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Research paper

Geomechanical effects of co_2 storage in geological structures: two case studies

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Abstract

Storage of CO_2 in subsurface can assist to mitigate CO_2 emission without extensively interfering with industrial activity and development. The main reason for geological storage to trap CO_2 underground for a long time. However, the injection of CO_2 may compromise the sealing characteristics of the caprock and, consequently, the containment of the underground CO_2 storage unit as well. For instance, the injection of CO_2 into a reservoir resulted in pore pressure and temperature changes leading to deformation and stress changes in the injection target and the rocks that surround it. These changes can influence the hydraulic integrity of the geological storage. The potential hazards could then impose different environmental, health, safety, and economic risks. Therefore, the geomechanical assessment of caprock integrity is critical for the storage of carbon dioxide. This research reviewed two different cases of underground CO_2 storage in Canada and the workflows used for the assessment of geomechanical effects of CO_2 injection on caprock integrity. It reviewed the processes of data collection, geomechanical characterization, and fluid flow modeling. These reviews highlighted the significance of geomechanical characterization and the fact that it is faced with significance challenges that could be addressed by data integration and geostatistical analysis. These reviewed studies implemented both analytical and numerical geomechanical models. While analytical models seem to be great choices for preliminary geomechanical analysis, numerical models are also necessary for a more detailed analysis.

Keywords: *CO2 Storage; Caprock Integrity; Geomechanical Analysis; Probabilistic Analysis.*

1. Introduction

Carbon dioxide (CO_2) is the main carbon origin for life and is produced naturally. As a result of human activities and manufacturing, the high amount of CO_2 released into the atmosphere has been causing severe environmental matters related to climate change. The progressive increment of CO_2 emissions from manufacturing have since motivated the industry to develop and discover new methods to capture the CO_2 emissions from diverse origins and subsequently sequester it in underground geological storages. Geomechanical analysis and reliability evaluation of the storage containment are vital to ensure that such CO_2 storage projects can be safely executed. Therefore, one of the several challenges facing CO_2 capture and storage is to examine the geomechanical integrity of the geological storage sites. Some of the major potential hazards related to the underground storage of CO_2 include the leakage of CO2 from the storage unit, induced seismic activity, significant ground deformation and well damage. Various cases have since been reported in which earthquakes were caused by the production and injection of gas or water in the underground storage sites [1-4]. There have been some attempts to describe the procedure leading to the seismicity in hydrocarbon production fields [5-6].
However, there is no direct or clear evaluation tool to explain induced seismicity during production and injection. Also several researchers have studied the mechanisms of ground surface movement due to production [7-10], the prediction of movement in the ground surface remains difficult [11]. Moreover, there are several evidence of well failure due to horizontal ground movement and faults sliding as a result of production [12]. Since the main objective of geological storage is to trap CO_2 underground for an unlimited period of time, CO_2 leakage has a special place among the geomechanical risks of such operations. The CO_2 trapping mechanism within a reservoir is dependent on the time period. Long-term trapping depends on solubility, ionic reaction, geochemical, and irreducible saturation [13]. However, in the injection phase, which is short-term trapping, the hydraulic integrity of the caprock has to be checked out as the major trapping mechanism. Consequently, for the storage of CO_2, the hydraulic integrity evaluation of the caprock is crucial.
Different researches are needed to assure that the reservoir integrity has not been compromised prior to the CO_2 sequestration and will not be compromised after it. Such studies must be designed to identify: i) initial sealing mechanisms; ii) potential alterations of these mechanisms during the previous exploitation period; and iii) effects of future operations on the present sealing mechanisms [14]. Typical mech-

