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HỘI NGHỊ KHOA HỌC TOÀN QUỐC "CƠ HỌC ĐÁ - NHỮNG VẤN ĐỀ ĐƯƠNG ĐẠI"

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Research on choosing the optimal water curtain pressure in the (LPG) storage cavern by numerical simulation

Ngo Minh Hoang^{1,2}, Boudey Émile³, Dang Van Kien^{1,*}, Do Ngoc Anh¹

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ABSTRACT: Energy security is a global concern, particularly in Europe, the United States, and China. In this paper, the construction of LPG storage systems is essential to secure energy supply and support economic development. Surface tanks, whether cylindrical or spherical, were commonly used but have many drawbacks: temperature variations requiring maintenance systems, risks of terrorist attacks, explosions or fires, pollution in case of leaks, and the occupation of large spaces, which alter the urban landscape. Floating tanks are exposed to marine weather conditions, increasing the risks of structural damage and maintenance costs. Leaks can cause environmental disasters, and their remote location complicates logistics and emergency operations. Underground storage caverns offer many advantages: natural protection against temperature variations, increased security against attacks, reduced risks of explosions and fires, limited environmental damage in case of leaks, and optimized space usage in urban areas. Being invisible, they preserve the aesthetic of the landscape. First, the goal is to understand the functioning of water curtains and underground storage caverns. The study result will be identified methods and hydraulic containment criteria based on international studies, as there is no such research in Vietnam. This paper proposes a 2D finite element model that best simulates the effect of water curtains in a concrete case study: the LPG underground storage project in Cai Mep.

Keyword: LPG; groundwater flow; Cai Mep LPG, numerical simulation.

1. Introduction

The storage gallery is located in the Cai Mep industrial park. Figure 1 below shows the location of the project at different scales (the LPG storage cavern is highlighted in purple in the images). The Cai Mep LPG Cavern project is the largest underground storage facility in Southeast Asia, with a capacity of 240,000 tonnes 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 showed in the 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 a 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 to one of the biggest cities in Vietnam, Ho Chi Min city, it can provides a competitive storage and a good ditribution in all the city.

2. Geological context



Figure 1. Location of Cai Mep LPG

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 $\gamma_g = 18 \text{ kN/m}$.

The site where the construction was carried out consists mostly of granite, present in various conditions, evaluated using the RMR scale from Grade 1 (very good condition) to Grade 5 (Poor condition). Figure 2 below shows the distribution of rock mass quality around the different parts of the storage cavern.

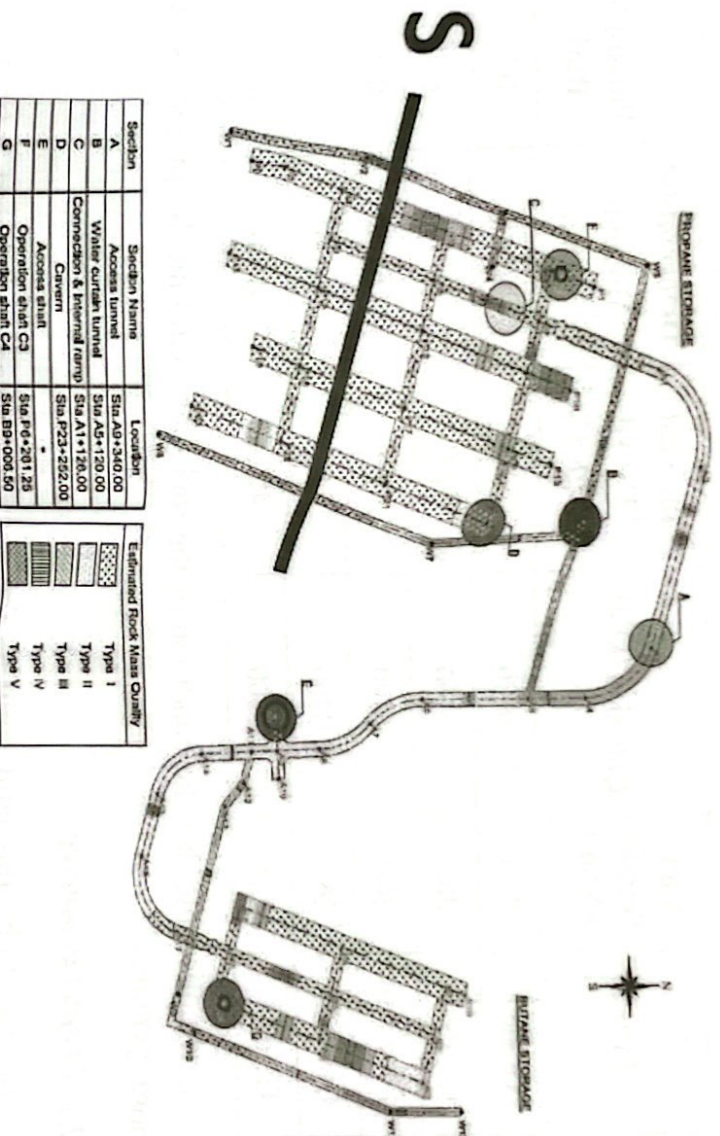


Figure 2. Storage cave plan with Rock Mass Quality rating

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 RMR classes for each section of the project

