Geomechanical Implications of CO_2 Sequestration in Saline Aquifers

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Summary

The implementation of carbon capture and sequestration (CCS) is widely recognized as a crucial method for mitigating the massive amount of carbon dioxide (CO_2) emissions and addressing the environmental and health threats associated with climate change. However, it is important to acknowledge that the CCS process is not without its associated geomechanical risks. These risks primarily stem from the pore pressure buildup resulting from the injection of CO_2 into subsurface formations. Changing pore pressure can result in caprock failure, reactivation of existing faults, changes in poroelastic response of rock, and well integrity loss (Zhu et al. (2021)). Furthermore, CO_2 injection can lead to changes in rock properties, including porosity, bulk modulus, and shear modulus. In this study, we examine the impact of CO_2 injection on formation pore volume and associated elastic and geomechanical properties for its effective monitoring over geological time scales.

Introduction

Fossil fuels accounted for 82% of global primary energy use in 2021, slightly lower than the 83% in 2019 and 85% five years ago (BP (2022)). This reliance on fossil fuels is projected to persist as the primary driver of economic growth worldwide in the coming decades (Figure 1). Carbon dioxide (CO_2) emissions resulting from human activities, primarily the burning of fossil fuels, have led to increased concentrations of greenhouse gases in the Earth's atmosphere (Li et al. (2021); Wei and Pan (2017)). Carbon dioxide emissions from various sources, including its use for energy generation, industrial processes, flaring, and burning of methane (converted to carbon dioxide equivalent), increased by 5.7% in 2021. Total carbon dioxide emissions reached 39.0 gigatons of carbon dioxide equivalent ($GtCO_2e$). Specifically, carbon dioxide emissions from energy use increased by 5.9% in 2021, reaching 33.9 Gt CO_2, which is close to the levels observed in 2019 (IEA (2021)).

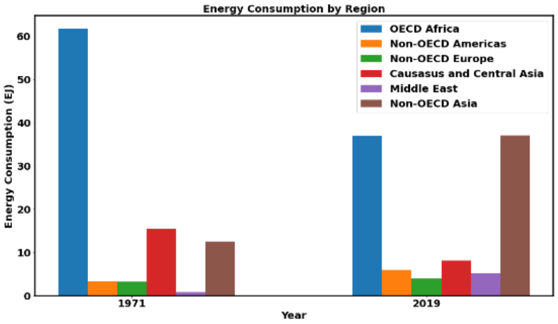

Figure 1: Total primary energy supply (IEA (2021))

Carbon dioxide emissions from flaring and emissions from methane and industrial processes rose more modestly, with increases of 2.9% and 4.6% respectively (BP (2022)). These emissions are a significant contributor to global climate change and its associated impacts. To mitigate the adverse effects of CO_2 emissions, various strategies for carbon capture and storage (CCS) have been explored. One promising method is the sequestration of CO_2 in deep saline aquifers (Zhu et al. (2021); Benson and Cole (2008)).

CO_2 sequestration aims to address two main objectives: the reduction of greenhouse gas emissions and the achievement of negative carbon dioxide emissions. By capturing CO_2 from large point sources such as power plants or industrial facilities, and then safely storing it in suitable reservoirs or geological formations, CO_2 sequestration provides a means to effectively remove CO_2 from the atmosphere and prevent its release. Deep saline aquifers, located thousands of meters below the earth's surface, offer large-scale and secure storage capacity for captured CO_2 (Kumar et al. (2005); Vilarrasa et al. (2013); Bachu (2015)).

Geomechanical property plays a crucial role in assessing the feasibility and safety of CO_2 sequestration in deep saline aquifers. These studies include investigating the elastic properties and the resulting geomechanical behavior of the reservoir rocks, the time-lapse response of the formation to injected CO_2, and the potential geomechanical risks associated with the storage process.

Hawkes et al. (2004) conducted a comprehensive review that outlined the primary geomechanical considerations affecting the integrity of sealing formations. This review likely encompassed factors such as caprock stability, fault reactivation, and wellbore integrity, providing a valuable foundation for subsequent research. To further investigate the behavior of CO_2 injection in aquifers, Rutqvist and Tsang (2002) and Rutqvist et al. (2008) employed hydromechanical simulations in synthetic (hypothetical) cases. Their studies aimed to assess the potential risks and geomechanical responses associated with CO_2 injection, including pressure buildup, induced seismicity, and geomechanical deformation. By utilizing numerical modeling, these studies contributed valuable insights into the behavior of CO_2 under various geomechanical conditions.

