4D Gravity and Subsidence: a guiding light to cost-effective reservoir monitoring

Egypt-Norway Technology Days
Outline

• About OCTIO Gravitude

• The **principles** of the technology
  • 4D gravity
  • Whole-field subsidence monitoring

• Case studies: the **value** of gravity and subsidence

• Concluding remarks
About Octio Gravitude

- Value of the technology proven in many fields on the NCS
- Gravitude performed 8 surveys in 6 fields since 2012
  - Best results to date
  - Safe operations with no HSE incidents
  - Ormen Lange field (operated by Shell) surveyed since 2012
- Octio has ten years of operational experience
- Highly skilled technical team with diverse background
The surveys in a nutshell

Sensor frame with 3 gravimeters and 3 pressure sensors

Primary measurements: gravity and pressure at the seafloor

Concrete platform 20’ per measurement
Repeated visits

ROV
Gravity and subsidence monitoring on the NCS

<table>
<thead>
<tr>
<th>Field</th>
<th>1st survey</th>
<th># of surveys</th>
<th>Seafloor depth (m)</th>
<th>Reservoir depth (m)</th>
<th>Area (km²)</th>
<th>N. stations</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Troll</td>
<td>1998</td>
<td>6</td>
<td>320</td>
<td>1400</td>
<td>30 x 50</td>
<td>113</td>
<td>Norway’s largest gas field</td>
</tr>
<tr>
<td>Mikkel</td>
<td>2006</td>
<td>4</td>
<td>230</td>
<td>2500</td>
<td>3 x 12</td>
<td>21</td>
<td>Smaller, deeper reservoir</td>
</tr>
<tr>
<td>Sleipner</td>
<td>2002</td>
<td>4</td>
<td>80</td>
<td>800 / 2350</td>
<td>4 x 10</td>
<td>50</td>
<td>Gas production + <strong>CO₂ injection</strong></td>
</tr>
<tr>
<td>Ormen Lange</td>
<td>2007</td>
<td>5</td>
<td>295-1130</td>
<td>2000</td>
<td>15 x 50</td>
<td>120</td>
<td><strong>Second largest gas field in Norway</strong></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Challenging oceanography, Shell-operated</td>
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<tr>
<td>Statfjord</td>
<td>2012</td>
<td>2</td>
<td>140-200</td>
<td>2750</td>
<td>5 x 25</td>
<td>53</td>
<td>Oil field, subsidence is the main motivation</td>
</tr>
<tr>
<td>Midgard</td>
<td>2006</td>
<td>4</td>
<td>240-310</td>
<td>2500</td>
<td>10 x 20</td>
<td>60</td>
<td>Deep reservoir</td>
</tr>
<tr>
<td>Snøhvit / Albatross</td>
<td>2007</td>
<td>2</td>
<td>250-340</td>
<td>2500</td>
<td>20 x 20</td>
<td>86</td>
<td>Gas production + <strong>CO₂ injection</strong></td>
</tr>
</tbody>
</table>
Gravity for reservoir monitoring

- Sensitive to changes of density in the subsurface
- It allows monitoring movements of fluid interfaces. Example:

\[ \rho_{water} > \rho_{gas} \Rightarrow \Delta g > 0 \text{ observed} \]
  - Magnitude proportional to the raise of the contact

- Spatial distribution of \( \Delta g \) tells about compartmentalization, permeability, aquifer strengths
Some applications of gravity

- Unproduced compartments?
- Volume of gas in place?
- Acquifer strengths?
- Hydrocarbon
- Water
Accuracy of gravity at the seafloor

1 µGal means:

• $10^{-8} \text{ m/s}^2$, or $10^{-9} \text{ g}$, or 100 kg at 0.8 m

• Sub-meter sensitivity in a gas-water contact
Value of the gravity data

- Increased recovery
- Infill well planning
- Installation of compression facilities
- Planning of production, pipeline use

