

CONCEPTUAL INJECTION OF CO₂ INTO BACKFILLED STOPE

by

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Thesis submitted to the School of Mining and Geosciences of Nazarbayev
University in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Petroleum/Mining Engineering/Geosciences

Nazarbayev University

12.04.2026

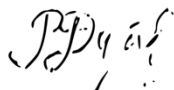
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ABSTRACT

The focus of conventional carbon capture and storage (CCS) is primarily in depleted oil and gas reservoirs, deep saline aquifers, and basaltic formations. This study explores novel conceptual CCS approach involving the storage of supercritical CO₂ in mined-out underground stope. In this approach, the stope is backfilled while intentionally leaving an unfilled void space at the top, which serves as localized CO₂ storage zone. The key objective is to evaluate whether backfilled stope opening can maintain sufficient structural integrity and stability for localized CO₂ storage, while potentially making use of existing mining infrastructure in an economically efficient manner.

A combined numerical modelling approach was adopted using ANSYS or RS3. ANSYS was used to simulate thermal response of the storage chamber and resulting thermally induced stresses in the cemented paste backfill (CPB). Subsequently, three-dimensional geomechanical modelling was carried out in RS3 to assess mechanical behavior of the surrounding rock mass and the backfill system. The RS3 model considered 4 sequential stages: virgin stress state, excavated stope, backfilled stope with and intentionally created void at the top, and CO₂ injection stage. As gases cannot be directly modelled in RS3, the mechanical effect of stored CO₂ were represented by equivalent loads applied to chamber boundaries.

Under the assumed supercritical storage conditions, the chamber temperature reaches approximately 405K (131°C) and induced thermal stress at the top of the backfill was about 3MPa. The modelling results indicate that excavation produces the greatest disturbance to the initial in situ stress regime, generating stress concentrations at crown and corners. In the virgin state, major principal stress ranged from 23 to 29MPa, whereas after the excavation maximum major principal stress increased to approximately 94MPa near the stope crown. Full stope excavation produced maximum total displacement of 0.042m, concentrated near roof and sidewalls. After backfilling maximum major principal stress decreased to 86MPa, indicating partial stress redistribution and improved support. After the CO₂ injection, the mechanical response remained localized around the storage chamber. The displacement directly beneath the chamber reached a maximum of 0.013m, with deformation decreasing toward the stope walls because of confinement from surrounding rock mass. Overall, the study indicates that CO₂ storage in the void space above the backfilled stope may be feasible at a conceptual level,

although chamber boundary and upper backfill interface remain the most critical zones for further investigation.

ACKNOWLEDGMENT

I would like express gratitude to my supervisor, Professor Ali Mortazavi. He provided a lot of help with guiding and supporting me through the entire process of completing my thesis. His knowledge and expertise were invaluable to improving the quality of this research; he was patient and always provided great feedback on all aspects of this project. I would like to extend my gratitude to the faculty and staff of the School of Mining and Geosciences at Nazarbayev University. They created a positive learning and research environment that enabled me to complete my degree. In addition, I wish to express my sincere gratitude to my fellow students (classmates) who have made significant contributions to this study by providing assistance, encouragement and motivation.

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1. INTRODUCTION

1.1 Background

For the past 250 years, humanity has relied on fossil fuels—such as coal, oil, and gas—for energy. This dependence on fossil fuels spurred economic growth and fueled the Industrial Revolution. However, this industrial progress has come with significant consequences. Since the onset of the 21st century, the world has witnessed dramatic changes, including the melting of ice caps, rising sea levels, droughts, and a decline in biodiversity. Most critically, the continuous burning of fossil fuels has led to increased carbon dioxide production, greatly contributing to global warming.

According to the Copernicus Climate Change Service (2024), the atmospheric concentration of CO₂ reached 419 parts per million (ppm) in 2023, marking an increase of 2.4 ppm from the previous year. Additionally, the global average temperature in 2023 was 14.98°C, which is 0.17°C higher than the previous record set in 2016. By 2024, the global average surface temperature was approximately 1.55°C above pre-industrial levels (1850-1900), according to the World Meteorological Organization (2025). This marked the first instance of the global average temperature exceeding the 1.5°C threshold established by the Paris Agreement.

Global warming poses serious threats to ecosystems, human health, and economies worldwide. As the global average temperature continues to rise due to human activities, there is an urgent need for action.

In recent years, growing attention has been directed toward the use of abandoned underground mines and mined-out openings as potential sites for carbon dioxide (CO₂) storage. Conventional carbon capture and storage (CCS) projects are typically associated with depleted oil and gas reservoirs, deep saline aquifers, and other regional-scale geological formations. However, underground mining operations also create extensive subsurface voids, including goafs, stopes, cavities, and excavated panels, which may offer additional storage opportunities if their geomechanical and sealing conditions are favorable. In this context, mined voids represent an emerging alternative for localized CO₂ sequestration, particularly where existing underground infrastructure may reduce the need for new excavation and lower the overall cost of storage development.

Among these possibilities, backfilled underground stope is of particular interest because they combine excavated storage space with engineered support. In many underground mines, stopes are filled after ore extraction to maintain stability and reduce ground movement. If a controlled void is intentionally left above the backfill, this remaining space may potentially serve as a confined chamber for CO₂ storage. Such a concept is attractive because the surrounding rock mass provides structural confinement, while the backfill may act as a supporting and sealing medium. Nevertheless, the feasibility of this concept depends on whether the stope-backfill-rock system can remain mechanically stable under the coupled effects of gas pressure and temperature change.

This study investigates the thermo-mechanical behavior of a backfilled stope during injection of supercritical CO₂. A conceptual storage scenario was considered in which a 1 m thick void space was intentionally left within the backfilled stope to serve as a storage chamber. During injection, CO₂ is introduced in its supercritical state, which is characterized by high density and enhanced storage efficiency under elevated pressure and temperature conditions. As the chamber is pressurized, both pressure and temperature evolve until thermodynamic equilibrium is reached. This process is important because the increase in chamber temperature may generate thermal stresses in the surrounding backfill, while the pressure exerted by the stored CO₂ imposes an additional mechanical load on the chamber boundaries.

The combined effect of gas pressure and thermally induced stress may alter the stress distribution within the backfill and surrounding rock mass. These coupled thermo-mechanical processes can influence the overall stability of the system by promoting localized deformation, modifying confinement conditions, and potentially creating zones of stress concentration near the storage chamber. For this reason, understanding the mechanical response of the stope environment during and after CO₂ injection is essential before such a storage concept can be considered viable.

Previous studies have shown that underground mine voids may provide useful storage opportunities when suitable geological and structural conditions are present. For example, underground coal mining creates extensive goafs, and once these voids are no longer influenced by active mining and retain an intact caprock, favorable storage volume, and adequate sealing capacity, they may serve as secure sites for CO₂ sequestration (Gao et al., 2023). Similar reasoning can be extended to backfilled stopes, where storage performance depends not only

on available void space but also on the interaction between the backfill, surrounding host rock, and the injected CO₂.

Given these considerations, this study applies numerical modelling to assess the behavior of the proposed storage concept. By evaluating stress redistribution, thermal effects, and displacement response, the research aims to determine whether CO₂ storage in a partially backfilled stope can be regarded as feasible at a conceptual level, and to identify the most critical zones requiring further investigation.

1.2 Objectives of the Thesis

1.2.1 Main Objectives

- To assess feasibility of storing supercritical CO₂ in the void space above the backfilled stope in terms of geomechanical stability.

1.2.2 Specific Objectives

- To simulate the injection process and determine the temperature and pressure evolution within the storage chamber using ANSYS.
- To estimate thermo-mechanical stresses induced by both the pressure of injected CO₂ and the associated temperature increase.
- To perform staged geomechanical modelling in RS3 to analyze stress redistribution and possible displacement during virgin state, excavated stope, backfilling the stope and CO₂ injection phases.
- To assess mechanical stability of the backfilled stope and identify potential deformation and failure zones

1.3 Hypotheses

- Temperature increases during CO₂ injection will induce significant thermal stress to backfill and surrounding rock.
- The combined effect of CO₂ pressure and thermal stress will change the stress distribution around the storage zone.

1.4 Justification of the R&D

Currently, mining companies are facing increasing pressure to reduce carbon emissions and adopt sustainable practices. At the same time many open stope mines contain large volumes of excavated voids that are subsequently backfilled. Utilizing these underground spaces for carbon dioxide storage presents an opportunity to combine mining operation with carbon management strategies. The results of this research may contribute to the development of a novel approach to integrate CSS technologies with underground mining operations. By assessing the mechanical response of supercritical CO₂ to backfilled stope, the study provides insight that may support safe utilization of backfilled stopes as potential CO₂ storage.

1.5 Scope of Work

1. Conducting primary research on CCS, focusing on existing CCS solutions, trapping mechanisms, criteria for potential storage sites and key factors influencing CO₂ storage.
2. Gathering required input data for numerical modelling by using case studies and existing literature.
3. Simulating the injection of supercritical CO₂ into the storage chamber using ANSYS to evaluate the temperature and pressure changes until the system reaches equilibrium.
4. Calculating thermal stress applied to the backfill and combining them with gas pressure to assess total pressure applied to the backfill.
5. Conducting 3D geotechnical simulation in RS3 on four sequential phases.
6. Interpret and analyze generated results.

2. LITERATURE REVIEW

2.1 Importance of the problem

For the past 250 years, humanity has relied on fossil fuels—such as coal, oil, and gas—for energy. This dependence on fossil fuels spurred economic growth and fueled the Industrial Revolution. However, this industrial progress has come with significant consequences. Since the onset of the 21st century, the world has witnessed dramatic changes, including the melting of ice caps, rising sea levels, droughts, and a decline in biodiversity. Most critically, the continuous burning of fossil fuels has led to increased carbon dioxide production, greatly contributing to global warming.

According to the Copernicus Climate Change Service (2024), the atmospheric concentration of CO₂ reached 419 parts per million (ppm) in 2023, marking an increase of 2.4 ppm from the previous year. Additionally, the global average temperature in 2023 was 14.98°C, which is 0.17°C higher than the previous record set in 2016. By 2024, the global average surface temperature was approximately 1.55°C above pre-industrial levels (1850-1900), according to the World Meteorological Organization (2025). This marked the first instance of the global average temperature exceeding the 1.5°C threshold established by the Paris Agreement.

Global warming poses serious threats to ecosystems, human health, and economies worldwide. As the global average temperature continues to rise due to human activities, there is an urgent need for action.

2.2 Current Carbon Capture Storage Solutions

According to (CaptureMap, 2024) tech company, there are 1007 carbon capture projects worldwide. Out of 1007, 228 are capture plants under the operation, 68 are in the engineering, procurement, and construction (EPC) phases, and 657 are in the feasibility stage. Most of the carbon capture plants are situated near industrial sites with high concentrations of CO₂, such as ammonia and hydrogen production facilities, ethanol plants and gas treatment plants with CO₂ separation. Most projects at various stages of development are situated in Europe (37% of all) and North America (47%), making these two regions the primary hubs of Carbon Capture projects.

In 2023, 204 new carbon capture projects were announced, but only half of them announced their capture capacities. On average each project captured 800,000 tons of CO₂ per year. Total reported capacity of the project for 2023 preached nearly 80 million tons of CO₂ (CaptureMap, 2024).

Currently, the CO₂ is injected into depleted oil and gas reservoirs, deep saline aquifers, unmineable coal seams and basalt formations. Major projects include Sleipner (Norway), Gorgon (Australia), Quest (Canada), CarbFix (Iceland). More than 50 large-scale carbon capture projects with a total capture capacity of 51 million tons of CO₂ per year are led by the USA, Canada and Australia.

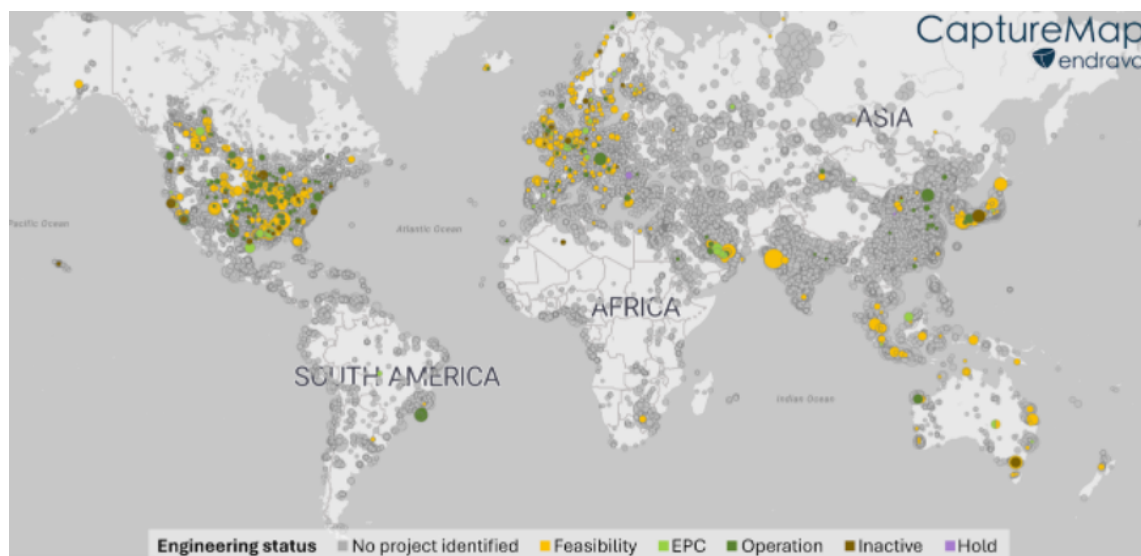


Figure 1. Carbon Capture projects of the world (CaptureMap, 2024).

2.3 Underground formations for CO₂ storage

It is important to differentiate between two terms: CCS (Carbon Capture and Storage) and CCU (Carbon Capture and Utilization). CCS projects are designed for the safe, permanent, or long-term storage of carbon dioxide, while CCU focuses on using the captured CO₂ to create more valuable products. Sequestering atmospheric CO₂ in geological formations is a significant method for reducing CO₂ concentrations. Among various industrial processes, burning coal for power generation accounts for 25% of all atmospheric CO₂ emissions, which is the primary focus of CCS projects.

According to NETL (National Energy Technology Laboratory of the US), there are five main types of underground formations for geologic carbon dioxide storage:

1. Depleted oil and natural gas reservoirs
2. Saline formations
3. Unminable coal seams
4. Organic-Rich Shales
5. Basalt formations

Table 1. Underground formations for CO₂ storage (Bravsar et al., 2023).

Storage type	Mechanism	Advantages	Limitations
Depleted oil and natural gas reservoirs	CO ₂ injected into previously exploited hydrocarbon reservoirs. Formations have proven seal integrity and known geological characteristics.	1. Well-characterized geology (extensive data from previous hydrocarbon extraction) 2. Existing infrastructure (utilization of wells and other existing infrastructure reduces cost) 3. Enhanced oil recovery (CO₂ injection can enhance residual oil recovery, providing economic incentives).	1. Limited capacity (storage volume is constrained by original hydrocarbon volume) 2. Potential leakage (risk of leakage through cracks or abandoned wells) 3. Pressure Management (require careful pressure monitoring to prevent caprock fracturing)
Saline formations	Deep underground porous rock formations saturated with salty water. CO ₂ is trapped by various mechanisms including structural, residual, solubility and mineral trapping.	1. Large storage capacity. 2. Multiple trapping mechanisms 3. Found in many regions worldwide.	1. Limited characterization (less geological data available compared to oil and gas reservoirs). 2. Monitoring challenges. 3. Potential geochemical reaction (CO₂ brine rock interaction).
Unminable coal seams	Injection of CO ₂ into deep coal seams that are not economically minable. CO ₂ absorbs into coal surface displacing the methane (CH ₄), which can be recovered as byproduct (Enhanced Coal Bed Methane recovery).	1. Simultaneous CO₂ injection and methane production. 2. High absorption capacity (coal has strong affinity for CO₂). 3. Utilization of existing infrastructure.	1. Total capacity is less than saline formations and oil and gas reservoirs. 2. Risk of leakage through natural fractures, faults. 3. Monitoring difficulties.

