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Research on the effect of groundwater flow in underground storage caverns

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Abstract: *Cai Mep underground storage cavern was constructed at a depth of approximately 150 meters in hard rock in Ba Ria-Vung Tau province, Vietnam. Geological analyses of the site were conducted by the Korean company HYOSUNG, which was also responsible for the construction. The site consists primarily of granite, present in various conditions, ranging from class 1 (very good condition) to class 5 (poor condition) on the RMR scale. The result of this 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 study result provides a reliable way to analyze the effect of Groundwater Flow in the (LPG) storage cavern and also will help to design or optimize the subsequent support.*

Keywords: *deformation, stress, plastic areas, storage caverns, groundwater flow*

1. Introduction

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 city in Vietnam, Ho Chi Min city, it can provides a competitive storage and a good ditribution in all the city [2-4].

In this paper, the stability analysis was carried out based on those parameters by using 2D FEM Phase^2 program. The calculated stress and displacements of surrounding rock and rock support by FEM analysis the effect of groundwater flow in underground storage caverns. The pattern of deformation, stress state, and the distribution of plastic areas are analyzed. Finally, the whole stability of surrounding rock mass of underground caverns was evaluated by RocScience -RS2- Phase^2 software. The calculated axial forces were far below design capacity of rock bolts. The strong rock mass strength and high horizontal to vertical stress ratio enhanced safe working condition throughout the excavation period. Thus wide span caverns and the system of coverns could be stabilityly excavated sedimentary rock during the underground cavern and the system of coverns excavation by blasting method. The new method provides a reliable way to analyze the stability of the caverns and the system of coverns and also will helpful to design or optimize the subsequent support.

2. Geological background

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. The site consists primarily of granite, present in various conditions, ranging from class 1 (very good condition) to class 5 (poor condition) on the RMR.

An additional soil layer lies above the rock mass. This layer is 54.6 meters thick and has an average bulk density of γg = 18 kN/m. 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 has been performed. The predominant RMR (Rock Mass Rating) classes for each section of the tunnel, from Section A (Access

Tunnel) to Section G (Operation Shaft) (**Error! Reference source not found.**) are provided in **Error! Reference source not found.**. Soil & Rock Properties in the project is presented on Table 2.

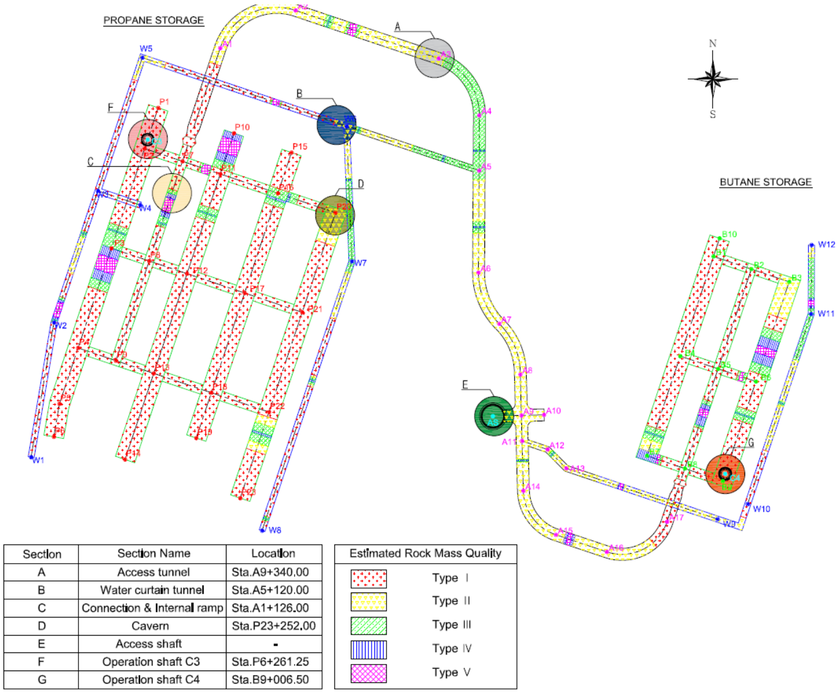

Fig. 1. Storage cave plan with Rock Mass Quality rating [1]

below. **Tab. 1.** The predominant RMR classes for each section of the tunnel [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

Tab. 2. Soil & Rock Properties [1]

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

A set of shotcrete liners and a rock bolt pattern were used to improve the mechanical stability of the gallery. The different properties of the support elements are available in the **Table 3** below. The elements were sized according to each type of gallery (different characteristics for sections B, C, and D of the model).

Tab. 3. Support Pattern of caverns [1]

Division	Support Pattern		I [> 40]	II [40~10]	III [10~4]	IV [4~1]	V [1~0.1]
Cavern (17x22) m	Shotcrete [cm]	Thickness	5.0 (S)	5.0 (Sfr)	6.0 (Sfr)	12.0 (Sfr)	20.0 (Sfr)
	Rock bolting	Spacing	Spot bolting	1bt/5.0㎡	1bt/4.0㎡	1bt/2.0㎡	1bt/1.0㎡
		Length	4.85 m				

3. Methodology

As indicated in Error! Reference source not found., the storage cavern is divided into three main sections to facilitate orientation, each representing different types of tunnels with various geometries. Each type of tunnel has uniform dimensions (e.g., Section D (Cavern) has the same dimensions for both the butane and propane areas) with height : 256 m, length : 521 m. This study will focus on the cross-section marked as S (in black dotted lines) on Error! Reference source not found.. The dimensions of this section, which correspond to the geometry of the model discussed later, are provided below in Error! Reference source not found..

