Numerical Simulation for Dynamic Response Characteristics of Underground Storage Cavern Subjected to Seismic Loadings

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Abstract

Due to the advantages in safety and cost, more and more large underground caverns are being built to store energy or hazardous waste in the world, especially in China. However, so far, there are few studies focusing on dynamic response characteristics of deep underground storage caverns with large span. In this paper, the dynamic time history analysis method is used to study the seismic response characteristics of such a facility and the aseismic effect of seismic measures. First, to investigate the internal force and deformation responses of the liner, a series of calculation cases of the underground storage cavern with different load conditions are implemented: static load only, dynamic load only, both static and dynamic loads. Then, a rubber material is placed between the primary and secondary liners as a coating layer, and the influence of thickness of the rubber layer on the seismic mitigation of underground storage cavern is also investigated. Results indicate that dynamic load significantly increases the internal force of the structure, but has little effect on the deformation. With the seismic measure by setting coating layer, the underground storage cavern has better performance: the peak values of internal forces and deformation of liner are all reduced. The seismic mitigation effect of the coating layer tends to be more obvious with the increase of the thickness of the coating layer. When the thickness of the layer reaches a critical value, i.e. 30cm, however, the improvement of the seismic mitigation of the coating layer is invisible and slight with the increase of its thickness.

Numerical Simulation for Dynamic Response Characteristics of Underground Storage Cavern Subjected to Seismic Loading

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ABSTRACT: Due to the advantages in safety and cost, more and more large underground caverns are being built to store energy or hazardous waste in the world, especially in China. However, so far, there are few studies focusing on dynamic response characteristics of deep underground storage caverns with large span. In this paper, the dynamic time history analysis method is used to study the seismic response characteristics of such a facility and the aseismic effect of seismic measures. First, to investigate the internal force and deformation responses of the liner, a series of calculation cases of the underground storage cavern with different load conditions are implemented: static load only, dynamic load only, both static and dynamic loads. Then, a rubber material is placed between the primary and secondary liners as a coating layer, and the influence of thickness of the rubber layer on the seismic mitigation of underground storage cavern is also investigated. Results indicate that dynamic load significantly increases the internal force of the structure, the structural design of underground caverns should take both static load and earthquake action into account. With the seismic measure by setting coating layer, the underground storage cavern has better performance: the peak values of internal forces and deformation of liner are all reduced. The aseismic performance of the coating layer tends to be more obvious with the increase of the thickness. When the thickness reaches a critical value, i.e. 30cm, however, the improvement of the seismic mitigation is not visible any more.

1. Introduction

Underground caverns are becoming the first choice for storing energy or hazardous waste due to their irreplaceable advantages: high safety factor, less space requirement, reduced resource consumption and pollution, low installation and operating costs, long service life, and fast loading and unloading. Unfortunately, under the action of earthquake, these important facilities may be damaged, and even produce environmental pollution, fire and other serious secondary disasters.

At present, all of earthquake damage investigation, theoretical analysis, numerical simulation and model test have been widely adopted to study the behavior of underground facility under seismic loading. Wang et al., 2001 investigated and evaluated 57 tunnels affected by the Chi-chi earthquake in Taiwan, of which 49 were damaged to varying degrees. Yu et al., 2021 presented a unified simplified analytical solution for deep tunnels with arbitrary cross-section shapes subjected to seismic loading. With reference to a proposed immersed tunnel in a highly seismic region, Anastasopoulos et al., 2007 proposed a simplified multiscale numerical model. In their methods, the tunnel segments are modeled as beams connected to the ground through properly calibrated interaction springs, dashpots, and sliders. A series of multi-point shaking table tests were conducted by Yu et al., 2016 on a long-immersed tunnel designed for the Hongkong-Zhuhai-Macau linkage under non-uniform seismic excitations. Results show that non-uniform seismic excitation significantly increases the immersion joints distortion. Until now, however, there are few studies focusing on seismic resistance analysis of deep underground storage caverns with a large span.

In general, the seismic performance of underground structure is superior to that of the surface structure. However, alerted by the reported serious damage of underground structures from recent strong earthquakes, researchers realize that measures were needed to mitigate the seismic response of underground structures. Among existing seismic measures, the coating layer made of rubber is considered the most suitable to improve the seismic performance of underground caverns (Chen et al., 2018).

