Geomechanical stability of the caprock during CO_2 sequestration in deep saline aquifers

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1. INTRODUCTION

Suitable saline aquifers should be capped by a low-permeability caprock. This caprock may undergo large pressure buildup because of CO_2 injection. This will affect the stress field and may induce large deformations, which can eventually damage the caprock and open up new flow paths.

Hydromechanical (HM) simulations capture phenomena that purely hydraulic (H) codes cannot predict. These include the initial pressure drop in the caprock as a response to CO_2 injection (Fig. 1) (Vilarrasa *et al*., 2010). Furthermore, failure mechanisms strongly depend on the initial stress state (Rutqvist *et al*., 2008).

Unlike open aquifers, in which pressure buildup is limited because brine can migrate out laterally, semi-closed aquifers experience an additional pressure buildup. This additional overpressure depends on the caprock permeability. Relatively permeable caprocks (k<10^{-18} m^2) diminish overpressure because brine can leak through them.

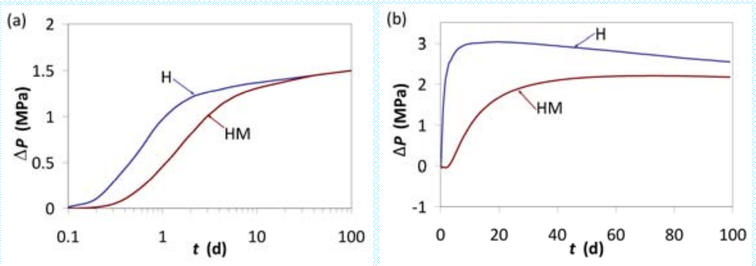

Figure 1: Fluid overpressure for a 100 days injection period, comparing pure hydraulic (H) with coupled hydromechanical (HM) simulation in (a) the aquifer at the contact between the aquifer and the caprock 400 m from the injection well and (b) in the caprock 50 m above the aquifer and 50 m away the injection well (Vilarrasa *et al*., 2010).

2. MODEL SETUP

CO_2 is injected uniformly throughout the entire thickness of the aquifer at a constant rate of 113 kg/s (3.6 Mt/yr) (Fig.2). We used the FEM code CODE_BRIGHT (Olivella *et al*., 1996) to simulate CO_2 injection.

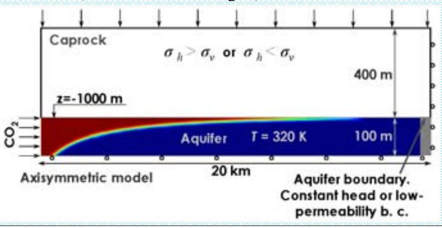

Figure 2: Schematic description of model geometry and boundary conditions

3. HYDROMECHANICAL COUPLING

Strain can be divided into elastic and viscoplastic strain $\mathrm{d}\boldsymbol{\varepsilon} = \mathrm{d}\boldsymbol{\varepsilon}^e + \mathrm{d}\boldsymbol{\varepsilon}^i$

Elastic strain is recoverable and is given by Hooke's law $\boldsymbol{\varepsilon}^e = (p'/3K)\mathbf{I} + 1/2G(\boldsymbol{\sigma}' - p'/3\mathbf{I})$

where $p' = (\sigma'_x + \sigma'_y + \sigma'_z)/3$, $\boldsymbol{\sigma}' = \boldsymbol{\sigma} + p_f\mathbf{I}$ is the effective stress tensor, $\boldsymbol{\sigma}$ is the stress tensor, p_f is fluid pressure, K is the bulk modulus and G the shear modulus.

Viscoplastic strain is irreversible and is computed as $d\boldsymbol{\varepsilon}^i = \Gamma\langle\Phi(F)\rangle dt(\partial G'/\partial\boldsymbol{\sigma}') = \Lambda(\partial G'/\partial\boldsymbol{\sigma}')$

where Γ is a viscosity parameter, Λ is a plastic multiplier, $F = q - Mp' - c\beta$ is the yield surface (F<0 implies elasticity; F≥0 viscoplasticity), $G' = q - \alpha(Mp' + c\beta)$ is the plastic potential, α is a non-associative parameter, c is cohesion, $q = \sqrt{3J_2}$ is the deviatoric stress and J_2 the second invariant of the stress tensor.

Combining equilibrium with Hooke's law and compatibility relationship gives the mechanical equation for elasticity $G\nabla^2\mathbf{u} + ((1/3)G + K)\nabla(\nabla\cdot\mathbf{u}) - \nabla p_f + \mathbf{b} = 0$ where $\mathbf{u}$ is the displacement vector.

