Area of Interest 1: Geomechanical Research

Development of Geomechanical Screening Tools to Identify Risk: An Experimental and Modeling Approach for Secure CO₂ Storage

DE-FE0023314

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The University of Texas at Austin
Presentation Outline

1. Benefit to the Program
2. Goals and Objectives
3. Technical Status from Tasks 2 to 6
4. Accomplishments to Date
5. Synergy Opportunities
6. Summary
Benefit to the Program

- Develop a **Geomechanical Screening Tool** to Identify Risk
  - Experimental & Modeling Approach for Secure CO$_2$ Storage
Project Overview: Goals and Objectives

- Develop a screening tool for improved understanding of geomechanical effects associated with CO₂ injection
- Derive a workflow from experimental and computational studies conducted for specific CO₂ sites, e.g. Frio, Cranfield

Task 1  Project management (M.F.W.–lead)

Task 2  Conduct laboratory experiments for hydro-mechanical rock properties (N.E.–lead)

Task 3  Upscale to bridge from laboratory to field scales (M.F.W.–lead)

Task 4  Extend simulator capability to model CO₂ storage field scale studies (M.D. and M.F.W.-lead)

Task 5  Perform parameter estimation & uncertainty quantification (M.F.W.–lead, S.S.–consultant)

Task 6  Integrate results to generate geomechanical screening tool / workflow (M.F.W.–lead, S.S.–consultant)
Task 2.
Conduct Laboratory Experiments for Petrophysical & Hydro-mechanical Rock Properties
(N. Espinoza—lead)
Task 2: Laboratory Experiments

**Objectives**

Complete modeling, perform reservoir simulations, and analyze geological uncertainty for two CO₂ storage field studies (Frio, TX & Cranfield, MS)

1. Measure mechanical properties
2. Collect other existing data (seismic, well logs, etc.)
3. Measure other reservoir rock properties and corroborate with field data

Site 1: Cranfield, Mississippi
(Source: DOE Cranfield Fact Sheet)

Site 2: Frio pilot study, Texas
Large Axisymmetric Triaxial Frame Connected to ISCO Pumps for Fluid Injection

- Experimental setup

1. Sample mounted on the loading frame
2. Data acquisition
3. Cylinders & pumps for flow system connected to the triaxial cell
Mechanical properties of Cranfield Tuscaloosa sandstones

From monitoring well 31F-3: 2 vertical (38V and 30V), 1 horizontal (26H), and caprock samples

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>3189.9</th>
<th>3192.9</th>
<th>3188.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_{loading} [GPa]</td>
<td>1.59</td>
<td>6.01</td>
<td>5.74</td>
</tr>
<tr>
<td>E_{unloading} [GPa]</td>
<td>8.07</td>
<td>22.04</td>
<td>6.70</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.31</td>
<td>0.28</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Ratio between Static/Dynamic: 0.24 (loading) and 0.56 (unloading)

\[ S_{h min} = \frac{\nu}{1 - \nu} S_{vert} + \alpha_p \frac{(1 - 2\nu)}{(1 - \nu)} P_p - \frac{E}{1 - \nu^2} \varepsilon_{CO2} \]

Biot coefficient < 1

Induced from CO₂ chemomechanical alteration
History match of Frio Pilot test using laboratory geomechanical properties in IPARS

Accurate measurements of rock compressibility by laboratory experiment under in-situ condition

\[ C_p = \frac{1}{V_p \Delta P_p} = \frac{\Delta \varepsilon_{vol}}{\Delta P_p} = 6.3 \cdot 10^{-6} \text{ psi}^{-1} \]

Reservoir properties and geomechanical properties assimilated into reservoir model

History match results
Cumulative amount of CO₂ injection without causing fault reactivation (red line) or hydraulic fracture at the injector (blue line) as a function of injection rate assuming closed reservoir compartments. Green triangles show actual cumulative CO₂ injection volume and injection rates attained in the field during the first Frio pilot test.
Task 3.
Upscale by Completing Bridge from Laboratory to Field Scales
(M.F. Wheeler–lead)
Task 3: Bridge from Laboratory to Field

Objectives

- Upscale measured rock properties (fluid flow & geomechanics) to scale relevant to field processes