In this paper, a 2D dynamic finite element model is built in the Finite Element software ABAQUS to evaluate dynamic response characteristics of underground storage cavern subjected to static seismic load only, dynamic load only, both static and dynamic loads. Then, a rubber material is placed between the primary and secondary liners as a coating layer, and the influence of thickness of the rubber layer on the seismic mitigation of underground storage cavern is also investigated.

2. *Numerical Modeling*

The deep cavern to be modeled is shown in Fig.1, which is a straight wall dome structure, and whose dome is connected with the wall as a whole. The inner diameter of the dome is 40 m, the thickness of primary liner is 0.35m, and the buried depth is 400 m. The long bolts are spaced by 3.6 m × 3.6 m, with a length of 12 m. The short bolts are distributed on a grid of 1.2 m × 1.2 m and have a length of 5 m.

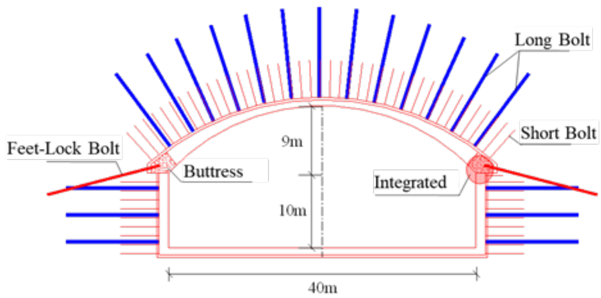


Fig. 1. Typical cross section of the cavern

2.1. *Numerical Model and Parameters*

Analytical solutions and simplified methods may be extremely useful in the preliminary design stage. However, for more thorough predictions, full dynamic analyses, considering ground-structure interaction, are needed. Thus, the Finite Element software ABAQUS is used to establish the nonlinear two-dimensional model for implicit dynamic calculation.

In the simulation, the height of the model is set to 600m and the width is set to 400m. The cavern is about 4.5 times of the span away from the lateral boundaries and 4 times away from the bottom boundary, which can effectively eliminate the boundary effect. The rock mass and the primary liner are simulated by four-node plane strain elements and the secondary liner is simulated by the 1D beam elements. The mesh is divided from coarse to fine, that is, the closer to the cavern, the smaller the mesh size (Fig.2).

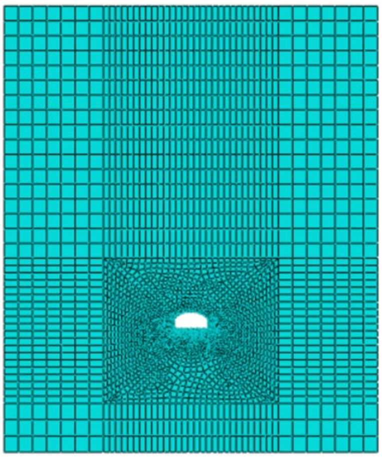


Fig. 2. Numerical model

The Drucker–Prager yield criterion is used for the rock in the numerical model., which has a smooth failure face and is quite suitable for calculation. While, the concrete material in the cavern is assumed to be elastic. The parameter values of rock mass and structures are listed in Table 1, where internal friction angle and cohesion are the parameters of Drucker–Prager model.

Table 1. Properties of Rock mass and Concrete

	Density (kg/m^3)	Elastic modulus (Gpa)	Poisson's ratio	Internal friction angle (°)	Cohesion (Mpa)
Rock	2400	8	0.3	49.4	1.197
Primary liner	2500	25	0.2		
Secondary liner	3500	31.5	0.2		

2.2. Rock Bolts Simulation

The effect of rock bolts is also considered in this model. According to the document (Bobet, 2009), rock bolts uniformly distributed around the tunnel change the mechanical properties of the original rock by increasing its stiffness in the radial direction, while in the tangential direction the stiffness is left largely unchanged. Thus, the rock mass around the cavern can be assumed to be radial composite material. And, the Young's modulus in the radial direction can be obtained by

$$E_r = E + \frac{1}{4}\frac{\pi d_b^2}{S_\theta S_z} E_b \tag{1}$$

where E and E_b are elastic modulus of the rock mass and the bolts, d_b is cross section diameter of the bolts, S_z and S_θ are bolt spacing in the longitudinal and tangential directions.

