Shock absorption analysis based on the tunnel-soil-surface building interaction system

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\textbf{ABSTRACT}
In order to apply damping technology to complex interaction system, a two-dimensional finite element-infinite element coupling model of tunnel-soil-surface building interaction system was established by ABAQUS. By analyzing the acceleration, displacement and stress response of key points of tunnel and surface buildings, the influence of the thickness and buried depth of the shock absorption layer on the damping effect of the system is studied when tunnel shock absorption layer (or foundation shock absorption layer) is set separately. And a combined shock absorption system is proposed for the complex interaction system, and the primary and secondary relationship of different factors on the damping effect is studied by orthogonal experiment. The results showed that: (1) setting up a tunnel shock absorption layer can significantly reduce the maximum principal stress of the tunnel and the acceleration of the surface building; (2) when the buried depth of the foundation shock absorption layer was 0 m, the damping effect was the best, which can significantly reduce the acceleration and relative displacement of the surface building; (3) The combined shock absorption system can achieve good damping effect under different seismic waves excitation and its damping effect was better than single shock absorption layer system.

\textbf{1. Introduction}
With the rapid development of urbanization, improving the seismic performance of buildings and ensuring the safety of people’s lives and properties have become issues that need to be studied urgently. In recent years, researches on damping technology has attracted people's attention. Compared with traditional anti-seismic methods for reinforcing structures and foundations, the damping technology can absorb seismic energy with its shock absorber so as to reduce the energy transferred to the structure. It can not only improve the anti-seismic performance of the structure more effectively, but also reduce the cost and facilitate the construction, which has great economic and social benefits (Zhao, Chen, and Yang 2018; Chen, Zhao, and Lou 2016).

Scholars from all over the world have carried out a large number of studies in terms of damping technology. Among them, the representative work on the shock absorption technology of underground structures are as follows: Seyyed et al (Hasheminejad and Miri 2008) explored the damping effect of different damping materials on underground tunnels, and find that the smaller the elastic modulus of the shock absorption layer is relative to surrounding rock, the more significant its damping effects; Chen et al (Chen, and Bian 2014) set rubber bearing and shear plate damper, respectively, in the middle column of subway station, and studied the damping effect of two damping measures on subway station. The results show that the two damping measures can effectively reduce the internal force response of subway station; Tao et al (Tao, Junhai, and Nan 2016) and Wang et al (Zhuang et al. 2019) set sliding bearing at the end of subway central column, and studied the influence of sliding bearing on the seismic response of subway station. The results show that sliding bearing can effectively improve the seismic performance of subway station; Huang et al (Huang et al. 2019) studied the influence of sponge rubber and foam board damping materials on the seismic response of a circular tunnel, and the results show that the shock absorption layer can effectively reduce the seismic response of the tunnel. When the sponge rubber is set as a shock absorption layer, the dynamic response of the circular tunnel dynamic response is more attenuated than that with foam board. In the study of damping technology of the underground structure, the shock absorption layer is usually set between the underground structure and the surrounding rock to cut off the binding force of the surrounding strata on the tunnel under the condition of ensuring its stiffness. At the same time, the flexible characteristics of
the shock absorption layer are used to block and absorb the energy of seismic wave, so as to reduce the energy of earthquake transmitted to the underground structure. So the seismic response of underground structure is greatly reduced. At present, the same conclusion has been obtained in the study of damping technology of underground structures: the material of the shock absorption layer must have certain elasticity, so that it will not be plasticized in the earthquake and can continue to play a role in the next earthquake. In addition, the smaller the elastic modulus of the shock absorption layer is relative to the surrounding rock, the more significant the damping effect is. Current common damping materials mainly include aluminum foam, rubber, concrete foam and geosynthetic materials with damping effect, etc.

As for the research on damping technology of surface building which started earlier, a large amount of research works have been carried out all over the world, rich research results had been obtained, and they have been applied in actual engineering. At present, eight major building damping systems have been formed (Zhang et al. 2020; De Domenico and Ricciardi 2018; Mohsen, Mehdì, and Sadjad 2019; Liu, Liu, and Zhu 2019). It is worth mentioning that sand cushion is a kind of damping technology developed in recent years. Its cost is relatively low, and it is easy to implement: Li et al. (Li 1991) find that the sand cushion has a good damping effect on low-rise buildings through shaking table test; Ahmad et al (Ahmad, Ghani, and Raghib Adil 2008) compared the seismic responses of the building with or without coarse dry sand through shaking table test, and the results show that the acceleration response of the top floor of the building with coarse dry sand shock absorption layer is significantly reduced; Liu et al (Liu et al. 2019; Liu, Ren, and Liu 2015) and Sheng et al (Sheng, Xiao, and Shuiming 2019) make certain improvements to the sand cushions, which make the damping technology of sand cushions have greater development prospects. In summary, there are two main ideas about the damping technology of surface buildings. One idea is to absorb seismic energy through damping measures, so as to reduce the energy transferred to the building. It can ensure that the building is in an elastic state, improve the reliability of the building and reduce the effect of earthquake on the building. Another idea is to reduce the horizontal stiffness of the building and extend the basic period of the building by setting the shock absorption layer, which makes the basic period of the building avoid the high-energy frequency band of seismic wave. This makes most of the displacement of the building occur in the shock absorption layer, which increases the relative displacement between the upper and lower parts of the shock absorption layer and reduces the acceleration response of the building itself. This ensures the safety of the building.

Generally speaking, the current damping research is still focused on the soil-underground structure interaction system or the soil-surface building interaction system. With the development of underground traffic, there are more and more engineering cases of underground structure passing through surface buildings in short distance, and the interaction between underground structure and surface buildings cannot be ignored. At present, there is no research on damping technology of underground structure-soil-surface building interaction system. Whether the traditional damping technology can be applied to complex interaction system and how to set damping measures in complex interaction system to achieve good damping effect need to be further explored.