anisms threatening the hydraulic integrity of the caprock include geochemical diagenesis, capillary leakage, and geomechanical mechanisms. There are concerns that the geochemical reactions between the reservoir CO_2 and sealing may change the petrophysical properties of the caprock such as its porosity and permeability, and consequently, may lead to CO_2 leakage out of the reservoir [15]. Therefore, geochemical studies are necessary to study these effects. In addition, capillary leakage occurs when the CO_2 flows into the caprock due to the capillary forces beyond the capillary entry pressure of the caprock. This pressure is generally controlled by the wettability, pore distribution, and interfacial tension between the replacing fluid and replaced fluid in the caprock. The thickness of the caprock is also a significant parameter for controlling capillary leakage.
Due to the variations in both temperature and pressure, the in-situ stresses change during production and injection. These alterations may lead to diverse geomechanical problems in the field including fault reactivation, fracturing and wellbore instability. Moreover, stress shifts can reactivate the dormant faults in the site. Stress changes do not only cause the ground to move and induce seismicity, but they may also change the sealing properties of the fault gauge and affect its role as the sealing barrier acting against fluid leakage. Furthermore, owing to stress changes, current fractures may reopen and act as flow conduits. They may even spread increasingly in the caprock and open up new routes for the fluid to flow out of the reservoir. All these leakage-related geomechanical risks are usually studied under a comprehensive program called geomechanical assessment of caprock integrity. It is important to note that a caprock integrity assessment is a dynamic process in the lifetime of the project and it may even continue after ceasing the injection/production operations.

2. Materials and methods

In the following sections, two case studies for the assessment of the geomechanical response to CO_2 storage injection and examination of the potential hazards of CO_2 sequestration in Canada are reviewed. The first case is a study for the storage of CO_2 in an exceptionally large carbonate reef, while the second case is a study for the storage of acid gas in a field including multiple small pinnacle carbonate reefs.

2.1. Case study 1: heartland area redwater project (HARP)

The Heartland Area Redwater Project (HARP), as a commercial-scale CO_2 injection site, is located northeast of Edmonton, Alberta in Canada. The target region is a carbonate reef with a covering area of 600 km^2 and thickness and depth of 300 m and 1000 m, respectively. The location of HARP is shown in Figure 1. Geomechanical analysis was performed to predict the deformations and stresses in the injected area and identify the effects of the induced deformations on the mechanical properties and integrity of the injection zone.

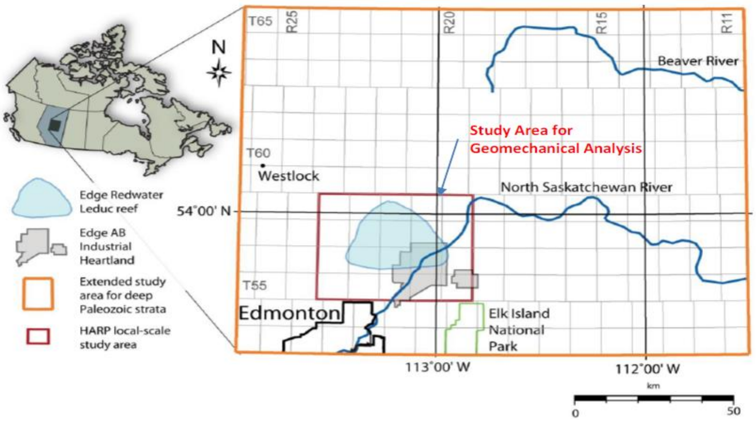

Fig. 1: Location of the Redwater Leduc Reef and Study Area for Geomechanical Analysis.

A three-dimensional Mechanical Earth Model (MEM) was developed for HARP using the wireline logs of 95 vertical wells. The geological model contained 49 surfaces and 35 zones. The model was conducted using the structural mechanics module of COMSOL Multiphysics [16]. This model was developed by assigning the properties interpreted for each unit into the geological model. The cross-section of Young's modulus in the three-dimensional mechanical model is shown in Figure 2.

