Sino-Australia CCS Training Course

Coupled Hydro-geomechanical Modeling—Theories and Applications

KENI ZHANG

College of Water Sciences, Beijing Normal University, China

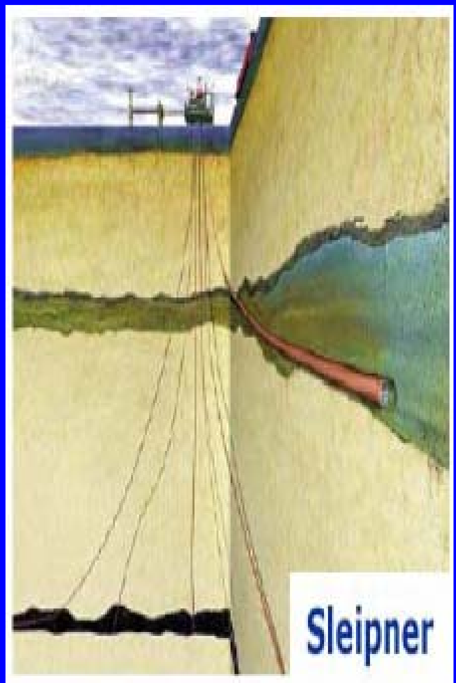
April 25, 2012 Beijing

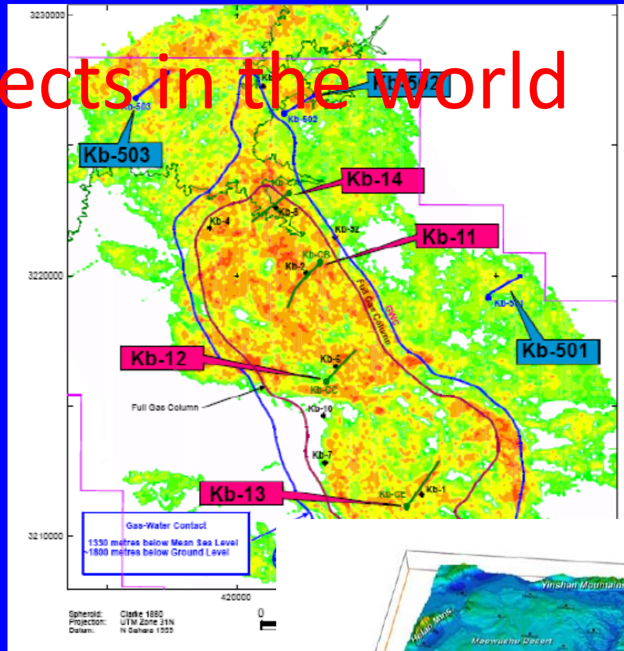
Overview

- Introduction
  - Forewords
  - Potential impacts of CCS
  - Monitoring techniques
- Theories concerning THM coupling
  - Fundamentals of geomechanics
  - Failure criteria
  - Basic ideals for THM coupling
- Implementation & applications on THM modeling
- Take-home points

Forewords

- On-going CCS projects in the world





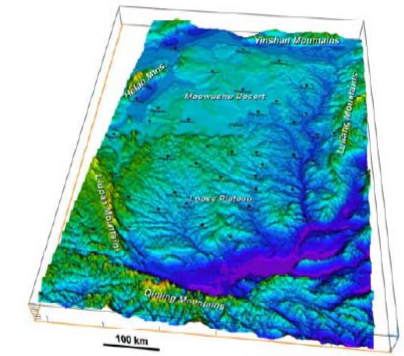


Figure 1. Geographic map of the Ordos Basin, China. From Jiao et al., 2010.

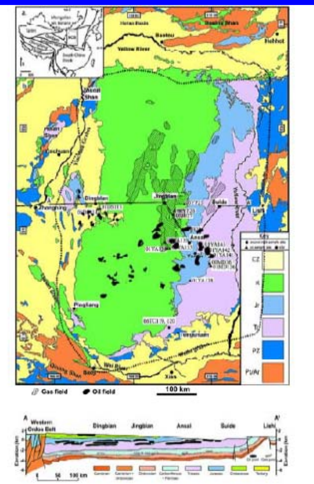


Figure 2. Geological map and cross section of the Ordos Basin show the huge monoclinal structure of the Shaanbei slope and the targeted CO_2 storage formation Ordovician carbonate. Modified from Li et al., 1992.

