Dynamic Finite Element Analysis of the Interaction of Rubber-Soil Foundation and Structure

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Abstract. A more reasonable method of semi-infinite foundation analysis was realized in this paper through the introduction of viscous-spring artificial boundary to simulate the radiation damping and elastic recovery performance of the foundation. The viscous-spring artificial boundary is realized by Combine14 element in ANSYS finite element software to realize the real dynamic characteristics of complex rubber-soil foundation under dynamic loading. Firstly, the reliability of the method is verified by comparing the method with the example of numerical solution. Finally, the optimal tunnel shape is obtained by combining the rubber-soil foundation with different shapes of tunnels.

Keywords. Rubber-soil foundation, viscous-spring artificial boundary, dynamic loading.

1. Introduction
Rubber as a polymer has been widely used in our life. Under natural conditions, waste rubber products are insoluble in water and organic solvents. Therefore, waste rubber products have caused a serious impact on our green water and green mountains, how to deal with waste rubber products has become a problem that could not be ignored. The engineering characteristics of rubber particles and sand and soil mixtures and the engineering application research have attracted great attention from scholars all over the world. Martin and Park [1] through the test of the compressive and tensile strength of the rubber sand with 5 ratios, it is found that the strength of the rubber sand is greatly affected by the mixing ratio and temperature. With the increase of rubber content, the strength of pure sand and rubber sand decreases. The optimum matching rate of rubber sand is 15%. Panjamani [2] studied the shear strength and brittleness index of rubber sand mixture with different volume and different confining pressure by the direct shear test, UU test and triaxial test. It shows that rubber sand has well isolation performance. Tafreshi and Norouzi [3] were used to reinforce the rubber debris into the soil under the foundation, and then the bearing capacity of the rubber soil was tested. The test results showed that the best suitable ratio of rubber soil, the thickness and depth of rubber soil. Wu Yanhui [4] proposed a composite isolation device combining soil and rubber particles, and the isolation technology and working principle were introduced. According to the shear strength of soil, the mechanism of new isolation device is expounded. The isolation performance of the new isolation device is analyzed by finite element numerical simulation. Wu Mengtao et al. [5] used rubber sand for foundation isolation. the basic mechanical properties were studied by static and dynamic experiments and discrete element
numerical simulation to obtain various mechanical parameters. It provides a reference for the rubber-soil foundation parameters in this paper.

For large-scale foundation research, due to the shortage of experimental conditions, a large number of large-scale foundation and the interaction between foundation and structure have been numerically analyzed at home and abroad. Lysmer [6] analysed the interaction of infinite foundation with finite element method. The results show that at least 8 elements are needed to discretize a wavelength to ensure the accuracy of calculation. Liu Jingbo et al. [7-8] gave a direct finite element method for dynamic interaction analysis of structure-foundation. The concept of uniform viscous-spring artificial boundary and viscous-spring artificial boundary element is proposed. Numerical examples show that the accuracy of viscous-spring boundary is higher than that of viscous boundary and is stable. The accuracy and effectiveness of two-dimensional model method are verified. Wang Chaoling et al. [9] applied viscous-spring boundary element in ANSYS software and Combine14 element is used to apply the viscous-spring boundary. Pei Qiang et al. [10] applied the viscosity and elasticity of Combine14 units. The seismic wave is transformed into the input stress wave of the boundary node as the external wave. The influence of element size and artificial boundary correction coefficient on boundary simulation accuracy is studied by using two-dimensional model. Liang Jianwen [11] based on the General Finite Software ANSYS, a Seismic Response Analysis Model for Underground Tunnels. It is concluded that there is a significant interaction between tunnels with small tunnel spacing and the nonlinear ground motion stress increases significantly.

At present, many achievements have been made in the study of rubber-soil mixture and the dynamic interaction between foundation and structure at domestic and abroad. However, for the application of the mixture of rubber and sand or soil to the soil layer as shock absorber, the high elasticity, energy absorption and energy dissipation characteristics of rubber are used to realize the shock absorption effect. It is not enough to study the interaction between rubber-soil foundation and structure. Therefore, this paper studies the interaction between rubber-soil foundation and structure to explore the application of rubber-soil material in foundation.

2. Theoretical Realization of Rubber-Soil Foundation

This paper introduces the viscous-spring artificial boundary to simulate infinite foundation, and the viscous-spring artificial boundary is realized by Combine14 spring damping element (figure 1) in large finite element software ANSYS. Apply the normal and tangential spring dampers on the boundary of the near-field finite field to simulate the infinite boundary:

\[ K = \alpha \frac{G}{r} \sum_{i=1}^{l} A_i \]
\[ C = \rho c \sum_{i=1}^{l} A_i \]  \hspace{1cm} (1)

In equation (1), G is the shear stiffness of soil material at the boundary, \( \rho \) is the mass density. \( r \) is the radiation radius from the scattering source to the node on the artificial boundary. When calculating the normal boundary physical element coefficient, \( c \) is the P wave velocity \( C_p \). When calculating the tangential boundary physical element coefficient, \( c \) is the S wave velocity \( C_s \). The parameter \( \alpha \) is the boundary parameter of the boundary in different directions.

