# Training and Research on Probabilistic Hydro-Thermo-Mechanical (HTM) Modeling of $CO_2$ Geological Sequestration (GS) in Fractured Porous Rocks

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U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for $CO_2$ Storage

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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

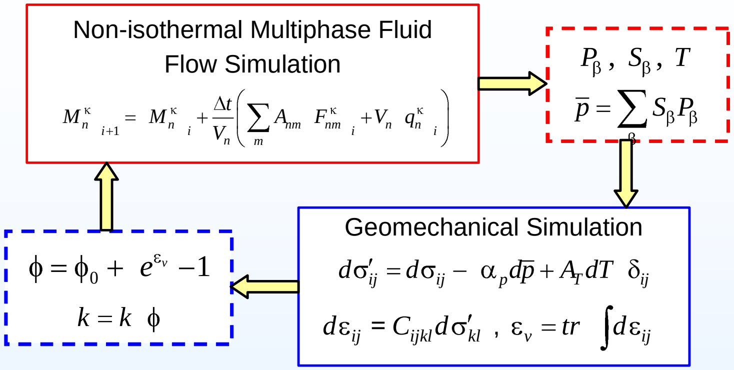
# Benefit to the Program

- Program goals being addressed.
  - Develop technologies that will support industries' ability to predict $CO_2$ 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 $CO_2$ 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.

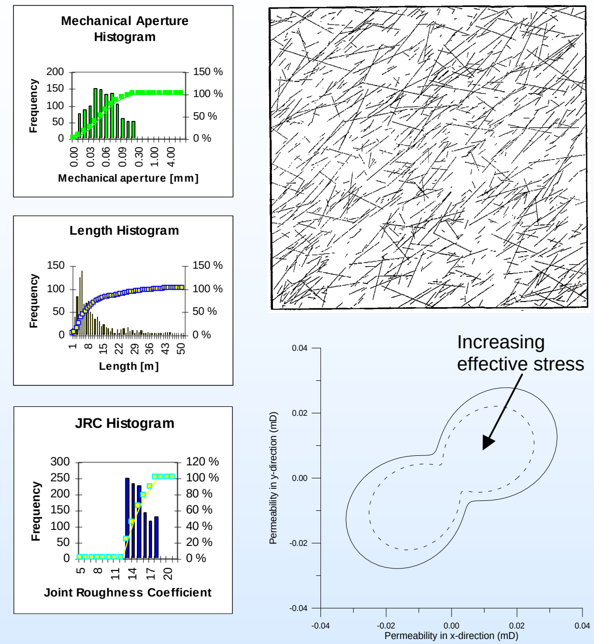
# **Project Overview**: Goals and Objectives

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.

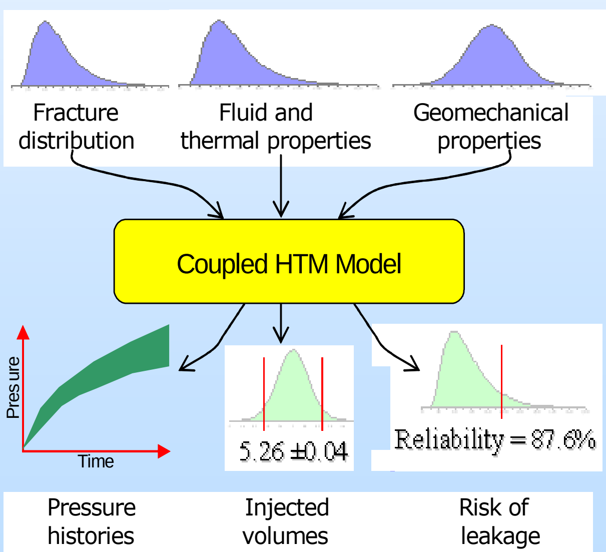
# Technical Status – Project Tasks



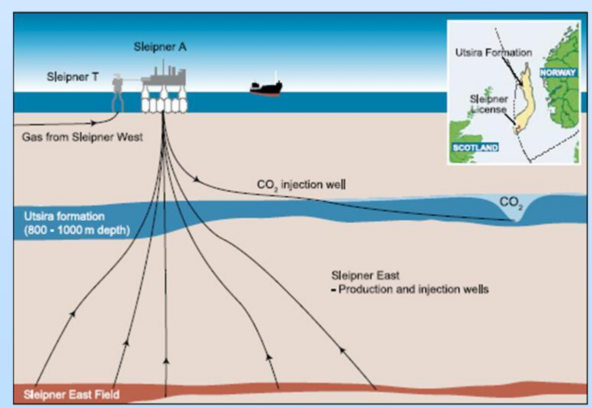

(1) Rigorous Procedure for Coupled Hydro-Thermo-Mechanical (HTM) Modeling using TOUGH2 and FLAC.




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



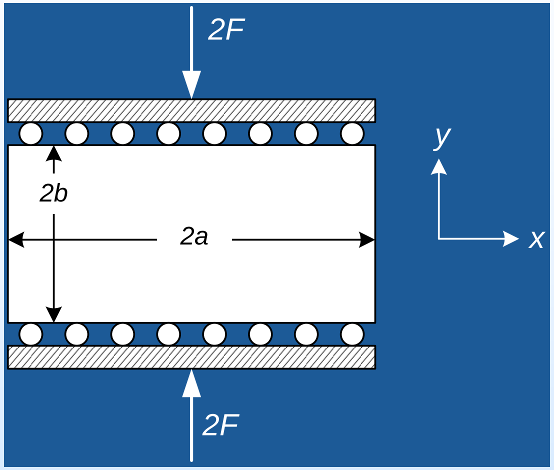

(3) Monte-Carlo Risk Assessment Procedure.

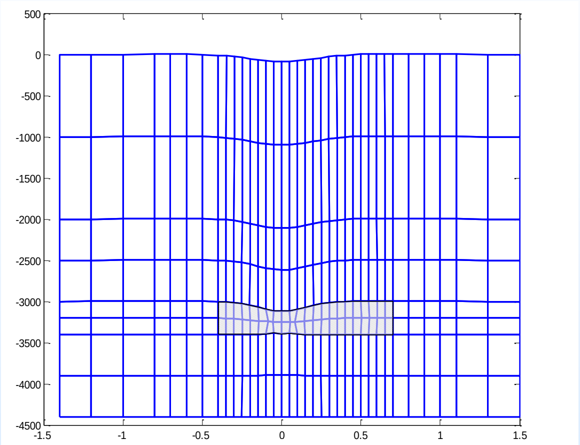


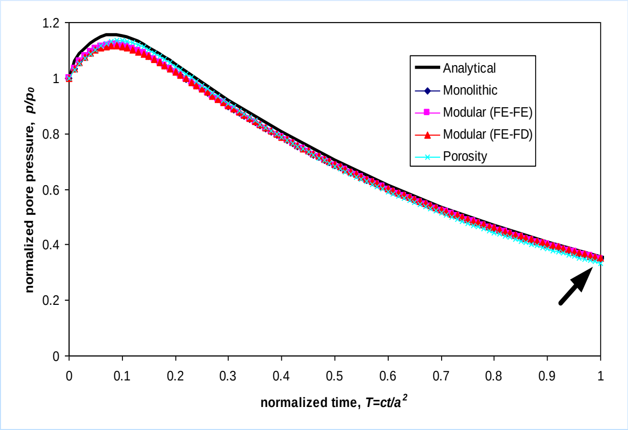

(4) Validation.