Based on the previous research, the damping technology was further applied to the complex interaction system in this paper for meeting the needs of modern urban construction to promote the development of shock absorption technology. Taking the tunnel-soil-surface building interaction system as the research object, a two-dimensional finite element-infinite element coupling model of the tunnel-soil-surface building interaction system is established by ABAQUS. Based on the seismic fortification intensity of 8 degrees, the seismic waves are input horizontally at the bottom of the boundary between the finite and infinite domains. By analyzing the changes of acceleration, displacement and maximum principal stress of the key points of the tunnel and the central column of surface building, the influence of the thickness of the shock absorption layer on the seismic response of the system was studied when the rubber shock absorption layer was set separately between the tunnel and the soil (hereafter referred to as “tunnel shock absorption layer”). And the influence of the thickness and buried depth of the shock absorption layer on the seismic response of the system was studied when the sand cushion shock absorption layer was set separately under the foundation of the surface building (hereafter referred to as “foundation shock absorption layer”). Then, aiming at the complex interaction system, a combined shock absorption system is proposed, which is to set the tunnel shock absorption layer and the foundation shock absorption layer at the same time, and the primary and secondary relationship of different factors on the damping effect is studied through orthogonal experiment. In addition, in order to explore the applicability of the combined shock absorption system, the damping effect of the combined shock absorption system under different seismic waves excitation was studied. The purpose is to explore the development of damping technology,
and the research results can provide reference for the construction of complex interaction system engineering.

2. Dynamic analysis model and solution method

The calculation model and the location of key points was shown in Figures 1 and 2. The surface building was a multi-layer shear frame structure, while the tunnel is shield with no changes in section and built along the length of buildings, which can be simplified as a two-dimensional plane problem. So soil was simulated by two-dimensional plane strain elements, and the frame structure was simulated by two-dimensional beam elements. The surface building was a two-span six-story concrete frame structure with a floor height of 3 m and a span of 6 m. Its beam section size was 300 mm×600 mm, its column section size was 600 mm×600 mm, and its foundation was a 1 m thick raft foundation. The outer diameter of the tunnel R is equal to 6.4 m, its lining thickness is 0.4 m, and its buried depth was 15 m. All components were made of C30 concrete. In order to avoid the influence of too many factors on the seismic response of the system, the soil can be considered as a single homogeneous soil layer. The molar-coulomb model is used for the constitutive relation of soil. The rubber shock absorption layer was set between the tunnel and the soil, while the sand cushion shock absorption layer was set under the foundation of surface building. The material parameters were shown in Table 1.

2.1. Dynamic solution method

The dynamic solution methods in ABAQUS include modal analysis method and direct integration method.
(Wang and Zhang 2014). The modal analysis method is suitable for calculating the natural frequency of the structure. When analyzing the nonlinear dynamic response problem, the method of directly integrating the equation of motion must be used. Direct integration methods in ABAQUS mainly include implicit integral algorithm and explicit integral algorithm. Compared with the explicit integral algorithm, the implicit method is more suitable for dynamic analysis with long calculation time. Therefore, we will choose the implicit integration method in this paper. When the time history analysis method is used, the solution of the motion equation of the system is completed by the step-by-step integration method. The dynamic equilibrium equation of the dynamic interaction system between tunnel, soil and surface building is (Zhuang 2006):

$$[M] \dot{u} + [C] \ddot{u} + [K] u = -[M] (l) xg(t) \quad (1)$$

Among them, $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $xg(t)$ is the acceleration time history of the input seismic wave, $\{u\}$ is the relative displacement vector of the structure, $\{l\}$ is the vector of inertial force.

Firstly, a parameter $\alpha$ is introduced to control the integral stability, the formula 1 is rewritten as follows:

$$\{u\}_{t+\Delta t} = \{u\}_t + \{\dot{u}\} \Delta t + (1/2 - \beta)u \Delta t^2 + \beta u t + \Delta t \Delta^2 + \beta u t \Delta t \Delta^2 + \Delta t \Delta^2 \quad (3)$$

$$\{\ddot{u}\}_{t+\Delta t} = \{\ddot{u}\}_t + (1 - \gamma)u \Delta t + \gamma u t + \Delta t \Delta t \quad (4)$$

In the formula,

$$\beta = \frac{1}{4} - a^2 \gamma = \frac{1}{2} - a $$

This integral method is unconditionally stable. When $\alpha = 0$, this method is called Newmark – $\beta$ method. Assuming that the acceleration value changes linearly in any time step, that is:

$$u = \{u\}_t + t^2 \{\Delta u\} + (t - t^2 \cdot \Delta t \cdot \{\dot{u}\}_t + \Delta t^2 (1 - t) \cdot \Delta t \cdot \{\ddot{u}\}_t + \Delta t^2 (1 - t) \cdot \Delta t^2 \cdot \dot{u} \quad (5)$$

Combine (1)(2)(3) to get:

$$u = \{u\}_t + t^3 \{\Delta u\} + t (t - t^2 \cdot \Delta t \cdot \{\dot{u}\}_t + \Delta t^2 (1 - t) \cdot \Delta t \cdot \{\ddot{u}\}_t + \Delta t^2 (1 - t) \cdot \Delta t^2 \cdot \dot{u} \quad (6)$$

$u = \frac{\gamma}{\beta \Delta t} \{\Delta u\}_t + \left(1 - \frac{\gamma}{\beta} \right) \{\dot{u}\}_t + \left(1 - \frac{\gamma}{2 \beta} \right) \cdot \Delta t \cdot \{\ddot{u}\}_t \quad (7)$

$$\Delta t = \frac{1}{\beta \Delta t^2} \{\Delta u\}_t - \frac{1}{\beta \Delta t} \{\dot{u}\}_t + \left(1 - \frac{1}{2 \beta} \right) \cdot \Delta t \quad (8)$$

The displacement, velocity, and acceleration of a point at any time within a certain time step can be obtained by using formulas (6), (7), and (8). It can be seen that the computational resources required by the implicit integral algorithm are relatively large, and when the computing model contact situation is complicated, it is easy to cause non-convergence. At this time, we can appropriately reduce the analysis step size or increase the grid size.