Orlic and Schroot (2005) focused on the feasibility of CO_2 re-injection in the Montmiral natural CO_2 accumulation in France, evaluating the geomechanical aspects involved in repurposing the reservoir for long-term CO_2 storage. Similarly, Vidal-Gilbert et al. (2008) investigated the feasibility of CO_2 storage in depleted hydrocarbon reservoirs in the Paris basin, assessing geomechanical factors such as reservoir integrity, faulting, and the potential for CO_2 leakage. Shi and Durucan (2008) explored the storage of CO_2 in the Atzbach-Schwanenstadt natural gas field located in Upper Austria. Their study focused on geomechanical considerations, including reservoir properties, caprock integrity, and the potential for induced seismicity. Additionally, Hofstee et al. (2008) analyzed the geomechanical aspects of CO_2 storage in the De Lier depleted gas field located in the Netherlands, examining reservoir suitability, caprock integrity, and the potential for induced seismic events. The study conducted by Shib Sankar Ganguli (2017) analyzed the subsurface formation in Cambay basin for the effective CO_2 EOR practices and potentially inform similar endeavors in other depleted oil reservoirs (hypothetical case).

Objectives

The objective of our study is to monitor the sequestration of CO_2 in a deep saline aquifer. Specifically, we aim to investigate the impact of CO_2 saturation on the pore volume alteration in the rock formation, below the caprock, in the caprock and above it. We will analyze how these changes in porosity and its spatial variation influence the bulk modulus and shear modulus of the rock, which are important elastic parameters and impacts the overall geomechanical behavior of the reservoir and cap rock properties. Additionally, we will examine how the presence of a CO_2 injection well affects these rock physical properties. By evaluating the variations in bulk modulus and shear modulus before and after the CO_2 injection, we can assess the potential alterations in the mechanical behavior of the rock due to the injection process.

Method and Materials

In this study, we work on monitoring the sequestration of CO_2 into deep saline aquifer once carbon dioxide (CO_2) is injected into this aquifer. In our model, we set the monitoring time of CO_2 sequestration from 1 November 2022 to 1 January 2086. We assumed there was no CO_2 present in the deep saline aquifer when we started simulation. We show how the presence of CO_2 affects the geomechanical property of the reservoir. CO_2 is injected in the aquifers with the help of five injection wells in a quarter-five-spot pattern. The injection process is regulated by the bottom hole pressure (BHP), which sets a limit on the maximum pressure allowed for CO_2 injection. The model reservoir properties, the cap rock properties, and model dimensions are detailed in Table 1 to Table 3.

In the study, a series of 3D mechanistic models were developed using the commercial simulation software T-navigator. Using T-navigator, which is a commercial simulation software, allows for the creation of detailed and comprehensive 3D models of the deep saline aquifer. These models were specifically built to simulate and analyze the behavior of deep saline aquifers, focusing on their potential for carbon dioxide (CO_2) storage.

Table 1: Reservoir Property

Lithology	Sandstone
Total Area, Square Kilometers	26
Top Depth, m	1458
Thickness, m	57
Porosity, Fraction	0.16
Permeability, md	400
Net to Gross Ratio (NTG)	0.75
Young Modulus, Pa	300000
Poisson Ratio	.2

Table 2: Grid Dimension

N_x	25
N_y	25
N_z	25
D_x	202.9
D_y	205
D_z	2.28
K_x	400
K_y	400
K_z	133

Table 3: Cap Rock Property

Thickness, m	2.28
Porosity, Fraction	0.05
Permeability, md	1E-9

Result and Discussions

The primary objective of this study was to investigate the influence of well pattern on pore volume, as well as the effects on bulk modulus and shear modulus of the formation and the cap rock. The analysis focused on well I3, as illustrated in Figure 2. The left side of the well consisted of wells I2 and I4, while the right side included wells I1 and I5. CO_2 injection was carried out up to 934 meters on both sides of the well.

