Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 8, No. 01, January, 2022

Numerical Simulation of the Stability of Rock Mass around Large Underground Cavern

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Received 02 October 2021; Revised 09 December 2021; Accepted 17 December 2021; Published 01 January 2022

Abstract

Geotechnical problems are complicated to the extent and cannot be expected in other areas since non-uniformities of existing discontinuous, pores in materials and various properties of the components. At present, it is extremely difficult to develop a program for tunnel analysis that considers all complicated factors. However, tunnel analysis has made remarkable growth for the past several years due to the development of numerical analysis method and computer development, given the situation that it was difficult to solve formula of elasticity, viscoelasticity, and plasticity for the dynamic feature of the ground when the constituent laws, yielding conditions of ground materials, geometrical shape and boundary conditions of the structure were simulated in the past. The stability of rock mass around an underground large cavern is the key to the construction of large-scale underground projects. In this paper, the stability analysis was carried out based on those parameters by using 2D FEM RS2 program. The calculated stress and displacements of surrounding rock and rock support by FEM analysis were compared with those allowable values. 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 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 conditions throughout the excavation period. Thus wide span caverns and the system of caverns could be stability excavated sedimentary rock during the underground cavern and the system of caverns excavation by blasting method. The new method provides a reliable way to analyze the stability of the caverns and the system of caverns and also will help to design or optimize the subsequent support.

Keywords: Large Cavern; Stability; Surrounding Rock; Cai Mep; Numerical Analysis; RS2.

1. Introduction

Cai Mep Project – Cai Mep LPG Cavern Project located in Ba Ria-Vung Tau province, Viet Nam. The project is an underground storage facility. Tunnels of underground storage facilities in this project are broadly categorized into the shaft, storage gallery, water curtain tunnel, connection tunnel, internal ramps, and access tunnel with start up the gallery to construct them [1, 2]. To carry out the functions of each facility harmoniously, it is necessary to secure a suitable space for each function and to select a section favorable in terms of construction stability, economical efficiency, and structural stability.

As main tunnels for storing propane and butane, typical sections were determined according to the storage capacity plan. The sections of the project can be classified into 7 types of usage and dimension: access shaft, operation shaft C3, operation shaft C4, access tunnel, connection tunnel & internal ramp, cavern (Figure 1) [1, 2]. The Q classification

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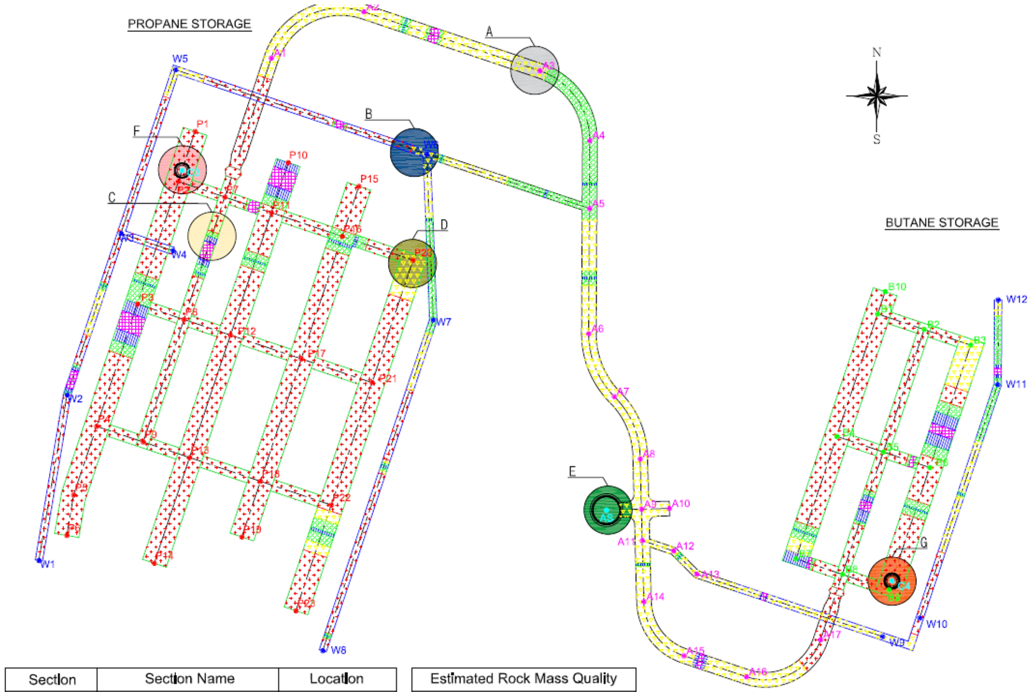
http://dx.doi.org/10.28991/CEJ-2022-08-01-06

proposed by Barton et al. in 1974 was chosen in the evaluation of the classification and support pattern report. Q-system was constituted by the plenty of data that was collected from tunnels in Norway and other countries [3]. Parameters of rock support around tunnels are determined from the values of Q-system and (Span or Height)/ (Excavation Support Ratio, ESR), (Equivalent Dimension, D_e), respectively (Table 1).