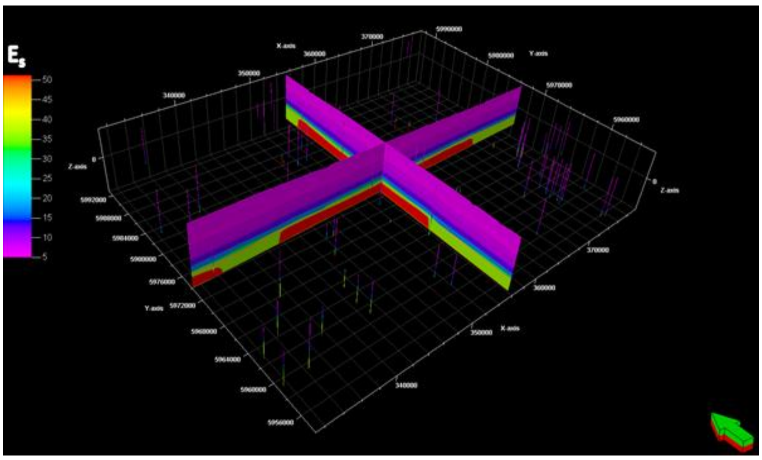

Fig. 2: Cross-Sections for the Distribution of Static Young's Modulus.

In Figure 2, the vertical lines show the locations of the wells that were used for the interpretation of the mechanical properties. In this study, Young's modulus was calculated using a geometric average, while for the other parameters, an arithmetic average value was considered. Each average value represents the magnitude of each property in the immediate vicinity of each well. The mechanical stratigraphic units used are shown in Figure 3. The material properties for these mechanical stratigraphic units were calculated by the weighted averaging of the mechanical properties of their constituent stratigraphic units. Geomechanical analysis was conducted for the commercial-scale injection situation based on 110 MT of the CO2 injection over a period of 50 years. The injection well is located around the southern edge of the Redwater Leduc reef. Pore pressure changes caused by injection were taken from output data files generated during the reservoir analysis.

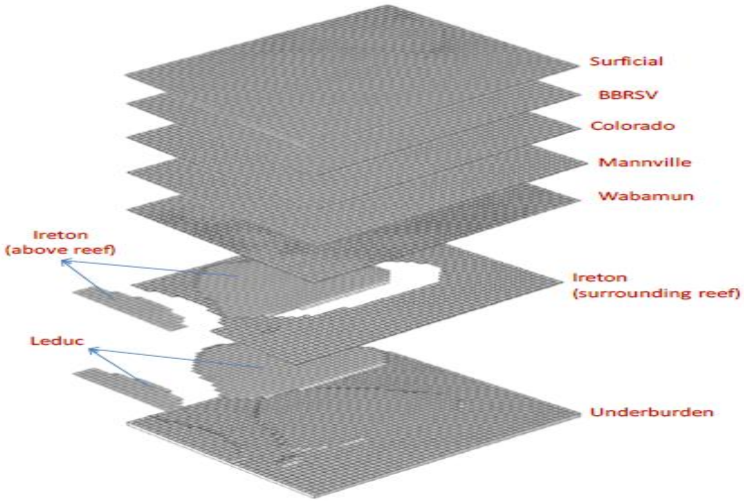

Fig. 3: The View of the Mechanical Stratigraphic Units.

In this study, two parameters, namely rock failure ratio (RFR) and fault failure ratio (FFR) were defined to quantify the potential for shear failure of undamaged rock and potential for fault reactivation, respectively. Rock failure ratio represents a ratio of shear stress to shear strength, in which a value of 1.0 or more indicates that failure of intact rock is predicted. The distribution of vertical deformation in the model after 25 years of CO_2 injection is illustrated in Figure 4.