Forewords

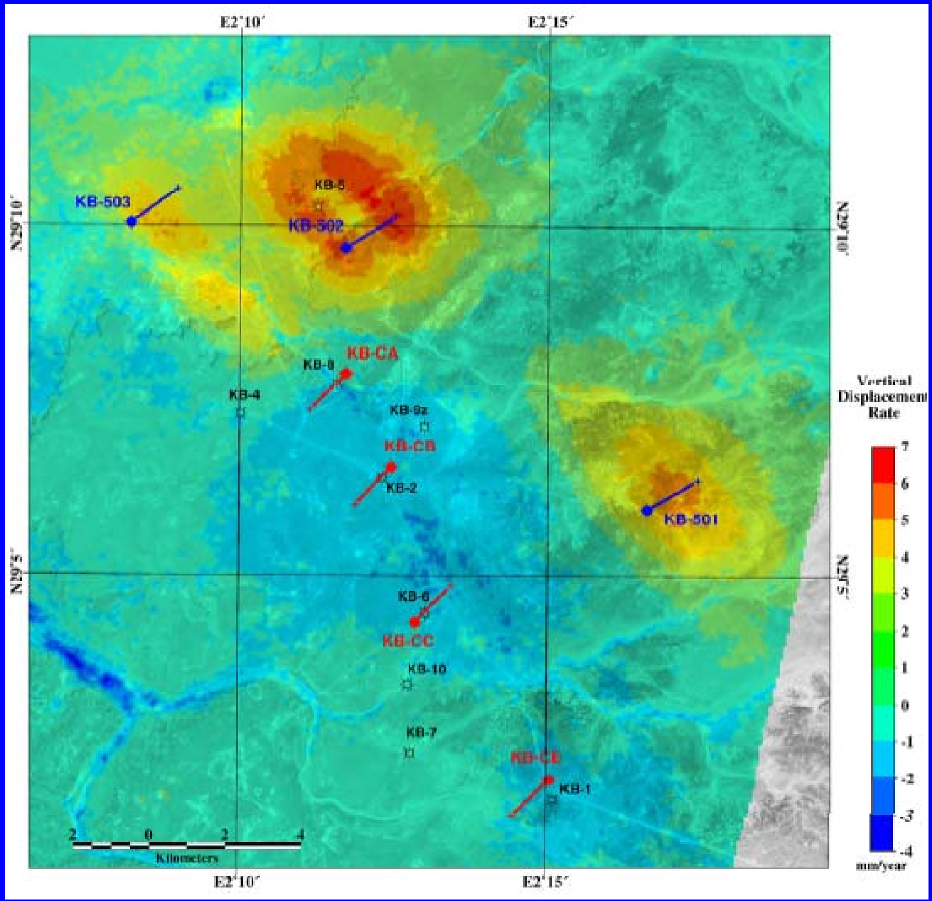
- Key issues concerning CCS
  - Storage capacity of reservoirs
  - Integrity of caprock seals
  - Potential impacts of CCS
    - Groundwater pollution or biotic perishing
    - Ground deformation or even mechanical failure (shear failure or hydraulic fracturing)
    - Activation of faults or microseismic events

How comes a THM modeling?

- Large amounts of CO_2 injection as a need,
- Safety security and environmental concerns increasingly important,
- Surface deformation data providing useful information on subsurface CO_2 flow behavior,
- Nothing but flow problem considered in traditional injection models.

