Geomechanical modeling for subsurface CO2 storage with active pressure management: A preliminary study

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１．Introduction

Geological CO2 storage (GCS) in subsurface aquifers has been proposed as a near-term solution for reducing CO2 emission and mitigating climate change. The concept of CGS –injection of CO2 captured from industrial processes into rock formations deep underground – is quite straightforward to understand. However, the projects with large-scale CO2 injection may face challenges. The pressure buildup in the aquifer due to large-scale CO2 injection may induce geomechanical issues, such as fault reactivation, induced seismicity, fluid leakage and surface uplift. The occurrence of these issues is thought to be negative to the project operation and public acceptance of GCS. Therefore, monitoring and modeling of geomechanical behavior of reservoir-caprock system are quite critical for a successful GCS project.

To mitigating pressure buildup and geomechanical risks, one approach called Active reservoir Pressure Management (APM) conducted by production reservoir brine has been proposed (Buscheck et al., 2011). The production of brine from reservoir can let the reservoir pressure (buildup) be partially relaxed and leaves more pore space to CO2. Some of the benefits of APM include reduced geomechanical risks and increased CO2 storage capacity. On the other hand, the brine production operation can also increase the cost.

In practice, when applying the APM approach in a project, the operator needs in situ information to understand the state of pressure buildup and geomechanical deformation and further to determine the rate of CO2 injection and brine production. Recently, distributed strain sensing (DSS) using optical fiber has been demonstrated as a valid monitoring method to provide such information. The DSS method can offer real-time and continuous profiles of in situ vertical strain along the fiber cable installed wellbore. One task left for APM is to understand the signal of measured strain response when performing the injection and production. A better understanding of the strain response helps for an optimized management of injection and production procedures, controlling the potential geomechanical risks and supporting the decision making.

In this study, we conducted geomechanical numerical modeling for APM with an emphasis of vertical strain changes during CO2 injection with and without brine production. We performed the modeling job on Oakbridge-CX Supercomputer System.

2. Mathematical equations

The modeling involves solving coupled equations of mass and flux of two-phase fluid flow and solid mechanics as follows.

(1) The mass conservation for fluid species κ is described by the equation

$$\frac{\partial M^{\kappa}}{\partial t}+\nabla\cdot\mathbf{F}^{\kappa}=q^{\kappa}$$

where M^{κ} is the mass, t is the time, q^{κ} is the source and $\mathbf{F}^{\kappa}$ is the advective flux, which is governed by the extended Darcy's law.

(2) The mechanical equation is expressed by stress with the coupling between effective stress and pore pressure through the Biot coefficient.

$$\sigma_{ij}^{\text{eff}}=\sigma_{ij}^{\text{tot}}+\alpha_B P_f$$

where σ^{eff} is the effective stress tensor, σ^{tot} is the total stress tensor, P_f is the pore pressure, and α_B is the Biot coefficient. The strain $\epsilon_{kl}^{\text{elastic}}$ is associated with the effective stress through the solid-mechanical constitutive law:

$$\sigma_{ij}^{\text{eff}}=E_{ijkl}\epsilon_{kl}^{\text{elastic}}$$

where E_{ijkl} is the elastic tensor.

3. Numerical modeling

The open-source code MOOSE is used for solving the two-phase fluid flow geomechanical model. MOOSE is a multiphysics FEM framework with the PETSc non-linear solver package and libmesh to provide the finite element discretization. The mumps SMP preconditioner and Newton solver with automatic scaling are applied.

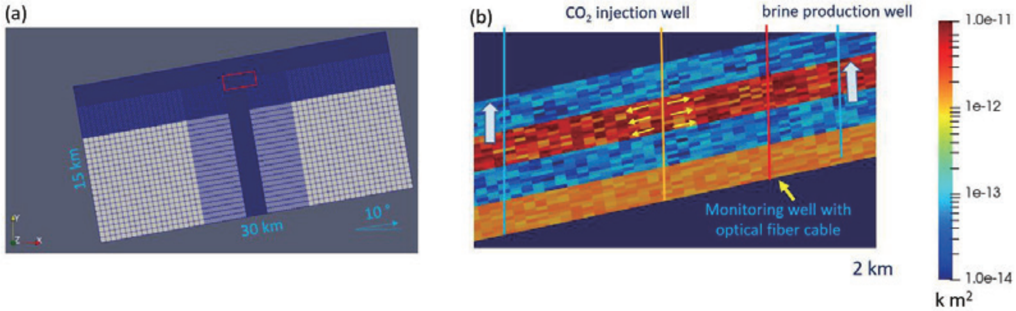

Figure 1. The numerical model. (a) The full domain model with the meshing; (b) The local region near CO2 injection well and brine production well.

In this preliminary study, for simplicity, we perform the modeling using a dipping two-dimensional model (so having dimensional effect compared to a three-dimensional model, Figure 1). The model is intentionally set by several units with different permeability (1e-14 ~ 1e-11 m^2). In each layer, Gaussian distributed heterogeneities are added. Otherwise, uniform elastic constants (bulk modulus 6 GPa, Poission' ratio 0.2 and Biot' s coefficient 1.0) are used. To avoid the boundary effect, we set a much larger modeling domain (30 km×15 km). We use dense Cartesian mesh gridding within the ROI and near-by regions and sparse gridding at other regions. A constant CO2 injection rate (20t/day) is set. Cases with and without brine production are considered. The rate of brine production is the same as CO2 injection rate.