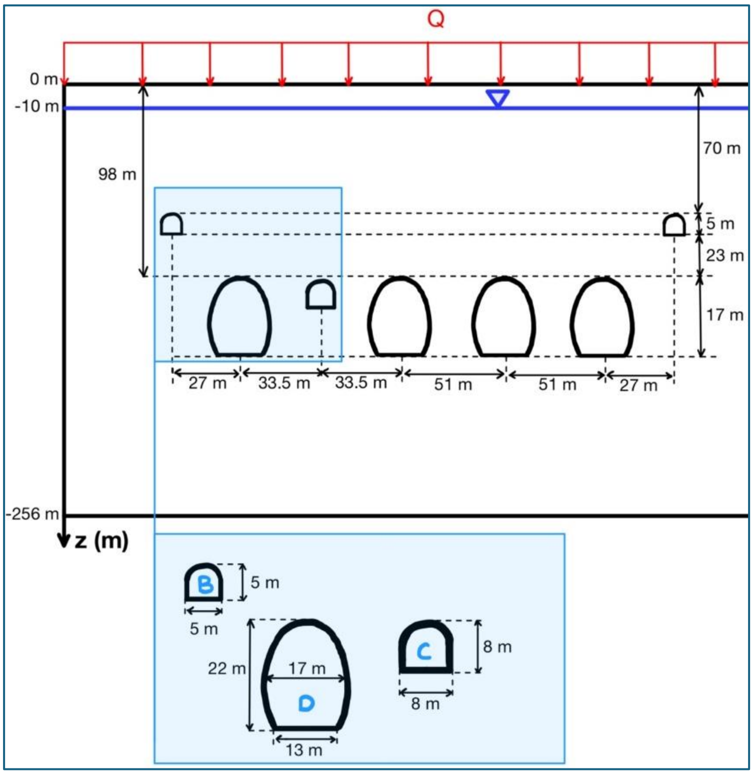

Fig. 2. Dimension of the models

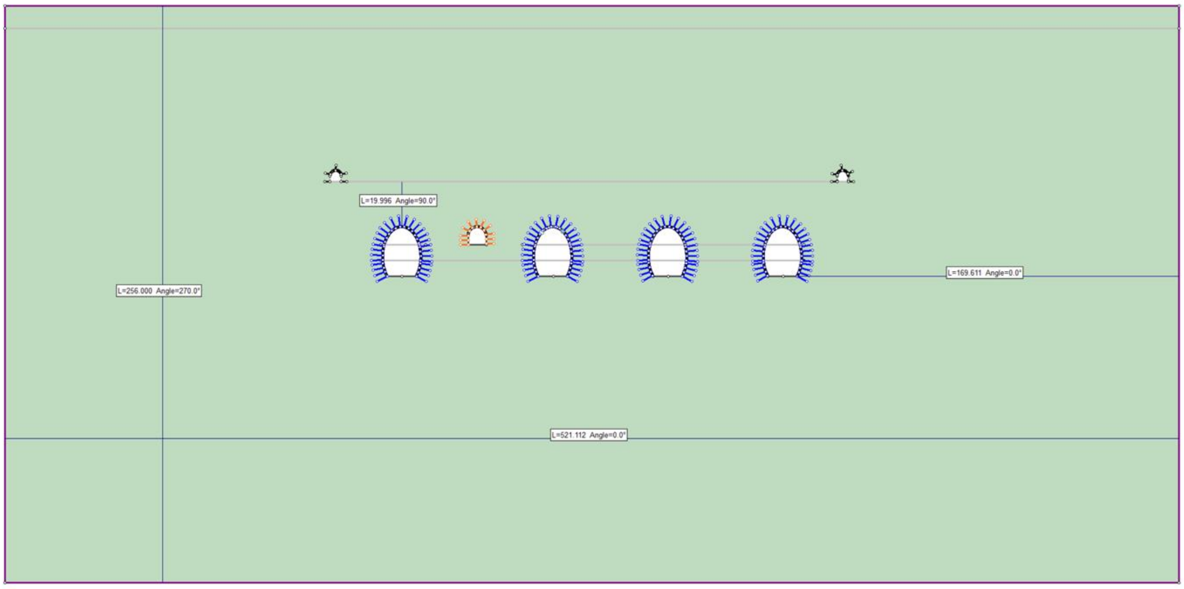

Fig. 3. Mesh, and boundary condition of the models

In the model, only the sections labeled B, C, and D will be included, as indicated in **Figure 3.**

3. Failure criterium

The RocScience Phase 2 software offers several mechanical representation models for rocks, including the Mohr-Coulomb, Hoek-Brown, and Cam-Clay models, each providing a specific failure criterion. The Hoek-Brown model is the most commonly 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 takes into account 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 suitable for sandy or gravelly soils, and therefore does not apply to our case. Similarly, the Cam-Clay model is used for clayey 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 envelope of the failure criterion based on the state of fracturing of the rock and the quality of the rock mass. This parameter is calculated from the Geological Strength Index (GSI) and the tunnel disturbance parameter (D). The D parameter depends on the excavation method : when it is close to 0, the tunnel was excavated without altering the quality of the rock; when it is equal to 0.8, the tunnel was heavily deteriorated due to the excavation method, for example, the use of explosives. This model allows for the integration of the presence of faults in the rock mass, thus offering a more accurate representation of the geological and hydrogeological conditions**.**

3.1. Water confinement criterium

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.

Studies have shown that if the pressure exerted by the water at the roof of the cavern is greater than the storage pressure of the LPG, the stored product is confined within the gallery.

The Figure 4 below represents the ideal case of the distribution of 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 aquifer (water height Dlw). The orange curve represents the equivalent hydrostatic distribution of the gas/liquid contained in the cavern (Equivalent pressure head Heq).

The contained gas/liquid is confined if the equivalent hydrostatic distribution is lower than the pressure exerted by the water present in the soil (including the safety margin). However, if this is not the case, the construction of a water curtain is required. The sealing criterion remains the same; the equivalent hydrostatic distribution must be lower than the pressure exerted by the water present in the soil (including the safety margin) and the additional pressure provided by the water curtain.

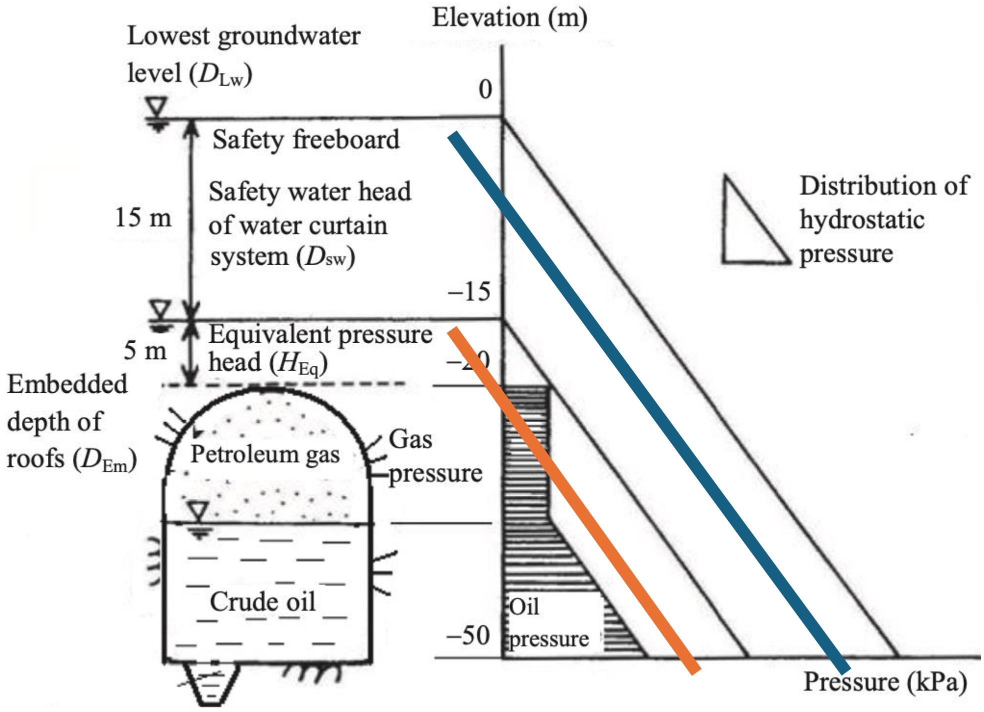

Fig. 4. Location depth of underground water-sealed oil storage cavern [5]