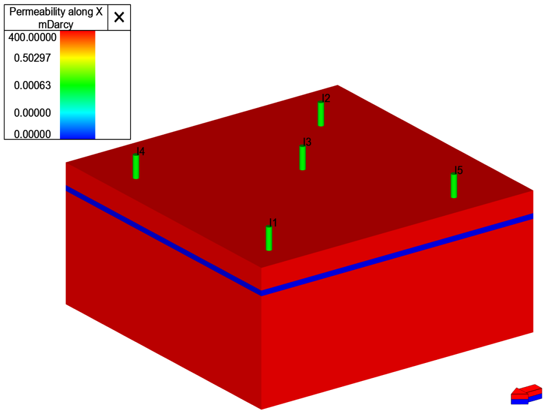

Figure 2: Permeability Distribution of Grid

Throughout the simulation period, the cap rock remained intact and showed no signs of fractures resulting from CO_2 injection. Consequently, no CO_2 was observed at or above the cap rock. The injected CO_2 volumes below the cap rock were 269,909.6 m^3 for the left side of the well and 82,779.7 m^3 for the right side. The findings are summarized in Table 4, which presents the results for the left side of the well, and Table 5, which illustrates the outcomes for the right side of the well.

Table 4: Changes in volumes to left side of the well

Year/Volume	At 2022	At 2086	Volume Changes
Pore Volume above cap rock, m^3	7587771.5	7587576.6	-194.9
Grain Volume above cap rock, m^3	39835800.8	39835995.8	194.9
Pore Volume of cap rock, m^3	592794.6	441166.2	-151628
Grain Volume of cap rock, m^3	58686670.9	58838299.3	151628.4
Pore Volume below cap rock, m^3	37938858.0	37953485.9	14627.92
Grain Volume below cap rock, m^3	199179004.4	199164376.5	-14627.9

Table 5: Changes in volumes to right side of the well

Year/Volume	At 2022	At 2086	Volume Changes
Pore Volume above cap rock, m3	6070217.2	6070061.3	-155.9
Grain Volume above cap rock, m3	31868640.7	31868796.6	155.9
Pore Volume of cap rock, m3	474235.7	352928.8	-121306.9
Grain Volume of cap rock, m3	58805229.8	58926536.7	121306.9
Pore Volume below cap rock, m3	30351086.3	30362793.3	11707
Grain Volume below cap rock, m3	159343203.6	159331496.6	-11707

To further analyze the effects of the well pattern, the study examined the different layers in the subsurface. The section was divided into three parts: above the cap rock (layers 1 to 4), the cap rock itself (layer 5), and below the cap rock (layers 5 to 25). The total volume of CO_2 injected across all layers was 1,657,204.2 m^3. The resulting changes in pore volume and grain volume are presented in Table 6.

The impact of these changes can be observed in Figures 3, which visually depict the effects on pore volume and grain volume in the different layers.

Table 6: changes in volumes in layers

Year/Volume	At 2022	At 2086	Volume Changes
Pore Volume above cap rock, m3	37938858.0	37937883.3	-974.6
Grain Volume above cap rock, m3	199179004.4	199179979.1	974.6
Pore Volume of cap rock, m3	2963973.2	2206281.8	-757691
Grain Volume of cap rock, m3	56315492.3	57073183.7	757691
Pore Volume below cap rock, m3	189694289.9	189766926.0	72636
Grain Volume below cap rock, m3	995895022.4	995822386.4	-72636

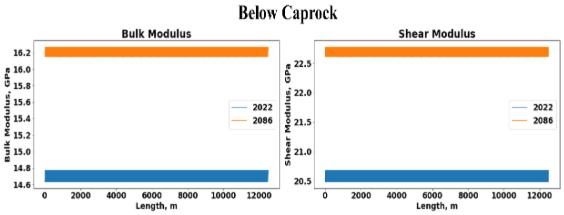

Figure 3: Changes in bulk and shear modulus due to CO_2 injection at caprock

Conclusions

The subsurface model considered in this work adequately represents the real scenario of saline aquifers located in Lithuania and therefore the results of change of pore volume and grain volume in the main reservoir, cap rock and the formation above cap rock warrants careful consideration. The injected CO_2 volume clearly shows the increase of pore pressure in the formation and therefore an increase in the pore volume which in turn clearly shows geomechanical implication for the cap rock and the formation above it. The estimated time-lapse bulk modulus shows a marginal increase of lower than 2 GPa and the shear modulus over the same time shows a marginal increase of slightly higher than 2 GPa. Although this increase in shear modulus is counter intuitive to the conventional understanding but given that the grain volume shows an increase in this formation indicates that the grain-to-grain contact has increased in this formation, thereby increasing the shear strength by a small margin. The future work will use a fully coupled geomechanical model to predict the time-lapse changes in the all the three-formation considered here for simulation.

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