### 2.2. Key issues of dynamic analysis

#### 2.2.1. Artificial boundary and mesh sensitivity analysis

At present, the infinite element method is widely used in the dynamic analysis of complex soil-structure interaction system. A kind of common idea is to divide the soil into a far-field area and a near-field area, that is, the coupling method of finite-infinite element. The near-field area is simulated by finite elements, while the far-field area is simulated by infinite elements. According to Jiang et al research results (Jiang, Xu, and Zheng 1999), if the finite element soil is more than 5 times, the width of the structure and the infinite element area reaches 20–25 m, precision requirements will be satisfied, when the coupling method of finite-infinite element is used for analysis. In this paper, the calculation depth and width of the finite element area is 60 m and 100 m, respectively, and the infinite element area is 60 m. The model is shown in Figure 1.

It is necessary to discretize the computational domain when using finite element method for numerical simulation. If the element size is too large, the propagation of high-frequency seismic waves will be hindered and the accuracy of numerical simulation will be reduced. If the element size is too small, the calculation amount will be increased and the calculation efficiency will be reduced. Therefore, it is necessary to reasonably consider the size of the element to ensure the accuracy of numerical simulation and reduce the

| Material | Damping ratio | Density Kg/m$^3$ | Elastic modulus Gpa | Poisson’s ratio | Cohesion | Friction angle |
|----------|--------------|-----------------|---------------------|----------------|----------|---------------|
| Soil     | 0.1          | 1800            | 0.216               | 0.4            | 20       | 25            |
| Concrete | 0.05         | 2500            | 30                  | 0.15           |          |               |
| Rubber   | 0.223        | 1000            | 0.001               | 0.45           | 0.6      | 6             |
| Sand cushion | 0.3  | 2000           | 0.023               | 0.31           | 0        | 39            |
time of calculation. From the existing research conclusions, the specifications of the mesh size in various documents are shown in Table 2.

In the table: \( \lambda \) is the wavelength corresponding to the highest frequency of the seismic wave, \( \lambda = V / f_{\text{max}} \).

\( V \) – shear wave velocity, \( V = \sqrt{\frac{E}{\mu (1 + \nu)}} \) is the elastic modulus, \( \mu \) is the Poisson’s ratio, \( \rho \) is the density;

\( f_{\text{max}} \) – Maximum frequency of seismic wave;

It can be seen from Table 2 that the specifications of the mesh size in various documents were similar. Therefore, we first take \( x \leq \lambda / 8 \) (i.e. \( x \leq 1 \text{m} \)) for modal analysis of the free field. In order to compare the influence of mesh accuracy on the resonance modes of each order, modal analysis meshing from coarse to fine is carried out. The results are shown in Table 3.

It can be seen from Table 3 that:

1. For the free field model, the simple empirical formula of the fundamental frequency is \( f_{\text{sf}} = 1 / T = V / (4H) = 0.8626 \) (\( H \) is the depth of soil), the numerical calculation results were consistent with the theoretical value. This showed that when \( x \leq 1 \), the accuracy of the calculation results was reliable.

2. For the tunnel-soil-surface building interaction system, comparing the calculation results of working conditions \( 1 \leq x \leq 2, 2 \leq x \leq 3, 3 \leq x \) with \( x \leq 1 \). The maximum change of natural frequency both occurs in 3rd order, the maximum changes were 0.41%, 6.37%, and 10.54%, respectively.

When \( 1 \leq x \leq 2 \), the change caused by the mesh size was very small, it can fully meet the general requirements, and the computational efficiency can be effectively improved. Therefore, the soil around the tunnel was divided into a mesh every 1 m in this paper, and the rest was divided into a mesh every 2 m.

While The beam and column of surface building were divided into a mesh every 1 m.

2.2.2 damping setting

Rayleigh damping model was adopted (Lin et al. 2020), assumed that the damping matrix of the structure was a combination of the mass matrix and the stiffness matrix, namely:

\[ [C] = [a] [M] + [\beta] [K] \]  \hspace{1cm} (9)

Among them, \([C]\), \([M]\), \([K]\) is the damping matrix, the mass matrix and the stiffness matrix, respectively; \( a \) is the damping coefficients proportional to the mass, \( \beta \) is the damping coefficients proportional to the stiffness. The calculation formula of the damping coefficient are as follows:

\[ a = \frac{2\omega_i \omega_j}{\omega_i + \omega_j} \]  \hspace{1cm} (10)

\[ \beta = \frac{2\xi}{\omega_i + \omega_j} \]  \hspace{1cm} (11)

In the formula: \( \omega_i, \omega_j \) are the characteristic frequency, the first and second fundamental frequencies of the system is selected in this paper; \( \xi \) is the damping ratio.

2.2.2. Contact relationship

By defining contact pairs between the soil and the structure, the interaction between soil and structure can be effectively simulated, whose key lies in the selection of “master surface”-“slave surface” and the contact tracking method. The interface condition included the master surface and slave surface. The nodes on the slave surface will not pass through the master surface, but the nodes of the master surface can pass through the slave surface. At the same time, there are normal and tangential forces between the contact surfaces.

According to the ABAQUS help file, the soil with larger size and coarser mesh was defined as the master surface. For tangential action, a penalty function algorithm was used to describe the friction characteristics between the contact surfaces, allowing elastic slip deformation. For normal action, it was defined as “hard contact”, that is, force transmission occurs only when two contact surfaces are in contact; In the contact tracking method, considering that the sliding deformation between the contact surfaces was small, the small sliding algorithm was adopted. To fix the contact between the slave surface node and the master surface node in the same local area during the analysis process, which can also improve the calculation speed.

