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Evaluating Caprock Integrity of a Carbon Storage Site Using 3D Coupled Reservoir Geomechanics Modeling

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Summary

Ensuring long-term containment of CO2 is critical for a safe geological storage of carbon dioxide. The process of CO2 injection alters the formation pressure and temperature leading to various changes in the reservoir (e.g. in-situ stresses, porosity and permeability). In this paper, we present an integrated coupled modeling approach encompassing various complex processes involved in CO2 injection for evaluating caprock integrity of a potential carbon storage site. The efficiency of this approach is demonstrated through case study of a proposed carbon storage site in Saskatchewan, where an injection rate of 600 tonne/day for 25 years followed by a 500 years of shut-in time is planned. The coupled geomechanics analysis indicates that although the proposed injection plan increases stress in the caprock, the increase is not significant enough to cause any failure in the caprock.

Introduction

Carbon Capture and Storage (CCS) has been identified as one of the options to reduce industrial greenhouse gas emissions. Ensuring long-term containment of CO2 is critical for a safe geological storage of carbon dioxide. Although CCS process can be feasible in depleted hydrocarbon fields, it can pose significant risk to safety and the environment if its containment is not ensured. Continuous injection of CO2 triggers complex coupled processes e.g. multi-phase fluid flow, chemical interactions between the aquifer rock/fluid and injected CO2. These processes alter the in-situ stress state, mechanical properties and strength of the rock around the injection wells as well as across the reservoir. Alteration in stress state can induce fractures or activate existing fractures creating escape routes for the CO2 and posing continued risk of containment breach of the caprock or fault reactivation. Therefore, an integrated coupled modeling approach encompassing mechanical, thermal, and hydraulic effects is essential in evaluating caprock and fault integrity of a potential carbon storage site.

Modeling Approach

This approach models the virgin and altered stress state using the reservoir geomechanics software, VISAGE* and the variation in formation pressure and temperature using the reservoir modeling software, ECLIPSE*. The modeling begins with the construction and calibration of 1D Mechanical Earth Model (MEM) for each injection well using all the available data from logs, cores, images, drilling, etc. Using these 1D MEMs and other data such as seismic, a 3D MEM is developed for the entire field under consideration. In the 3D model, not only the main reservoir area but sufficient layers from caprock, over-burden, under-burden and side-burdens are also included to account for the boundary effects. For each injection cycle, ECLIPSE computes the change in formation pressure and temperature and VISAGE computes the corresponding stresses and strains iteratively. Volumetric strains obtained from the 3D model give rise to change in porosity ($\Delta\phi$) and permeability (Δk) which is computed by VISAGE. The values of $\Delta\phi$ and Δk are transferred to ECLIPSE for computing the change in formation pressure (Δp) and temperature (ΔT). For each Δp and ΔT corresponding stresses, strains and change in porosity and permeability are computed. These iterative computations between VISAGE and ECLIPSE continue until the equilibrium states in pore pressure and stress are achieved within a given tolerance. Next, induced stresses are checked against various failure criteria. In order to predict if there will be any fault reactivation, the movement of fractures and faults due to interaction between mechanical, thermal and hydraulic processes is computed.

Case Study

The efficiency of the coupled approach is demonstrated through a case study, Aquistore, a proposed carbon storage site located in the vicinity of Regina, Saskatchewan. The proposed base case injection rate is 600 tonne/day for 25 years followed by 500 years shut-in time. The coupled geomechanical analysis of the reservoir and the caprock was carried out as a technical feasibility study using the proposed base case injection pressure information. The overall goal of the study was to ensure long-term containment of the injected CO2 in the proposed storage site. The main geological data with the interpreted well logs, structural maps of several horizons, faults and the 3D grid of the reservoir were provided in a 3D Petrel model. Available geomechanical parameters, average reservoir pressures which will be used for CO2 injection and reservoir engineering data with injection scenarios were also provided. The missing data that were required for geomechanical simulation were obtained from the public databases, open literature and the internal reports.

The 3D geomechanics model embedding over, under and side burdens was developed for this area to study the impact of CO2 injection on the reservoir, bounding seals and surrounding rock of the field. The ECLIPSE simulation grid consisting of 203x193x24 cells was used to input all the data from reservoir simulation model to VISAGE. In order to eliminate the boundary influences, the grid was further embedded in VISAGE by adding extra cells to the top, bottom, and the surrounding of the initial reservoir grid cells. In order to reduce the simulation running time, a course grid is used for the embedded outer grid cells. The overburden of the reservoir was embedded up to the elevation of 585 meters, which was the average surface elevation of the area. The under-burden was embedded down to 25000 meters below sea level. The final embedded model dimension is shown in Fig. 1.

