Geomechanical Modeling of Salt Cavern Stability for Carbon Dioxide Storage in Northeast Thailand

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ABSTRACT

Greenhouse gases like carbon dioxide (CO2) are crucial regarding global atmospheric temperatures. In Thailand, CO2 emissions quadrupled over the past 3 decades since 1989. The power generation sector is the main contributor by burning fossil fuels to produce electricity. These emissions are among the main reasons for Global Warming. Therefore, the power generating industry has come under scrutiny and been pressed by society to take responsibility. Carbon Capture and Storage (CCS) is one of the many methods to deal with CO2 emissions. Generally, CO2 is captured and stored in geological formations, e.g. rock salt deposits which are found in many regions worldwide. Consequently, salt caverns have been intensively studied regarding their usage for CO2 storage because of their favourable characteristics, e.g. low permeability and self-healing capabilities which can prevent the leakage of CO2. Additionally, creation of salt caverns by cost-efficient solution mining is economically beneficial as overall cost for CCS are reduced. In this case study, northeast Thailand was chosen as location for CO2 storage because the sources of CO2 (mainly natural gas power plants) are in immediate vicinity of potential sinks. Northeast Thailand exhibits large deposits of evaporite minerals (including rock salt), which are part of the Maha Sarakham Formation. Salt layers within the formation are suitable to store CO2 in its supercritical fluid (SCF) state. For local communities the safety of these storage facilities is of utmost importance. Therefore, it is imperative to maximize cavern stability and safety factor as well as to minimize volume shrinkage and ground subsidence, which can be achieved by adequate cavern design.

Keywords: CO_2 storage, salt cavern, cavern stability, safety, northeast Thailand

1. Introduction

Carbon Dioxide (CO_2) is a crucial greenhouse gas regarding atmospheric temperatures and consequently the sustainability of life on Earth. Disruptions of the complicated climate system due to human activities causes problems. Nowadays, huge amounts of anthropogenic CO_2 are being emitted; especially from the fossil fuel industry and associated power plants (responsible for > 40% of anthropogenic CO_2). These emissions are among the main reasons for Global Warming. Therefore, the industry has come under scrutiny and been pressed by society to take responsibility. Regardless of any controversial opinions, prevention by reducing CO_2 emissions into the atmosphere is preferable to maintenance or rehabilitation.

Carbon Capture and Storage (CCS) is one of the many methods to handle CO_2 emissions. Generally, CO_2 is captured and stored in geological formations, preventing it from entering the atmosphere. Examples of geological storages are, among others, depleted oil and gas fields, unmined coal seams, and salt caverns. Rock salt deposits are found in many regions worldwide. Consequently, salt caverns have been intensively studied regarding their usage for CO_2 storage because rock salt has many favorable characteristics, e.g. low permeability (10^{-21} - 10^{-24} m^2) and self-healing capabilities which can prevent the leakage of CO_2. Additionally, creation of salt caverns by cost-efficient solution mining is economically beneficial as overall cost for CCS are reduced (Bachu, 2003; Dusseault, Bachu, & Rothenburg, 2004; El Tabakh, Utha-Aroon, & Schreiber, 1999; Wang et al., 2013).

A large deposit of evaporite minerals (rock salt and potash) is present in northeast Thailand. Thick salt layers are an integral part of the Maha Sarakham Formation (El Tabakh et al., 1999; Utha-Aroon, 1993). Therefore, salt caverns are a potentially adequate choice for CO_2 storage.

For local communities, the safety of these storage facilities is crucial. Therefore, potential mechanical problems, e.g. the creep properties of rock salt, which may lead to the collapse of the salt cavern, must be treated with the utmost care. It is imperative to maximize cavern stability and safety factor as well as to minimize volume shrinkage and ground subsidence. Longevity and safety can be achieved by adequate cavern design.

2. Overview

2.1 Sources of CO_2

In Thailand, CO_2 emissions quadrupled over the past 3 decades since 1989 (Figure 1). The power generation sector is the main contributor by burning fossil fuels (coal, oil and gas) to produce electricity (Energy Policy and Planning Office, 2017).

In northeast Thailand CO_2 emissions originate from several smaller biomass power plants and a fossil fuel power plant (natural gas) (Figure 2). The biomass power plants emit 0.456 million tons of CO_2 per year. The natural gas power plant, which satisfies most of the electricity needs in northeast Thailand, emits 2 million tons of CO_2 per year, making it the main contributor to greenhouse gas emissions in the region (Choomkong, Sirikunpitak, Darnsawasdi, & Yordkayhun, 2017).

2.2 Salt Cavern Location Selection

Sequestration facilities must be located relatively close to the sources of CO_2 (Dusseault et. al., 2004).

Additional criteria for selecting a suitable location to develop salt caverns include: 1) the thickness of the salt layer and 2) the depth of the salt layer and 3) temperature and pressure. A depth of > 800 m guarantees an environment (temperature > 31.1°C, pressure > 7.39 MPa) sufficient to store CO_2 in its supercritical state (SCF: CO_2 exhibiting features of both, gases and liquids). The benefit of storing CO_2 as SCF is the increased amount of sequestrated CO_2 due to a higher density .

In northeast Thailand potential locations for CO_2 storage within salt caverns are in the direct vicinity of the above-mentioned fossil fuel power plant.

