Modal Research of Underground Arch Structure With Elastic Support

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Abstract. Elastic support is a commonly used method of vibration isolation and vibration reduction. The research on the mode of underground arch structure with elastic support can improve the battlefield survival ability of personnel and equipment in underground protection engineering. In this paper, the ANSYS/LS-DYNA nonlinear explicit dynamic finite element analysis program is used to numerically simulate the mode of the elastically supported underground arch structure, and the natural vibration cycle frequency variation curve and mode diagram of the structure are obtained. The results show that the elastic support reduces the natural frequency of the structure, prolongs the natural vibration period of the structure, and has a good vibration isolation and vibration reduction effect; the critical stiffness coefficient causes the first and second modes of the structure to be easily excited at the same time, which should be avoided in structural design.

1. INTRODUCTION

When the earth penetrating projectile penetrates into the soil to a certain depth and explodes, it will release huge energy in a very short time and spread around in the form of strong shock wave through the overburden of rock and soil, which makes the underground protection engineering vibrate violently under the impact load. The protection ability of underground protection engineering is facing severe challenges, which poses a serious threat to the internal personnel and weapons. By setting elastic support for underground protection engineering, the elastic support can bear and consume part of the energy generated by the ground penetrating bomb explosion, which can effectively reduce the dynamic load of underground protection engineering, reduce the internal force of the structure, and reduce the impact of vibration on the internal personnel and weapons equipment. Therefore, it is necessary to study the mode of underground arch structure with elastic support.

In 2004, Yang Y B[1] studied the dynamic characteristics of bridges with elastic support. The results show that elastic support can significantly reduce the natural frequency of the structure; in 2005, Kitamura S[2] carried out vertical loading and unloading tests on the disc spring with external diameter of 1000mm and inner diameter of 500mm. The results show that the fluctuation range of load displacement curve of large disc spring is small, which is suitable for vertical vibration isolation of structures; in 2014, Jia F[3] combined numerical simulation and experimental testing to study the mechanical properties of disc spring vibration isolators with viscous dampers, and found that friction damping significantly affected the static stiffness and loading/unloading stiffness of the combined vibration isolator, but had little effect on its static mechanical properties; in 2017, Chakraborty[4] compared basic vibration isolation such as composite rubber bearings, NZ-type foundation isolation pure friction system, and friction pendulum elastic friction foundation vibration isolator. The dynamic
The response of the device shows that a reasonable choice of basic vibration isolation system for stiffness and type can effectively reduce structural vibration.

Elastic support can effectively reduce the damage to the structure caused by instantaneous strong dynamic load or short-term strong dynamic load. By setting elastic support, the transient and strong impact energy generated by the explosion is stored in the form of potential energy, which can promote the elastic support to produce deformation and consume energy. The reflection values of the structure under external load are controlled within the allowable range, so as to reduce the structural vibration. In this paper, the elastic support is set at the bottom of the side wall and bottom plate of the underground arch structure. The influence of the elastic support with different stiffness coefficients on the natural frequency and vibration mode of the structure is numerically simulated by using ANSYS/LS-DYNA.

2. CALCULATION CONDITION
Elastic support is set at the bottom of side wall and bottom plate of underground arch structure to form underground arch structure with elastic support. In order to facilitate the study, the buried depth of the structure is 10m and the depth is 10m. The rock mass in the simulation section is class III surrounding rock, and the lithology is moderately weathered granite. The natural rock mass is an inhomogeneous medium with joints and fissures. In order to facilitate the study, the surrounding rock is regarded as a continuous and isotropic homogeneous body, and the heterogeneity, discontinuity and anisotropy of the rock are not considered, and the influence of joint fissures is not taken into account. The thickness of surrounding rock is 2m, and the diameter of early strength mortar anchor is 22mm. The underground arch structure with elastic support is composed of covering structure, bottom plate and elastic support. It is made of C35 concrete, equipped with HRB400 reinforcement, and the thickness of protective layer is 25mm. The reinforcement is arranged in a double-layer mesh with circumferential direction C22@200, longitudinal C12@200, and the joint modeling with concrete. The thickness of the covered structure is 0.5m, the rise height of inner contour is 4.5m, the clear span is 14m, the height of side wall is 2m, and the thickness of bottom plate is 0.5m. The bottom of the side wall and bottom plate of the underground arch structure with elastic support is set with 0.5m high elastic support, which is set on the upper part of 0.5m thick reinforced concrete cushion. The underground arch structure with rigid support is not provided with elastic support, and the bottom plate is in direct contact with the cushion.