This graph, taken from [5], indicates a safety water head of 15 m (safety water head of water curtain system Dsw). However, more recent studies recommend a safety water head of 20 m. If the water curtain is too close to the gallery, it could impact the stability of the cavern elements and deteriorate the mechanical characteristics of the rocks. The confinement criterion that we will use in our analysis is therefore the water pressure 20 m above the roof of the storage caverns must be greater than the storage pressure of the gas. This criterion was demonstrated by researcher (Aberg, 1977) [6] and is used in most studies concerning the confinement of underground storage caverns).

3.2. Other criteriums

Other criteria to ensure the stability of the cavern and the functioning of the water curtain are used by Norwegian and Swedish researchers and reused in other studies. We will additionally use the following two criteria. Flowchart of the study is presented on Figure 5.

(1) 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 must be greater than the hydraulic pressure around the cavern (Bjørn Nilsen, 2021) [7]

(2) The vertical hydraulic flow gradient must be greater than 1 (downward) above the roof of the caverns to ensure water flow towards the caverns (B. Aberg, 1977) [6].

3.3.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. It can 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, it can be determined an equivalent water height to represent the water pressure injected into the rock.

Pascal's law is written as $Pw = \rho w.\, g.\, hw + z$, i.e. $h_{eq} = \frac{P_w - z}{P_w g}$

With ρ_w the water's volumic mass (ρ_w = 1000 kg/m^3), g the gravitational constant (g = 9.81 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.

After finding the optimal design solution for the water curtains (optimal height above the cavern roofs and optimal pressure), it can be then checked 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) [4]:

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

Where : σ_1 , the major main constraint ; σ_3 , the minor principal stress ; σ_c , the uniaxial compressive strength of the intact rock ; m_b , s and a are material parameters that depend on the GSI and the disturbance index D (formulas in the appendix) (D = 0 , no perturbation D = 0.8 maximum perturbation) [4];

$$m_b = m_i . \exp\left(\frac{GSI-100}{28-14.D}\right) ; s = exp\left(\frac{GSI-100}{9-3D}\right) ; a = 0{,}5 + \frac{1}{6} . \left(e^{-\frac{GSI}{5}} - e^{-\frac{20}{3}}\right)$$

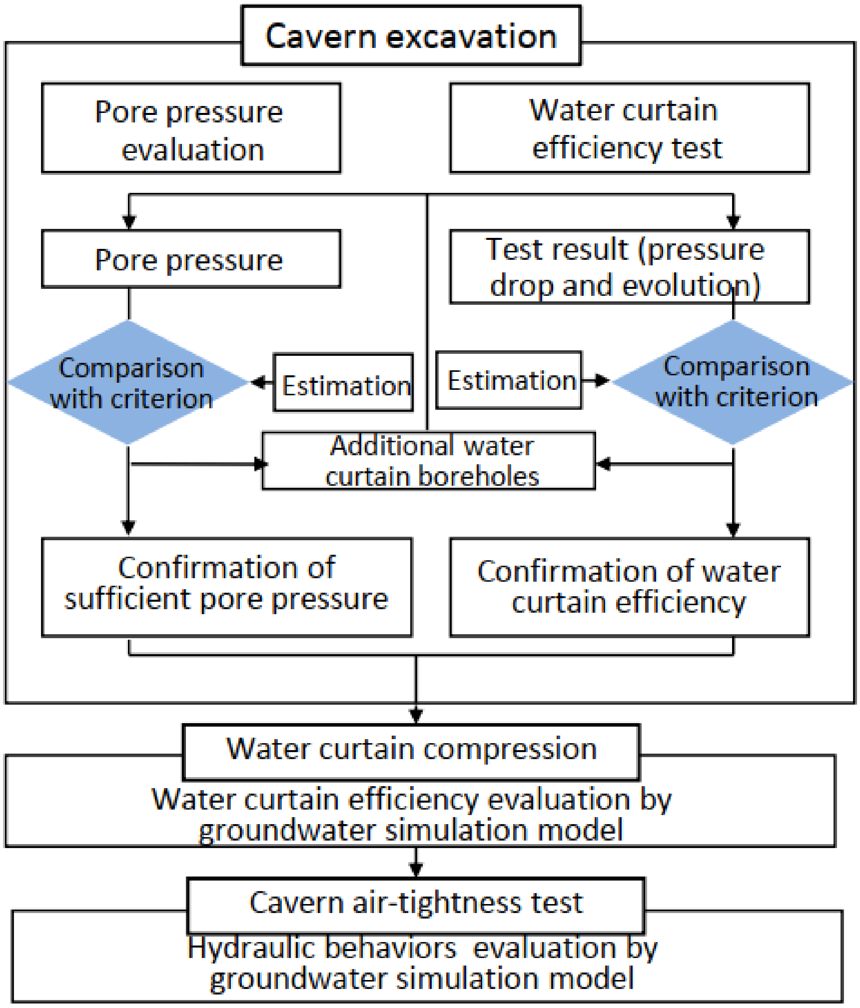

Fig. 5. Flowchart of the study

To facilitate representation and ensure continuity of the model, the safest rock quality class is used in this study. 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. The rock type and condition, the rock quality class (RMQ), and the disturbance level during excavation is put in the model. 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. The study 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 4**) . The adjusted parameters used are provided in **Table 5** below:

Tab. 4. Input parameters in Rock lab

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

Tab. 5. Parameters of the failure Hoek-Brown criterion (calculated by Rocklab)

Hoek Brown failure criterium	**mb**	**s**	**a**
Value	2.055	0.0357	0.501

3.4.Hydraulical 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, the hydraulic parameters found in previous studies conducted on the same type of rock of similar quality is assumed for the hydraulic parameter of this study. The permeability coefficient Ks 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.

3.5. Used boundary conditions

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

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 . 54,6 = 982,8 kN/m^2 or = 0.9828 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.

3.7.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 and Figure 7 below show all the hydraulic boundary conditions applied to the different borders of the model (blue points). 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.

