Enhanced Analytical Simulation Tool for CO$_2$ Storage Capacity Estimation and Uncertainty Quantification

DE-FE0009301

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Benefit to the Program/Goals and Objectives

- **Project benefit**
  - Support industry’s ability to predict CO$_2$ storage capacity in geologic formations to within ±30 percent.

- **Major goal**
  - Develop an Enhanced Analytical Simulation Tool (EASiTool) for simplified reservoir models to predict storage capacity of brine formations.

- **Objectives**
  - Provide fast, reliable and science-based estimate of storage capacity
  - Integrate analytical/semi-analytical models
  - Provide uncertainty analysis
  - Implement models into an easy to use interface (MATLAB)
Project Overview

• Task 2&3 completed.
• Task 4 ongoing.

Inputs

Task 2
Development of Pressure Buildup Models

Task 3
Integration of Rock Geomechanics

Task 4
Integration of Active Reservoir Management

Outputs

• Reservoir Storage Capacity
• Number of Required Wells
• Uncertainty Quantification of the Results

Project start date: 5/1/2013
Accomplishments to Date-1

- Finding the optimized rate to maximize storage capacity

\[
\begin{align*}
\Delta P_{max} &= P_{max} - P_{pi} \\
\{q^1, q^2, q^3\} &= \begin{bmatrix}
\frac{1}{2} \left( \ln(t_D) + 0.80908 \right) + S_a \\
- \frac{1}{2} \frac{\lambda_g}{\lambda_w} E_i \left( - \frac{r_{D1-2}^2}{4\eta_{D3}^2 t_D} \right) \\
- \frac{1}{2} \frac{\lambda_g}{\lambda_w} E_i \left( - \frac{r_{D2-1}^2}{4\eta_{D3}^2 t_D} \right) \\
\end{bmatrix}
\end{align*}
\]
Accomplishments to Date-2

- Pore pressure stress coupling
  - Change in total stress ($\Delta \sigma$) is coupled with change in pore pressure ($\Delta P$).
  - We define $\beta_h = \frac{\Delta \sigma_h}{\Delta P}$ and $\beta_v = \frac{\Delta \sigma_v}{\Delta P}$ & typically $\beta_h > \beta_v$

- Thermal stress
  - Injected CO$_2$ is generally colder than formation brine.
  - Shrinkage of the rock formation (specially near the injection well) by $\sigma^{\Delta T} = 2\alpha_T E \Delta T / (1 - 2\nu)$

- Mohr-Coulomb shear failure criterion
  $$\tau = c + (\sigma_n - \alpha \cdot P_{\text{max}}) \mu$$

Accomplishments to Date-3

• Normal fault system

\[
P_{\text{max}} = \frac{1}{2\alpha - \beta - \beta_h - (\beta_v - \beta_h) \cos 2\theta + (\beta_v - \beta_h) \sin 2\theta / \mu}\]

\[
\left[\left((1 + K) + (1 - K \cos 2\theta - (1 - K \sin 2\theta / \mu)\sigma_{v0} - \left((\beta_v + \beta_h) + (\beta_v - \beta_h) \cos 2\theta - (\beta_v - \beta_h) \sin 2\theta / \mu\right)P_{\text{pi}} - \frac{2\alpha T E \Delta T}{1 - 2\nu}\right]\]

• Reverse fault system

\[
P_{\text{max}} = \frac{1}{2\alpha - \beta_h - \beta - (\beta_h - \beta) \cos 2\theta + (\beta_h - \beta) \sin 2\theta / \mu}\]

\[
\left[\left((K + 1) + (K - 1) \cos 2\theta - (K - 1) \sin 2\theta / \mu\right)\sigma_{v0} - \left((\beta_h + \beta_v) + (\beta_h - \beta_v) \cos 2\theta - (\beta_h - \beta_v) \sin 2\theta / \mu\right)\alpha_T E \Delta T\right]

• Strike-slip fault system

\[
P_{\text{max}} = \frac{1}{\alpha - \beta_h} \left[\left(\frac{1 + K_H}{2} + \frac{1 - K_H}{2} \cos 2\theta - \frac{1 - K_H}{2} \sin 2\theta / \mu\right)\sigma_{h0} - \beta_h \cdot P_{\text{pi}} - \frac{\alpha_T E \Delta T}{1 - 2\nu}\right]

\alpha\text{ is Biot coefficient, }\theta\text{ is angle between the pre-existing fracture and minor principal stress, }\mu=\tan\phi\text{ is the coefficient of friction, }K=\sigma_{h0}/\sigma_{v0}\text{ is the initial ratio of total horizontal stress to total vertical stress, }\sigma_{v0}=\left(\rho_{sat} \cdot g\right)\text{ is the initial total vertical stress, }P_{\text{pi}}\text{ is initial fluid pore pressure, }\alpha_T\text{ is the coefficient of thermal expansion, }E\text{ is Young’s modulus, }\Delta T\text{ is thermal drop, and }\nu\text{ is Poisson’s ratio and }c=0\text{ for cohesion.}

\Delta P_{\text{max}} = P_{\text{max}} - P_{\text{pi}}
Accomplishments to Date-4
Accomplishments to Date-5

