Use of a Dual-Continuum Approach for Modeling Coupled Hydro-mechanical Processes of CO_2 Injection at In Salah, Algeria*

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Descriptive Statement

Presented here is a newly developed dual-continuum approach for modeling coupled hydro-mechanical processes and its application in studying CO_2 injection at In Salah site in Algeria.

References

Coyner, K.B., 1984, Effects of Stress, Pore Pressure, and Pore Fluids on Bulk Strain, Velocity, and Permeability of Rocks, Ph.D. Dissertation, Massachusetts Institute of Technology.

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Website

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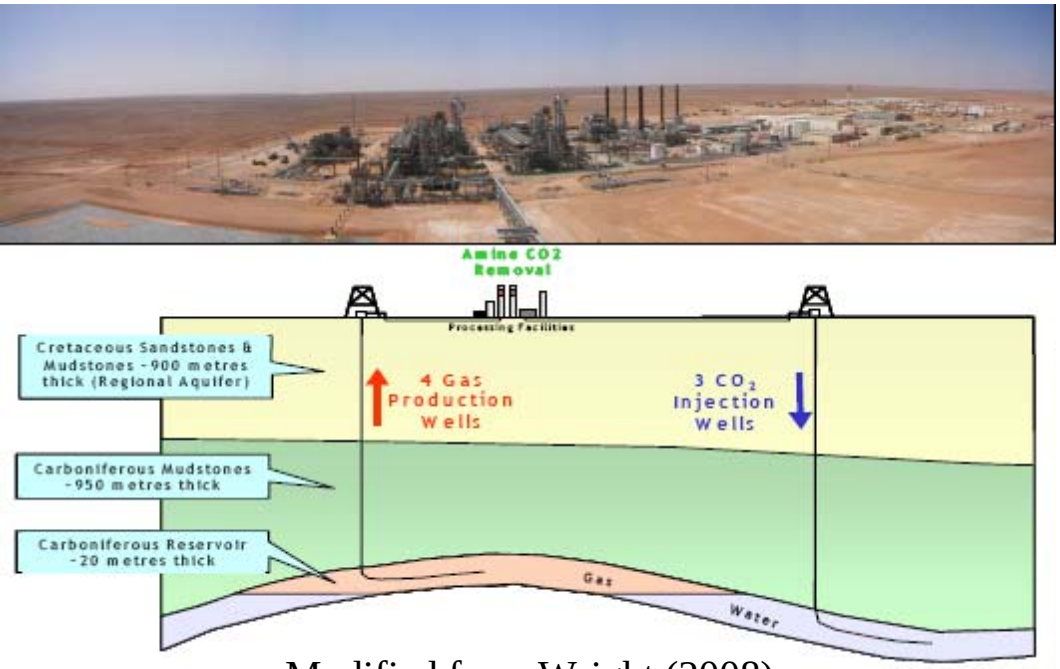
Outline