Organic-Rich Shales	CO ₂ absorbed onto organic matter and clay minerals.	1.Potential for enhanced gas recovery (CO ₂ injection can displace natural gas). 2. Widespread presence.	1.Low permeability makes CO ₂ injection challenging. 2.Limited research (less understanding of long term behavior). 3.Monitoring difficulties
Basalt formations	CO ₂ reacts with minerals to form stable carbonate minerals, effectively locking CO ₂ in solid form (mineral carbonation).	1.Permanent Storage 2. Abundance of basalt formations worldwide. 3.Low leakage risks. 4.Rapid Mineralization (some projects demonstrated quick conversion rates)	1. Requires high pressure injection. 2. Fewer pilot projects compared to other storage types. 3. Variability in mineral composition can affect carbonation. 4. Monitoring difficulties.

Among the five types of underground formations suitable for geologic carbon capture and storage, depleted oil and gas reservoirs are considered ideal sites. These reservoirs have contained hydrocarbons for thousands to millions of years and possess conditions that are favorable for CO₂ storage. According to Wei, Wang, Li, and Aishan (2023), carbon dioxide can be effectively stored in oil and gas reservoirs because of their strong storage capacity, good sealing performance, and existing infrastructure.

CO₂ can be stored underground in a supercritical state. The term "supercritical" refers to carbon dioxide at temperatures exceeding 31.1°C (88°F) and pressures greater than 7.38 MPa. Under these high temperature and pressure conditions, carbon dioxide becomes dense like a liquid but has a viscosity similar to that of a gas. Storing CO₂ in a supercritical form allows for the capture of significantly more CO₂ compared to standard conditions at room pressure.

As depth increases, both temperature and pressure naturally rise. At depths below 800 meters, the natural temperature and pressure typically exceed the critical point of CO₂ in most regions of the Earth. This means that CO₂ injected at this depth or deeper will remain in a supercritical state due to the prevailing temperature and pressure conditions (National Energy Technology Laboratory).

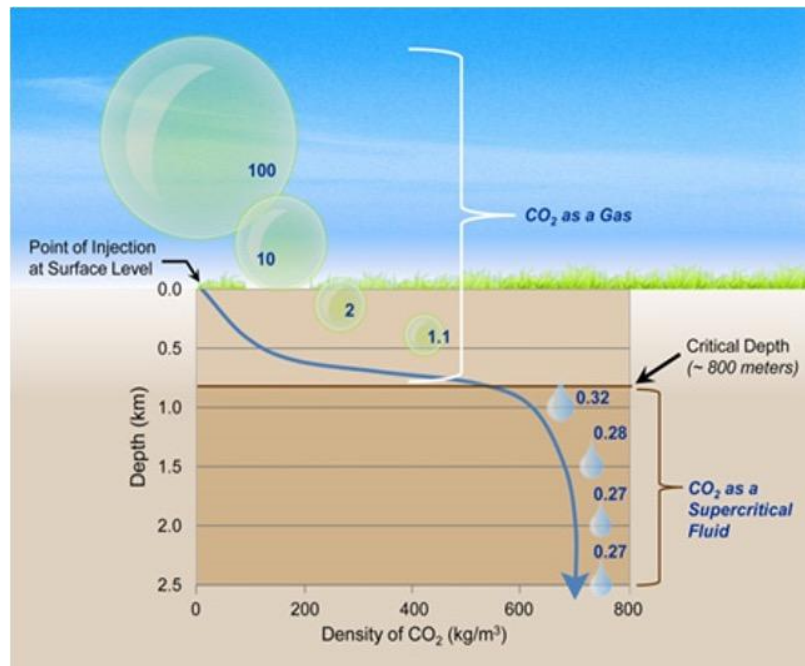


Figure 2. Illustration of pressure effect on CO₂ (National Energy Technology Laboratory).

2.4 Trapping Mechanisms of CO₂

Shukla et al. (2010) identified four primary mechanisms for sequestering CO₂ in saline aquifers located in sedimentary basins: mineral trapping, solubility trapping, structural trapping, and hydrodynamic trapping.

1. **Mineral Trapping:** This mechanism involves the chemical reaction of CO₂ with mineral components present in brine water.
2. **Solubility Trapping:** In this process, CO₂ chemically reacts with minerals found in the brine, resulting in the formation of stable solid compounds.
3. **Structural Trapping:** This occurs when CO₂ accumulates beneath an impermeable caprock. Since CO₂ is less dense than both air and water, it tends to rise until it is halted by the impermeable top seal.
4. **Hydrodynamic Trapping:** This mechanism restricts the movement of CO₂, preventing it from escaping the targeted reservoir zone due to the presence of the aquifer.

2.5 Storage Site Suitability for CO₂ Injection

An ideal site for CO₂ storage should have sufficient capacity, available infrastructure, and integrity to resist buoyancy-driven flow, ensuring that CO₂ can be stored long-term without leakage. The caprock should not be prone to fracture propagation, and the formation must possess adequate mechanical stability to prevent fault slippage (Ojala, 2011). According to Bhuiyan et al. (2020), an ideal caprock is impermeable, non-fractured, non-porous, and non-reactive. It should remain unaffected by changes in fluid composition, stress induced by injection, or tectonic activities over geological time.

Due to the heterogeneous and anisotropic characteristics of deposits, particularly shale, each storage site can differ significantly from others. Therefore, it is essential to assess local stress conditions before planning and initiating a CO₂ storage project. The complexity of heterogeneous and anisotropic tight reservoir rocks necessitates a detailed examination at every stage of subsurface storage research. Additionally, the chemical and mechanical effects of CO₂ injection into geological formations are complex and can vary from one location to another. These factors should be considered on different scales and over time, particularly in the context of fluid-rock interactions (Ozatta et al., 2021).

The design and operation of CO₂ storage, especially in underground stopes involve several critical considerations. Material compatibility of both backfill and surrounding rock material is extremely important. The materials are expected to maintain structural integrity under extreme pressure conditions. Thermal management is also crucial to avoid crossing the phase boundary and ensure that fluid remains in supercritical state (Dai et al., 2022). Accidental leakage of CO₂ from pressurized vessels can lead to rapid depressurization and phase change.

In geological CO₂ storage, careful consideration must be given to the geochemical interaction between CO₂ and the backfill material or rock matrix. For example, when supercritical CO₂ contacts sandstone at right temperature and pressure, it diffuses into pores, forms a weak acidic fluid with formation water, then reacts with rock. The CO₂ at supercritical state (60°C and 10MPa) reacted with sandstone. The weight of the rock decreased over time, indicating dissolving response (Peng et al., 2022).

2.6 Factors influencing CO₂ storage

According to Wei et al. (2023), there are two main groups of factors that influence CO₂ storage in depleted oil and gas reservoirs: geological factors and engineering factors.

Table 2. Factors influencing CO₂ storage in DOGR.

Geological factors	Engineering factors
Caprock integrity	Well integrity
Fault	
Capillary force	
CO ₂ dissolution and reactions	Injection pressure
Wettability	
Salt precipitation	

Caprock integrity is a key factor in determining the long-term safety of CO₂ storage in depleted oil and gas reservoirs (DOGR). The integrity of these reservoirs can be compromised by various factors, including reservoir decompression, injection fracturing, pore and osmotic pressure, and capillary leakage (Wei et al., 2023).

As highlighted by Shukla et al. (2010), several aspects require careful consideration, such as caprock thickness, the vertical and lateral extent of the hydrocarbon column, and the caprock's ability to tolerate mechanical deformation. The caprock acts as a barrier to prevent upward CO₂ movement and must be capable of enduring changes in the stress field and the physicochemical properties resulting from CO₂-brine-rock interactions.

The mechanical strength and seal integrity of the caprock can be compromised by tectonic extrusion, tensile strength issues, seismic disturbances, and the dissolution or precipitation of minerals. Notably, caprock thickness is particularly crucial, especially when the pressure surpasses the caprock's mechanical strength. Ultimately, caprock failure results from the combined influence of these mechanisms (Wei et al., 2023).

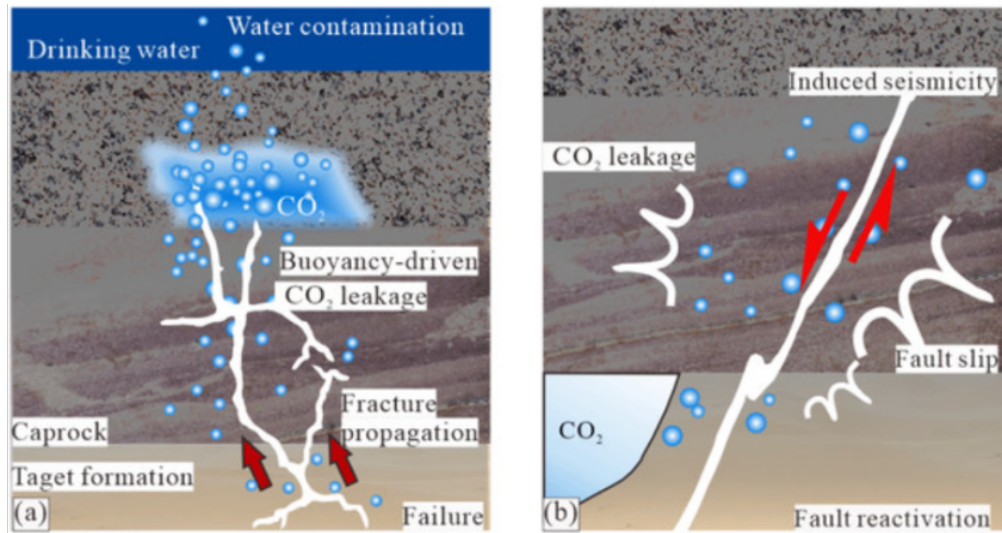


Figure 3. (a) Caprock failure (b) fault leakage Song et al. (2023).

Cracks and faults can serve as potential pathways for CO₂ movement. The injection and storage of CO₂ can induce the formation of fractures and even reactivate existing faults. For instance, if the formation pressure is too high or if the stress state changes due to large-scale CO₂ injection, the maximum stress acting on a fault surface may exceed its shear strength. This can initiate slippage along fault planes or reactivate previously sealed faults (Wei et al., 2023). Even when fluid pressure near faults is insufficient to activate original faults, it can still lead to the formation of new faults in structurally weak zones (Ozatta et al., 2021). Changes in mineralogy, such as dissolution, precipitation, or the migration of minerals, can cause existing cracks to either widen or close. However, the precise dynamics and likelihood of these geochemical processes remain topics for further investigation (Wei et al., 2023).

In addition to cracks and faults, capillaries can act as potential migration and leakage pathways for CO₂. The movement of CO₂ and brine, when considered as a two-phase fluid system, is significantly influenced by the balance of viscous, capillary, and gravitational forces. The primary interactions occur at the CO₂-water interface, where capillary forces resist the upward migration of CO₂. When the combined effects of capillary and viscous forces acting on the CO₂ in the pores exceed the buoyancy forces, the CO₂ will become trapped and collected within the rock pores (Wei et al., 2023).

Fault slippage and reactivation was first recognized as a possible cause of fluid flow in faulted areas by Sibson in 1990 and is fundamentally ruled by Mohr-Coulomb failure criterion. Fault reactivation is influenced by the shear and normal stress components acting on the fault plane.

In two-dimensional scenario under normal faulting regime, these stresses can be described mathematically as (Nacht, Oliveira & Roehl, 2010):

$$\tau = \frac{1}{2}(\sigma_v - \sigma_h) \sin(2\theta) \quad (1)$$

$$\sigma_n = \frac{1}{2}(\sigma_v + \sigma_h) + \frac{1}{2}(\sigma_v - \sigma_h) \cos(2\theta) \quad (2)$$

$$\tau_{slip} = c + \mu(\sigma_n - \alpha p) \quad (3)$$

Θ - faults dip angle

p - pore pressure

α - Biot's coefficient

c - fault's cohesion

$\mu = \tan\phi$ - fault's friction coefficient

$\sigma_n - \alpha p = \sigma'_n$ - effective normal stress on the fault plane

The likelihood of fault reactivation can be assessed using the modified slip tendency (ST) parameter.

$$ST = \frac{\tau}{\tau_{slip}} \quad (4)$$

ST ranges within $0 \leq ST \leq 1$. Higher ST, more susceptible to reactivation.

Field evidence indicates that faults tend to become hydraulically conductive when the shear stress exceeds the limit defined by Mohr-Coulomb failure criterion. Byerlee(1978) states that hydraulically active faults have angle of friction within ($31^\circ \leq \phi \leq 45^\circ$), although the faults containing clay minerals may have lower values. Cohesion along such faults is generally less than 1MPa and often considered as null (Nacht, Oliveira & Roehl, 2010).

2.7 Pressure Conditions

Injection pressure must be high enough to store CO₂ in a supercritical state.

- Pressure $\geq 7.38\text{MPa}$
- Temperature $\geq 31.1^\circ\text{C}$

Supercritical fluids have physical, and transport properties intermediate between gases and liquids, making them attractive as reaction media. From a technological point of view, supercritical CO₂ provides an attractive medium for chemical reactions. At supercritical state compressibility becomes high. As a result, even small pressure variations can cause significant changes in density. The density changes influence properties such as diffusivity, viscosity, dielectric behavior and solvation (Polikhronidi et al., 2019).

Injection pressure must be low enough to:

- Avoid fracturing of rock or backfill
- Avoid forcing CO₂ into pore spaces of surrounding materials

Injection Pressure must stay below the capillary entry pressure of both

- The surrounding rock
- Top layer of backfill

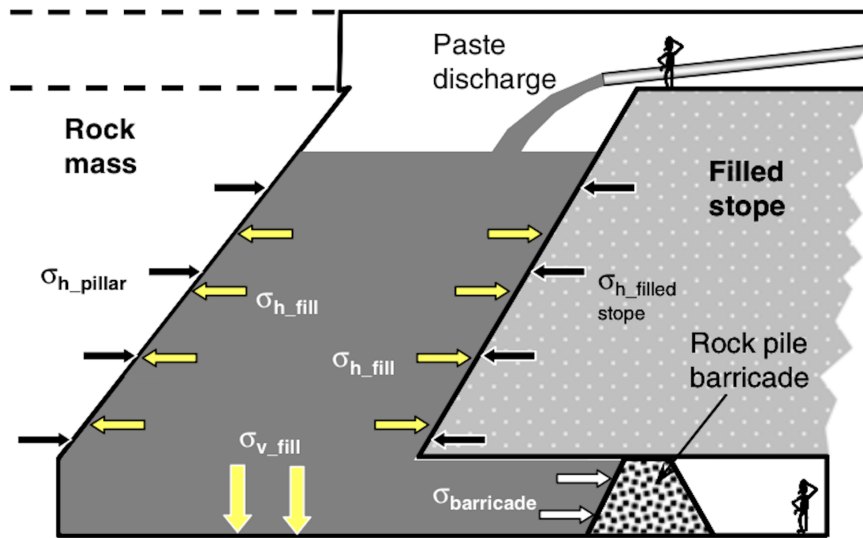


Figure 4. Schematic layout of backfilled stope components and stress field redistribution (Belem & Benzaazoua, 2007).