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 C3	I
G	Operation and Shaft C4	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

Type	Unit Weight (kN/m ³)	Cohesion (kPa)	Internal Friction Angle (°)	Deformation Modulus (MPa)	Poisson's Ratio
Grade I	26.6	9000	54.8	41000	0.25
Grade II	26.5	7100	52.6	31300	0.25
Grade III	26.4	5100	49.4	16100	0.25
Grade IV	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.

2.1. Project geometry

In this study, this study will be focused on the section labeled S (in black dashed lines) in Figure 3. 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 our model, only the sections labeled B (water curtain), C (connection and internal ramp), and D (main cavern) will be included, as shown in Figure 6.

SUPPORT

A set of shotcrete liners and a rock bolt pattern were used to improve the mechanical stability of the gallery. The various properties of the support elements are available in Table 11: 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).

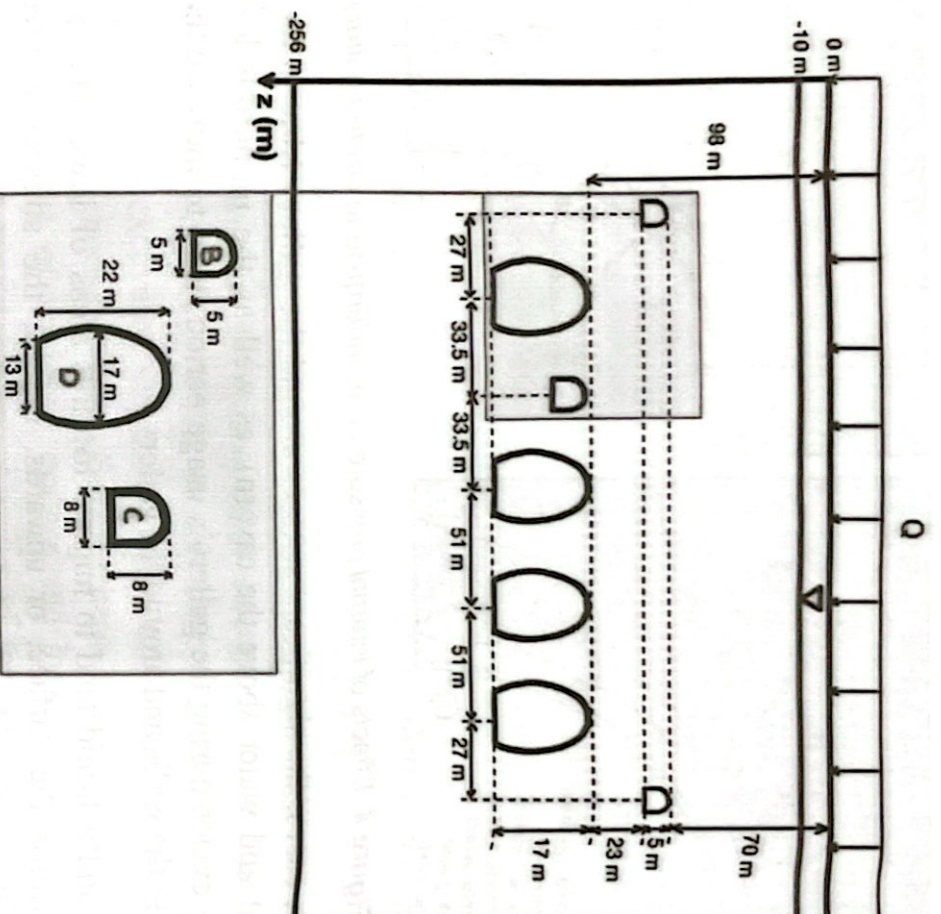


Figure 3. Model geometry

2.2. Properties of geometry water curtains

In underground storage caverns, like the one in the studied project, energy resources are stored in gaseous, liquid, or sometimes both states simultaneously. These resources are kept under pressure, which varies depending on the nature of the resource, the ambient temperature of the rock, and the depth of the cavern below the surface. This pressure is exerted on the inner walls of the gallery.