Northeast Thailand has large deposits of evaporite minerals, such as rock salt and potash, within the Khorat and Sakon Nakhon basins (Figure 2) (El Tabakh et al., 1999; Utha-Aroon, 1993). The rock salt deposits are part of the Maha Sarakham Formation. The stratigraphy of the Maha Sarakham Formation is divided into three members which are Upper, Middle and Lower Member as shown in figure 3 (El Tabakh et al., 1999).

The Lower Member was chosen as potential location for CO_2 storage because the salt layers within this member are extremely thick (up to 1.1 km) and reaching deep enough to store CO_2 as SCF.

Drill hole data from the Department of Mineral Resources (DMR), confirms the presence of salt domes in Ban Nong Plue, Amphoe Borabue (district), Maha Sarakham (province). For drill hole K-89 the interval from 86 to 1169 m is proven to be rock salt, interbedded with anhydrite bands a (Japakasetr & Suwanich, 1982) as shown in figure 4.

The geothermal gradient of the salt layer is 31 ℃/km (Thienprasert & Raksaskulwong, 1984). Therefore, the area around K-89 is suitable for developing salt caverns to store CO_2 in northeast Thailand.

2.3 Salt Cavern Design, Construction and Operational Stages

The designated location for the salt cavern is the Lower Member of the Maha Sarakham Formation. The cavern is constructed by solution mining, a process during which salt is replaced by brine, over a period of 2 years (24 months). The cavern is designed as a sphere with a diameter of 100 m and would have a volume of ~ 520,000 m3. The working volume, which is the free space available for CO2 storage, is less than the actual volume due to some brine at the bottom of the cavern which cannot be discharged by injecting CO2. The midpoint depth of the cavern is 900 m. The mean overburden stress is ~18 MPa and the temperature is 52 ℃.

The pressure inside the cavern changes over time with regard to the current operational phase (Figure 5). We distinguish 4 stages: 1) solution mining, 2) discharge of the brine by injecting CO2, 3) pre-closure CO2 pressure adjustment and 4) cavern closure.

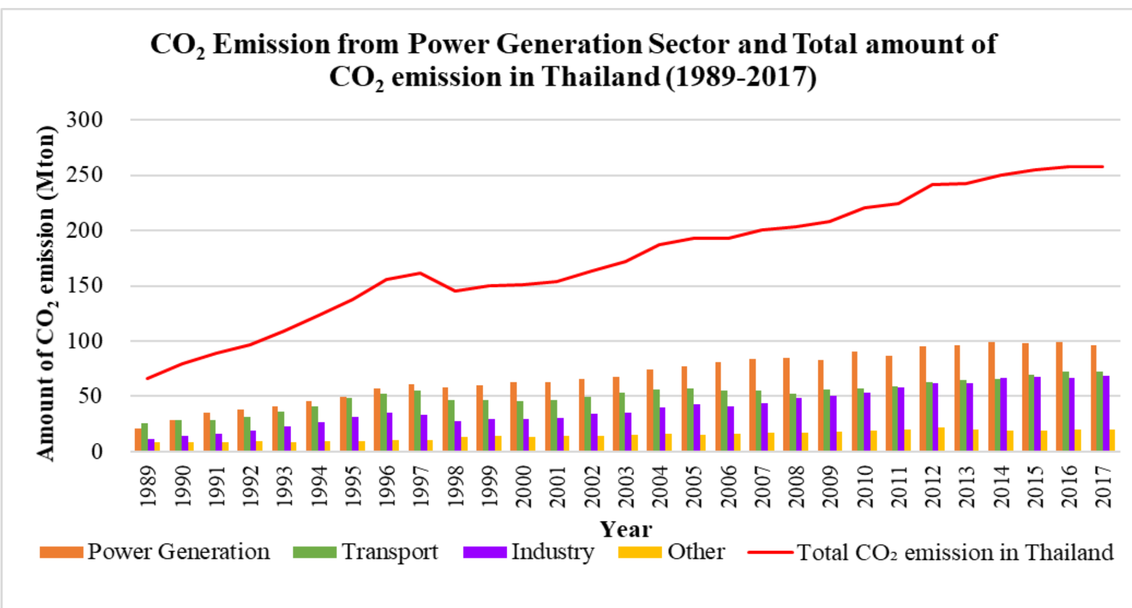

Figure 1. CO_2 Emission from Power Generation Sector and Total amount of CO_2 emission in Thailand (1989-2017) (modified from Energy Policy and Planning Office, 2017).

Stage 1 which last about 2 years (24 months) shows a pressure decrease within the cavern from 100 to 56% of the lithostatic pressure. The pressure inside the cavern is based on the hydrostatic pressure of the brine, the density of the brine being 1180 kg/m3(Jeremic, 1994). During stage 2 the pressure inside the cavern is kept constant (pressure of injected CO2 = brine pressure). After the brine is completely discharged the CO2 pressure is adjusted pre-closure. The two common ways are: a) the pressure of the injected CO2 is kept at brine pressure, b) the pressure of the injected CO2 is raised to 90-95% of the lithostatic pressure. In this study, we follow the latter as it will minimize the volume decrease (Bachu & Rothenburg, 2003; Dusseault et al., 2004). The pressure of the injected CO2 is raised from 56% to 95% of the lithostatic pressure during stage 3. After cavern closure (stage 4), the pressure within the cavern will remain at 95% of the lithostatic pressure.

In this research, we will investigate the salt cavern stability for a time span of 500 years after cavern closure.

