CHARACTERIZING AND INTERPRETING THE IN SITU STRAIN TENSOR DURING CO₂ INJECTION

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Strain from Fluid Injection/Recovery

Earthquakes (red) and injection wells (grey)

Damaged home, Prague, OK

Deformed well casing

Strain field in the vicinity of an injection well

Subsidence, Central Valley CA
Project Overview
Goals and Tasks

**Goal:** evaluate how subsurface strain measurements can be used to improve the assessment of geomechanical properties and advance an understanding of geomechanical processes that may present risks to CO₂ storage.

**Tasks**
1. Instrument Development
2. Theoretical Analysis
3. Field Demonstration

**Outline**
- Technical Status
- Accomplishments
- Lessons Learned
- Synergy
- Summary
Instrument Development

- Multiple components of strain, tilt vector
- Geodetic resolution (~$n\varepsilon$, $n\text{rad}$)
- Cost

→ Prototypes
  - Removable multicomponent
  - Expendable, grout-in multicomponent
  - Expendable single component, cheap
Instrument Development

Grout-In Eddy Current System
- Commercial sensor integration
- 2 tilts, 3 horizontal & 1 vertical strain
- ~1 part-per-billion resolution

Volumetric Optical Interferometer
- Pair of 220 m wrapped fibers
- Welded exterior, fully potted interior
- ~1 part-per-trillion resolution
Instrument Deployments

Local Field Site (Clemson, SC)

- Tensor & Tilts
- Volumetric

Injection Analog Site (Avant, OK)

- Gladwin Tensor
- Tensor & Tilts
- Volumetric
Instrument Development

M 7.7 - 198km ESE of Nikol’skoye, Russia

Teleseisms on tensor strainmeter
(Avant, OK)

Tides on volumetric strainmeter
(Clemson, SC)

M 7.7 - 198km ESE of Nikol’skoye, Russia

Teleseisms on volumetric strainmeter
(Clemson, SC)
Field Experiment

- **Objective**: Measure/interpret strain during waterflood as analog to CO2 injection
- **Location**: Bartlesville Sandstone, Pennsylvanian North Avant Field, Osage County, OK
  100+ years of oil production

Inola Limestone Marker

Bartlesville Sandstone

HEC facies 1000 mD

Savanna Shale

Brown Limestone

Stratigraphic Conceptual Model

HEC Analog
Rakaia River, NZ

Permeable sand isopach
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Well 9A Test Site
Avant Field, Oklahoma

Injection
Well 9A

500m

P monitoring

Injection

strainmeters

Monitoring well

AVN3
AVN2
AVN4
Injection Test at 9A

- **Observed**
  - Areal strain
  - Circumferential strain
  - Radial strain
  - Pore pressure

- **Simulated**
  - Areal strain
  - Circumferential strain
  - Radial strain

**Graphs**
- Time (hours since injection)
- Pressure (kPa)
- Nanostrain
- Nanostrain x3

**Legend**
- $p_{observed}$
- $e_{RR}$
- $e_{circum}$
- $e_{area}$

**Map**
- Injection point at 9A
- AVN strainmeters
- Injection Test at 9A

**Notes**
- 500m
- 5000m
- 10
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Shut-in Test at 1A

500 m

Nanostrain

Time (days of 2017)

Nanostrain

Time (d)
Inversion Approach

Space Filling
• Monte Carlo
• Sparsest sampling (Voronoi)

High Efficiency Minimization (Exploitation)
• Delayed rejection sampling
• Genetic Algorithms (NSGAII, SPEA2) - global
• Gradient descent – local

Uncertainty Evaluation (Exploration)
• Markov chain Monte Carlo (McMC)
• Reversible jump McMC
Avant Field Forward Model

- **Code:** Poroelastic, single phase, FEM, GeoCentric (Josh White)
- **Geometry:** Depth, thickness, wells from site data
- **Mesh generation:** Automated scripts with 30+ wells
- **Heterogeneities:** Idealized lens similar to known features
- **Data:** Strain at 3 shallow locations representing strainmeters

![Image of model with strainmeters and permeable lens]
Locating Permeable Lens using data from 3 shallow strainmeters

1. Space filling algorithms (eg Voronoi) begin by running simulations with diverse set of zone geometries

1. Delayed rejection algorithm selects best data-fits and runs simulations with similar geometries
Accomplishments to Date