2.8 Joule-Thomson effect

Joule-Thomson effect describes a phenomenon that occurs when high pressure gas passes through a suddenly compressed section. As a result, the pressure of the gas will be reduced and

temperature will change due to local resistance. In the context of underground salt cavern gas storage, both injection and withdrawal of gases cause fluctuations in cavern pressure, which in turn lead to corresponding changes in gas temperature as a direct result of the Joule-Thomson effect.

According to molecular theory, this phenomenon happens due to mutual transformation between heat and work. During gas injection, the outside world performs work on the gas to compress it. Both pressure and temperature of the gas in the storage tank increase. In this case mechanical energy is converted into thermal energy. Conversely, during gas withdrawal, the gas expands and performs work on its surroundings, reducing its internal pressure. Intermolecular distances increase, heat is converted to function to overcome the intermolecular forces, resulting in decrease in temperature due to the transformation of thermal energy into work (Zhang, Li, & Chen, 2022).

To investigate how volume affects temperature variations resulting from the Joule–Thomson effect, (Zhang, Li, & Chen, 2022) analyzed two ellipsoidal models of different sizes. Both models were subject to identical boundary conditions, with the outlet pressure reduced from 10 MPa to 5 MPa simultaneously. The gas temperature within each model was averaged across the region.

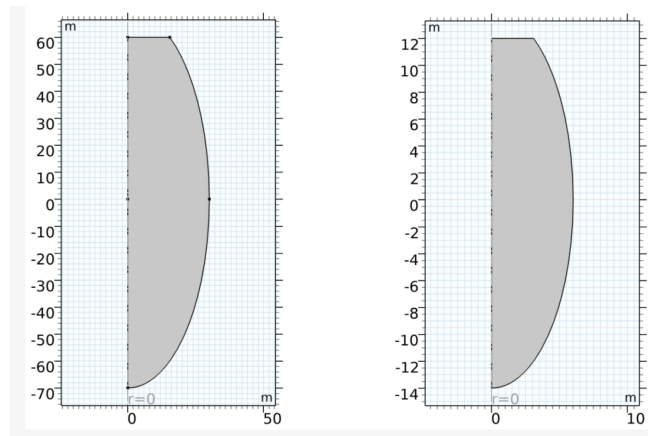


Figure 5. Models of Different sizes (Zhang, Li, & Chen, 2022).

The figure shows that temperature changes from the Joule–Thomson effect depends solely on pressure, not on storage volume or injection/withdrawal time. Continued gas injection or

withdrawal is feasible, with rates and intervals influenced by heat exchange with surrounding rock.

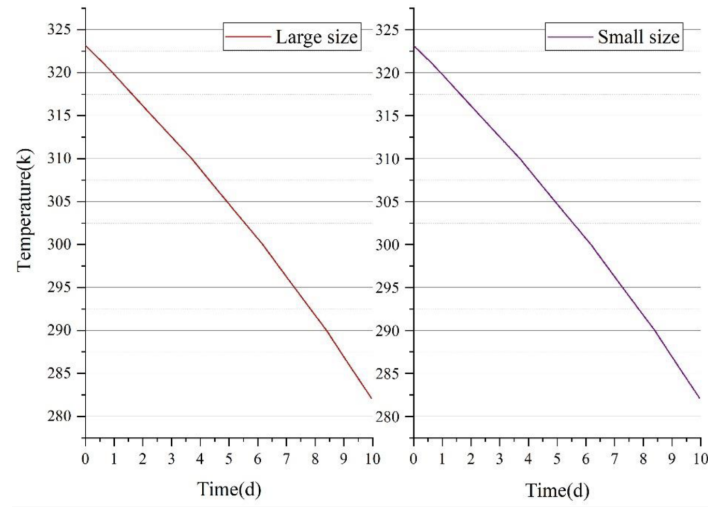


Figure 6. Diagram of temperature change over time (Zhang, Li, & Chen, 2022).

To assess how container shape affects temperature changes from the Joule–Thomson effect, two 2D axisymmetric models—ellipsoidal and cylindrical—were compared under identical boundary conditions with a pressure drop from 10 MPa to 5 MPa (Zhang, Li, & Chen, 2022).

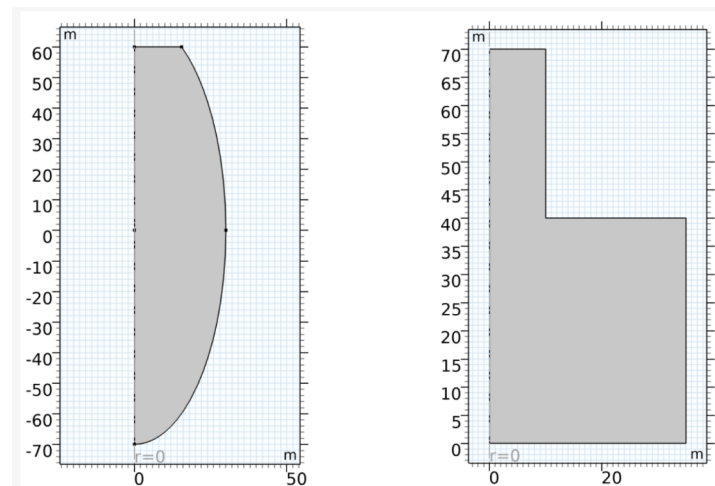


Figure 7. Models with different shapes (Zhang, Li, & Chen, 2022).

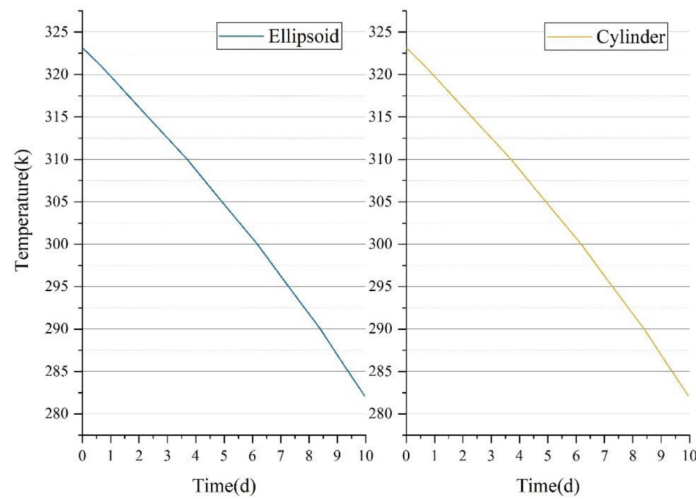


Figure 8. Diagram of temperature change over time (Zhang, Li, & Chen, 2022).

The simulated temperature results showed that both storage shapes exhibited similar trends and magnitudes of temperature change.

2.9 Open Stope Mining

Open stoping is an underground mining method where rock is extracted, leaving behind a large void known as a stope. Mining is conducted at predetermined vertical intervals, referred to as main levels and sublevels. This method is applicable to steeply dipping or vertical ore bodies. The stope dip should be greater than the angle of repose of broken ore, ideally exceeding 55 degrees. The thickness of the ore body should be at least 15 to 20 meters, and a minimum width of 5 meters is required to minimize extensive dilution. Additionally, the rock mass must possess fair to good strength to remain self-supporting (Potvin, 1981).

In open stoping, ideal conditions exist when neither pillars nor backfill is used to support the excavated stopes. This approach is known as full lens open stoping, where the ore body is competent enough to support itself. However, full lens open stoping is often not feasible, and pillars are left in place to maintain overall stability. For mines that leave permanent pillars, the maximum recovery of the ore body can reach up to 80%. In highly stressed rock environments, where rock bursts are a potential problem, sequencing stoping with backfilling operations can be advantageous. For projects where pillar recovery is considered expensive, the "stope and fill" method may be beneficial, potentially offering recovery rates of up to 90%. When backfill is utilized, various sequencing strategies can be implemented to optimize recovery and enhance overall revenue.

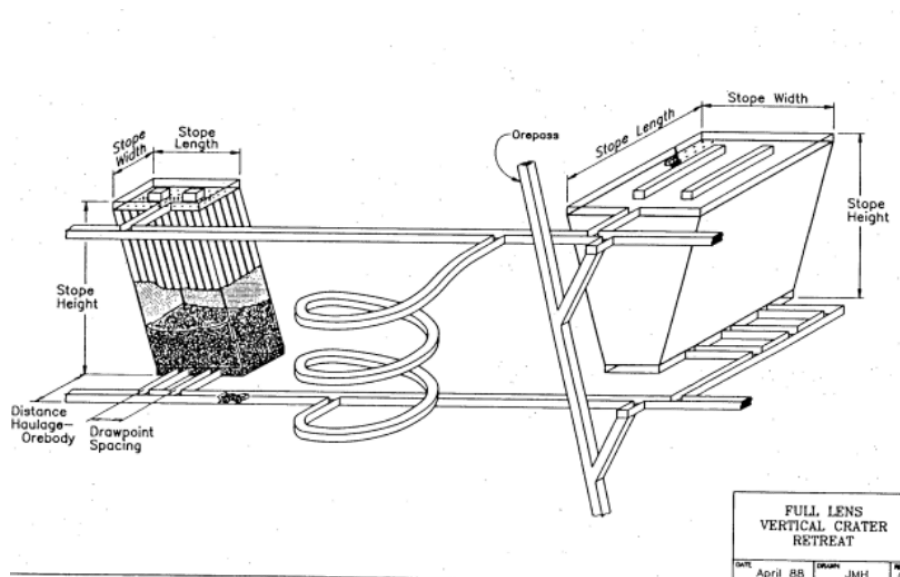


Figure 9. Idealized isometric drawing of “full length” open stope mining methods (Potvin, 1981).

According to Potvin (1981), there are three main aspects of open stoping that affect the stability of the stopes. The first aspect is the properties of the rock mass itself. The second aspect involves the effects of stress fields on the rock mass, which includes zones of high stress and zones of relaxation. The stress acting on any underground opening result from a combination of the pre-mining state of stress and the distributed stress caused by the created void. Stress concentration can impact the stability of an opening based on its geometry and the nature of the rock. The state of relaxation, particularly in jointed rock masses, provides greater freedom of movement for individual blocks.

The third aspect influencing the stability of open stopes involves the geometry, size, and orientation of the openings. Additional factors are also of utmost importance, including the effects of production blasting, the influence of support systems, time-related effects, and the impact of backfill in adjacent stopes.

Potvin identifies three characteristics that distinguish open stoping from other mining methods:

1. Open stoping is a non-entry method, meaning there is no need to enter the stope once production begins.
2. Stopes remain open until they are completely mined, with backfill introduced only after all broken ore has been extracted (this is known as delayed backfill).
3. Underground excavations are designed to be stable, in contrast to caving methods, where ore is intended to collapse under its own weight.

2.10 Backfilling in Open Stope Mining

Backfill refers to the material used to fill the stopes after ore has been excavated. A well-designed and properly managed backfill system enhances ground stability and significantly improves mining productivity. Backfill can be made from various materials such as coarse rockfill, sand, or tailings, and it can be considered a specialized type of soil, allowing for the application of soil mechanics principles. However, the mechanical and curing properties of underground fill vary depending on the characteristics of the fill material, preparation methods, and specific mining environment conditions (Caceres Doerner, 2005).

Today, cemented fill, which is made from a variety of materials, has become widely used as artificial support. The most commonly used type of cemented fill consists of classified tailings, rock, or sand mixed with cement. Practical studies have shown that cement content and slurry density are crucial factors affecting both the stability of the fill and the cost-effectiveness of backfilling. Relying solely on theoretical or numerical modeling for fill design, without experimental or practical validation, can lead to fill block failure or excessive use of cementing materials (Chen and Jiao, 1991).

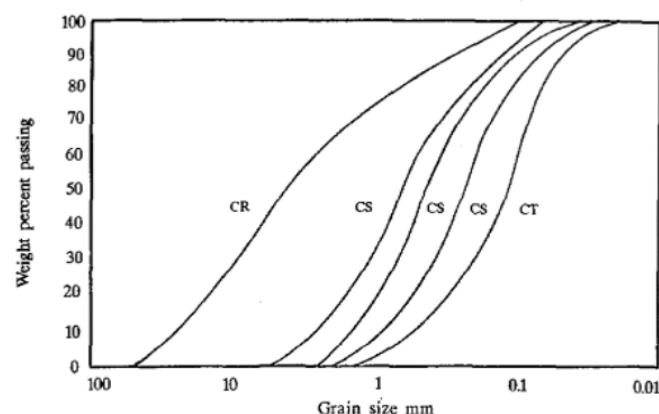


Fig. 1. Grain size distribution for various types of cemented backfill. CR = cemented rockfill; CS = cemented sandfill; CT = cemented tailings fill.

Figure 10. Grain size distribution for various types of cemented backfill (Chen, L. J., & Jiao, D., 1991).

In cemented backfills, mill plant tailings are used as the primary components and are typically deslimed using hydro cyclones to enhance percolation. The particle size distribution of the tailings depends on the processing and desliming techniques applied. In regular tailings, particles smaller than 10 μm constitute less than 20% of the total mass, classifying the material

as coarse to very coarse fill. Ordinary Portland cement, with a specific gravity of 3.1 g/cm³, is commonly used as the binding agent in backfill. In mining applications, the cement-to-tailing ratio varies between 1:4 and 1:30 (Thomas, 1989).

The major factors affecting backfill strength include:

- Cement-rock ratio
- Grain size
- Slurry density
- Curing time

The size of crushed rock used in backfills is limited to less than 60 mm and is typically kept below 45 mm. Tests conducted show that the average grain sizes measured are 10.85 mm for crushed rock, and 2.06 mm, 1.08 mm, and 0.53 mm for sand (Chen and Jiao, 1991).

To ensure long-term safety of CO₂ storage in backfilled stope by structural trapping, it is crucial to select suitable backfill material with following characteristics:

- Impermeable material (to retain CO₂)
- Sufficient mechanical strength (to support mine stability)
- Chemical compatibility with CO₂ (to avoid excessive reactions with CO₂)

Table 3. Different backfills and properties

Property	Rock Backfill	Hydraulic Backfill	Cemented Paste Backfill
Binder	None/minimal	Cemented or not cemented	Only cemented
Grain size	>20cm (made of coarse broken waste rocks)	>20 μm (>90%)	>20 μm (>15%)
UCS	<0.5 MPa	<1MPa (sand to binder ratio 10:1)	<4.2 MPa ((1:6:2) cement: fly ash: desulfurized gypsum)
Placing speed	100-400 tons/h	100-200ton/h	50-200 ton/h
Barricade	Not required	Expensive	Cheap

Transport	Transportation shaft, mobile equipment	Drillhole and pipeline	Drillhole and pipeline
Permeability	High (large pore spaces)	Moderate to low	Low (highly compact, small pore sizes)

2.11 Numerical Modelling

For stability assessment and stress analysis of open pit slopes and underground openings having complex geology and non-planar failure surfaces, numerical modelling can be utilized. In underground mining, the primary function of numerical modelling is to calculate stress distribution around underground excavations. Currently, there are different types of numerical models, each having a different degree of sophistication. Some models are limited to two-dimensional problems, assuming plane strain or plane stress conditions, while others can handle three-dimensional geometries. In numerical modelling, the behaviour of rock mass can be modelled by two different approaches (Potvin, 1981):

Continuum approach: assumes rock mass as a continuous medium, with few or no significant geological discontinuities.

Discontinuum approach considers rock mass as an assemblage of blocks, capable of sliding and rotating. Today, the continuum approach is the most popular and best-developed method of numerical modelling.