2.2.3. Seismic wave input

According to the “Code for Seismic Design of Buildings” (GB 50,011–2010) of China, when the time-history method is used for calculation, at least two

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**Table 2.** The specifications of the mesh size in the documents.

| Reference       | Specifications of the mesh size |
|-----------------|--------------------------------|
| (Yuxian 2009)   | \( x \leq (1/8 - 1/4) \lambda \) |
| (Wang 1997)     | \( x \leq (1/8 - 1/5) \lambda \) |
| (Kellezi 2000)  | \( x \leq (1/8 - 1/2) \lambda \) |

**Table 3.** Mesh sensitivity analysis.

| Calculation model          | Free field | Tunnel-soil-surface building interaction system |
|----------------------------|------------|-----------------------------------------------|
| Range of mesh size (m)     | \( x \leq 1 \) | \( 1 \leq x \leq 2 \) | \( 2 \leq x \leq 3 \) | \( 3 \leq x \) |
| Natural frequency          |            |                                               |                                               |                                               |
| 1                          | 0.8626     | 0.8589                                       | 0.8591                                       | 0.8776                                       | 0.9169                                       |
| 2                          | 1.6713     | 1.6616                                       | 1.6635                                       | 1.6877                                       | 1.7755                                       |
| 3                          | 2.1665     | 1.8844                                       | 1.8766                                       | 2.0044                                       | 2.0831                                       |
| 4                          | 2.2719     | 2.2709                                       | 2.2669                                       | 2.2968                                       | 2.4491                                       |
| 5                          | 2.5871     | 2.2816                                       | 2.2889                                       | 2.3681                                       | 2.4567                                       |
actually captured seismic waves and one artificially synthesized seismic wave should be selected for analysis according to the environment and site of the building. Beijing area is taken as the research background that its seismic fortification intensity is 8 degree, its earthquake group is 2nd group, its site type is class II, and its characteristic period is 0.4s. According to the spectrum characteristics of seismic waves, El-Centro waves with wide frequency distribution and close to characteristic period of the site, Kobe waves with narrow frequency distribution and Shanghai artificial waves with long characteristic period are selected respectively. The seismic response of tunnel-soil-surface building interaction system under different spectral characteristics of seismic wave excitation is compared. The seismic waves are input horizontally at the bottom of the boundary between the finite and infinite domains. The acceleration time history, Fourier amplitude and acceleration response spectrum are shown in Figures 3–5:

2.3. Calculation conditions

Focusing on the tunnel-soil-surface building interaction system, the influence of the shock absorption layer on the seismic response of the system under different factors was explored. The calculation conditions were as followed:

(1) Analysis of single shock absorption layer

a. A rubber shock absorption layer between the tunnel and the soil was set up: the damping effect was explored when the thickness of the shock absorption layer were 20 cm, 40 cm, 60 cm, and 80 cm respectively;

| Table 4. Factor-level table. |
|-----------------------------|
| Level | Thickness of tunnel shock absorption layer(cm) | Buried depth of foundation shock absorption layer(m) | Thickness of foundation shock absorption layer(cm) |
| 1     | 20     | 0      | 20     |
| 2     | 40     | 2      | 40     |
| 3     | 60     | 4      | 60     |
| 4     | 80     | 6      | 80     |

b. A sand cushion shock absorption layer under the foundation was set up: the damping effect when the thickness of the shock absorption layer was 20 cm, 40 cm, 60 cm, 80 cm respectively, and the buried depth of the shock absorption layer was 0 m, 2 m, 4 m, 6 m, respectively, (the distance between the shock absorption layer and the bottom of the foundation) was explored.

(2) Analysis of combined shock absorbing system

The orthogonal experiment designed of 3 factors and 4 levels was carried out on the system without considering the interaction. The factor-level table was shown in Table 4. The orthogonal experiment results would be analyzed to explore the primary and secondary effects of each factor on the damping effect of the system.

(1) The influence of seismic wave excitation

The damping effect of setting up combined shock absorption system with different seismic wave excitation (el-Centro wave, Kobe wave and Shanghai artificial wave) was explored.

3. Analysis of calculation results

3.1. Analysis of shocking effect of tunnel shock absorption layer

It can be seen from Figure 4 that the frequency distribution of El-Centro wave was relatively uniform, which can effectively simulate seismic wave excitation of various frequencies, so the El-Centro wave was selected in this section. The calculation and analysis in this section were subject to the conditions of 8 degree seismic fortification intensity, 0.2 g designed basic seismic acceleration amplitude and II site type. The seismic response analysis of the system was carried out by setting a rubber shock absorption layer between the tunnel and the soil. The relationship of the acceleration, displacement and maximum principal stress peak value at each key point of the tunnel and surface structure and the thickness of the shock absorption layer were shown in Figures 6 and 7, respectively.

Figure 4. Seismic wave Fourier amplitude curve.
3.1.1. Influence of shock absorption layer thickness on tunnel

As can be seen from Figure 6, under the same shock absorption layer (SAL) thickness, the peak values of acceleration, displacement and maximum principal stress of tunnel lining had high symmetry at the same horizontal plane. This showed that the tunnel lining had better integrity under earthquake. At the arch shoulder and arch foot of tunnel lining, there were high stress areas. That was, the maximum principal stress presents an “X” distribution on the lining. This was consistent with the conclusions obtained in the literature (Zhiping, Wei, and Zhang 2017; Pan and Peng 2019).