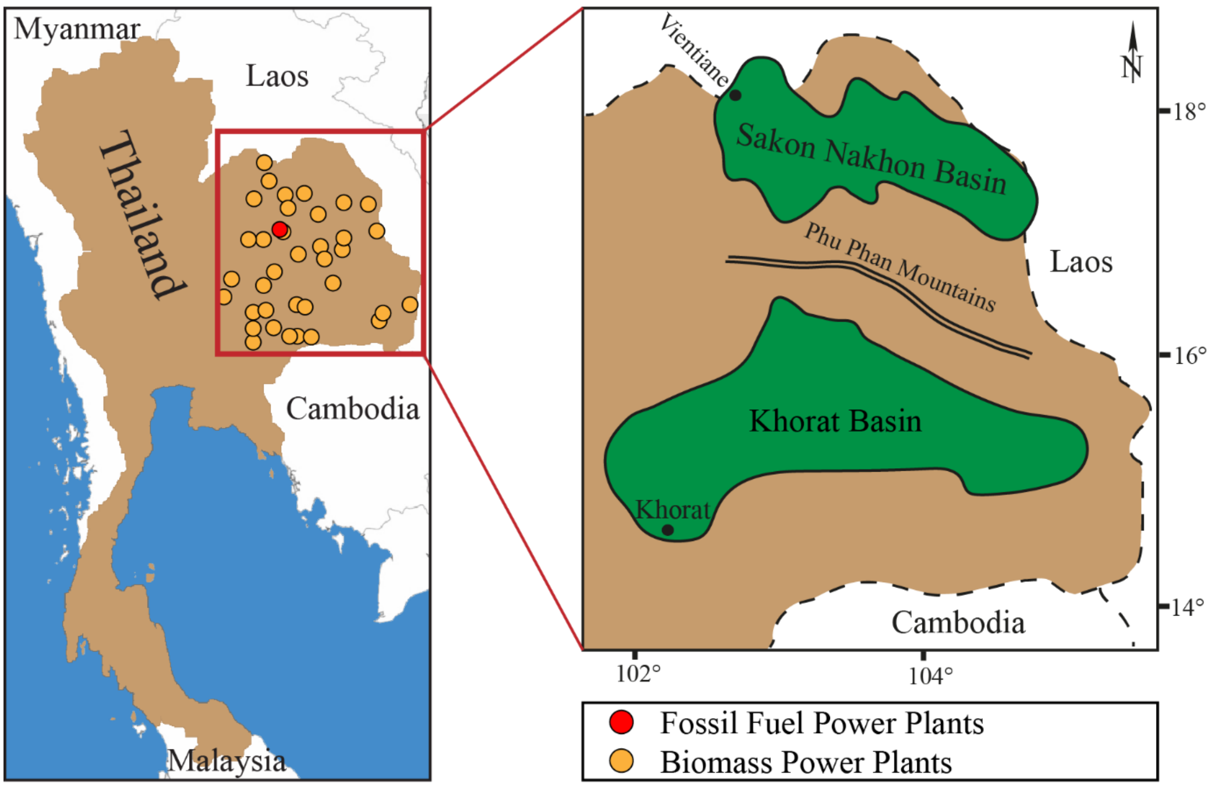

Figure 2. Location of CO_2 emission sources from fossil fuel and biomass power plants in Sakon Nakhon basin and Khorat basin, Northeast Thailand (modified from El Tabakh et al., 1999; Choomkong et al., 2017).

3. Geomechanical Modeling

In this research, the Finite Element Method (FEM, ANSYS Student 2019 R2) is used to compute the salt cavern stability. The process will be divided into three steps: preprocessing, processing and postprocessing.

Preprocessing involves geometry, material properties and meshing (PLANE183: quadratic, 8 nodes, 2D elements). Solutions for the model are obtained during the processing step which includes defining boundary conditions (forces or displacements) and the type of analysis (static vs. transient). The solution stage has been divided into four substages according to the above-mentioned operational stages of the salt cavern for CO_2 storage. The results (stresses, displacements, safety factor, volume decrease, etc.) obtained during processing can be viewed in the postprocessing step.