3. METHODOLOGY

3.1 Overview of the study

Unlike traditional oil and gas reservoirs, where the supercritical CO₂ is typically injected into the porous geological media, the innovative approach proposes the injection of CO₂ into a confined underground void space. The purpose of this study was to investigate whether a 1 m void space left at the top of a backfilled underground stope could conceptually be used for supercritical CO₂ storage. The chosen 1m distance is sufficiently large to capture the interaction zone between the injected CO₂, backfill material and surrounding rock mass, while remaining realistic for underground stope conditions. In addition, the 1m gap improves numerical stability

and allows stress redistribution and deformation behavior to be observed more clearly within the analysis.

In underground mining, a stope is an excavated opening created after ore extraction. In many cases, the stope is later filled with backfill material to improve stability and provide support. In this study, the stope was assumed to be backfilled, but with a 1 m unfilled gap left at the top. This gap was treated as a possible storage chamber for CO₂.

The main concern was whether storing CO₂ in this space could create unsafe mechanical effects in the backfill and surrounding rock mass. In particular, the study aimed to understand:

- How temperature related to CO₂ storage could affect the backfill,
- How excavation changes the natural in-situ stress field,
- How backfilling changes that stress field,
- How the additional loading caused by the stored CO₂ could influence stress redistribution and displacement around the stope.

Because this problem involves both thermal effects and mechanical effects, one software package was not enough to study the whole system. For this reason, the analysis was divided into two parts:

1. ANSYS was used for the thermal part of the problem,
2. RS3 was used for the geomechanical part of the problem.

This two-step approach allowed the study to separately examine the thermal influence of the storage chamber and the overall rock mechanics response of the stope system.

3.2 Data collection

The input data required for the ANSYS modelling were obtained from published literature sources. The thermo-mechanical properties of the cemented paste backfill (CPB), including density, Young's modulus, thermal conductivity, specific heat capacity, and coefficient of thermal expansion, were selected based on values reported for typical underground backfill materials.

Similarly, the thermodynamic properties of CO₂, including its behaviour under elevated pressure and temperature conditions, were adopted from existing studies on supercritical CO₂. This data were used to define the thermal conditions within the storage chamber. The selected parameters were chosen to represent realistic ranges for underground mining environments and to ensure consistency with previously reported experimental and numerical studies.

For three-dimensional numerical modelling in the RS3 environment, the real case of Nexa Resources Zinc Underground Mine, located in the municipality of Vazante (Northern of Minas Gerais State) in Brazil was chosen. The mining method used in the mine is open stoping (Guimarães & Gomes, 2024).

Vazante Mine data was used in the RS3 model because it was a good match for the type of problem studied in this thesis. The mine uses an open stope mining method, which is similar to the stope geometry considered here, and detailed geomechanical properties are available in the published literature. Another important reason is that the host rocks are competent, which makes them more suitable for a conceptual CO₂ storage study since stronger rocks can provide better confinement and overall stability around the storage zone. Because this thesis is a conceptual feasibility study

The figure below illustrates the geometry of mining block 9140 (a) and lithologies of surrounding rocks (b). The block is located at the depth of 268.5 meters from the surface.

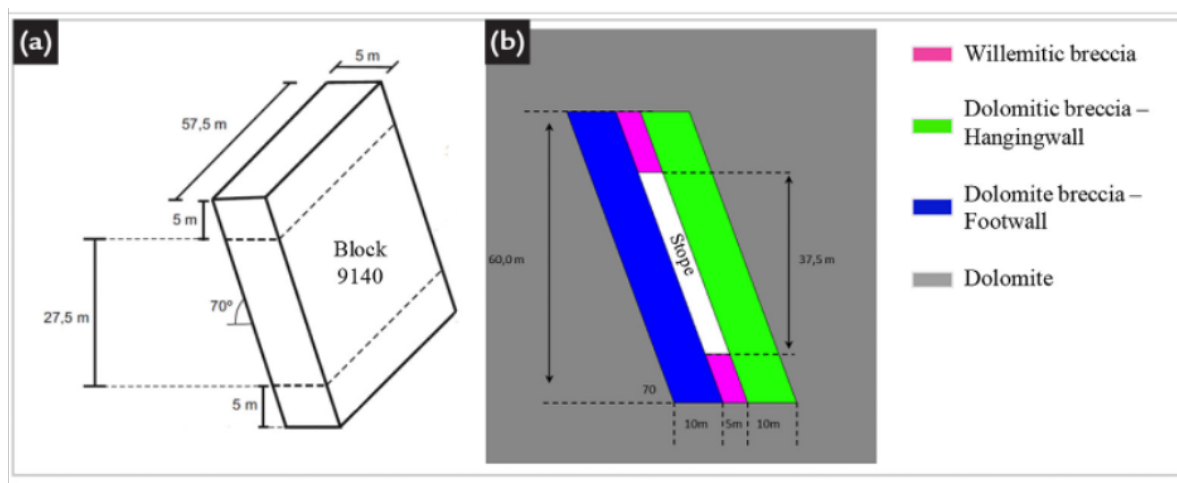


Figure 11. Mining block geometry (a), positioning of stope and lithologies involved (b) (Guimarães & Gomes, 2024).

γ (MN/m ³)	h(m)	K [^] (NW-SE)	σ_v (MPa)	σ_h (MPa)
0.027	268.5	1	7.95	7.95

Figure 12. In-situ stress state (Guimarães & Gomes, 2024).

Hoek-Brown Parameters	Dolomite	Hanging wall Pink Dolomitic Breccia	Footwall Gray Dolomitic Breccia	Willemitic Breccia
σ_c (MPa)	124	136	101	108
GSI	60	42	42	44
m_i	12.5	23.9	23.9	20.9
Ei (GPa)	58	42	55	63
m_b	2.99564	3.01153	3.01153	2.82851
s	0.011744	0.00158933	0.00158933	0.001985
a	0.502841	0.509923	0.509923	0.508658

Figure 13. Hoek and Brown Parameters for each lithology (Guimarães & Gomes, 2024).

Initial geomechanical parameters were established by the Vazante mine team. The Hoek and Brown criterion was applied to determine the rock mass characteristics of each lithology (Guimarães & Gomes, 2024).

Among different backfill types Cemented Paste Backfill (CPB) was chosen for carbon capture storage in backfilled open stopes because of highly compact small pore size, which provides low permeability enough to limit CO₂ migration. High strength with UCS values up to 4MPa, allows CPB withstand high pressures.

3.3 Applied methods of numerical modelling

It is not practical to test this storage concept directly in an actual underground mine during an academic study. Such testing would require time, cost, field instrumentation, and safety approval. Therefore, this research used numerical modelling, which is a computer-based method for simulating the behaviour of materials and structures under given conditions.

Numerical modelling makes it possible to apply loads, temperatures, and material properties to a digital model and then calculate how the model responds. In this study, numerical modelling was used to estimate:

- Temperature effects in the backfill,
- Thermal stress caused by temperature change,
- Stress redistribution in the surrounding rock mass,
- Displacement of the stope-backfill system.

3.3.1 Thermodynamic simulation in ANSYS

The first part of the study was carried out in ANSYS.

ANSYS was used because it is suitable for modelling thermal behaviour and the stresses that develop when temperature changes. In this project, ANSYS was not used to model everything. Instead, it was used to answer a more specific question:

“If CO₂ is stored in the top void space, what temperature condition may develop there, and how could that temperature create thermal stress in the backfill below it?”

To answer this question, the ANSYS analysis was divided into two parts.

- Thermodynamic estimation of chamber temperature
- Thermal stress analysis of the backfill

Thermodynamic estimation of chamber temperature

The first step was to estimate the temperature inside the storage chamber when the chamber pressure reached the target value. The chamber in this case was the 1 m thick gap left above the backfill. This temperature estimation was needed because the stored CO₂ was expected to affect the thermal condition of the materials surrounding the chamber. The purpose of this step was not to perform a complete gas-flow simulation, but to obtain a reasonable temperature value representing the chamber condition at the target pressure.

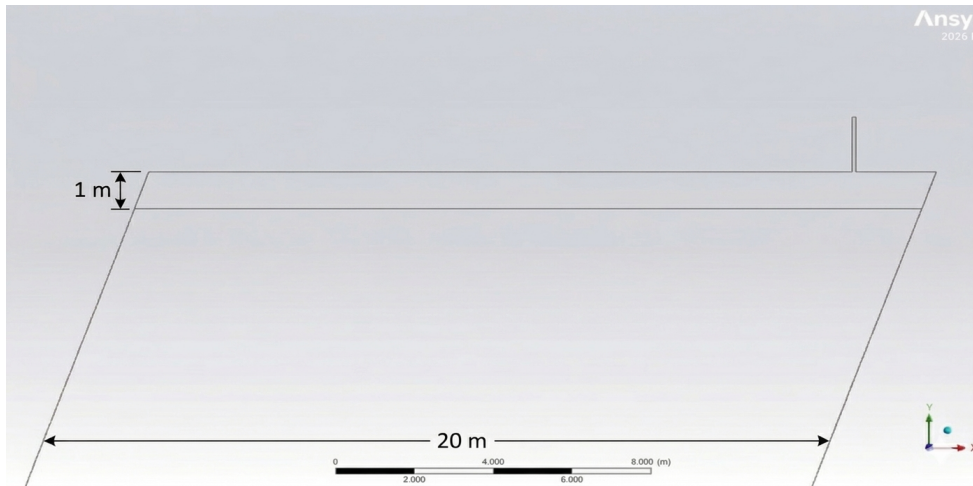


Figure 14. Thermodynamic model.

A thermodynamic model was developed to estimate the temperature conditions inside the CO₂ storage chamber when the chamber pressure reaches 10 MPa. The conceptual storage configuration consisted of a void space with dimensions 20 m × 20 m × 1 m, located at the top of a backfilled stope. This void represents the storage chamber for supercritical CO₂.

The purpose of this model was to determine the equilibrium temperature within the chamber corresponding to the target pressure. This temperature represents the thermal state of the storage cavity after pressurization and was used as input for subsequent thermal stress analysis.

Thermal stress analysis of the backfill

A steady-state thermal analysis was performed to simulate heat transfer from the storage chamber into the backfill. The upper surface of the backfill, corresponding to the interface with the CO₂ storage chamber, was assigned a constant temperature boundary condition equal to the temperature obtained from the thermodynamic model. The remainder of the backfill was assumed to be at in-situ temperature conditions.

Heat transfer within the backfill was assumed to occur primarily through conduction, resulting in a temperature gradient decreasing with depth. The steady-state assumption represents the post-injection equilibrium condition, where temperature remains constant over time.

The resulting temperature field was then imported into a static structural analysis to evaluate thermally induced stresses. The backfill was modelled as a linear elastic material, and thermal

strains were calculated based on the temperature change and the coefficient of thermal expansion. Mechanical boundary conditions were applied to represent the confinement provided by the surrounding rock mass, restricting free deformation.

The stress distribution was evaluated using the finite element method, with results expressed in terms of equivalent (von Mises) stress to assess the magnitude and distribution of thermal stresses within the backfill.

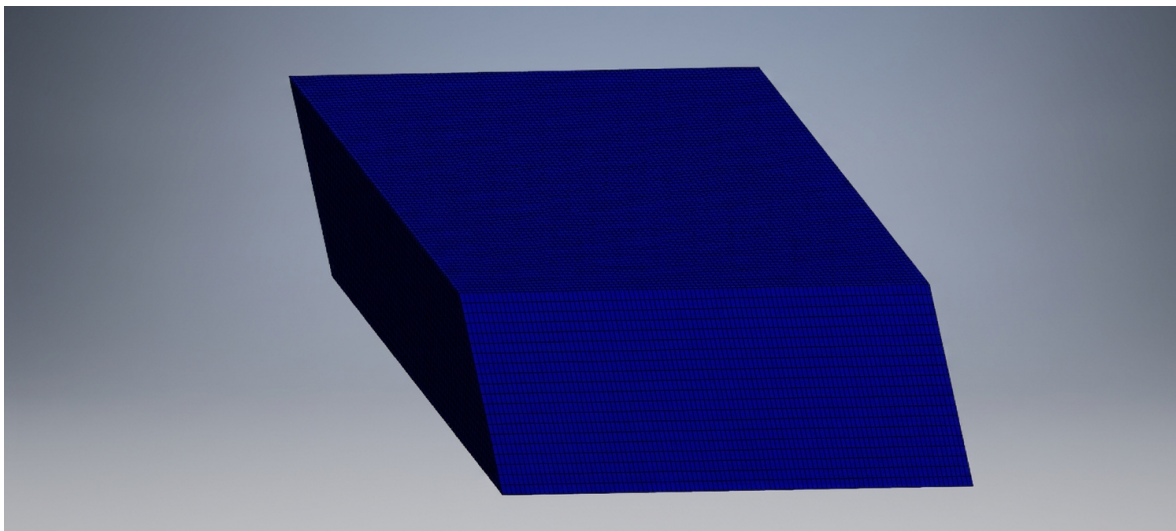


Figure 15 shows the backfill model developed in ANSYS for the assessment of thermally induced stress. The model represents the backfill body placed inside the stope and was used to study how heating from the CO₂ storage chamber may affect the mechanical behavior of the backfill.

In this model, the upper surface of the backfill was assumed to be in direct thermal contact with the storage chamber. Therefore, this surface was assigned a constant temperature boundary condition equal to the final gas temperature estimated inside the chamber after CO₂

Figure 15. Backfill model for thermal stress analysis.

injection. This assumption was made to represent the thermal influence of the stored CO₂ on the backfill immediately below the chamber.

3.3.2 Geomechanical simulation in RS3

Part two of the study took place at RS3. RS3 is a three-dimensional geotechnical numerical modeling program using Finite Element Method (FEM) to simulate the response of different parts of a model to applied stresses and deformations. This is done by dividing the model into many individual elements. Once each element's behavior has been determined for an applied load, it can then be summed up to find the total behavior of all the elements as a whole; including both the backfill and the surrounding rock mass. RS3 was used because the main research goal of the thesis was geomechanical: to understand how the stope environment responds to excavation, backfilling, and simulated CO₂ storage loading.

The RS3 model was used to evaluate:

1. how the original virgin stress field changes after excavation,
2. how backfill affects the mechanical response of the stope,
3. how the top void changes confinement conditions,
4. how the stored CO₂ load changes local principal stresses and displacement.

A 3D model was developed to represent the surrounding rock mass, excavated stope, backfill, and void space intended for CO₂ storage. The analysis was carried out in sequential phases to capture the evolution of the stress state during mining and storage development. These phases included:

Phase 1 – Virgin Stress State

The phase represents in-situ stress conditions of the rock mass prior to excavation. At this stage rock mass is undisturbed and the initial stress field is defined based on regional stress conditions and depth of the mine.

Phase 2 – Excavated Stope

In the second phase, the stope is excavated and the local stress regime is disturbed by excavation. Excavation leads to stress redistribution around the opening and may result in stress concentration along the stope boundaries.

Phase 3 – Backfilled Stope

In the third phase, the stope is backfilled while maintaining the 1m opening at the top of the stope. The void space represents the proposed CO₂ storage chamber. The numerical analysis will show how stress conditions change after the stope is backfilled.

Phase 4 – CO₂ injection

The final stage simulated conditions following the CO₂ injection. The gas exerts its storage pressure on the surrounding and there is additional induced thermal stress. The combined effect of these stresses will be modelled by concentrated loads in RS3.

Since RS3 does not directly simulate gas behavior, the mechanical effect of stored CO₂ was represented by applying equivalent loads to the relevant surfaces of the storage cavity. These loads were used to approximate the action of gas pressure on the stope-backfill system. The thermal stresses obtained from the ANSYS analysis were then incorporated into the geomechanical interpretation to evaluate their combined influence with gas pressure. The RS3 model was used to assess changes in principal stresses, stress redistribution, and displacement within the rock mass and backfill, thereby allowing evaluation of the stability of the proposed CO₂ storage configuration.