Section	Section Name	Location
A	Access tunnel	Sta.A9+340.00
B	Water curtain tunnel	Sta.A5+120.00
C	Connection & Internal ramp	Sta.A1+126.00
D	Cavern	Sta.P23+252.00
E	Access shaft	-
F	Operation shaft C3	Sta.P6+261.25
G	Operation shaft C4	Sta.B9+006.50

Estimated Rock Mass Quality
Type I
Type II
Type III
Type IV
Type V

Figure 1. Cai Mep LPG Cavern Project layout

The Cavern surface of this project is located at STA.P23+252.00 and the proposed tunnel support types are Type-2 for the cavern. The tunnel is located Grade II bedrock and the maximum height of soil on the tunnel is 98.0m. The purpose of this analysis is to review the feasibility of the above tunnel support types for cavern with the previous excavation done by civil works. The shape and size of the cavern, and distance of the system of caverns are shown in Figures 2 and 3. The soil & rock properties in this project are presented in Table 2. The depth of the cavern is 98.0m in the bedrock of Grade II (The total thickness of the upper soil layers is 54.6m). Parameters of shotcrete and pattern of rock bolts for cavern are presented in Table 3. The physical properties of reinforcement materials are presented in Table 4. The applied allowable stress of shotcrete and rock bolt is shown in Tables 5 and 6 [1, 2].

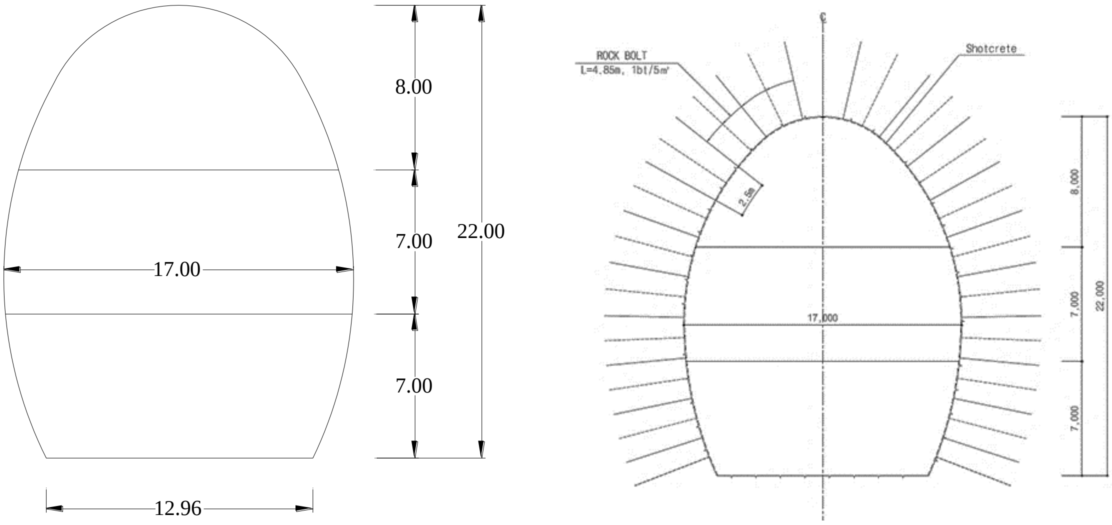


Figure 2. The shape and size of the caverns (Unit in Meter)

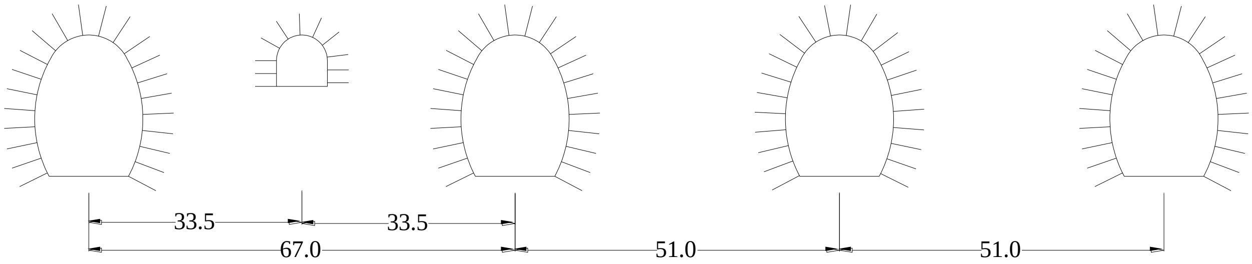


Figure 3. System of caverns (Unit in Meter)

Underground cavern and the system of caverns has the advantages of less land occupation, higher security, lower cost, and environmental benefits compared with traditional storage method, which is a widely used oil storage method. Understanding the deformation characteristics of the caverns is particularly important for accurately analyzing the surrounding rock stability and rock support [5-9]. Construction of the cavern is based on the Heading and Benching method. The geology and the height of the cavern decide the number of benches in excavating the cavern. The excavation of the cavern is being carried out by the drilling and blasting method. For maximum efficiency, the same crew for drilling, hauling, scaling team, and charging were used to excavate at several tunnel faces. This helps in constructing the cavern in minimum time. The tunnels are located close to each other and in a system with the same elevation as shown in Figure 3, we carry out checking the stability of the rock support and the rock mass during tunnels excavation at the save time. The system consists of 4 caverns and connecting tunnel & internal ramp tunnel (see Figure 3). The stability analysis was carried out based on those parameters by using 2D and 3D FEM [10-17]. However, the stability analysis system of caverns during excavation has not yet been thoroughly and simultaneously evaluated. This main focus of this study was thus estimating stability of the system Cai Mep LPG Caverns in Ba Ria-Vung Tau Region.

2. Numerical Simulation of the System Cai Mep LPG Caverns in Ba Ria-Vung Tau

The excavation of the cavern cross-section is divided into three parts stages. The top portion of the cavern tunnel is known as the heading, and the two bottom portions as a bench. The first excavation stage of the cavern is the heading with an excavated height of 8.0m, followed by the excavation of the first part of the bench with a height 7.0 m, and the last excavation stage at the bottom is 7.0 m in height as seen in Figures 3 and 6 [2].