# Technical Status – Key Findings

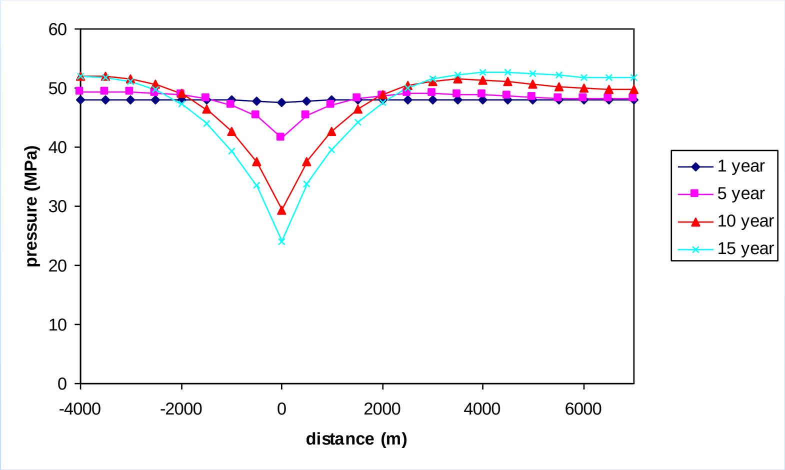
## Coupled Hydro-Thermo-Mechanical (HTM) Modeling Using TOUGH2 and FLAC




Verification of Mandel-Cryer Effect.




Verification of Nordbergum Effect.

# Technical Status – Key Findings

## Hydro-Mechanical Model (HM) for Fractured Porous Rocks

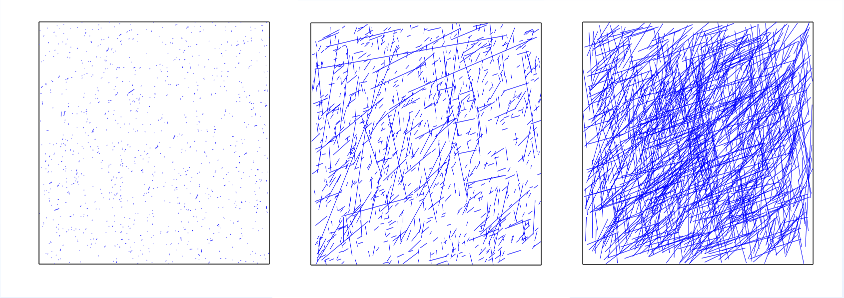
Oda's permeability tensor

$$k_{ij}^{c} = \lambda \; 1-\alpha \;\; P_{kk}\delta_{ij} - P_{ij}$$

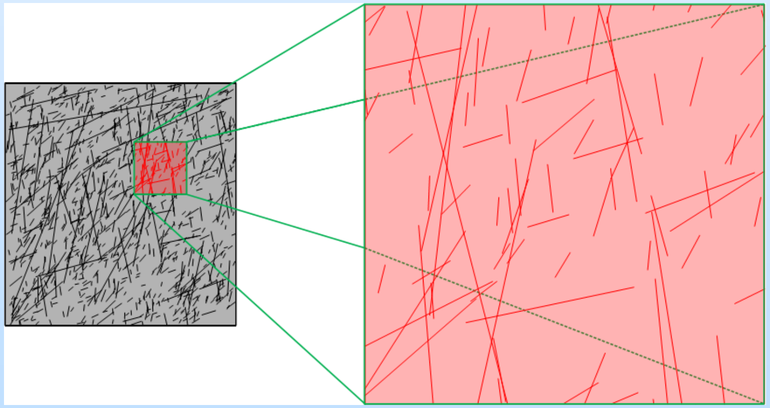
$$P_{ij} = \frac{1}{V}\sum_{k=1}^{m^{v}} T r^{k} \;\; t^{k} \;{}^{3} \;\; n_i n_j$$

where

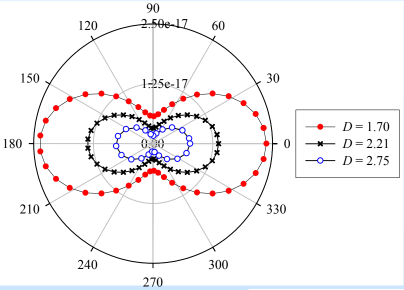
$\lambda$ = Connectivity  $\alpha$ = Threshold value  $\delta_{ij}$ = Kronecker delta
$V$ = Volume of rock  $T$ = Width of rock volume  $r$ = Length of fracture
$t$ = Aperture of fracture  $n_i$ and $n_j$ = Unit vector along $i$ and $j$ axies



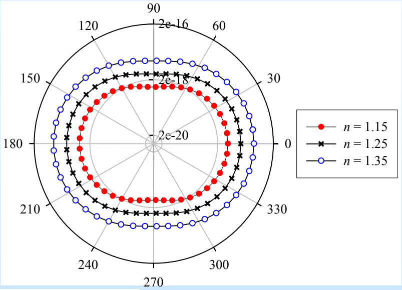
Examples of Fracture Geometry Realizations



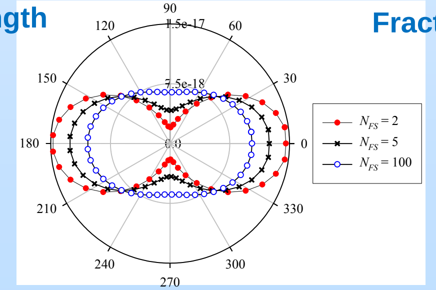
Selection of an REV
(Representative Element Volume)