Remote sensing as an effective surveillance tool for CCS induced surface deformation

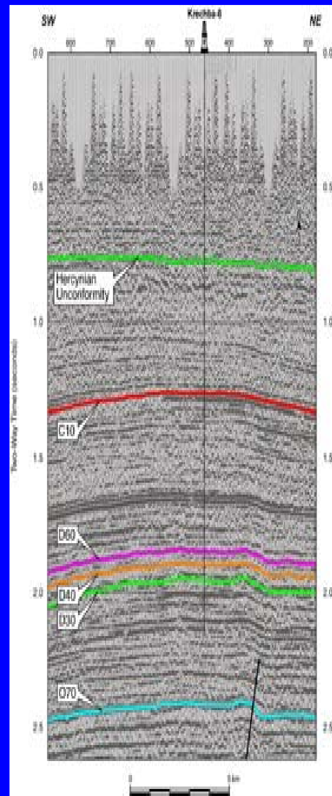
- Capability of Interferometric Synthetic Aperture Radar (InSAR) imaging
  - Resolution: order of cms or up to mms
  - Effective in all weather, day and night conditions
- Application
  - Calibration of THM models
  - Derivation of permeability (inverse modeling)



Vertical displacement rate (2004/7/31 - 2008/5/31) around the Krechba field detected by DInSAR stacking, after Onuma and Ohkawa (2008)

Surface-based or near surface monitoring for geodeformation

- State-of-art means
  - Time-lapse 3D seismic imaging
  - Tiltmeter
  - Global Positioning System (GPS)
- Application
  - Calibration of InSAR data or THM model



3D seismic at Krechba, modified from Mathieson et al. (2010)

COUPLING SIMULAIONS

- H
- TH
- THM
- THMC
- THMCB

EQUATIONS FOR FLOW SIMULATION

Mass/Energy Balance Equations:

$$\frac{d}{dt}\int_{V_n} M^{\kappa} dV_n = \int_{\Gamma_n} F^{\kappa} \bullet n d\Gamma_n + \int_{V_n} q^{\kappa} dV_n$$

Space and Time Discretized Equations:

$$R_n^{\kappa}(x^{t+1}) = M_n^{\kappa}(x^{t+1}) - M_n^{\kappa}(x^{t}) - \frac{\Delta t}{V_n}\{\sum_m A_{nm} F_{nm}^{\kappa}(x^{t+1})$$
$$+ V_n q_n^{\kappa,t+1}\} = 0$$

Solution Using Newton/Raphson iteration

$$-\sum_i \left.\frac{\partial R_n^{\kappa,t+1}}{\partial x_i}\right|_p (x_{i,p+1} - x_{i,p}) = R_n^{\kappa,t+1}(x_{i,p})$$

Theories concerning THM coupling

- Fundamentals of geomechanics
  - Important concepts
    - Load, stress, pressure, strain, bulk volume and pore volume, stiffness
    - Mean stress, mean effective stress, deviatoric stress
    - Cohesion, internal friction angle, Young's modulus, Bulk modulus, shear modulus, elastic modulus, Poisson's ratio

Theories concerning THM coupling

- Fundamentals of geomechanics
  - Hook’s Law

$$d\sigma = Kd\varepsilon_v$$

  - Terzhagi Equation (Terzhagi, 1936) generalized by Biot and Willis (1957)

$$\sigma' = \sigma_M - \alpha P$$

  - where σ' is effective stress, σ_M mean stress, P is pore pressure, and α is Biot coefficient.

Theories concerning THM coupling

- Failure criteria
  - Tensile failure
    - Fluid pressure>the normal stress
  - Shear failure
    - Mohr-Coulomb failure criterion

$$\tau \geq \sigma' \tan\theta + c$$

    - Drucker-Prager yield function

$$F = q - M\sigma'_M - c\beta$$

    - Where F<0 denotes elastic behavor, and yet F≥0 implies viscoplastic strain (Vilarrasa et al., 2010).