For this project, the initial model of Vazante mine was modified while keeping the rock properties unchanged. The dimensions of the stope are 20 meters by 40 meters, representing its length and height, respectively. The hanging wall and footwall each have a length of 60 meters and a height of 60 meters. The figure below illustrates the design that will be used for further analysis in the RS3 environment.

To begin numerical modeling in RS3, it is essential to first develop the geometries of the open stope and the surrounding geological formations. Below are the screenshots showing the stope and the surrounding rock units.

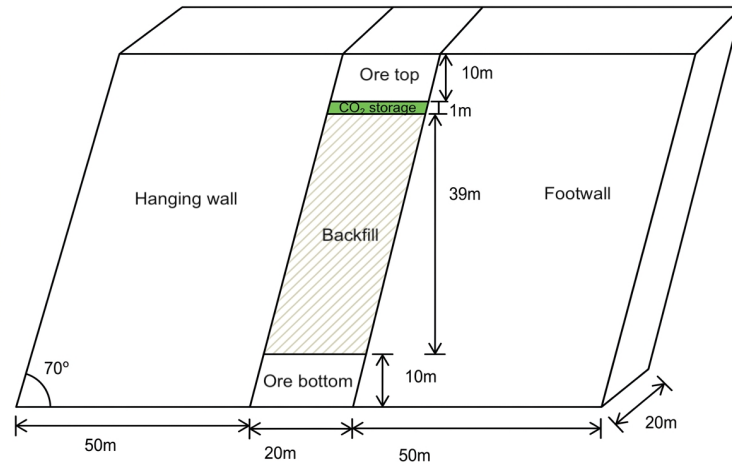
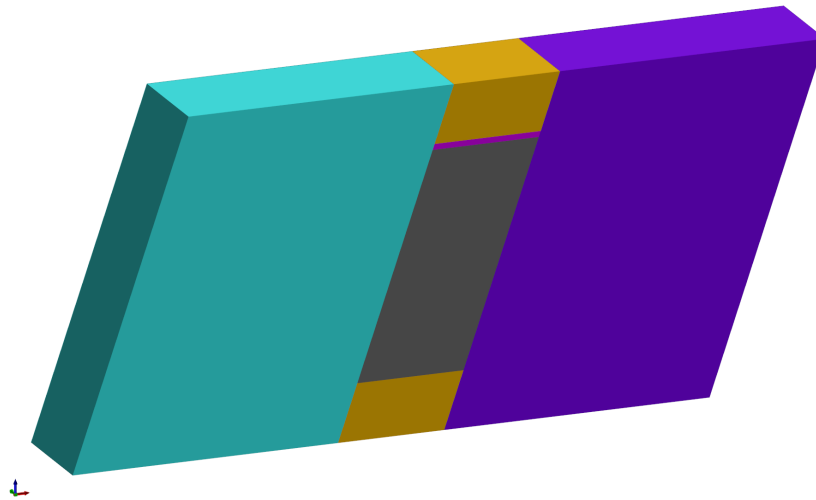


Figure 16. Figure. Geotechnical model dimensions. View to the north



Once all the strings for each geology have been created, the next step is to produce solid materials from them, a process known as wireframing. The figure above illustrates four different wireframes representing the hanging wall, footwall, and the stope's top and bottom (colored yellow, green, and red, respectively). Both the top and bottom of the stope share the same material properties. After wireframes were successfully created the model is exported from Micromine to RS3. It is important to create an external box.

Figure 17. Model wireframes.

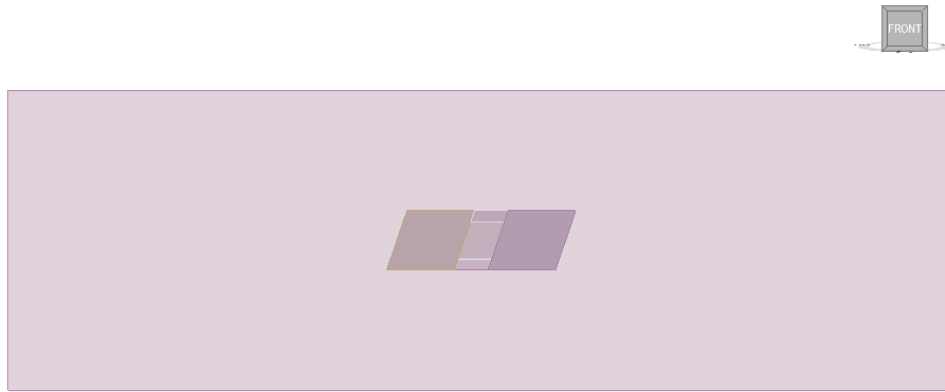


Figure 18. External Box

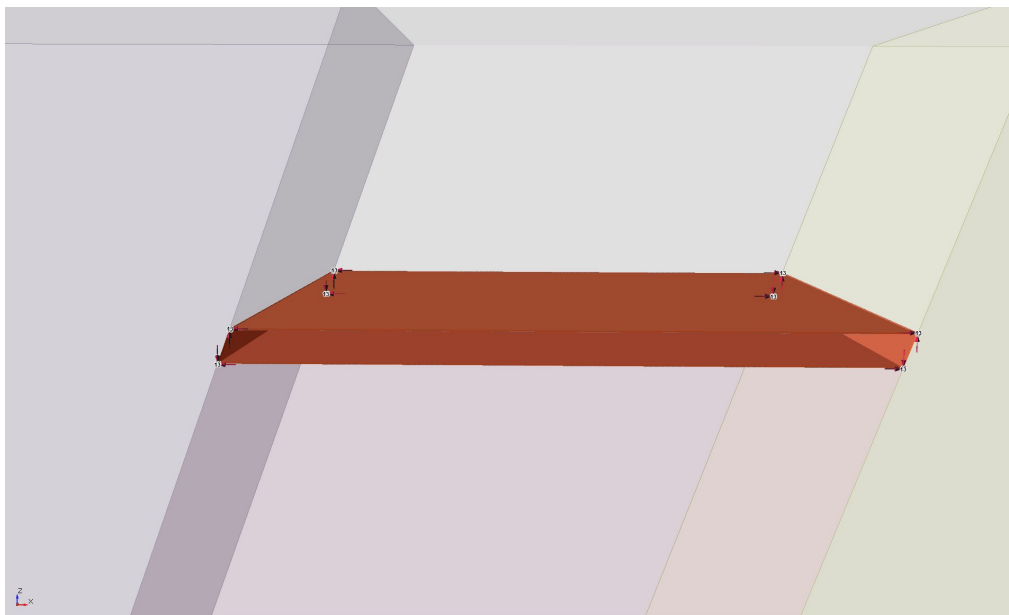


Figure 19 shows the concentrated loads applied to the boundaries of the CO₂ storage chamber in the RS3 model. These loads were used to represent the mechanical effect of stored CO₂ pressure, since direct gas simulation is not available in RS3. The loads were applied to the chamber walls and roof to simulate how pressure from the stored CO₂ acts on the surrounding

Figure 19. Concentrated loads applied to CO₂ storage walls.

backfill and rock mass. Concentrated loads of 13MPa are applied to the internal boundaries of the storage chamber in upward, downward and left and right directions inside the storage chamber.

The project could not be studied properly using only one software package.

ANSYS was suitable for estimating the temperature-related effects, especially the thermal stress generated in the backfill due to chamber heating.

RS3 was suitable for the rock mechanics part, including excavation, backfilling, principal stress redistribution, and displacement of the rock-backfill system.

Therefore, the study used ANSYS to understand the thermal loading component, and RS3 to understand the mechanical response of the underground structure.

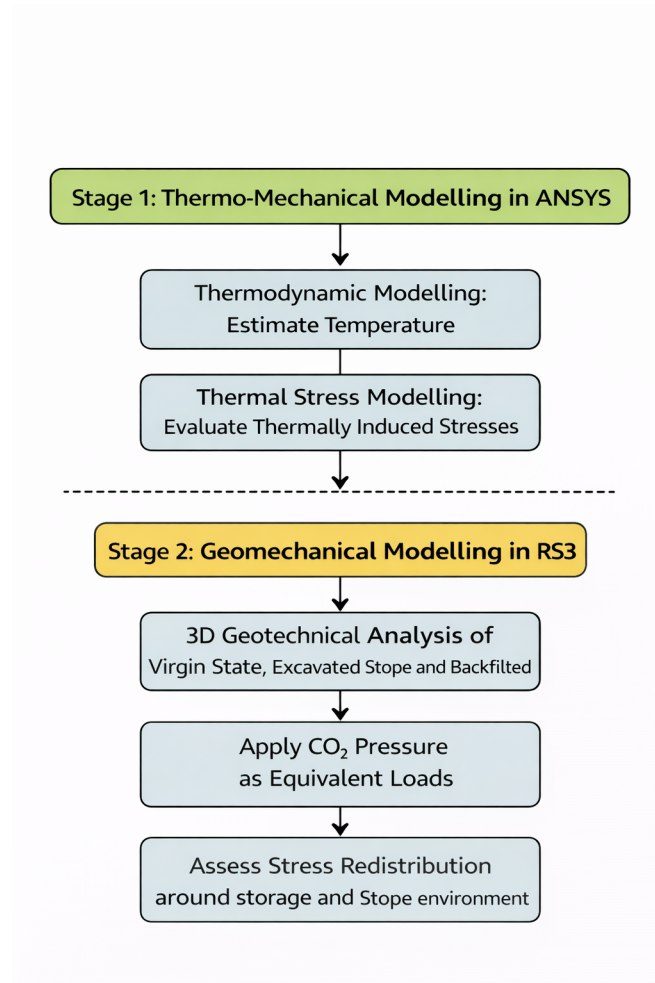


Figure 20. Modelling Strategy.

3.4 Input parameters used for numerical modelling

Input data for ANSYS Thermodynamic and Thermal stress modelling.

Table 4. Modelling approaches in ANSYS

Modelling approaches applied in ANSYS		State	Description
	Stage 1	Transient	Temperature evolution during injection. CO ₂ is injected until storage temperature reaches 10MPa.
	Stage 2	Steady state	Thermal stress evaluation. Final

			temperature inside the storage at 10MPa pressure is obtained and used as input for thermal stress analysis.
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Table 5. Initial data for thermodynamic modelling.

	Parameter	Value	Unit
Initial conditions (inside chamber)	Initial gas	Air	
	Initial pressure	1	MPa
	Initial temperature	35	°C
	Injection gas	CO ₂	
Injection parameters	Injection pressure	10	MPa
	Injection temperature	45	°C
	Final storage pressure	10	MPa
	CO ₂ state	supercritical	

Table 6. Backfill properties.

Backfill properties	Parameter	Value	Unit
	Unit weight	0.025	MN/m ³
	Thermal Conductivity	0.7	W/mK
	Specific heat	1500	J/kg K

	Coefficient of thermal expansion	10	microstrains/°C
	Young's modulus	3	GPa
	Poisson's ratio	0.2	

The initial values were selected to represent a conceptual but realistic underground CO₂ storage scenario. The chamber was assumed to initially contain air. The initial pressure of 1 MPa and temperature of 35°C were chosen as simplified underground starting conditions. The injection pressure and final storage pressure were set to 10 MPa so that the storage condition would remain above the critical pressure of CO₂. Together with the injection temperature of 45°C, these values allow the CO₂ to be treated as supercritical, which is relevant for underground storage because of its higher density and more stable confined behavior. These parameters were therefore selected to provide a technically reasonable basis for conceptual thermodynamic modeling.

Initial data for RS3 Geomechanical modelling.

Table 7. Footwall properties

DOLOMITIC_BRECCIA_FOOTWALL	
Colour:	
Initial Element Loading:	Field Stress & Body Force
Unit Weight (kN/m ³):	27
Failure Criterion:	Generalized Hoek-Brown
Material Type:	Plastic
Define by:	GSI, mi, d
Peak Strength	
UCS of intact rock (intact) (MPa):	101
GSI:	42
mi:	23.9
d:	0
Set Residual Values to Peak Values:	Yes
Residual Strength	
GSI Residual (set from peak):	42
mi Residual (set from peak):	23.9
Poisson's Ratio:	0.2
Young's Modulus (kPa):	10062825.889
Use Residual Young's Modulus:	No
Generalized Hoek-Brown Estimation	
Compute Rock Mass Elastic Modulus:	Yes

Estimation Method:	Generalized Hoek Diederichs
Use Type:	EI
EI (GPa):	55

Table 8. Hanging wall properties.

DOLOMITIC_BRECCIA_HANGING_WALL	
Colour:	
Initial Element Loading:	Field Stress & Body Force
Unit Weight (kN/m3):	30
Failure Criterion:	Generalized Hoek-Brown
Material Type:	Plastic
Define by:	GSI, mi, d
Peak Strength	
UCS of intact rock (intact) (MPa):	136
GSI:	42
mi:	23.9
d:	0
Set Residual Values to Peak Values:	Yes
Residual Strength	
GSI Residual (set from peak):	42
mi Residual (set from peak):	23.9
Poisson's Ratio:	0.2
Young's Modulus (kPa):	7684339.769
Use Residual Young's Modulus:	No
Generalized Hoek-Brown Estimation	
Compute Rock Mass Elastic Modulus:	Yes
Estimation Method:	Generalized Hoek Diederichs
Use Type:	EI
EI (GPa):	42

Table 9. Ore properties.

WILLEMITIC_BRECCIA_STOPE_TOP_BOTTOM	
Colour:	
Initial Element Loading:	Field Stress & Body Force
Unit Weight (kN/m3):	35
Failure Criterion:	Generalized Hoek-Brown
Material Type:	Plastic
Define by:	GSI, mi, d
Peak Strength	
UCS of intact rock (intact) (MPa):	108
GSI:	44
mi:	20.9
d:	0
Set Residual Values to Peak Values:	Yes
Residual Strength	
GSI Residual (set from peak):	44

mi Residual (set from peak):	20.9
Poisson's Ratio:	0.2
Young's Modulus (kPa):	13186089.106
Use Residual Young's Modulus:	No

Generalized Hoek-Brown Estimation

Compute Rock Mass Elastic Modulus:	Yes
Estimation Method:	Generalized Hoek Diederichs
Use Type:	EI
EI (GPa):	63

Table 10. Surrounding rock properties.

DOLOMITE_BOUNDARY

Colour:	
Initial Element Loading:	Field Stress & Body Force
Unit Weight (kN/m3):	27
Failure Criterion:	Generalized Hoek-Brown
Material Type:	Plastic
Define by:	GSI, mi, d

Peak Strength

UCS of intact rock (intact) (MPa):	124
GSI:	60
mi:	12.5
d:	0
Set Residual Values to Peak Values:	Yes

Residual Strength

GSI Residual (set from peak):	60
mi Residual (set from peak):	12.5
Poisson's Ratio:	0.2
Young's Modulus (kPa):	10400000
Use Residual Young's Modulus:	No

Generalized Hoek-Brown Estimation

Compute Rock Mass Elastic Modulus:	Yes
Estimation Method:	Generalized Hoek Diederichs
Use Type:	EI
EI (GPa):	58

Table 11. Backfill properties

backfill	
Colour:	
Initial Element Loading:	Field Stress & Body Force
Unit Weight (MN/m ³):	0.025
Failure Criterion:	Generalized Hoek-Brown
Material Type:	Plastic
Define by:	GSI, mi, d
Peak Strength	
UCS of intact rock (intact) (MPa):	4
GSI:	85
mi:	10
d:	0
Set Residual Values to Peak Values:	Yes
Residual Strength	
GSI Residual (set from peak):	85
mi Residual (set from peak):	10
d Residual (set from peak):	0
Dilation Parameter:	0
Tensile Cutoff Type:	None
Elastic Type:	Linear Isotropic
Use Unloading Condition:	No
Poisson's Ratio:	0.2
Young's Modulus (MPa):	926.593
Use Residual Young's Modulus:	No
Generalized Hoek-Brown Estimation	
Compute Rock Mass Elastic Modulus:	Yes
Estimation Method:	Generalized Hoek Diederichs
Use Type:	EI
EI (MPa):	1000
Material Behavior	

Material Behavior Type:	Drained
Porosity Type:	Porosity
Porosity:	0.3

4. RESULTS

4.1 Thermodynamic simulation results

The first phase corresponds to the CO₂ injection process and is defined as the Transient Phase. During this stage, CO₂ is actively injected into the storage chamber, and both pressure and temperature vary continuously due to compression, expansion, and thermo-mechanical coupling effects. The injection pressure was set at 10 MPa, and the injection temperature was 45°C. These conditions ensure that CO₂ is introduced in its supercritical state.