As can be seen from Figure 6(a), under the action of the shock absorption layer, the peak acceleration of each key point of the tunnel lining was reduced compared with the condition without shock absorption layer. This was because the seismic energy was absorbed by the rubber shock absorption layer during the propagation process, thereby the energy transmitted to the tunnel is reduced and the acceleration response of tunnel is weakened. When the thickness of the shock absorption layer was 20 cm, the damping effect was the best, with an average reduction of about 12%. However, with the increased of the thickness of the shock absorption layer, the peak acceleration of
each key point of the lining increases. This showed that the acceleration response of the tunnel lining did not decrease with the increase of the thickness of the shock absorption layer, but the best shocking effect can be achieved only when a shock absorption layer of reasonable thickness is installed. So for setting rubber shock absorption layer, its thickness should be controlled between 20 cm and 40 cm, which has the best weakening effect on the acceleration response of the tunnel.

As can be seen from Figure 6(c), as the thickness of the shock absorption layer increases, the maximum principal stress peak value at each key point of the tunnel lining is decreased. Especially at the arch shoulder and arch foot of high stress area, the reducing effect was very significant. This was because the rubber shock absorption layer were a flexible material with a small elastic modulus and has a good cushioning effect. At the same time, the rubber shock absorption layer also has so good shocking characteristics that the seismic energy was consumed by repeated compression and deformation in the process of seismic wave propagation, which reduced the stress distribution of the tunnel. Compared with no shock absorption, at the most vulnerable arch shoulder and arch foot, when the shock absorption layer of 20 cm, 40 cm, 60 cm and 80 cm was set, respectively, the reducing effect of maximum principal stress was about 43%, 69%, 75% and 78%, respectively. That was, as the thickness of the shock absorption layer increased, the damping effect is more obvious. However, when the thickness of shock absorbing layer increased to a certain extent, the damping effect gradually tended to be stable. Considering the economy, the thickness of shock absorption layer should be controlled at about 60 cm, which can effectively reduce the stress distribution of tunnel lining in practical engineering.

As can be seen from Figure 6(b), with the change of the thickness of the shock absorbing layer, the variation law of the displacement of the tunnel was different from that of the acceleration and the maximum principal stress. Setting the shock absorption layer did not reduce the peak displacement of the tunnel, but increased the peak displacement response of the key points of the tunnel. This was because the elastic modulus of the shocking layer set was too small, which did not exert a good constraint effect on the lining under the action of earthquake. So the displacement deformation of the tunnel structure was enlarged to a certain extent, but the amplification effect of the shocking layer on the displacement of the tunnel structure was limited. It can also be seen that it was not that the smaller elastic modulus the better, when choosing the material of the tunnel shock absorption layer. The shock absorption layer material with too small elastic modulus can weaken the acceleration and stress response of tunnel lining obviously, but it will enlarge the displacement response of tunnel.

### 3.1.2. Influence of shock absorption layer thickness on surface building

As can be seen from Figure 7(a), the peak acceleration of the center column showed a decreasing trend with the increased of the thickness of the shock absorption layer. This was because the seismic wave interacts with the shock absorption layer during the propagation process, a new wave source was formed on the surface of the shock absorption layer and it scattered in all directions, which changing the site response of the soil. At the same time, the rubber shock absorption layer also absorbed the seismic energy to a certain extent. Under the joint action of the two the acceleration response of the surface building was reduced. Especially for the top layer with the greatest acceleration response, the reducing effect reached about 25%. However, the reducing effect of the shock absorption layer of different thickness on the acceleration response of the center column was relatively close. As can be seen from Figure 7(b), the surface displacement of the soil is changed when setting up a shock absorption layer, thereby the displacement response of the surface building is reduced. When the thickness of the shock absorption layer was 20 cm, 40 cm, 60 cm, and 80 cm respectively, the peak displacement of the surface building was reduced. And the reducing effect of the shock absorption layer of different thickness on the displacement of the center column was about 10%. As can be seen from Figure 7(c), setting the shock absorption layer has little effect on the maximum principal stress distribution of the center column. When the seismic wave is input, the center column of the first floor was a high-stress area, which should be considered emphatically in anti-seismic design.

### 3.2. Analysis of damping effect of foundation shock absorption layer

#### 3.2.1. Influence of foundation shock absorption layer thickness

In this section, the El-Centro seismic wave with a peak acceleration of 0.2 g was input, and the damping effect of different thickness sand cushion at 0 m under the foundation was compared and analyzed. The changes of peak value of acceleration, displacement and maximum principal stress at key points of surface building structure and tunnel with the thickness of shock absorption layer were showed in Figures 8 and 9 respectively.

As can be seen from Figure 8(a), When the foundation shock absorption layer was set, the acceleration response of the center column was significantly
reduced. This is because the sand cushion shock absorption layer extended the natural vibration period of the surface building. At the same time, the sand cushion shock absorption layer has a good filtering effect on the high frequency components of seismic waves. The acceleration response of the structure increased in the low frequency range and decreased in the high frequency range. As the thickness of the shock absorption layer increased from 20 cm, 40 cm, 60 cm, and 80 cm, respectively, the

acceleration response of the center column gradually decreased, and the reducing effect of the peak acceleration of the top layer of the center column was about 15%, 22%, 26%, and 32%, respectively. As can be seen from Figure 8(b), When the foundation shock absorption layer was set, the peak displacement response of the center column of the bottom layer was increased. This was because the shock absorbing layer with a smaller elastic modulus under the foundation resulted in the vertical stability is weakened, which increased the displacement response caused by the horizontal motion component, and produced greater deformation under the earthquake. Although the shock absorption layer increased the absolute displacement of the bottom center column, but the
displacement of the top center column was reduced. When the thickness of the shock absorption layer increased from 20 cm, 40 cm, 60 cm, and 80 cm, respectively, the relative displacement reducing effect of the top and bottom layer of the center column was about 37%, 36%, 43%, and 42%, respectively. That was, the shock absorption layer effectively reduced the relative displacement between the top and bottom of center column of the surface building. Accordingly, the frame structure avoided the damage caused by excessive relative deformation under the earthquake. Its shock absorption principle was similar to the shock absorption measures of rubber bearing shock absorption system (Zhang 2018) and sliding friction shock absorption system (Du et al. 2019).

