Permanent seismic source for continuous reservoir monitoring

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Reservoir Monitoring Consortium Semi-Annual Review meeting @ University of Southern California
• Geophysical reservoir monitoring
• New development of permanent active source (ACROSS)
• Numerical simulation test
• Field test
  - Awaji island (Japan)
  - Aquistore (Canada) on-going
• Summary
Geophysical reservoir monitoring is very important for optimized oil & gas development.

Repeatability of seismic-source is one of the most important aspects for success reservoir monitoring.

CO2-EOR

http://www.kgs.ku.edu/Publications/AnnRep05/05techniques.html
Conventional Seismic Sources

On Land

- Vibroseis
- Dynamite

Offshore

High repeatability is very challenging

- Surface condition may vary over time
- Accurate positioning is challenging
## Comparison of seismic source between conventional and ACROSS

<table>
<thead>
<tr>
<th></th>
<th>Vibroseis</th>
<th>Dynamite/Air gun</th>
<th>ACROSS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power of Source</strong></td>
<td>Good</td>
<td>Best</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Deployment</strong></td>
<td>Best</td>
<td>Best</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Control/Repeatability</strong></td>
<td>Medium</td>
<td>Medium</td>
<td>Best</td>
</tr>
<tr>
<td><strong>P &amp; S-wave</strong></td>
<td>Good</td>
<td>P-wave</td>
<td>Best</td>
</tr>
</tbody>
</table>
• Geophysical reservoir monitoring

• **New development of permanent active source (ACROSS)**

• Numerical simulation test

• Field test
  - Awaji island (Japan)
  - Aquistore (Canada) **on-going**

• Summary
JOGMEC together with Japanese seismologists have developed new permanent active source (ACROSS).

ACROSS is installed on the surface and fixed by concrete.

Very stable & repeatable seismic waves can be continuously excited by ACROSS.
Accurately Controlled Routinely Operated Signal System (ACROSS)

http://www.jogmec.go.jp/library/recommend_library_01_2.html
Accurately Controlled Routinely Operated Signal System (ACROSS)

- ACCURATE mass control by GPS (<100 μs accuracy)
- stacking over time to enhance S/N
- 10 year continuous operation (for fault slip prediction in Japan)
- 5-50Hz sweep frequency
Vertical/horizontal forces reconstructed

Eccentric mass

Diagram by courtesy of Hasada
• Up-sweep (180 s) + down-sweep (20 s) = 200s
• One cycle is continuously repeated over time
Sweep-type Wave: 1 hour

1 hour

Clockwise rotation 14 times x 200 sec

Counter-clockwise rotation

Frequency (Hz)

Time (sec)
3 weeks – continuous recording (Vertical component, by ACROSS vertical force) (3C-geophones)

Takanashi et al. (2014)
Beauty of stacking

\[ S/N \text{ greater by } \sqrt{\frac{19 \times 24}{2}} = 15 \text{ times} \]

19 days >> 2 hours

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Numerical Testing on ACROSS Monitoring: time-lapse elastic FWI

- Model of Ketzin, Germany (Kasahara et. al., 2012)
- CCS (Carbon Capture and Storage) pilot test
- Two ACROSS sources
- 50 3C-geophones on the surface (2D line)
- Elastic Full Waveform Inversion (FWI)

Takanashi et al. (2014)
P-wave velocity before injection

Two ACROSS
50 geophones on surface (40m spacing)  

Takanashi et al. (2014)
P-wave velocity after injection

Velocity decrease due to CO2 injection (200 m x 20m)

Takanashi et al. (2014)
Elastic FWI

- Continuous source operation over time
  \[ f(\omega) \]

- Differential data due to fluid replacement
  \[ \Delta d = H_2 - H_1 \]

- Elastic reverse time migration (gradient)
  \[ \mathbf{I} = \int u_s(x,t)u_r^*(x,t)dt \]

- Velocity update
  \[ \mathbf{p}^{(k+1)} = \mathbf{p}^{(k)} - \alpha^{(k)} \nabla \rho E^{(k)} \]
P-wave velocity difference: True Model

Vp decrease in true model = 0.45 km/s

Takanashi et al. (2014)
P-wave velocity difference: Elastic FWI result after 5 iteration

\[ V_p \text{ decrease in true model} = 0.45 \text{ km/s} \]

Takanashi et al. (2014)
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• Summary
Air-injection Test at Awaji island (Japan) in 2011.

- 80-ton air injection into 100m-deep layer
- About two weeks injection
- Two active seismic sources (ACROSS)
- 32 3C geophones on the surface
- one 3-C geophone at depth 800 m

80-ton air injection
Travel time and amplitude changes before and after injection

- One day after injection
- Maximum travel-time delay is up to 12 ms
- Amplitude changes

Kasahara et al. (2012)
Imaging: Back-propagation of Residual Wave

(Reverse time migration)

Kasahara et al. (2012)
Field Test2 : CCS Aquistore project (Canada)

- CO2 will be captured from a power plant and injected into 3,300m aquifer.
- Injection start : April 27 2015

http://www.rite.or.jp/news/events/pdf/White_20140123_RITE_CCS_WS.pdf
Geometry of Aquistore

[Diagram showing the layout of Aquistore with various geophysical equipment and infrastructure.]
Geometry of Aquistore

ACROSS-house

ACROSS

Observation Well

Power Plant

Injection Well
Synthetic study

Takanashi et al. (2015)
Across shot gather (two hours)

Takanashi et al. (2015)
Current and future work

• ACROSS is safely set up at Aquistore Site in Saskatchewan, Canada.

• Analysis of baseline data confirmed excellent repeatability of ACROSS shot gather and reflection from the injection target.

• JOGMEC continues to process the permanent array geophone data to remove the ACROSS signal to provide continuous passive data for 300+ geophones and three-component broadband receivers to PTRC/GSC.

• We will perform ACROSS operation during CO2 injection; the schedule will be discussed with PTRC and GSC.

• Time-lapse imaging will be performed using differential ACROSS data before and after CO2 injection for delineation of the CO2-injected zone.
Summary

- New seismic source (ACROSS) has been developed for permanent reservoir monitoring.

- Ultra-high repeatability of ACROSS enables suppression of any waveforms that do not change over time (potential capability of 3-4 km-deep reservoir monitoring).

- Numerical test (German) & Awajishima field test (Japan) showed promising results for ACROSS monitoring.

- CCS monitoring in Aquistore project (Canada) is on-going.
  - CO2 injection started since April 27

- Newly developed ACROSS monitoring system is planned to be applied into actual oil & gas fields.