In ideal conditions, high-quality rock and shotcrete would be completely impermeable. However, as illustrated in Figure 4, there are microcracks not only in the shotcrete but especially in the surrounding rocks (particularly in the rock joints). These cracks are generally present in the rock as soon as the gallery is excavated due to tectonic mechanisms, weathering, or erosion. The cracks in the shotcrete, on the other hand, often appear during the usage phase, after a certain number of loading and unloading cycles of the LPG tunnels, leading to variations in internal pressure.

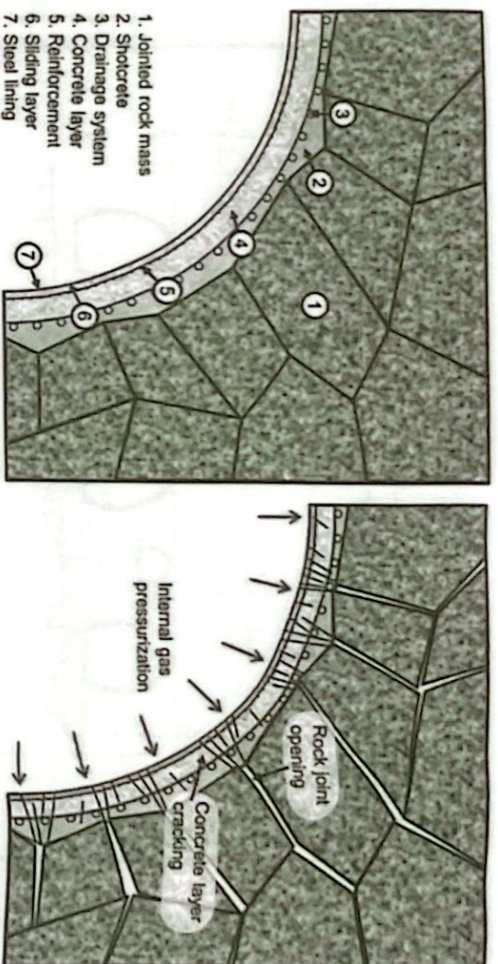


Figure 4. Effects of internal pressure on a underground coated gallery

In both cases, the significant stresses around the gallery (due to the pressure of the soil and water above the cavern), as well as the numerous loading and unloading cycles during the gallery's usage period, tend to increase the number of cracks in the walls and around the gallery.

A gas and a liquid tend to migrate towards areas of lower pressure, which means towards the surface, or upwards. Indeed, the stresses exerted by the weight of the rocks and groundwater increase with depth, preventing the stored gas or liquid from moving downward. As it rises, the gas or liquid will widen the existing cracks, enlarging the path it takes. This can deteriorate the quality of the rock mass and potentially compromise the mechanical stability of the structure. Moreover, such a leak could cause serious ecological hazards to the surrounding environment (the rock mass, aquifers, and even the surface) as well as economic losses due to the waste of gas or liquid. It is therefore essential to ensure optimal containment of the resources stored in the underground gallery by making the storage tunnel completely impermeable. The technology of water curtains is a recent hydrodynamic method that ensures optimal containment by adding hydraulic pressure around the gallery. The principle is quite simple: relatively small tunnels, compared to the main galleries, are dug above them, slightly to the side. In the walls of these tunnels, holes are drilled at regular intervals (usually spaced 10 meters apart and about 10 centimeters in diameter) to inject water at the required pressure. The water thus injected flows through the rock, creating around the tunnels a zone of hydraulic pressure higher than the hydrostatic pressure. This zone then forms a sort of curtain where a certain level of water or hydraulic pressure is maintained around the tunnels.

The water curtain system helps control potential leaks of oil, gas, or other liquids contained in the galleries by generating sufficient hydraulic pressure to prevent these substances from migrating through the cracks in the surrounding rock and shotcrete. This technology has the advantage of being able to adjust the injection pressure according to weather conditions (for example, if rain recharges the water table and increases hydrostatic pressure without a water curtain, water injection is reduced), loading and unloading cycles (when the pressure exerted by the gas in the cavern is zero, as in the case of unloading, less water is injected because there is no gas or liquid to contain), or other geological variations (such as faults or erosion).

