Modeling of the CO_2 long-term periodic injection experiment (CO_2LPIE) into stratified hard clay rock at Mont Terri

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1. Introduction

CO_2 Long-term Periodic Injection Experiment (CO_2LPIE) aims at investigating the caprock sealing capacity in geologic carbon storage in a highly monitored environment at the field scale. The experiment is carried out in the sandy facies of Opalinus Clay at the Mont Terri rock laboratory, Switzerland, to gain knowledge on the changes in the geomechanical properties induced by the geochemical reactions resulting from CO_2 injection (Rebscher et al., 2019; 2020). The presence of bedding planes in Opalinus Clay is responsible for its anisotropic hydrogeological and geomechanical behavior. The hydraulic anisotropy is defined by a

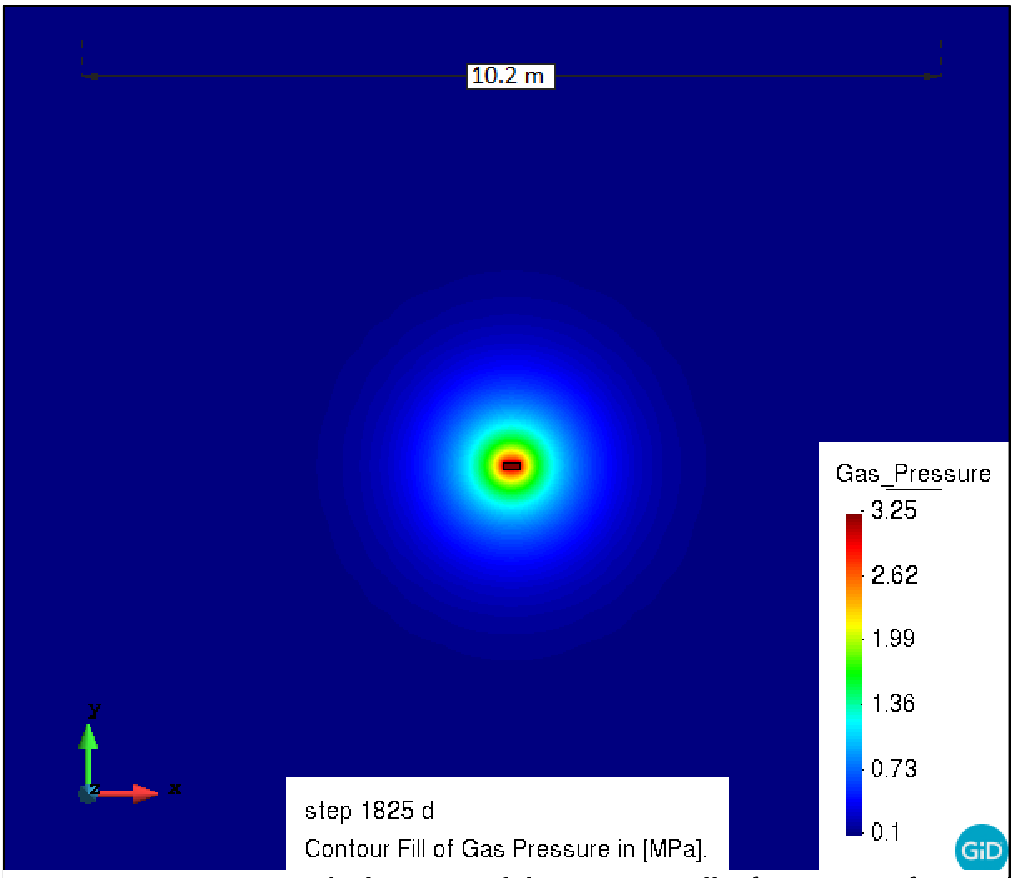

Figure 1: Gas pressure built up around the injection well after 5 years of CO_2 injection.

permeability parallel and perpendicular to the bedding planes of $2.4 \cdot 10^{-20}$ m^2 and $0.8 \cdot 10^{-20}$ m^2, respectively, and we assume it can increase by up to two orders of magnitude due to fracture opening. Mechanically, the drained Young's modulus parallel and perpendicular to the bedding planes is measured to be 1.7 GPa and 2.1 GPa, respectively (Makhnenko et al., 2017; Makhnenko & Podladchikov, 2018). Excavation reports document a dip of 45° for the bedding planes at the experiment location (Jaeggi et al., 2020).

In this study, we perform a series of coupled hydro-mechanical simulations to predict the rock response to CO_2 injection and assist the experiment design in optimizing injection periodicity and amplitude, location of monitoring devices, and developing methodologies for characterizing fractured rock.