- Development of **homogenization** schemes combining numerical and analytical approaches

- Particular emphasis will be put on including **natural fractures** in effective properties and localization effects

- Obtain field scale constitutive parameters to perform **coupled fluid flow and geomechanical** numerical simulation

\[
\sigma = C \varepsilon - \alpha p_c I \\
\varphi = \frac{p_c}{N + \alpha \varepsilon_V}
\]
Adaptive Homogenization for Upscaling

• Problems Statement
  – Computationally prohibitive to incorporate multiscale property data from well-logs, geological models and parameter estimation

• Objective
  – A computationally efficient general upscaling framework
  – Extension to general non-linear multicomponent, multiphase flow problems

• Strategy
  – Adaptive mesh refinement for accuracy with local upscaling for computational efficiency

• Novelty
  – Preserves accuracy at the saturation/concentration front
  – Can incorporate more complex fluid flow and phase behavior descriptions with relative ease
Benchmark Homogeneous Case

- Tracer slug injection and transport in a homogeneous medium
- Verify adaptive mesh refinement
- Three comparison
  - Fine scale
  - Coarse or homogenized
  - Adaptive with fine and coarse
- Space (Adaptive 2) and time gradient (Adaptive 2) as adaptivity criteria
Tracer Transport: Heterogeneous Porous Media

- SPE10 comparative project dataset: layer 37
  - Highly channelized permeability distribution
- Tracer slug injection and transport in a heterogeneous medium
- Computational speedup: 4X with adaptive homogenization
- Comparison
  - Concentration profiles
  - Tracer concentration production history
Tracer Transport: Heterogeneous Porous Media

- Adaptivity criteria
  - Space gradient based criteria performs better
- Comparison
  - Concentration profiles do not show substantial differences
  - Tracer concentration production history shows the differences
Multiphase Flow: Heterogeneous Porous Media

- Multiphase flow
  - Two-phase oil/water, air/water
  - Three-phase black oil
- Computational speedup: 3.5X with adaptive homogenization
- SPE10 comparative project dataset: layer 20
  - Gaussian permeability distribution
Multiphase Flow: Heterogeneous Porous Media

- Oil Rate (STB/day)
  - Time (days)
  - Rate (STB/day)
  - Fine
  - Adaptive
  - Coarse

- Cumulative Oil Production (STB)
  - Time (days)
  - STB
  - Fine
  - Adaptive
  - Coarse

- Sw at time 50 days
  - x
  - y

- Fine Permeability Distribution
  - Coarse Permeability Distribution
Task 4.
Simulator Development and Modeling CO$_2$
Storage Field Scale Studies
(M. Wheeler–lead)
Task 4: Simulator Development

Objectives

Complete simulator development with numerical schemes for coupled processes

- Develop computational methods for coupled processes based on multiscale discretization for flow, geomechanics & hysteresis
- Development of efficient solvers & pre-conditioners
- Model CO₂ storage field sites and perform simulations
Cranfiled Numerical Model

X-Permeability

Relative Permeability - Capillary Pressure (Delshad et al, 2013)

<table>
<thead>
<tr>
<th>Numerical Model of Cranfield field test</th>
<th>PVT data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Type</td>
<td>CO₂</td>
</tr>
<tr>
<td>Reservoir size</td>
<td>547.56</td>
</tr>
<tr>
<td>Number of grid blocks</td>
<td>1070.4</td>
</tr>
<tr>
<td>Initial water saturation</td>
<td>0.255</td>
</tr>
<tr>
<td>Initial pressure</td>
<td>0.224</td>
</tr>
<tr>
<td>Initial temperature</td>
<td>44.01</td>
</tr>
<tr>
<td>Salinity</td>
<td>-0.19</td>
</tr>
<tr>
<td></td>
<td>0.09</td>
</tr>
</tbody>
</table>
Injection Scenarios

- Continuous CO₂ injection
  
  16 yrs CO₂ injection

- Water Alternating Gas (WAG)

  20 years in total, 16 years of CO₂ injection

  4 yrs CO₂  1 yr water  3 yrs CO₂  1 yr water  3 yrs CO₂  1 yr water  3 yrs CO₂  1 yr water