Fracture length




Fracture aperture



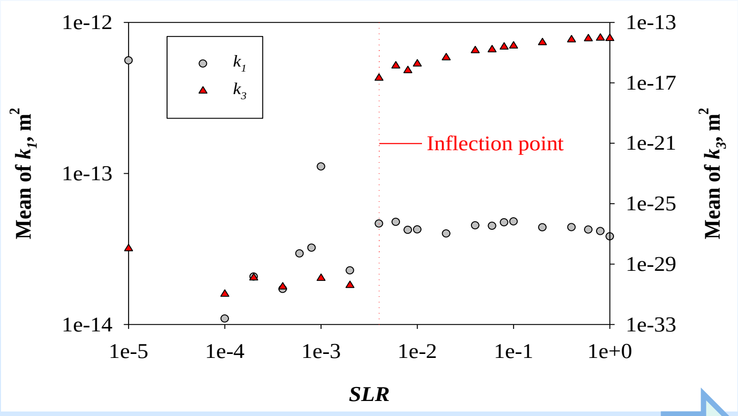

Fracture orientation

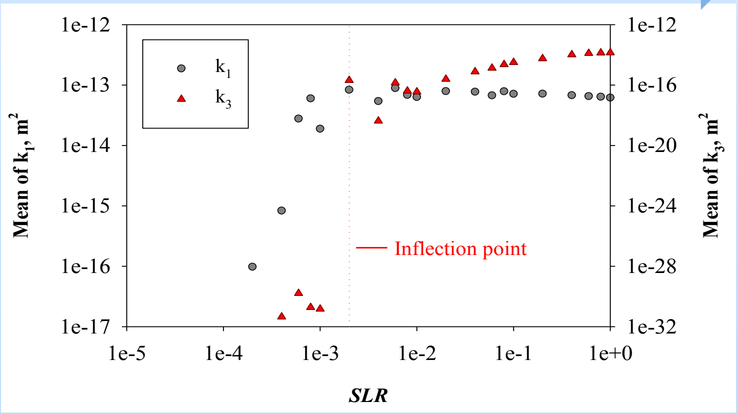
Permeability Polar Plots

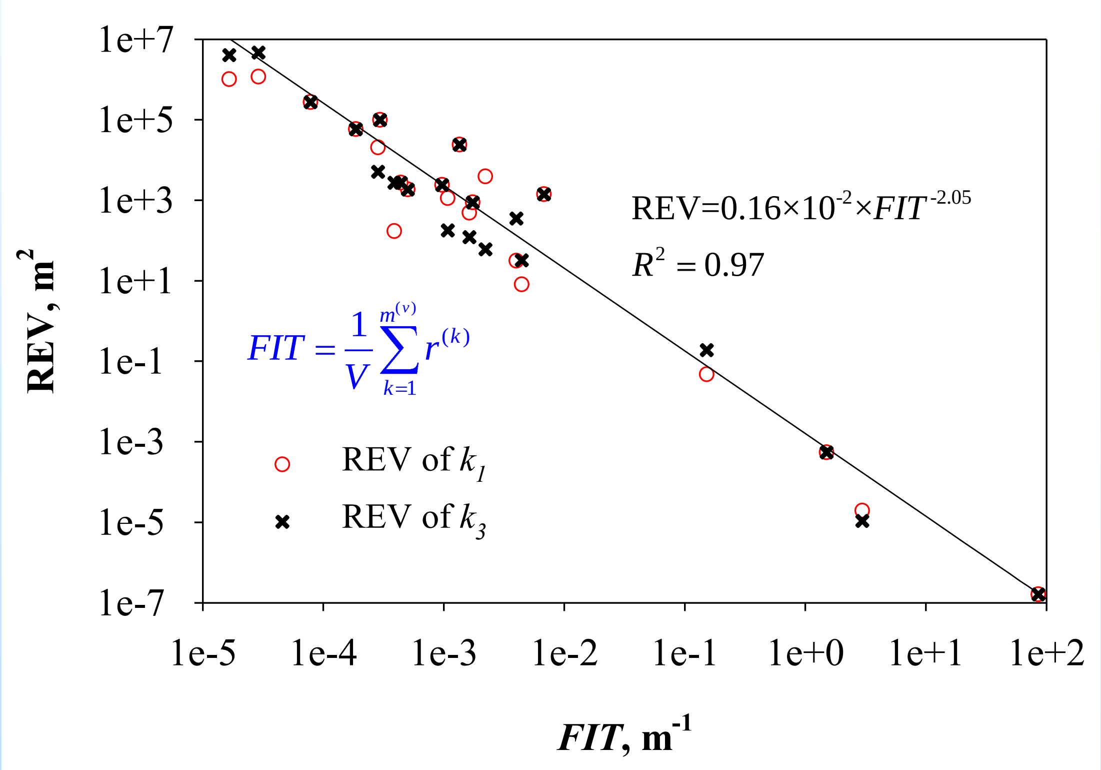
# Technical Status – Key Findings

## Hydro-Mechanical Model (HM) for Fractured Porous Rocks

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




REV for Fractured Rock Mass Permeability

# Technical Status – Key Findings

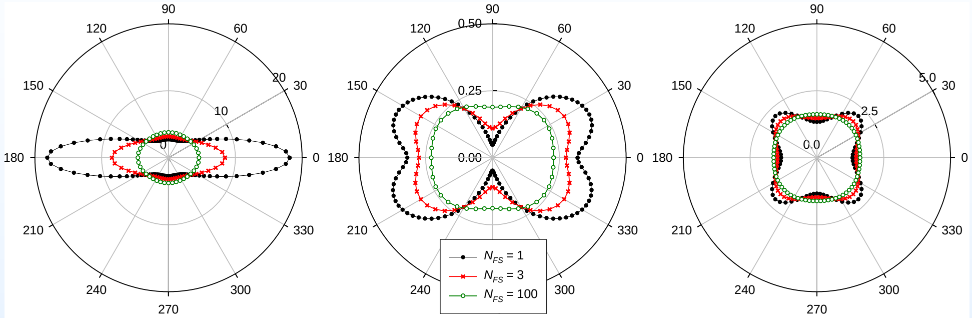
## Hydro-Mechanical Model (HM) for Fractured Porous Rocks

### Oda Compliance Tensor

$$S_{ijkl}^{f}=\left(\frac{1}{K_n}-\frac{1}{K_s}\right)F_{ijkl}+\frac{1}{4K_s}\ \delta_{ik}F_{jl}+\delta_{jk}F_{il}+\delta_{il}F_{jk}+\delta_{jl}F_{ik}$$