3. Constitutive model and material parameters
The *MAT_PLASTIC_KINEMATIC constitutive model is used to describe surrounding rock, anchor rod reinforcement surrounding rock and steel bars. The material parameters of the surrounding rock reinforced by the bolts are selected by changing the physical and mechanical parameters of the surrounding rock in the affected range, and the elastic modulus, yield stress and failure strain of the surrounding rock are increased by 20%. The material parameters of surrounding rock, bolt reinforcement of surrounding rock and steel bar can be referred to reference [5].

The *MAT_RHT constitutive model is used to describe concrete, and the material parameters can be referred to reference [6].

The *MAT_SPRING_ELASTIC constitutive model is used to define the linear stiffness coefficient of the elastic support, and the *MAT_DAMPER_VISCOUS constitutive model is used to define the viscous damping coefficient.

4. THE INFLUENCE OF THE STIFFNESS COEFFICIENT OF ELASTIC SUPPORT ON THE NATURAL VIBRATION CIRCLE FREQUENCY OF THE STRUCTURE
The mode is the natural vibration characteristic of the structure, which is determined by the overall stiffness and quality of the vibration system. Each mode corresponds to a specific frequency, damping and modal parameters, and the fixed vibration form is also called the modal mode. The analysis method obtains the main modal characteristics of the structure in the susceptible frequency range, and can predict the actual vibration response of the structure in this frequency band under the influence of external
vibration sources. In this section, ANSYS/LS-DYNA is used to analyze the modality of the underground arch structure with elastic support and the underground arch structure with rigid support.

Define the relative stiffness coefficient \( k = KL / EI \) of the elastic support at the bottom of the side wall, where \( K \) is the stiffness coefficient, \( EI \) is the flexural stiffness of the structure, and \( L \) is the net span of the structure.

![Figure 1](image1.png)

**Figure 1** Natural circular frequency of underground arch structure with rigid support

![Figure 2](image2.png)

**Figure 2** Variation curve of natural frequency with \( k \) of underground arch structure with elastic support

| Order | Rigid support | 0  | 500k | 1000k | 1266.3k | 1500k | 2000k | 2500k | 3000k |
|-------|---------------|----|------|-------|---------|-------|-------|-------|-------|
| \( \omega_1 \) | 91.0 | 3.7 | 57.6 | 80.8 | 90.4 | 90.6 | 90.7 | 90.8 | 90.8 |
| \( \omega_2 \) | 182.0 | 15.1 | 70.9 | 89.7 | 90.4 | 98.0 | 111.8 | 123.5 | 133.4 |
| \( \omega_3 \) | 335.8 | 91.3 | 91.7 | 101.1 | 112.4 | 121.7 | 139.5 | 155.2 | 169.2 |
| \( \omega_4 \) | 432.4 | 188.5 | 189.2 | 189.9 | 190.4 | 190.8 | 191.9 | 193.3 | 194.9 |
| \( \omega_5 \) | 476.2 | 337.3 | 337.3 | 337.4 | 337.4 | 337.4 | 337.5 | 337.6 | 337.7 |

**Table 1** Natural circular frequency of each order of structure (UNIT: RAD/S)
It can be seen from Figure 1 and Figure 2 that the natural frequency of natural vibration circle of underground arch structure with rigid support and underground arch structure with elastic support increases with the increase of modal order, and the first five natural frequency of underground arch structure with elastic support is less than that of underground arch structure with rigid support; it can be seen from Figure 1 and Table 1 that the natural circular frequency of the underground arch structure with rigid support is positively correlated with the modal order, the higher the order, the greater the natural circular frequency, with $\omega_2 \sim \omega_3$ having the largest increase of 153.8 rad/s, $\omega_4 \sim \omega_5$ has the smallest increase of 43.8 rad/s; it can be seen from Figure 2 and Table 1 that when $k = 850$, $\omega_2 \approx \omega_3$, and $k = 1266.3$, $\omega_1 \approx \omega_2$, the adjacent natural frequency curves turn when they are close to each other, and there are $\omega_1 = 2\omega_1$, $\omega_3 = 3\omega_1$, $\omega_4 = 3\omega_1$, $\omega_5 = 4\omega_1$, $\omega_6 = 10\omega_1$, multiple frequency relationships among the natural frequencies; it can be seen from Figure 2 that when $k \in [0, 3000]$, the natural frequency of each order of the underground arch structure with elastic support increases with the increase of $k$, the growth rate of $\omega_1$, $\omega_2$, $\omega_3$, $\omega_4$, $\omega_5$ is in the order of $\omega_1 > \omega_2 > \omega_3 > \omega_4 > \omega_5$.