4. Results

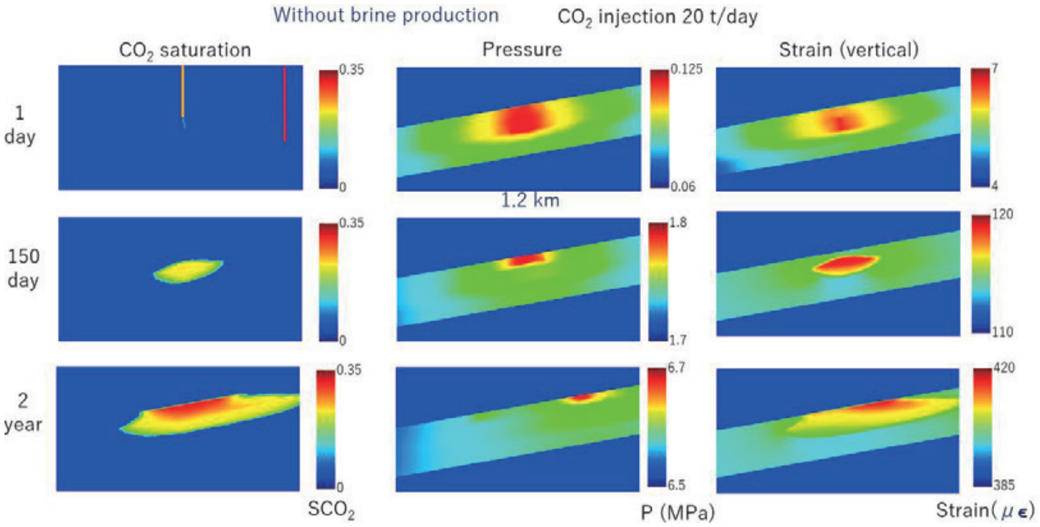

Figure 2. The results numerical modeling for the case without brine production.

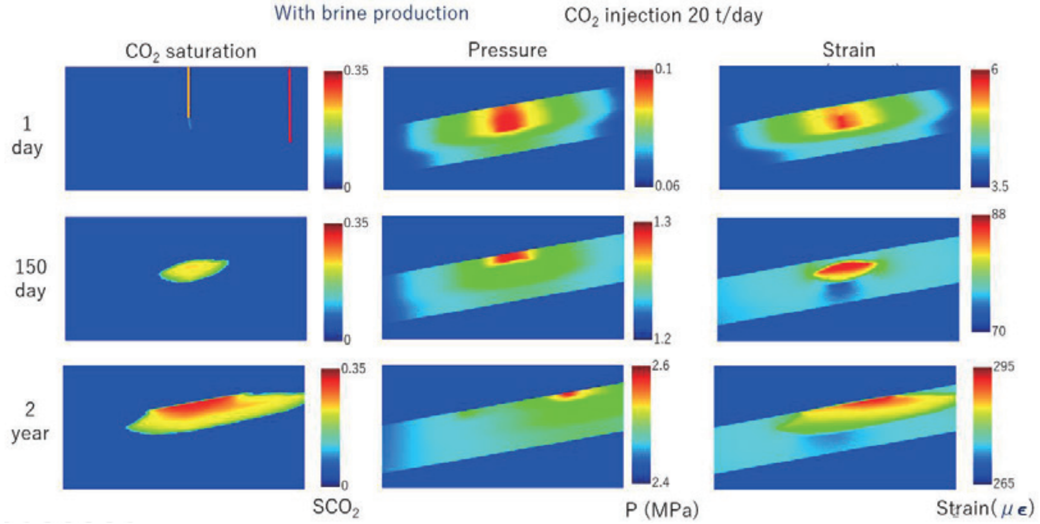

Figure 3. The results numerical modeling for the case with brine production.

Figures 2 and 3 show the modeling results modeled CO2 saturation, pressure, and vertical strain at different time since CO2 injection for the two cases without and with brine injection. We see that the CO2 plume distribution for the two cases is quite similar at the injection and production flow rate. In contrast, the shapes and magnitudes of fluid pressure distribution and strain between them are quite different. With the brine production, the magnitude of pressure changes and deformation is reduced as expected. This supports the effectiveness of APM through brine production and using DSS as a monitoring tool. Moreover, we can find that dilation strain developed around the injection well. At the earlier stage (since the injection beginning), the strain pattern is mainly induced by the pore pressure diffusion and the strain magnitude is small ($< 10\ \mu\epsilon$). There is an obvious strain front corresponding to the pressure front. Later, the strain pattern is affected by the development of CO2 plume. This is because the relatively large pressure changes near the plume boundary due to the changes in relative permeability and capillary pressure. Therefore, in addition to the geomechanical purpose, we can use the strain signal to understand the state of pressure and CO2 plume migration.

5. Conclusions

In this short report, we presented our preliminary modeling results of geomechanical modeling of CO2 injection with active pressure management in subsurface aquifer. We emphasized the deployment of distributed strain sensing method for the monitoring purpose. The modeling results suggest that the strain measurement can be used for a better understanding of the state of pressure buildup and geomechanical risks and perhaps CO2 plume migration. Therefore, DSS can be expected to play an important role in CO2 storage project. More investigations are needed to evaluate the effects of hydromechanical parameters, well placement, brine extraction interval and rate.

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