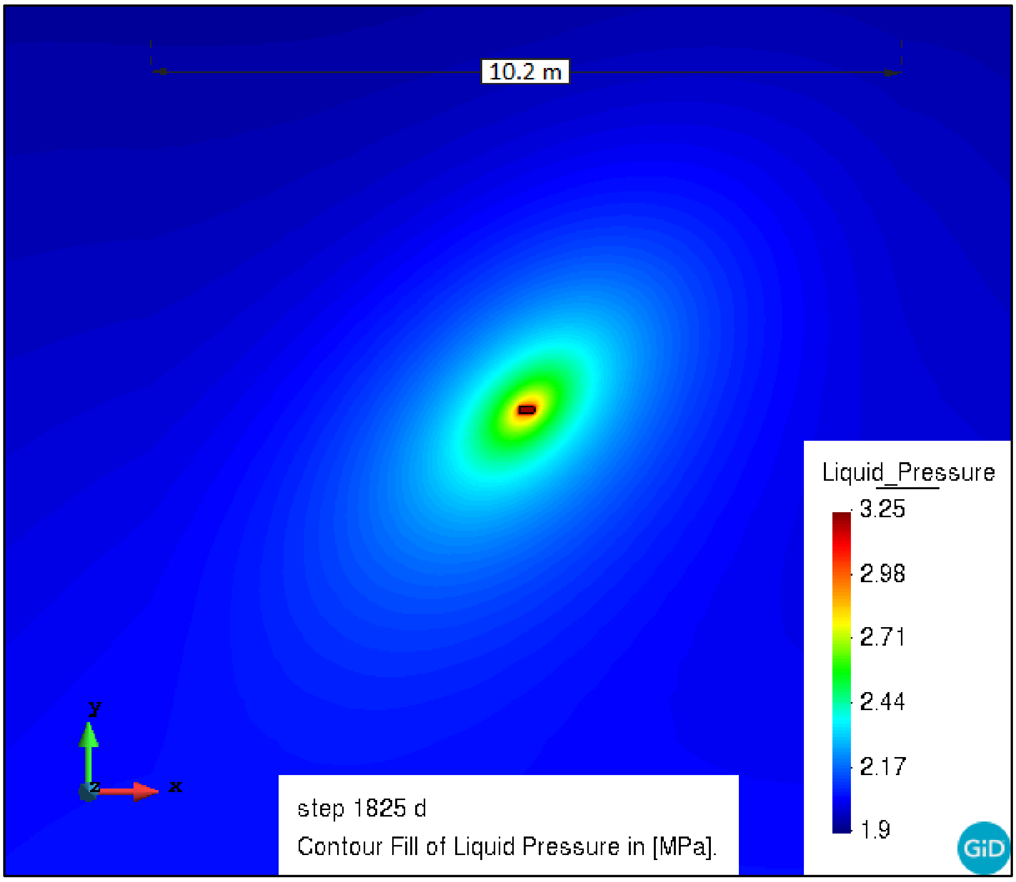

Figure 2: Liquid pressure built up around the injection well after 5 years of CO_2 injection.

2. Methods

To describe the long-term behavior of the undisturbed rock, we simulate a periodic CO_2 injection at an average pressure of 3 MPa during 5 years. The pressure fluctuates between 3.25 MPa and 2.75 MPa (the amplitude of the signal is thus 0.25 MPa) and the period of the signal corresponds to $\frac{\pi}{2}$ d (≈1.57 d). We simulate a 2D plane strain, whose domain extends for 10 m in x and y directions. A transverse isotropy is assigned on the surfaces. The direction of the orthotropic axes is inclined at 45° with respect to the x direction, which corresponds to the horizontal. As far as the stress state is concerned, a lithostatic gradient is defined to obtain $\sigma_1 \equiv \sigma_y = 6.5$ MPa and $\sigma_3 \equiv \sigma_x = 2.2$ MPa at the depth of the well, with a specific weight of 25 kN/m^2. At the beginning of the simulation, a hydrostatic gradient is defined to obtain 2 MPa of liquid pressure at the well. The gas pressure is assumed to be uniform and equal to 0.1 MPa. Thermal effects are neglected and the temperature is considered uniform and equal to 14 °C.

CO_2 is injected as gas phase from the horizontal well, located in the middle of the model. It extends 200 mm horizontally and 86 mm vertically. Coupled hydro-mechanical processes are simulated using CODE_BRIGHT (Olivella et al., 1996), a finite element code which solves the stress equilibrium and the mass balance of both water and air in a fully coupled way. The mesh is composed of 2560 quadrilateral structured elements, 400 for the well and 2160 for the rock material. The element length varies from 2 mm (around the wellbore) up to 2.5 m (for the boundary elements).