Evaluating the maximum displacement of rock mass around tunnels and load-bearing capacity of construction structures performed based on FEM by Rocscience - RS2 software. This software allowed to analyze the sequence of tunnel face excavation and install the rock support. The software is also given maximum stress and strength of rock support. At the time of modeling, the analysis area is considered to be 8.0 of the tunnel diameter in the horizontal and downward direction, such that the influence of the artificial constraint conditions at the boundary on the result of the analysis should be within the allowable range in terms of engineering.

There are total 4 storage caverns at lower level. The dimension of each storage cavern is 340 m in length, 17 m in width and 22.0 m in height as shown in Figure 3. Excavation is done into 3 stages namely top heading (TH) with 8 m height, bench 1 (B_1) and bench 2 (B_2) with 7 m height in each stage. Flowchart of this study are presented on Figure 4.

Table 1. The Q classification proposed by Barton et al. in 1974 [3]

Rock classes	I	II	III	IV	V
Q	Q > 40	40 ≥ Q >10	10 ≥ Q >4	4 ≥ Q >1	1 ≥ Q >0,1
Rock quality	Very Good	Good	Fair	Poor	Very poor

Table 2. Soil & Rock Properties

Type	Unit Weight (kN/㎥)	Cohesion (kPa)	Internal Friction Angle (°)	Deformation Modulus (MPa)	Poisson's Ratio	Remarks
Grade Ⅰ	26.6	9000	54.8	41000	0.25	-
Grade Ⅱ	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	-

Table 3. Support Pattern of caverns

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				

Table 4. Physical Properties of Reinforcement Materials

Division		Modulus of elasticity (MPa)	Internal Friction Angle (°)	Cohesion (MPa)	Unit Weight (kN/㎥)	Poisson's Ratio
Shotcrete	Soft	5000	-	-	24.0	0.2
	Hard	18000	-	-	24.0	0.2
Rockbolt		350000	-	-	18.3	0.3

Table 5. Applied Allowable Stress of shotcrete

Division	Criteria	Characteristic Strength [MPa]	Allowable Stress [MPa]
Allowable Compressive Stress	$0.4f_{ck}$	$f_{ck} = 26$	10.40
Allowable Tensile Stress	$0.13\sqrt{f_{ck}}$	$f_{ck} = 26$	0.66
Flexural Bending Strength	f_{bk}	-	4.50

Table 6. Applied Allowable Stress of Rock bolt

Division	Specification	Ultimate Strength [MPa]	Area [m^2]	Allowable Axial Force [kN/EA]
Allowable Axial Force	GRFP	1.000	0.000491	165.00

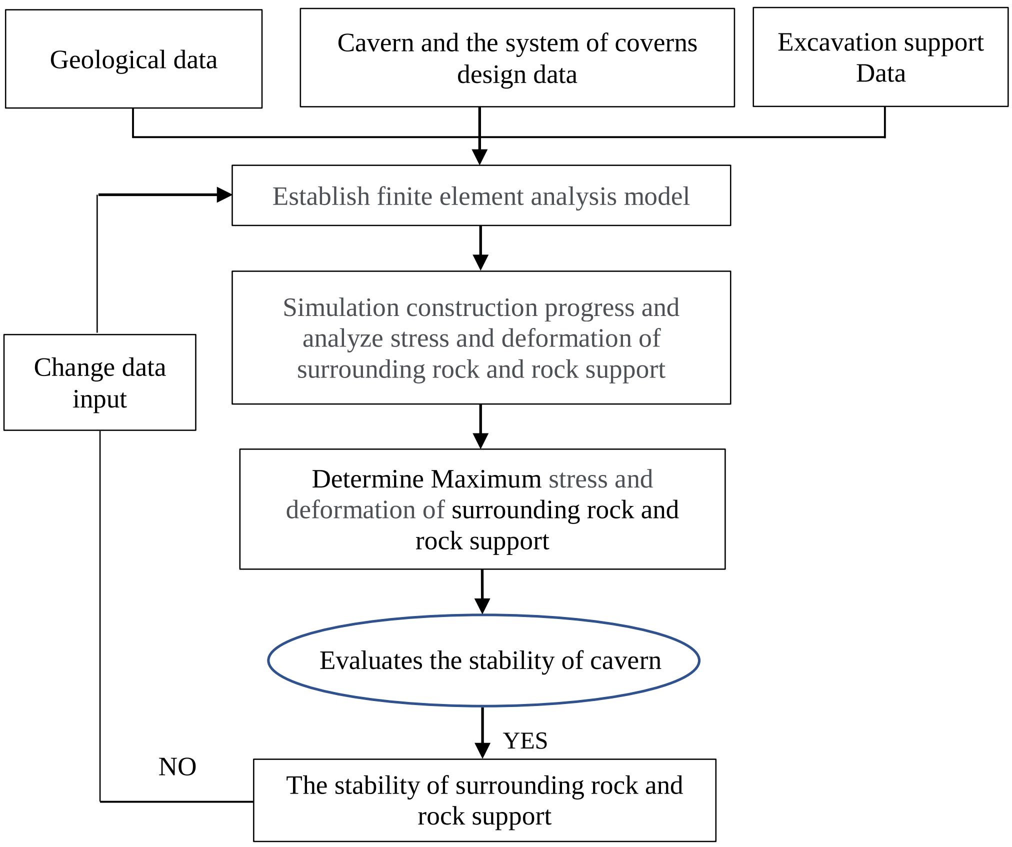
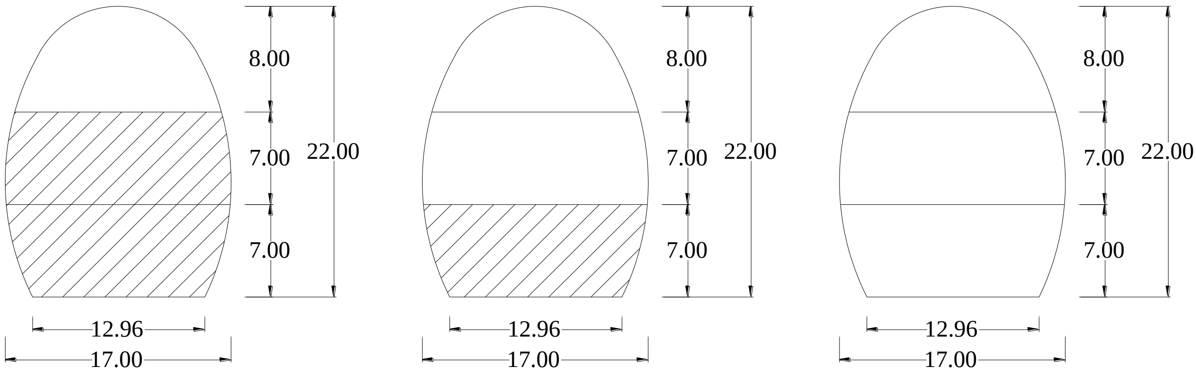