2.3. Dynamic Damping

Natural dynamic systems contain some degree of damping of the vibration energy within the system; otherwise, the system would oscillate indefinitely when subjected to driving forces. In this work, Rayleigh damping is adopted, which is commonly used in engineering. In the dynamic equation, damping matrix *C* is related to stiffness matrix *K* and mass matrix *M*, which is as the following:

$$C = \alpha M + \beta K \tag{2}$$

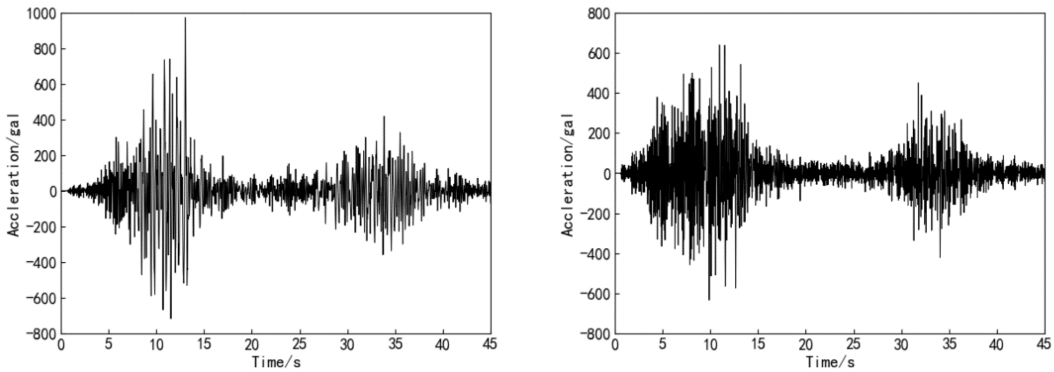
where α and β are the mass ratio damping coefficient and the stiffness ratio damping coefficient, respectively.

2.4. Analysis procedures

The numerical simulation is conducted in following two steps: (i) excavation and construction; (ii) input of seismic wave.

The excavation process is approximated by stepwise release of stress. After getting the initial stress equilibrium, all the elements corresponding to the excavation are deactivated, while, the corresponding reaction forces are applied around the opening. Until the reaction forces are reduced to 60%, the elements of primary liner are activated, and the radial stiffness of the rock mass reinforced by bolts is strengthened. The applied reaction forces are then cleared to zero. Finally, secondary liner is introduced to the model.

After excavation and construction, the original constraints on lateral boundaries are replaced by horizontal kinematic tied-degrees-of-freedom (TDOF) constraints, which enforces nodes with the same burial depth on the lateral boundaries move together. Acceleration time histories of the Wenchuan earthquake recorded in Wolong Station are applied at the bottom of the model: East-West (E-W) acceleration as horizontal input motion; Up-Down (U-D) acceleration as vertical input motion. The corrected and filtered acceleration records are shown in Fig. 3. Before inputting the motion, the peak value of E-W acceleration is scaled to 400 gal, while that of U-D acceleration is scaled to 270 gal.



(a) (b)

Fig. 3. Seismic input motions: (a) E-W acceleration; and (b) U-D acceleration.

3. Results and Discussions

In this paper, the objectives are to evaluate the dynamic response characteristics of the structure and effects of aseismic measure. Also, to limit the amount of data, the seismic response information is measured at serval monitoring points. As is shown in Fig. 4, the 10 monitoring points are all located in the left half of the secondary liner because of the symmetry.

