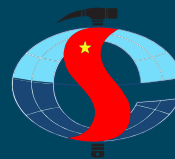




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Volume 2

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Research on the effect of thermodynamics in the LPG storage cavern of Cai Mep

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Abstract: The underground storage of GPL in a salt rock cavern must take the effects of temperature variations into account to model the different stress applied on the walls. The variations in temperature are caused either by the filling/emptying of the cavern but also because of the natural temperature of the rock around the cavern. The objective of this study is to understand and model the thermal and mechanical effects occurring within a salt cavern during LPG injection and withdrawal cycles. These processes are highly interdependent and governed by a set of coupled physical equations describing heat transfer, rock deformation, gas compression, and volume changes due to creep. The paper estimates stress and displacements of surrounding rock and rock support of the (LPG) storage cavern by FEM analysis. The pattern of deformation, stress state, and distribution of plastic areas are analyzed by RocScience – RS2 software. The stress concentrations, plasticity development, and displacements are all consistent with theoretical predictions and acceptable performance limits. This integrated approach strengthens the reliability of the design and supports the long-term use of salt caverns for LPG storage, with the condition that long-term surveillance and adaptive operational control are strictly followed. The study result provides a reliable way to analyze the effect of thermodynamics in the (LPG) storage cavern and also will help to design or optimize the subsequent support.

Keywords Thermodynamics, storage cavern, LPG, Cai Mep, FEM analysis.

INTRODUCTION

The Cai Mep LPG Cavern project is the largest underground storage facility in Southeast Asia, with a capacity of 240,000 tons of liquefied petroleum gas. This project is allowing the country to secure its energy needs by providing a consequent reserve of LPG, reducing the risks associated with importation or local production disruptions. This project is contributing to Vietnam's economy by decreasing gas prices and strengthening the country's strategic position in the regional energy sector. As shown in Figure 1, the Cai Mep LPG storage cavern was constructed near Vietnam's largest commercial port (Cai Mep's Port) to maximize logistical and economic efficiency. Situated just 10 km from the port, the cavern has direct access to the maritime transport infrastructure, facilitating the importation and the exportation of liquefied petroleum gas. This proximity decreases transportation costs and delivery costs. Near one of Vietnam's largest cities, Ho Chi Min city, it can provide a competitive storage and a good distribution in all the city.

Temperature variations cause thermal expansion and contraction in surrounding rock and soil, which leads to significant changes in stress and displacement. This can result in an increase in stress and deformation, affecting the overall stability of the storage cavern. Higher temperatures can increase deformation

rates and the risk of damage, especially near the cavern walls, while cyclic temperature and pressure changes can cause fatigue and creep deformation over time. It makes the increased stress and deformation: Temperature variations induce thermal stresses, which, combined with existing stress from the surrounding rock mass, can cause significant stress changes and lead to deformation. Greater deformation: Higher temperatures lead to greater deformation, with the maximum vertical and horizontal displacement often occurring in the vault (roof) and sidewalls of the cavern. Stress concentration: The range and concentration of principal stress increase with temperature, potentially leading to a greater plastic zone around the cavern. Cyclic loading effects: Repeated cycles of temperature and pressure changes, such as during gas injection and withdrawal, can lead to creep deformation and affect the long-term stability of the cavern. Research on the effect of thermodynamics in the LPG storage cavern is often carried out through analytical methods, experimental methods, and numerical modeling methods. However, the numerical modeling method is used more because it takes into account many influencing factors such as geological conditions, geomechanics, groundwater... In addition, numerical method takes into account heterogeneity, containing cracks in the rock mass [2-12]. The LPG storage cavern analysis has made remarkable growth for past several years due to development of numerical analysis method and computer development, given the situation that it was difficult to solve formula of elasticity, viscoelasticity and plasticity for dynamic feature of the ground when the constituent laws, yielding conditions of ground materials, geometrical shape and boundary conditions of structure were simulated in the past. That is, numerical analysis method has been introduced to geotechnical engineering and has contributed to analysis of creep feature, plastic (yielding) conditions and non-linearity of stress strain relations of the ground. The study selects the numerical method using Phase 2 software to simple analysis and more

reasonable design and construction management materials have been obtained.