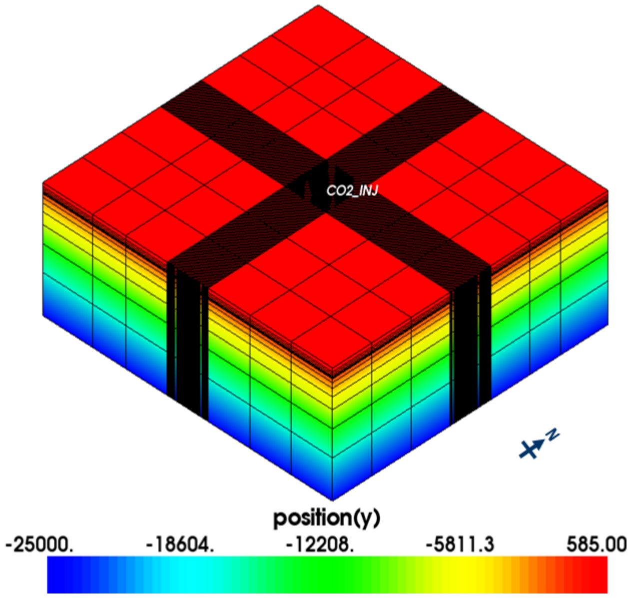

Figure 1. 3D model of Aquistore storage area with embedded grid.

The coupled geomechanical simulation was conducted for six pore pressure steps over an injection period of twenty years. The initialization date of the geomechanical simulation was January 1, 2013. The subsequent six stress steps were selected from reservoir simulation time steps as 1 month, 1 Year, 5 years, 10 Years, 15 years, and 20 years after starting the injection. The variation in stresses and rock properties induced by injection and their potential effects on caprock integrity were investigated.

Injection of CO2 will cause formation pore pressure to increase, initially in the vicinity of the injector, then vertically and horizontally away from the wellbore. The effective stress changes within the reservoir are predominantly controlled by the pore pressure changes. In the reservoir, effective stresses decrease when the pore pressure increases. In the caprock layer, effective minimum horizontal stress decreases in the vicinity of the injection well. The largest variation in pressure and stress, and hence the possibility of failure of the caprock will occur first in the immediate vicinity of the injection well considering only one injection well in the area. The stress change in the caprock is mainly caused by the stress change in the reservoir formations beneath it. Variations in the effective vertical stress and the shear stress were found to be small except in the vicinity of the injection well as shown in Figure 2. Effective horizontal stress changes are too small to be seen in the stress variation maps.

Generally, the minimum principal stress is considered to be the formation fracture pressure. If the net injection pressure surpasses this pressure, tensile failure of the formation will occur. The minimum horizontal stress of the caprock in this case is approximately 10 MPa higher than the corresponding net injection pressure which does not cause tensile failure. Stress changes in the reservoir will cause changes in both the normal and shear stresses in the caprock. As a result, formation shear failure may occur even before the net injection pressure reaches the fracture pressure. The geomechanical simulation also gave the shear failure value for the caprock. When the shear failure value is negative, formation shear failure will not occur. Zero is the critical value. In this study, the shear failure value of the caprock is from -10000 to -9950 during the twenty year injection period as shown in Fig. 3. These values indicate that the rock is entirely elastic and remains significantly below the failure point. This means that the proposed injection plan is safe to the integrity of the caprock from geomechanics point of view. If injection pressure increases to a certain threshold, the caprock shear failure may occur sooner in the northern part of the study area than the southern part.

Conclusions

The simulation results indicate that although the base case injection plan would increase both the normal and shear stresses in the caprock, the increase is not significant enough to cause any failure in the caprock. The current injection plan will neither cause tensile failure nor shear failure in the caprock. This means that the current injection plan is safe to the integrity of the caprock from geomechanics point of view. However, other processes, such as chemical processes which are not considered in this study may also change the mechanical and hydraulic properties of rock. It is recommended that the effects of these processes are also considered for a thorough analysis of caprock integrity.