Figure 4. Flowchart of the study



a) Excavation heading; b) Excavation the bench 1; c) Excavation the bench 2

Figure 5. Phases of caverns excavation (Unit in Meter)

The stratum boundary is considered when creating the mesh. Then the surrounding of the excavation face where the stress changes are subdivided due to excavation to acquire more precise analysis results. For the tunnel support, frame element for shotcrete, and truss element for rock bolt are applied. For shotcrete, to compensate the modulus of elasticity according to change of time, the cross-section, the elastic modulus, and the geometrical moment of inertia, with the physical properties at different time points shotcrete work is inputted. In this study, the analysis model is used the elastoplastic model of Mohr-Coulomb. Since excavation of a tunnel generates the transverse arch effect on the ground and the longitudinal arch effect on the tunnel face, it is not possible to strictly apply 2-dimensional plane strain conditions. Considering the longitudinal arch effect and the shotcrete curing time under the plane strain conditions, the total load caused by excavation is distributed to each stage of excavation, soft shotcrete and hard shotcrete, which is called the load distribution ratio [1]:

Load Distribution Ratio at Excavation:

$$\alpha(\%) = 3.34 \times L + 3.778 \times E \quad (1)$$

Load Distribution Ratio of Soft Shotcrete:

$$\beta(\%) = 100 - (\alpha + \gamma) \quad (2)$$

Load Distribution Ratio of Hard Shotcrete:

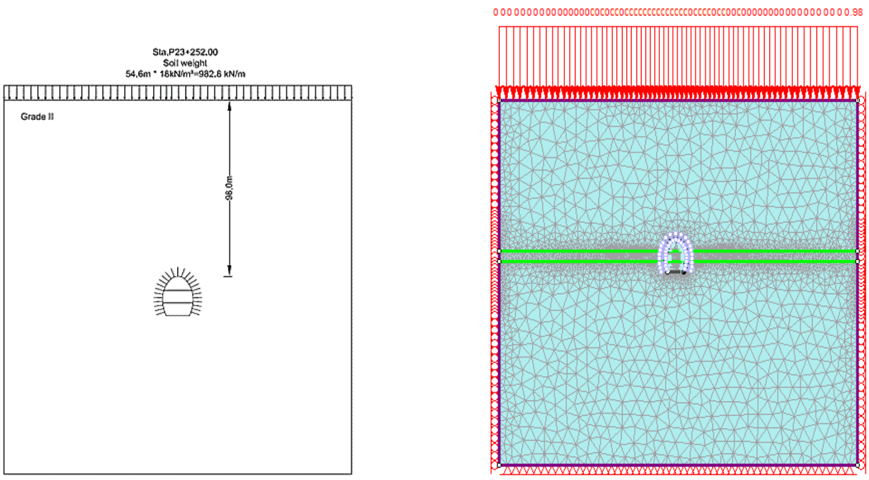
$$\gamma(\%) = -3.126 \times L + 3.391 \times D \quad (3)$$

Where; L: advance, D: equivalent diameter, E: modulus of elasticity of rock mass.

Boundary condition: the left, right and the bottom boundary of the model is fixed (vertical and horizontal movement is equal to zero). The boundary at the surface of the model is free, allowing vertical and horizontal displacement as shown in Figures 6b and 7b. The stratigraphic pressure acts on the surface of the model equal to the weight of the upper soil layers of bedrock:

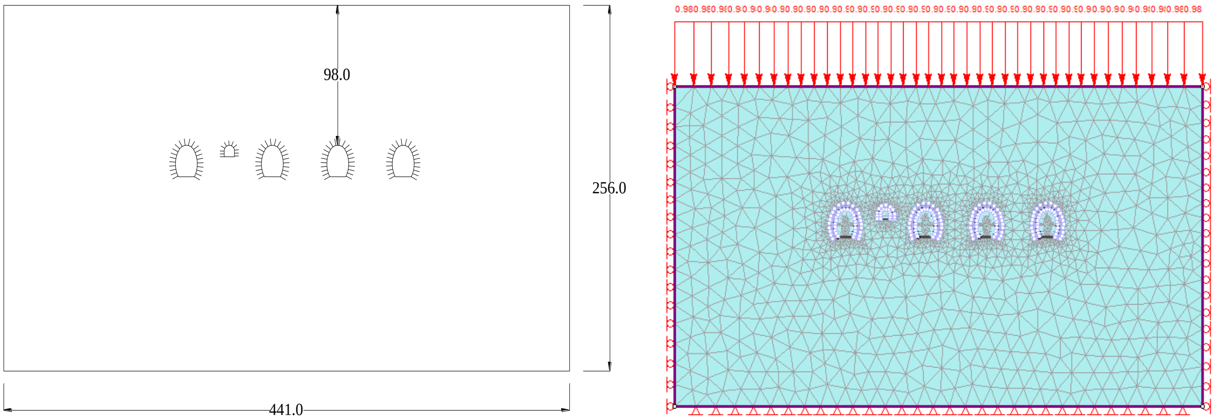
$$P = H_d \times P_d = 54.6 \times 18.0 = 0.9828\ MN/m \quad (4)$$

where H_d – is thickness above soil layers; (m); P_d = 18 kN/m^2 - earth pressure acting on 1 m^2.