2.3. Numerical model and characteristics of material failure criterion models

All the modeling I conducted was done using the Roc Science Phase 2 software. The software, developed by Rock Science, specializes in analyzing deformations and stresses in underground structures. It is well-suited for modeling this project due to its ability to simulate complex interactions between the rock mass and excavated structures, considering various parameters and allowing the user to choose different failure criteria and calculation methods. It also includes a range of modeling options and hydraulic analysis elements, which is particularly useful for the objective of my internship. However, the version of the software I had access to is relatively old (2011). While it is effective for mechanical analyses, it is less practical than newer versions for hydraulic conditions, as it doesn't allow for the direct modeling of certain conditions. For example, with this version, I couldn't model multiple hydraulic conditions on the same boundary, which posed a problem for some analyses. My approach to finding solutions and equivalent methods to properly model the issue is detailed in the following sections. The rock parameters used in the model were calculated using the Rock Lab software. Created by the same company, it also allows for the direct input of calculated values into Roc Science Phase 2.

A significant part of my internship involved reading, understanding, and sorting scientific articles to better comprehend the studies that have already been conducted. These readings allowed me to determine the methods to use, structure my approach, anticipate the expected results, and understand the phenomena involved. The articles I used as a basis for my work are cited throughout the report and are available at the end in the bibliography.

The RocScience Phase 2 software offers several models for the mechanical representation of rocks, including the Mohr-Coulomb, Hoek-Brown, and Cam-Clay models, each providing a specific failure criterion. The Hoek-Brown model is the most used for representing caverns excavated in hard rock. It was specifically designed to better represent rock materials. The Mohr-Coulomb model, on the other hand, is very simple and only considers the internal friction and cohesion of a soil. The assumptions of isotropy, homogeneity, and linear elasticity in this model are too simplistic for our study due to the presence of faults in the rock material, which will impact the hydrology of our project. This model is more suited for sandy or gravelly soils and, therefore, does not apply to our case. Similarly, the Cam-Clay model is used for clay soils and is not suitable for our study. The RS2 software also offers the generalized Hoek-Brown model, which is more accurate than the simplified model. It introduces an additional parameter, “a”, which adjusts the failure criterion envelope based on the degree of fracturing of the rock and the quality of the rock mass. This parameter is calculated from the Geological Strength Index (GSI) and the disturbance factor (D). The D parameter depends on the excavation method: when it is close to 0, the tunnel was excavated without affecting the rock quality; when it is equal to 0.8, the tunnel was significantly damaged due to the excavation method, for example, the use of explosives. This model allows the incorporation of faults within the rock mass, providing a more accurate representation of the geological and hydrogeological conditions.

2.3.1. Hydraulic confinement criterion

We aim here to ensure that the galleries are perfectly sealed so that the LPG stored in the cavern does not escape through the cracks in the rock and concrete. *Xue et al. (2022)* [5] demonstrated that if the water pressure at the top of the cavern is higher than the LPG storage pressure, the stored product remains confined within the gallery. Figure 5 below shows the ideal case of pressure distribution, including hydraulic pressures and gas pressures (where the construction of a water curtain is not necessary). The blue curve represents the hydrostatic distribution due to the natural water table (water level Dlw). The orange curve represents the equivalent hydrostatic distribution of the gas/liquid contained in the cavern (Equivalent pressure head Heg). The gas/liquid is confined if the equivalent hydrostatic distribution is lower than the pressure exerted by the water in the ground (including the safety margin). However, if this is not the case, the construction of a water curtain is required. The sealing

criterion then remains the same: the equivalent hydrostatic distribution must be lower than the pressure exerted by the water in the ground (including the safety margin) and that added by the water curtain.

