Proof-of-Feasibility of Using Wellbore Deformation as a Diagnostic Tool to Improve CO2 Sequestration

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Developing the Technologies and Infrastructure for CCS
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Presentation Outline

• Preliminaries
• Current project status
• Plans

Improve characterization  Anticipate problems
Benefit to the Program

Measuring and interpreting casing deformation should improve the ability to characterize flow and geomechanical properties of injection zones and confining units, as well as help identify problems with wellbore integrity that could lead to leakage.

Program Goal:

✓ Develop technologies that will support industries’ ability to predict CO₂ storage capacity in geologic formations to within ±30 percent
✓ Develop technologies to demonstrate that 99 percent of injected CO₂ remains in the injection zones
Evaluate feasibility of using wellbore deformation as a diagnostic tool.

1. What deformation should be expected?
   – FEM analyses, Task 2
2. Can that deformation be measured?
   – Instrumentation assessment, Task 4
3. Can the measurements be interpreted?
   – Inverse analyses, Task 3
What can be measured? Task 4

Goal: Assess capabilities to measure deformation (components, magnitudes, rates) of wellbores under field conditions.

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Logistics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gladwin Borehole Strain Meter (BSM)</strong></td>
<td><strong>Clemson 5DX</strong></td>
</tr>
<tr>
<td>• 4 axis, horizontal</td>
<td>• 3D + shear</td>
</tr>
<tr>
<td>• &lt;0.001 με resolution</td>
<td>• ~0.1 με resolution</td>
</tr>
<tr>
<td>• Grouted in place</td>
<td>• Optical</td>
</tr>
<tr>
<td>• Tectonic strain</td>
<td>• Removable</td>
</tr>
<tr>
<td></td>
<td>• Well testing</td>
</tr>
</tbody>
</table>

**Clemson Tilt-X**
- Axial+tilt
- ~0.01 με resolution
- Electrical
- AGI tiltmeter
- Removable
- Well testing

**Baker WIRE**
- Multicomponent
- ~1 με
- Optical
- Outside casing

**In SAR**

**Geodetic GPS**
Field Test of *WIRE* in Belridge Field, California

from Roger Duncan, Baker Hughes

Baker *WIRE*
- Multicomponent
- \(\sim 1 \, \mu e\)
- Optical
- Part of casing
Strain Measurement Overview
Reference Values and Surface Methods

Based on *Plate Boundary Observatory Report* [1999]
Strain Measurement Overview

Borehole methods

Based on *Plate Boundary Observatory Report* [1999]
What deformation is expected? Task 2

Goal: characterize deformation in the vicinity of wellbores used for storage.

Injection, 1MPa, 6 lps ~100gpm, Axial symmetry
Aquifer: $k: 10^{-13} \text{m}^2$, $b$: 100m, $E$: 15GPa, $R = 30 \text{km}$
Confining: $k: 10^{-16} \text{m}^2$, $b$: 1000 m; $E$: 15GPa
Casing: $k$: 1nd; 8-inch, 8mm wall, $E$: 200GPa
Screen: $k$: $10^{-13} \text{m}^2$; 8-inch, 8mm wall, $E$: 200GPa
Response in Injection Well

Hydromechanical type curves

- Pressure (MPa)
- Radial displacement (microns/10)
- Axial Strain (microstrain/10)

1MPa
6 μm
4με

Vertical Profiles on Wellbore

- Reservoir
- Confining

- Radial Displacement (m)
- Axial strain

0 50 100 150 200
0 10 20 30 40 50

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Wellbore Integrity

Increase $k$
Increase $E$

$P$ injection, 1MPa
Confining: $k$: 10µD

$t = 10^4 s$
Sealed casing

Casing leak

Radial displacement (m)

Axial strain

$z = 5m$
$z = 0.5m$
Sealed
Leak

Time (sec)
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Magnitudes and Rates of Strain

1 km
Magnitudes and Rates of Strain
Expected Strain Rates and Measurement Capabilities

Based on Plate Boundary Observatory Report [1999]
How can measurements be interpreted? Task 3:

**Goals:** a.) Quantify ability of data to constrain model parameters, b.) assess how uncertainty in parameters translates into risks; c.) optimize methods for efficient large-scale reservoir characterization

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**Reservoir Parameters**

- Log10 Permeability [m²]
  - Iterations
  - Units: [m²]

**Geomechanical Signals**

- Pressure [Pa]
  - Time [s]

- Loading efficiency []
  - Iterations

- Displacement [mm]
  - Time [s]

**MCMC:** Good search of parameter space. Avoid traps in local minima.
MCMC + Genetic → Hybrid Optimization

- **MCMC**: Good coverage of parameter space
- **Genetic**: Good convergence
- **Hybrid**: Best of both
Applications
Data Location, Measurement Type, Heterogeneity

<table>
<thead>
<tr>
<th>Data Location</th>
<th>Measurement Type</th>
<th>Heterogeneity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional</td>
<td>Pressure</td>
<td>Tilt</td>
</tr>
<tr>
<td></td>
<td>Strain</td>
<td></td>
</tr>
</tbody>
</table>

Data (Observed + Fit)

- Pressure
- Strain
- Tilt

Iterations

- Estimated Parameters
- Formation: Log10 Young's modulus
- Formation: Log10 permeability
- Formation: Poisson ratio
Applications

Data Location, Measurement Type, Heterogeneity

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</table>

1 km

100m

100m

Data (Observed + Fit)