Theories concerning THM coupling

- Failure criteria
  - Hydraulic fracturing,

Park et al. (2011): $$f_s^{\,H} = \frac{P}{\sigma_3} > 1$$ i.e., Pore fluid pressure larger than the minimum principal stress

Basic ideas of THM coupling

- Porosity-mean effective stress relation
  - Rutqvist and Tsang (2002):

$$\phi = (\phi_0 - \phi_r)\exp(5 \cdot 10^{-8} \cdot \sigma'_M) + \phi_r$$

$$\sigma'_M = (\sigma'_1 + \sigma'_2 + \sigma'_3)/3$$

$$\sigma'_i = \sigma_i + \alpha\overline{P} \quad (i = 1,2,3)$$

  - McKee et al. (1988):

$$\phi = \phi_0 \frac{e^{-c_p(\sigma' - \sigma'_0)}}{1 - \phi_0\left(1 - e^{-c_p(\sigma' - \sigma'_0)}\right)}$$

Basic ideas of THM coupling

- Permeability-porosity relationship
  - Rutqvist and Tsang (2002):

$$k = k_0 \exp[22.2(\phi / \phi_0 - 1)]$$

  - Where k_0 is the zero stress permeability, ϕ_0 porosity at zero stress. Equation was modified from Davis and Davis (1999).

Basic ideas of THM coupling

- Permeability-porosity relationship
  - McKee et al. (1988):

$$k \propto \frac{\phi^{3}}{(1-\phi)^{2}}$$

- Permeability-effective stress relationship
  - Ostensen (1986):

$$k^{0.5} = D \ln(\sigma'^{*} / \sigma')$$

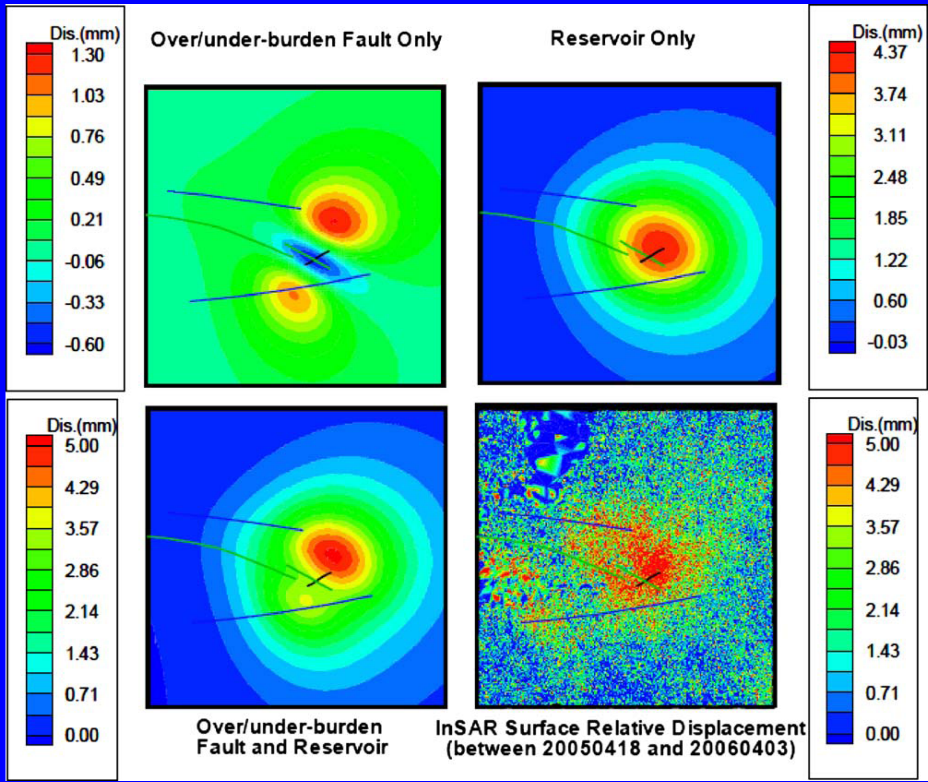
THM modeling codes

- TOUGH2-FLAC3D (Rutqvist and Tsang, 2002)
  - Assumption: linear elastic and isotropic hydromechanical properties
  - Feature: coupled through external functions
- TOUGH2-CSM (Winterfeld and Wu, 2011)
  - Assumption: hydrostatic and linear poroelasticity
  - Feature: parallelized, fully implicit numerical scheme
- COORES^{TM1}-ABAQUS^{TM2} (Deflandre et al., 2010)
  - Assumption: poroelastic behavior
  - Feature: in-house software, one-way coupling
- ECLIPSE (ECL, when?)
  - Feature: industry standard coupled flow-geomechanical numerical simulator