Acknowledgements

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[*] Mark of Schlumberger

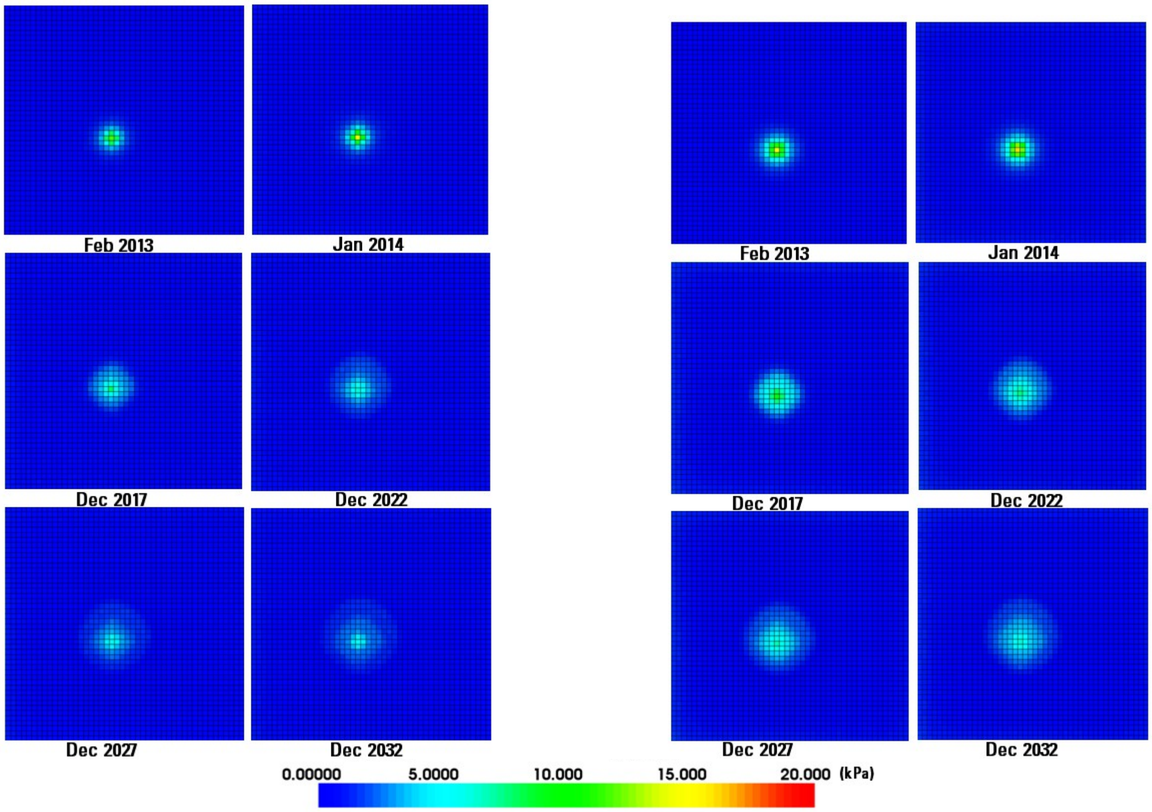

Figure 2. Variation of effective vertical (left) and shear (right) stresses.

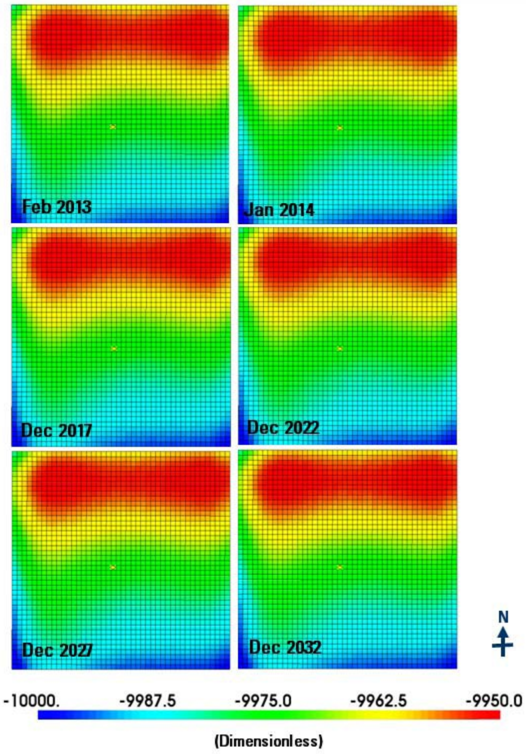

Figure 3. Shear failure in caprock layer.