Pressure

Strain

Tilt

Iterations

Estimated Parameters

Formation: Log10 Youngs modulus

Formation: Log10 permeability

Formation: Poisson ratio
Applications
Data Location, Measurement Type, Heterogeneity

Pressure
Tilt
Strains (3)
- radial
- vertical
- circumferential

Cap rock Data
Applications

Data Location, Measurement Type, Heterogeneity

Regional Data

Pressure
Tilt
Strains (3)
- radial
- vertical
- circumferential

Formation Data (far)

Formation: Log10 Youngs modulus
Formation: Log10 permeability

Heterogeneity: Log10 permeability
Heterogeneity: Distance

Cap rock: Pressure
Cap rock: Vertical strain
Cap rock: Radial strain
Cap rock: Circumferential strain
Cap rock: Tilt meter: grad uz

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## Status of Inverse Analyses

<table>
<thead>
<tr>
<th>Measurement Type</th>
<th>2D</th>
<th>3D</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure vs. Geomech</td>
<td>X</td>
<td></td>
<td>Geomechanical data constrains parameters better than pressure alone, combination is best</td>
</tr>
<tr>
<td>Strain versus tilt</td>
<td>X</td>
<td></td>
<td>Strain data constrains better than tilt meter, combination is best</td>
</tr>
</tbody>
</table>

### Data Location

<table>
<thead>
<tr>
<th>Location</th>
<th>2D</th>
<th>3D</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir</td>
<td>X</td>
<td></td>
<td>Instruments in reservoir can constrain parameters</td>
</tr>
<tr>
<td>Caprock</td>
<td>X</td>
<td></td>
<td>Instruments in cap rock can constrain parameters</td>
</tr>
<tr>
<td>Well Bore</td>
<td>X</td>
<td></td>
<td>Forward model ready</td>
</tr>
</tbody>
</table>

### Heterogeneity

<table>
<thead>
<tr>
<th>Type</th>
<th>2D</th>
<th>3D</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial Contact</td>
<td>X</td>
<td></td>
<td>Geometry and physical parameters constrained</td>
</tr>
<tr>
<td>Compartmenal Fault</td>
<td>X</td>
<td></td>
<td>Can identify model error, investigating non-uniqueness of parameters</td>
</tr>
<tr>
<td>Leaky Fault</td>
<td>X</td>
<td></td>
<td>Investigating non-uniqueness of parameters</td>
</tr>
<tr>
<td>Channel Heterogeneity</td>
<td>X</td>
<td></td>
<td>Geometry and physical parameters constrained</td>
</tr>
<tr>
<td>Channel Heterogeneity</td>
<td>X</td>
<td></td>
<td>Forward model ready</td>
</tr>
<tr>
<td>Stresses on Fault</td>
<td>X</td>
<td></td>
<td>Forward model under development</td>
</tr>
</tbody>
</table>
Accomplishments to Date

• Measurement
  • Instruments to measure axial, radial, 3D
  • Resolution/Logistics: $1 \mu\varepsilon \rightarrow 0.001 \mu\varepsilon$
  • Demonstrated in the field

• Analyses
  • Benchmarks, Verification, 2D axial, 3D
  • Patterns of deformation; Magnitudes: ~ $1 \mu$m, strain: ~$1 \mu\varepsilon$, strain rate: measurable
  • Sensitivity, Uncertainty analysis; factor of $2 \sim 3$

• Interpretation
  • MCMC 1 chain, Analytical, numerical
  • MCMC multi-chain, HPC
  • MCMC/Multiobjective genetic algorithm $\rightarrow$ hybrid
  • Parameters constrained with geomechanical data
  • Parameters constrained with shallow cap rock observations
  • Heterogeneities identified, parameters and geometry constrained
Summary

– Key Findings
  • Expect $\mu m/\mu$ε-scale displacements
  • Possible to measure magnitudes and rates
  • Interpretation appears feasible
    – Remote sensing of change in pressure
    – Formation properties, heterogeneities, geomechanics
    – Leakage, casing integrity

– Future Plans
  • Forward analyses; reservoir structure, casing-cement-formation
  • Instrument evaluation; multi-axis strain
  • Hybrid optimization; wellbore, heterogeneities, non-uniqueness, real field data
Radial Displacement

Open Hole and Cased Hole

TOTAL
- P in casing, elastic load
- P in frm, poroelastic load

Poroelastic only
- No Pressure in Casing

Elastic only
- No pressure in formation

Radial displacement (micron)

r-coordinate (m)
What deformation is expected?

Task 2

Goal: characterize deformation in the vicinity of wellbores used for sequestration.

- Benchmark simulations
  - FLAC, Abaqus, Comsol, GMI Wellcheck…

- Response Scenarios
  - Reservoir types
  - Heterogeneities
  - Wellbore completion
Applications

Data Location, Measurement Type, Heterogeneity

Regional

Pressure
Tilt
Strain

Iterations

Formation: Log10 Youngs modulus

Formation: Log10 permeability

Heterogeneity: Log10 permeability

Heterogeneity: Distance

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Applications
Data Location, Measurement Type, Heterogeneity

Regional

Pressure
Tilt
Strains (3)
  - radial
  - vertical
  - circumferential

Data Cap rock Formation - radial - vertical - circumferential

Formation: Log10 Young's modulus

Formation: Log10 permeability

Formation: Poisson ratio

Cap rock: Pressure
Cap rock: Radial strain
Cap rock: Vertical strain
Cap rock: Circumferential strain
Cap rock: Tilt meter, grad U/V

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