GEOLOGICAL CONTEXT

This underground storage cavern was constructed at a depth of approximately 150 meters in hard rock. Geological analyses of the site were conducted by the Korean company HYOSUNG, which was also responsible for the construction. An additional soil layer lies above the rock mass. This layer is 54.6 meters thick and has an average unit weight of 18 kN/m^3 .

The site where the construction was carried out consists in different rock quality, present in various conditions, evaluated using the RMR scale from Grade 1 (VERY GOOD condition) to Grade 5 (POOR condition). Figure 1 below shows the distribution of rock mass quality around the different parts of the storage cavern [1].

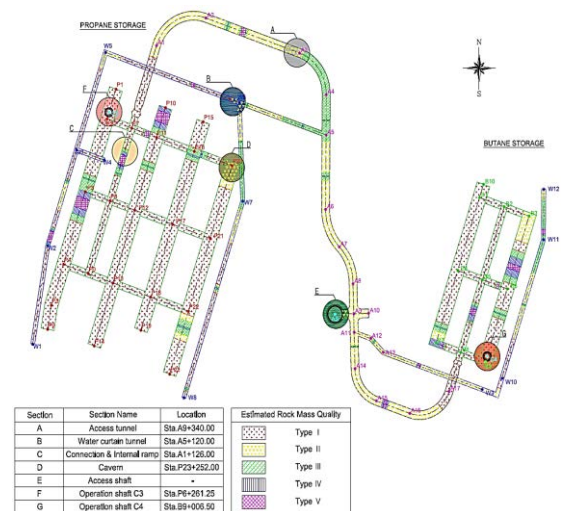


Figure 1. Storage cave plan with Rock Mass Quality rating

The entire storage cavern has been divided into different sections based on their use. For each section, an analysis of the distribution of rock classes was conducted. The predominant RMR (Rock Mass Rating) classes for each section of the tunnel, from section A (Access Tunnel) to section G (Operation Shaft) (Figure 2), are available in Table 1 below.

Table 1. Predominant RMQ classes for each section of the project [1]

Section	Section Name	Most Prevalent Rock Class
A	Access Tunnel	II
B	Water Curtain Tunnel	I
C	Connection and Internal Ramp	I

D	Cavern	I
E	Access Shaft	II
F	Operation and Shaft C ₃	I
G	Operation and Shaft C ₄	I

An estimation of the rock mass properties was then carried out on-site. Table 2 below summarizes the properties of the rocks sorted by RMR class (from Grade I to Grade V).

Table 2. Mechanical characteristics of the rock according to the RMR class [1]

Type	Unit Weight (kN/m ³)	Cohesion (kPa)	Internal Friction Angle (°)	Deformation Modulus (MPa)	Poisson's Ratio
GradeI	26.6	9000	54.8	41000	0.25
GradeII	26.5	7100	52.6	31300	0.25
GradeIII	26.4	5100	49.4	16100	0.25
GradeIV	26.1	3700	44.5	8300	0.25
Grade V	25.6	2500	40.6	4400	0.26

It is noticeable that the condition of the rocks surrounding the project is not homogeneous.

PROJECT GEOMETRY

In this study, this study will be focused on the section labeled S (in black dashed lines) in Figure 2. To simplify conversions and calculations, this section S will have a thickness of 1 meter for the subsequent modeling. The dimensions of this section, which represent the geometry of the model presented later, are shown below in Figure 3.

In this model, only the sections labeled B (water curtain), C (connection and internal ramp), and D (main cavern) will be included, as shown in Figure 2. A set of shotcrete liners and a rock bolt pattern were used to improve the mechanical stability of the gallery. Mechanical characteristics of support (by section) in the appendix. The elements were sized according to each type of gallery (different characteristics for sections B, C, and D of the model) [1].