In general, the different thickness of the shock absorption layer can reduce the relative displacement of the top and bottom of the center column. The shock absorption layer has a certain reducing effect on the maximum principal stress peak value of the center columns of the 2nd and 3rd floors, but has little reducing effect on the first layer – this was the high stress area. In summary, considering the reducing effect of the shock absorption layer on the peak acceleration of the center column and the relative displacement
between the top and bottom of the column, as well as the economy in engineering practice, it was more appropriate to control the thickness of the foundation shock absorption layer at about 60 cm.

As can be seen from Figure 9(a), the acceleration peak distribution at each key point of the tunnel lining varies slightly with the thickness of the foundation shock absorption layer. When the thickness of the shock absorption layer was 60 cm, the acceleration peaks at the key points of the tunnel showed a certain increase. And when the thickness of the shock absorption layer was 80 cm, the maximum acceleration peak appeared at the bottom of the tunnel lining, at the same time, the symmetry of acceleration peak of the tunnel still existed. As can be seen from Figure 9(b,c). As the thickness of the shock absorption layer increased, the displacement and maximum principal stress changed at each key point of the tunnel lining were smaller. On the whole, different thickness of the foundation shock absorption layer has a greater impact on the acceleration of the tunnel, but less impact on the displacement and maximum principal stress of the tunnel. The reason may also be that the distance between foundation shock absorption layer and the tunnel was long and the constraint effect of soil on tunnel, so the interaction between shock absorption layer and tunnel is not obvious.

3.2.2. Influence of buried depth of foundation shock absorption layer

In this section, the El-Centro seismic wave with a peak acceleration of 0.2 g was input waves. By changed the buried depth a 60 cm thick sand cushion shock absorption layer under the foundation, the damping effect of the buried depth of the foundation shock absorption layer on the system was explored. The change of peak value of acceleration, displacement, and maximum principal stress at key points of surface building and tunnel with different buried depth of shock absorption layer are shown in Figures 10 and 11, respectively.

As can be seen from Figure 10(a), when the buried depth of shock absorption layer was 0 m, the acceleration response of each key point of the center column was reduced, and the reducing effect of the top layer of the center column reached 22%. As the buried depth of the shock absorption layer increased, the peak acceleration at the top of the center column gradually increased, and when the shock absorption layer was set at 0 m below the foundation to produce the best shocking effect on the acceleration response.

![Figure 10. The acceleration, displacement, and maximum principal stress peak value at each key point of the center column with different buried depth of the foundation shock absorption layer.](image)

![Figure 11. The acceleration, displacement and maximum principal stress peak value at each key point of the tunnel with different buried depth of the foundation shock absorption layer.](image)
of the surface building. As can be seen from Figure 10 (b), setting a shock absorption layer under the foundation can reduce the displacement of the column bottom to a certain extent. When the buried depth of the shock absorption layer was 2 m, 4 m, and 6 m, respectively, the reducing effect on the displacement of column was about 4%, 10%, and 4%, respectively. But the relative displacement of the top and bottom of the center column has not changed too much. When the buried depth of shock absorption layer was 0 m, the relative displacement of the top and bottom of the center column can be effectively reduced, and the reducing effect was about 42%. Therefore, in order to achieve a good reducing effect on the acceleration and relative displacement of the surface building, a shock absorption layer should be set at 0 m below the foundation.

As can be seen from Figure 11(a), shock absorption layer with different buried depths had a significant influence on the peak acceleration distribution of the tunnel. This was because the shock absorption layer scattered seismic waves and changed the transmission of seismic energy. When the buried depth of the shock absorption layer was 0 m, the peak acceleration of each key point of the tunnel lining showed a certain increase; When the buried depth of the shock absorption layer was 2 m, the peak acceleration of each key point of the tunnel lining has been reduced, and the reducing effect was about 11%; When the buried depth of the shock absorption layer was 4 m and 6 m, the acceleration peak distribution at each key point of the tunnel lining had changed, and the maximum value appeared at the right arch waist and left arch foot, respectively. For these phenomena, the author was currently unable to make reasonable explanation, but this showed that various factors may affect acceleration response results in the interaction system. Accordingly, when conducting seismic analysis, the interact influence of various factors cannot be ignored. As can be seen from Figure 11 (b,c), the buried depth of the shock absorption layer has a limited influence on the peak displacement and maximum principal stress peak at each key point of the tunnel lining. But this conclusion was not universal and regular. In the interaction system, factors such as the buried depth and diameter of the tunnel and the height-to-width ratio and location of the surface building can affect the interaction between the structures. Therefore, it must be analyzed based on actual problems, and the factors with greater influence should be given priority in engineering practice.

4. Analysis of combined shock absorption system

Through the above analysis, it can be found that factors such as the thickness of the tunnel shock absorption layer, the thickness, and the buried depth of the foundation shock absorption layer will affect the seismic response of the system. Then, it is necessary to study the shocking effect of the system under the simultaneous action of various factors and to get the primary and secondary relationship of each influence factor. Accordingly, in engineering practice, the factors that have great effect on the system should be given priority. Carrying out orthogonal experiment will greatly reduce the computational effort. Therefore, in this section, three different influence factors, including the thickness of the tunnel shock absorption layer, the thickness of the foundation shock absorption layer, and the buried depth of the foundation shock absorption layer, were selected for analysis at 4 levels for each factor, regardless of interaction. The orthogonal experiment factors and levels are shown in Table 4, and the experimental results and calculation analysis are shown in Table 5. The seismic wave excitation in each of these orthogonal experiments was an El-Centro wave with a peak acceleration of 0.2 g.

In the table:

$K_{ij}$ is the sum of the experimental results with level “i” in column “j”;

$\bar{K}_j$ represents the average value of the test results when the factor level of column “j” is “i”, among them, $R_j$ (‘m’ is the number of occurrences of the level “i” on the j’th column).