- Interface between injection zone and upper caprock
- Middle line of injection zone
- Vertical line of interest
- Fluid injection (-ΔT)
- Outlet

- Injection Zone
- Caprock
- Base

Dimensions:
- 2 km
- 1000 m
- 900 m
- 10 m
- 45 m
- 5 m

Not scaled
Accomplishments to Date-6

(a) Change in total stress, \( \Delta\sigma \) (MPa)

(b) Change in total stress, \( \Delta\sigma_z \) (MPa)

Injection time (day)

5 m above the interface (caprock)
5 m below the interface (aquifer)
Middle in the injection aquifer
Aquifer-caprock interface
50 m above the interface (caprock)
Accomplishments to Date-7

(a) \( \sigma'_v = q_{slip} \sigma'_h \)

(b)

(c) 1. 50 m above the interface (caprock)
2. 5 m above the interface (caprock)
3. Aquifer-caprock interface
4. 5 m below the interface (aquifer)
5. Middle in the injection aquifer

(d)
Accomplishments to Date-8
Accomplishments to Date-9

Change in total stress, $\Delta\sigma_r$ (MPa)

Injection time (day)

Change in total stress, $\Delta\sigma_z$ (MPa)

Injection time (day)

- 5 m above the interface (caprock)
- 5 m below the interface (aquifer)
- Middle in the injection aquifer

5 m above the interface (caprock)
5 m below the interface (aquifer)
Middle in the injection aquifer
Accomplishments to Date-10

1. 5 m above the interface (caprock)
2. Aquifer-caprock interface
3. 5 m below the interface (aquifer)
4. Middle in the injection aquifer

(a) Middle in the injection aquifer
(b) 5 m below the interface (aquifer)
Summary

• Second version of EASiTool released on 4/30/2015.
• Geo-mechanical calculations for maximum injection pressure added to EASiTool.
• Geomechanical model integrates thermal and pore pressure stresses.
• EASiTool interface and code updated to include latest developments (MATLAB).
• EASiTool is available for download:
  – http://www.beg.utexas.edu/gccc/EASiTool/
Future Plans

- Currently under Task 4 the main focus is to integrate extraction wells.
  - Model development
  - Model verification
- EASiTool Interface development
Future plans

CO₂ Injectors  Brine Extractors

Saline Formation

![Graph showing capacity vs. brine extraction rate](chart.png)
Future plans

Effect of Placement of Extraction Wells on Storage Capacity
» Questions/Comments
Appendix

- Organization Chart
- Gantt Chart
- Bibliography
- Extra Slides
## Organization Chart

**Project PI:** Seyyed A. Hosseini

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<td>Rock Geomechanics Impact on Pressure Buildup and Capacity Estimation</td>
<td>Brine-Management Impact on CO\textsubscript{2} Injectivity and Storage Capacity</td>
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<td>Task Leader/Backup Hosseini/Sun</td>
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Bibliography

- Journals
  - Kim, S., Hosseini, S.A, 2013, Above-zone pressure monitoring and geomechanical analyses for a field-scale CO\textsubscript{2} injection project in Cranfield, MS, Greenhouse Gases: Science and Technology, 4 (1), 81-98, DOI: 10.1002/ghg.1388

- Conferences
## Capacity Estimation Methods

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<th>Tool/Approach Name</th>
<th>DOE/NETL</th>
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<th>USGS</th>
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Analytical model

Vertically averaged gas saturation

Radial distance from injection well

- Salt
- Brine saturated with CO$_2$
- Dissolved CO$_2$ reduces volumetric flow rate
- CO$_2$ saturated with water
- Brine free of CO$_2$

Development of dry-out zone leads to increase in relative permeability
Accomplishments to Date-6

(a) Change in total stress, $\Delta \sigma_z$ (MPa) vs Injection time (day)
   - Middle in the injection aquifer
   - 5 m below the interface (aquifer)
   - 50 m above the interface (caprock)
   - Aquifer-caprock interface

(b) Change in total stress, $\Delta \sigma_r$ (MPa) vs Injection time (day)

(c) Change in pore pressure, $\Delta P$ (MPa) vs Injection time (day)

(d) Temperature (K) vs Injection time (day)
Accomplishments to Date-9

(a) Change in total stress, $\Delta \sigma_r$ (MPa)

(b) Change in total stress, $\Delta \sigma_z$ (MPa)

(c) Change in pore pressure, $\Delta P$ (MPa)

(d) Temperature (K)

Injection time (day)
Maximum pressure derivation

\[ p_{\text{max}} = \frac{1}{\alpha} \left[ \frac{1}{2} (\sigma_1 + \sigma_3) + \frac{1}{2} (\sigma_1 - \sigma_3) \cos 2\theta - \frac{1}{2} (\sigma_1 - \sigma_3) \frac{\sin 2\theta}{\mu} \right] \]

where, \( \sigma_1 \): major principal stress
\( \sigma_3 \): minor principal stress
\( \theta \): angle with respect to minor principal stress

where, \( K = \sigma_{h0}/\sigma_{v0} \) (normal-faulting stress regime)
or \( = \sigma_{H0}/\sigma_{v0} \) (reverse-faulting stress regime)