Study on Vibration Response of Surrounding Environment Caused by High-Speed Train Operation

Ruiyao Yang¹*, Zhifan Xia¹,², Bin Xu¹,², Yue Liu¹, Lingyun Zeng¹ and Ziyue Chen¹

¹ School of Civil Engineering and Architecture, Nanchang Institute of Technology, Nanchang, 330099, China
² Jiangxi Province Key Laboratory of Hydraulic and Civil Engineering Infrastructure Security, Nanchang, 330099, China
Email: 3355316790@qq.com

Abstract. A finite element calculation model is established on basis of a ballastless high-speed railway passing through a section of Nanchang to study the propagation law of high-speed railway vibration in soil and the influence of hollow trench isolation on soil vibration. The three-dimensional finite element model for calculating the vibration response of high-speed railway and the two-dimensional finite element model for vibration isolation of high-speed railway are established. It is concluded that, as the train speed increases, the displacement, speed and acceleration of the soil increase, and the vibration period shortens; as the distance from the vibration source increases, the surface displacement, velocity, and acceleration of the soil shows a trend of increasing first, then decreasing, and then increasing fluctuations along the roadbed-soil propagation path. The horizontal vibration response of the soil is greater than the vertical vibration response. And within a certain range, the empty groove farther from the centerline of the track, the better the vibration isolation effect. When the train speed is 350 km/h, the distance from the vibration source should be 16 ~ 22 m, and the vibration isolation effect is better.

Keywords. High-speed railway, ground vibration, numerical simulation, ballastless track.

1. Introduction
With the wide extension of high-speed railway lines, people experience convenience while also feeling that the vibration and noise problems caused by high-speed railway operations have a great impact on the sleep, life and work of residents near the line [1]. Therefore, studying the response of high-speed railway operation vibration to the environment is of great significance to the further development of high-speed railway, residents’ normal life, and environmental safety assessment and design. It also has broad prospects in theoretical research and practical applications.

The establishment of foreign high-speed railways earlier than ours determined its earlier research on train vibration. Since 1904, Lamb [2] studied the propagation of seismic waves on the surface of the earth in an article and proposed the propagation of waves in the ground for the first time. Since then, many scholars have successively studied the law of wave propagation in the semi-infinite space boundary [3-5] and have obtained many theoretical and empirical results. However, due to the diversity of influencing factors, different projects should be analyzed according to the situation. In China, researchers in my country simulate and analyse railway train vibrations by establishing finite element models and measured scale models, and compare field measured data, and then continue to
achieve theoretical systemization, and have also achieved relatively fruitful results [6-8]. In this paper, according to the properties of soil in Nanchang area, through the method of numerical simulation, analysis and research in Nanchang high railway, no frantic jumble orbit propagation law of train vibration in the surrounding environment, and according to the relevant rules and regulations, vibration isolation measures in the area to the specified standard, for the region’s high-speed rail vibration isolation measures to provide the reference.

2. Analysis of Environmental Vibration Response Caused by High-Speed Railway Operation

2.1. Analysis Model of High-Speed Railway Running Vibration
The model is mainly composed of track, the subgrade and soil. The track model ignores the complex shape of the rail and the fastener, and the rail spacing is 1.435 m according to the Chinese standard. This article refers to the “Code for Design of High-speed Railway Subgrade”. In the model establishment, the thickness of the surface of the subgrade is 0.4 m, the thickness of the bottom of the subgrade is 2.3 m, and the thickness of the basic body of the road is 2 m; The thickness and composition of foundation soil are determined according to the actual situation in Jiangxi province. The elastic constitutive model is used for the track slab, concrete base, and roadbed; the soil body adopts the Mohr-Coulomb constitutive model according to the actual situation, and the size is 80m×100 m. The finite element model of ballastless track for analysing vibration of high-speed rail is shown in figure 1.