THERMAL MODELING OF THE CAVERN

This equation models how temperature changes in the rock mass over time due to heat diffusion from or toward the cavern. It accounts for the 2D axisymmetric geometry of the cavern and is essential to capture the

thermal behavior of the surrounding salt (Figure 3) [4].

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right)$$

In our case:

$k = 5 \text{ W/(m}^*\text{K)}$ the Thermal conductivity;

$\rho = 2650 \text{ kg/m}^3$ the density of the rock;

$C_p = 900 \text{ J/(kg}^*\text{K)}$ the heat capacity of the rock [4].

$$\alpha = \frac{k}{\rho x C_p} = \frac{5}{2650 \times 900} = 2,1 \times 10^{-6} \text{ m}^2/\text{s}$$

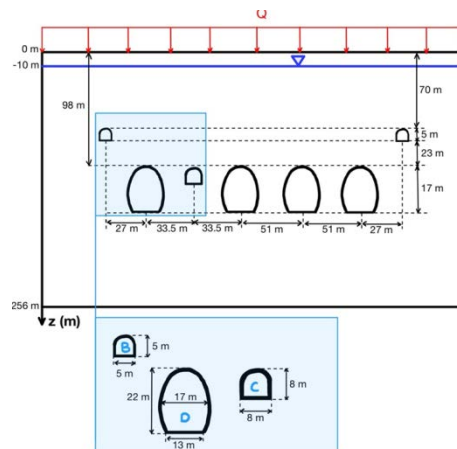


Figure 2: Model geometry

This diffusion controls how fast the rock heats

or cools. If it's low, heat stays trapped in the rock, delaying equilibrium with the gas. This influences cavern wall temperatures and resulting thermal stresses. Another equation can describe the rate at which heat is transferred through the rock to or from the gas [4]:

With: $q_{cond} = -k_{salt} \chi \frac{\delta T}{\delta r}$; $k_{salt} = 5 \text{ W/(m}^2\text{K)}$

$T_{rock} = 25 + 0.03 \cdot 161 = 30^\circ\text{C}$ the temperature of the rock at 161m deep (half of the cavern $T_{gas} = 15^\circ\text{C}$ as we can see on Figure 3 below; $e = 25\text{m}$, the distance from the cavern where the rock is affected by the gas temperature from Figure 3 below.

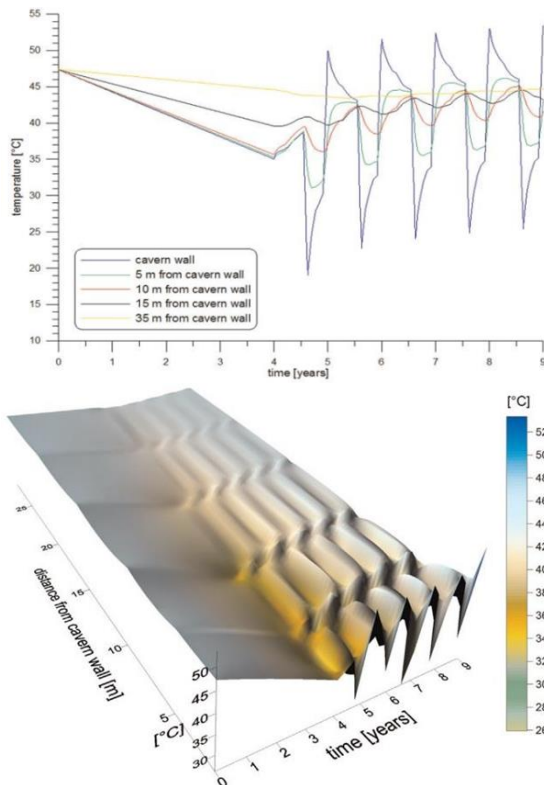


Figure 3. The temperature over time in underground cavern

With this result we can quantify how quickly the gas will equilibrate thermally, if this value is too high, it can affect the rapidity of the variation in stresses and so weaken the rock. The injection of GPL in the cavern can make variations in the gas temperature and convection can append in this situation. We can calculate it by using the equation [4]:

$$q_{conv} = hx(T_{salt} - T_{gas})$$

with:

$H = 17\text{m}$, the height of the cavern;

$T_{salt} = 30^\circ\text{C}$ and $T_{gas} = 15^\circ\text{C}$ as before

$$q_{conv} = h \times (T_{salt} - T_{gas}) = 17 \times (30 - 15) = -255 \text{ W/m}^2.$$

This equation allows to estimate the heat exchange between the rock and gas that can affect the pressure of the gas and the stress in the cavern. After calculating the thermal exchanges between the rock and the gas, we can estimate the stresses in the rock salt.