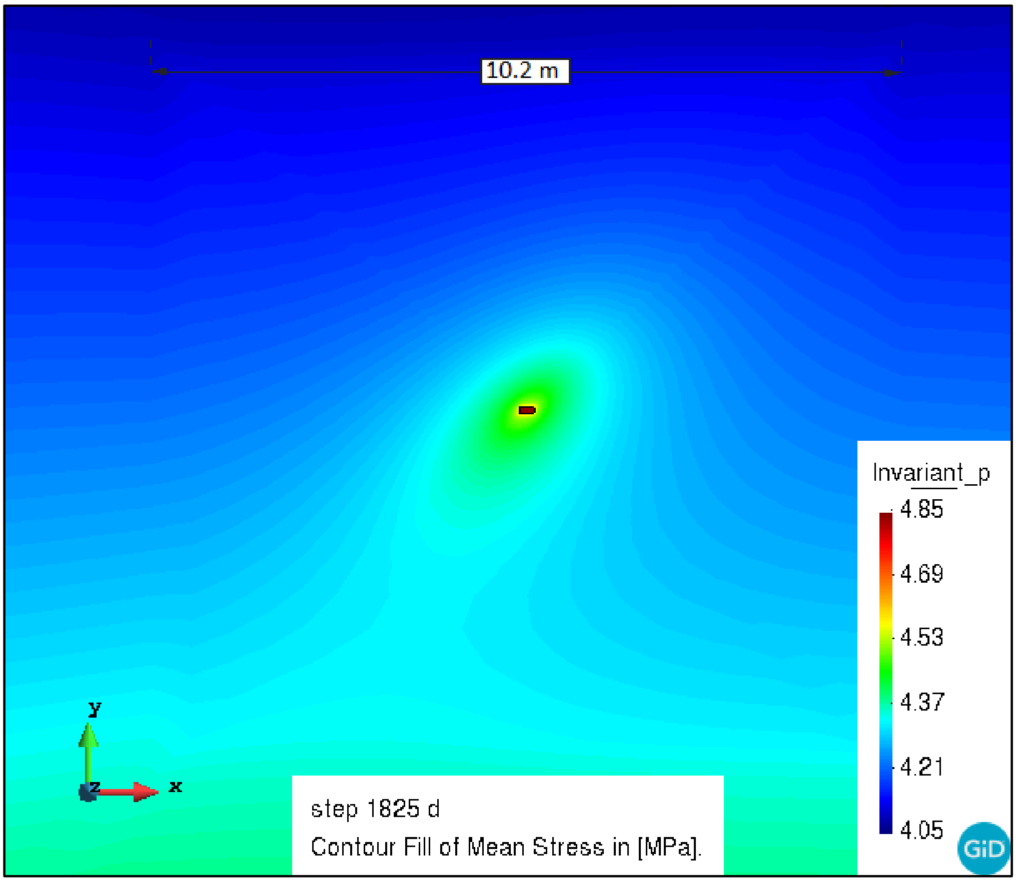

Figure 3: Distribution of the mean stress around the injection well after 5 years of CO_2 injection.

3. Results

CO_2 injection generates an overpressure of the brine that propagates into the formation. The differential pressure between CO_2 and water pressures, i.e., capillary pressure, is lower than the entry pressure and thus, CO_2 diffuses through the pores but does not flow as a free phase. This is the reason why the gas overpressure spreads isotropically in Figure 1. On the contrary, the liquid overpressure distribution is distorted by the hydraulic anisotropy, preferentially advancing along the bedding planes, whose permeability is higher than the one perpendicular to the bedding (Figure 2). Pore pressure changes induce a coupled hydro-mechanical response that should be taken into account (Figure 3). The pore pressure buildup induces a poromechanical stress increase (Figure 3) and an expansion of the rock that leads to a permeability enhancement of up to two orders of magnitude. The model for computing the fracture permeability increase is based on the cubic law and calculates the fracture aperture changes as a function of the volumetric strain changes (Olivella and Alonso, 2008).

The cyclic stimulation propagates trough the domain faster and with a lag time and an attenuation, the latter is given by the ratio between the signal amplitude and the amplitude registered at a certain distance. Both the lag time and the attenuation grow with distance from the source and their values depend on the permeability, porosity and stiffness of the rock. As a result of the model orthotropy, the attenuation and the lag time change with direction. In our case, they are higher in the direction perpendicular to bedding and lower in the direction parallel to bedding.

4. Conclusions

Given the very low permeability of Opalinus Clay, the overpressure generated by the injection requires extended time scales to diffuse into the rock. Furthermore, the amplitude attenuation dissipates quite rapidly, so monitoring wells should be placed as close to the injection well as possible. Further study of amplitude attenuation and time lag is necessary to determine how they can be useful to evaluate the evolution of the hydro-mechanical properties as the rock is altered by the acidic nature of CO_2. Comparison between field data and numerical simulations will be a useful tool to fill the gap.

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