Training and Research on Probabilistic Hydro-Thermo-Mechanical (HTM) Modeling of CO$_2$ Geological Sequestration (GS) in Fractured Porous Rocks

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Presentation Outline

• Benefit to the program (Program goals addressed and Project benefits)
• Project goals and objectives
• Technical status – Project tasks
• Technical status – Key findings
• Lessons learned
• Summary – Accomplishments to date
Benefit to the Program

- Program goals being addressed.
  - Develop technologies that will support industries’ ability to predict CO\textsubscript{2} storage capacity in geologic formations to within ±30%.

- Project benefits statement.
  - The project is developing and validating an advanced simulation and risk assessment model for predicting the fate, movement and storage of CO\textsubscript{2} in underground formations. The model has the following capabilities: 1) takes into account the full coupling of physical processes, 2) describes the effects of stochastic hydro-thermo-mechanical parameters, and 3) focuses on porous fractured rocks.
Project Overview: Goals and Objectives

1. Develop a rigorous procedure for coupled hydro-thermo-mechanical (HTM) modeling of CO$_2$ GS in fractured porous rocks.

2. Develop a hydro-mechanical (HM) model for fractured porous rocks with random fracture geometries.

3. Develop Monte-Carlo-based risk assessment procedure for CO$_2$ GS in fractured porous rocks.

4. Perform comprehensive study on the effects of stochastic HM parameters on CO$_2$ GS in fractured porous rocks.

5. Validate models using an inverse analysis procedure.
Technical Status – Project Tasks

Non-isothermal Multiphase Fluid Flow Simulation

\[ M^{\beta}_{i,j} = M^{\alpha}_{i,j} + \frac{\bar{N}}{n} \sum_{m} A_{i,m} F^{\alpha}_{i,m} + V_{i,j} q_{i,j}^{\alpha} \]

\[ \bar{P} = \sum S_{\beta} P_{\beta} \]

Geomechanical Simulation

\[ \phi = \phi_0 + e^{\varepsilon/\phi} - 1 \]

\[ k = k \phi \]

(1) Rigorous Procedure for Coupled Hydro-Thermo-Mechanical (HTM) Modeling using TOUGH2 and FLAC.

(2) Hydro-Mechanical (HM) for Fractured Porous Rocks

(3) Monte-Carlo Risk Assessment Procedure.

(4) Validation.
Technical Status – Key Findings

Coupled Hydro-Thermo-Mechanical (HTM) Modeling Using TOUGH2 and FLAC

Verification of Mandel-Cryer Effect.

Verification of Nordbergum Effect.
Technical Status – Key Findings

Hydro-Mechanical Model (HM) for Fractured Porous Rocks

Oda’s permeability tensor

\[ k_{ij}^c = \lambda \left(1 - \alpha\right) P_{kk} \delta_{ij} - P_{ij} \]
\[ P_{ij} = \frac{1}{V} \sum_{k=1}^{m} Tr^k t^k n_i n_j \]

where

\[ \lambda = \text{Connectivity} \quad \alpha = \text{Threshold value} \quad \delta_{ij} = \text{Kronecker delta} \]
\[ V = \text{Volume of rock} \quad T = \text{Width of rock volume} \quad r = \text{Length of fracture} \]
\[ t = \text{Aperture of fracture} \quad n_i \text{ and } n_j = \text{Unit vector along } i \text{ and } j \text{ axes} \]

Examples of Fracture Geometry Realizations

Selection of an REV (Representative Element Volume)

Fracture length

Fracture aperture

Fracture orientation

Permeability Polar Plots
Technical Status – Key Findings

Hydro-Mechanical Model (HM) for Fractured Porous Rocks

Stochastic analysis of permeabilities to establish REV of fractured porous rocks.

\[ \text{REV} = 0.16 \times 10^{-2} \times \text{FIT}^{-2.05} \]

\[ R^2 = 0.97 \]
Technical Status – Key Findings

Hydro-Mechanical Model (HM) for Fractured Porous Rocks

Oda Compliance Tensor

\[ S_{ijkl}^{f} = \left( \frac{1}{K_n} - \frac{1}{K_s} \right) F_{ijkl} + \frac{1}{4K_s} \delta_{ik} F_{jj} + \delta_{jk} F_{ii} + \delta_{ji} F_{jk} + \delta_{ij} F_{ik} \]

\[ F_{ij} = \frac{1}{V} \sum_{k=1}^{m} A_{ijkl} r_{n_i} n_j \]

where \( K_n \) and \( K_s \) = fracture stiffness along normal and shear direction, \( \delta_i \) = Kronecker delta, \( F_{ijkl} \) and \( F_{ij} \) = fourth and second rank tensors, \( V \) = volume of rock, \( r \) = fracture length, \( A \) = fracture surface area \( m^{(r)} \) = total number of fractures, \( n_i \) = directional cosine of the normal to the fracture orientation