$R_j$ indicates the range of the j’th column, among them, $R_j = \max(K_j) - \min(K_j)$, the larger the range, the greater the influence of this factor on the experimental results.

As can be seen from Table 5, in the A4B4C1 working condition, there was the best reducing effect on the acceleration response of the top layer of the center column, and the reducing effect was 46.53%. While, under a single shock absorption layer, when the buried depth of the foundation shock absorption layer was 0 m and its thickness was 80 cm, the reducing effect on the acceleration response of the top layer of the center column was the best, and the reducing effect was about 32%. It can be seen that the shocking effect of combined shock absorption system is better than single shock absorption layer, and this is very beneficial for improving the anti-seismic performance of complex interaction systems.

As can be seen from Table 5, the biggest influencing factor for the reducing effect of the acceleration response of the top layer of the center column was the buried depth of the foundation shock absorption layer, followed by the thickness of the tunnel shock absorption layer, and finally the thickness of the foundation shock absorption layer, namely $C > A > B$. In the
| Test number | A (Thickness of tunnel shock absorption layer) | B (Thickness of foundation shock absorption layer) | C (Buried depth of foundation shock absorption layer) | Peak acceleration reduction rate of top layer of center column (%) |
|-------------|---------------------------------------------|-----------------------------------------------|---------------------------------------------------|---------------------------------------------------|
| 1           | 1 (20cm)                                    | 1 (20cm)                                      | 1 (0m)                                            | 27.34                                             |
| 2           | 2 (40cm)                                    | 2 (40cm)                                      | 1                                                  | 36.15                                             |
| 3           | 3 (60cm)                                    | 3 (60cm)                                      | 1                                                  | 44.33                                             |
| 4           | 3 (80cm)                                    | 4 (80cm)                                      | 1                                                  | 46.53                                             |
| 5           | 3 (60cm)                                    | 2 (40cm)                                      | 2                                                  | 26.66                                             |
| 6           | 1 (20cm)                                    | 2 (20cm)                                      | 2                                                  | 25.52                                             |
| 7           | 2 (40cm)                                    | 1 (0m)                                        | 2                                                  | 24.48                                             |
| 8           | 1 (20cm)                                    | 4 (0m)                                        | 2                                                  | 23.92                                             |
| 9           | 1 (20cm)                                    | 3 (40cm)                                      | 2                                                  | 23.6                                              |
| 10          | 1 (20cm)                                    | 3 (40cm)                                      | 3                                                  | 24.67                                             |
| 11          | 1 (20cm)                                    | 3 (40cm)                                      | 3                                                  | 24.97                                             |
| 12          | 1 (20cm)                                    | 3 (40cm)                                      | 3                                                  | 26.05                                             |
| 13          | 1 (20cm)                                    | 3 (40cm)                                      | 3                                                  | 26.02                                             |
| 14          | 1 (20cm)                                    | 3 (40cm)                                      | 3                                                  | 26.32                                             |
| 15          | 1 (20cm)                                    | 3 (40cm)                                      | 3                                                  | 24.94                                             |
| 16          | 1 (20cm)                                    | 3 (40cm)                                      | 3                                                  | 23.69                                             |
| \(K_1\)     | 98.55                                       | 102.81                                        | 1                                                  | 154.34                                            |
| \(K_2\)     | 110.24                                      | 111.41                                        | 1                                                  | 100.58                                            |
| \(K_3\)     | 121.14                                      | 119.93                                        | 1                                                  | 99.29                                             |
| \(K_4\)     | 125.25                                      | 121.44                                        | 1                                                  | 100.97                                            |
| \(K_r\)     | 24.64                                       | 25.7                                          | 1                                                  | 38.59                                             |
| \(K_s\)     | 27.56                                       | 27.85                                         | 1                                                  | 25.15                                             |
| \(K_0\)     | 30.29                                       | 29.88                                         | 1                                                  | 24.82                                             |
| \(K_0\)     | 31.31                                       | 30.36                                         | 1                                                  | 25.24                                             |
| \(R\)       | 6.67                                        | 4.66                                          | 1                                                  | 13.76                                             |
same way, it can be concluded that the magnitude of the influence of various factors on the peak acceleration, peak displacement and maximum principal stress peak damping effect of the tunnel and the center column. Due to space limitations, here was no longer a list calculation, the primary and secondary relationship of the influence of various factors on the system's shocking effect are shown in Table 6.

As can be seen from Table 6, the buried depth of the foundation shock absorption layer is the main factor that influences the damping effect of the surface building. That is, when the buried depth of the shock absorption layer is different, the change of seismic response of surface buildings is the most obvious. The reason is that the damping way of the shock absorption layer to the surface buildings has changed with the change of the buried depth of the foundation shock absorption layer. Only when the depth of the shock absorption layer is 0 m, the damping layer can absorb the energy of the seismic wave, and extend the natural vibration period of the surface building so that avoid the resonance between the surface building and the seismic wave, and effectively reduce the seismic response of the surface building. However, with the increase of the buried depth of the foundation shock absorption layer, the shock absorption layer can only absorb the limited seismic wave energy to produce damping effect on the surface buildings, so the damping effect is limited. Relatively speaking, the thickness of foundation shock absorption layer and tunnel shock absorption layer have no significant influence on the seismic effect of surface buildings. Because the change of the thickness of the shock absorption layer does not change the damping way of the shock absorption layer, the thickness of different foundation shock absorption layer and tunnel shock absorption layer have little influence on the damping effect of surface buildings.