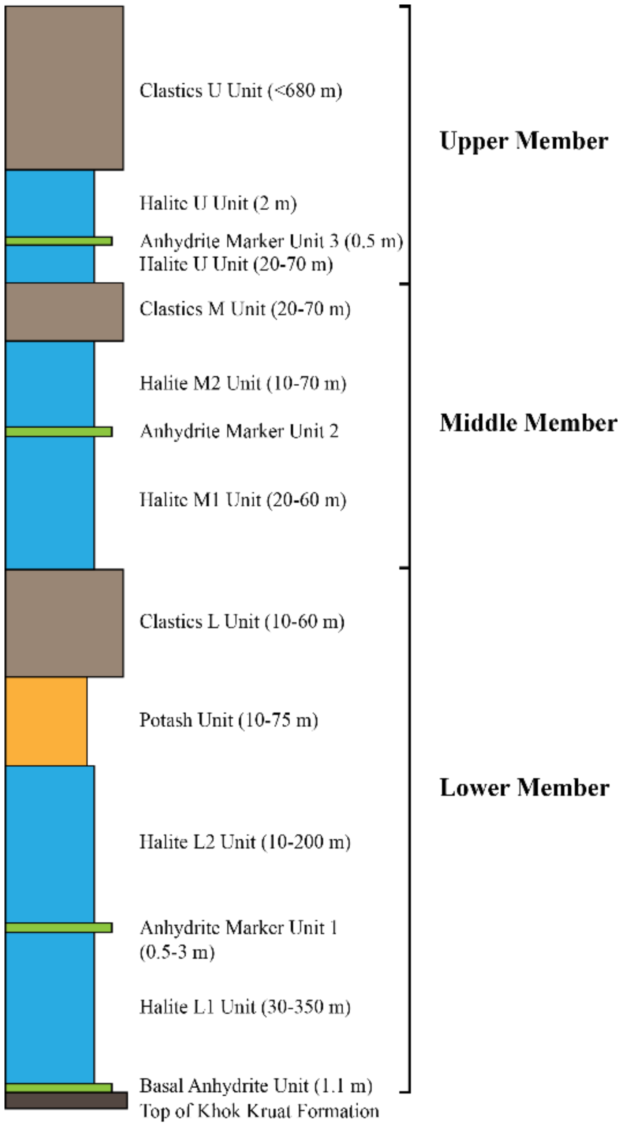

Figure 3. Stratigraphy of Maha Sarakham Formation (modified from El Tabakh et al.,1999).

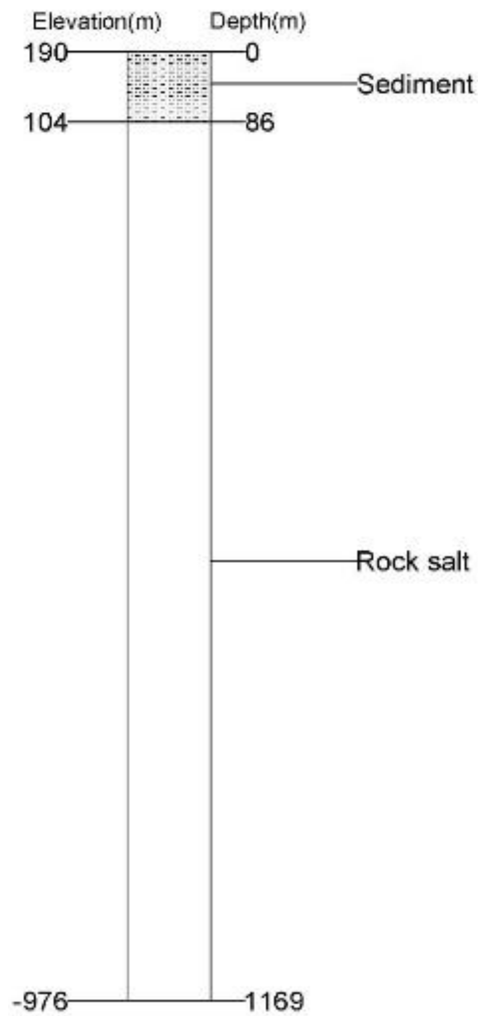

Figure 4. Stratigraphy of drill hole K-89 (modified from Japakasetr & Suwanich, 1982).

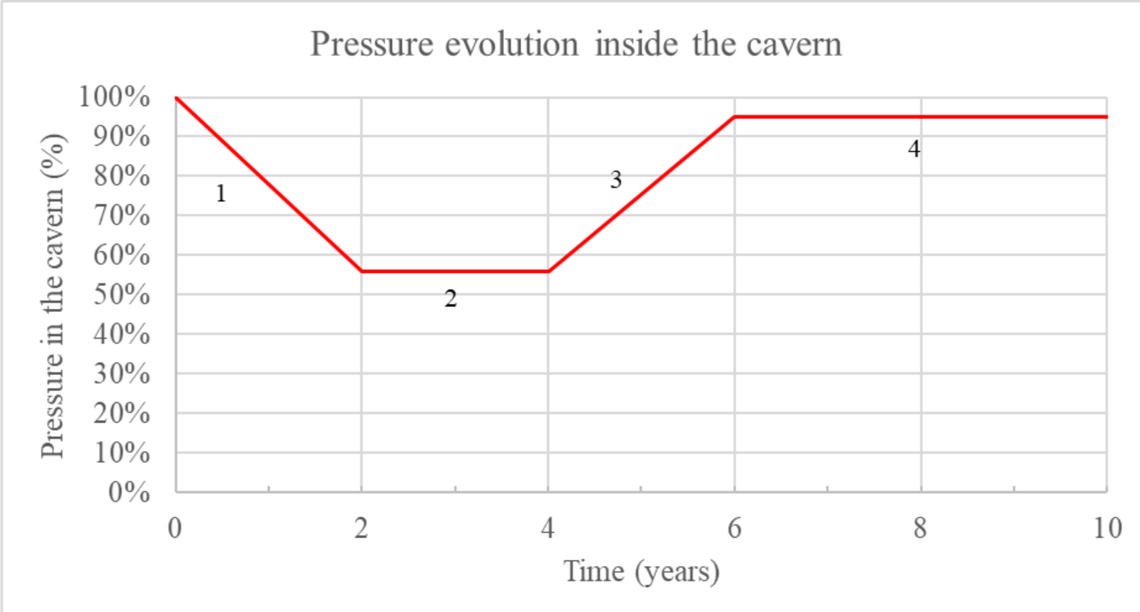

Figure 5. Evolution of the internal cavern pressure for the first 10 years

3.1 Geometry

A mentioned above, the cavern is designed as a sphere with a diameter of 100 m. The midpoint-depth of the cavern is at 900 m. The model has a width of 500 m and a total height of 1169 m. The top 86 m represent clastic sediments, while the part of the model from 86 to 1169 m, based on drill hole K-89, consists of rock salt (Figure 6).