a) Dimension of the model [m] b) Mesh and boundary condition of the model

Figure 6. Dimension, mesh, and boundary condition of the model (Cavern)



a) Dimension of the model [m] b) Mesh and boundary condition of the model

Figure 7. Dimension, mesh, and boundary condition of the model (system of caverns)

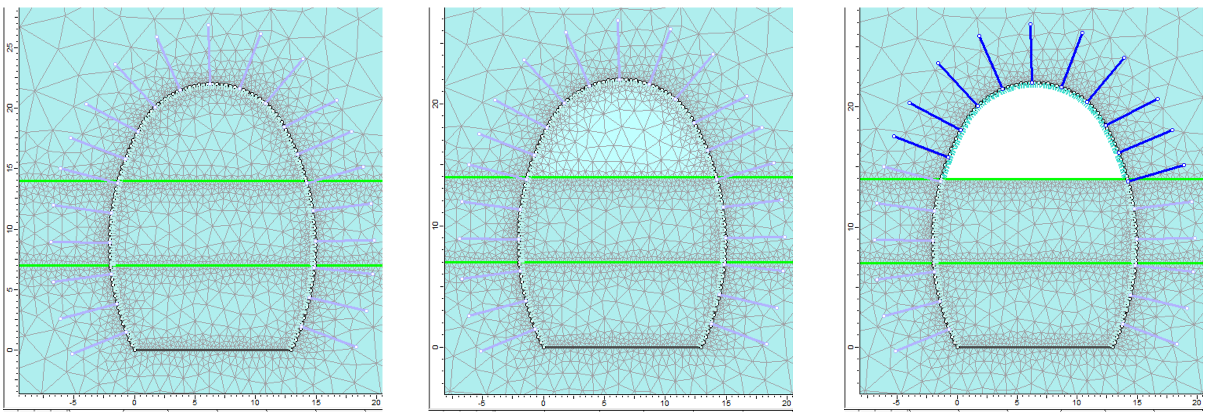
Analysis Sequence: The sequence of tunnel face excavation and installation of the rock support of caverns is presented in Table 7.

Table 7. Analysis Sequence

Phase	Description
Step 1	Initial Stress
Step 2	Initialize displacement of heading
Step 3	Installed supports (Rock bolt & Shotcrete) of heading Hardened shotcrete
Step 4	Initialize displacement of bench 1
Step 5	Installed supports (Rock bolt & Shotcrete) of bench 1 Hardened shotcrete of bench 1
Step 6	Initialize displacement of bench 2
Step 7	Installed supports (Rock bolt & Shotcrete) of bench 2 Hardened shotcrete of bench 2

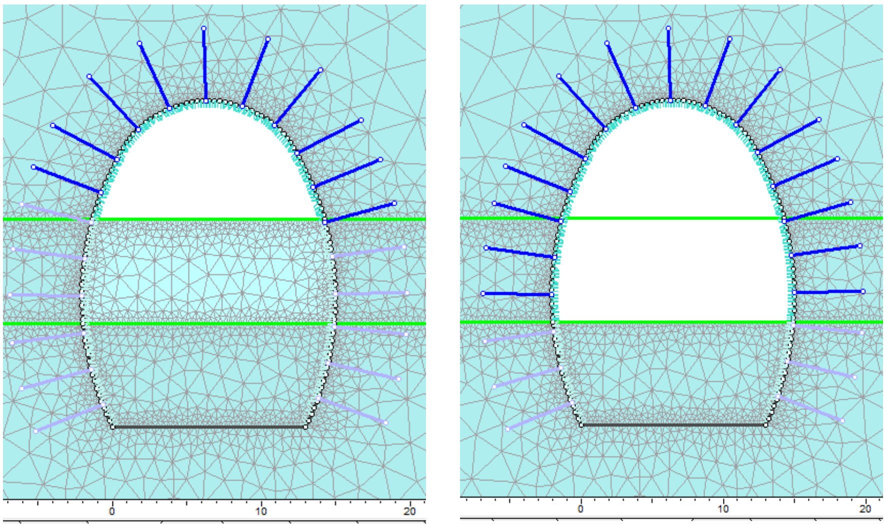
3. Evaluates the Stability of the Underground Cavern and the System of Caverns at Cai Mep LPG Project in Ba Ria-Vung Tau

The step of analysis sequence numerical simulations of underground cavern is described from Figures 7 to 10. Tables 8 and 9 are presented the maximum displacement values of rock mass around tunnels and load-bearing capacity of construction structures. The displacement value of rock mass around the tunnel is presented in Figure 11. The result of shotcrete bending stress and rock bolt axial force obtained by FEM is presented in Figure 12.