- Update actual volume of hydrocarbon reserves
- Prediction of water breakthrough
- Understanding reservoir behavior away from wells

Gravity
- Aquifer strength
- Lateral compartmentalization
- Reservoir parameters (e.g., permeability)

Seismic
Well data

• At a cost ~15% of that of time-lapse seismic
Subsidence

Measured through time-lapse changes in water pressure (after applying tide and environmental corrections)
The value of subsidence data

- Accuracy on subsidence (published values):
  - **Mikkel** 2006-2011 time-lapse: 2.5 - 3.7 mm
  - **Sleipner** 2002-2005 time-lapse: 2.3 mm
Survey setup

• Pressure and gravity measured at each of the concrete platforms (typically 20 minutes)

• Tide gauges deployed during the whole survey at a subset of stations
  • Allow to refer all pressure measurements to normal sea and atmospheric conditions
  • Enables comparison of data from different vintages

• In all:
  • **No storage issues:** < 2 Gb per survey
  • **Fast turnaround:** three months from survey to final report
  • Environmental friendly
Field cases
Troll 2002-2009: subsidence

Pore compressibility:
- Troll West PDO (1991): $\sim 80 \cdot 10^{-5}$/bar
- Revised core data (2000): $\sim 9 \cdot 10^{-5}$/bar
- Subsidence history-matching: $\sim 3 \cdot 10^{-5}$/bar

Maximum $\sim 1$ cm / year

Zero-level stations

Troll 2002-2009: 4D gravity

- Significant raise of ~2 m of the gas-water contact observed in some stations already in 2002-2005
- Time-lapse seismic lines shot in 2002 and 2006 showed no evidence of the raise yet
  - 5-10 m were required for it to be visible over effect of pressure drop
- Updated aquifer strengths in the reservoir simulation model

http://www.slideshare.net/Statoil/alnes-et-al-gravity-and-subsidence-monitoring

Mikkel 2006-2011: 4D gravity

- Initial uncertainties on:
  - External aquifers
  - Total volume of gas
- The system has low tolerance for water production due to risk of hydrate formation
- Results show lower water influx than expected
- Aquifer volume reduced by factor 4
- Mikkel contains more gas than expected
- This input enabled:
  - Better prediction of water breakthrough
  - Better long term planning

Midgard 2006-2012: 4D gravity and subsidence

• Uncertainties in the model:
  • Aquifer support and drainage patterns
  • Fault distribution and compartmentalization

• Learnings from 4D gravity and subsidence: one segment underproduced, indicating sealing faults
  • Reinterpretation of available seismic data
  • Updated reservoir model with the sealing fault as the most likely realization

• A new well target was identified, which is now number one producing well in all the Åsgard complex

Ormen Lange

- Increased recovery involved decisions on:
  - Compression facilities
  - Infill wells
- Water break-through and compartmentalization identified as a significant uncertainties
- Feasibility studies for measuring water influx:
  - Nearly impossible with 4D seismics
  - Would take > 7 years with EM
- Abstract submitted to EAGE 2017 with Gravitude and Shell authors

Dunn et al., A long-term seafloor deformation monitoring campaign at Ormen Lange gas field, first break volume 34, October 2016

Gravifetime’s feasibility studies

Define alternative scenarios reflecting:
• Uncertainties on reservoir model
• Value of the new information

Model the strength of 4D gravity and subsidence signals for each alternative scenario

Environment conditions
• Oceanography
• Seafloor quality

Requirements from installation safety on subsidence precision

Feasibility report
• Ability to distinguish reservoir scenarios
• Increased safety from subsidence monitoring
• Survey design and cost

Value of the gravity and subsidence data

Optionally
Conclusions

• 4D gravity - subsidence surveys provide:

  • Key information for reservoir management, e.g.
    • Movement of fluid contacts
    • Identification of non-producing compartments
    • Reservoir compaction
    • Information for whole-field – not only producing wells
  
  • Improved safety of the field and installations
Thank you

hugo.ruiz@octio.com