- Surfactant Alternating Gas (SAG-foam)

  20 years in total, 16 years of CO₂ injection

  4 yrs CO₂  1 yr surfactant  3 yrs CO₂  1 yr surfactant  3 yrs CO₂  1 yr surfactant  3 yrs CO₂  1 yr surfactant
Simulation Results (CO\textsubscript{2} Saturation)

Continuous CO\textsubscript{2} Injection

Top view

Bottom view

Water Alternating Gas (WAG) – without Hysteresis Modeling

Top view

Bottom view
Simulation Results (CO$_2$ Saturation)-Cont’d

Water Alternating Gas (WAG) – with Hysteresis Modeling

Surfactant Alternating Gas (SAG) – Foam
Summary of Results (Field Statistics)

- In continuous CO$_2$ injection, 34% of the total injected CO$_2$ does NOT store inside the selected sector model and is produced through the boundaries.
- CO$_2$ lost from reservoir boundaries decreases from 34% to 19% and 10.1% using WAG and SAG processes, respectively.

<table>
<thead>
<tr>
<th>Injection Scenario</th>
<th>CO$_2$ injection</th>
<th>WAG w/o hysteresis</th>
<th>WAG with hysteresis</th>
<th>SAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field average CO$_2$ concentration</td>
<td>0.24</td>
<td>0.22</td>
<td>0.28</td>
<td>0.31</td>
</tr>
<tr>
<td>Cum CO$_2$ injected (MMscf)</td>
<td>2.10E+05</td>
<td>2.10E+05</td>
<td>2.10E+05</td>
<td>2.03E+05</td>
</tr>
<tr>
<td>Cum CO$_2$ lost from boundaries (MMscf)</td>
<td>7.15E+04</td>
<td>8.19E+04</td>
<td>4.00E+04</td>
<td>2.05E+04</td>
</tr>
<tr>
<td>CO$_2$ lost from boundaries (%)</td>
<td>34</td>
<td>39</td>
<td>19</td>
<td>10.1</td>
</tr>
</tbody>
</table>

- In continuous CO$_2$ injection, 34% of the total injected CO$_2$ does NOT store inside the selected sector model and is produced through the boundaries.
- CO$_2$ lost from reservoir boundaries decreases from 34% to 19% and 10.1% using WAG and SAG processes, respectively.
### Geomechanical Effects of CO₂ Injection with a Poro-plasticity Model

| Fluid Flow | \[
\frac{\partial(\rho(\phi_0 + \alpha\varepsilon_v + \frac{1}{M}(p - p_0)))}{\partial t} + \nabla \cdot \left( \frac{K}{\mu} (\nabla p - \rho g \nabla h) \right) - q = 0
\] |
| Stress Equilibrium | \[
\nabla \cdot (\sigma'' + \sigma_o - \alpha(p - p_0)I) + f = 0
\] |
| Hooke’s law | \[
\sigma'' = D^e : (\varepsilon - \varepsilon^p)
\]  | Druker-Prager Yield Surface |
| Strain-Displacement Relation | \[
\varepsilon = \frac{1}{2}(\nabla u + \nabla^T u)
\] |
| Plastic Strain Evolution | \[
\varepsilon^p = \lambda \frac{\partial F(\sigma'')}{\partial \sigma''}, \quad \text{at } Y(\sigma'') = 0
\]
\[
\varepsilon^p = 0, \quad \text{at } Y(\sigma'') < 0
\] |
| Yield and Flow Functions | \[
Y = q + \theta \sigma_m - \tau_0
\]
\[
F = q + \gamma \sigma_m - \tau_0
\] |
With plasticity, we have observed permanent deformations after loading/unloading. Compared discretely meshed-in well versus Peaceman.

Ran Cranfield simulations to compare results with compositional flow, linear elasticity, and plasticity models.