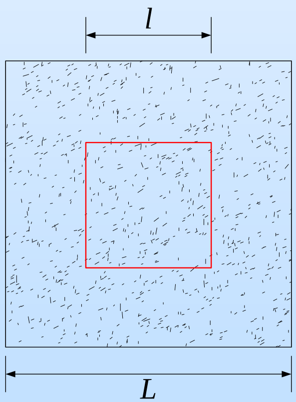
$$F_{ij}=\frac{1}{V}\sum_{k=1}^{m^{v}}A^{(k)}r^{(k)}n_i^{(k)}n_j^{(k)}\quad F_{ijkl}=\frac{1}{V}\sum_{k=1}^{m^{v}}A^{(k)}r^{(k)}n_i^{(k)}n_j^{(k)}n_k^{(k)}n_l^{(k)}$$

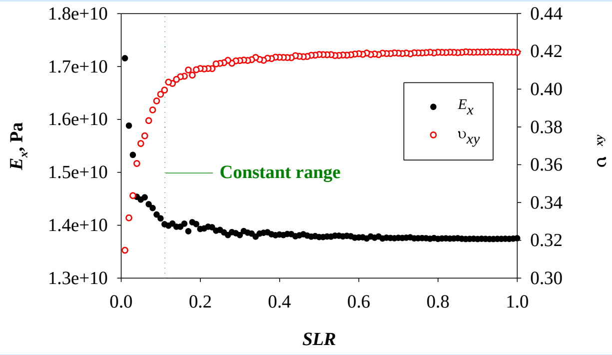
where $K_n$ and $K_s$ = fracture stiffness along normal and shear direction, $\delta_{ij}$ = Kronecker delta, $F_{ijkl}$ and $F_{ij}$ = fourth and second rank tensors, $V$ = volume of rock, $r$ = fracture length, $A$ = fracture surface area $m^{(v)}$ = total number of fractures, $n_i$ = directional cosine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



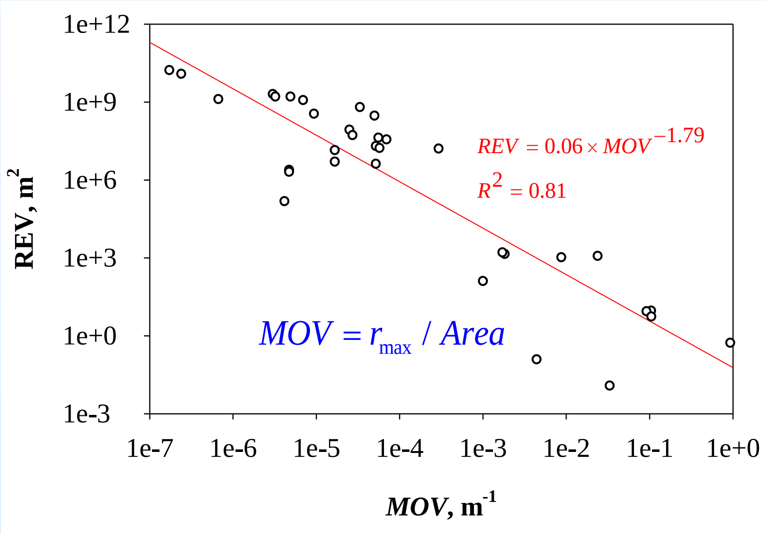

(a) Young's modulus (GPa) (b) Poisson's ratio (c) Shear modulus (GPa)

Polar Plots of Elastic Moduli




Elastic Moduli as Function of Sampling Volume

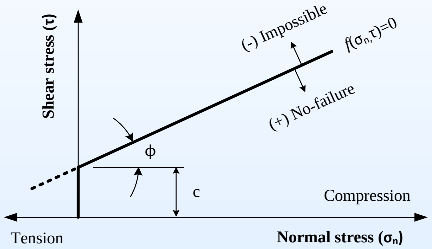



REV for Elastic Moduli

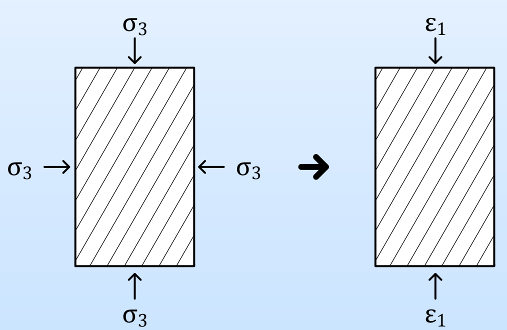
# Technical Status – Key Findings

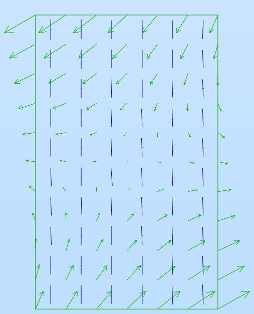
## Hydro-Mechanical Model (HM) for Fractured Porous Rocks

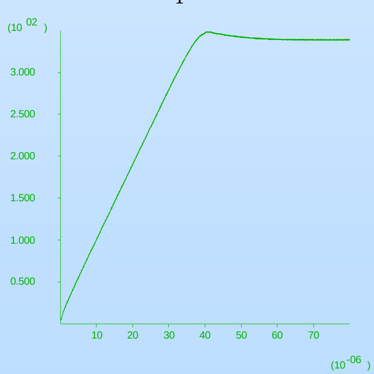
### Elasto-plastic Model for Fractured Rocks

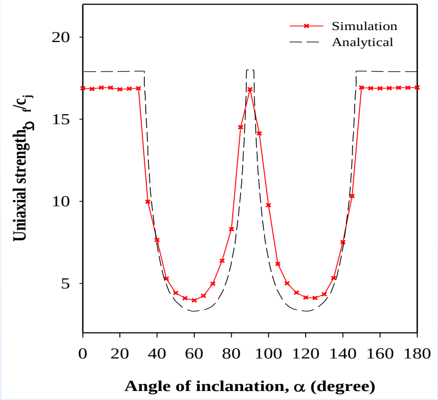



$$\sigma_1^N = \sigma_1^I - S_{12}\lambda^s \tan\psi - S_{14}\lambda^s$$
$$\sigma_2^N = \sigma_2^I - S_{22}\lambda^s \tan\psi - S_{24}\lambda^s$$
$$\sigma_3^N = \sigma_3^I - S_{32}\lambda^s \tan\psi - S_{34}\lambda^s$$
$$\tau_{12}^N = \tau_{12}^I - S_{42}\lambda^s \tan\psi - S_{44}\lambda^s$$