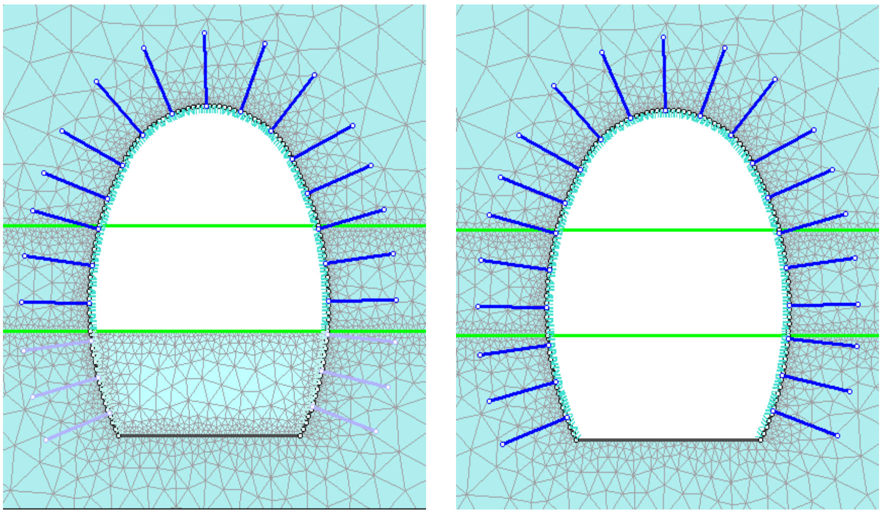
a) Initial Stress (Step 1) b) Initialize displacement of heading (Step 2) c) Install supports (Rock bolt & Shotcrete) of heading (Step 3)

Figure 8. Phases of excavation the heading



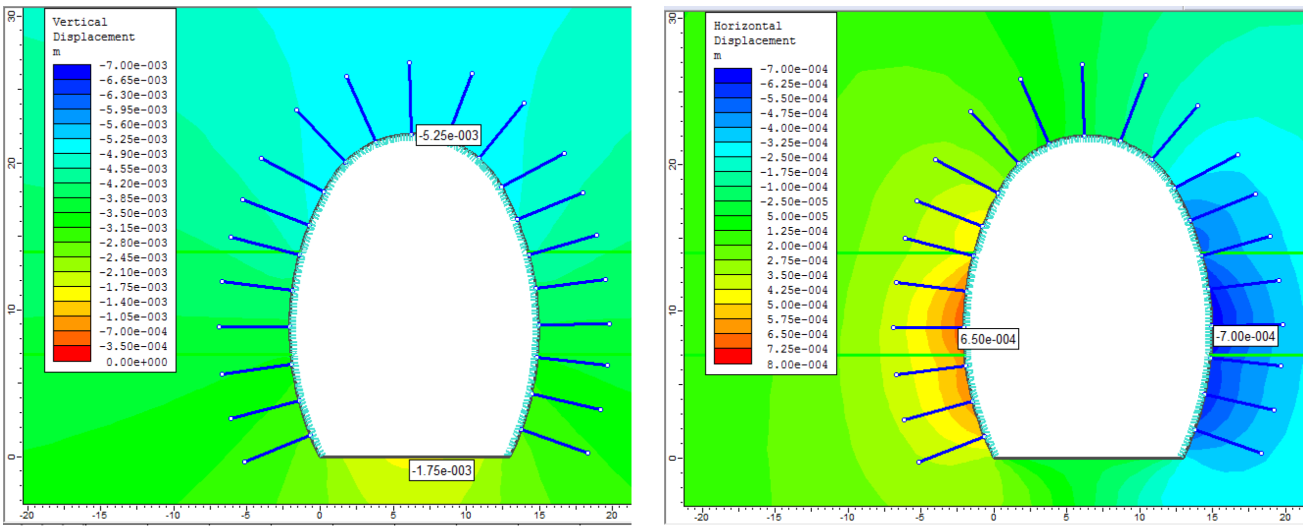
a) Step 4 b) Step 5

Figure 9. Phases of bench 1



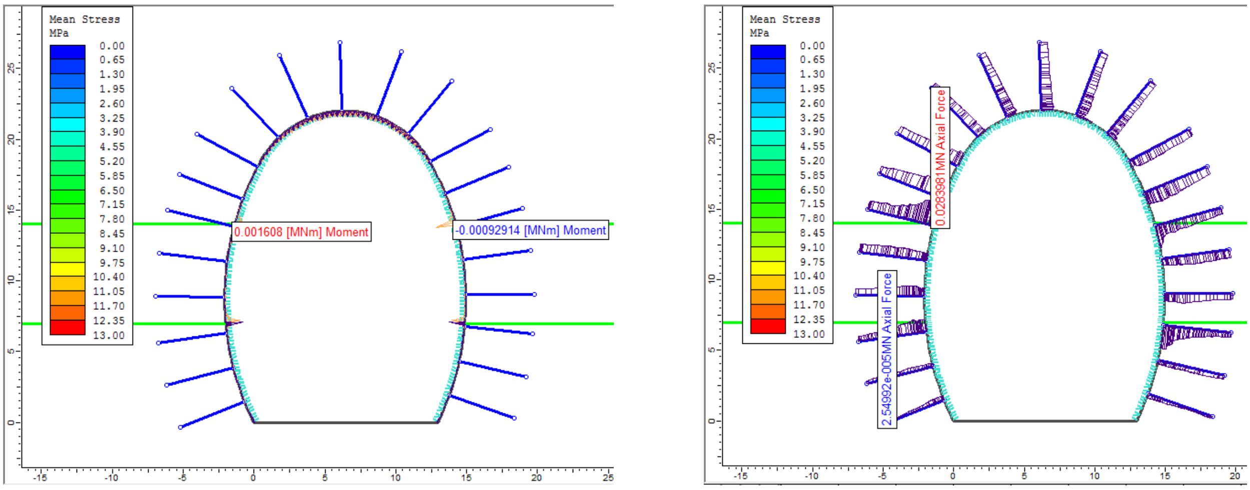
a) Step 6 b) Step 7

Figure 10. Phases of bench 2



a) Vertical displacement b) Horizontal displacement

Figure 11. The displacement value of rock mass around tunnel



a) Moment bending in shotcrete **b) Rock bolt axial force**

Figure 12. Result of moment bending in shotcrete and Rock bolt axial force obtained by FEM