And the mass conservation of fluid can be written as $\phi\beta\,\partial p_f/\partial t + \mathrm{d}/\mathrm{d}t(\nabla\cdot\mathbf{u}) + \nabla\cdot\mathbf{q} = 0$

4. NUMERICAL SIMULATIONS

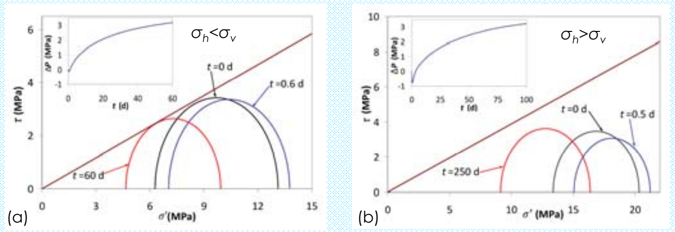

Figure 3. Stress state evolution represented by Mohr circles in a point of the caprock close to the injection well for (a) horizontal stress lower than vertical stress and (b) horizontal stress greater than vertical stress. Note that the initial pressure drop in fluid pressure (see inlet) displaces the circle to the right, but the subsequent overpressure moves the circle to the left, approaching the failure criterion. Note also that the changes in horizontal stress caused by lateral confinement change the circle size.

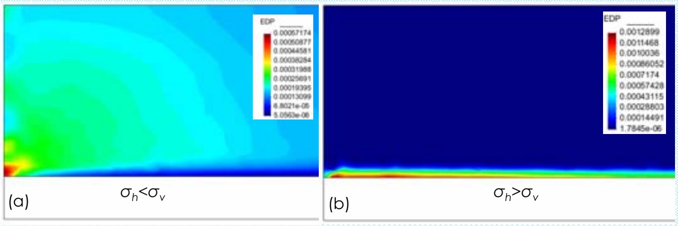

Figure 4. Plastic strain after 250 days of injection for (a) horizontal stress lower than vertical stress (plastic strain propagates through the whole thickness of the caprock) and (b) horizontal stress greater than vertical stress (plastic strain propagates horizontally in the contact with the aquifer). Only the first 700 m in the radial direction are shown.

The initial stress state determines how the stress changes in the caprock as a response to fluid pressure evolution during CO_2 injection (Fig. 3). Plastic strain tends to propagate subvertically in geologic formations with horizonal stress greater than vertical stress (Fig. 4a). This may open up fractures in the caprock through which CO_2 could migrate out the aquifer. Plastic strain concentrates in the contact aquifer-caprock if horizontal stress is greater than vertical stress, which may damage the caprock capillary barrier (Fig. 4b).

The permeability of the caprock affects fluid pressure evolution, both in the aquifer and the caprock. Brine can leak through relatively permeable caprocks (k ≥10^{-18} m^2), reducing the pressure buildup in the aquifer. Furthermore, the distance affected by the pressure perturbation grows with the square root of the permeability. Thus, the greater the permeability, the larger the volume of the caprock affected by pressure buildup. This implies different displacement behaviour depending on the caprock permeability (Fig. 5).

Aquifers surrounded by low-permeability boundaries experience an additional increase in fluid pressure once the pressure buildup cone reaches the boundary. However, fluid pressure does not increase uniformly in the whole aquifer, making these aquifers mechanically safe (Fig.6).

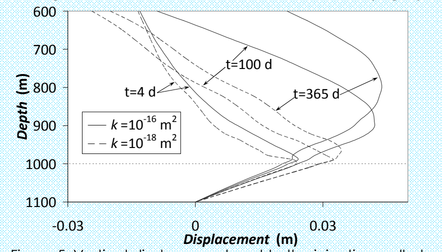

Figure 5. Vertical displacement next to the injection well at various injection times and caprock permeabilities. A low-permeability caprock limits the vertical displacement and even produces compaction. The dotted line indicates the contact between the aquifer and the caprock.

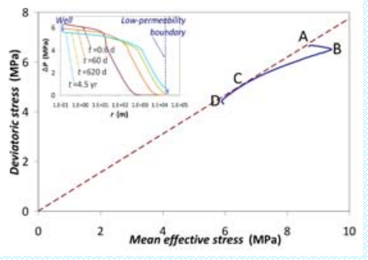

Figure 6. q-p' trajectory of a point of the caprock close to the injection well for σ_h<σ_v in an aquifer surrounded by a low-permeability boundary. The dashed line represents the yield surface. Point A shows the initial state, B is reached after the initial pressure drop, C is the most critical state (60 d) and D coincides with the time at which fluid pressure begins to drop (620 d). Although fluid pressure increases in the outer boundary once the pressure buildup cone reaches it, pressure drops in the vicinity of the injection well (see inlet)

5. CONCLUSIONS

-The initial stress state controls the plastic strain propagation pattern. If σ_h<σ_v, plastic strain may propagate through the entire thickness of the caprock and may facilitate CO_2 migration. If σ_h<σ_v, plastic strain concentrates in the contact between the aquifer and the caprock, which may break the caprock capillary barrier.

-The caprock acts as a plate that bends. Thus, its upper part undergoes horizontal extension, which produces compaction. This may cause settlement instead of uplift in low-permeability (k≤10^{-18} m^2) caprocks.

-Semi-closed aquifers may not be critical from the mechanical point of view, but interesting because the amount of brine that migrates out of the aquifer is reduced with respect to open aquifers.

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