Firstly, with the thermal strain, that can be used to know if the salt will expand or contract and can prevent the potential cracks if the tension is too high.

$$\varepsilon_{th} = \alpha_T \times \Delta T = 4 \times 10^{-5} \times -15 = -6 \times 10^{-4}$$

With $\alpha_T = 4 \times 10^{-5}^\circ\text{C}^{-1}$, the coefficient of thermal expansion of the rock.

The thermal stress is the next calculation. It helps to find the stress caused by the change in temperature in the rock [4].

$$\sigma_{th} = E \times \alpha_T \times \Delta T$$

With, $E = 25000 \text{ MPa}$, the Young modulus of the salt rock

$$\sigma_{th} = E \times \alpha_T \times \Delta T = 25000 \times 4 \times 10^{-5} \times -15 = -15 \text{ MPa}$$

This tensile traction simulates the effect of thermal contraction due to the LPG cooling the cavern wall, but since salt is in a confined state, it cannot expand freely and then is subject to internal stress changes.

This stress needs to be inferior to the tensile strength of the salt which is around 1,5 MPa or it can cause fracturing and increase the permeability of the rock.

Then, effective stress is used to evaluate the combination of gas pressure and in-situ stresses, to verify the condition of the rock [4].

$$\sigma_{eff} = \sigma_{min} - P_{cavern}$$

With: $\sigma_{min} = 2650 \times 9.81 \times 161 = 4 \times 10^6 \text{ Pa}$ the

minimum stress on the cavern walls; $P_{cavern} = 0.8 \text{ MPa}$, the pressure of the LPG in the cavern.

$$\sigma_{eff} = \sigma_{min} - P_{cavern} = 4 - 0.8 = 3.2 \text{ MPa}$$

NUMERICAL MODEL OF THERMAL CAVERN

To make the model of the cavern, the study used the software Phase2, used for all types of models. It is particularly useful for analyzing slope stability, designing underground and surface excavations, and assessing support systems in rock and soil. It's also used for groundwater analysis, dynamic analysis, and even the design of foundations and embankments (see Figure 4).

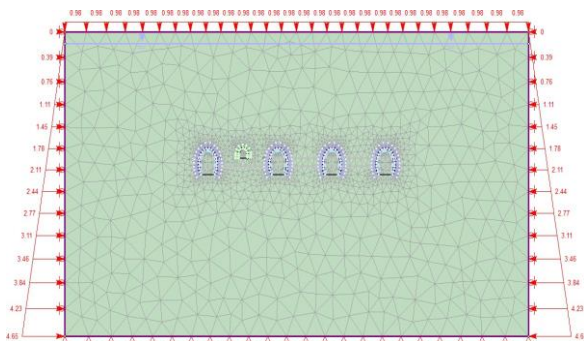


Figure 4. Numerical model with the thermodynamics boundary conditions

To create the model, the study need to start by adding the geometry of the project, with the excavations the study will do later. The model only represents the rock part, there is a layer of 54,6m of soil of 18 kN/m³, above, defined by the added the studyight of 18x54,6=984 kPa ≈0,98 MPa.

The boundaries added are, on the bottom, fixed in x and y axis, to stabilize the model and represent the fact that there is rock under and on the sides of the model, so the rock can't move. On the sides, the x axis is fixed to represent the rocks on the sides outside of the model.