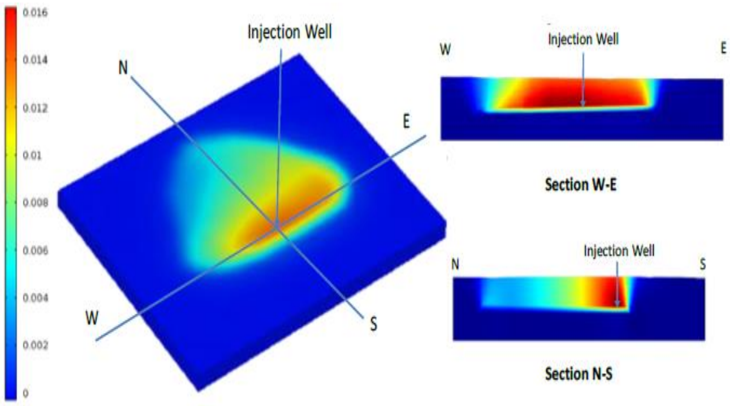

Fig. 4: Distribution of Vertical Deformation after 25 Years of CO_2 Injection.

The maximum pressure change within the reservoir would be approximately 4 MPa, predicted after 25 years. The results from the deformations predicted by the 3D aeromechanical model showed that after 25 years of CO2 injection, the reservoir would experience approximately 1.62 cm of vertical expansion. This demonstrated that the surface deformation is controlled almost entirely by the reservoir expansion and that other mechanical stratigraphic units have a negligible effect. Similar analyses were performed for the case of 50 years of CO2 injection, in which the maximum pressure change within the reservoir would be approximately 3.5 MPa, which was smaller than the 4 MPa predicted at 25 years.
This demonstrated that the results predicted by the geomechanical model at 50 years were less critical compared to the 25-year case. In this study, a sensitivity analysis was also implemented to check the effect of uncertainties on the estimation of the input data. Uncertainties are usually reflected in geometry, the mechanical properties of rock, in-situ stresses, and pore pressure. For instance, the sensitivity analyses showed that induced stress changes in the cross-sectional plane were not sensitive to Young's modulus values and that they only depended on Poisson's ratio.

2.2. Case study 2: acid gas injection at the Zama oil field, Alberta, Canada

The Zama oil field is located in Alberta, Canada and has approximately 400 pinnacle reefs of Middle Devonian Keg River Formation as shown in Figure 5. The purpose of this case study was to employ the geomechanical model in a probabilistic analysis for induced fracturing or fault reactivation accompanied with pore pressure changes in pinnacle reef reservoirs during injection operations of acid gases; CO_2 and H_2S. In this project, acid gas injection (70% CO_2+30% H_2S) started in 2006 for both oil recovery and storage purposes [17-18]. The midpoint depth of the pinnacle analyzed was 1500 m, with initial reservoir pressure estimated at 14.5 MPa. Static shear modulus, static Poisson's ratio, peak friction angle, peak cohesion, and residual friction angle were considered as the geomechanical properties of the pinnacle reef reservoir.

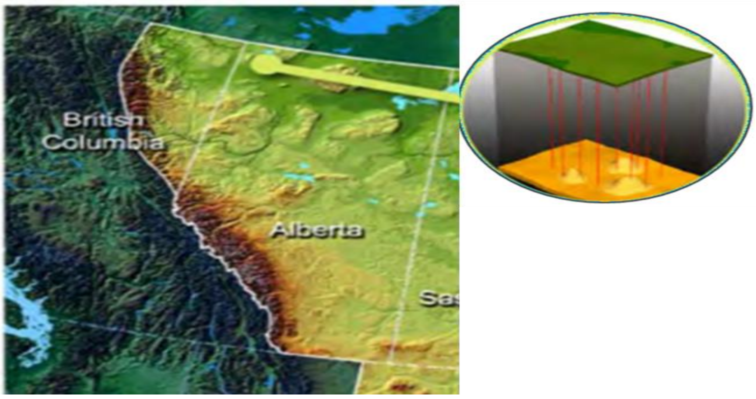

Fig. 5: Location of the Zama Project.

