The Fluidal Interface is Where the Action is in CO_2 Storage

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Summary

We examine the mechanical integrity of a deep saline aquifer during the injection of supercritical CO_2. The analysis is conducted with a numerical scheme of the capillary pressure and non-wetting pressure for multiphase flow. In this study, unidirectional hydromechanical coupling is considered: fluid pressure and phase saturation influence mechanical stress via the momentum equation, while feedbacks to fluid pressure from mechanical deformation are not considered. Caprock stability is monitored in time, referenced to the potential for hydraulic fracture and shear slip along an optimally oriented shear plane for a suite of injection pressures. For reasonable parameter values and the chosen aquifer geometry, significant mechanical failure (and potential breach of integrity) is expected in the shale caprock for all but low injection rates. This indicates that the analysis of the hydromechanical response is crucial for proper selection of injection sites, injection rates, and total storage capacity.

Introduction

In this paper, we utilize the open source scientific software OpenGeoSys for the simulation of coupled thermo-hydro-mechanical-chemical processes in porous media to analyze mechanical reservoir changes [*Kolditz et al.*, 2008; *Park et al.*, 2008; *Wang and Kolditz*, 2007]. The study is to identify potential failure of a caprock and an aquifer in a hypothetical two-layer reservoir system. In an effort to reduce failure potential in both the caprock and the aquifer and to demonstrate the relationship between CO_2 injection and mechanical failure, different scenarios for CO_2 injection are analyzed. Finally, we provide information on the weakest area of the reservoir for mechanical failure in CO_2 capture and storage (CCS).

Theory for Failure Modes

We consider two potential failure modes. The first assumes, conservatively, that hydraulic fracturing (e.g., tensile failure) may occur when the pore fluid pressure, $p_f \left(= p_w S_w + p_{nw} S_{nw}\right)$, exceeds the current minimum principal stress, σ_3. This defines a factor of safety for hydraulic fracturing,

$$f_S^H = \frac{p_f}{\sigma_3} \tag{13}$$

so that $f_S^H \geq 1$ implies incipient failure. The second mode allows for shear slip/failure along an optimally oriented fracture plane. In two dimensions, the Mohr-Coulomb failure criterion says that the failure is favorable when the current maximum shear stress, $\tau_m = 1/2\left(\sigma_1 - \sigma_3\right)$, becomes [*Jaeger et al.*, 2007],

$$\left|\tau_m\right| \geq C_h \cos\theta + \left(\sigma_m - p_f\right)\sin\theta \tag{14}$$

where σ_1 is the maximum principal stress, $\sigma_m = 1/2\left(\sigma_1 + \sigma_3\right)$ is the mean normal stress, C_h is the cohesion, and θ is the internal friction angle. This relationship defines a factor of safety for shear slip/failure,

$$f_S^S = \frac{|\tau_m|}{C_h \cos\theta + (\sigma_m - p_f)\sin\theta} \tag{15}$$

As before, $f_S^S \geq 1$ implies incipient failure.

Example definition

The problem domain is chosen to be a vertical cross-section 100m in length and 10m in depth, with the caprock/aquifer interface located at 6m above the bottom impermeable boundary. The lower boundary is located at 3010m from the surface (Figure 1). A volumetric injection rate of 1.87×10^{-3} m^3/day at the point source over a 20 year life is back calculated from an equivalent total injection rate of 500 tones/year in the 1km long horizontal well. For given conditions of porosity in the aquifer and caprock (Table 1), 500 tons/yr is chosen so as to allow observable changes in primary variables over the injection life. A larger injection rate would likely be sustainable for a thicker aquifer system.