Implementation and applications

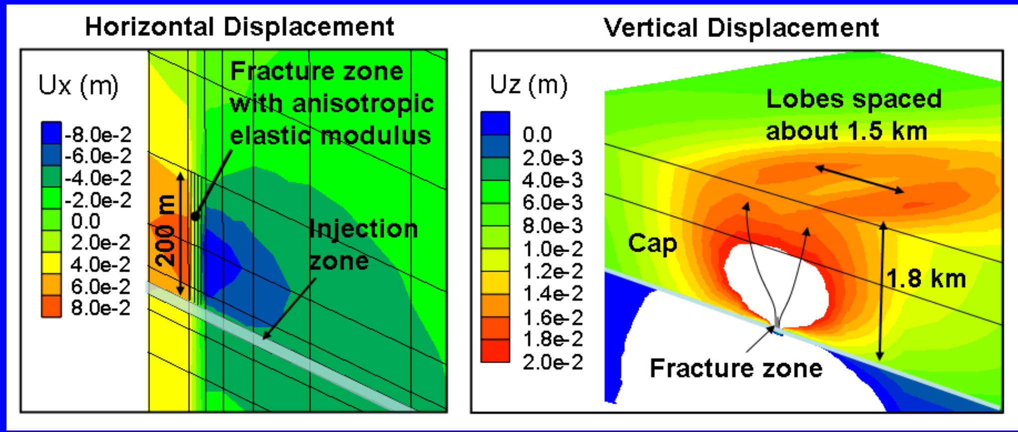
- In Salah, Algeria
  - Morris et al. (2011)

Through a combination of the reservoir and vertical fault pressurization (rather than either alone), the best fit is obtained in both the magnitude and the pattern of two-lobe of the surface uplift.



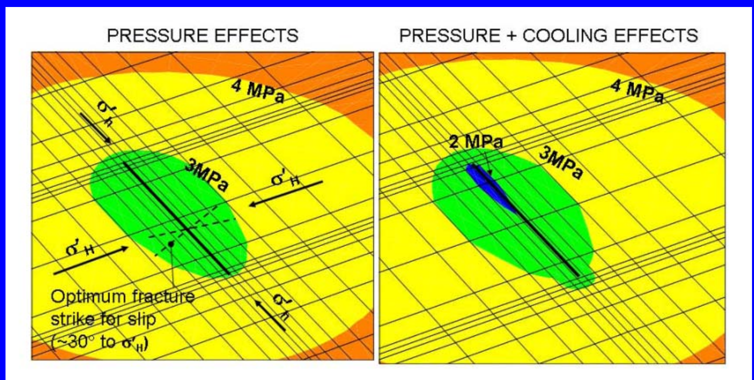
Comparison of predicted uplift with InSAR data at 1 year assuming a normal stiffness of 0.01 GPa/m on the fault.

- In Salah, Algeria
  - Rutqvist et al. (2010)



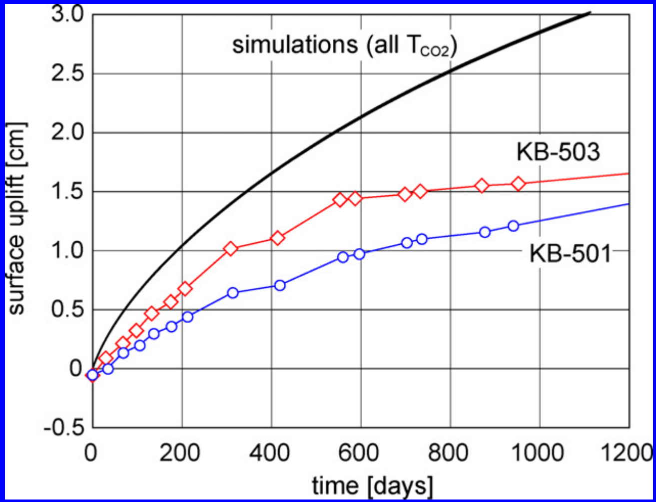
The highest potential for injection-induced micro-seismicity was caused by the combined effects of injection-induced cooling and pressure. However, the potential for microearthquakes is relatively low .