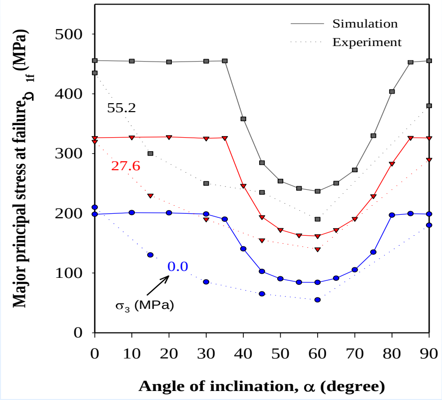


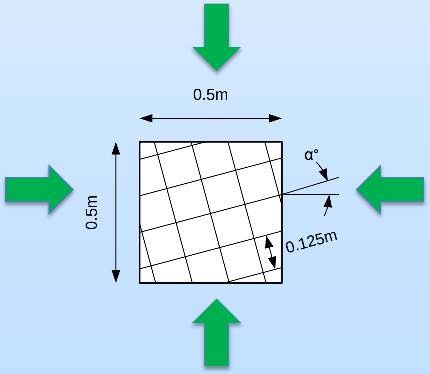


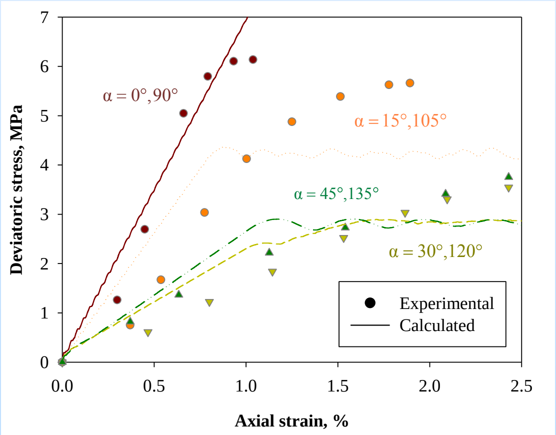




Model Prediction vs. Analytical Solution




Model Prediction vs. Experimental Results

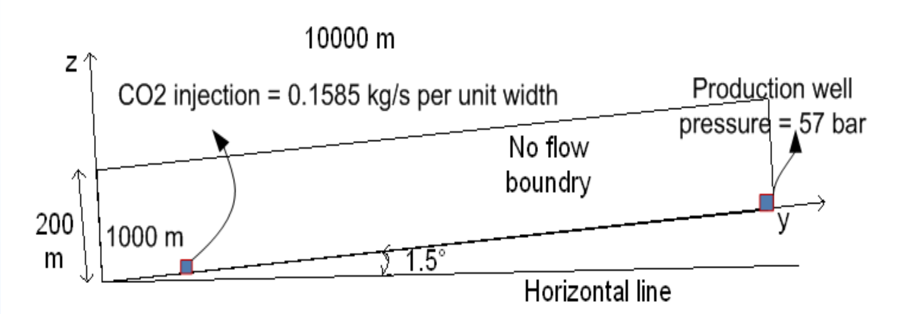


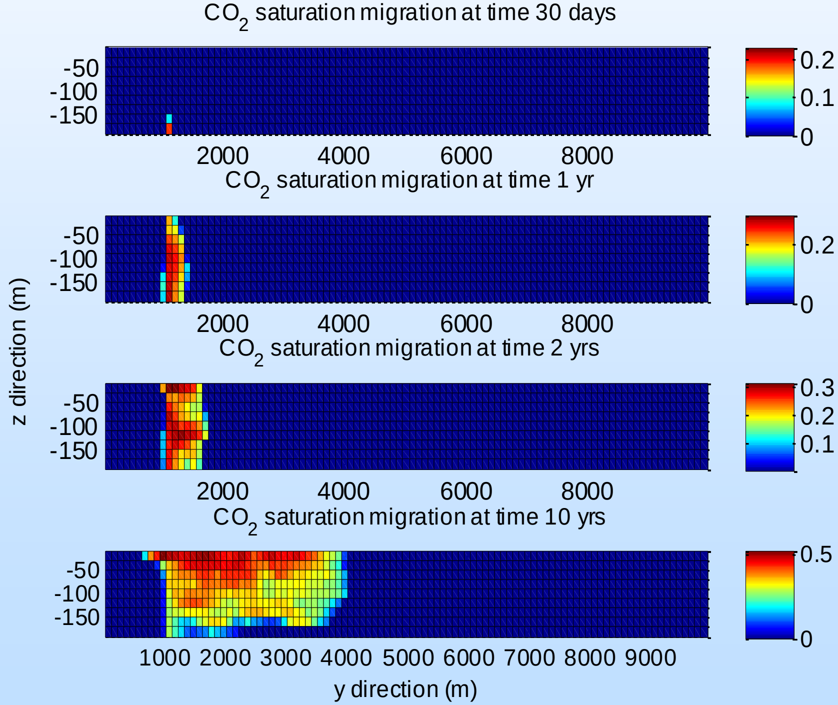



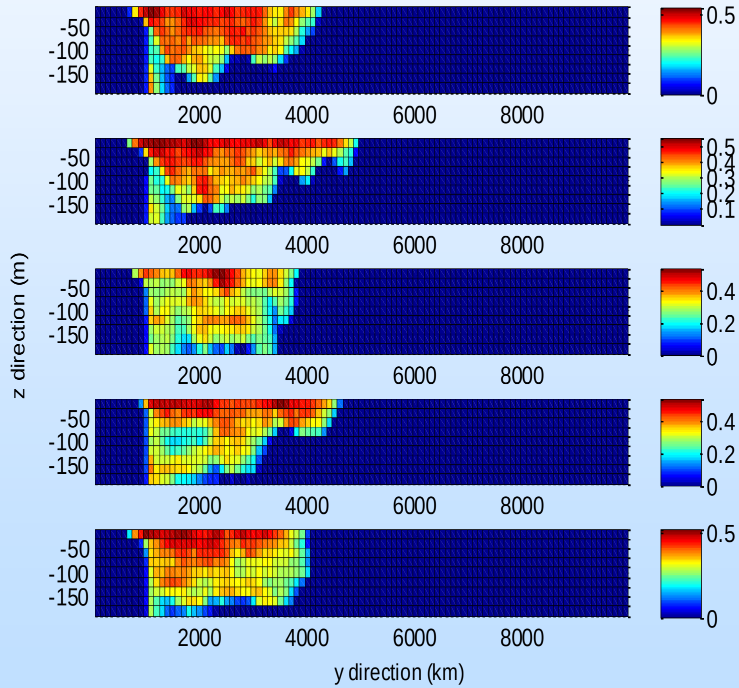

Model Prediction vs. Experimental Results from Biaxial Test.