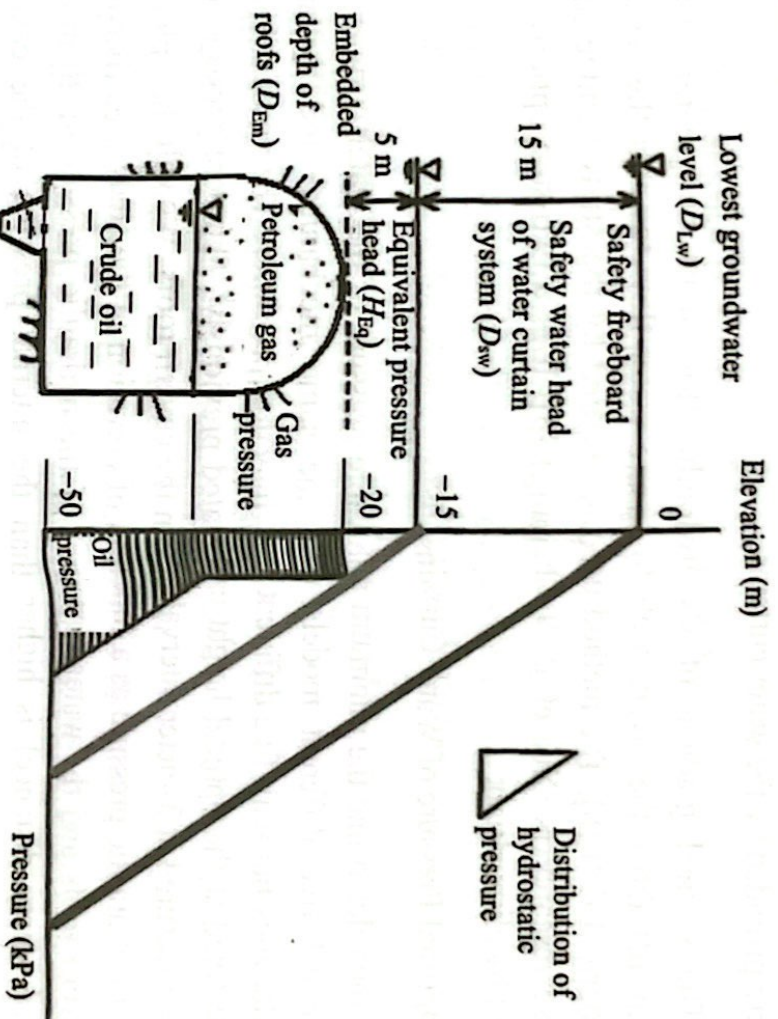


Figure 5. Ideal case of hydraulic confinement (without water curtain)

This graph, taken from a Chinese study titled “*Design and operation problems related to water curtain system for underground water-sealed oil storage caverns*” conducted by Z. Li et al. in 2016, indicates a safety water head of 15 m (safety water head of water curtain system D_{sw}). However, more recent studies recommend a safety water head of 20 m. If the water curtain is too close to the gallery, it could affect the stability of the cavern elements and deteriorate the mechanical properties of the rocks. The confinement criterion that we will use in our analysis will be as follows:

The water pressure at 20 m above the top of the storage caverns must be higher than the LPG storage pressure. This criterion was demonstrated by the researcher Aberg in 1978 [6] and is used in most studies concerning the confinement of underground storage caverns. Other criteria to ensure the stability of the cavern and the functioning of the water curtain have been used by Norwegian and Swedish researchers and have been reused in other studies. The study also applied the following two criteria:

- To prevent excessive deformation, which could deteriorate the mechanical properties of the rocks (and increase the size and number of existing cracks), the minor principal stress around the cavern must be higher than the hydraulic pressure provided by the water curtains.

- The vertical gradient of the hydraulic flow must be greater than 1 (downward) above the cavern roofs to ensure water flow towards the caverns. (B. Aberg, 1978) [8]. The method used is inspired by the study conducted by Chinese researchers (Xue et al. /J Zhejiang) [5]. It is a two-step optimization process by elimination:

- Optimal Pressure of Water Curtains

To then determine the minimum allowable pressure of the water curtains, we will model five different models with the same mechanical and hydraulic characteristics but with five different WC injection pressures. The vertical height will be fixed at the optimal height calculated previously. The pore pressure will then be measured at 3-meter intervals from the cavern roofs. We will then plot the curves of hydraulic pressure as a function of elevation in the study area (between the cavern roofs and the water curtains). If the hydraulic pressure at 20 m (the imposed safety distance) is higher than the internal pressure of the caverns (exerted by the pressurized LPG), then the confinement criterion is met, and the minimum pressure meeting the criterion is the optimal pressure. However, the injected pressure in the system must be as low as possible. Indeed, if more water than necessary is injected around the galleries, the costs of drainage and injection will increase. Additionally, the rock mass parameters could be deteriorated, and criterion (2) would no longer be met. However, the injected pressure in the system must be as low as possible. Indeed, if more water than necessary is injected around the galleries, the costs of drainage and injection will increase. Additionally, the rock mass parameters could be deteriorated, and criterion (2) would no longer be met.

2.3.2. Method for calculating the equivalent water head for the water curtain

The version of the RS2 software that I had available was quite old (2011). It does not allow the direct application of a water pressure value along the entire length of the water curtain boreholes. The only available options were to apply zero pressure (which is not suitable here) or to apply a water height on the model elements. We will see that this also creates problems when modeling the gas pressure at the tunnel edges. However, if we consider that the water is distributed

near the water curtains according to Pascal's law linear distribution, we can determine an equivalent water height to represent the water pressure injected into the rock.

Pascal's law is written as $P_w = \rho_w \cdot g \cdot h_w +$, soit h —

With ρ_w the water's volumic mass ($\rho_w = 1000 \text{ kg/m}^3$), g the gravitational constant ($g = 9.81 \text{ m/s}^2$), P_w the water pressure injected in the rock by the water curtain's boreholes and z the depth of the boreholes under the rock layer. This is the formula we will use to calculate the equivalent water height to input into the software to represent the water pressure injected into the water curtain.