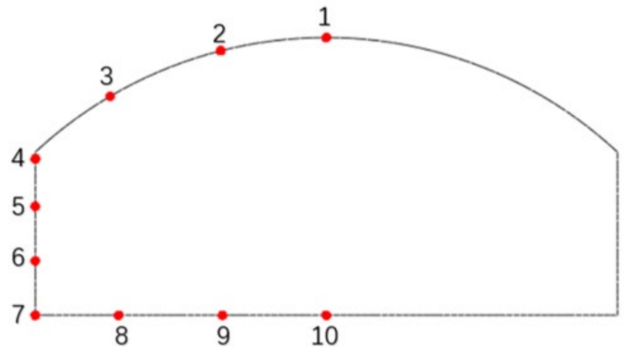
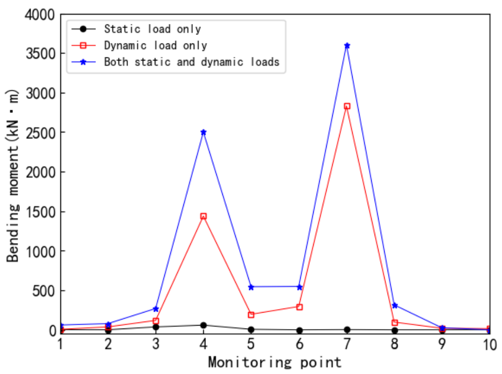


Fig. 4. Monitoring points at the Secondary liner

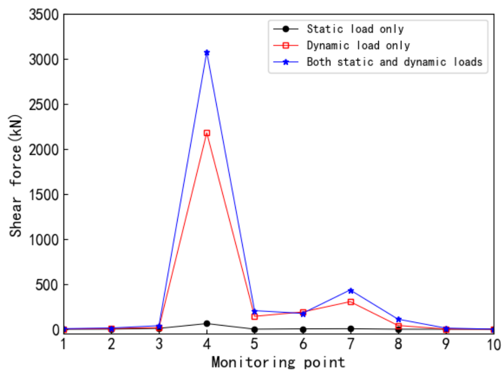
3.1. Dynamic Response of the structure

Fig. 5(a)-(d) shows the distribution of the peak bending moment (absolute value), shear force (absolute value), axial forces in the secondary liner, under three scenarios: static load only, dynamic load only, both static and dynamic loads. From the calculation results, the weak seismic parts of the structure are near points 3, 4 and 7, because the peak internal force appears in these parts. In the event of an earthquake, these locations are the first to break down and even cause the liquid or gas stored inside to leak out. Setting seismic joints at these positions can reduce stiffness of the structure and make internal forces more uniform.

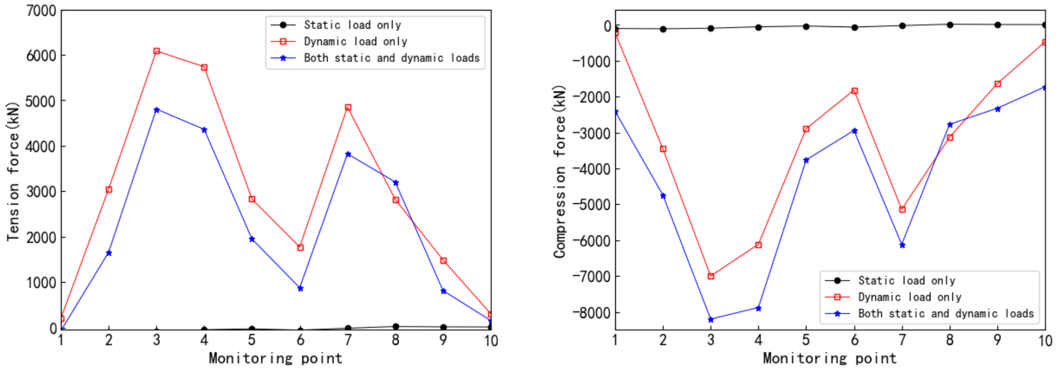
Comparing two scenarios: static load only and dynamic load only, we can conclude that the seismic load will have an adverse impact on the structure safety. If both static and dynamic loads are considered, the bending moment, shear and compression force of the structure will increase, while the tension force will decrease slightly. Taking the data of monitoring point 4 for example, the peak of bending moment, shear, and compression force increase by 73.2%, 41.0% and 28.9% respectively. However, the tension is reduced by 24.0%. It can be inferred that the structural design of underground caverns should take both static load and earthquake action into account. In addition, it is not completely reasonable to superimpose the result of static and that of dynamic calculation directly.