- Instruments
  - 4 new strainmeters designed, built, deployed, working
  - Gladwin strainmeter deployed, working
  - Data available, https://www.unavco.org/instrumentation/networks/status/pbo/overview/AVN2
  - Removable instrument under development

- Analyses
  - Cloud-based optimization method developed
  - Inversion of synthetic field case promising

- Field demo
  - Gladwin, volumetric, tensor strainmeters working at Avant Field
  - 3 pressure transducers deployed, measuring ambient
  - Brief injection test
  - Shut-in detected, field operation may be used to characterize
Lessons Learned

Technical
  Coupling to rock
  Grouting
  Calibration

Logistics
  Well field operation
  Accessibility
  Land owner, mineral rights

Communication
  Multiple PIs, Industry partners
Synergy Opportunities

- Strain monitoring demonstrations at other sites
- Other monitoring methods at Avant Field site
- Oklahoma earthquakes
- Stress change
Measure and interpret strain tensor during injection

--Instruments
  • high rez, removeable, grout-in, volumetric
  • Prototypes built, installed, working. Data available

--Analysis
  • Cloud-based inversion method
  • Application using synthetic data looks good

--Field demo
  • Working strainmeters at Clemson site, Avant Field site
  • Preliminary data from injection encouraging
  • Longer injection tests August-January
  • Fluid handling operations may be used for characterization
Two-Axis Tiltmeter

- Crossed flexure hinge design
- Re-zero sensors w/actuator:
  - Removable: $\pm 4.2^\circ$
  - Expendable: $\pm 12.9^\circ$
- 0.17 m baseline, $\sim 5$ s free period
- Differential eddy current sensors
  $\sim 0.1$ nm for nrad resolution
Scott update of instruments

Fiber instrument
Volumetric and casing
Permeable Channel Identification

Preliminary Avant field inversion:
- Uses synthetic strainmeter data to locate permeable zone representing a channel

- \( Z = 0 \text{m (ground surface)} \)
- \( Z = -100 \text{m (strainmeters)} \)
- \( Z = -500 \text{m (rectangular zone)} \)
Inversion Methods

Workflow

• **MySQL**: Centralized, long-term storage of highly-structured dataset

• **Python**: Inverse methods, mesh generation scripts, simulation post-processing, visualization

• **SQS/S3**: Temporary cloud storage for efficient distribution of input files to decentralized pool of compute nodes
Benefit to the Program

Project Goal evaluate how subsurface strain measurements can be used to improve the assessment of geomechanical properties and advance an understanding of geomechanical processes that may present risks to CO2 storage.

Carbon Storage Program goals
• support industry’s ability to predict CO2 storage capacity in geologic formations to within ±30 percent.
• Develop and validate technologies to ensure for 99 percent storage permanence

Contribute to Area of Interest 1 – Geomechanical Research by developing and demonstrating innovative instrumentation and theoretical techniques for characterizing the strain field resulting from injection (Research Need 3)
Theoretical Analysis

- **Numerical**: strain field in various scenarios, Avant Field demo
- **Analytical**: new solution of 3D poroelastic inclusions
- **Inversion**: New algorithm to enhance efficiency on many processors, move to cloud
Test Deployment Spectra

- Loosely coupled to surface
- Clear free period signal
  - Remove using deconvolution
- Large 1 cycle-per-day (CPD)
  - Thermoelastic
  - Barometric

- Uncoupled from surface
- Analog/Digital converter noise
  - Resolution limit of sensor and A/D
- Also 1 cycle-per-day (CPD)
  - Barometric
  - Residual temperature?

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Field Sites

Avant Field
North of Tulsa, Oklahoma
Sedimentary rock

Clemson Site
western South Carolina
Saprolite over xtln rock
Strainmeter Installation
North Avant Field, Sept 2016
Project Overview: Goals and Objectives

• **Overall Goal:** evaluate how subsurface strain measurements can be used to improve the assessment of geomechanical properties and advance an understanding of geomechanical processes that may present risks to CO2 storage.

  – **Instrument Development Task** Design/build instrumentation for measuring the in-situ strain tensor and evaluate performance characteristics relative to the existing state of the art.

  – **Theoretical Analysis Task** Develop theoretical analyses for characterizing the strain field associated with injection in the vicinity of critical features, such as contacts and faults, and then develop and demonstrate innovative methods for inverting these data to provide a quantitative interpretation.

  – **Field Demonstration Task** Demonstrate the best available strain measuring instrumentation during a field injection test, interpret the result data, and compare the interpretation with currently available information.