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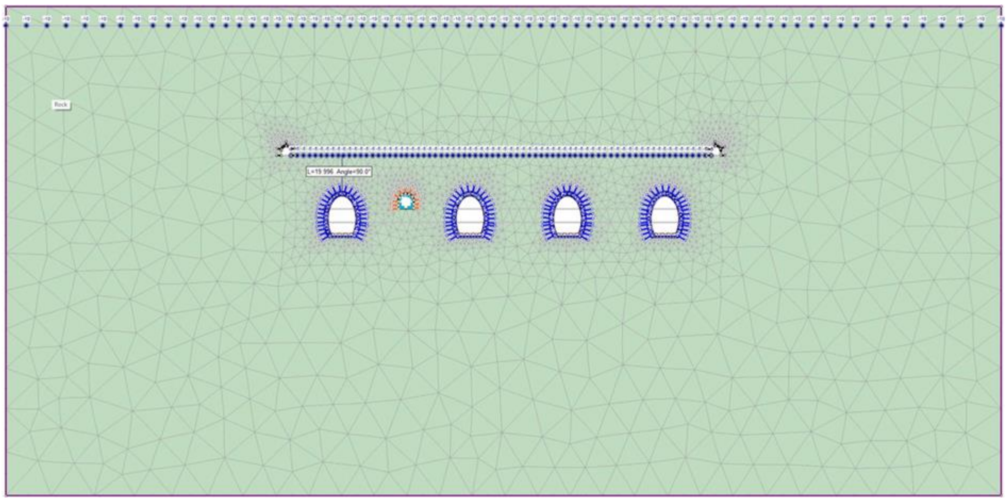

Fig. 6. Model with the hydraulic boundary conditions

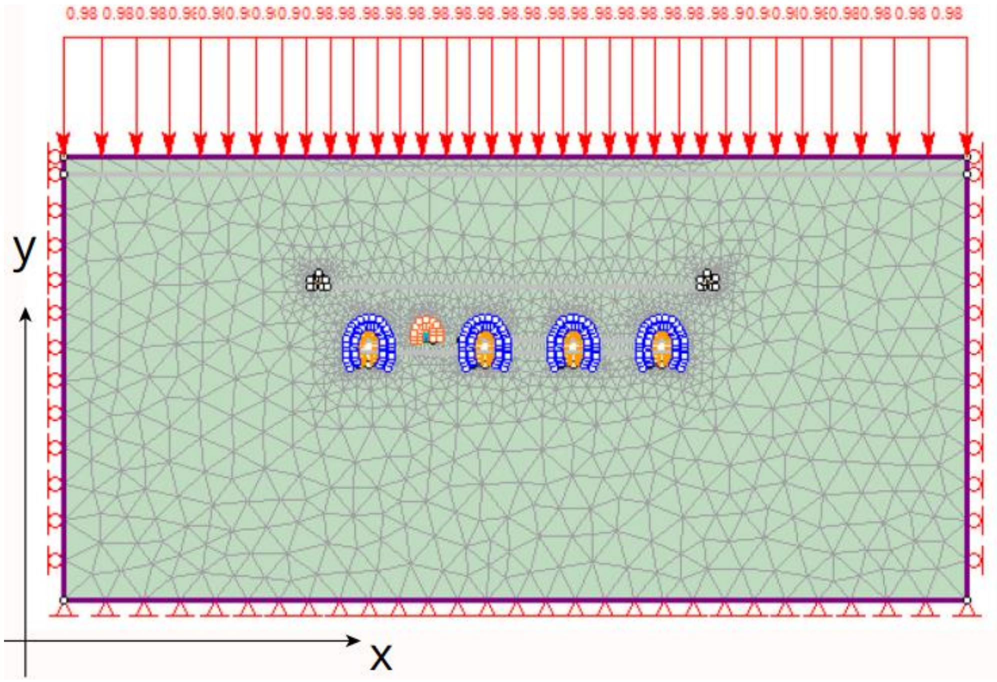

Fig. 7. Boundaries conditions of numerical model

3.8.Boundaries conditions

All laterals nodes bloqued horizontally (along the x-axis). All lower nodes bloqued both horizontally and vertically (along the x and y axes). Linear loading (cavern, water curtain tunnels and upper soil).

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 to 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.

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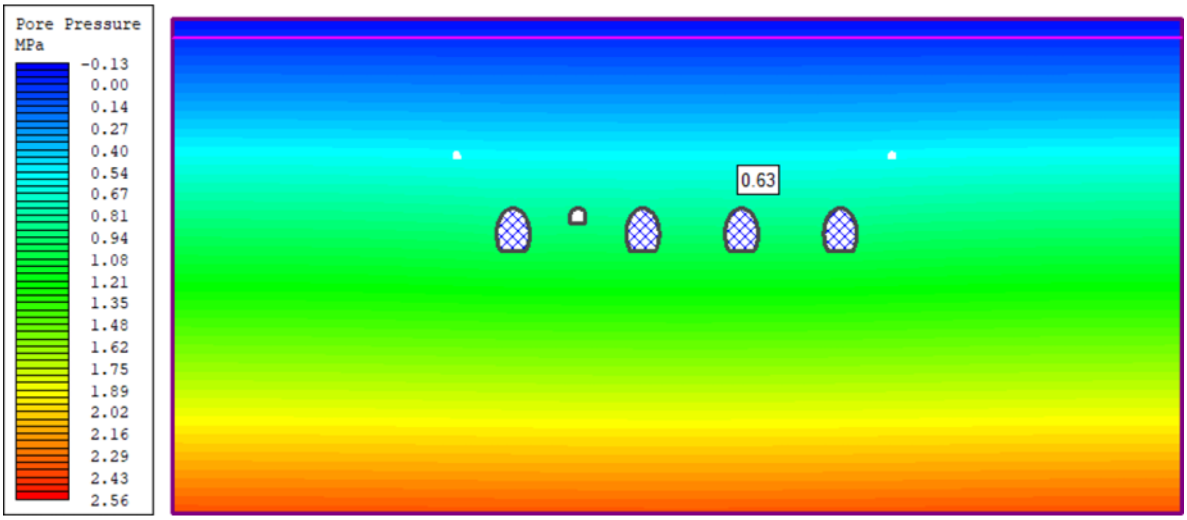
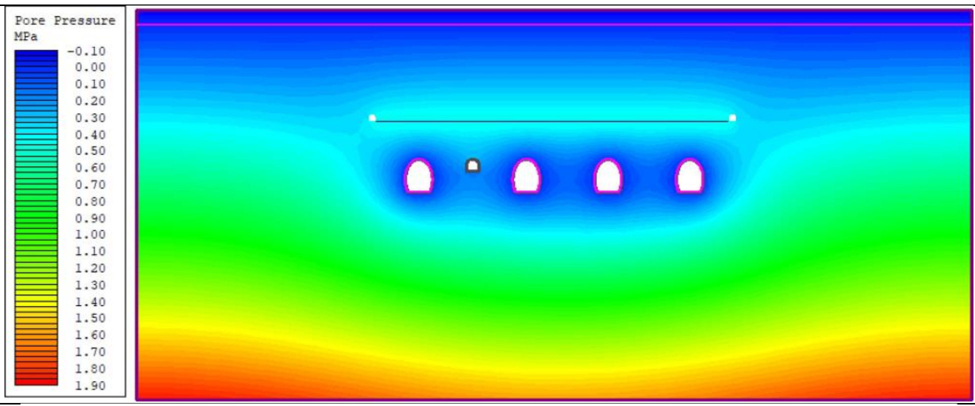
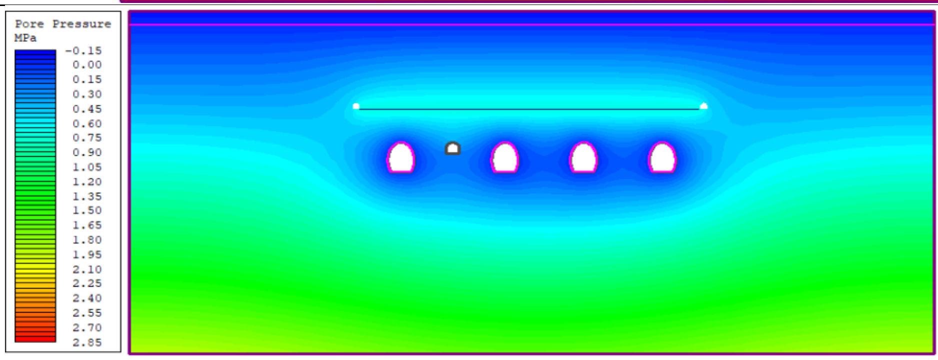