3.2 Material Properties

3.2.1 CO_2 properties

To store CO_2 in its supercritical state (SCF), pressures and temperatures of at least 7.39 MPa and 31.1 °C are required. In our study, at a depth of 900 m the lithostatic pressure is 18.42 MPa with an ambient temperature of 52 °C. The density of the CO_2 varies over time due to the aforementioned operational stages. During stage 2, when the injected CO_2 is discharging the brine, the density of the CO_2 is approximately 400 kg/m^3. At the moment of cavern closure (stage 4), when the pressure within the cavern is at 95% of lithostatic pressure, the density of the CO_2 has increased to 740 kg/m^3.

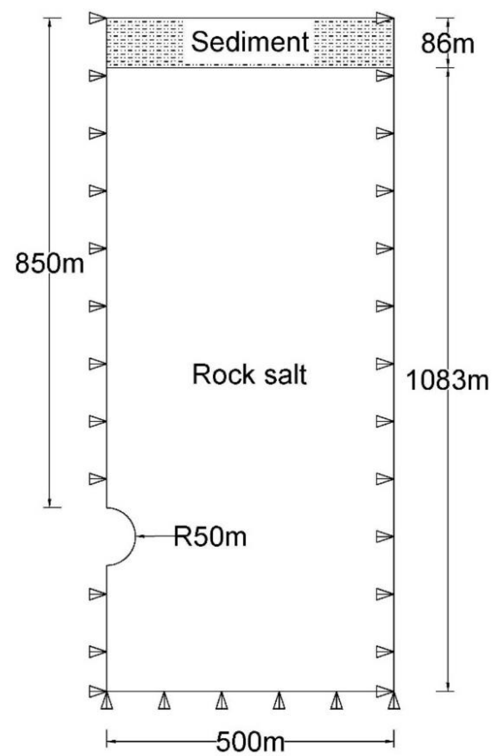

Figure 6. Schematic of designed salt cavern geometry.

3.2.2 Rock salt and sediments properties

The solid materials in the model consist of clastic sediments and rock salt. Their material properties have been retrieved from the Environmental Impact Assessment report of a Potash mining project (Asia Pacific Potash Corporation, 2014). The material properties used in our model are shown in table 1 and table 2.

Table 1. Material properties of rock salt.

Material properties	Rock salt
Density (kg/m^3)	2120
Young's Modulus (GPa)	4
Poisson's Ratio	0.2
Uniaxial Compressive Strength (MPa)	29.7
Thermal Conductivity (Wm^{-1}K^{-1})	4.65 [1]

[1] Data retrieved from; Heat flow in northern Thailand (Thienprasert & Raksaskulwong, 1984)

Table 2. Material properties of sediments.

Material properties	Sediments
Density (kg/m^3)	1750
Young's Modulus (GPa)	0.2
Poisson's Ratio	0.41

3.3 Choice of a Creep Law and Creep Parameters

Salt exhibits viscoplastic behavior under differential stress. The temperature as well as the difference between the stress and the pressure within the cavern are used to predict the creep rate. A pressure increase in the cavern leads to a diminishment of this difference. Therefore, the creep rate slows and a stress state reflecting the stress field prior to the construction of the cavern (virgin stress) is approached asymptotically.

In our study, the salt mass is subjected to a relatively small range of temperature and differential stress. Consequently, a full constitutive model for the behavior of salt over a wide range of temperature and shear stress is not necessary. For our salt cavern models we focus on secondary or steady state creep acting over very long time spans. The Norton Power Law, as shown in Equation 1, was applied in our simulations:

$$\dot{\varepsilon}_{cr} = A\sigma^n \exp\left(\frac{-Q}{RT}\right) \quad (1)$$

Where $\dot{\varepsilon}_{cr}$ is the steady state creep strain rate; A is the pre-exponential constant; σ is the stress; n is the stress exponent; Q is the activation energy; R is the universal gas constant; T is the absolute temperature (Carter, Horseman, Russell, & Handin, 1993).

In this research, low and high creep strain rates were chosen to investigate the effect of the creep strain rate on the cavern stability. The values chosen for this study are shown in table 3.

Table 3. Creep parameters of rock salt for low creep rate and high creep rate.

Creep Parameter: Norton Law	Low creep strain rate	High creep strain rate
A (MPa · n · s^{-1})	$9\times10^{-34.2}$ [2]	$8.12\times10^{-25.52}$ [3]
n	3.2 [2]	3.42 [3]
Q (J/mole)	54,428 [4]	51,596 [3]
R (J K^{-1}mol^{-1})	8.314 [4]	8.314 [4]

[2] Data retrieved from; Environmental Impact Assessment report of Potash mining project (Asia Pacific Potash Corporation, 2014)
[3] Data retrieved from; Rheology of rock salt (Carter et al., 1993)
[4] Data retrieved from; Creep in Rock salt (Le Comte, 1965)

4. Results and Discussion

In this study we conducted a stability analysis for a spherical salt cavern with an

Table 4. Model results for using low creep strain parameter.