Forward coupled numerical modelling of CO2 injection with pressure inflation of the vertical fracture zone that results in a double lobe uplift response on the ground surface similar to observations



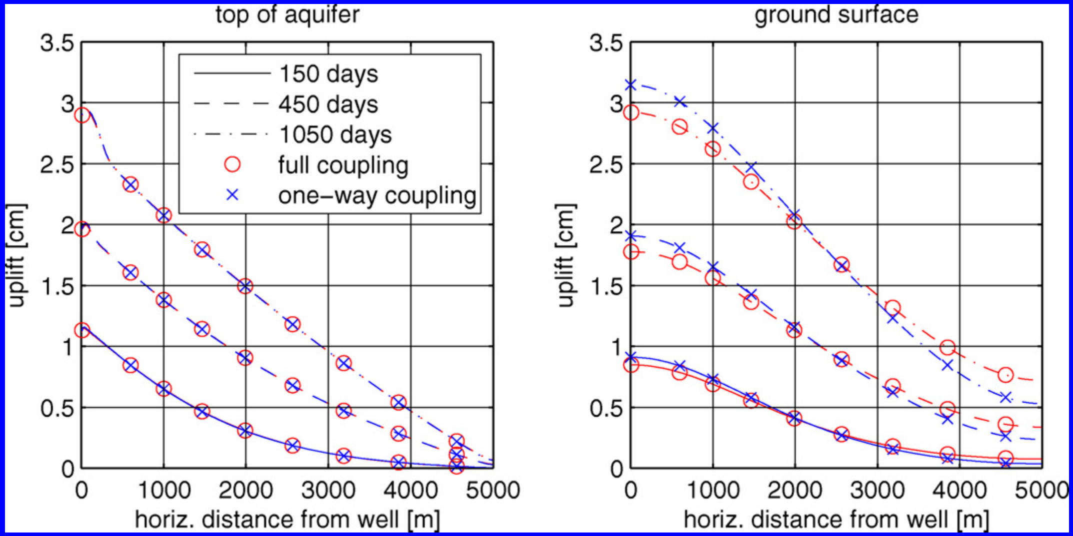
Calculated potential for induced seismicity expressed in terms of a strength-to-stress margin after about 3 years of injection. The margin of 2 Mpa means that the rock mass strength exceeds the stress by 2 MPa, which indicates that no injection-induced seismicity would occur.

- In Salah, Algeria
  - Preisig and Prévost (2011)

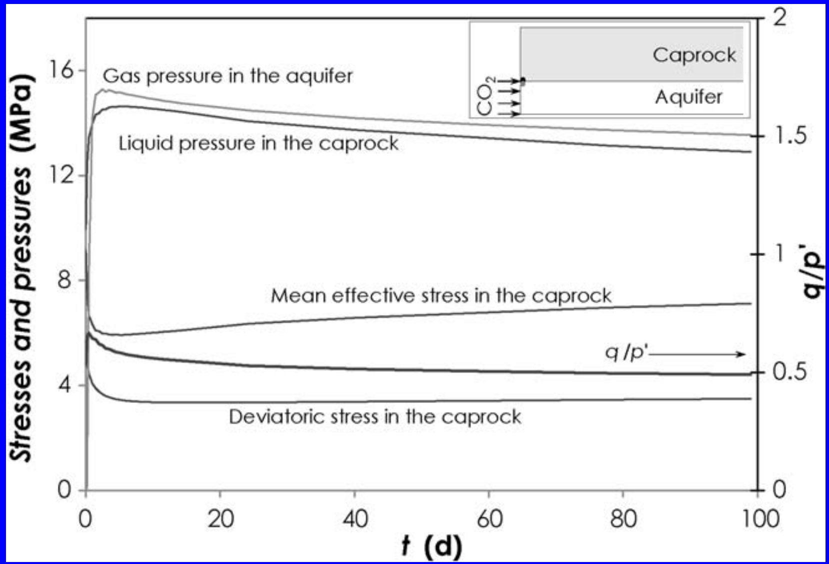


Ground uplift above the injection well, computed values vs. measured values.