Fig. 8. Pore pressure around the full caverns (without Water Curtain)

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 8 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).

4. 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.

	0.5
	0.75

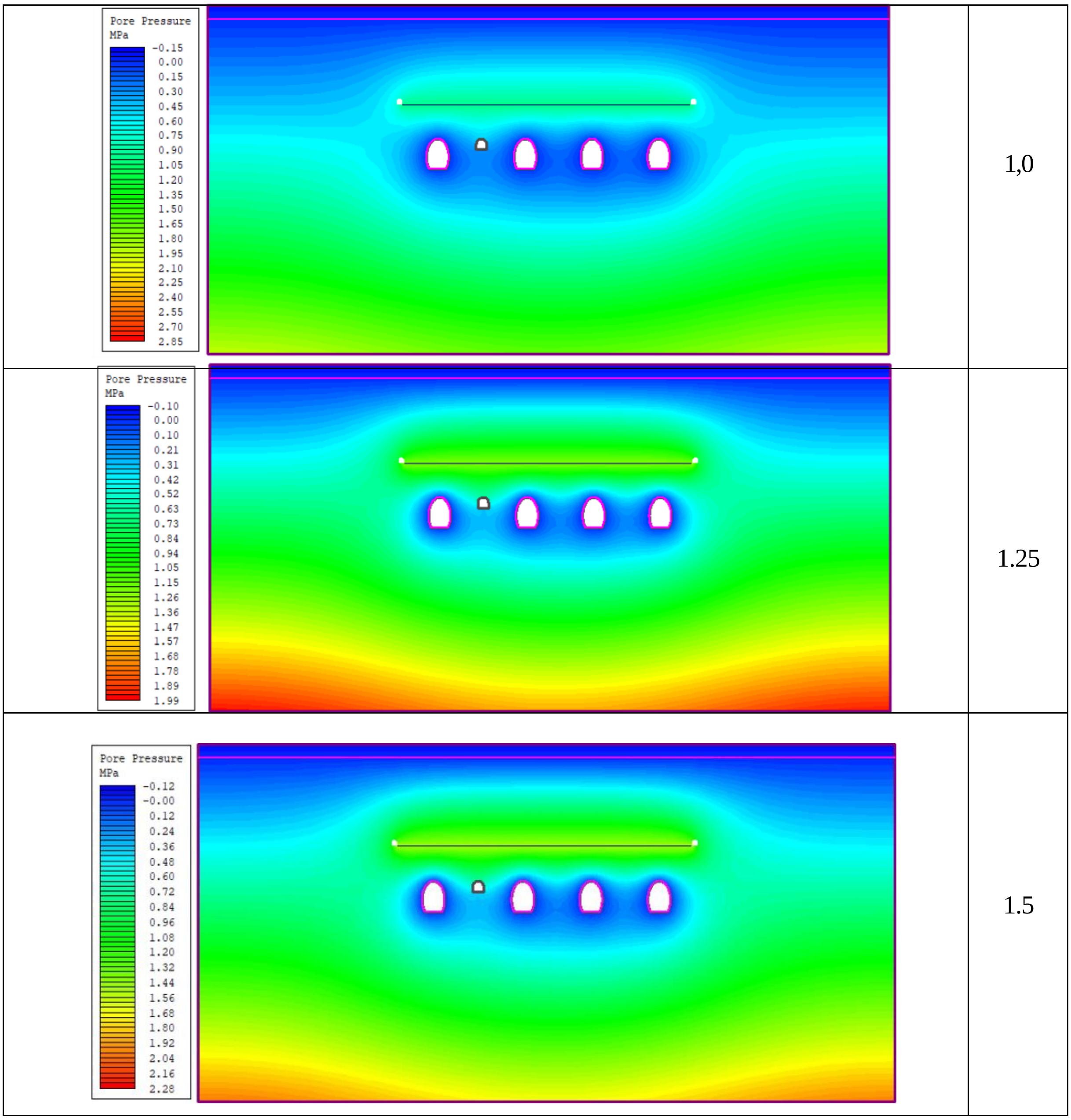


Fig. 9. The result of hydraulic pressure (pore pressure) with different water curtains pressures

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).