To estimate the value of the stress added by the increase of temperature depending on the depth on the sides of the model, the study need to know the temperature at the bottom of the model. The study know that the dept is

310m so by estimating an added temperature of 0.03°C/m, the study can find:

$$\Delta T_{310m} = 310 \times 0.03 = 9,3 \text{ }^{\circ}\text{C}$$

By using the equation

$$\sigma_{therm} = E \times \alpha \times \Delta T$$

The study can find added stress due to the temperature of the rock, With, $E = 25000 \text{ MPa}$, the young modulus of the salt rock, $\alpha = 4 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$, the coefficient of thermal expansion of the rock; $\Delta T = 15^{\circ}\text{C}$,

$$\sigma_{therm} = E \times \alpha \times \Delta T = 25000 \times 4 \times 10^{-5} \times 9,3 = 9,3 \text{ MPa}$$

The added stress due to the increase in temperature in the model is 9,3 MPa, that we can add on the vertical sides of the model by using a triangular force because the stress increase with the depth (see Figure 5).

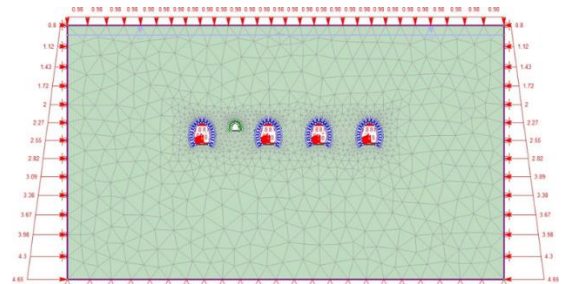


Figure 5. Model geometry

In the present simulation, thermal stresses induced by gas injection were modeled. The injected LPG enters the cavern at a temperature of approximately 15°C, while the surrounding rock mass at a depth of 160 meters maintains a natural geothermal temperature of around 30°C. This results in a negative thermal gradient between the cavern wall and the gas.

Due to this temperature drop, the surrounding rock tends to contract. However, because this contraction is limited by the surrounding formation, it generates tensile thermal stresses that act radially toward the cavern center. To simulate this mechanical behavior, an equivalent thermal traction load of 15 MPa was applied inward on the cavern wall in the model.

The magnitude of this thermal stress is estimated using the classical linear thermoelastic formula:

$$\sigma_{therm} = E \times \alpha \times \Delta T = 25000 \times 4 \times 10^{-5} \times -15 = -15 \text{ MPa}$$

Where:

$E = 25 \text{ GPa}$ is the Young's modulus of salt rock;

$\alpha = 4 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$ is the thermal expansion coefficient;

$\Delta T = -15 \text{ } ^\circ\text{C}$ is the temperature difference between the rock and the gas.

This gives a resulting tensile stress of -15 MPa , consistent with the value used in the model. The direction and magnitude of the load were validated and applied in the numerical simulation, ensuring realistic representation of thermal contraction effects. This consideration is essential to assess potential fracturing or dilatancy risks due to cooling of the cavern wall (See Figure 6).

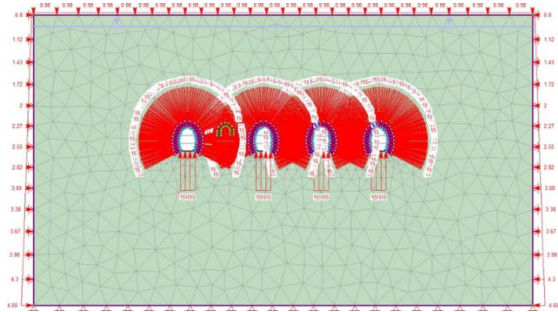


Figure 6. Model geometry

RESULTS OF NUMERIAL MODEL

Stress distribution

The simulation results show a redistribution of the mechanical stress field around the cavern due to the presence of excavations and the application of internal pressure and thermal contraction. As expected, stress concentrations appear around the cavern roof, floor, and side walls, particularly at points where the geometry is a curve or has discontinuities. This is consistent with theoretical predictions from elastic cavity

mechanics, where local curves increase stress magnitude (See Figure 7).