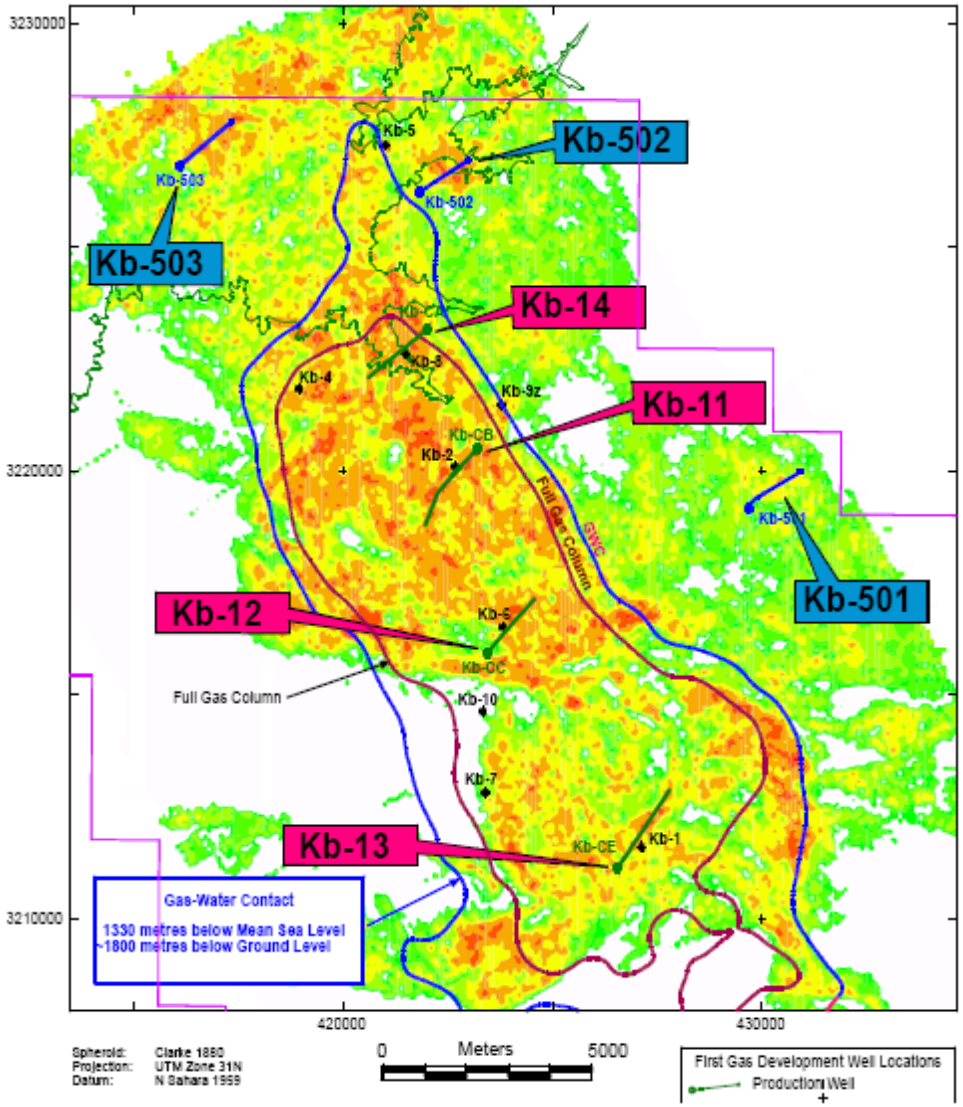
- A dual-continuum approach for coupled hydro-mechanical processes
  - *A new stress-strain relationship*
  - *Governing equations*
  - *Effective parameters*
- Simulation of injection at In Salah
  - *Model development*
  - *Data use*
  - *Sensitivity study*

CO_2 Geological Sequestration at In Salah



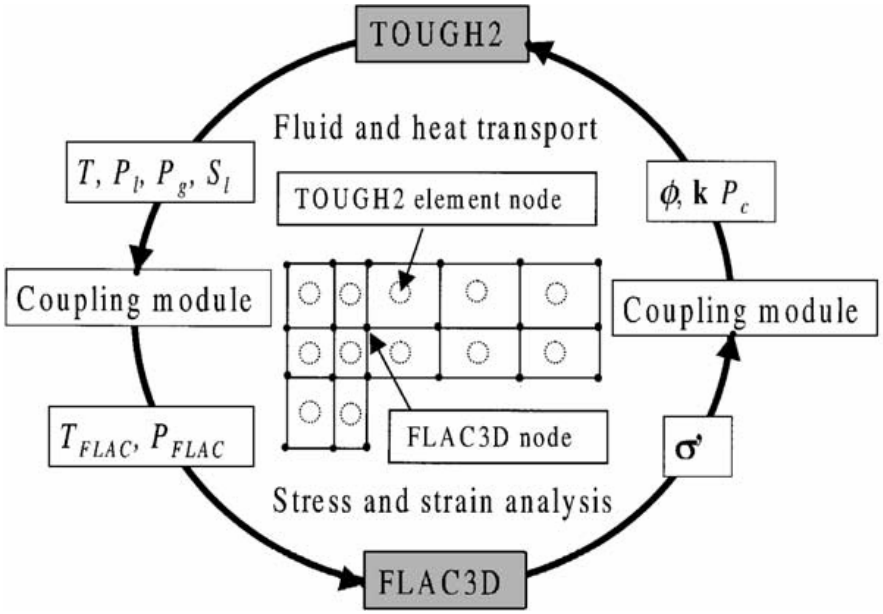
Modified from Wright (2008)

Fractures occur in nearly all geological settings and play a major role for hydrocarbon migration as well as entrapment (Iding and Ringrose, 2008).



Modeling Coupled Hydro-Mechanical Processes Using a Dual-Continuum Approach

- "Fully" and "partially" coupled modeling approaches for hydro-mechanical processes.
- Are governing equations for fluid flow in TOUGH2 (or other reservoir simulators) adequate for deformable rocks?
- How are effective parameters determined for modeling mechanical deformation of a dual-continuum system?



