4C-OBS Experiment at Frøya Tunnel, central Norway

Preliminary Results
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Outline of presentation

Aim

Present preliminary results from multiple 4C-ocean bottom seismometers survey to delineate sediment units and variations in bedrock velocities in fjords

Introduction – 4C seismics

Tunnel experiment at Frøya

⇒ Data available
⇒ Review of field data acquired
⇒ Snapshots of 4C seismic data collected
⇒ Preliminary results from refraction tomography and ray-tracing
⇒ Converted waves: Simulations vs. the real world

Summary and looking ahead
Introduction – 4C seismics

**Pressure/Primary waves**
- Sense matrix + pore fluids
- Standard exploration practice (2D-4D)
- Refractions + reflections
- Recorded with hydrophones or geophones/seismometers

**Shear/Secondary waves**
- Sense matrix, less pore fluids
- Lower velocity, higher resolution
- Dynamic shear modulus
- Converted waves: downgoing P, upcoming S
- Requires seabed-coupled geophones/seismometers

\[ V_P = \sqrt{\frac{K + 4\mu/3}{\rho}} \]

\[ V_S = \sqrt{\frac{\mu}{\rho}} < V_P \]

\[ 2 \leq \frac{V_P}{V_S} \leq 20^+ \]

Source for animation: web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm
Introduction – 4C seismics
### Introduction – 4C seismics

**Integrated PP + PS/SS surveys (4-component)**

| Imaging: | Imaging through gas clouds  
| Sub-salt imaging  
| Sub-basalt imaging  
| Low-impedance contrast imaging  
| Improved fault mapping  
| Improved stratigraphy  
| Improved shallow resolution |

| Characterization: | Lithology characterization  
| Fluid characterization  
| Reservoir characterization  
| Anisotropy and fracture characterization  
| Geomechanical soil conditions |

| Quantification: | Micro-scale distribution  
| Shallow water flows  
| Fluid saturation  
| Gas and hydrates  
| Velocity-based pore pressure and effective stress estimation |

Seismic data: Caldwell et al., 1999; Southern China Sea
Survey preparation/design

**Aim**

Determine bedrock velocity (P and S) from 4C OBS arrays and airgun shots

- Area with (thin) sediment cover
- Refraction seismology

**Available data from target area**

- Bathymetry, from contour data received from SSV
- Refraction data: no field data received, P-wave velocity zonations/ranges
- Reports received from SSV

*Note: Projection conversion from ngo1948 akse2 to UTM32, WGS84*

**(Full-waveform) Simulations and Modelling**

- “forecast” seismic response from sub-surface using 1D and 2D soil model
- Investigate the influence of airgun submersion depth for refractions
- Assist in understanding the events occurring on time-domain data, in particular P-to-S converted waves
Location map – Frøya Tunnel

Source: Google maps...
Available data (not digital though)

Basin with sediment infill
Actual survey details

2-day active surveying
- 3 OBS arrays deployed (orange)
- 8 seismic lines shot
- 4 relocation “lines”
- Simultaneous acquisition of SC streamer data
- 2 airgun sources used (40 and 250 in³), flexible and efficient
- SC Reflection and Refraction

- Weather not perfect (currents, waves and wind)
- No dGPS on vessel

Data quality variable
Note: topography
**P-wave travel time analysis: refraction and tomography**

**Method:** 2D refraction tomography and ray-tracing (using ReflexW)
- FD approximation of Eikonal equation for wave propagation
- Tomography requires vertical velocity gradients in sub-surface
- Tomography: no layers are needed

**Procedure:**
- Picking of first arrivals on all OBS along given line
  - hydrophone and vertical component
- Ray-tracing through uniform velocity model (Vp = 5 km/s);
- Ray-tracing through preliminary velocity model based on geological map;
- 2D P-wave velocity tomography using data from 4 OBS instruments
Travel-time picks: QC

Data processing/editing prior to first arrival picking needed

⇒ first arrival waveform consistent up to 1.5 km from OBS instrument

⇒ Picking error = 1 sample (1 ms)
2D ray-tracing through uniform velocity model

Model parameters

- 2 layers with constant velocity
- Water body: 1500 m/s
- Bedrock: 5000 m/s
- “Smooth” bathymetry
2D ray-tracing through “geological” model

Model parameters
⇒ Basin infill and fractured zonations from geological maps
⇒ Coarse bathymetry (pre-survey)
**Ray-tracing results from all 4 OBS**

**Model parameters**
- Initial model: 2 layers with constant velocity
- Water body: 1500 m/s
- Bedrock: 5000 m/s
- “Smooth” bathymetry

**Results**
- Reasonable fit when using 4 travel-time curves
- “Smooth” bathymetry
Tests on 2D tomography sensitivity

Inversion parameters:
- Structural model from geological map (coarser bathymetry)
- Initial velocity model containing weak zones
- Inverted model similar to inverted model with no assumption, but data fit not as good
## Travel-times residuals – example along line A

<table>
<thead>
<tr>
<th>RMS values</th>
<th>Uniform model</th>
<th>Geological model</th>
<th>Inverted model</th>
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<tbody>
<tr>
<td>OBS 1</td>
<td>16.7</td>
<td>13.1</td>
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<td>OBS 4</td>
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<td>Four OBSs</td>
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Final model and data coverage

Preliminary Tomography Results

- Thicker sediment infill around OBS locations (basin)
- Lower velocities within fractured areas
- Depth of investigation in the order of 100 mbsl
Summary – Looking ahead

⇒ Multiple 2D 4C-OBS profiles successfully acquired along Frøya tunnel
⇒ P-wave refraction tomography reveals sedimentary basin and lateral variations in bedrock velocities
  → Sedimentary basin not included in starting model but well resolved
  → Well-constrained by deployment of 4 OBS units across basin
  → Using more OBS instruments would be helpful to constrain lateral velocity variations better
  → 3D topography within fjord and bedrock complicates matters

Looking ahead...
⇒ Refine P-wave refraction tomography and ray-tracing for all lines acquired
  → Match/compare at cross-points, pseudo-3D
  → Investigate the effect of dipping bedrock zonations (forward modelling)
  → Validation/cross-checking with tunnel data
⇒ The hunt for converted waves
Converted waves – Simulations vs. Field Data

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- PS-reflection/refraction?
- PP-refraction
- PPS-refraction
- Converted waves – Simulations vs. Field Data
- lineC-040901-x, wagc=.05
## Acquisition/Survey log

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