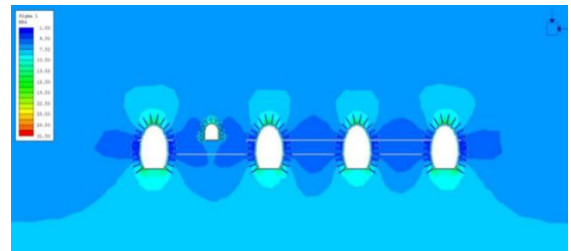


Figure 7: Stress distribution around the cavern

The peak vertical stress reaches values around 22 MPa in the top and floor of the cavern. This remains below the compressive strength of salt, which generally lies between 25 and 30 MPa in confined conditions. The horizontal stresses also show better values in the inter-pillar zones between neighboring caverns, with the geometry increasing the stress intensity locally.

Importantly, the presence of thermal stress slightly reduces confinement near the cavern wall. However, it does not cause the vertical or horizontal principal stress to become tensile anywhere in the model. The minimum principal stress remains negative, indicating that tensile failure does not occur even under the applied cooling condition.

This stress state is critical for safety. Theoretical framework, salt's tensile strength is very low ($1\text{--}3 \text{ MPa}$ unconfined), and tensile fracturing is a major risk during rapid cooling. In this model, thermal loading has been applied as a static traction, ensuring that this aspect of the design remains within safe boundaries

Plastic Zones

The next critical result from the simulation involves identifying the development of plastic zones around the cavern boundary. Phase2 identifies zones where the stress state meets or exceeds this limit, marking them as "yielded."

In the current simulation, yielded zones are most prominent in the roof and shoulder regions of the cavern, where geometric curves

intensify stress. This aligns with expected theoretical behavior: the transition from wall to roof typically concentrates both shear and tensile components of stress. These areas are often the most critical in underground excavation design.

The yielded zones remain shallow and do not extend beyond 4 meters from the cavern wall. Furthermore, yielded zones remain disconnected and localized, avoiding formation of continuous failure surfaces and no plasticization occurs in the vertical bolts separating adjacent caverns, ensuring that the mechanical separation is preserved Figure 7.

Yielded zones in salt are not necessarily indicative of failure because of salt's ductile nature means that some localized yielding is expected and even beneficial, as it allows stress redistribution without catastrophic rupture. However, if yielding becomes continuous or progresses to large zones, the risk of progressive damage increases, especially under cyclic loading or long-term creep.

During the use of the storage cavern, these plastic regions are likely to accelerate local creep, meaning displacements may concentrate in these zones over time. Also, because the yield penetration remains limited, there is no indication of global instability in the cavern system under current loading. Vietnam's tropical monsoon climate, with three-quarters of its territory being mountainous and a coastline of over 3,260 km, provides significant renewable resource potential. The country possesses abundant biomass, solar, hydropower, and wind resources.

Displacement Field

Mechanical convergence and vertical displacement are natural responses of salt under pressure. In Phase2, displacements are calculated using the elastic and plastic properties of the material and boundary conditions. These results provide information about cavern closure behavior, surface settlement risk, and long-term deformation trends.

The simulation shows that radial convergence of the cavern walls reaches a maximum of 6 mm at the center of the walls, this displacement is symmetric around the cavern, indicating stable boundary conditions and a well-centered cavity.

Convergence of this order is expected in salt storage caverns, especially during early operational phases. It reflects a combination of, internal gas pressure, thermal stress and elastic-plastic material response.

In practice, such displacements would be compensated by pressure adjustments to maintain volume integrity. The magnitude and symmetry of this result confirm that the model behaves consistently with real-life salt cavern operations.

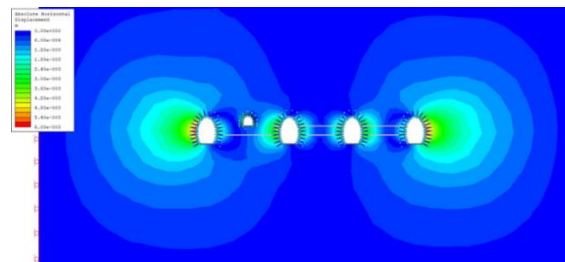


Figure 7. Plastic zones around the cavern

Vertical movements were also recorded, with the roof settlement that is observed at around 2,5 cm, concentrated above the cavern and surface settlement at the top of the domain remains minimal, at less than 4 mm.