# Technical Status – Key Findings

## Monte-Carlo Simulation of $CO_2$ GS – Injection Phase



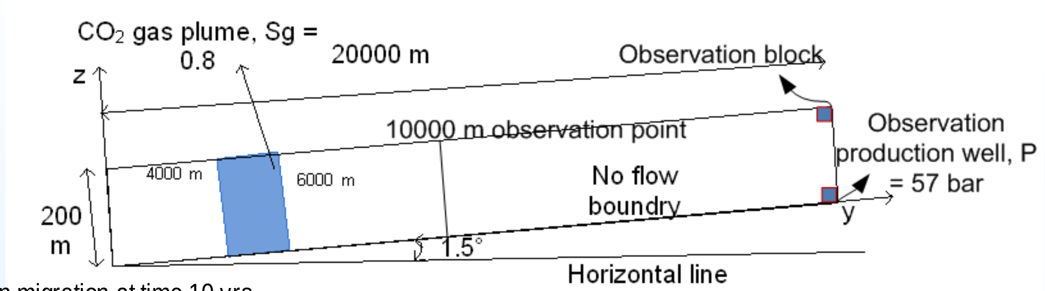



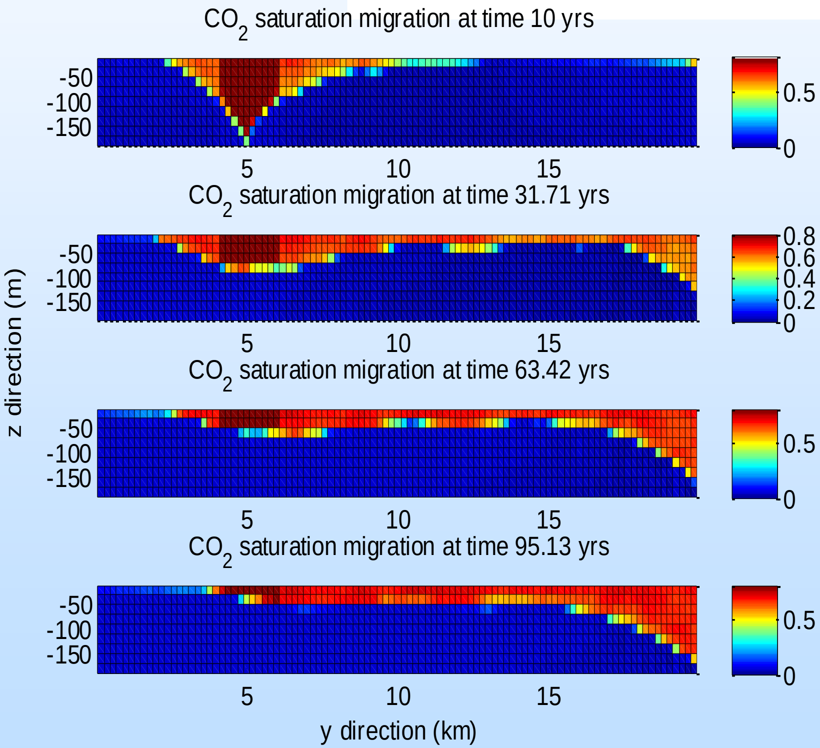

CO-$_2$ saturation profiles at different times for a single realization.

CO-$_2$ saturation profiles at 10 years of injection for 5 realizations.

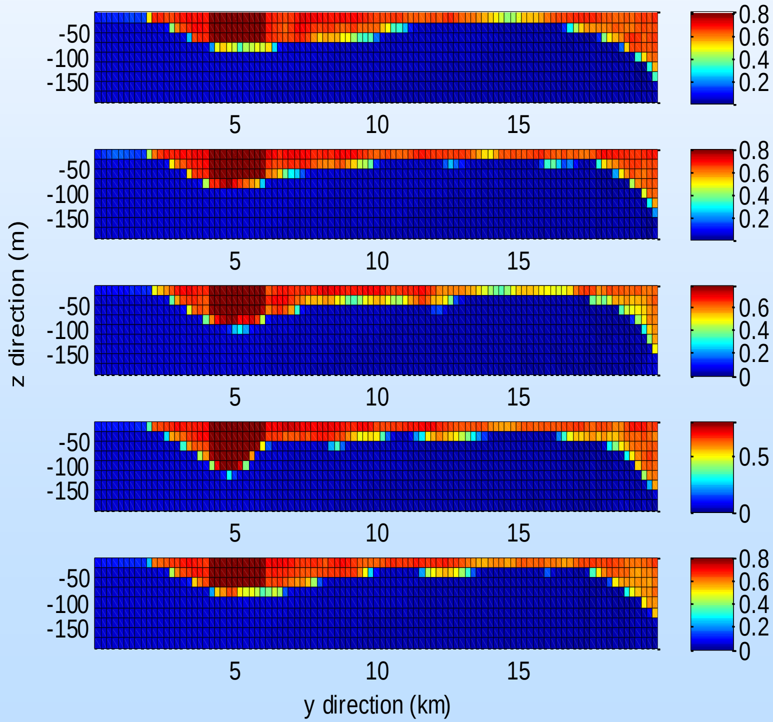
# Technical Status – Key Findings

## Monte-Carlo Simulation of $CO_2$ GS – Migration Phase




$CO_2$ saturation profiles at different times for a single realization

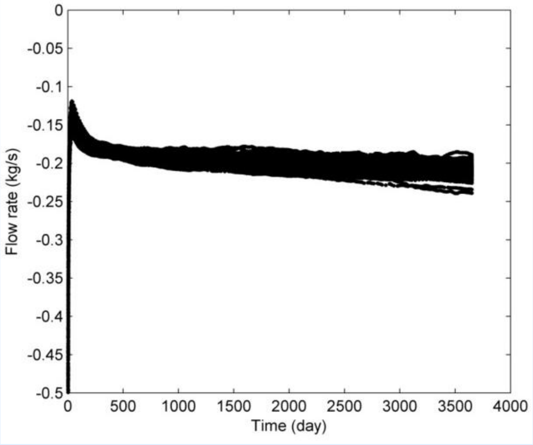



$CO_2$ saturation profiles at 10 years of injection for 5 realizations.

