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Parameter estimation of reservoir and geomechanical modeling of a CO_2 injection test and surface uplift at In Salah, Algeria

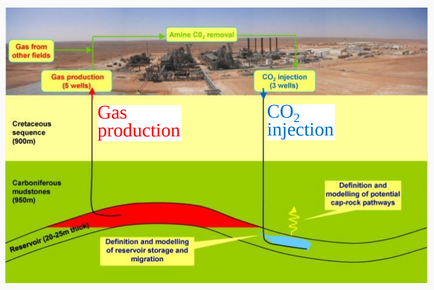
Hongkyu Yoon[1], Pania Newell[1], Mario J. Martinez[1], Joseph E. Bishop[1], Bill W. Arnold[1], and Steven L. Bryant[2]

[1] Sandia National Laboratories, Albuquerque, NM; [2] University of Texas, Austin, TX

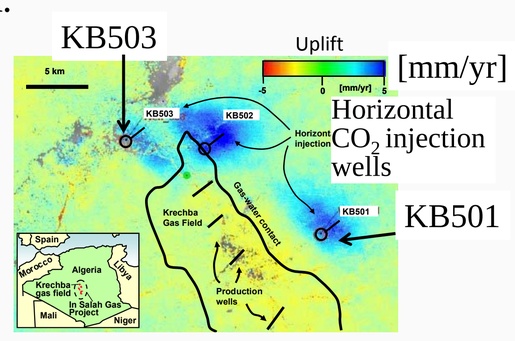
Center for Frontiers of Subsurface Energy Security

Introduction

In Salah, an industrial-scale CCS project in Algeria has been in operation since 2004. In Salah is currently the world's largest onshore CO_2 storage project. Almost one million tonnes of CO_2 per year have been separated from the produced gas in the field and about 70% of it has been re-injected back to the subsurface. The injection zone is 20 m thick and it is located at a depth of around 1810 m below the surface ground. CO_2 has induced uplift at the ground surface measurable by InSAR.



In Salah CO_2 storage site (Iding et al. 2010)



InSAR data of rate of vertical displacements for first 3 yrs of CO_2 injection (Rutqvist, 2012)

Objectives

The motivations and objectives for this study are as followings:

1) Validation of coupled flow and geomechanics model against observed uplift
2) Sensitivity to key material parameters and conceptual models
3) Parameter estimation and uncertainty quantification for coupled model

Multiphase Flow and Geomechanics

Sierra: a framework of coupled multiphysics simulation software composed of a suite of highly parallelized finite element analysis code modules for coupled fluid, solid, thermal, and chemical processes. This work utilizes the coupling of the *Sierra/Aria* module for multiphase flows with the *Sierra/Adagio* module for nonlinear geomechanics (Martinez et al., 2013)

Multiphase flow:

$$\frac{\partial(\rho_w \phi S_w)}{\partial t} = \nabla.\left(\rho_{\mathbf{w}} \frac{\mathbf{k_{rw}}}{\mu_{\mathbf{w}}} \mathbf{k}.(\nabla \mathbf{p_w} - \rho_{\mathbf{w}} \mathbf{g})\right) + \mathbf{Q_w}$$

$$\frac{\partial(\rho_n \phi S_n)}{\partial t} = \nabla.\left(\rho_{\mathbf{w}} \frac{\mathbf{k_{rn}}}{\mu_{\mathbf{n}}} \mathbf{k}.(\nabla \mathbf{p_w} + \nabla \mathbf{p_c} - \rho_{\mathbf{n}} \mathbf{g})\right) + \mathbf{Q_n}$$

$$s_w + s_n = 1$$

Solid: $\nabla.\sigma + \rho_s \mathbf{g} = 0 \quad \sigma^{eff} = \lambda tr(\epsilon)\mathbf{I} + 2G\epsilon \quad \epsilon = \frac{1}{2}\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right)$

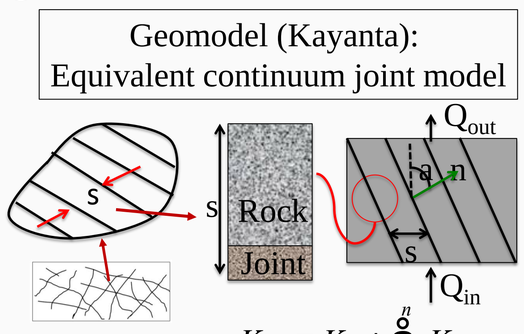
Coupling:

Fluid Mechanics ARIA (Pore pressure) ⇄ **Coupled: Arpeggio** ⇄ Solid Mechanics ADAGIO (Displacement)

Joint Model: Kayenta

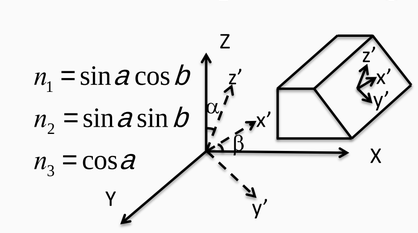
Motivations: Evidence of near-vertical fractures or joints at the reservoir/aquifer level (e.g., core samples). Therefore, it is essential to use a geomechanical constitutive model to account for pre-existing fractures.