For the tunnel, the thickness of the tunnel shock absorption layer is the main factor that influences the damping effect of the response of the displacement and the stress. This is because the shock absorption layer is a flexible material with a small elastic modulus and has a good cushioning effect. At the same time, the rubber shock absorption layer also has so good damping characteristics that the seismic energy is consumed by repeated compression and deformation in the earthquake, which reduces the stress response of the tunnel. Meanwhile, due to the elastic modulus of the shock absorption layer is too small, which does not exert a good constraint effect on the tunnel under the action of earthquake, so that the displacement deformation of the tunnel is enlarged to a certain extent. Therefore, with the change of the thickness of the shock absorption layer, the response of the stress and the displacement of the tunnel are changed significantly. Relatively speaking, the thickness and the buried depth of the foundation shock absorption layer are the secondary factors. This is because the foundation shock absorption layer does not act directly on the tunnel, but reduces the seismic response of the tunnel by absorbing the reflected seismic waves. Therefore, the influence of foundation shock absorption layer on the response of the displacement and the stress of tunnel is not significant. But the buried depth of the foundation damping layer is the main factor affecting the seismic response of the tunnel. This is due to the scattering phenomenon of the foundation damping layer to the seismic wave, which makes the acceleration response of the tunnel produce singular values. These result in the irregular change of the acceleration response of tunnel with the increase of buried depth of foundation.

In general, in order to reduce the seismic response of surface buildings, the buried depth of foundation shock absorption layer should be given priority. However, the influence of different thickness of foundation shock absorption layer and tunnel shock absorption layer on the seismic response of surface buildings is not obvious. So the thickness of shock absorption layer can be reduced appropriately in practical engineering. It can not only effectively reduce the construction cost, but also reduce the structural movement caused by the deformation of the shock absorption layer and improve the stability of the system; Due to the tunnel is constrained by soil, it has high symmetry and stability under earthquake. In the tunnel-soil -surface building interaction system, surface buildings are more likely to be damaged in earthquake than underground tunnels. So authors suggest that shock absorption of surface buildings should be given priority in seismic design.

### 4.1. Influence of seismic wave

It can be seen from the above chapters that the combined shock absorption system has obvious reducing effect on the acceleration of the surface building and

| Evaluation index | Primary and secondary relationship of influencing factors |
|------------------|--------------------------------------------------------|
| 1                 | C > A > B                                               |
| 2                 | C > B > A                                               |
| 3                 | C > B > A                                               |
| 4                 | C > A > B                                               |
| 5                 | A > B > C                                               |
| 6                 | A > C > B                                               |
the maximum principal stress of the tunnel. Therefore, in this section, A3B3C1 combined shock absorption system was taken as the research object, and the reducing effect of peak acceleration of the surface building and the peak maximum principal stress of the tunnel were taken as the shocking evaluation indexes. According to the “Code for Seismic Design of Buildings” of China, El-Centro seismic wave, Kobe seismic wave and Shanghai artificial seismic wave with 0.2 g peak maximum acceleration were input respectively in this section, so as to explore the effect of setting combined shock absorption system on the seismic response of this system under the different seismic waves were input. The results are shown in Figures 12 and 13.

As can be seen from Figures 12 and 13, under the action of different seismic waves, the distribution law of the acceleration peak of the surface building and the maximum principal stress peak of the tunnel was almost the same, and there were only some differences in numerical value. It can be seen that the seismic response of the system has strong regularity under the earthquake. And due to the relationship between the frequency composition of seismic waves and the frequency of the system, the transmissibility of different seismic waves in this system was different. Under the action of El-Centro wave, Kobe wave and Shanghai artificial wave, the maximum reducing effect of combined shock absorption system for the peak acceleration of the center column can reach about 44%, 35%, and 30%, respectively, and the reducing effect of the maximum principal stress peak of the tunnel can reach about 76%, 74%, and 75%, respectively. The shocking effect was significant. It can be seen that under the earthquake, setting up combined shock absorption system has a good damping effect on the seismic response of the tunnel-soil-surface building interaction system. This was very beneficial to the anti-seismic design of the system.

5. Conclusion

Taking the tunnel-soil-surface building interaction system as the research object, a two-dimensional finite element-infinite element coupling model of the tunnel-soil-surface building interaction system is established by ABAQUS. Based on the seismic fortification intensity of 8 degrees, the seismic waves are input horizontally at the bottom of the boundary between the finite and infinite domains. By analyzing the changes of acceleration, displacement and maximum principal stress of the key points of the tunnel and the central column of surface building. The influence of the thickness of the shock absorption layer on the seismic...
response of the system was studied when the rubber shock absorption layer was set separately between the tunnel and the soil. And the influence of the thickness and buried depth of the shock absorption layer on the seismic response of the system was studied when the sand cushion shock absorption layer was set separately under the foundation of the surface building. Then, aiming at the complex interaction system, a combined shock absorption system is proposed, and the primary and secondary relationship of different factors on the damping effect is studied through orthogonal experiment. In addition, the damping effect of the combined shock absorption system under different seismic waves excitation was studied. The main conclusions are as follows:

1. Setting a rubber shock absorption layer between the tunnel and the soil can reduce the maximum principal stress and accelerated of tunnel under the earthquake. Especially, the reducing effect of the maximum principal stress was particularly significant; At the same time, due to the influence of the interaction, it has a certain reducing effect on the acceleration and displacement response of the surface building. As the thickness of the shock absorption layer increases, the shock absorption effect gradually stabilizes.

2. Setting a sand cushion shock absorption layer under the foundation can effectively reduce the acceleration response of the surface building. And when the buried depth of the shock absorption layer was 0 m, the relative displacement of the ground buildings can be effectively reduced, and the best damping effect can be achieved. Since the tunnel was constrained by the surrounding soil, its seismic response has high symmetry and stability under earthquakes. Therefore, the influence of the foundation shock absorption layer on the seismic response of the tunnel was small.

3. The combined shock absorption system had a good reducing effect on the seismic response of tunnels and surface buildings. Its reducing effect on the system was better than single shock absorption layer. When the combined shock absorption system is set, the influence of different factors on the damping effect of the system has a primary and secondary relationship. In engineering practice, the factors that had great effect on the system should be given priority.

4. The results showed that the combined shock absorption system can achieve good damping effect for different seismic waves excitation.

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