The second phase represents the Post-Injection Steady-State (Stabilization) Phase, in which the system approaches thermodynamic equilibrium. In this stage, pressure and temperature gradients gradually diminish until quasi-steady conditions are achieved. Since supercritical CO₂ requires temperatures above 31.1°C and pressures exceeding 7.38 MPa, the 10 MPa storage pressure was assumed as a storage pressure.

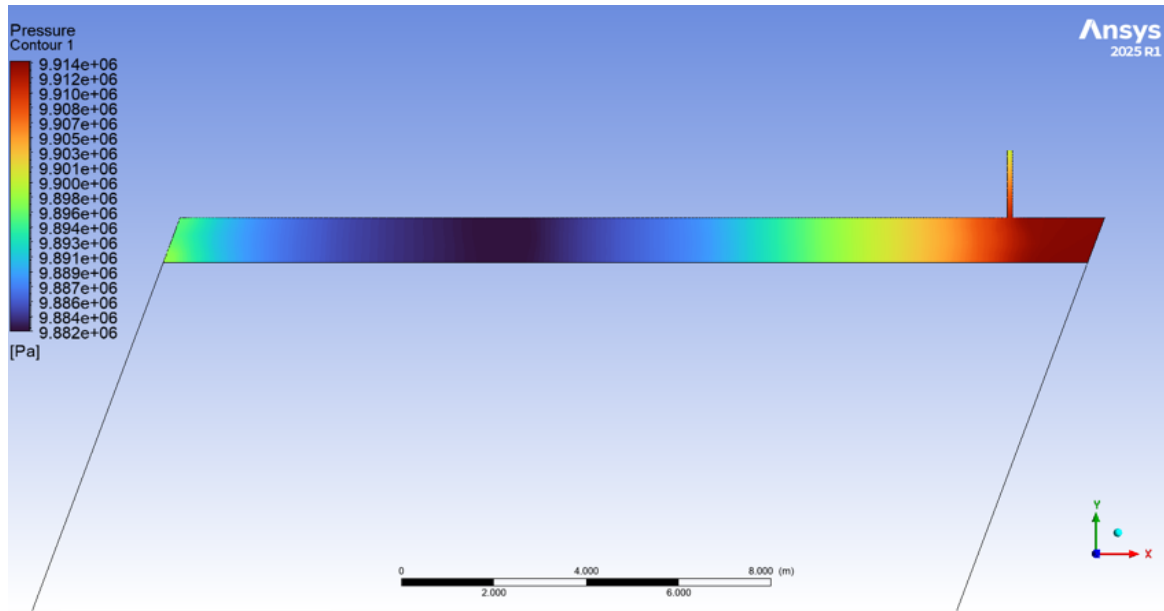


Figure 21. Pressure variations within the model.

Figure 21 shows the pressure distribution within the storage chamber at the stage when the chamber pressure reached approximately 10 MPa. The results indicate that pressure is

distributed along the chamber, with only small variations across the model. This figure represents the pressure condition used to define the chamber state for the subsequent thermal analysis.

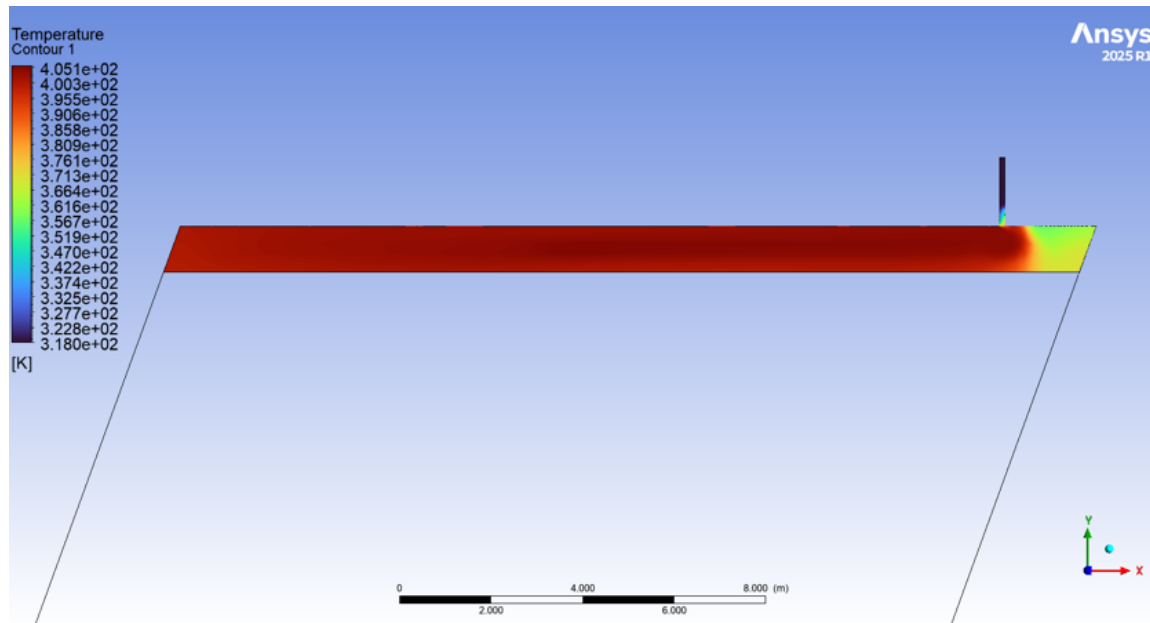


Figure 22. Temperature variations within the model.

Figure 22 shows the temperature distribution within the storage chamber at the stage when the chamber pressure reached approximately 10 MPa. The results indicate that the chamber temperature is generally high throughout most of the chamber, with only localized variation near the injection point. This temperature field was used to define the thermal condition for the subsequent backfill thermal stress analysis. When the internal storage pressure reaches 10 MPa, the chamber temperature increases to approximately 405 K (131°C).

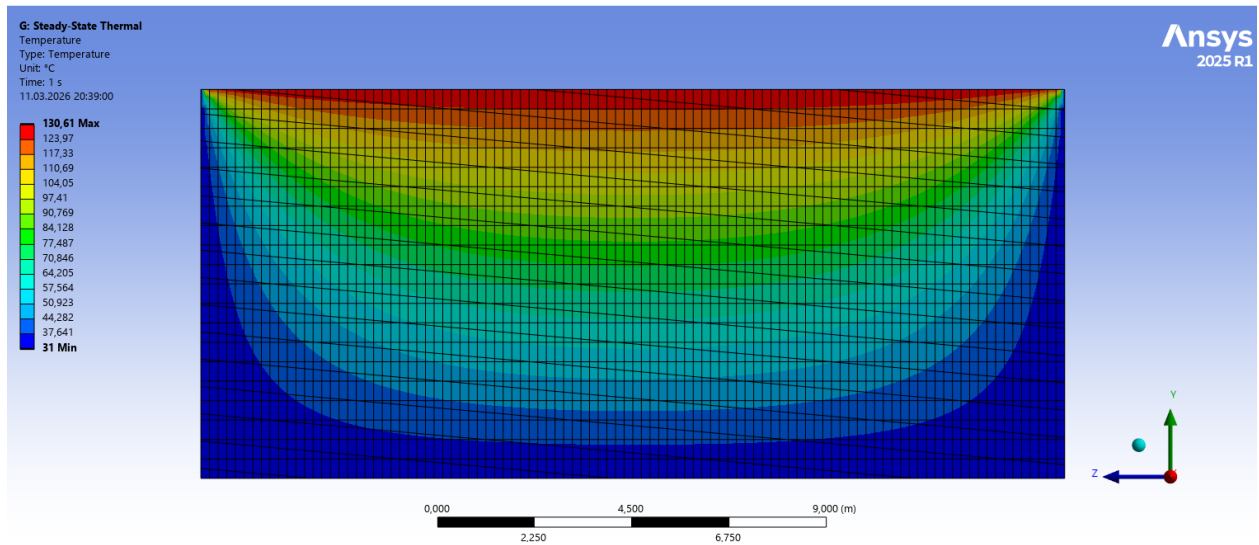


Figure 23. Temperature variation within the cross-section of backfill.

Figure 23 shows the temperature distribution within the backfill obtained from the steady-state thermal analysis. The highest temperatures occur along the top surface, where the chamber temperature was applied as a boundary condition. Temperature then gradually decreases with depth, creating a clear thermal gradient through the model.

The results indicate that heat is transferred downward from the heated upper boundary into the backfill, while the lower part of the model remains at lower temperatures. Overall, the figure shows that the thermal effect is strongest near the top of the backfill and weakens with distance from the chamber.

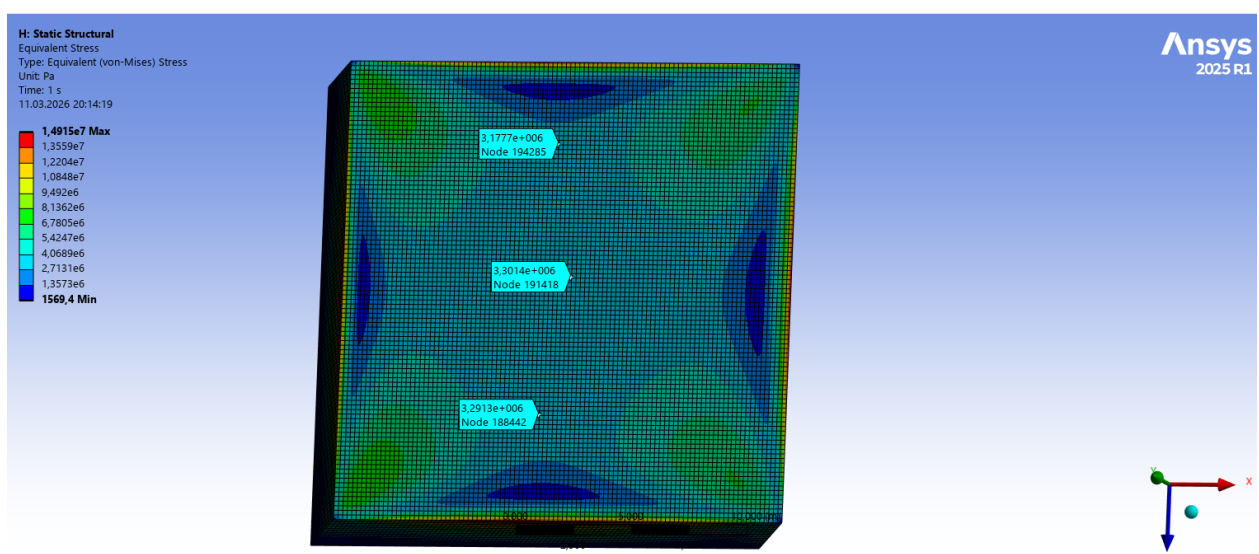


Figure 24. Thermal stress field at top of the backfill (top view).

Figure 24 shows the thermal stress distribution at the top of the backfill model obtained from the static structural analysis. The results indicate that thermally induced stress develops across the heated upper region of the model, with stress variations observed between the edges and the central part. Higher stress values appear near the model boundaries, while the interior shows a more moderate stress level. The stress within the top part of the model is approximately 3 MPa.

4.2 Geomechanical simulation results

Virgin State



Figure 25. 3D simulation result representing major principal stress (σ_1) at virgin state.

The figure 25 illustrates the distribution of major principal stress (σ_1) under virgin stress regime. The results indicate uniform stress regime across the model domain, reflecting undisturbed in-situ stress state prior to excavation.

The value of (σ_1) range between 23 and 29MPa, with slightly higher stresses observed at greater depths. The increase in stress with depth is consistent with gravitational loading. No significant stress concentrations or anomalies observed within the model, indicating that the system is in

stable equilibrium conditions. The smooth stress gradients indicate that boundary effects are minimal, and the model adequately represents the initial geostatic stress field.



Figure 26. 3D simulation result representing minor principal stress (σ_3) at virgin state.

The distribution of minor principal stress for the Virgin Stress State is shown at the figure above. Similar to the σ_1 results, σ_3 fields exhibit uniform and continuous distribution.

The σ_3 values range from approximately 0 to 29MPa, with lower values occurring near upper regions of model and increasing with depth. The trend reflects the variation in horizontal confinement. The relatively high σ_3 values in deeper regions indicate a well confined rock mass, which contributes to overall stability of system. The absence of localized stress concentrations suggests that the initial conditions are purely controlled by in-situ stress distribution, without any influence from excavation or external loading.

Excavated Stope



Figure 27. 3D simulation result representing major principal stress (σ_1) after the stope excavation.

The figure above represents the distribution of major principal stress (σ_1) after the excavation of stope. Compared to virgin state, excavation of stope resulted in pronounced redistribution stresses within the surrounding rock mass. The removal of ore created stress free opening, causing pre-existing compressive stress to be transferred to the rock adjacent to the excavation boundaries.

According to the simulation results highest (σ_1) values are concentrated around the stope crown and upper corners, where the stress reached maximum of approximately 94 MPa. These localized stress concentrations indicate that the excavation induced significant load transfer to immediate rock mass surrounding the opening. High (σ_1) values are also observed along the sidewalls, and their magnitude decreases progressively with distance from excavation. This behavior is characteristic of underground excavations. The excavation void causes stress arching and concentrations around the excavation perimeter.

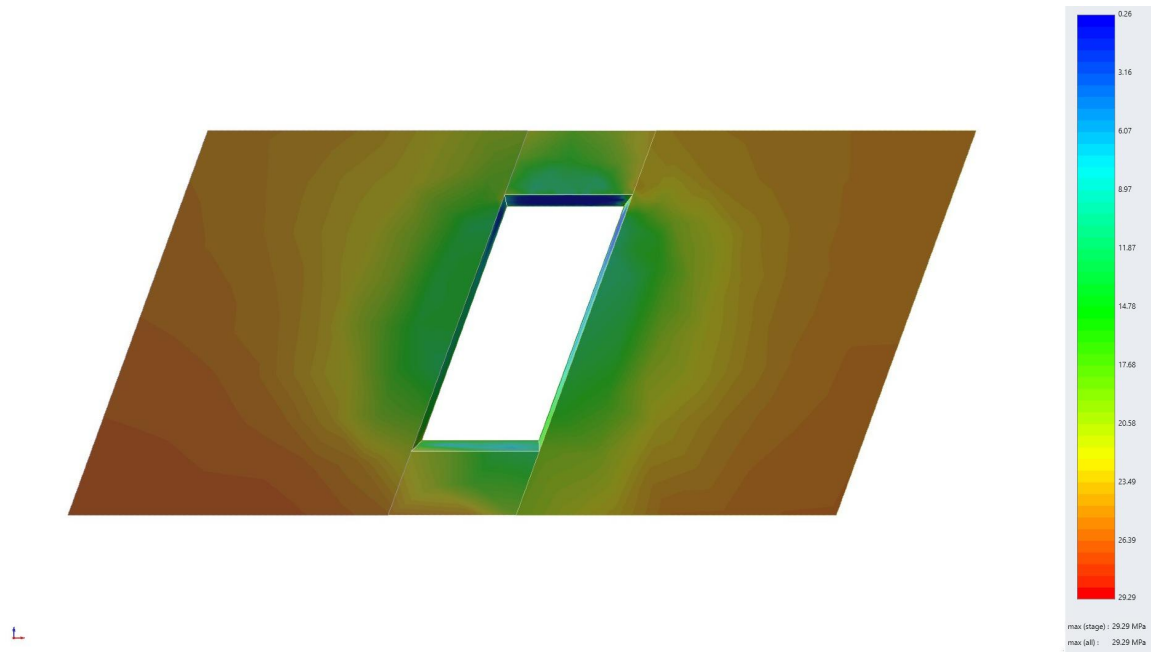


Figure 28. 3D simulation result representing minor principal stress (σ_3) after the stope excavation.