5. INFLUENCE OF STIFFNESS COEFFICIENT ON STRUCTURAL VIBRATION MODE

Figure 3 shows the modal shapes of $\omega_1$ to $\omega_5$ of underground arch structure with rigid support. After comparison and analysis with that of the underground arch structure with elastic support, it is found that at $k < 1266.3$, the modal vibration mode diagrams of $\omega_1$ and $\omega_2$ of underground arch structure with elastic support are symmetric and antisymmetric respectively, which are opposite to those of underground arch structure with rigid support; at $k > 1266.3$, the mode shapes of $\omega_1$ and $\omega_2$ of underground arch structure with elastic support are antisymmetric and symmetric, which are the same as those of underground arch structure with rigid support. It can be seen from Table 1 that when $k = 1266.3$, $\omega_1$ and $\omega_2$ of the underground arch structure with elastic support are approximately equal. Under the influence of strong impact load, the first and second modes of the structure are easy to be excited at the same time, resulting in mutual coupling effect. Therefore, $k = 1266.3$ is the dividing point of dynamic characteristics of underground arch structure with elastic support, which should be avoided in structural design.

One of the basic principles of vibration isolation is to reduce the natural frequency of the vibration system. From the above analysis, it can be seen that compared with the underground arch structure with rigid support, the natural frequency of the underground arch structure with elastic support is reduced, the natural vibration period is prolonged, the probability of resonance phenomenon caused by low-order mode excitation caused by external load is reduced, and the elastic support plays the role of vibration isolation.

![Figure 3](image-url)
6. Conclusion

(1) Compared with the underground arch structure with rigid support, the natural frequency of the underground arch structure with elastic support is reduced and the natural vibration period is prolonged. The probability of resonance phenomenon caused by low-order mode excitation is reduced due to the influence of external load.

(2) When $k = 850$, $\omega_2 \approx \omega_3$, and $k = 1266.3$, $\omega_1 \approx \omega_2$, the adjacent natural frequency curves turn when they are close to each other, and there are $\omega_3 = 2\omega_1$, $\omega_3 = 3\omega_1$, $\omega_4 = 3\omega_1$, $\omega_4 = 2\omega_1$, $\omega_5 = 5\omega_1$, $\omega_5 = 10\omega_1$, multiple frequency relationships among the natural frequencies.

(3) When $k < 1266.3$, the modal shapes of $\omega_1$ and $\omega_2$ of underground arch structure with elastic support are opposite to those of underground arch structure with rigid support; when $k > 1266.3$, the modal mode shapes of $\omega_1$ and $\omega_2$ of underground arch structure with elastic support are the same as those of underground arch structure with rigid support, $k = 1266.3$ is the boundary point of the dynamic characteristics of the elastically supported underground arch structure. When $k = 1266.3$, the first-order mode and the second-order mode of the structure are easy to be excited at the same time and the mutual coupling effect should be avoided during design.

References

[1] Yang Y B, Lin C L, Yau J D, et al. Mechanism of resonance and cancellation for train-induced vibrations on bridges with elastic bearings[J]. Journal of Sound and Vibration, 2004, 269(1-2):345-360.

[2] Kitamura S, Okamura S, Takahashi K. Experimental Study on Vertical Component Seismic Isolation System With Coned Disk Spring[M]// Realism and Moralism in International Relations: Kluwer Law International, 2005.

[3] Jia F, Zhang F C. A study on the mechanical properties of disc spring vibration isolator with viscous dampers[J]. Advanced Materials Research, 2014, 904:454-459.

[4] Chakraborty, Subrata, Ghosh, et al. Performances of various base isolation systems in mitigation of structural vibration due to underground blast induced ground motion[J]. International Journal of Structural Stability and Dynamics, 2017, 17(4):586.

[5] Wang Li. Elastoplastic damage model of rock and its application [D]. Beijing: Beijing University of science and technology, 2006.

[6] Jiang Hua, Wang Junjie. Numerical simulation of projectile vertical penetration into reinforced concrete [J]. Journal of Tongji University: Natural Science Edition, 2010, 38(4): 557-563.