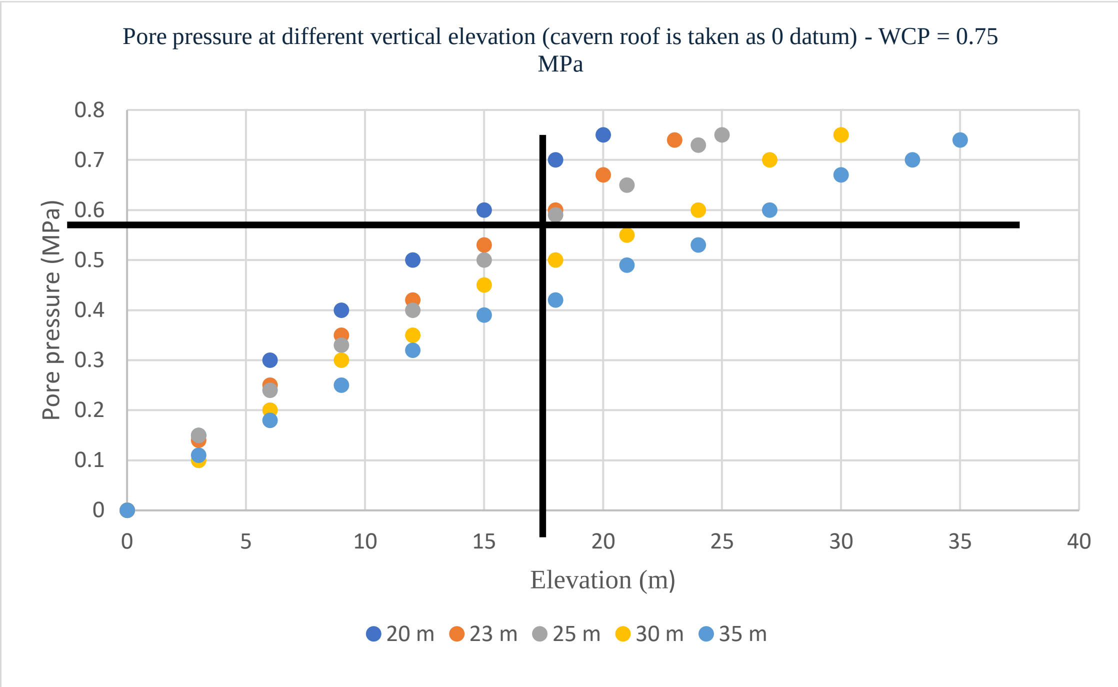


Fig. 10. Pore pressure at different vertical elevation -WCP = 0.75 MPa

The measurement was carried out on the 3rd caver from the right. It is around this tunnel that the lowest hydraulic pressure was observed during the tests (due to its location). The section used has a thickness of 1 m.

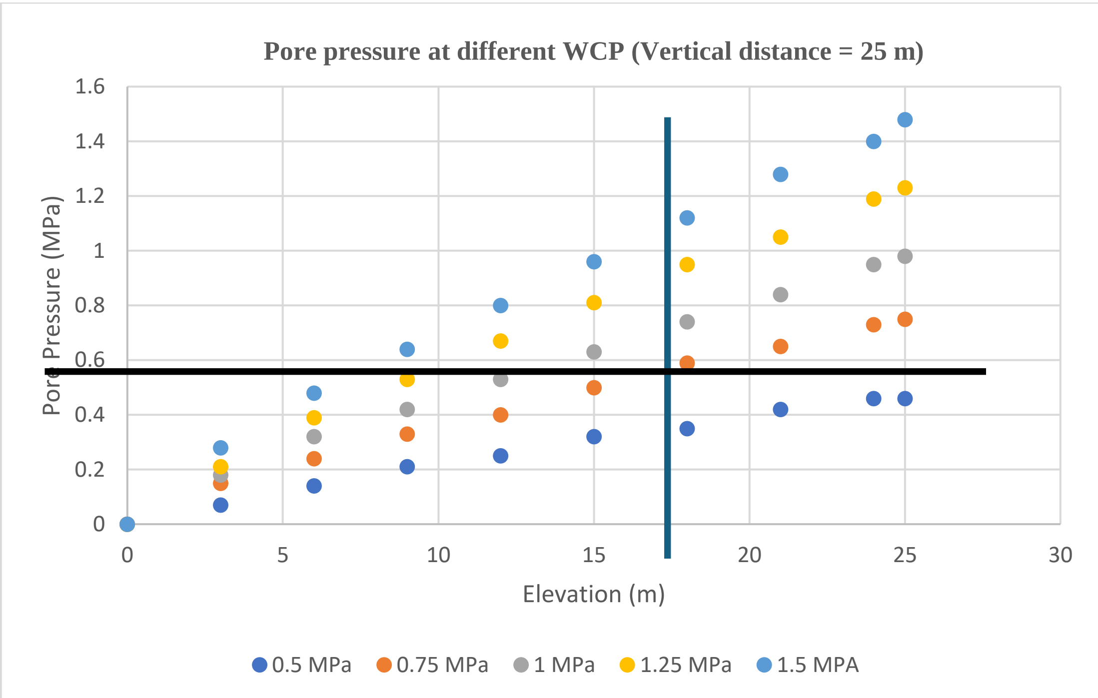


Fig. 11. Pore pressure at different WCP (Vertical distance = 25 m)

The hydraulic pressures measured at 20 m for WCPs from 0.5 MPa to 1.5 MPa m are respectively 0.4 MPa, 0.61 MPa, 0.8 MPa, 1.0 MPa and 1.2 MPa. WCPs of 0.5 MPa and 0.75 MPa are therefore not suitable. The WCP of 1 MPa is the most suitable (the lowest) and meets the criterion. The optimal solution for operating the water curtain with the characteristics decided above is suitable with WCP = 1 Mpa and height between the roof of the cavern and the WC = 25 m.

5. Stability of the cavern

The addition of a water curtain is beneficial for the proper sealing of an underground tunnel but can cause stability issues due to the presence of water flow around the tunnels. After determining the constructive solutions for achieving optimal hydraulic confinement, we will now verify that the caverns remain stable. The other characteristics of the model (mechanical and hydraulic boundary conditions, cavern layout, etc.) remain the same as before.

5.1. Yielded elements

Figure 12 below shows the plasticity of the rock elements according to the chosen failure criterion, which in this case is the Generalized Hoek-Brown criterion. The scale (in percentage) represents the percentage of plasticity of the elements, ranging from 0% (no plasticity) to 100% (maximum plasticity of the elements). The rock used in the model is of very high quality (Good quality granite on the RMQ scale). All rock elements in the model exhibit very low plasticity (between 0% and 2% yielded elements). Therefore, all elements remain within an elastic zone and can still support additional loads before reaching their plasticity limit. Thus, no stability issues are observed on the side of the rock mass.