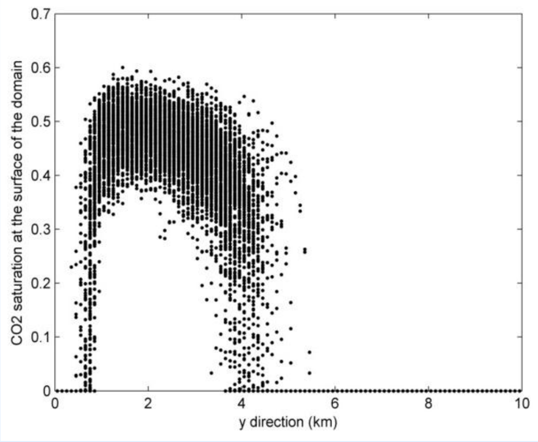
# Technical Status – Key Findings

## Monte-Carlo Simulation of $CO_2$ GS

**Injection Phase**

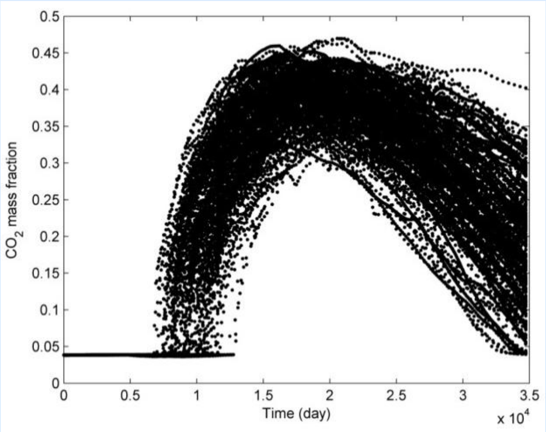



Total flow rate at production well (kg/s) for all realizations.

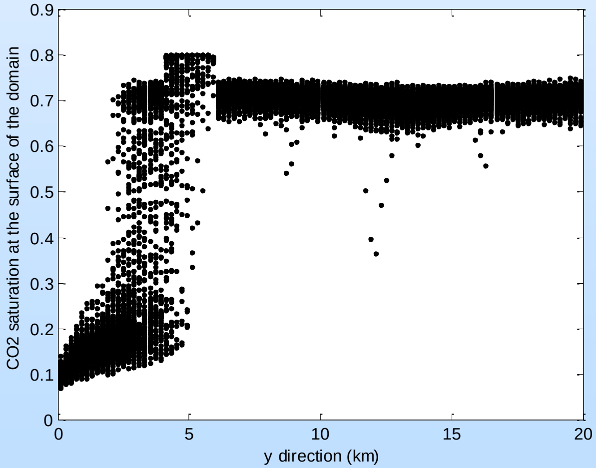



$CO_2$ saturation at the surface for all realizations at 10 years.

**Migration Phase**



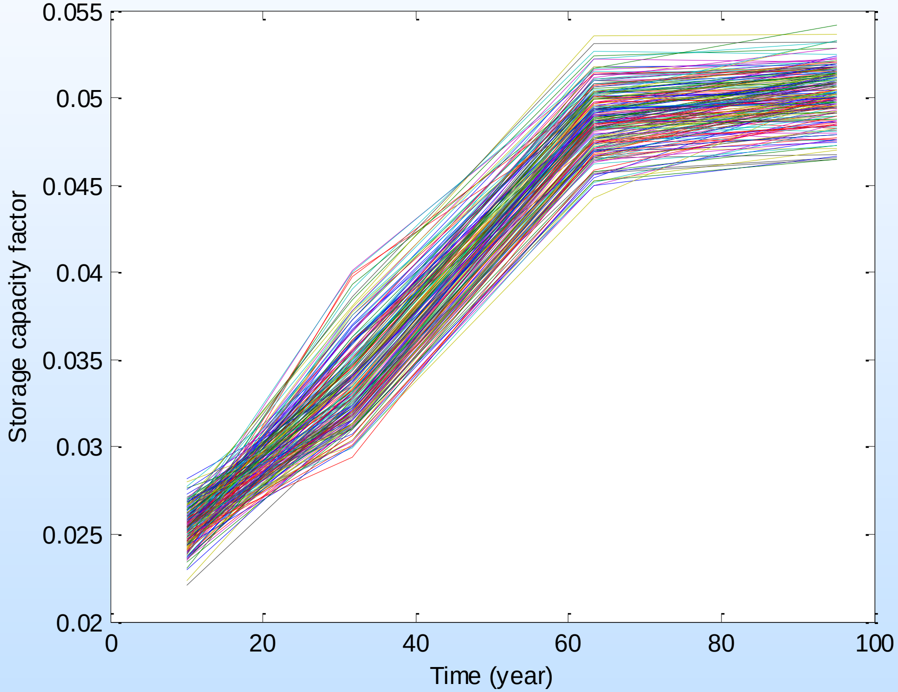

$CO\text{-}_2$ saturation profiles at different times for a single realization.



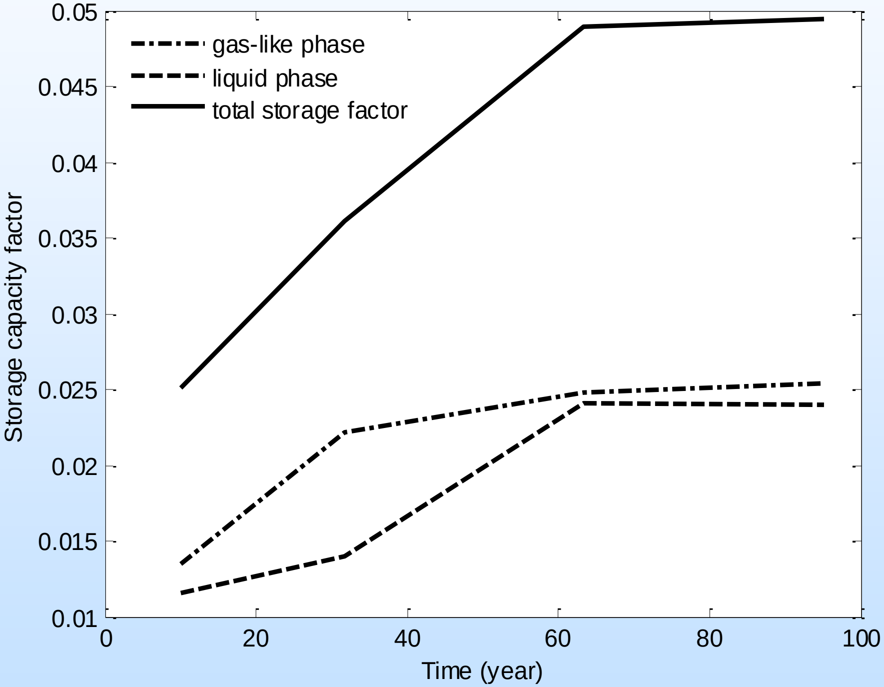

$CO_2$ saturations at 31.71 years for 5 realizations

# Technical Status – Key Findings

## Monte-Carlo Simulation of $CO_2$ GS




Storage capacity at different times for different realization.