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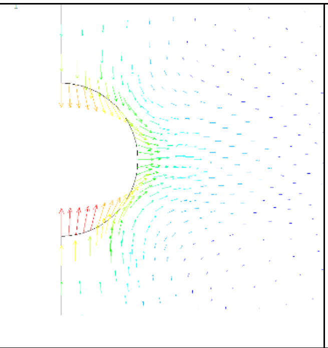
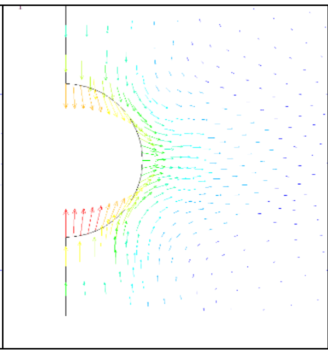
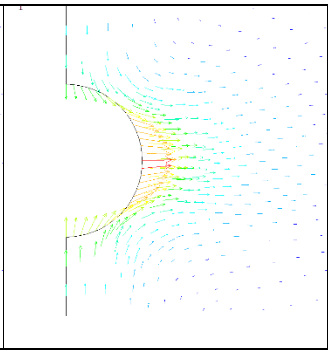
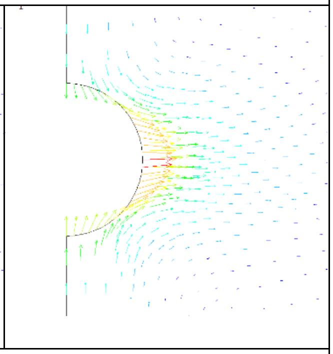
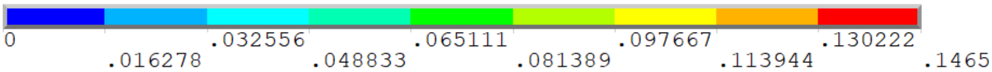
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="4">
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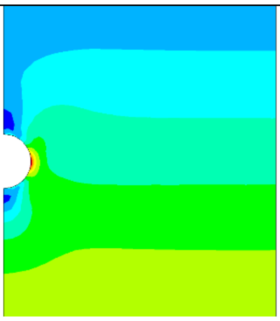
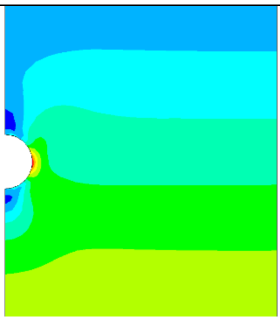
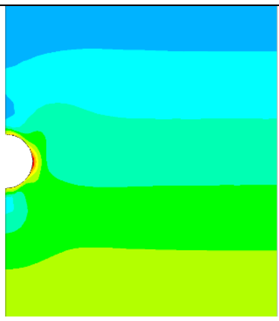
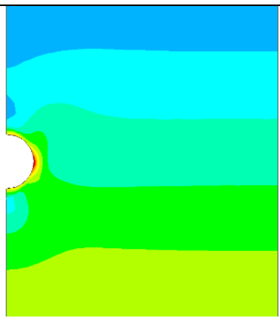
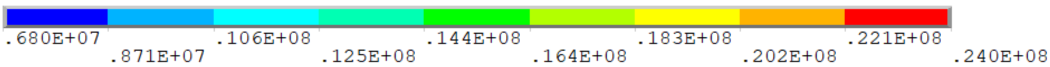
<tr><td>Solution mining</td><td>Brine discharge</td><td>CO_2 injection</td><td>Cavern closure</td></tr>
<tr><td colspan="4">Von Mises stress</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="4">
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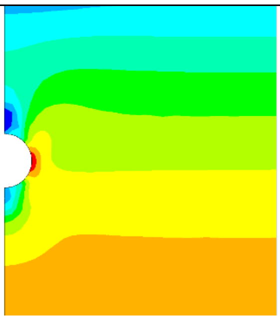
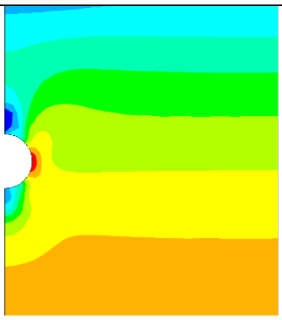
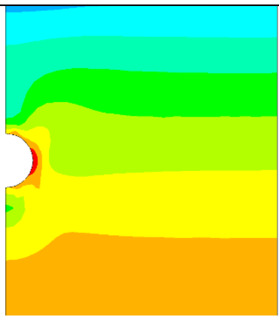
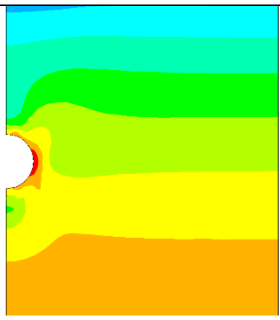
<tr><td colspan="4">Safety Factor</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
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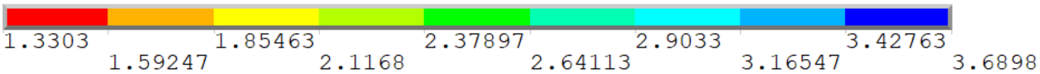

Solution mining	Brine discharge	CO_2 injection	Cavern closure

Table 5. Model results for using high creep strain parameter.