2.3.3. Verification of the stability of the caverns after implementation of the water curtain

After finding the optimal design solution for the water curtains (optimal height above the cavern roofs and optimal pressure), we will then check the limit values of the support elements and determine whether there is rock failure or not. Rock failure is determined by the failure criterion of the model used, which in this case is the generalized Hoek-Brown model. The failure envelope of this model is given by the equation (1):

$$\sigma_1 = \sigma_3 + \sigma_c \cdot \left(m_b \cdot \frac{\sigma_3}{\sigma_c} + s \right)^a \quad (1)$$

σ_1 , the major principal stress; σ_3 , the minor principal stress; σ_c , the uniaxial compressive strength of intact rock, s and a are material parameters that depend on the GSI (Geological Strength Index) and the disturbance factor D (formulas in the appendix in the Equations 1).

To facilitate representation and ensure continuity of the model, we will use the safest rock quality class. According to Table 1 above, the predominant rock quality classes for the different sections of the project are Grade 1 and Grade 2. Therefore, we will use Grade 2 (whose characteristic values are available in Table 2). The mechanical parameters used were calculated using the Rock lab software, based on the mechanical characteristics provided in Table 2. The software allows for reliable estimations of the rock mass properties and provides visualization of the failure envelopes. The four different parameters are first estimated by the software using integrated graphs and tables. I had to input the rock type and condition, the rock quality class (RMO), and the disturbance level

during excavation. In the Cai Mep underground storage cavern project, the tunnel was excavated using tunnel boring machines, which significantly reduces the disturbance of the rock mass around the gallery. Consequently, the disturbance factor **D** was set to 0. Secondly, the software allows for the calculation of Mohr-Coulomb equivalents of the parameters used. In other words, the software calculates an equivalent cohesion and an equivalent friction angle based on the previous input parameters. I then adjusted the first set of Hoek-Brown model parameters calculated by the software with the estimates derived from the included tables and graphs to match the values provided in the geological report (**Table 2**). The adjusted parameters used are provided in **Table 3** below.

Table 2. Input parameters in Rock lab

Parameter	σ_{ci} (MPa)	GSI	m	D	E_r (MPa)
Value	220	70	6	0	31300

Table 3. Parameters of the failure Hoek-Brown criterion (calculated by Rocklab)

Hoek Brown failure criterion				
Value	2.055	0.0357	0.501	

2.3.4. Hydraulic parameters

The rock is in saturated conditions due to the presence of a water table 10 meters deep (within the rock layer). Lacking information on the hydraulic parameters of the project, we will assume the hydraulic parameters found in previous studies conducted on the same type of rock of similar quality. The permeability coefficient K_s of the rock is assumed to be (1.10 - 10) m/s. For high-quality granite (which hardly allows water to pass through), this value is quite representative as it is very low.

2.3.5. Used boundary conditions

For all the models created, I used two types of boundary conditions.

2.3.6. Boundary conditions on displacements and loads

All nodes on the lateral edges were constrained horizontally (along the x-axis). All nodes on the bottom boundary of the model were constrained both horizontally and vertically (along the x and y axes). A linear load with a value of $q = \gamma s$. h was applied to the top edge of the model to account for the weight of the soil above. This load has a value of $q = 18 \times 54,6 = 982,8 \text{ kN/m}^2$ or $= 0.9828 \text{ MPa}$. The study

did not model the soil above this rock layer here because the study focuses only on the rock mass around the galleries.

2.4. Hydraulic boundary conditions

To eliminate the effects of hydraulic flow on the edges (zero hydraulic flow), the distance between the caverns at the right and left ends and the respective edges is set to 10 times the largest diameter of the main cavern (here, 17 m). To represent tunnel drainage, a zero-pressure condition is applied at the tunnel edges (perfect drainage), where water can flow freely. This condition also allows water to exit the model (as if it were drained and then brought back to the surface). To represent the water pressure injected by the water curtain, an equivalent water height will be used. The procedure used to calculate it for the various tests has been described above. Figure 6 below shows all the hydraulic boundary conditions applied to the different borders of the model (blue points).