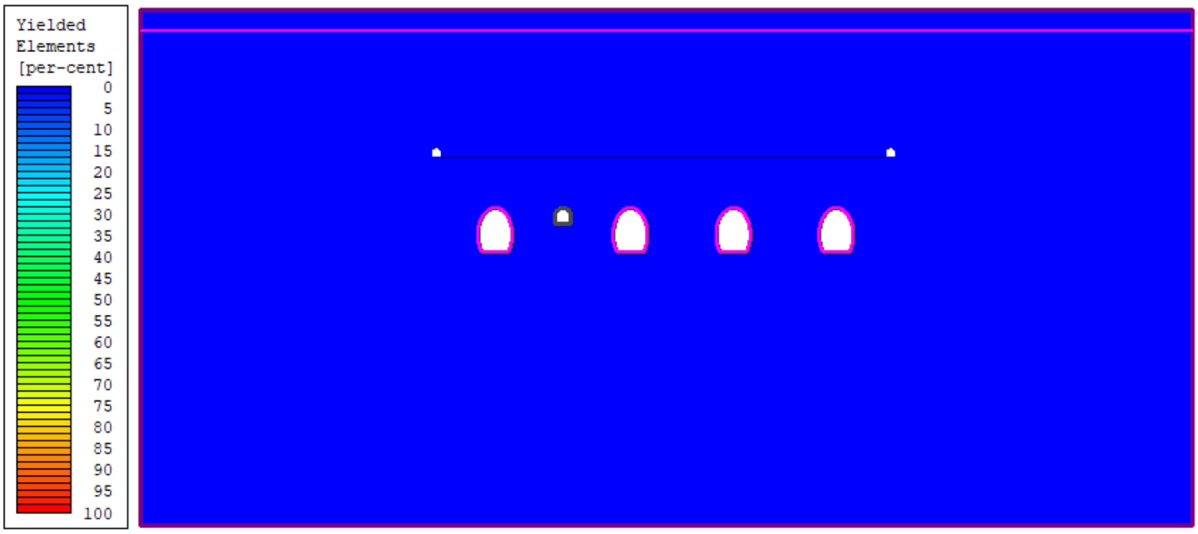


Fig. 12. Yielded elements of the model

5.2.Verification of criterion (2) - sigma 3

Criterion (2) presented earlier suggests that the minor principal stress, sigma 3, around the gallery should be lower than the hydraulic pressure provided by the water curtain to prevent further opening of cracks in the rock. In Figure 13 below, we observe that the sigma 3 stress is zero around the caverns. This is due to the application of a perfect drainage condition around the gallery. We will analyze the sigma 3 stress values within a 1-meter zone around the cavern to assess this criterion, considering the effect of drainage.

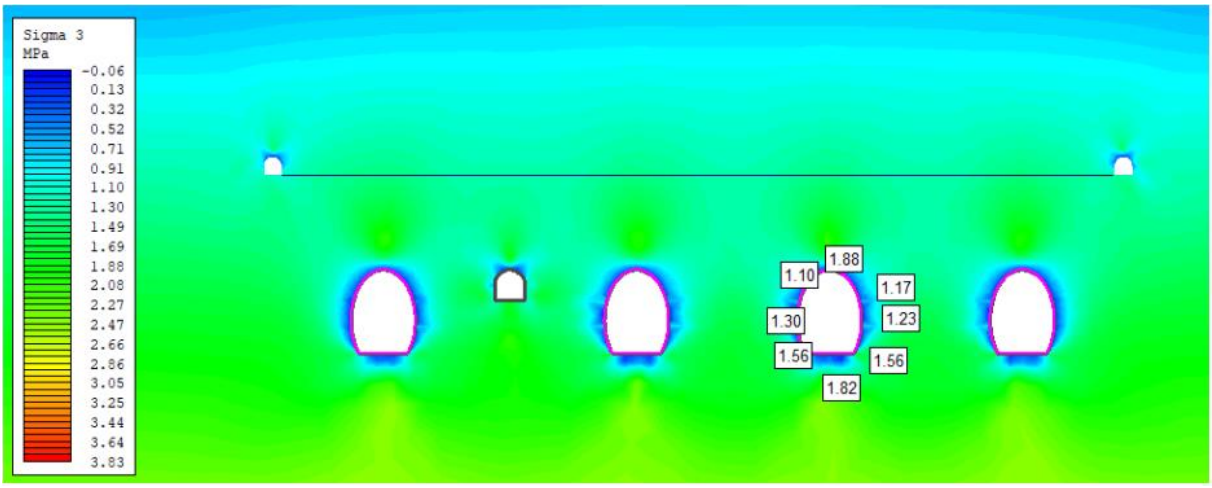


Fig. 13. Distribution of the minor principal stress around the model

In a 1-meter zone (still around the third cavern), the lowest observed minor principal stress, sigma 3, is 1.1 MPa. According to criterion (2), such a distribution of sigma 3 stress helps prevent the opening of cracks in the rock (at least within a 1-meter zone around the cavern). This condition also helps ensure good sealing (if the cracks tend not to open, the stored LPG will have more difficulty escaping).

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5.3.Verification of criterion (3) - vertical hydraulic gradient

Figure 14 below shows the distribution of pore pressure on our section and also allows us to observe the general hydraulic flow (purple arrows). It is noted that the water flow is indeed directed towards the interior of the caverns, which is essential to ensure the proper sealing of the system. **Figure 15** below shows the distribution of the vertical hydraulic gradient across the entire S section. The hydraulic gradient appears relatively constant in the elements furthest from the tunnels.