Rutqvist et al. (2002)

A New Stress-Strain Relationship:

Theory

- Hooke's Law:

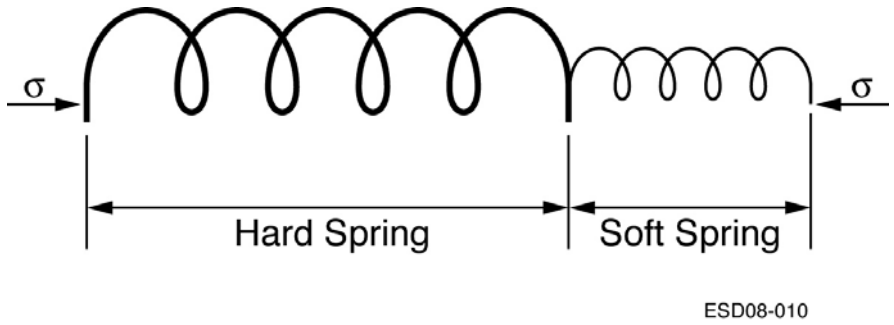
$$d\sigma = Kd\varepsilon_v$$

- Engineering and true (natural) strains

$$d\varepsilon_{v,e} = -\frac{dV}{V_0} \qquad d\varepsilon_{v,t} = -\frac{dV}{V}$$

- "Two-Parts" model:

A rock body can be divided into two parts: the hard part and soft part (that corresponds to a fraction of pore volume subject to a large degree of relative deformation [such as cracks])



•Stress-Strain Relationship (Liu et al. 2009)

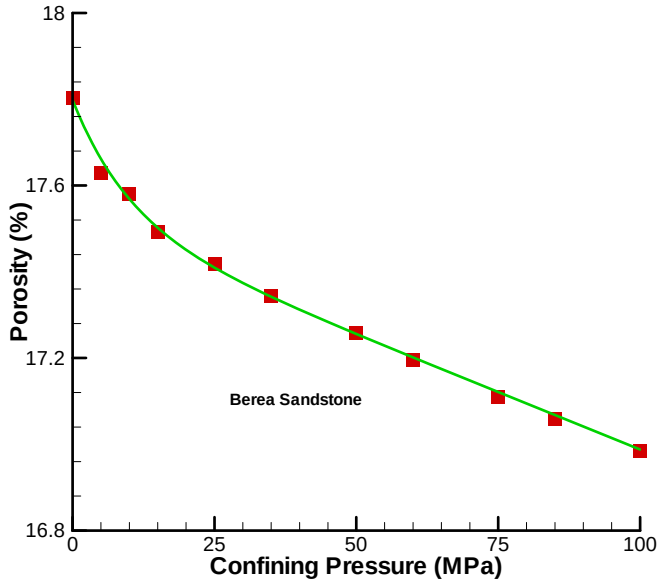
$$-\frac{dV}{V_0} = \gamma_e \frac{d\sigma}{K_e} + \gamma_t \frac{d\sigma}{K_t} \exp\left(-\frac{\sigma}{K_t}\right)$$

A New Stress-Strain Relationship:

Rock Porosity

- The derived relationship

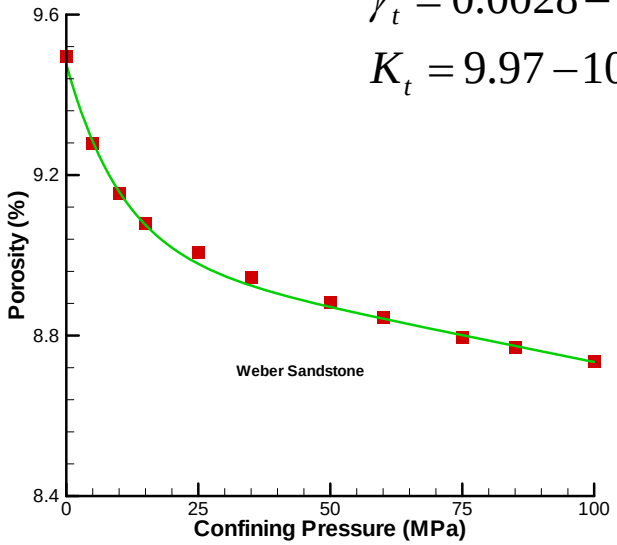
$$\phi = \phi_e (1 - C\ \sigma) + \gamma_t \exp(-\frac{\sigma}{K_{t,m}})$$



- The result matches porosity data set (Coyner, 1984)

$$\gamma_t = 0.0028 - 0.0048$$

$$K_t = 9.97 - 10.60 MPa$$



A New Stress-Strain Relationship:

Fracture Aperture

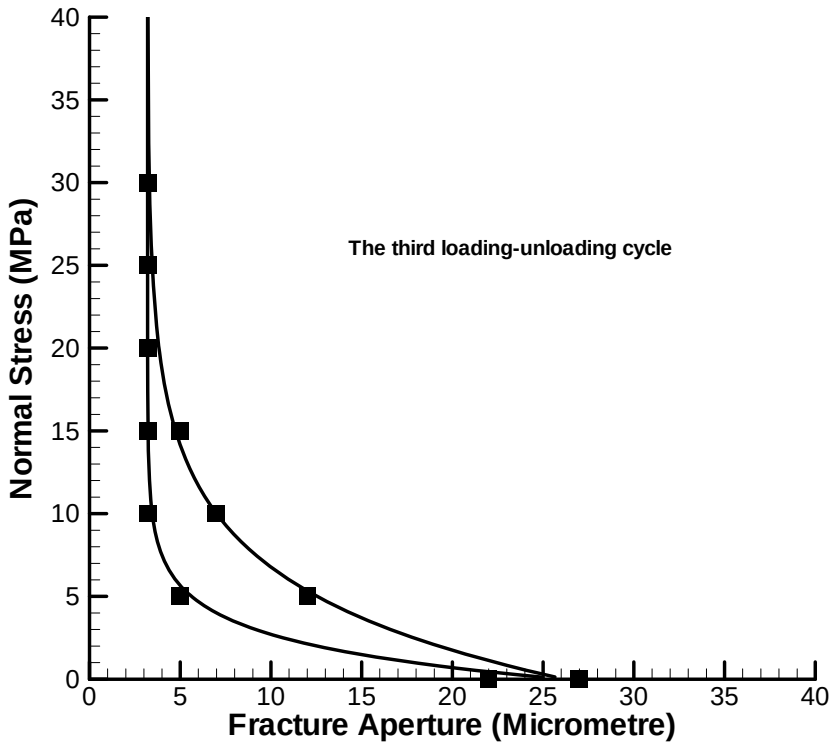
- The derived relationship

$$b = b_{0,e}(1 - \frac{\sigma}{K_{F,e}}) + b_{0,t} \exp(-\frac{\sigma}{K_{F,t}})$$

- The result is consistent with data and an empirical relation (Rutqvist et al., 2002)

$$b \approx b_{0,e} + b_{0,t} \exp(-\frac{\sigma}{K_{F,t}})$$

- A significant portion of fracture aperture is “soft”.



A Dual-Continuum Approach:

Governing Equations

- Pore Space Conservation

$$\frac{\partial \phi_j}{\partial t} + \nabla \bullet \left(\phi_j \boldsymbol{V}_s \right) = \Phi_j \alpha_j \frac{\partial \varepsilon_{v,j}}{\partial t}$$

- Governing Equation

$$\frac{\partial \left(M_{j,\psi}^k \right)}{\partial t} + \nabla \bullet \boldsymbol{q}_{j,r\psi}^k + \frac{M_{j,\psi}^k}{\phi_j} \left(\Phi_j \alpha_j \frac{\partial \varepsilon_{v,j}}{\partial t} - \frac{\partial \phi_j}{\partial t} \right) - \boldsymbol{Q}_{j,\psi}^k = 0$$

Additional storage term

A Dual-Continuum Approach:

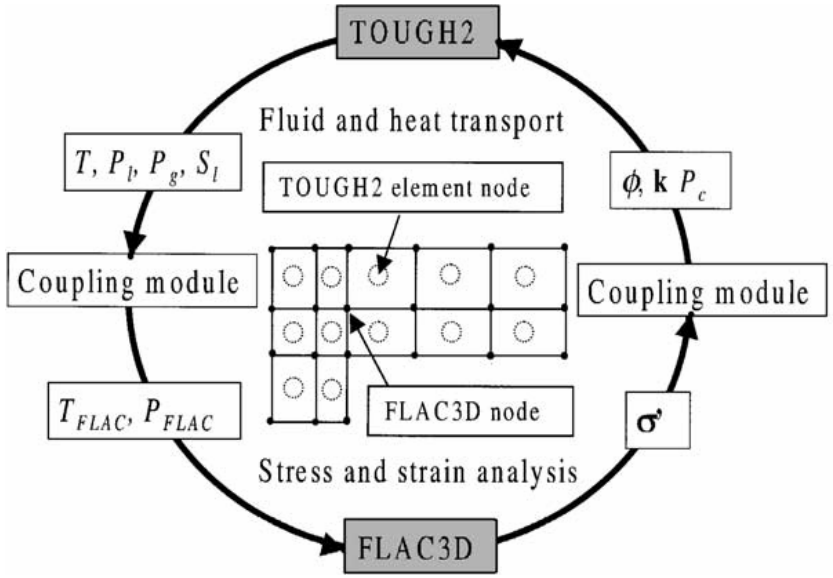
Effective Mechanical Parameters

- Effective stress for a single continuum

$$\sigma = \sigma_t - \alpha P$$

- Effective stress for a dual-continuum system

$$\sigma = \sigma_t - \frac{\alpha_F \Phi_F K_{eff}}{K_F} P_F - \frac{\alpha_M \Phi_M K_{eff}}{K_M} P_M$$