Table 8. The value of maximum displacement of rock mass

Caverns	Displacement of rock mass around tunnels		Remark
	Horizontal displacement [mm]	Vertical displacement [mm]	
	0.7	5.25	O. K

Table 9. Stress / Force of rock support

Caverns	Shotcrete		Max. Rockbolt Axial Force [kN]	Remark
	Max. Compressive Stress [MPa]	Max. Tensile Stress [MPa]		
	3.84 [10.40]*	2.23 [4.50]*	28.3 [165]*	O.K

The step of analysis sequence numerical simulations of the system of the system of caverns is described on Table 10. Table 11 are presented the maximum displacement values of rock mass around the system of caverns and load-bearing capacity of construction structures. The displacement value of rock mass around the system of caverns is presented in Figures 11 and 12. The result of shotcrete bending stress and rock bolt axial force obtained by FEM is presented in Figure 15. The result of shotcrete bending stress and rock bolt axial force obtained by FEM is presented in Figures 14 and 5.

Table 10. Analysis Sequence

Construction Phase	Description
Step 1	Initial Stress
Step 2	Initialize displacement
Step 3	Install supports (Rock bolt & Shotcrete)
Step 4	Hardened shotcrete

Result of numerical simulation is presented from Figures 13 to 16.

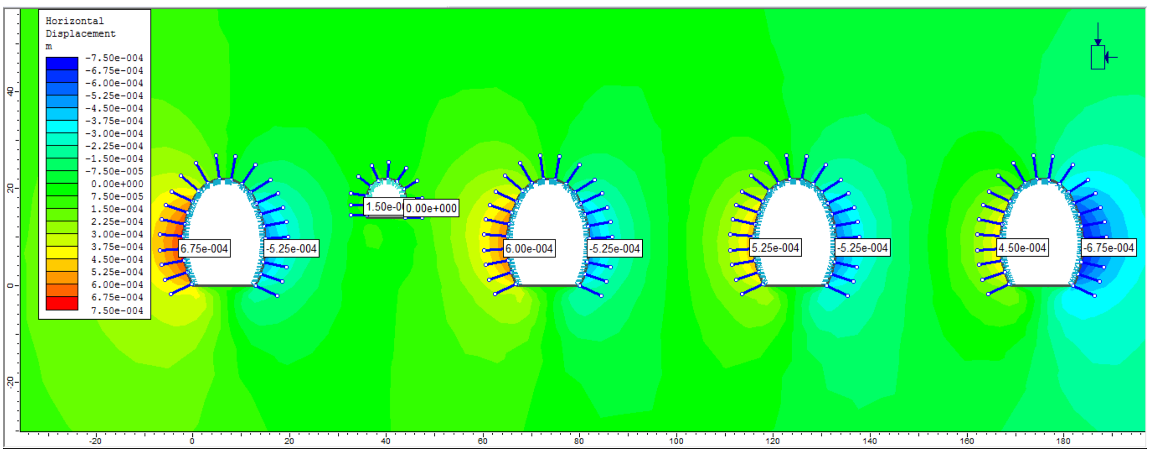


Figure 13. Horizontal displacement

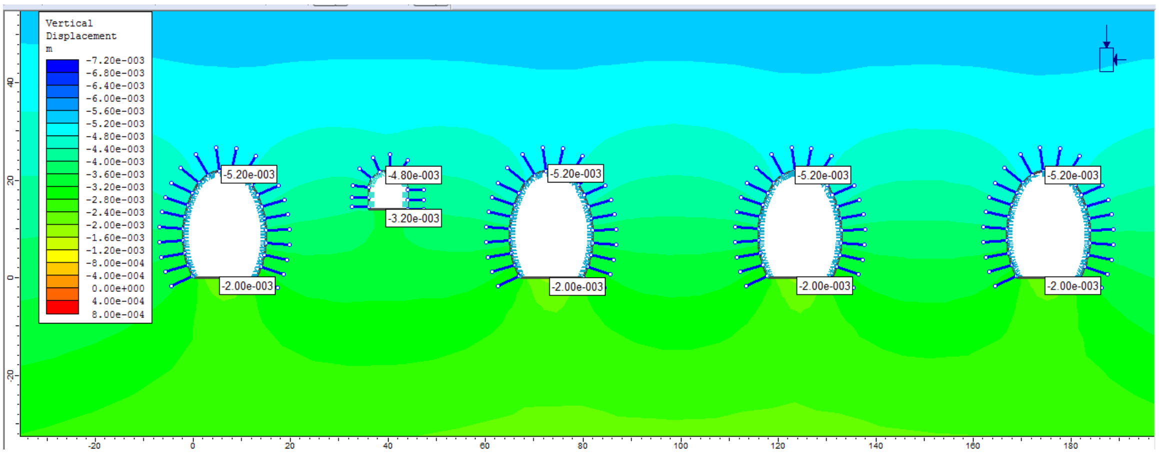


Figure 14. Vertical displacement

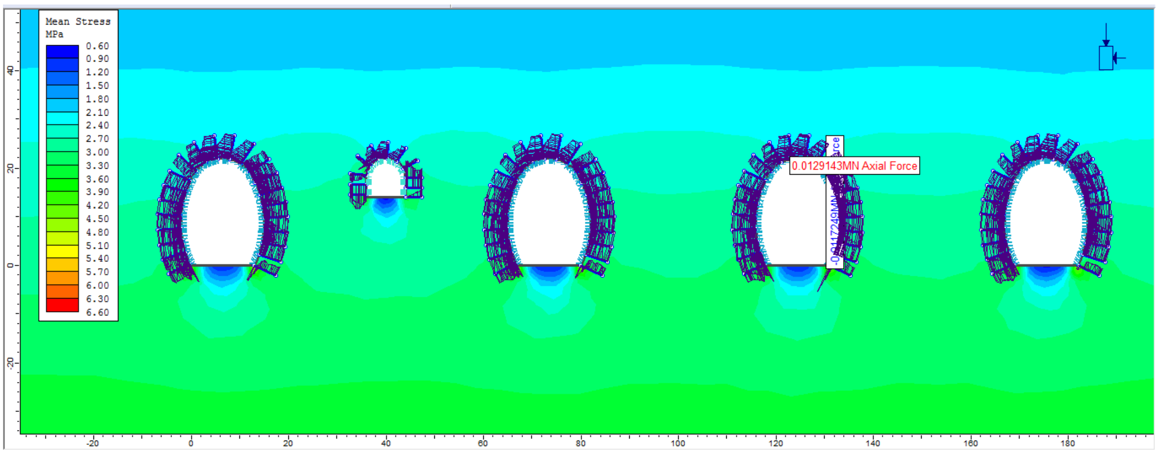


Figure 15. Result of shotcrete bending Stress

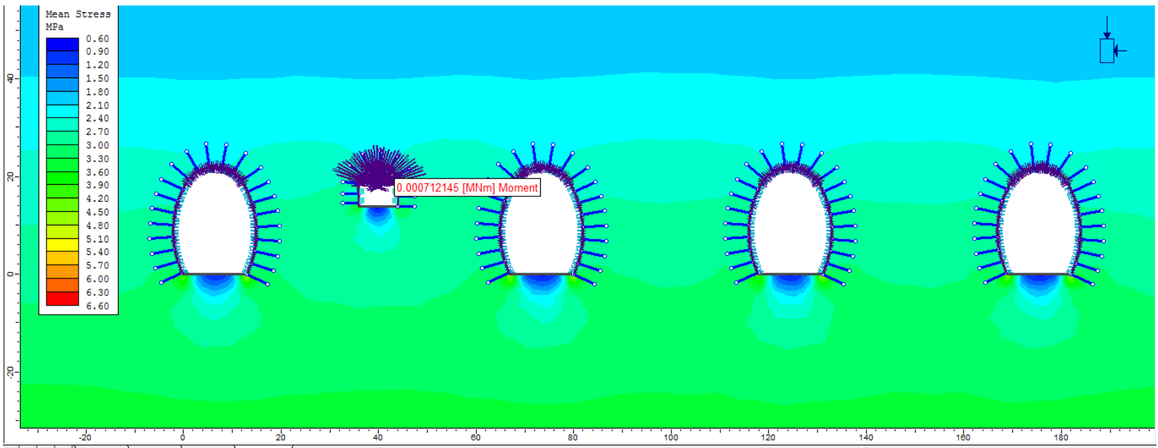


Figure 16. Result of rockbolt axial force

Tables 11 and 12 are presented the maximum displacement of rock mass around the system of caverns and load-bearing capacity of construction structures.

Table 11. The value of maximum displacement of rock mass around covern

Type	Displacement of rock mass around tunnels		Remark
	Horizontal displacement [mm]	Vertical displacement [mm]	
Covern 1	0.675	5.2	O.K
Connection tunnel & internal ramp	0.150	4.8	O.K
Covern 2	0.600	5.2	O.K
Covern 3	0.525	5.2	O.K
Covern 4	0.675	5.2	O.K