(a)



(b)



(c) (d)

Fig. 5. The distribution of peak internal forces of the secondary liner: (a) bending moment (absolute value); (b)shear force (absolute value); (c) tension force; and (d) compression force.

3.2. *The effects of the aseismic measure*

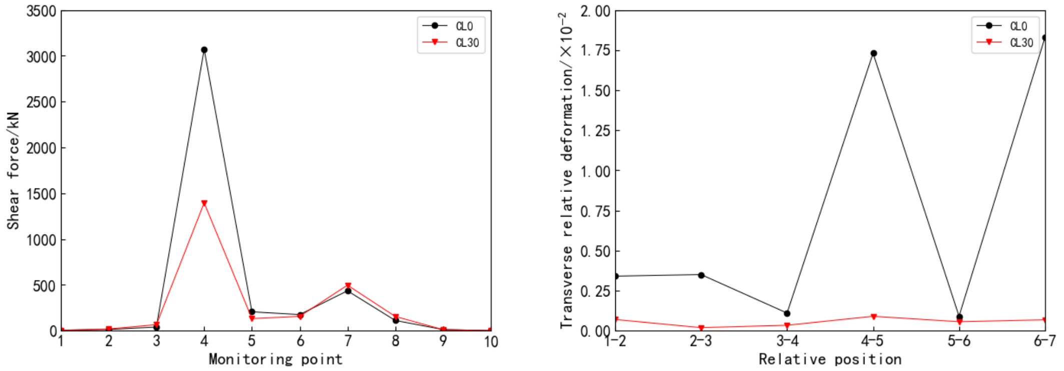
A rubber coating layer is adopted as the aseismic measure. The built-in hyper-elastic model (ABAQUS 2008) is used to simulate the rubber material, whose parameters are listed in Table 2.

Table 2. Property of the rubber material (Huang et al., 2009)

Density (kg/m3)	C_{10}	C_{01}	D_1
1068	0.68×10^6	0.17×10^6	0.1176×10^{-7}

To study the effects of the aseismic measure, two scenarios are compared: no coating layer (CL0) and 30 cm thick coating layer (CL30). Due to the limited space, only peak shear force (absolute value) and peak transverse relative deformation δ_{ij} of the secondary liner are given in Fig. 6. The δ_{ij} between point i and j (δ_{ij}) is defined as

$$\delta_{ij} = \frac{\left|x_i - x_j\right|_{\max}}{\left|h_i - h_j\right|} \tag{3}$$



(a) (b)

Fig. 6. The distribution of peak values: (a) shear force (absolute value); (b) transverse relative deformation.

After setting the coating layer, the peak shear force decreased significantly, especially at point 4. As for deformation, δ_{ij} turns to be smaller and more uniform. Thus, setting rubber coating layer is a qualified aseismic measure, which can improve the seismic performance of the structure by isolating the deformation of rock mass.

The increase of coating layer's thickness usually improves seismic isolation performance. However, excessive thickness will greatly increase the project cost and construction difficulty, while the marginal benefit will also reduce. Thus, to find an optimal design, the peak shear forces (absolute value) of secondary liner with coating layers of different thicknesses are compared (Fig.7). The seismic mitigation effect of the coating layer tends to be more obvious with the increase of the thickness. When the thickness of the layer reaches 30cm, however, the improvement is invisible and slight with the increase of its thickness.

4. Conclusions

In this study, numerical modeling is performed to investigate dynamic response characteristics of underground storage cavern subjected to seismic loading. A rubber coating layer is adopted as the aseismic measure, the effects of whose thickness are analyzed. The following are the main conclusions obtained from the research:

(1) The input of dynamic load significantly increases the internal force of the structure, the structural design of underground caverns should take both static load and earthquake action into account.

(2) Setting rubber coating layer is a qualified aseismic measure, which can improve the seismic performance of the structure by isolating the deformation of rock mass.

(3) The aseismic performance of the coating layer tends to be more obvious with the increase of the thickness. When the thickness reaches a critical value, i.e. 30cm, however, the improvement of the seismic mitigation is not visible any more.

Note that the responses of the cavern liner are associated with the specific conditions used in the analysis and cannot be generalized.

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