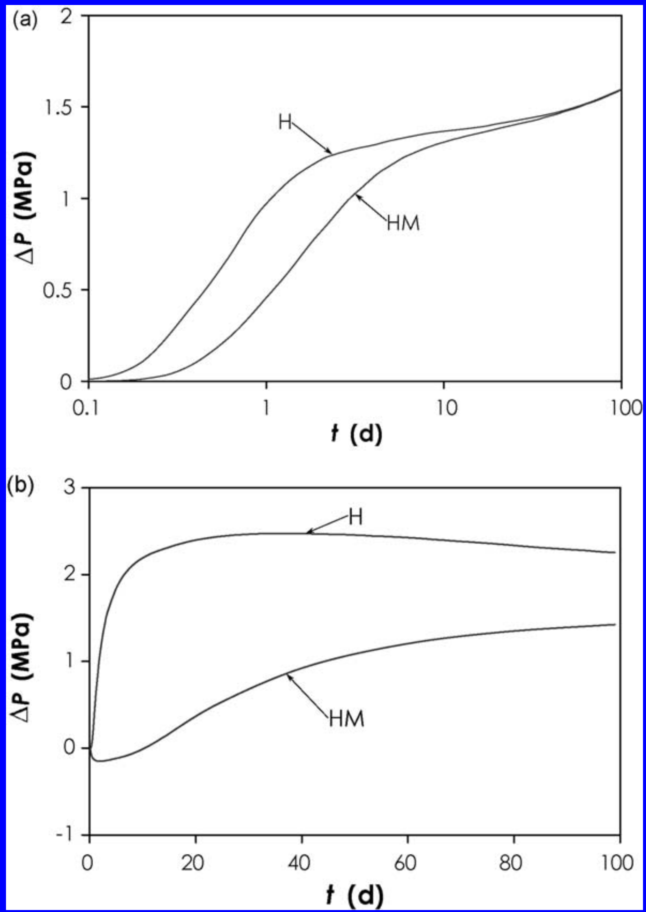
Uplift profiles on top of the aquifer and at the ground surface: results are given for full coupling and for one-way coupling (T = −40 ◦ C).



- Synthesized site
    - Vilarrasa et al. (2010)

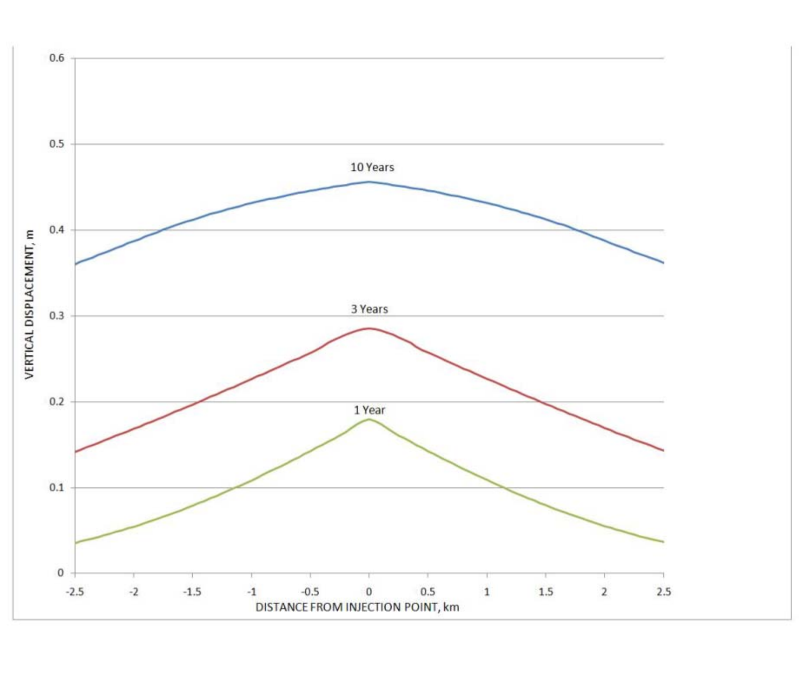


Stress and pressure evolution with time at the beginning of CO2 injection at the base of the caprock next to the injection well.