The image above illustrates the distribution of minor principal stress (σ_3) for the excavated stope. The excavation caused significant reduction in confinement near to stope boundaries, particularly within the roof and wall regions directly adjacent to the opening. The lowest minor principal stress values occur around the stope perimeter. This reflects stress relaxation and unloading effects caused by excavation. In comparison, higher (σ_3) values remain in the rock mass farther from the excavation, where the influence of excavation becomes less pronounced. The reduced (σ_3) around the openings is important from geomechanical point of view, as loss of confinement may promote yielding, crack initiation and local instability.



Figure 29. 3D simulation result representing total displacement after the stope excavation.

Figure 29 represents the total displacement distribution within the model for excavated stope case. The results indicate that the excavation induced measurable deformation in the surrounding rock mass, with the maximum total displacement reaching approximately 0.042m. The highest values are concentrated around the stope boundaries, particularly near the roof and sidewalls. The rock mass displacement gradually decreases away from the stope, indicating that deformation is localized primarily with the immediate influence zone of excavation. The displacement pattern is consistent with the stress results, confirming the excavation caused both stress concentration and deformation of the surrounding rock mass.

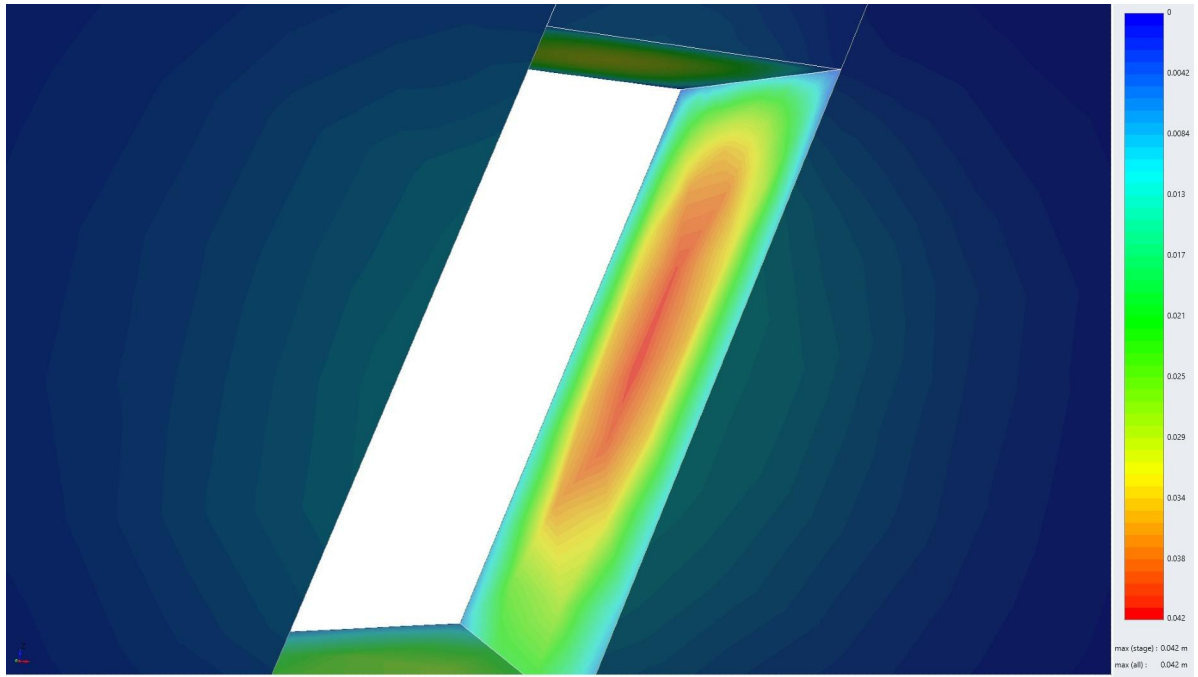


Figure 31. 3D simulation result representing total displacement after the stope excavation (footwall).

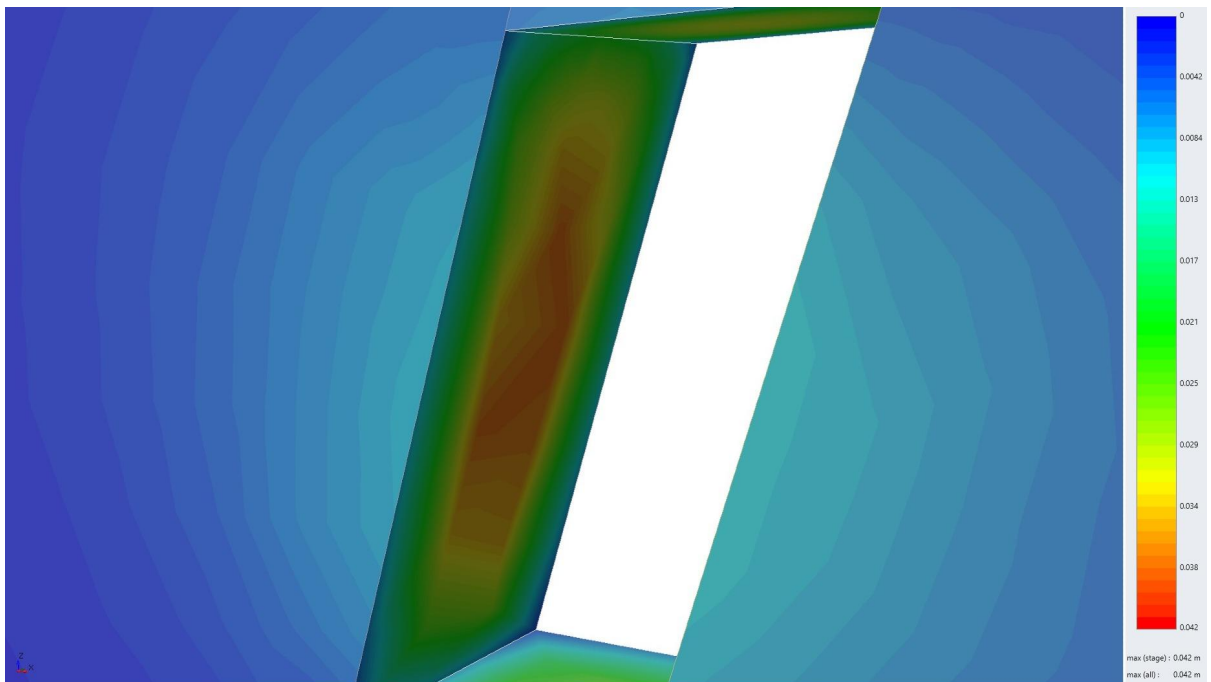


Figure 30. 3D simulation result representing total displacement after the stope excavation (hanging wall).

A detailed view of total displacement around the excavation surfaces is presented in figures 29 and 30. The results indicate that the deformation is concentrated primarily along the inclined sidewalls and near the excavation corners, rather than being uniformly distributed. In the both figures highest rock mass displacement is observed in the rock mass adjacent to stope

boundaries, forming elongated deformation zones on hanging wall and footwall. The figures indicate that excavation caused localized mechanical response in the surrounding rock mass, where the removal of material led to unloading and inward deformation toward the void. The concentration of high displacement on the sidewalls suggests that these areas experienced greatest loss of confinement.

Backfilled Stope

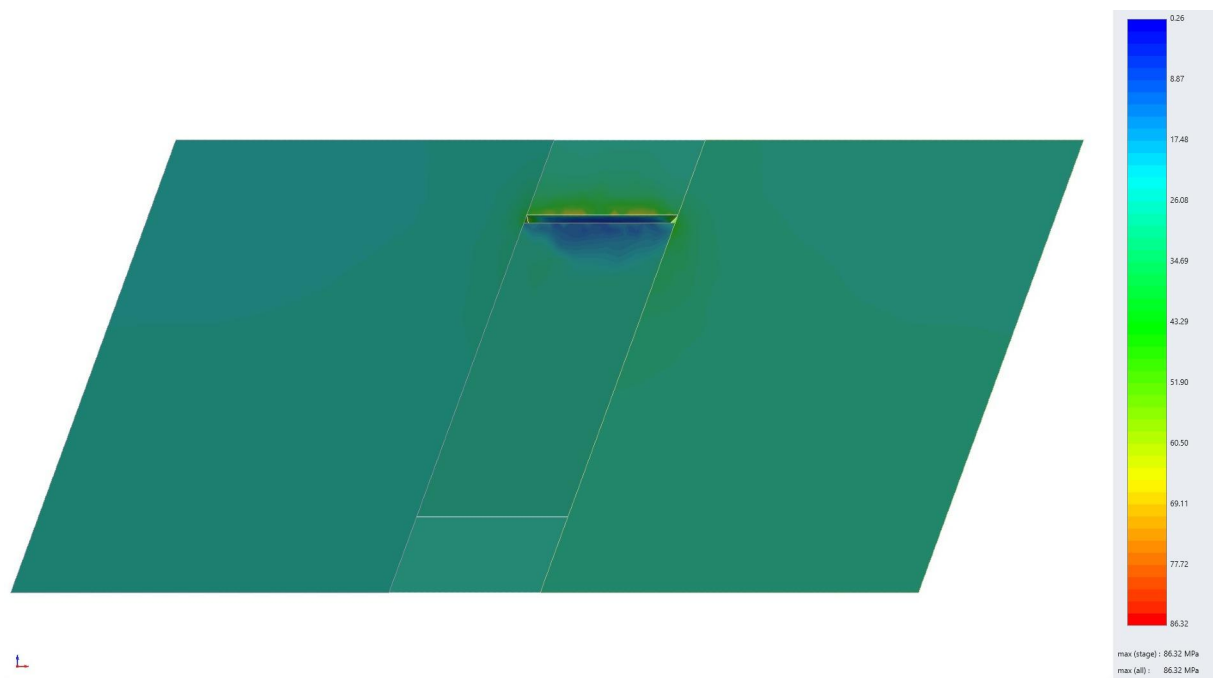


Figure 32. 3D simulation result representing major principal stress (σ_1) after the backfilling.

The figure 32 illustrates the distribution of major principal stress for the backfilled stope. In comparison with excavated stope case, results show that the introduction of backfill substantially modifies the stress field around the excavation. The sigma 1 contours show that high compressive stresses remain concentrated near the roof of the stope and around the upper backfill interface, with maximum value of approximately 86MPa. This indicates that after placement of the backfill, a significant portion of overlying load is transferred to the backfill and its contact zone with surrounding rock. The concentration of σ_1 near the crown suggests that upper backfill interface act as critical load transfer region.

Away from excavation, stress becomes more uniform, indicating that backfill helps to reduce the intensity of stress perturbations in the surrounding rock mass. Overall, the backfill

contributes to mechanical support of excavation, while also introducing localized stress concentration near the upper boundary of filled stope.

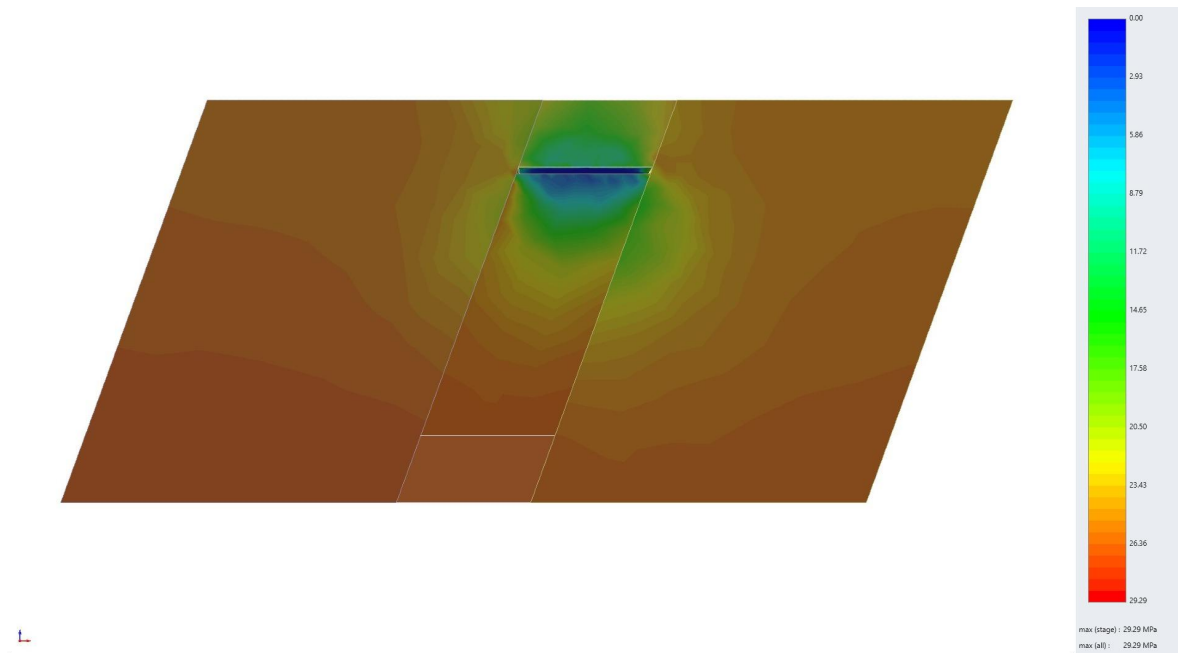


Figure 33. 3D simulation result representing major principal stress (σ_3) after the backfilling.

The figure above shows minor principal stress distribution for backfilled stope case with 1m void space left at the top. The results indicate that backfilling re-establishes some confinement within the stope. However, confinement remains relatively low near the void space, which is CO_2 storage.

The stress contours suggest that backfill interacts mechanically with the surrounding rock and redistributes the part of in situ stress. Compared to the excavated stage, disturbed zone around the excavation becomes less pronounced, indicating that backfill contributes to improving overall mechanical stability.



Figure 35. 3D simulation result representing total displacement after the backfilling.