These values are considered safe because the vertical displacements are moderate and do not threaten the integrity of the cavern roof and surface settlements remain well below thresholds of concern for infrastructure.

These observations are consistent with the typical behavior of salt formations, in which stress redistributes laterally, limiting vertical deformation propagation. This further supports the validity of the model geometry and boundary conditions.

THERMAL Effects

The interaction between thermal loading and mechanical response is a central concern

in the design and operation of LPG storage caverns. The injection of cooler LPG into warmer rock salt leads to a temperature gradient that induces stress through thermoelastic contraction.

This stress is tensile and radial, acting inwardly on the cavern wall. In the simulation, this is implemented as a boundary load of -15 MPa. The value is significant because the tensile strength of salt is low (1-3 MPa unconfined), but under confined in-situ conditions, salt can accommodate higher tensile stresses due to lateral support from the surrounding material.

The simulation shows that this thermal stress can reduce the confinement at the cavern boundary, increases the potential for yielding, particularly near curved zones and has a controlled and symmetric effect.

If LPG were injected at 0 °C instead of 15 °C, the thermal gradient would increase to -30 °C:

$$\sigma_{th} = E \times \alpha_T \times \Delta T = 25000 \times 4 \times 10^{-5} \times -30 = -30 \text{ MPa}$$

This level of thermal stress would approach or exceed the confined tensile strength of the salt, so most likely cause fracturing, particularly in already yielded or curved areas

This shows the importance of thermal management to avoid rapid temperature changes, control injection temperature to prevent excessive contraction and monitor thermal fronts through sensors embedded in the salt body.

The low thermal diffusivity of salt means that temperature changes propagate slowly. This supports the simulation's decision to apply a uniform thermal stress over the cavern wall, representative of a long-duration thermal equilibrium.

One limitation of the current model is its inability to explicitly simulate fracture initiation. Phase2 models plasticity and stress states, but not discrete cracking unless additional fracture mechanics modules are

used. However, based on the theoretical tensile stress thresholds and the observed stress fields, it is clear that the current 15°C thermal gradient is safe, but a greater thermal gradient (>30°C) could initiate fracture. Also, repeated thermal cycling could degrade integrity over time through fatigue.

To mitigate such risks, the design must limit thermal gradients to below 20-25°C during rapid injections and possibly preheat caverns or slow down injection rates. Moreover, there is a need to consider integrating a fracture model in future simulations to be sure about the stability of the cavern.

In reality, heat exchange between the LPG and surrounding rock is not instantaneous. Instead, a thermal front develops around the cavern, that causes stress to build up progressively as this front move,

The thermal diffusivity α is around $2.1 \times 10^{-6} \text{ m}^2/\text{s}$, as found before. This low value justifies the assumption of near stable conditions in the simulation and supports the use of uniform radial thermal stress instead of transient thermal-mechanical coupling.

However, for more precise simulations, we should use a transient thermal field that could be computed using time-stepping (not possible on this version of Phase2). This would yield time- varying thermal stress, allowing the evaluation of fracture timing. It would also better capture thermal fatigue over multiple injection cycles.

CONCLUSION

In this study, a numerical analysis using finite element software has been conducted to investigate on the effect of the thermodynamics in the LPG storage cavern of Cai Mep. Some interesting conclusions arising from numerical simulations are given: the modeled LPG storage cavern, located at 160 meters depth in a salt formation, is mechanically stable and operationally safe under the modeled conditions. The stress concentrations, plasticity development, and

displacements are all consistent with theoretical predictions and acceptable performance limits.

This integrated approach strengthens the reliability of the design and supports the long-term use of salt caverns for LPG storage, with the condition that long-term surveillance and adaptive operational control are strictly followed.

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