History Matching Results using various physical models.
Task 5.
Parameter Estimation & Uncertainty Quantification
(M.F.W.—lead, S. Srinivasan—consultant)
Task 5: Uncertainty Quantification

Objectives
Update input parameters for numerical models, e.g., simulated responses match observations

A Priori Model
(k, md)

Multi-modal histogram of permeability

History Matching

Gaussian histogram of Level-set parameters

A Posteriori Model
(k, md)

Multi-modal histogram of permeability

Task 5
History Matching Coupled with Level-Set Parameterization, MFDFrac, and EnKF

1 Initialization
- Generate initial fractured realizations

2 Level-Set Parameterization
- Convert non-Gaussian to Gaussian parameters
  - $\Phi$: level set at the node
  - $r$: fracture length
  - $\theta$: fracture orientation

3 Simulation using MFDFrac
- Mimetic Difference Approach

4 Inverse Modeling using EnKF
- EnKF for updating Gaussian parameters
  - Ensemble mean of initial fracture realizations
  - Ensemble mean of final fracture realizations
## History Matching Coupled with Level-Set Parameterization, MFDFrac, and EnKF

### 1 Lab-scale Sandpack

- **1 fracture**
- **1 injector**
- **4 producers**

### 3 Prior Models

<table>
<thead>
<tr>
<th>1st</th>
<th>100th</th>
</tr>
</thead>
</table>

### 2 Observed Lab Data

**Water Production Rate**

- production rate
- producer
- injector
- closed wells

### 4 Posterior Models (History-matched)

<table>
<thead>
<tr>
<th>1st</th>
<th>100th</th>
</tr>
</thead>
</table>

(Jing et al., 2016)
History Matching of a Fractured Reservoir: at the Well KB-503 in the In Salah CCS Field

<table>
<thead>
<tr>
<th>Vertical Displacement</th>
<th>Global-Objective Optimization</th>
<th>Multi-Objective Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Observed data = InSAR (vertical displacement resulting from CO₂ injection)</td>
<td>• After history matching, high permeability regions were obtained near all three CO₂ injection wells.</td>
<td>• After 4-objective history matching, permeability values were lowered near KB-501 and KB-503 wells.</td>
</tr>
<tr>
<td>• Simulator: CMG-GEM</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Nwachukwu et al., 2016; Min et al., 2016)

Injector KB-503

Injector KB-502

Oil producer

Injector KB-501

Injector KB-503

Permeability (md)

Injector KB-502

Oil producer

Injector KB-501

Gas producer

CO₂ injector

Abandoned
**History Matching of a Fractured Reservoir**: at the Well KB-503 in the In Salah CCS Field

<table>
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</thead>
<tbody>
<tr>
<td>• InSAR: satellite measured vertical displacement resulting from CO₂ injection&lt;br&gt;• Simulator: CMG-GEM</td>
<td>• High permeability near the KB-503 well yielded underestimated BHP compared to observed BHP.</td>
<td>• Low permeability near the KB-503 well improved the matching quality of BHP.</td>
</tr>
</tbody>
</table>

(Nwachukwu et al., 2016; Min et al., 2016)
Task 6.
Integrate Results to Generate Geomechanical Screening Tool/Workflow
(M.F.W.–lead)
Task 6: Geomechanical Screening Tool

Objectives
Derive a workflow based on project tasks performed - experimental and numerical investigation of geomechanical processes, effects, & conditions related to CO₂ storage and analysis of two CO₂ storage field case studies.

- Geomechanical laboratory Measurements (Task 2)
- Scale-up to field scale Variability (Task 3)
- Coupled hydro-chemical-mechanical modeling (Task 4)

Calibration to field scale observations (Tasks 2, 3, 4, 5)
Parameter estimation & uncertainty quantification (Task 5)

Sensitivity analysis & risk assessment
Development of a Multiple Model Optimizer: IRMS (Integrated Reservoir Management S/W)

All products of the tasks are being integrated with CSM’s IPARS for Subsurface Modeling

### OS
- Scientific Linux
- Windows

### Algorithm
- Global-objective genetic algorithm
  - GA.exe
- Global-objective evolution strategy
  - ES.exe
- Multi-objective genetic algorithm
  - NSGA-II.exe
- Multi-objective evolution strategy
  - ε-MOES.exe