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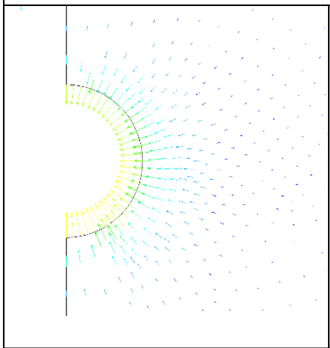
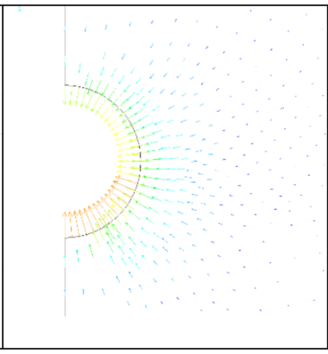
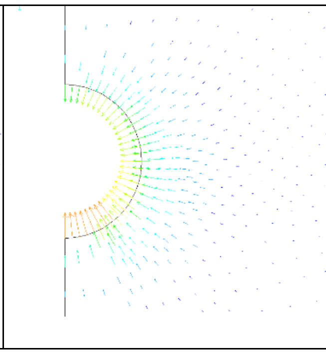
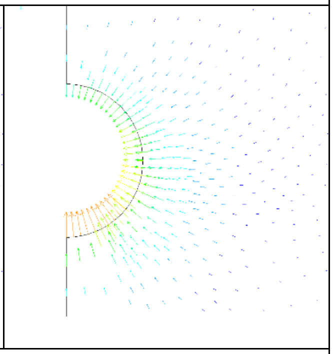
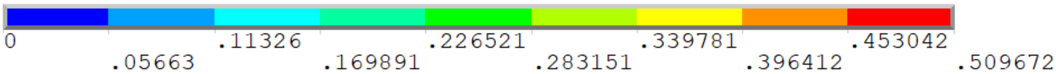
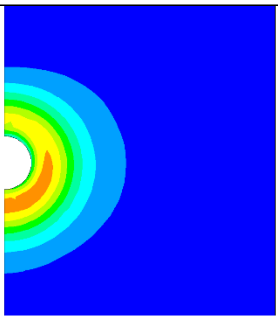
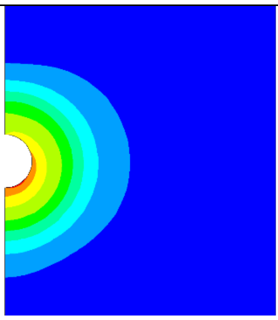
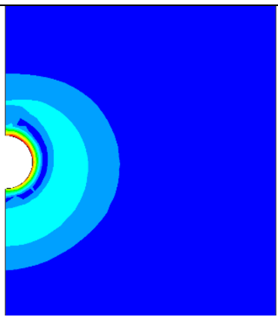
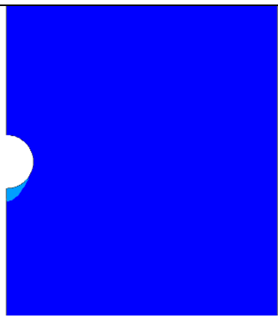
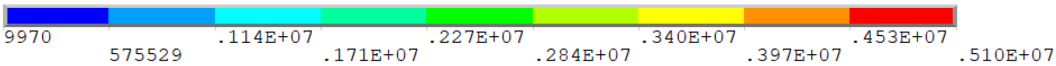
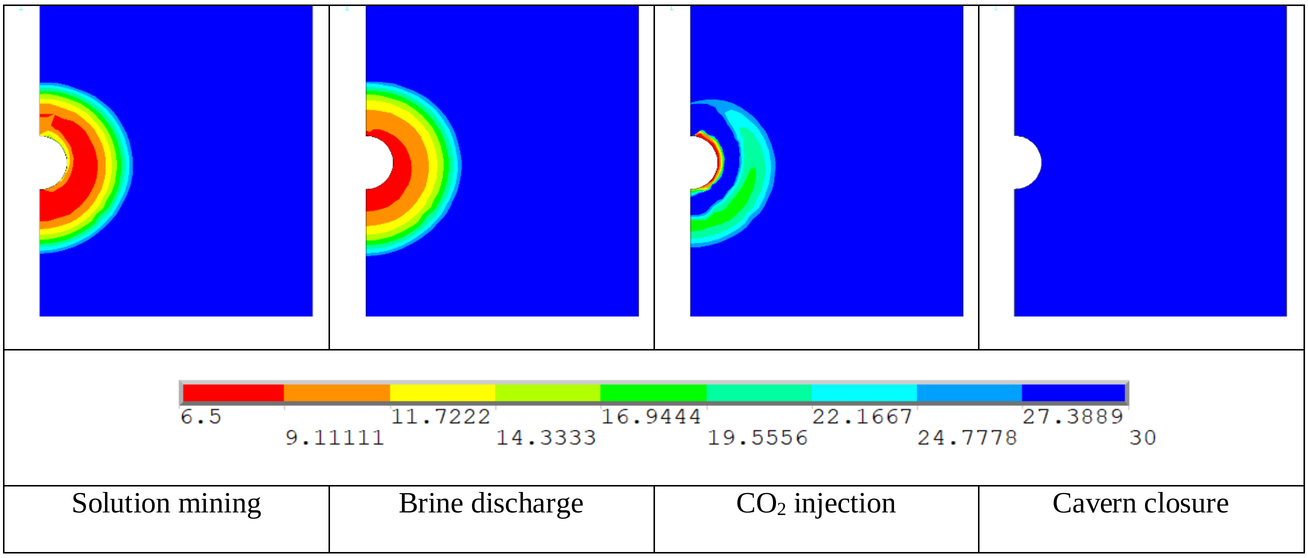
			