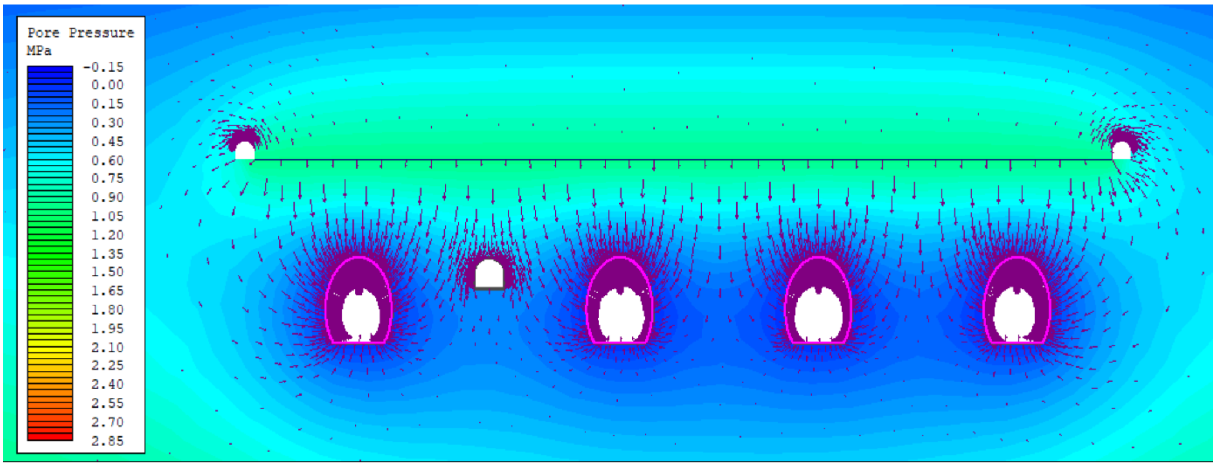

Fig. 14. Water flow around the caverns

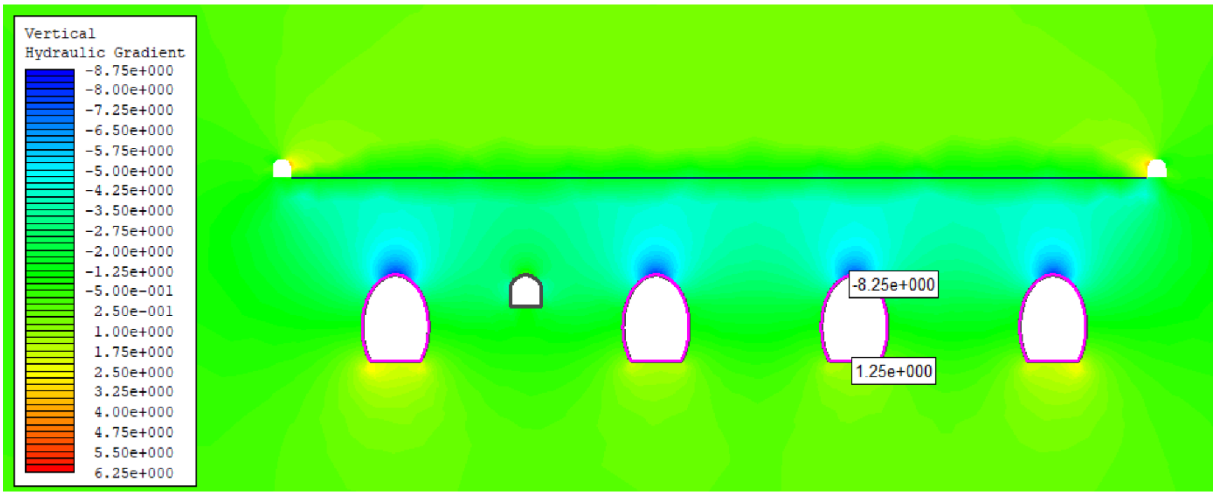

Fig. 15. Vertical hydraulic Gradient around the caverns

At the tunnel roofs (measurement is taken at the roof of tunnel 3, the most unfavorable), the hydraulic gradient is negative and equals i = -8.25 (dimensionless). This negative gradient results from the fact that the zero depth (z = 0 m) is located at the top of the model, and depths are then indicated with a negative symbol. As can be seen in Figure …, the arrows representing the hydraulic flow are directed inward, confirming that the gradient is oriented in the correct direction. Consequently, the hydraulic gradient at the bottom of the cavern changes sign; it enters the cavern but from below. Thus, the hydraulic gradient at the cavern roofs is indeed downward and greater than 1 (or less than 1 if we consider the chosen sign); criterion (3) is also met.

5.4. Verification of the support elements

First, the displacements of the rock mass around the caverns is analyzed. Table 8 below shows the maximum observed horizontal and vertical displacements. These were recorded in three different cases to highlight the role of the water curtain. Table 6 below shows the maximum observed horizontal and vertical displacements. These were recorded in three different cases to highlight the role of the water curtain.

Tab. 6. Maximum displacements observed in 3 different cases

	Displacement of rock mass (with Water Curtain)	**Displacement of rock mass (without Water Curtain) - Joséphine [8]**	**Displacement of rock mass (without water curtain – cavern full)**

Caverns	Horizontal displacement (mm)	Vertical displacement (mm)	Horizontal displacement (mm)	Vertical displacement (mm)	Horizontal displacement (mm)	Vertical displacement (mm)
	0.2	5.1	0.7	5.25	1.35	12.3

The first column shows the horizontal and vertical displacements observed in the model incorporating the optimized water curtain. The second column indicates the displacements calculated by Joséphine Donnard in her report. These represent the case without water curtains, without drainage, and with empty caverns. The third column shows the displacements in the case without water curtains but with the cavern full (under 0.8 MPa pressure).

In Table 6, it can be observed that the displacements with the water curtain (columns 1 and 2) are lower than those without the water curtain. This difference can be explained by two reasons. The first reason is that Joséphine [8] did not pressurize the tunnels. To demonstrate the effect of internal tunnel pressure, this table shows the displacements without a water curtain but with pressurized caverns. These are significantly higher compared to the other cases (seven times higher for the maximum horizontal displacement and twice as high for the maximum vertical displacement). Without water curtains to balance the external pressure (exerted by water and rocks) with the internal pressure (exerted by the pressurized LPG), the very high internal pressure significantly increases displacements. The second reason was mentioned in the previous paragraph. Although the internal gas pressure is high, it is compensated by the pressure from the water curtain, reducing the displacements of the rock mass but increasing the forces on the support elements. Table 7 below shows the maximum values of the different forces within the support elements. These were calculated using the RocScience Phase 2 software, which allows us to display the most stressed elements. The maximum values of the elements are higher than those in the case without a water curtain analyzed by Joséphine [8] but remain below the limit value.

Tab. 7. Verification of the support elements

Caverns	Concrete			
	Max Compressive Stress (MPa)	Allowable Value (MPa)	Max bending stress (MPa)	Allowable Value (MPa)
	6.78	10.4	3.41	4.5

6. Conclusion

In conclusion, for the Cai Mep underground LPG storage cavern project, a water curtain is necessary according to the models to limit leaks of the stored product, which would prevent ecological and economic disasters.

To ensure effective hydraulic confinement while minimizing water inflow into the gallery for economic reasons, it is recommended to place the water curtains 25 meters above the cavern roof and inject water at a pressure of 1 MPa into the system's boreholes. All the criteria for the proper functioning of the confinement system, based on international studies, have been validated. This solution optimizes the stability of the cavern and the surrounding rock mass. However, the support elements are subjected to higher forces due to the addition of hydraulic pressures around the gallery, although these forces remain within the limits set by the construction company. Nonetheless, the model and the chosen solutions may be subject to criticism. Firstly, this study does not use a safety factor, unlike European or French civil engineering standards. This is due to the absence of standards adapted to the specific terrain of Vietnam. Additionally, this study relies on numerous simplifying assumptions due to a lack of information (exact topography, water table height, orientation of rock joints, precipitation not considered) and necessary simplifications to use the software (rock homogeneity, simplification of the upper soil layer modeled as a uniform load). To improve the results, it would be beneficial to conduct more detailed geological analyses, particularly on rock joints, which strongly influence water behavior. Integrating different types of rocks while ensuring the continuity of the model would provide flow analysis results closer to reality, as lower- quality rock is generally more water-conductive and influences hydraulic flows. Finally, it is important to use a monitoring system that tracks hydraulic flows, pore pressures, and displacements around the cavern. The condition of the cavern tends to change over time, subjected to recharge/discharge cycles. If a significant abnormal variation is detected, appropriate action should be taken to prevent a disaster.

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