![Figure 1. 3D finite element model.](image)

2.2. One-Way Train Vibration Analysis
For load dynamic calculation, fixed boundary is still adopted at the bottom of the model, and the surface is still completely free. Viscoelastic boundary is established at the four sides, which is basically consistent with the actual situation of high-speed railway operation. The model was selected to simulate the model of EL-18 standard train, and the train speed was selected to be 250 km/h, 300 km/h and 350 km/s for mutual comparison, so as to analyse the vibration response of high-speed railway.

At 0 m, 4 m, 8 m, 12 m, 16 m, 22 m, 28 m, 34 m from the centerline of the track, set 1-8 pick-up points in sequence, by analysing the speed, acceleration and displacement of the vibration pick-up points at points 1, 5, and 8, under 250 km/h and 350 km/h speeds, study the influence of train speed on soil vibration response and the law of vibration propagation in soil.

2.3. Analysis of the Influence of Train Speed on Environmental Vibration Response

2.3.1. Ground Vibration Displacement Analysis. When the high-speed rail is running at 250 km/h and 350 km/h, the horizontal displacement and vertical displacement time history curves of the three vibration pickup points are shown in figures 2-3, from which it can be seen that:
After the train enters the track, as the vibration wave propagates, the displacement of each vibration pickup point located on the roadbed and the soil first increases and then decreases, reflecting the process of loading and unloading. Since the point 5 vibration pickup point is far away from the vibration source, the loading and unloading phenomenon is not obvious. The vibration amplification zone is within the range of 16 ~ 34 m from the track centerline. When the high-speed railway runs at a speed of 250 km/h, the maximum horizontal displacement of the soil within the range of 16 ~ 34 m can reach 1.888×10^{-4} m; the vertical displacement can reach 2.509×10^{-4} m. When the high-speed railway runs at 350 km/h, the maximum horizontal displacement can reach 8.574×10^{-4} m; the vertical displacement can reach 4.061×10^{-4} m. The vertical displacement of the soil attenuates faster than the horizontal displacement. When the high-speed rail speed increases, the amplitude of soil displacement increases and the frequency increases. When the high-speed railway runs at a speed of 250 km/h, the horizontal displacement is higher than the vertical displacement within 16m from the track centerline; the vertical displacement is slightly greater than the horizontal displacement within 16-34 m from the track centerline. When the high-speed rail is running at 350km/h, the horizontal displacement of the soil is greater than the vertical displacement.

Figure 2. Displacement variation curve with distance of high-speed railway running at 350 km/h and 250 km/h.

Figure 3. Time-history curve of displacement of vibration pickup point when high-speed railway is running at 350 km/h and 250 km/h.
2.3.2. Ground Vibration Velocity Analysis. When the high-speed railway runs at 250 km/h and 350 km/h, the time-history curves of horizontal velocity and vertical velocity at the three vibration pickup points are shown in figures 4-5, from which it can be seen that:

After the train enters the track, along with the propagation of vibration wave, the velocity of each vibration pickup point located in the roadbed and soil body increases first and then decreases, which reflects the process of loading and unloading. The vertical velocity of soil decreases faster than the horizontal velocity. When the speed of high-speed rail increases within a certain range, the soil velocity increases and the frequency increases. The horizontal velocity of the soil is greater than the vertical velocity in the short distance from the centerline of the track.

![Figure 4. Variation curve of velocity with distance when high-speed railway runs at 350 km/h and 250 km/h.](image)

![Figure 5. Speed history of vibration pickup point when high-speed railway is running at 350 km/h and 250 km/h.](image)
3. Study on Vibration Isolation Measures of High-Speed Railway Running Vibration

3.1. Train Load Simulation

There are many factors that affect the mechanism of train load generation. In the model established in this chapter, the improved excitation force function is used for calculation and simulation [9]:

\[
F(t) = F_1k_2(P_0 + P_1 \sin \omega_1 t + P_2 \sin \omega_2 t + P_3 \sin \omega_3 t)
\]  

(1)