Solution mining	Brine discharge	CO_2 injection	Cavern closure
Von Mises stress			
			



Solution mining	Brine discharge	CO_2 injection	Cavern closure
Safety Factor			



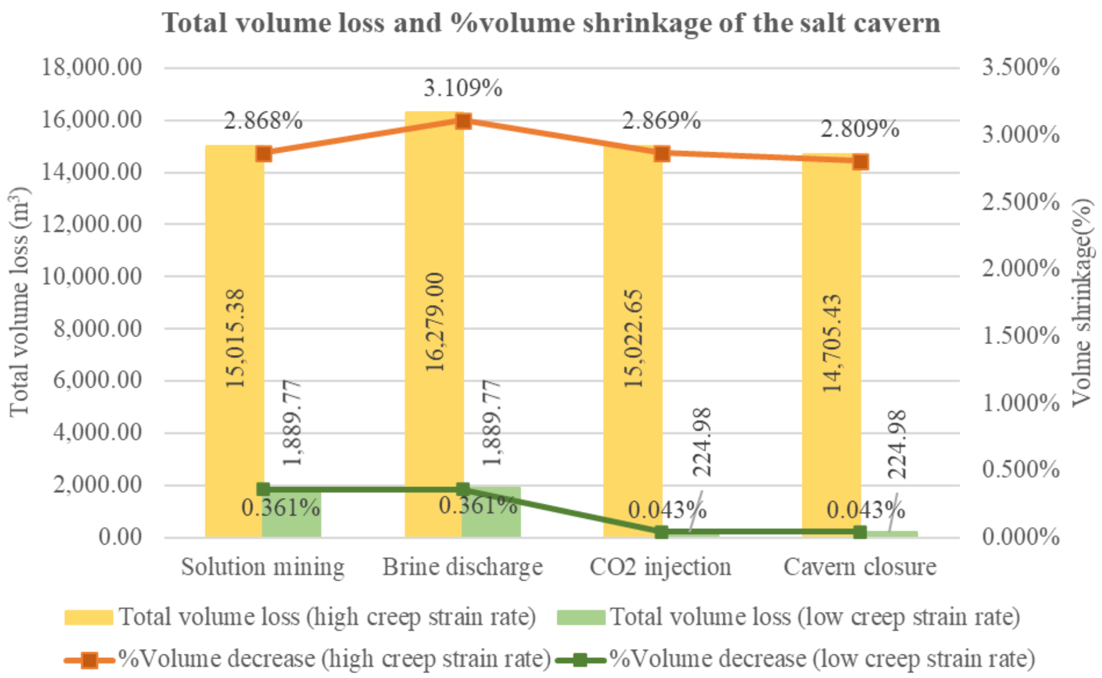


Figure 5. Total volume loss and %volume decrease of the salt cavern.

emphasis on creep parameters. The results, with a focus on displacement, von Mises stress, volume decrease, and safety factor are shown in Table 4, Table 5 and Figure 7.

Displacement within the model, especially within the vicinity of the cavern and related volume changes of the cavern depend on the selected creep parameters and the pressure inside the cavern. Opting for either high or low creep strain rates will affect the amount and direction of the displacement. During the processes of solution mining and brine discharge, when the cavern pressure was kept at approximately 56% of the lithostatic pressure, most of the displacement occurred vertically (y-direction). The stress acting upon the cavern is generated by the overburden (rock column). After the complete discharge of the brine, the cavern pressure was raised by injecting CO_2 until it reached 95% of the lithostatic pressure. The displacement during this phase differed from the previous stages. While the model with the high creep strain rate showed a similar behavior to the previous stages, the model with the low creep strain rate exhibited a shift to mainly horizontal displacement (x-direction). In the case of the low creep strain rate, the total strain was dominated by elastic strain with only a very small amount of creep strain. Consequently, the cavern reacted to any contraction in the y-direction with an elongation in x-direction.

The cavern volume changed throughout the different stages. The creep parameters affected the amount of volume change, with the high creep strain rate model exhibiting the highest volume decrease (~3%). In both cases, high and low creep strain rate, maximum volume decrease was observed during brine discharge (stage 2). CO_2 injection at high pressure (stage 3) led to a volume increase while remaining under the designed cavern volume.

The process of CO_2 sequestration in salt caverns affects the stress field. Before the start of the cavern construction, the prevailing stress field (virgin stress) was dominated by the lithostatic pressure. During and after the construction process, a disturbance of the stress field can be recognized caused by solution mining and brine discharge and the associated difference between stress and cavern pressure (56% of the lithostatic pressure). Due to the injection of CO_2 at high pressure (95% of the lithostatic pressure) this difference is diminished, causing the creep rate to slow, and ultimately the virgin stress is approached asymptotically.

The safety factor is used to describe the stability of the cavern. In our models, the safety factor is based on the ratio between rock strength (Uniaxial Compressive Strength) and von Mises stress. A structure is considered to be safe if the safety factor has a value > 1. The lowest value for the safety factor in our models has been 1.33 (low creep strain rate). Consequently, based on our modeling results, salt caverns can be considered a safe option for CO_2 storage in its supercritical state.

Ground subsidence is a critical value for local communities, as it affects their lives directly, leading to damage of infrastructure and housing. Due to the depth of the cavern, the amount of ground subsidence predicted by our models is less than 1 mm within the time span of 500 years and can be considered insignificant.

5. Conclusions

The Maha Sarakham Formation exhibits very thick rock salt layers, especially the Lower Member. The area in the vicinity of drill hole K-89 is ideally suited for the storage of CO_2 in its supercritical fluid state (SCF) in salt caverns.

The modeling results show that the salt cavern stability is ensured for a time span of at least 500 years. Ground subsidence is insignificant. The sequestration process is shown to be safe and negative effects on the local communities improbable.

This study shows that storage of CO_2 in salt caverns in northeast Thailand is a technically viable and safe solution for the reduction of anthropogenic CO_2 emissions into the atmosphere.

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