The pinnacle reef reservoir analyzed predominantly consists of relatively porous Keg River formation dolomites, which are overlain and bounded by the anhydrites of Muskeg formation and underlain by lower-porosity carbonates of Keg River as shown in Figure 6. According to this figure, the reef has a 90 m height, base area of 0.16 km^2 and circular in plan view, which corresponds to a circle with 450 m diameter. Several numerical simulations were performed to evaluate the effect of non-homogeneous surrounding rock, non-spheroidal reservoir geometry, and non-uniform distribution of pressure change within the reservoir on stress changes induced by pore pressure change in a pinnacle reef. These numerical analyses indicated that the assumptions of ellipsoidal geometry and homogeneous surrounding rock lead to minor modifications in stress change compared to the numerical analyses results.

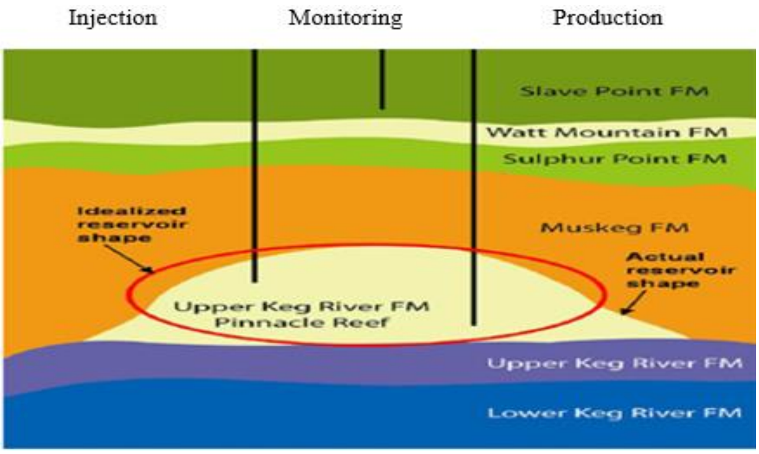

Fig. 6: Geometry of Actual and Idealized Reservoir [19].

In this study, induced shear failure was analyzed and the possibility of fault reactivation was performed. Ambient pore pressure gradient, vertical stress gradient, and reservoir aspect ratio were considered as the input parameters with the minimum statistical alteration. The value of the ambient pore pressure gradient was fixed to 10 kPa, while the values of the vertical stress gradient and reservoir aspect ratio were considered as 24 kPa and 0.2, respectively. All other inputs were considered to have truncated normal probability distributions. The sampling was carried out as a Monte Carlo simulation.

A probabilistic approach was then developed, which accounted for the significant uncertainty in the input parameter. In the probabilistic analysis, two issues were addressed. The first matter was the specification of inputs in probabilistic form, and the second was the selection of input parameters for the geomechanical model. The input parameters included shear modulus ratio (R_μ), Poisson's ratio (ν), peak friction angle (ϕ_p), peak cohesion (c_p), residual friction angle (ϕ_{fault}), minimum horizontal stress gradient (σ_{Hmin}), and maximum horizontal stress gradient (σ_{Hmax}). Probabilistic analyses for fault reactivation were performed for different locations including inside the storage unit, at the sideburdens and in the caprock. The outcomes of the analysis for inflicted fracturing showed a very high critical pressure change during production compared to actual pressure change. The amount for actual pressure change was estimably 10.5 MPa.

For the injection scenario, the tensile fracturing was in the range of 9-15 MPa and showed that the faults that appeared within the reservoir and in the caprock were improbable to reactivate. Results also showed that the higher limit of pressure enhanced during the time of injection was in the neighborhood of 12 MPa. This pressure ruled by fault reactivation and tensile fracturing based on the position and orientation of the fault. The critical pressure change showed 90% confidence during the production scenario. This value demonstrated that fault reactivation had a larger probability in the sideburdens and was unlikely within the reservoir and in the caprock. Figures 7 and 8 demonstrate the sensitivity of the critical pressure shift to the alteration of the probabilistic input data for the most resistless positions during injection and production, respectively.