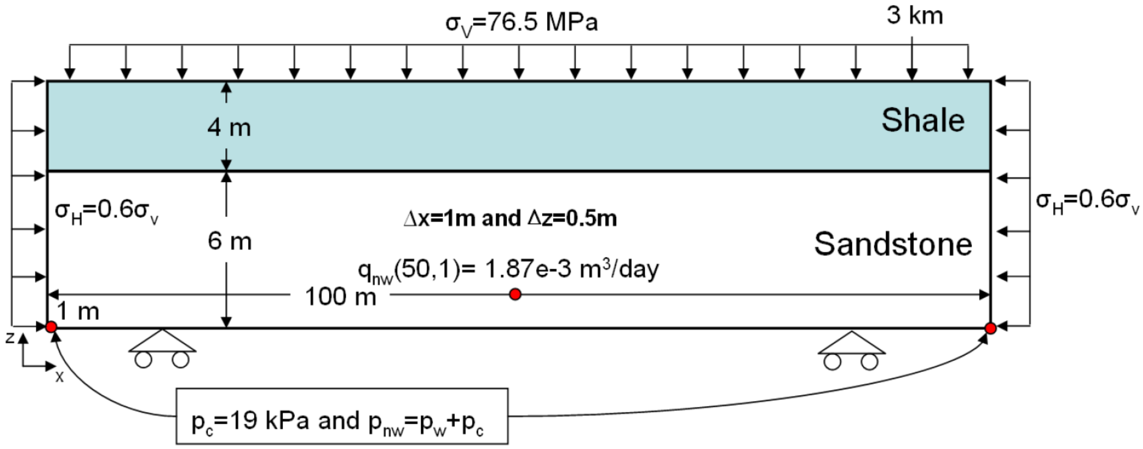

Figure 1: Model domain and boundary conditions for two-phase flow and elastic mechanical deformation for CO_2 benchmark

Due to the caprock from the aquifer vertically, the scheme tends to propagate horizontally over 100 years of simulation time (Figure 2).

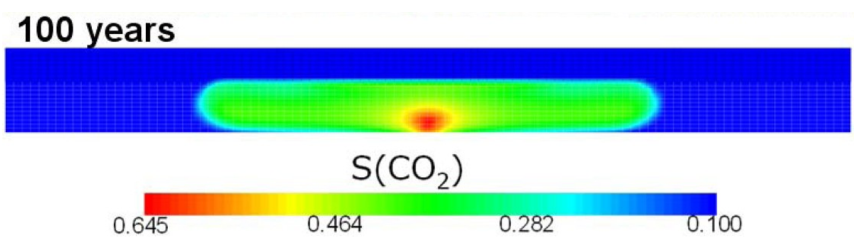

Figure 2: CO_2 saturation with 20 years of the injection at 100 years

The observation that mechanical stability improves over time introduces the motivation for alternate injection scenarios that may reduce the risk of failure. An additional simulation was thus conducted with a linearly increasing injection rate, and the results compared with those obtained from the uniform injection of 500 tons/year. The cumulative amount of CO_2 injected for both injection scenarios is identical over the chosen time period of 10 years. Since the injection rate increases linearly from a lower injection rate (250 tons per year) compared to the reference (500 tons/year), safety factor should be reduced in early times. This occurrence is observed in Figure 3 for the first 5 years of injection. The injection rate at 5 years in both scenarios is identically 500 tons/year, but the size of the CO_2 plume for the linear injection case is a bit smaller due to the reduced amount of CO_2 injected. Interestingly, distribution of safety factor for shear slip shows a similar pattern. However, a striking difference in both injection scenarios is observed at 10 years. Failure potential with the linearly increasing injection is far more significant than those even at early times with the uniform injection. This indicates that incremental injection does not improve stability of the caprock and the aquifer for the same amount of CO_2 injected. One other important observation is that a high potential for shear failure is still observed at the edge of CO_2 plume.

Table 1: Media properties for the CO_2 example

Fluid properties			
Property	Unit	Saline Water	Supercritical CO_2
Density	kg/m^3	1173	734.27
Viscosity	Pa·s	1.252×10^{-3}	6.24×10^{-5}
Residual saturation	-	0.1	0.1
Maximum saturation	-	0.9	0.9
Medium properties			
Property	Unit	Caprock (Shale)	Aquifer (Sandstone)
Young's modulus	GPa	0.2	21
Poisson's ratio	-	0.2	0.25
Biot's parameter		1.0	1.0
Porosity	-	0.01	0.15
Intrinsic permeability	m^2	1×10^{-20}	1.0×10^{-17}
Brook-Corey's index	-	2	2
Entry pressure	kPa	3100	19.6

Conclusions

In this paper, we have demonstrated that the benchmark was carefully defined to analyze mechanical failure during CO_2 injection at various rates and under different injection scenarios. We provide the following conclusions.