Geomodel (Kayanta): Equivalent continuum joint model



$$K_{eff} = K_R + \sum_{J=1}^{n} K_J$$

$$n_1 = \sin a \cos b \quad n_2 = \sin a \sin b \quad n_3 = \cos a$$



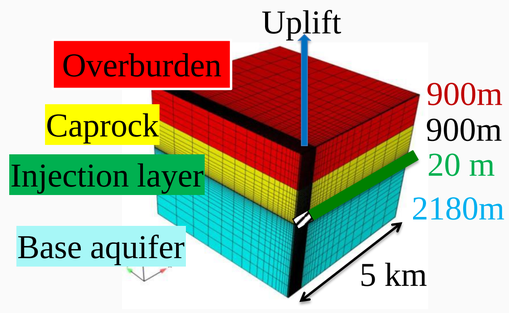
$$K_J = \frac{b^3}{12s}\begin{bmatrix} 1-n_1^2 & -n_1 n_2 & -n_1 n_3 \\ -n_1 n_2 & 1-n_2^2 & -n_2 n_3 \\ -n_1 n_3 & -n_2 n_3 & 1-n_3^2 \end{bmatrix}$$

Joint opening

Coupling:

- Solid Mechanics Adagio: K_j
- Fluid Mechanics Aria: K_R
- Effective Permeability : K_{eff}

InSalah Model Problem



Injection rate: 0.2 Mt/yr for 3 yr

Injection zone(500m long)

Observed data: Uplift at the ground surface (KB501 & KB503 wells)

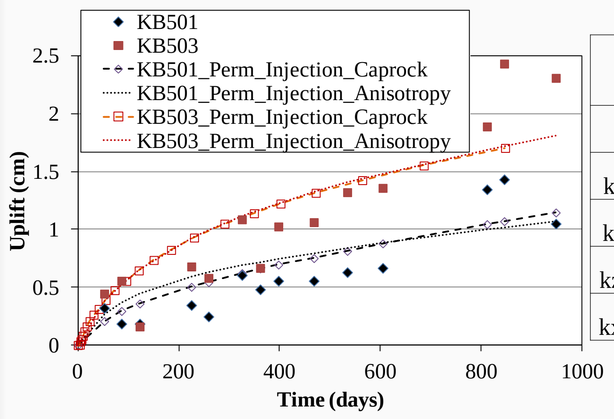
Parameters of interest (values in parenthesis are the reference):

- Intrinsic permeability of caprock (1.0E-19m^2) & injection zone (1.3E-14m^2)
- Anisotropy ratio of caprock (1.0) & injection zone (1.0)
- Biot's coefficient of injection zone (1.0)
- Presence of pre-existing joints (Kayenta model): OFF

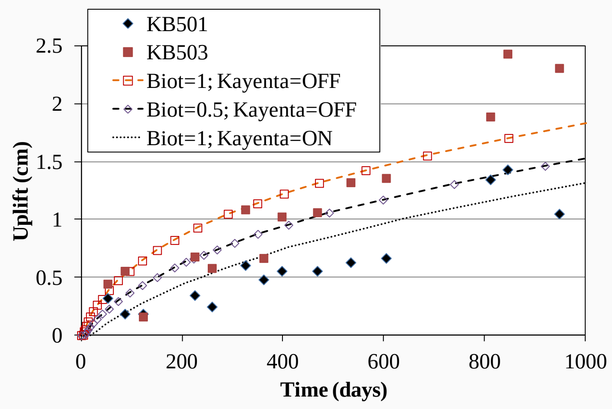
Parameter estimation and uncertainty quantification:

- PEST (Parameter ESTimation software)
- DAKOTA (Design Analysis Kit for Optimization and Terascale Applications)

Calibration results with two parameters



	KB501 data		KB503 data	
	k_Inj_Cap	k_inj_aniso	k_Inj_Cap	k_inj_aniso
kz_caprock	2.15E-18	1.00E-19	1.00E-19	1.00E-19
kx_caprock	2.15E-18	1.00E-19	1.00E-19	1.00E-19
kz_injection	5.66E-14	1.35E-15	1.32E-14	9.44E-16
kx_injection	5.66E-14	2.26E-14	1.32E-14	1.29E-14



Reference case with biot and kayenta model

- Multiple calibrated models can match the observed data
- Horizontal permeability of the injection zone is sensitive to the observed data
- Both low Biot coefficients and inclusion of the pre-existing fractures within the injection zone (kayenta=ON) affect the degree of uplift considerably
- Parameter estimation with other parameters are required
- Computationally efficient parameter estimation and uncertainty quantification is required (e.g., non-gradient based search, polynomial chaos expansion, null-space Monte Carlo)

References

Iding, M. and P. Ringrose (2010). "Evaluating the impact of fractures on the performance of the In Salah CO2 storage site." International Journal of Greenhouse Gas Control **4**(2): 242-248.

Martinez, M. J., Newell, P., Bishop, J. E. and Turner, D. Z. (2013). "Coupled multiphase flow and geomechanics model for analysis of joint reactivation during CO2 sequestration operations." International Journal of Greenhouse Gas Control.

Rutqvist, J. (2012). "The Geomechanics of CO2 Storage in Deep Sedimentary Formations." Geotech Geol Eng **30**: 525-551.

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