In the equation, \(k_1\) is the superposition coefficient, which is generally 1.2~1.7; \(k_2\) is the dispersion coefficient, which is generally 0.6~0.9; \(P_0\) is the static wheel load; \(P_1, P_2, P_3\) respectively correspond to the smooth driving vibration load of typical value of rail surface waveform wear and performance. The unsprung mass of the train is \(M_0\), then the vibration load amplitude of the train is:

\[
F_i = M_0a_i\omega_i^2
\]

(2)

\[
\omega_i = \frac{2\pi v}{L_i}
\]

(3)

In the equation, \(M_0\) is the unsprung mass of the train; \(a_i\) is the vector height of the track geometric irregularity; \(\omega_i\) is the frequency of the vibration circle; \(v\) is the running speed of the train; \(L_i\) is the wavelength of the geometric irregularity curve. For the British track with a speed \(v=200\ km/h\), the geometric irregularity management standards are shown in table 1 [9]:

| Control condition                  | Wavelength /m | Versine /mm |
|-----------------------------------|---------------|-------------|
| According to driving stability (I)| 50            | 16          |
|                                   | 20            | 9           |
|                                   | 10            | 5           |
|                                   | 5             | 2.5         |
| Additional dynamic load acting on the line (II)| 2    | 0.6         |
|                                   | 1             | 0.3         |
| Wave wear (III)                   | 0.5           | 0.1         |
|                                   | 0.05          | 0.005       |

In the model, the train speed is 350 km/h, the static load \(P_0\) is 80kN, and the unsprung mass \(M_0\) is 750 kg. The values of the wavelength and the positive vector are: \(L_1=10\ m, a_1=3.5\ mm; L_2=2\ m, a_2=0.4\ mm; L_3=0.5\ m, a_3=0.08\ mm\). The train vibration load function is:

\[
F(t) = 80 + 6.3 \sin 30.54t + 28 \sin 305.36t + \sin 1221.45t
\]

(4)

From this, the simulated load curve of the train can be obtained.

3.2. Vibration Isolation Model for High-Speed Railway Operation

According to related literature research, the location of the vibration isolation trench is the most important for the hollow trench isolation [10]. In this chapter, the depth of the vibration isolation trench is 9 m and the width is 0.5 m, which are set at 16, 22, and 28 m away from the centerline of the track. Midas is used to establish models respectively to analyse the dynamic response of point 8 under three conditions. This model sets a one-way ballastless track high-speed train speed of 97.2 m/s (350 km/h). The model is shown in figure 6.
Figure 6. Two-dimensional vibration isolation finite element model.

3.3. Analysis of Vibration Isolation Characteristics of High-Speed Railway Operation

In this section, time history analysis will be carried out on the horizontal vibration displacement, velocity and acceleration at the soil boundary point: point 8. It can be seen that: when the gap is 22 m away from the track line, the maximum surface horizontal velocity is 6.814×10^{-8} m/s, the maximum surface displacement is 1.058×10^{-8} m, and the maximum surface acceleration is 5.573×10^{-7} m/s^2.

Therefore, when setting the location of the vibration isolation ditch, it is more appropriate to take 16 ~ 22 m. The vibration damping effect of the vibration isolation ditch is the most prominent, and it meets the VC-E standard requirements in the “Technical Specification for Vibration of Precision Instruments”.

4. Conclusion

In this paper, a rail-roadbed - soil finite element model is established to study the response of different train speeds to the surrounding environment of high-speed railway. The two-dimensional finite element model of vibration isolation is established to obtain the most effective setting distance of hollow trench. The main conclusions are as follows: when the train speeds up, the amplitude of the maximum displacement, speed and acceleration of the ground increases, and the period shortens. When the train is running, the vertical displacement, velocity and acceleration of soil mass attenuate relatively fast. When the train is running, the soil mass has a large vibration area within a certain range. During the operation of high-speed railway, the horizontal response is dominant within the subgrade. But the vertical response is dominant in the soil. The horizontal velocity of the building caused by vibration can be significantly reduced by the setting of the vibration isolation ditch. In Jiangxi area, when the high-speed train speed is 350 km/h, within the range of 34m from the track center line, the position of vibration isolation trench should be set at 16 ~ 22m to make the vibration reduction effect most prominent.

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