- The potential for shear slip is in general more likely to occur than hydraulic fracture. This finding is consistent with previous work [*Rutqvist et al.*, 2008]. For a uniform pumping rate, the greatest instability occurs in earlier times following the onset of injection. Different injection scenarios can alter this result.
- Both failure modes are most likely at the outer edge of the CO_2 plume. Therefore, in addition to profiling of mechanically weaker zones caused by heterogeneity, tracking of the dynamic fluidal interface between CO_2 and water may be important for failure monitoring.
- A linearly increasing injection scenario does not improve the stability of the formation. An increase in injection pressure beyond the mechanical capacity of the reservoir can induce failure at any time. The existence of a dormant, CO_2-water interface at the onset of an improperly selected injection rate can potentially induce failure some distance from the injection site.

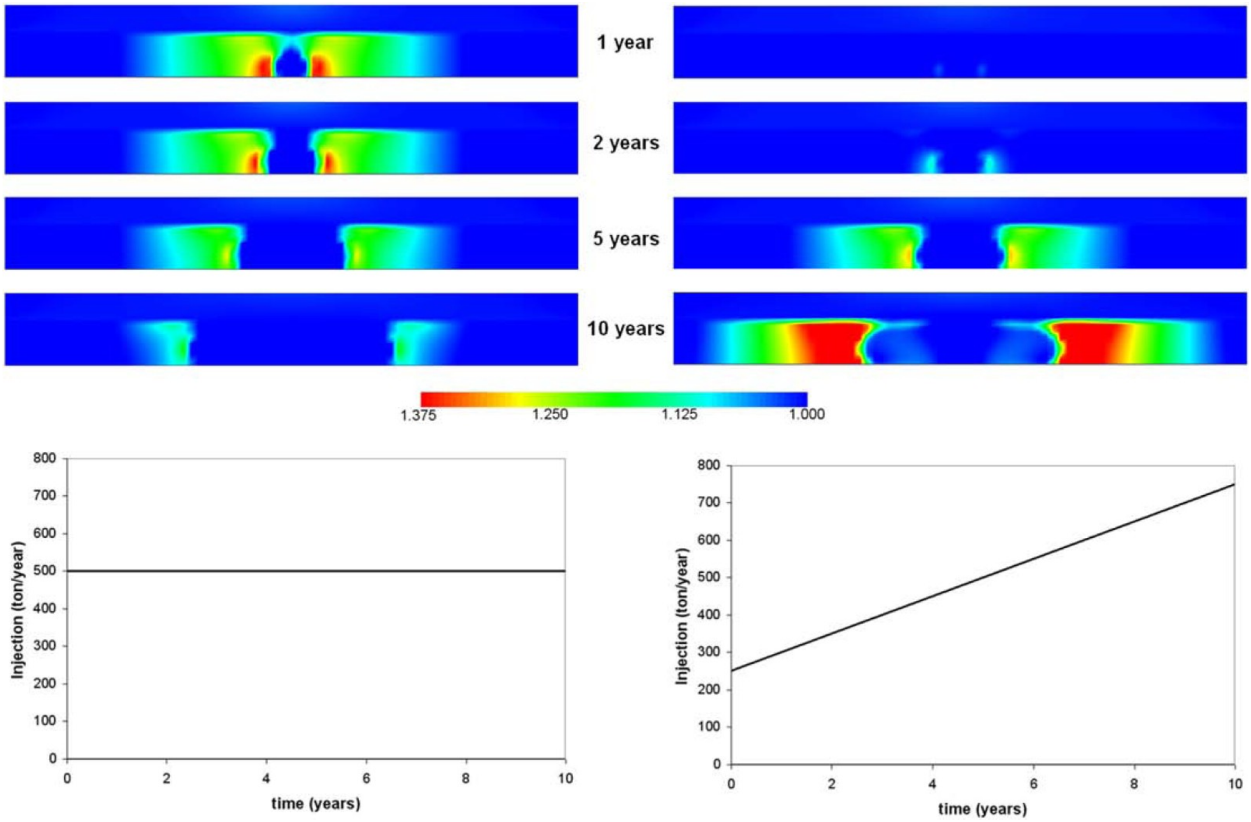

Figure 3: Safety factors for shear slip under two different injection scenarios: A uniform injection scenario in the first column and a linear injection scenario

Acknowledgements

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