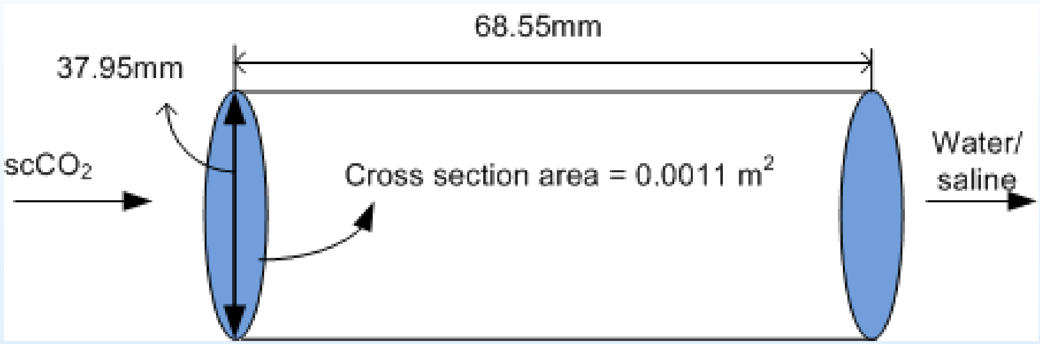



Storage capacity at different times in terms of fluid phase behavior.

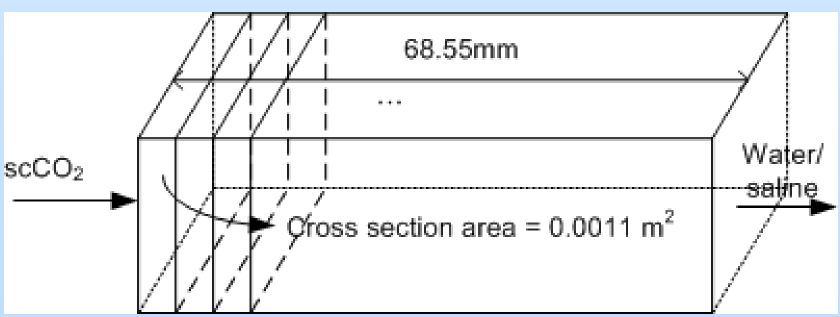
# Technical Status – Key Findings

## Inverse Analysis and Model Validation

- Experimental model




- 1-D simulation FDM model

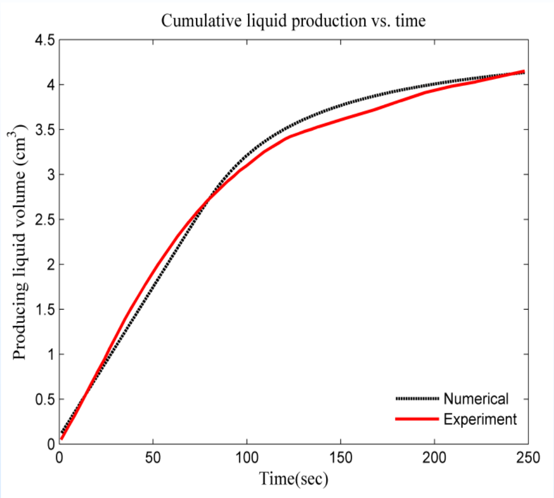



Simulation conditions for forward analysis.

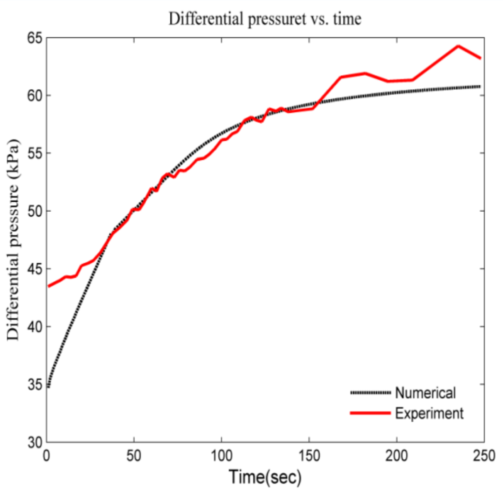
| Simulation parameters | Values |
|---|---|
| Temperature | 40° C |
| Initial pore pressure | $10^7$ Pa |
| Injection rate | 2.0 $cm^3$/min |
| Porosity | 0.21 |
| Absolute permeability | 0.039 Darcy |
| Assumed water/gas irreducible saturation $S_{wr}/S_{gr}$ | 0.30/0.00 |
| Water/$CO_2$ viscosity | 0.65/0.07 cp |
| Pore volume for the sample | 16.2827 cm-$^3$ |
| Van Genuchten exponent $\lambda$ | 2.464 |
| Van Genuchten parameter $\alpha$ | $6.63\times10^{-4}$ Pa |

# Technical Status – Key Findings

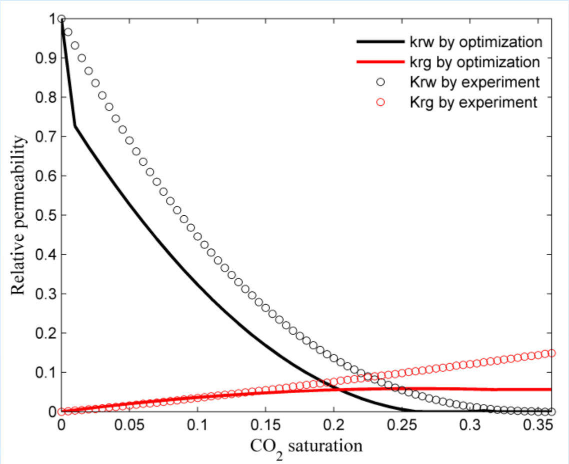
## Inverse Analysis and Model Validation



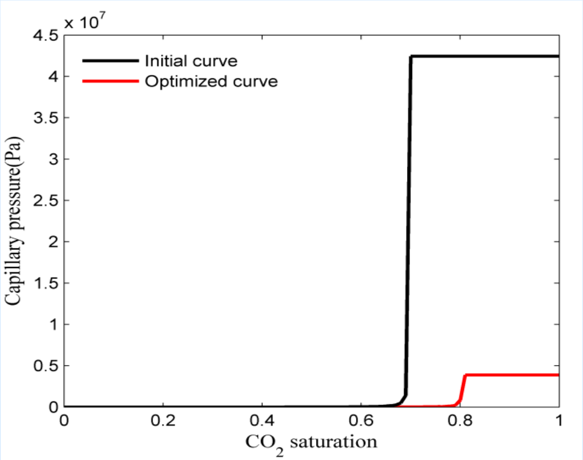

Comparison of saline water production.




Comparison of differential pressure.




Comparison of relative permeability curves.




Capillary pressure vs. $CO_2$ 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.