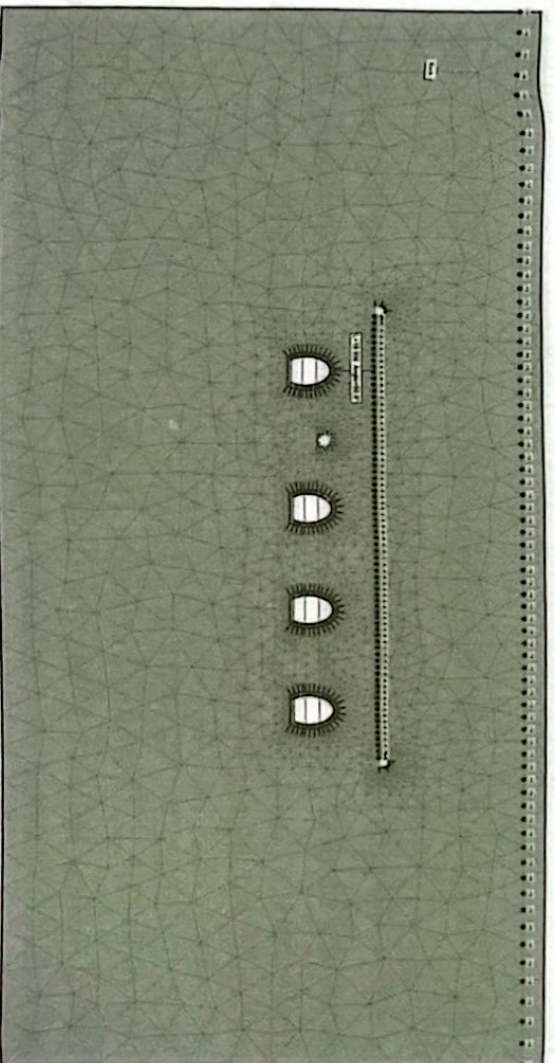


Figure 6. Model with the hydraulic boundary conditions

2.5. Results

All the analyses were conducted with the scenario where the tunnel is full (the most unfavorable case). When the tunnel is filled with LPG, it is under uniform pressure. At 30 °C (considering the temperature increase in Vietnam of $(2 \div 3)$ °C for every 100 meters of depth), LPG is generally stored at 0.8 MPa. This pressure is uniform along the internal edges of the tunnel. This value of 0.8 MPa will serve as our reference value for verifying the hydraulic confinement criterion (1). In this Results section, we will present the results of the various models, as the name suggests. The analysis of the results and the determination of optimal heights and pressures will be conducted afterward in the Analysis of the results section.



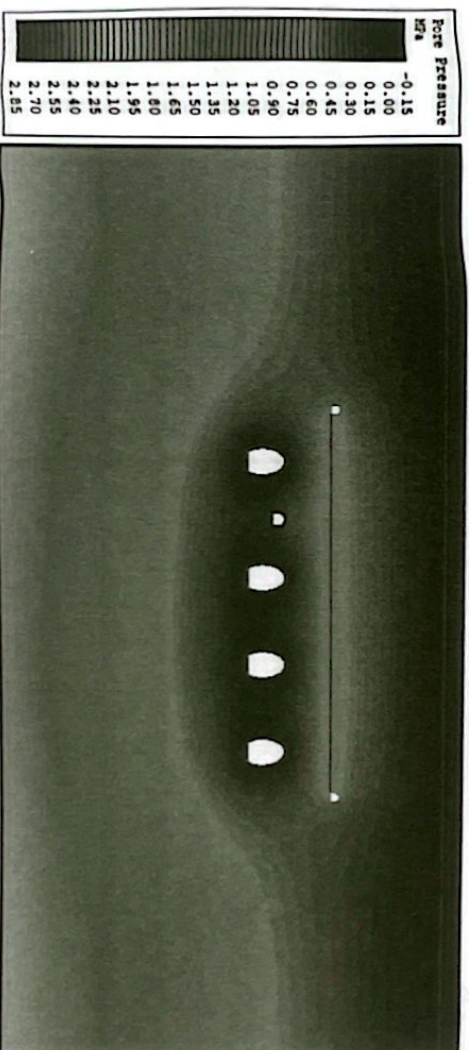
Figure 7. Pore pressure around the full caverns (without Water Curtain)

To verify the necessity of a water curtain, I modeled all the caverns by applying a water height of -16 m on the edges of the galleries (calculated using the equivalent water height method presented earlier), which represents the effect of LPG pressure in the surrounding rock mass. The Figure 7 shows the distribution of pore pressure across the entire model. The pressure calculated at a height of 20 m is 0.63 MPa. The pink line observed at the top of the figure represents the natural water table. The area of negative pore pressure above this line represents a zone where the rock is not saturated with water. This is automatically calculated by the software.

The pore pressure measured at 20 meters is lower than the LPG storage pressure (0.8 MPa). Therefore, criterion (1) is not met, and the cavern is not considered sealed without a water curtain. Following the optimization method for water curtain parameters explained in the section Optimization method used will now determine the maximum height of the water curtain and the optimal water curtain pressure (WCP).

