Numerical modeling and optimization of rock layers arrangement to reduce the effect of surface impact loading on underground spaces

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ABSTRACT

Today, the use of buried spaces to protect sensitive facilities and equipment is not hidden from anyone. Buried safe spaces, especially tunnels, are used to create warehouses, maintain defense and military equipment, and also store some special materials and equipment. In addition, it is common to use these spaces as tunnels for urban services such as water transmission lines, telecommunications, energy, etc. Ensuring the security of these spaces against surface loads is one of the most important things in their construction and design. Buried spaces are exposed to various loadings, one of which is surface impact loading caused by explosion. In this article, impact loading in buried environments is numerically modeled using the Eulerian-Lagrangian (CEL) method in the ABAQUS software environment. For this purpose, using single-layer, double-layer and three-layer stone arrangement, the maximum pressure caused by impact load has been investigated in different models. According to the simulation results in this research, the highest amount of shock wave damping was obtained when the rock layer with the highest degree of weathering (porous rock) is located in the closest position to the buried space. Based on this, the safe depth of the modeled buried space was found to be about 12 meters for weak or porous rock, about 14 meters for medium rock, and about 18 meters for strong or pristine rock. Also, based on the results, the amount of transfer stress from weak rock to strong rock increases and the amount of stress from strong rock to weak rock decreases.

KEYWORDS

Impact load, Numerical modelling, Protective layers, Optimization, Buried space

1. Introduction

A critical issue concerning underground spaces is ensuring their stability. The focus of this research is on reinforcing underground spaces against loads generated by external factors. Important underground infrastructures, such as subway tunnels, communication tunnels, and military facilities, require protection. Impact loading can occur on the surface or after penetration into the ground. The study of impact loading and underground spaces dates back to World War II, with increased attention following terrorist attacks in various locations [1]. Countries like Japan, France, and Germany suffered significant damage during World War II. Additionally, in the 20th century, terrorist attacks such as the bombing of the World Trade Center in London, the Federal Building bombing, and the attacks on the Twin Towers, as well as the subsequent damages in Afghanistan and Iraq, highlighted the importance of this issue [2]. Numerous studies have been conducted to examine this topic, which can be categorized into different groups, such as experimental and numerical studies [3-19].

2. Modeling

To validate the buried space modeled by Tiwari and colleagues [4], an analysis was conducted using the ABAQUS software. For modeling the rock, the Drucker-Prager failure criterion was employed. The failure behavior of the rock is characterized by local nonlinearity. The properties of the rock used in the analysis are the same as stone used in Tiwari and colleagues [4].

As previously explained, the JWL-EOS model was employed for the simulation of TNT and its parameters [15]. The governing equation for this model and the relevant parameters are presented below:

$$p = A\left(1-\frac{\omega}{R_1\bar{\rho}}\right)e^{R_1\bar{\rho}} + B\left(1-\frac{\omega}{R_2\bar{\rho}}\right)e^{R_2\bar{\rho}} + \omega\rho e_{\text{int}} \quad (1)$$

Figure 5 illustrates the positioning of TNT in both the buried and assembled configurations within the ABAQUS software environment. The modeling was conducted using the Coupled Eulerian-Lagrangian (CEL) method. To enhance the accuracy of the simulation, a mesh sensitivity analysis was employed. Consequently, a mesh size of 4 cm was selected for this study.

Rocks can be classified into three general categories based on their resistance to impact loading: strong (H), medium (M), and weak (L). The characteristics of these categories are provided in Table 1. The Drucker-Prager constitutive model has been employed in ABAQUS software to model the behavior of these rocks.

Table 1. Rocks' characteristics used for modeling [18]

Rock Type	H	M	L
Specific gravity (G)	2.65	2.65	2.65
Density (qr) (kg/m3)	2550	2420	2350
Elastic modulus (ER) (GPa)	28	14	4
Poisson's ratio (m)	0.25	0.28	0.4
Angle of internal friction (u)	42	39	33
In situ stress ratio (K0)	0.5	0.5	0.5
Dilation angle (w)	5	5	5
Cohesion (c) (MPa)	2.3	1.54	1.4
fc (MPa)	40	28	10.5
RQD range	75-90	30-40	20-10
RMR	47	33	20

The dimensions of the buried space were modeled in the ABAQUS software based on the research conducted by Brox and Lee [19]. The buried space was modeled with a length of 10 meters, a width of 7.5 meters, a depth of 30 meters, and a thickness of 0.25 meters. The properties of the concrete used are the same as in [4].

Upon modeling, it is observed that at a depth of approximately 18 to 20 meters for strong (intact) rock, the rotation of the upper wall of a square tunnel with a thickness of 0.25 meters is about 2 degrees. According to the analysis results, the maximum pressure exerted on the buried space in this scenario is approximately 10 to 12 MPa. Therefore, it can be concluded that when the maximum pressure exerted on the buried space is around 10 to 12 MPa, the rotation of the upper wall of the square tunnel reaches 2 degrees, which is the maximum allowable wall rotation according to the UFC 2014 code.

Additionally, based on the obtained results and in accordance with the UFC 2014 code, the pressure exerted on the buried space is approximately 1.7 times the maximum pressure exerted on the soil or rock layer above it, which is referred to as the reflection coefficient. The maximum pressure exerted on the soil or rock is determined to be around 7 MPa by dividing 12 MPa by 1.7. In the following sections, we will examine the modeling results for single-layer, double-layer, and triple-layer rock under an impact loading of 2000 kg/m².

