Analysis of the Damping Effect of Rubber Damping Layer under Explosive Load

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Abstract. In order to study the influence of the thickness of the rubber damping layer on the damping performance of the rock mass arch structure under explosive load, a finite element model was established based on the ANSYS/LS-DYNA dynamic finite element analysis software, and four rubber damping layers with different thicknesses of 0 m, 0.2 m, 0.4 m and 0.6 m are set between the rock mass and the lining. The fluid-solid coupling algorithm is used to compare and analyze the maximum effective stress, peak pressure and peak displacement of the outer lining dome, spandrel and arch foot elements. Numerical simulation results show that the maximum effective stress of the arch, spandrel and arch foot decreases after setting the vibration damping layer, and the arch foot reduces by more than 80%; with the increase of the thickness of the vibration damping layer, the peak pressure of the vault, spandrel and arch foot decreases, and the peak displacement increases. When the thickness exceeds 0.4 m, the damping and anti-blasting effect is not obvious, and the peak displacement tends to be stable; the vault is a strong response part, and reinforcement measures should be taken; comprehensive consideration of economic factors, it is recommended to set a 0.4 m thick damping layer.

1. Introduction
The rapid development of precision-guided ground penetrating bombs poses a serious threat to today's underground protection engineering. Although the protection project is built in a rock mass with high strength and good integrity[1-3], the strong vibration generated by the explosion will still make the structure respond violently, causing casualties and equipment damage.

In recent years, scholars at home and abroad have conducted a lot of research on vibration reduction and isolation of underground structures[4-6], and found that setting a vibration reduction layer between the lining and the structure layer can effectively reduce structural vibration damage. Huang Sheng et al.[7] found that both rubber and rubber shock-absorbing layers showed good seismic effects; Xu Hua et al.[8] compared different shock-absorbing layer setting modes and found that soft shock-absorbing layers should be used; Wang Shuaishuai et al.[9] analyzed the stress changes after the tunnel was installed with the shock-absorbing layer, and obtained the optimal shock-absorbing layer design method; Cui Guangyao et al.[10] studied the shock-absorbing layer shock-absorbing technology under strong vibration through experiments; for the underground structure Wang[11], Zhao et al.[12] and Chen et al.[13] put forward the idea of seismic isolation of seismic isolation layer, and then carried out related theoretical analysis and experimental research; Shen Yusheng et al.[14] proposed seismic measures for damping layer combined with flexible joints it effectively suppressed the longitudinal crack propagation of the cross tunnel under the action of strong earthquakes. Feng Muhua et al.[15] conducted
pressure analysis of the rubber layer surrounding the underground well structure under impact load and found that the rubber layer can effectively reduce the impact pressure on the wellbore; Chen Wen\cite{16} technical and economic analysis of the rubber shock-isolating cushion layer shows that it has the characteristics of extending the vibration period of the building, reducing the seismic effect, low-cost, high-quality, economical and environmentally friendly. The above studies show that the rubber damping layer in the underground structure has a good damping effect and high application value.

Due to the high risk and high cost of the explosion experiment, this article aims at the research on the vibration reduction of the underground cavern under the explosion load. Based on the ANSYS/LS-DYNA numerical simulation method, the finite element model of the underground cavern with rubber damping layer is established. Four rubber damping layers with different thicknesses of 0 m, 0.2 m, 0.4 m and 0.6 m are set between the rock mass and the lining. The dynamic response of the structure is discussed from the angles of effective stress, pressure and displacement of the lining vibration effect.

2. Numerical simulation

2.1. Numerical model
The calculation model is: a straight wall arch structure in type III rock mass, with a span of 14 m and an arch height of 6.5 m, of which the straight wall is 2.0 m high and the buried depth is 10 m. The rock mass is granite. The numerical model is composed of surrounding rock, bolt reinforcement layer, damping layer, lining, air and explosives. The damping layer is made of high elastic rubber, and the full section is set between the reinforcement layer and the lining layer.

The lining is reinforced concrete with double-layered reinforcement and mixed pouring. Considering that the surrounding rock has a higher strength level and a better self-carrying capacity, at the same time, to coordinate the deformation of the damping layer, the floor and the straight wall are set separately. The specific setting is shown in Fig 1, and the distribution of steel bars is shown in Fig 2.

The working condition is that the GBU-28 ground penetrating projectile penetrates the roof of the cave vertically. According to the past experience formula, the penetration depth formula of the ground penetrating projectile suitable for rock mass is summarized. For the type III surrounding rock, the calculation can be obtained that the penetration depth of the GBU-28 penetrating projectile is 4.85 m, which is taken as 5.0 m in this paper. Considering only the destructive effect of weapon explosions on the structure of the rock mass, it is a closed explosion. The explosive is placed vertically inside the rock mass, and the tip is 5.0 m from the ground. Considering the calculation efficiency, the depth is 2.0 m, and the 1/4 model is modeled. The equivalent cylindrical charge size is 0.3 m*0.3 m*2.1 m, the TNT charge is 306 kg, and the center detonation. The symmetry plane imposes corresponding symmetry constraints, and the non-reflective boundary is set on other surfaces except the upper surface. The dynamic calculation model is shown in Fig 3.