### Simulator
- Schlumberger
  - ECL
- CMG
  - IMEX
  - BEM
  - STARS

### Run
- Parallel
  - Start
  - Evaluate model
  - Evaluate model
  - ... Stop
- Serial
  - For i=1:N Evaluate model
  - Stop

### Storage
- Supercomputer
- PC
Road Ahead

- CO₂ storage volume increased by 15% and 24% of total CO₂ injection volume during WAG and SAG processes, respectively.
- It is essential to model relative permeability hysteresis during cyclic processes (WAG, SAG here) to capture the physics of the problem more accurately.
- During SAG process, foam is created at the high permeability streaks and upper layers with higher CO₂ flow rates and diverts the CO₂ flow into low permeability regions and bottom layers leading to more efficient areal and vertical sweep efficiencies.
- Optimization of WAG and SAG processes using advanced optimization toolbox
  - Genetic Algorithm (GA)
  - Evolutionary Strategy (ES)
  - Ensemble Kalman Filter (EnKF)
Accomplishments to Date

• Task 2
  – Hydro-mechanical rock properties for Frio and Cranfield rocks
  – History matching for Frio field combining laboratory experiments and field data
• Task 3
  – Handle multiscale data: well-logs, geological models, and laboratory experiments
  – General upscaling framework using adaptive homogenization
• Task 4
  – Multiphase hysteretic relative permeability model for capillary trapping
  – Poroelastoplastic model for reservoir deformation
  – CO2 foam injection for high storage capacity
• Task 5
  – History matching for Cranfield
  – General multi-objective optimization framework
Synergy Opportunities

Assistance in Decision Making
• Assist in selection of suitable sites for safe CO₂ storage using generalized S/Ws based on a posteriori knowledge

Interdisciplinary Collaboration
• Enhance understanding of the effects of CO₂ migration on open and closed faults and fractures

Training & Education
• Support training and education of students who will take part in an interdisciplinary work, e.g. IPARS tutorial

Contribution to Identifying Geological Risk for Secure CO₂ Storage!
Acknowledgements

Thank you for your attention

Contact: mfw@ices.utexas.edu
# Organization Chart

## Project Director

**M.F. Wheeler**

### Task 1
**Management**
- Task Leader: M.F. Wheeler
- Key Personnel:
  - M. Delshad
  - S. Srinivasan
  - N. Espinoza
  - ½ Postdoc
  - 1 Student (Y 1&2)

### Task 2
**Laboratory Program**
- Task Leader: N. Espinoza
- Key Personnel:
  - M. Delshad
  - S. Srinivasan
  - N. Espinoza
  - ½ Postdoc
  - 1 Student

### Task 3
**Bridging between Laboratory and Field Scales**
- Task Leader: M.F. Wheeler
- Key Personnel:
  - M. Delshad
  - S. Srinivasan
  - N. Espinoza
  - ½ Postdoc
  - 1 Student

### Task 4
**Modeling and Field Studies**
- Task Leader: M. Delshad
- Key Personnel:
  - M. Delshad
  - S. Srinivasan
  - N. Espinoza
  - ½ Postdoc
  - 1 Student (Y 3)

### Task 5
**Uncertainty Quantification and Parameter Estimation**
- Task Leader: M.F. Wheeler
- Key Personnel:
  - M. Delshad
  - S. Srinivasan
  - N. Espinoza
  - Postdoc
  - Student

### Task 6
**Integrate Results to Generate Geomechanical Screening Tool / Workflow**
- Task Leader: M.F. Wheeler
- Key Personnel:
  - M. Delshad
  - S. Srinivasan
  - N. Espinoza
  - Postdoc
  - Student
### Gantt Chart

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>1 Management</td>
<td></td>
<td>A, B</td>
<td></td>
</tr>
<tr>
<td>2 Laboratory Experiment</td>
<td></td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>3 Upscale from Lab. to Field</td>
<td></td>
<td></td>
<td>H</td>
</tr>
<tr>
<td>4 Simulator Development</td>
<td></td>
<td>J</td>
<td>K</td>
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<tr>
<td>5 Uncertainty Quantification</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>6 Integrated Geo-Screening Tool</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A to P : Milestones

- Accomplished
- Scheduled
• **Publication:**


• **Publication:**
Bibliography


• **Conference:**