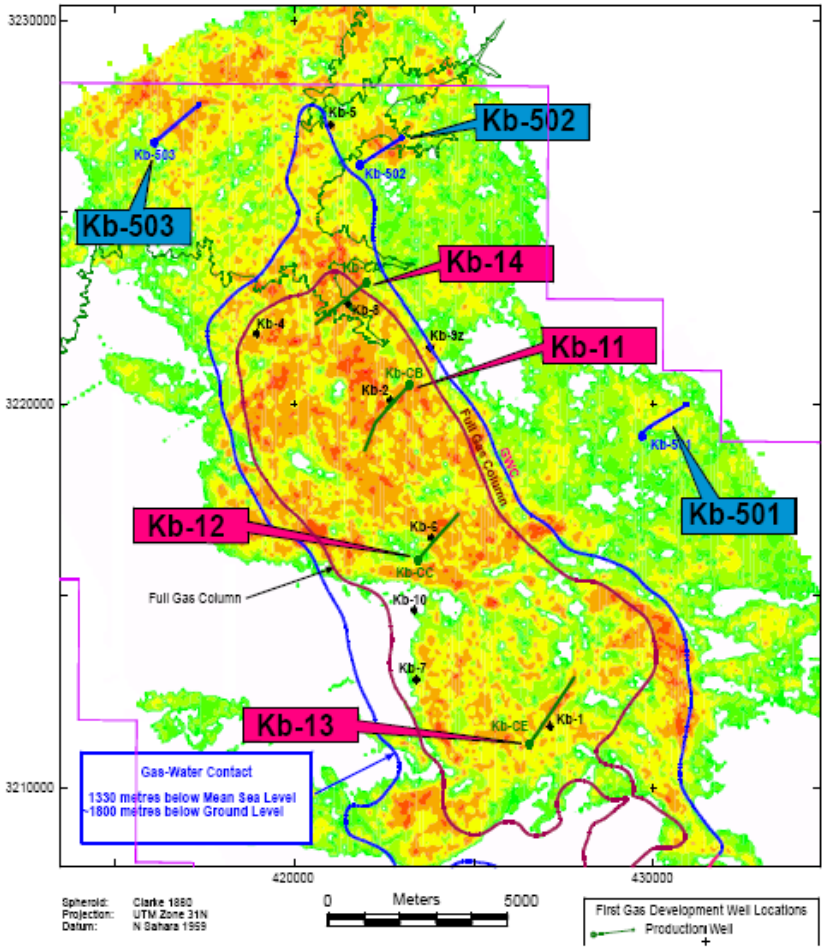
Rutqvist et al. (2002)

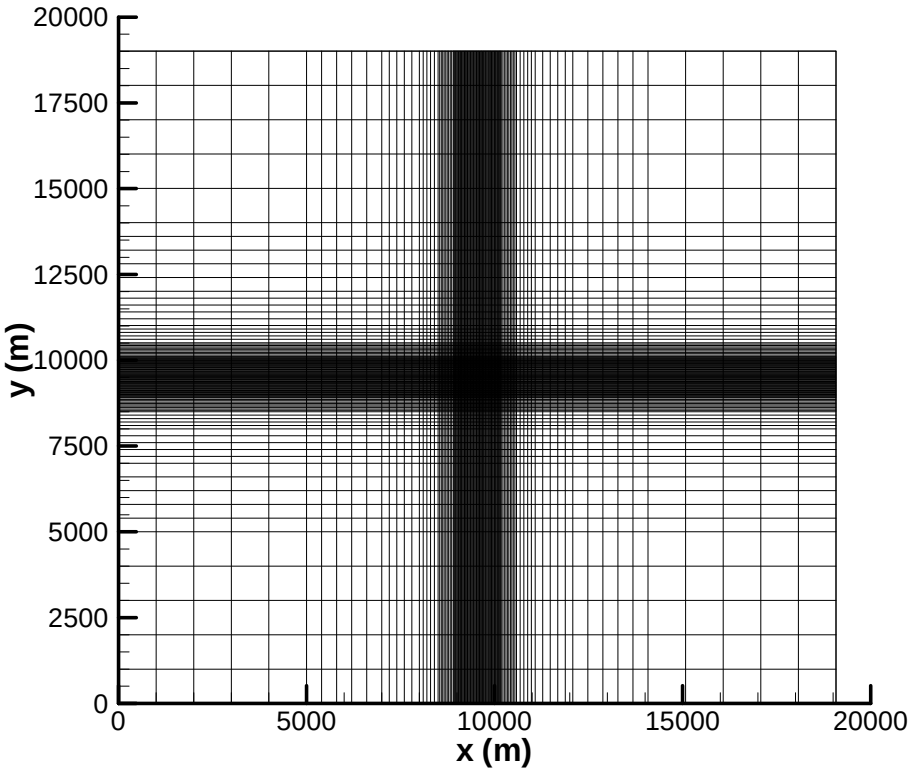
- Effective modulus for a dual-continuum system