Fig1. Lining elements Fig2. Steels elements
2.2. Element and material model

The reinforcement element type is Link160, and the other element types are 3D Solid164. The fluid-solid coupling algorithm in LS-DYNA is used to describe the whole process of the explosion. The air and explosives are defined as fluids. The space where the explosives may expand is set up with ALE space. For rock mass, reinforcement layer, damping layer and lining, Lagrange algorithm is adopted. The coupling method deals with the effect of explosives on rock masses and caverns. The interaction between the lining and the damping layer is simulated by a contact algorithm.

The plasticity follow-up strengthening model (*MAT_PLASTIC_KINEMATIC) related to the material selection rate of steel bar, surrounding rock and reinforcement layer, see reference [17] for parameters. The concrete adopts the H-J-C constitutive model. This model can better describe the mechanical behavior of concrete under high strain rates such as explosive load. See reference [18] for specific parameters. Rubber adopts the *MAT_MOONEY-RIVLIN_RUBBER model, and the parameters are shown in Table 1. The air is described by the *EOS_LINEAR_POLYNOMIAL state equation and *MAT_NULL model, and the specific parameters can be found in literature [19]. TNT explosives are described by the *MAT_HIGH_EXPLOSIVE_BURN material model combined with the *EOS_JWL equation of state, and the specific parameters are described in the literature [20].

![Fig3. Dynamic analysis model](image)

### Tab1. Rubber model parameters

| RO/kg.m³ | PR | A      | B      | REF |
|----------|----|--------|--------|-----|
| 1150     | 0.5| 500000 | 35000  | 0   |

3. Simulation result analysis

Select the external vault, spandrel and arch foot units of the cavern lining, and compare the maximum effective stress, peak pressure and peak displacement under different working conditions.

3.1. Stress analysis

It can be seen from the comparison of Fig4 that: (1) The effective stress is the largest at the vault as it is closest to the burst center. The arch foot is close to the vault without a vibration damping layer. This is because the upper load is mainly transmitted to the lower part through the arch foot, and the spandrel is effective. The stress is the smallest; (2) The maximum effective stress of the arch and the arch foot is reduced after the vibration damping layer is installed, and the maximum effective stress of the arch foot is reduced by more than 80%, which is less than the spandrel stress at this time. This is because the rubber under the arch foot changed the original rigid contact and buffered the
load transmitted by the arch foot through deformation, indicating that the rubber vibration damping layer improved the internal force of the lining layer and played a vibration damping effect; (3) The spandrel is the most effective after setting the vibration damping layer. The stress is first reduced and then increased, but it is still less than the rigid contact condition after the increase. This is because the vibration damping layer displaces each part of the cavern, and the spandrel is located at the upper and lower connection parts of the cavern to coordinate the increase of internal deformation stress. (4) As the thickness of the damping layer increases, the maximum effective stress of the vault and arch foot continues to decrease. When the thickness of the damping layer exceeds 0.4 m, the damping effect is not obvious.

3.2. Pressure analysis
It can be seen from Fig5 that with the increase of the thickness of the vibration damping layer, the pressure of the outer lining generally decreases, indicating that the rubber layer has a greater attenuation of the stress wave than the reflected load, which has the effect of reducing vibration; On the one hand, the upper damping layer has low wave impedance and attenuates the stress wave. On the other hand, there is also a lower damping layer to buffer the upper load and improve the force of the arch foot; the pressure attenuation effect is not good after the damping layer is 0.4 m thick. The pressure increased slightly.

3.3. Displacement analysis
During the load application process, the stress wave passes through the arch, the spandrel and the arch foot successively, and the pressure is transmitted from the arch foot to the lower material of the cavity.
When the damping layer is not installed, the arch foot is in rigid contact with the rock mass and cannot be deformed greatly, so the internal force is relatively large; after the damping layer is installed, the stress wave is attenuated, the arch foot is displaced, and the explosion energy is absorbed to improve the lining power situation.

It can be seen from Fig6: (1) After the vibration damping layer is installed, the displacement of each part of the lining increases, and the peak displacement of the dome is the largest, increasing from 14 mm to 30 mm. The displacement of the spandrel and arch foot is small, and the spandrel is slightly larger than the arch foot, the overall displacement is controlled within 30 mm, which can ensure the safety of the cavern. (2) The spandrel and arch foot are connected by a straight wall with reinforced steel, the relative displacement is small, and the peak displacement increases with the increase in thickness, and finally stabilized at about 25 mm. (3) With the increase of the thickness of the vibration damping layer, the peak displacement continues to increase. When the thickness exceeds 0.4 m, the increase is not obvious.

Fig6. Maximum displacement curves of different conditions

4. Conclusion
When the 306 kg equivalent explosive exploded 5 m above the straight wall arch structure in a rock mass of 10 m deep, the lining was in a stable state. Comparison of different working conditions draws the following conclusions:

(1) The rubber damping layer is set to reduce the effective stress of the lining, and the arch foot is reduced by more than 80%, which has a damping effect;

(2) The rubber damping layer attenuates the stress wave and reduces the stress on the structure. The arch foot reduces most obviously, which plays a role of anti-explosion;

(3) As the layer thickness increases, the maximum effective stress and peak pressure decrease, and the peak displacement increases, and the change is not obvious after 0.4 m;

(4) The two angles of force and displacement are both the maximum value of the vault, and measures should be taken to strengthen the vault. Considering economic factors, it is recommended to install a 0.4 m thick rubber damping layer.

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