Polar Plots of Elastic Moduli

Elastic Moduli as Function of Sampling Volume

REV for Elastic Moduli

\[ MOV = r_{\text{max}} / \text{Area} \]

\[ REV = 0.06 \times MOV^{-1.79} \]

\[ R^2 = 0.81 \]
Hydro-Mechanical Model (HM) for Fractured Porous Rocks

Elasto-plastic Model for Fractured Rocks

\[ \sigma_1^N = \sigma_1' - S_{12} \lambda^s \tan \psi - S_{14} \lambda^s \]
\[ \sigma_2^N = \sigma_2' - S_{22} \lambda^s \tan \psi - S_{24} \lambda^s \]
\[ \sigma_3^N = \sigma_3' - S_{32} \lambda^s \tan \psi - S_{34} \lambda^s \]
\[ \tau_{12}^N = \tau_{12}' - S_{42} \lambda^s \tan \psi - S_{44} \lambda^s \]
Technical Status – Key Findings

Monte-Carlo Simulation of CO₂ GS – Injection Phase

CO₂ saturation migration at time 30 days

CO₂ saturation migration at time 1 yr

CO₂ saturation migration at time 2 yrs

CO₂ saturation migration at time 10 yrs

CO₂ saturation profiles at different times for a single realization.

CO₂ saturation profiles at 10 years of injection for 5 realizations.
Technical Status – Key Findings

Monte-Carlo Simulation of CO$_2$ GS – Migration Phase

CO$_2$ saturation profiles at different times for a single realization

CO$_2$ saturation migration at time 10 yrs

CO$_2$ gas plume, S$_g$ = 0.8

Observation block

Observation production well, P$_p$ = 57 bar

No flow boundary

Horizontal line

CO$_2$ saturation migration at time 10 yrs

CO$_2$ saturation migration at time 31.71 yrs

CO$_2$ saturation migration at time 63.42 yrs

CO$_2$ saturation migration at time 95.13 yrs

y direction (km)
z direction (m)

CO$_2$ saturation profiles at 10 years of injection for 5 realizations.
Technical Status – Key Findings

Monte-Carlo Simulation of CO\textsubscript{2} GS

Injection Phase

Total flow rate at production well (kg/s) for all realizations.

Migration Phase

CO\textsubscript{2} saturation profiles at different times for a single realization.

CO\textsubscript{2} saturations at 31.71 years for 5 realizations
Technical Status – Key Findings

Monte-Carlo Simulation of CO₂ GS

Storage capacity at different times for different realization.

Storage capacity at different times in terms of fluid phase behavior.
Simulation conditions for forward analysis.

<table>
<thead>
<tr>
<th>Simulation parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>40° C</td>
</tr>
<tr>
<td>Initial pore pressure</td>
<td>$10^7$ Pa</td>
</tr>
<tr>
<td>Injection rate</td>
<td>2.0 cm$^3$/min</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.21</td>
</tr>
<tr>
<td>Absolute permeability</td>
<td>0.039 Darcy</td>
</tr>
<tr>
<td>Assumed water/gas irreducible saturation $S_{wr}/S_{gr}$</td>
<td>0.30/0.00</td>
</tr>
<tr>
<td>Water/CO$_2$ viscosity</td>
<td>0.65/0.07 cp</td>
</tr>
<tr>
<td>Pore volume for the sample</td>
<td>16.2827 cm$^{-3}$</td>
</tr>
<tr>
<td>Van Genuchten exponent $\lambda$</td>
<td>2.464</td>
</tr>
<tr>
<td>Van Genuchten parameter $\alpha$</td>
<td>$6.63 \times 10^{-4}$ Pa</td>
</tr>
</tbody>
</table>
Technical Status – Key Findings

Inverse Analysis and Model Validation

Comparison of saline water production.

Comparison of differential pressure.

Comparison of relative permeability curves.

Capillary pressure vs. CO₂ saturation from inverse modeling.
Lessons Learned

• Rigorous coupling between geomechanics and two-phase fluid flow achieved using a staggered solution technique allowing for use of two existing computer programs (TOUGH2 and FLAC).
• Coupled geomechanics and fluid flow simulation tested against poroelastic effects predicted by Mandel-Cryer, and Nordbergum.
• Stochastic permeability and mechanical properties of fractured rocks established from fracture properties and distribution using Monte-Carlo Simulations.
• REV for both permeability and mechanical behavior defined from fracture distribution and geometry.
• Significant uncertainties observed in both simulated CO$_2$ injection and migration due to random input parameters.
• Models rigorously validated using an inverse analysis procedure.
Lessons Learned

Effects of uncertainties on simulation of CO$_2$ GS in fractured porous reservoirs:

- During migration, CO$_2$ saturation profiles are less random compared to other quantities such as block-to-block flow rate, well flow rate and CO$_2$ mass fraction.
- Uncertainty in CO$_2$ saturation profiles during injection is more significant than during migration.
- Uncertainty in intrinsic permeability has the strongest influence in CO$_2$ flow during in the injection process.
- Uncertainty in porosity cannot be neglected particularly in evaluating the storage capacity factor in the injection process.
Summary - Accomplishments to Date

- Monte-Carlo-based risk assessment procedure developed.
- Hydro-mechanical (HM) model for fractured porous rocks developed and implemented in a simulation program.
- Comprehensive study on the effects of stochastic fracture distribution on the elastic compliance, permeability and REV of fractured rock masses completed.
- Comprehensive study on the effects of stochastic hydro-mechanical (HM) parameters on CO$_2$ geological sequestration completed.
- Back-analysis procedure using inverse analysis to validate stochastic models against experimental data completed.