$$K_{eff} = \frac{1}{\frac{\Phi_F}{K_F} + \frac{\Phi_M}{K_M}} \qquad K_j = \frac{1}{\frac{\gamma_{e,j}}{K_{e,j}} + \frac{\gamma_{t,j}}{K_{t,j}} \exp(-\frac{\sigma_j}{K_{t,j}})}$$

Simulation of injection at In Salah:

Model Development

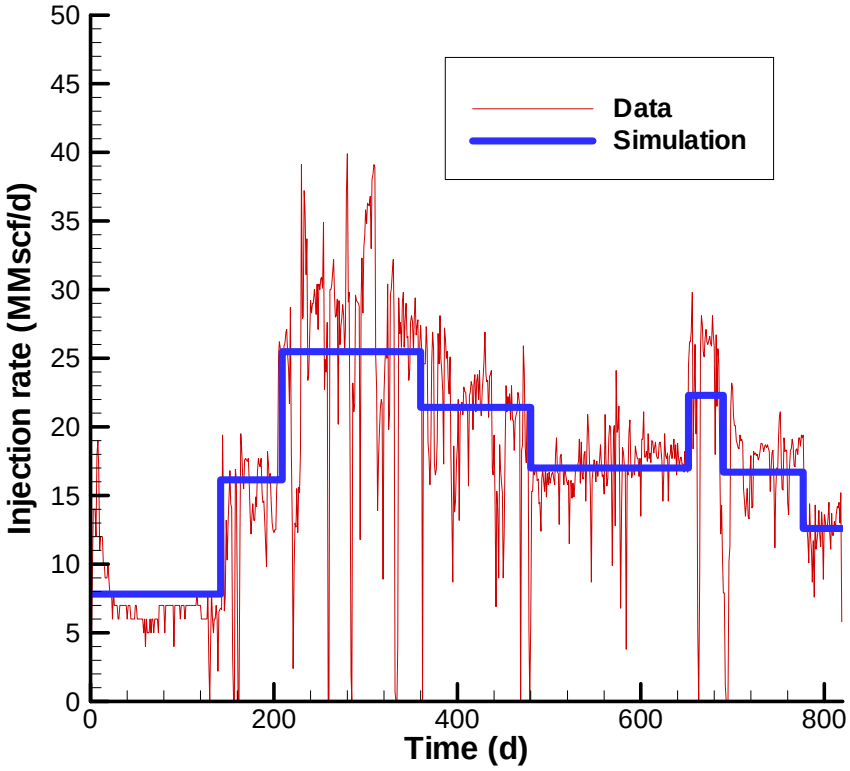


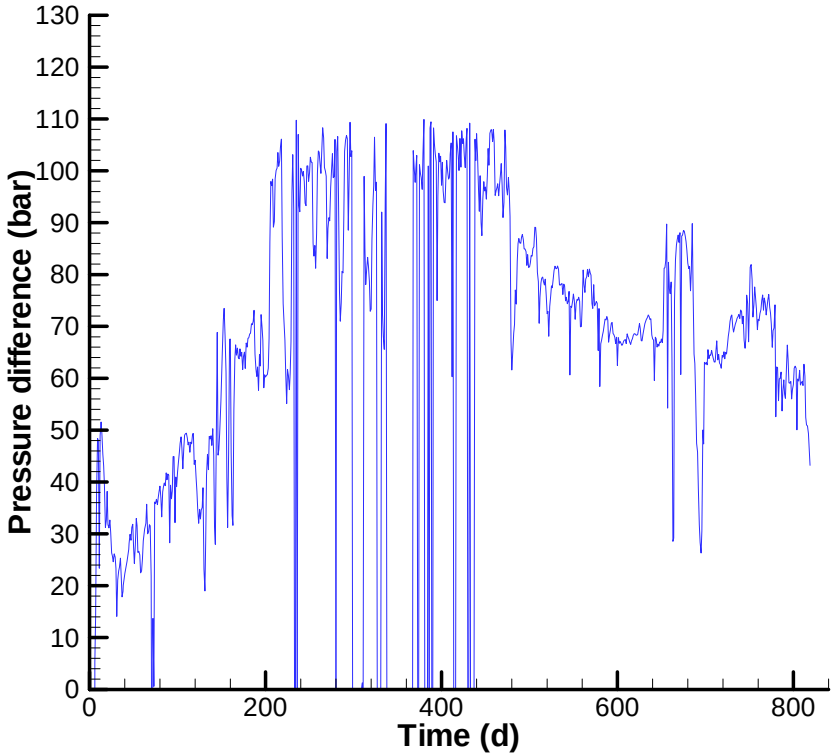


Wright (2008)

Simulation of injection at In Salah:

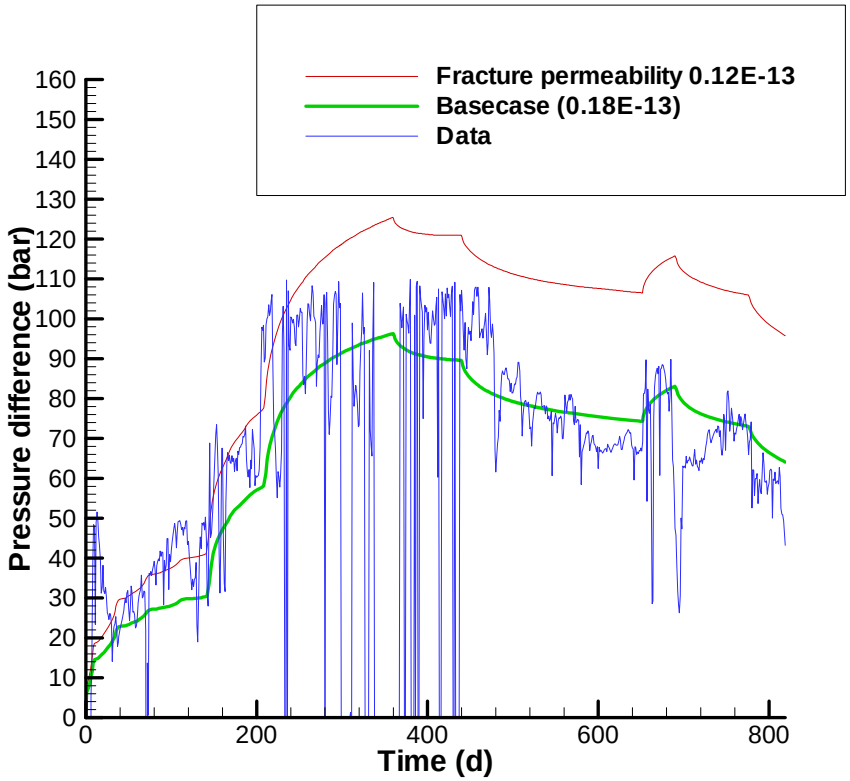
Data Use

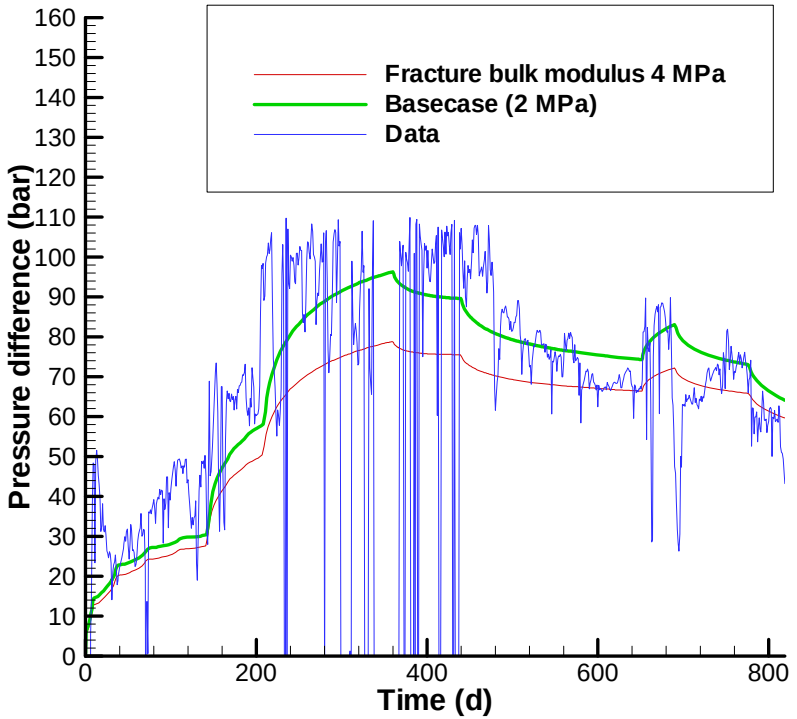




Simulation of injection at In Salah:

Sensitivity Study of Fracture Properties

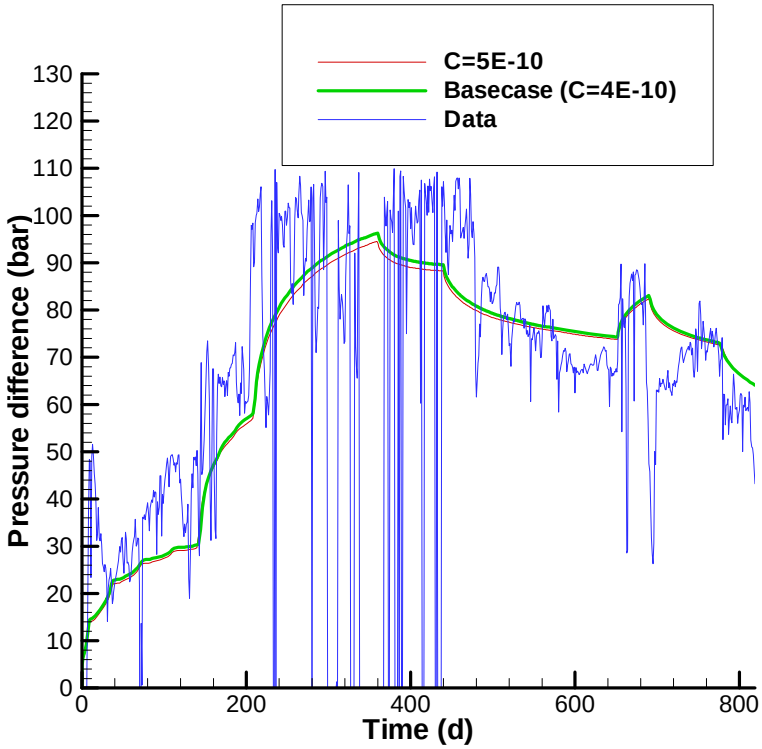


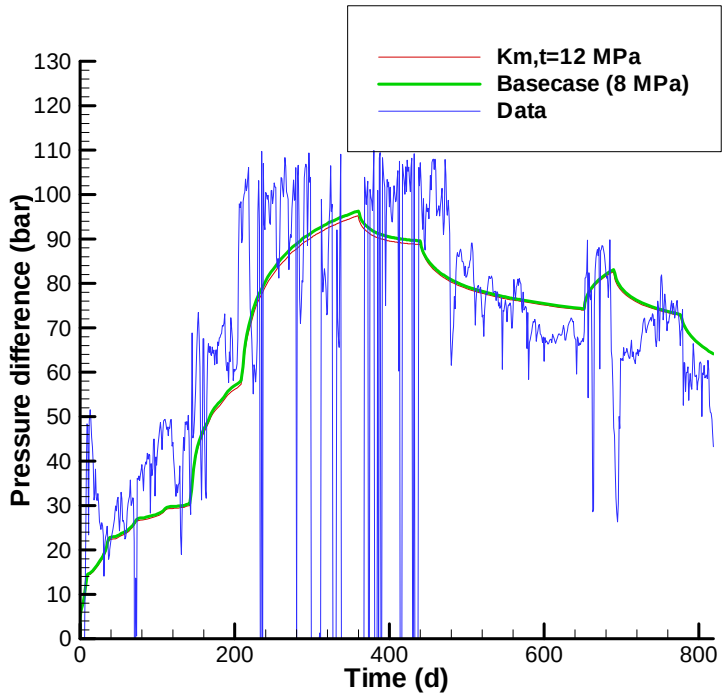


$$b \approx b_{0,e} + b_{0,t} \exp(-\frac{\sigma}{K_{F,t}})$$

Simulation of injection at In Salah:

Sensitivity Study of Matrix Properties





$$\phi = \phi_e (1 - C\,\sigma) + \gamma_t \exp\left(-\frac{\sigma}{K_{m,t}}\right)$$

Conclusions

- A dual-continuum approach for coupled hydro-mechanical has been developed for modeling CO_2 geological sequestration at In Salah.
- The governing equation for liquid flow includes an additional storage term owing to effects of rock deformation.
- Coupled hydro-mechanical process plays an important role in determining CO_2 injectivity.
- Fracture properties have significant effects on CO_2 injection process at the In Salah site.

Acknowledgement

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