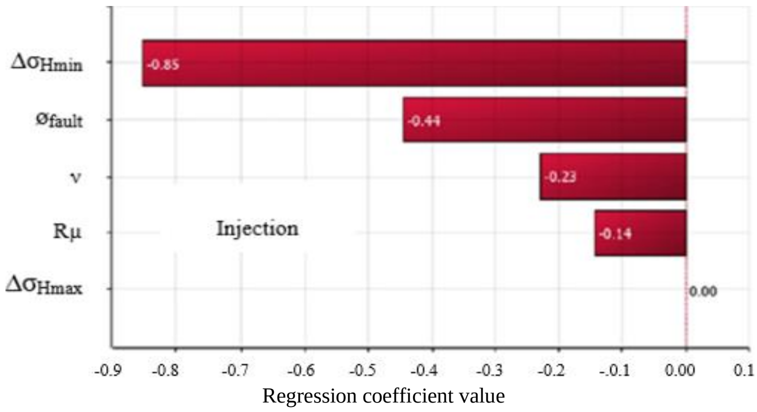

Fig. 7: Critical Pressure Change at the Side burden Parallel to Σ_{hmax} for Injection Scenario.

As illustrated in Figures 7 and 8, residual friction angle(ϕfault), which is represented the fault strength, has an important effect in both cases. Unlike the injection scenario, in the case of production, the lowest horizontal stress had more influence on the results when compared to the elastic properties. Results also confirmed that shear fracturing within the reservoir and in the surrounding rocks during the production scenario was insignificant. Also from the results, it could be concluded that the critical pressure variations for inflicted shear fracturing under injection situations were too conceptual in reality.

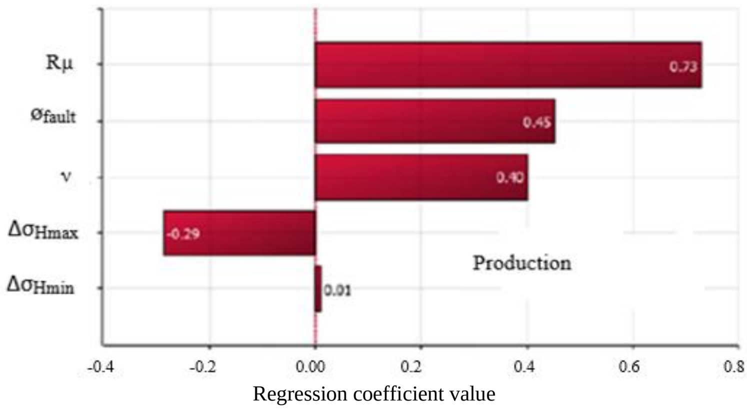

Fig. 8: Critical Pressure Change at the Sideburden Parallel to Σ_{hmin} for Injection Scenario.

3. Conclusions

In this research, two different underground CO_2 storage case studies were reviewed and the geomechanical effects of CO2 geological reservoir were investigated. In the first case study, namely HARP, a three-dimensional Mechanical Earth Model (MEM) was developed using the mechanical properties of 95 wells in the HARP study area. The model was developed and used as the basis for numerical modeling to evaluate the geomechanical response to CO_2 injection. The geomechanical analyses were applied for two scenarios of injection including after 25 and 50 years of injection, respectively.

The simulation was performed using a linear elastic model applying the Drucker-Prager failure criterion. The results showed that the maximum surface predicted by this model was approximately 1.62 cm. The effects of uncertainties in the elastic properties, pore pressures and horizontal stress magnitudes were studied by performing a series of sensitivity analysis. These analyses demonstrated a total ground surface uplift of 1-2 cm, which was small and in an acceptable range.

In the second case study, an analytical model was implemented using the probabilistic analysis of the geomechanical response of a reservoir in the Zama oil field in Alberta, Canada. In this study, hydrocarbon production occurred in the past and acid gas was injected in the depleting reservoirs. The outcomes showed that the inflicted shear fracturing was less likely at any location within the reservoir during both scenarios of production and injection. This case proved the straightforwardness and significance of probabilistic analysis to study the potential of these dangers.

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