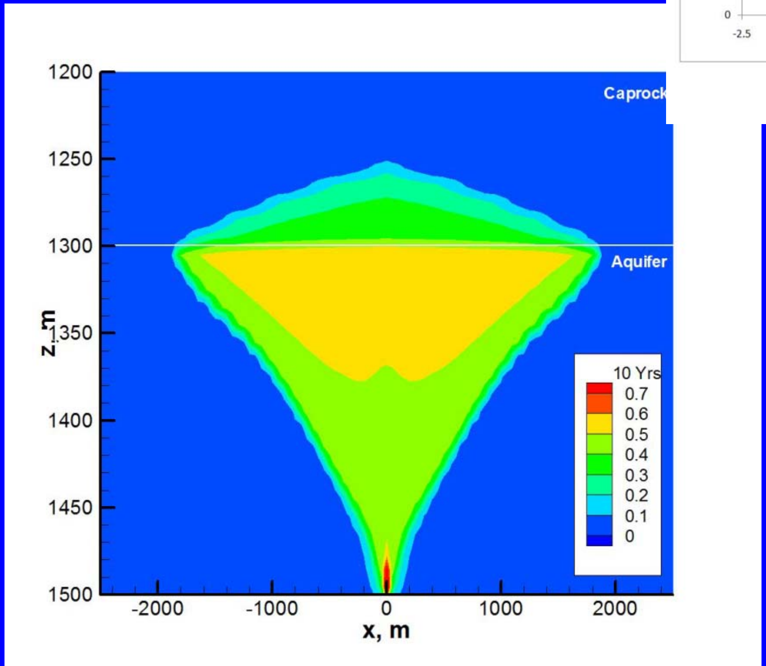


Fluid overpressure, comparing pure hydraulic (H) with coupled hydromechanical (HM) simulation in (a) the aquifer at the contact between the aquifer and the caprock 400m from the injection well and (b) in the caprock 50m above the aquifer and 50m away the injection well.

- Synthesized site
  - Winterfeld and Wu (2011)



Surface uplift at 1, 3, and 10 years by using coupled THM simulator TOUGH2-CSM



CO2 saturation profile at 10 years

Take-home points

- Coupled THM modeling can capture the initial drop of the fluid pressure due to mechanical effects, which otherwise cannot be identified by purely hydraulic models.
- The least favorable moment takes place at the beginning of injection (Vilarrasa et al., 2010).
- Shear failure usually occurs at a lower injection pressure than hydro-fracturing (Rutqvist et al., 2008).

Take-home points

- The cooling effect of the injected CO_2 causes reduction of compressive stresses or even tensile stresses, and probably creation or re-opening of fractures.
- Ground surface uplift can be explained by poro-elastic response to the injection induced over-pressurization. Development of poro-elastic stress can be an important factor in suppressing the likelihood of injection-induced micro-seismicity.

Take-home points

- The response of a system to CO_2 injection is to relieve the build-up in pressure by elastic deformation, creating surface uplift, and by fracturing.

References

- Deflandre J., Estublier A., Baroni A., Daniel J., Adjemian F., 2010. Energy Procedia, 00: 000-000.
- Morris J. P., Hao Y., Foxall W., McNab W., 2010. In Salah CO2 storage JIP: Hydromechanical simulations of surface uplift due to CO2 injection at In Salah. Energy Procedia, 00: 000-000.
- Vilarrasa V., Bolster D., Olivella S., Carrera J., 2010. Coupled hydromechanical modeling of CO2 sequestration in deep saline aquifers. International Journal of Greenhouse Gas Control, 4: 910-919.
- Winterfeld P. H., Wu Y. S., 2011. Parallel simulation of CO2 sequestration with rock deformation in saline aquifers. SPE 141514: 1-22.
- Rutqvist J., Tsang C, 2002. A study of caprock hydromechanical changes associated with CO2-injection into a brine formation. Environmental Geology, 42: 296-305.
- Rutqvist J., Liu H., Vasco D., Pan L., Majer E., 2010. Energy Procedia, 00:1-8.

Thank you!