Table 12. Stress / Force of rock support

Shotcrete		Max. Rockbolt Axial Force [kN]	Remark
Max. Compressive Stress [MPa]	Max. Tensile Stress [MPa]		
1.70 [10.40]*	1.82 [4.50]*	12.90 [166]*	O.K

* Allowable Value

4. Conclusion

In this study, a numerical analysis using finite element software has been conducted to investigate the stability of rock mass surrounds the underground cavern and the system of caverns. 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, the output conditions of the design model, the stability of surrounding rock of cavern and the system of caverns has been conducted by Rocscience - RS2. The maximum displacement of rock mass around cavern and the system of caverns is performed based on rock property in the site investigation report. It is smaller than allowable values. However, it is required to check the displacement by observing during tunnels excavation time. Maximum compression stress and tensile stress in shotcrete, the maximum axial force of rock bolt in cavern and the system of caverns obtained by Rocscience - RS2 software is also than allowable values. So, rock support of cavern and the system of caverns is stable. The above results are only considered during the construction phase, to calculate and analyze the stability of rock support in the cavern and the system of caverns using time, it is necessary to have more output data such as the largest and smallest air pressure on cavern and the system of caverns lining; the temperature of the gas in the vault during operating. It allows the calculation of tunnels and caverns according to different load combinations to ensure the highest safety of underground above construction systems.

5. Declarations

5.1. Author Contributions

Conceptualization, D.V.K. and D.N.A.; software, D.V.K. and D.N.T.; validation, D.V.K.; data curation, D.V.K. and D.N.T.; writing—original draft preparation, D.V.K.; writing—review and editing, D.N.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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