![Figure 1](image-url)  \hspace{1cm} Figure 1. Combine14 Schematic diagram of damping-spring unit.
3. Method Validation

Figure 2 shows the verification model of the method in this paper. The length is $L=200$ m, the height is $H=100$ m, and the mesh size is $10 \times 10$ m. The soil material is ordinary clay. The detailed parameters are as follows: $G=5\times 10^8$ Pa, $\rho=2000$ kg/m$^3$, $\mu=0.25$, $\alpha_n=0.5$, $\alpha_t=0.5$. The dynamic load $F(t)$ acts on the model point A, the calculation time step is 0.01s, and the total time is 1.2 s. The expression of dynamic load $F(t)$ is shown in equation (2).

$$F(t) = \begin{cases} 5 \times 10^4 \sin(10\pi t) \text{KN} & t \leq 0.2s \\ 0 & t > 0.2s \end{cases} \quad (2)$$

Reference example [12] also uses two-dimensional viscous-spring artificial boundary conditions. The approximate theoretical solution is calculated by the fixed boundary model with large size, and the mesh size in the observed area is the same. Observation point coordinates are shown in table 1. The horizontal and vertical displacement time history curves of C points under sinusoidal load are given in figures 3-4, and the vertical displacement time history curves of E, F points are given in figures 5-6. The following conclusions are obtained by comparing the calculation results with the examples of literature:

Comparing with the horizontal displacement, the vertical displacement changes more obviously, and the vertical displacement peak value is larger than the horizontal displacement peak value. The peak value of vertical displacement is at the bottom B point. Since the wave energy can be completely absorbed when the B wave is perpendicular to the incident boundary, the simulation accuracy of B point is higher than that of D point. The results of this paper are compared with the examples in the literature. However, the error between approximate theoretical solution and literature solution is large, especially in the range 0-4 s. Therefore, the viscoelastic boundary of this method can better simulate the radiation damping effect of foundation. This method is suitable for the study of infinite rubber land base which provides an effective method for the later study.

| Table 1. Observation point coordinates. |
|-----------------------------------------|
| Observation points | A | B | C | D |
| Coordinates        | (0,0) | (0, -100) | (-60, -60) | (-100, 0) |
4. Influence of Tunnel Shape on Layered Rubber-Soil Foundation

4.1. Load Introduction

$P(t)$ is the vertical Ricker wavelet pulse concentrated load. The time domain expression of the load is:

$$P(t) = P_0 \left( 1 - 2 \left( \frac{t-t_s}{t_0} \right)^2 \right) \exp \left( - \left( \frac{t-t_s}{t_0} \right)^2 \right)$$

(3)

where, $t_s=5$, $t_0=4/\pi$, $P_0=1000$.

4.2. Example Analysis

The model size is 72 m x 12 m. In this section, we select the square, horseshoe and circular tunnels combining with rubber-soil foundation (figures 7-9). Three layers rubber soil with different rubber content are choices. The soil parameters are shown in table 2. The distribution of soil is shown in table 3. Observation point coordinates are shown in table 4. We apply Ricker pulse load $P(t)$ at origin O.
Table 2. Rubber-soil different rubber particle content parameters.

| Rubber content /% | ρkg/cm³ | E/MPa  | μ    |
|-------------------|--------|--------|------|
| 10                | 1600   | 10.49  | 0.4729 |
| 20                | 1400   | 5.77   | 0.4792 |
| 30                | 1200   | 4.34   | 0.4833 |

Table 3. Distribution of soil.

| No. | Soil       | Rubber content /% | H/m |
|-----|------------|-------------------|-----|
| 1   | Rubber-soil| 10                | 5   |
| 2   | Rubber-soil| 20                | 2   |
| 3   | Rubber-soil| 30                | 5   |

Table 4. Observation point coordinates.

| Observation points | A      | B     | C     | D     |
|--------------------|--------|-------|-------|-------|
| Coordinates        | (0, -2)| (0, -8)| (15, 0)| (0, -11) |

By comparing the transverse displacement time history of different points in figures 10-13, it can be concluded that the displacement of horseshoe tunnel at the top of tunnel is the smallest and the displacement of circular tunnel is the largest. At the bottom of tunnel, the displacement of horseshoe tunnel is the smallest, and that of rectangular tunnel is the largest. With the increase of depth, the lateral displacement of the vertical point decreases gradually and there is almost no effect on the time history of the lateral displacement of points on the horizontal plane under different working conditions. From figures 14-15, it can be seen that the shape of the tunnel under impulsive load has a weaker influence on the vertical displacement of the top and bottom of the tunnel as the depth increases. By giving the above analysis, the horseshoe tunnel is the best condition.

![Figure 10](image1.png)  
**Figure 10.** Horizontal displacement history of point A.

![Figure 11](image2.png)  
**Figure 11.** Horizontal displacement history of point D.
5. Conclusion

1. A two-dimensional model is selected to simulate the radiation damping of infinite layered foundation by applying a continuous distributed artificial boundary, that is, viscous-spring artificial boundary, so as to realize the infinite foundation model.

2. By comparing the method in this paper with the verification example, the correctness of the method in this paper is verified. Simulation of radiation damping and elastic recovery of infinite foundation. Realize the true vibration characteristics of complex rubber soil foundation under dynamic load.

3. By comparing the time-history curves of transverse displacement of tunnel with different shape and rubber foundation, it can be concluded that the displacement of horseshoe tunnel is smaller. With the increase of depth, the influence of tunnel shape on vertical displacement of tunnel vertex and bottom point becomes weaker. So the shape of the horseshoe tunnel is optimal.

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