3. Optimal water curtain pressure (wcp)

The height between the water curtains and the cavern roofs is set to 25 m. The pressure of the water curtains (referred to as WCP hereafter) was set to 0.5, 0.75, 1, 1.25, and 1.5 MPa, respectively. This pressure is the one injected into the tunnels (and boreholes) of the water curtains. Here, the study will be used the result found to set the optimal height of our water curtains, the height between the water curtains and the cavern roofs is thus set to 25 m.



1

1.25



Table 8. Distribution of pore pressure at different WCP (elevation = 25m)

4. Analysis of the results

This section deals with a parametric study conducted based on the results presented above. Measurements were taken on the 3rd tunnel from the right. The lowest hydraulic pressure (pore pressure) was observed around this tunnel during the tests, due to its location. The pore pressure against elevation is plotted on Figure 9, with measurement points taken every 3 meters (starting from the cavern roof).

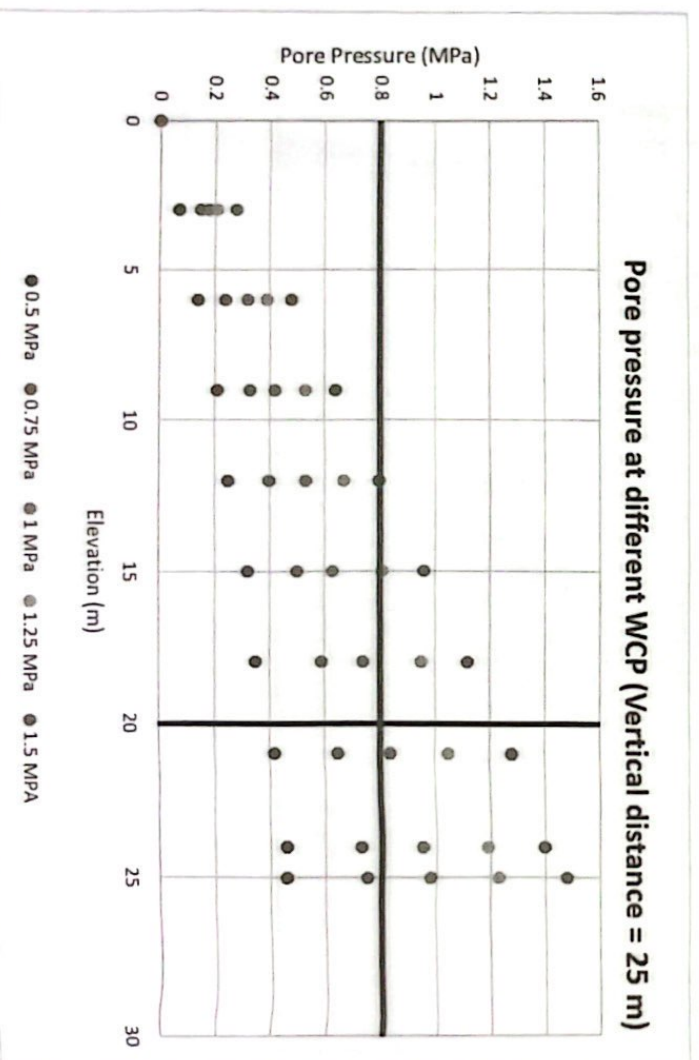


Figure 9. Pore pressure at different WCP (Vertical distance = 25 m)

The hydraulic pressures recorded at 20 meters for WCPs ranging from 0.5 MPa to 1.5 MPa are 0.4 MPa, 0.61 MPa, 0.8 MPa, 1 MPa, and 1.2 MPa, respectively.

The internal pressure of the cavern is 0.8 MPa; with WCPs of 0.5 MPa and 0.75 MPa, the sealing of the cavern would not be ensured.

5. Conclusion

In this study, a numerical analysis using finite element software has been conducted to investigate the stability of (LPG) storage cavern during change water curtain pressure in the (LPG) storage cavern in hard rock. Some interesting conclusions arising from numerical simulations are given: Based on the technical design with the temporary rock support of bolt pattern and shotcrete liner, rock support of concrete, the output conditions of the design model, the stability of (LPG) storage cavern and the system of caverns has been conducted by RocScience-RS₂. The result of model shows that the maximum displacement of the system of caverns is performed based on rock property in the site geology investigation report. The value of stress and force of rock support are smaller than allowable values. This study deals with a parametric study conducted based on the results presented above. Measurements were taken on the 3rd tunnel from the right. The lowest hydraulic pressure (pore pressure) was observed around this tunnel during the tests, due to its location. It allows the calculation of tunnels and caverns according to different load combinations to ensure the highest safety of underground above construction systems.

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