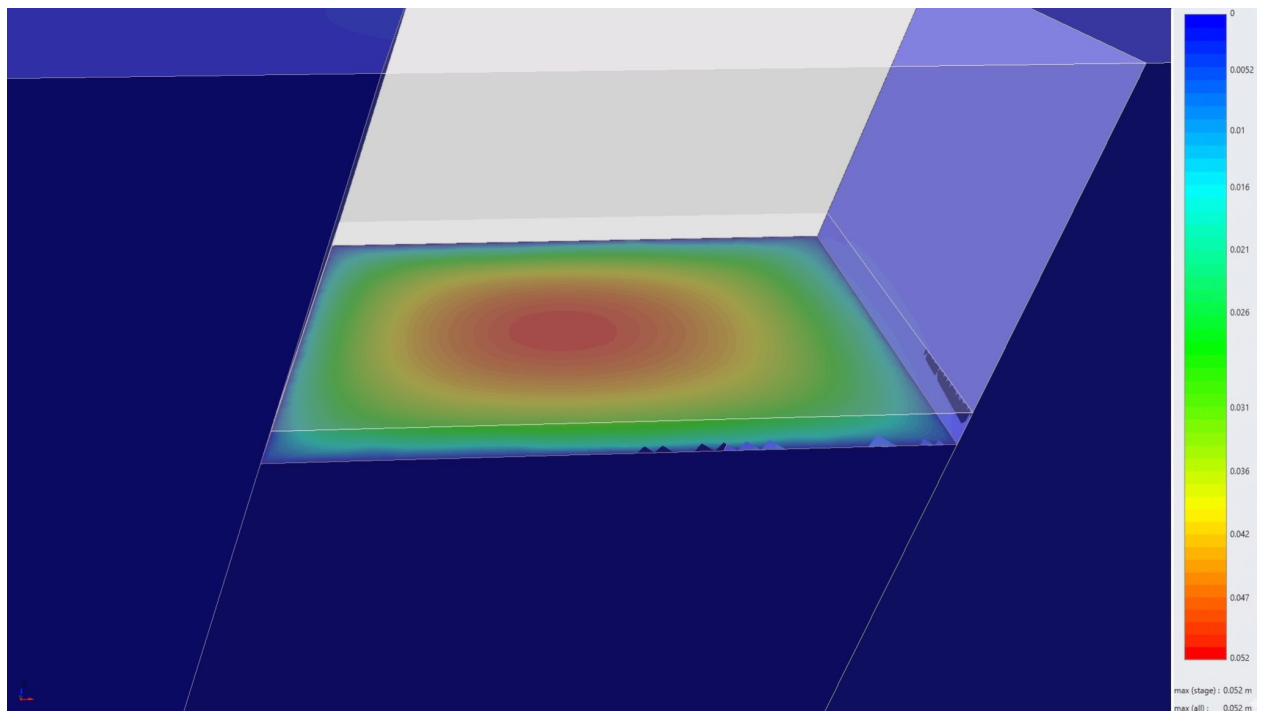


Figure 34. 3D simulation result representing total displacement after the backfilling (top of the backfill).

Figures 34 and 35 show the displacement distribution for the backfilled stope. The results demonstrate that in general the model experiences low displacement, indicating that the backfill significantly reduces the deformation compared to excavated stope stage. However, notable

displacement is observed at the top surface of the backfill, where maximum displacement is approximately 0.052m.

The localized displacement at the top of the backfill boundary and confinement conditions of the system. Unlike lower and lateral parts of the backfill, which are confined by the surrounding rock mass, the upper surface of the backfill is adjacent to the 1m void space. As a result, the upper surface behaves like a less- confined free surface, allowing it to deform more easily.

The backfill body is subjected to vertical loading from rock mass above, while lacking support at its top boundary. This causes a condition in which the upper surface of the backfill undergoes settlement and localized deformation, while deeper portions remain more constrained by lateral confinement. That is why the high displacement observed at top of the backfill does not necessarily indicate global instability but rather reflects expected compressive settlement and deformation of partially confined backfill mass.

CO₂ injection



Figure 36. 3D simulation result representing major principal stress (σ_1) after the CO₂ injection.

The figure illustrates the distribution of major principal stress after the application of simulated CO₂ injection load. The results show that most of the stress buildup occurs close to the storage

chamber—particularly along the roof of the chamber and at the boundary between the storage void and the upper backfill. This concentration of stress suggests that the applied chamber load creates a localized compressive zone around the storage area, while the stress levels in regions farther away remain largely unaffected.

Overall, the findings indicate that the mechanical impact of CO₂ injection is highly localized rather than spread throughout the entire model. The backfill and surrounding rock mass respond mainly in the immediate vicinity of the chamber, with the greatest stress changes occurring along the chamber boundary where the load transfer is most direct.



Figure 37. 3D simulation result representing major principal stress (σ_3) after the CO₂ injection.

Figure 37 shows the distribution of the minor principal stress (σ_3) following CO₂ injection. Similar to the behavior observed for σ_1 , changes in σ_3 are concentrated around the upper portion of the backfilled stope and along the interface between the storage chamber and the surrounding material. The contour pattern reveals that the applied load alters the confinement conditions beneath the chamber, forming a distinct stress disturbance zone.

As the distance from the chamber increases, the stress contours become smoother, which implies that the injection-induced effects quickly diminish away from the source. This pattern confirms that the main influence of CO₂ injection is confined to the chamber and its immediate

surroundings, rather than causing a widespread redistribution of stress across the entire rock mass.

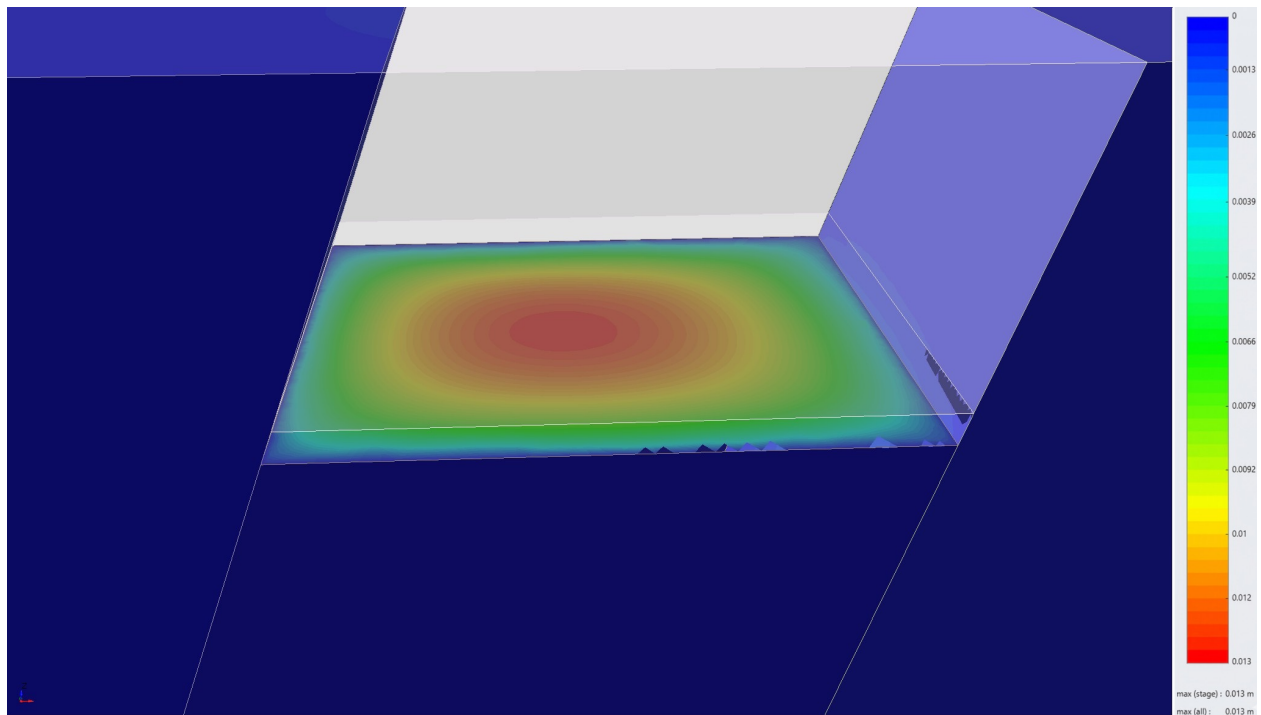


Figure 38. 3D simulation result representing total displacement after the CO₂ injection (top of the backfill).

Figure 38 gives a closer look at the displacement distribution below the storage chamber. The contours reveal a nearly symmetrical deformation zone centered under the chamber. Maximum displacement reaches 0.013m and occurs near the center of the upper backfill surface and gradually decreases toward the edges.

These results suggest that the chamber load is effectively transferred into the backfill, where it is absorbed mainly through compression and settlement of the upper layer. The displacement smaller near the stope walls reflects the beneficial confinement provided by the surrounding rock, which limits outward deformation and keeps most of the response within the central support zone.

5. DISCUSSION

The aim of this study was to evaluate whether a 1 m void space left at the top of a backfilled underground stope could conceptually be used for supercritical CO₂ storage, with particular attention to the thermal response of the backfill and the geomechanical response of the stope-rock-backfill system. To address this, the study combined ANSYS for thermal and thermal-stress analysis with RS3 for staged geomechanical modelling. This two-step approach was appropriate because the problem involves both temperature-related effects and excavation-induced stress redistribution.

The ANSYS results show that when the chamber pressure reaches 10 MPa, the chamber temperature rises to about 405 K (131°C) and remains high throughout most of the chamber, with only localized variation near the injection point. When this chamber temperature is applied to the top surface of the backfill, a clear temperature gradient develops, with the highest temperatures at the top and decreasing temperatures with depth. This indicates that the thermal influence of stored CO₂ is concentrated mainly in the upper part of the backfill. The resulting thermal stress at the top of the model is about 3 MPa, which suggests that heating alone is sufficient to create a meaningful stress field in the backfill, even before considering the additional mechanical effect of chamber pressure. In other words, the thermal part of the study supports the assumption that CO₂ storage may affect the backfill not only through pressure but also through temperature-induced stresses under confinement.

The RS3 results show a logical mechanical progression from the virgin state to excavation, backfilling, and finally CO₂ injection. In the virgin state, both major and minor principal stresses are distributed smoothly through the model, with stress increasing with depth and no clear concentration zones. This is an important baseline result, because it shows that the initial model behaves as an undisturbed rock mass under geostatic loading. The absence of major anomalies at this stage suggests that the subsequent changes observed in later phases are caused mainly by excavation, filling, and chamber loading rather than by initial conditions.

After stope excavation, the stress field changes significantly. The excavation creates a stress-free opening, causing the original in-situ stresses to redistribute into the surrounding rock mass. As a result, the highest major principal stress develops near the stope crown and upper corners, while the minor principal stress decreases around the excavation boundary due to loss of

confinement. This behaviour is typical of underground openings, where the rock close to the excavation unloads and the adjacent rock mass carries increased stress.

The displacement results support this interpretation. The maximum total displacement after excavation is approximately 0.042 m, occurring mainly near the roof and inclined sidewalls. More detailed views show elongated deformation zones along both the hanging wall and footwall, indicating that movement is concentrated in the rock immediately adjacent to the opening rather than spread through the whole model.

After backfilling, the stress field becomes more uniform and the disturbed zone around the opening becomes less pronounced, indicating that the backfill provides mechanical support. High compressive stresses remain near the roof and upper backfill interface, suggesting that the backfill begins to carry part of the overlying load and transfer it to the surrounding rock. The minor principal stress results also show partial restoration of confinement, although confinement remains lower near the 1 m void, which is intentionally left open for storage.

The displacement pattern in the backfilled stage is also important. Top surface of the backfill experiences localized settlement, with a maximum displacement of about 0.052 m. This does not necessarily indicate instability. Because the top of the backfill lies directly beneath the void, it is less confined than the lower and side portions of the fill, while still carrying vertical load from the overlying rock. Therefore, the observed movement is better interpreted as localized compression and settlement of a partially confined backfill mass rather than failure of the backfill body.

The CO₂ injection stage shows that the additional loading from the storage chamber affects the system mainly in a localized manner. Both σ_1 and σ_3 indicate that the main stress changes occur close to the chamber roof and around the boundary between the storage void and the upper backfill. Farther from the chamber, the stress field becomes much smoother. This suggests that the mechanical influence of the simulated chamber loading does not propagate widely through the entire model but remains concentrated in the immediate chamber support zone. From a conceptual storage perspective, this is a positive outcome, because it implies that the main mechanical response to storage occurs where it would be expected: directly around the void and in the backfill beneath it.

The displacement results after CO₂ injection strengthen this interpretation. Total displacement is concentrated in the upper central zone of the backfill directly beneath the chamber, while the

surrounding rock mass experiences very little movement. The maximum displacement is about 0.013 m, which is smaller than the maximum displacement in the backfilled case. This suggests that the simulated storage load does not produce widespread deformation of the stope environment. Instead, the backfill appears to act as the main deforming and load-accommodating medium beneath the chamber. The detailed displacement contour beneath the chamber is nearly symmetrical, which supports the idea that the chamber load is transferred downward into the fill and dissipated toward the stope walls, where confinement is stronger.

In addition to the applied chamber loading, the geometry of the storage void likely contributes to the localized stress and displacement patterns observed after CO₂ injection. Sharp corners and abrupt boundary changes are known to intensify local stress concentration, which may explain why the strongest response occurs near the chamber edges and the upper backfill interface.

Several limitations must be recognized when interpreting the results. First, this is a conceptual feasibility study, not a site-specific design. Second, the thermodynamic part of the ANSYS analysis was simplified to estimate chamber temperature, rather than fully modelling coupled fluid flow and heat transfer. Third, in RS3 the effect of stored CO₂ was represented using equivalent concentrated loading, because direct gas simulation is not available. For this reason, the CO₂ injection results should be understood mainly in terms of the location and pattern of stress redistribution and deformation rather than exact field values. Finally, the material properties were adopted from literature and mine data rather than being measured specifically for a real storage site. These limitations do not invalidate the modelling framework, but they do mean that the present results should be treated as an initial conceptual assessment that would need refinement through site-specific data, laboratory testing, and more advanced coupled modelling.

Overall, the concept of CO₂ storage may be mechanically feasible at a conceptual level, provided that the backfill is capable of carrying localized loading beneath the chamber and that the chamber remains confined within competent surrounding rock.

6. CONCLUSIONS AND RECOMMENDATIONS

This study investigates, at a conceptual level, whether a 1 m void space left above a backfilled underground stope could be used for supercritical CO₂ storage. A combined numerical modeling approach was adopted, using ANSYS to estimate chamber temperature and thermally induced stress in the backfill, and RS3 to evaluate the geomechanical response of the stope-rock-backfill system through the virgin, excavated, backfilled, and CO₂ injection stages.

The results showed that excavation caused the greatest disturbance to the original stress field, with stress concentration and displacement developing mainly near the stope roof, corners, and inclined sidewalls. After backfilling, the stress field became more uniform and confinement within the stope was partially restored, indicating that the backfill provided mechanical support to the excavation. Although localized settlement occurred at the top of the backfill beneath the storage void, this response was interpreted as compression of a partially confined backfill mass rather than overall instability. During the CO₂ injection stage, the main changes in major and minor principal stresses remained concentrated around the storage chamber and the upper backfill interface, while displacement remained localized beneath the chamber. Overall, the maximum displacements remained within an acceptable range, with values of approximately 0.042 m after excavation, 0.052 m in the backfilled stage, and 0.013 m after simulated CO₂ injection.

Based on these results, the study suggests that CO₂ storage in the proposed void space is feasible at a conceptual level. The mechanical effects of storage were largely localized and did not indicate widespread instability of the surrounding rock mass under the adopted modeling assumptions. At the same time, this work represents a conceptual feasibility study rather than a site-specific design. The input parameters were taken from published sources, the thermal analysis was simplified, and the CO₂ effect in RS3 was represented using equivalent concentrated loading. Therefore, the findings should be interpreted as an initial assessment of the stress redistribution and deformation pattern associated with the proposed concept.

Future studies

- Conduct site-specific laboratory testing of cemented paste backfill under combined thermal and pressure loading.
- Perform sensitivity analyses for key parameters such as backfill stiffness, chamber pressure, void thickness, and rock mass properties.

- Apply advanced coupled thermo-mechanical numerical modeling, for example using UDEC, to more accurately simulate geomechanical response of pressurized supercritical gas in underground backfilled stopes.
- Investigate the long-term performance of the storage chamber, including possible CO₂ migration through backfill and interfaces.
- Assess the influence of different chamber geometries and storage dimensions on stress redistribution and overall stability.

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