3. Results and Discussion

Modeling of single-layer, double-layer and three-layer rock configurations with a surface impact load of 2000kg was done in ABAQUS software in order to find the optimal arrangement. The schematics of two/three-layer models are shown in figure1. The results are as follows:

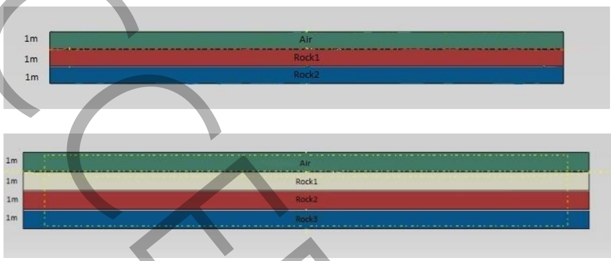

Figure 1. Teo-layer (up) and Three-layer (down) model; the upper layer is the Air.

Single-layer rock model

The safe burial depth for weak or porous rock (L) is approximately 12 meters, for medium-strength rock (M) it is about 14 meters, and for strong or intact rock (H) it is around 18 meters. Following the modeling, the maximum pressure for the midsection of the single-layer rocks at depths of 5, 10, 15, 20, and 25 meters was recorded. Rock type H exhibits higher maximum pressure compared to rock types M and L. In contrast, rocks M and L reduce the maximum pressure exerted on the structure at depths of 5, 10, 15, and 25 meters by 50%, 66%, 32%, 52%, 23%, 54%, 17%, and 37%, respectively, compared to rock type H.

Two-layer rock model

Six configurations for the two-layered model were conducted: H-L, H-M, L-H, L-M, M-H, and M-L. The maximum pressure results for the mid-sections of the layers were compared.

In the first layer, the least effective configuration in terms of damping the maximum pressure from impact loading is H-L, whereas L-H is the most effective configuration for damping maximum impact pressure. It can be concluded that the configurations H-M, M-L, M-H, L-M, and L-H reduce the maximum impact pressure by 8%, 34%, 44%, 62%, and 63%, respectively, compared to H-L.

In the second layer, the configurations with the least effectiveness in damping the maximum pressure from impact loading are L-H and M-H, while H-L is the most effective configuration for damping the maximum impact pressure. It can be concluded that the configurations M-H, L-M, H-M, M-L, and H-L reduce the maximum impact pressure by 0.2%, 16%, 21%, 47%, and 51%, respectively, compared to L-H.

Three-layer rock model

In the first layer, the most inappropriate mode that has the lowest amount of maximum pressure damping from impact load is H-L-M mode, also L-H-M is the most suitable mode for maximum pressure damping from impact load. It can be concluded that H-M-L, M-L-H, M-H-L, L-M-H and L-H-M modes reduce the maximum pressure resulting from the shock load by 6%, 43%, 46%, 63% and 65%, respectively, compared to the H-L-M mode.

In the second layer, the most inappropriate mode that has the lowest amount of maximum pressure damping due to shock load is M-H-L mode, also H-L-M is the most suitable mode for maximum pressure damping due to shock load. It can be concluded that L-H-M, H-M-L, L-M-H, M-L-H, and H-L-M modes reduce the maximum pressure resulting from impact load by 2%, 5%, 16%, 34%, and 43%, respectively, compared to M-H-L mode.

In the third layer, the most inappropriate mode that has the lowest amount of maximum pressure damping due to impact load is M-L-H mode, also H-M-L is the most suitable mode for maximum pressure damping due to impact load. It can be concluded that L-M-H, H-L-M, L-H-M, M-H-L and H-M-L reduces the maximum pressure resulting from impact load by 12%, 26%, 37%, 61% and 62%, respectively, compared to the M-L-H mode, which is the most inappropriate mode for the third layer.

The L-M-H configuration, with layer thicknesses of 5, 10, and 15 meters respectively, and the H-M-L configuration, with layer thicknesses of 15, 10, and 5 meters respectively, have been modeled in the ABAQUS software for a TNT charge of 2000 kilograms, which are shown in figure 2.

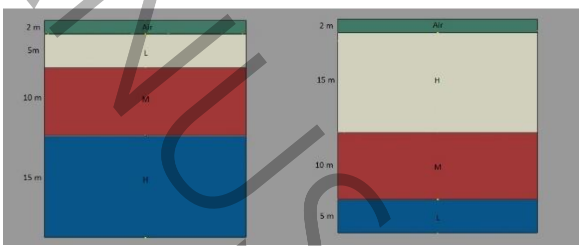

Figure 2. the L-M-H (Left) and H-M-L (right) configurations.

4. Conclusions

In this study, previous research on the design of buried spaces was reviewed, and numerical modeling was employed to examine the behavior of buried spaces under impact loading. The goal was to mitigate the effect of transmitted impact forces on buried spaces by leveraging the properties of the surrounding environment. The study utilized finite element modeling to simulate single-layer, double-layer, and triple-layer rock arrangements, as well as layers of varying rock thicknesses. The simulation results indicated that the arrangement of rock layers significantly influences the reduction of peak pressure resulting from impact loading. The greatest wave attenuation was observed when the rock layer with the highest degree of weathering was positioned closest to the buried space. The maximum damping of the impact wave occurred when the most weathered rock layer (porous rock) was in the closest proximity to the target buried space. The safe burial depth, according to the graph, was approximately 12 meters for weak or porous rock (L), around 14 meters for medium-strength rock (M), and about 18 meters for strong or intact rock (H). The results also showed that at the boundary between two layers, the transmission of stress from weak rock to strong rock increases, while the stress transmission from strong rock to weak rock decreases.

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