amplitudes)
Valhall reservoir, North Sea

- One-way coupling: hexahedra mesh
- VIP model run alone, pore pressure output monthly
- Pore pressure used by Elfen as applied load
- Not all files available (possibly missing well perforation data)
- Elfen mode solved in parallel – domain divided into 4 sections
- 3 element groups are mapped (VIP-Elfen)
  - Reservoir Tor
  - Reservoir Hod
  - Reservoir faults
## Elastic Properties

<table>
<thead>
<tr>
<th>Layer</th>
<th>$E_1$ (MPa)</th>
<th>$E_2$ (MPa)</th>
<th>$v_1$</th>
<th>$v_2$</th>
<th>$\alpha_1$</th>
<th>$G_1$ (MPa)</th>
<th>$G_2$ (MPa)</th>
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<td>1</td>
<td>240</td>
<td>160</td>
<td>0.25</td>
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<td>65</td>
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<td>2</td>
<td>300</td>
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<td>0.25</td>
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<td>3</td>
<td>Intra mid Nannocene</td>
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<td>240</td>
<td>0.25</td>
<td>0.15</td>
<td>180</td>
<td>68</td>
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<td>4</td>
<td>Tri110</td>
<td>500</td>
<td>300</td>
<td>0.25</td>
<td>0.15</td>
<td>200</td>
<td>110</td>
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<td>5</td>
<td>Intra late Cretaceous</td>
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<td>260</td>
<td>130</td>
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<td>6</td>
<td>Intra late Eocene</td>
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<td>450</td>
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<td>0.15</td>
<td>300</td>
<td>165</td>
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<td>Eocene</td>
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<td>800</td>
<td>0.25</td>
<td>0.1</td>
<td>800</td>
<td>200</td>
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<td>10</td>
<td>Santa</td>
<td>1100</td>
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<td>0.2</td>
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<td>1000</td>
<td>0.3</td>
<td>0.2</td>
<td>461.5394515</td>
<td>360</td>
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<td><strong>Reservoir &amp; Intermediate</strong></td>
<td>$E = 1000 \phi^{-3.3}$</td>
<td>0.175</td>
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<td>X</td>
<td></td>
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<tr>
<td>12 to 15</td>
<td>Tor</td>
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<tr>
<td>25 to 24</td>
<td>Hod</td>
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<td>4000</td>
<td>0.2</td>
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<td>X</td>
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<td>X</td>
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The diagram illustrates the transition from shear to compaction, with the overburden and reservoir stages distinguished. The elastic and elastoplastic regions are highlighted, indicating the stress-strain behavior under different conditions.
Vertical displacements after 23.5 years production

Vertical displacement seafloor after ~23.5 years production (end simulation)

Vertical displacement top Tor after ~23.5 years production (end simulation)

Vertical displacement top Hod after ~23.5 years production (end simulation)
Reservoir case study

P-wave anisotropy

Baseline

~ 8 years

~ 16 years

~ 25 years

ΔV_p

+0.5  0.0  -0.5
Hall & Kendall (2003)
Passive seismics

Depth (m)  Valhall Microseismicity
X (m)

Compaction failure type events

Shear failure type events
Tight-gas reservoir

Velocity predictions

Low friction

AVOA predictions

High friction

CiPEG Centre for Integrated Petroleum Engineering and Geoscience
In Salah CO₂

Gourmelen et al. (2011)
InSAR/geomechanical

- Inversion method
  - Poroelastic model (Geerstma, 1973)
  - Transient pore pressure (Dake, 2001)
  - Monte Carlo inversion (Cervelli et al. 2001)
  - Gibbs sampler for inversion statistics (Geman & Geman, 1984)

Data versus modeling

Parameter inversion

Gourmelen et al. (2011)
Current challenges

• Consistent method to handle anisotropy, fluid and stress effects
  • Need better rock physics models for multiphase fluids and patchy saturation
  • Need significantly more data sampling shallower depths between reservoir and surface

• Need to improve consistency:
  • Fractures and joints – we are attempting to resolve with GESER industry funded consortium
  • Scaling (static measurements to dynamic measurements) – significant knowledge gaps, but can apply site specific empirical relationships

• Microseismic and fracture modelling
  • Have developed some simple approaches that are qualitatively helpful
  • Seek to enhance FE continuum approach (can be quite complex)
  • Explore DEM approach – focus on linking microseismic to fracture development
Bigger challenges

- History match fluid-flow and geomechanical simulation models
- Larger database of rock and petro-physical properties:
- Systematic approach to build geomechanical models
  - Constitutive models (ie material properties)
  - Structure (ie geometry)
  - Meshing (ie gridding)
- Calibration of the models to work towards more accurate quantitative prediction