Influence of track irregularity on vibration accelerations of ballastless track subgrade

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Abstract. In order to investigate the impact of track irregularity on the vibration characteristics of ballastless track subgrade of high-speed railway, a three-dimensional finite element of ballastless track-subgrade system was established to simulate the running process of an eight-row grouped CRH380A at 300km/h, spatial-temporal distribution of internal acceleration of the subgrade and its frequency attenuation characteristics were analyzed in consideration of constant speed dead load or train load with track irregularity load. It is observed that the vertical vibration acceleration of the subgrade shows obvious periodic characteristics under the action of train load, and it also shows random vibration characteristics under the condition of track irregularity. The vertical acceleration amplitude is more than twice of the constant speed load conditions. The attenuation of the vibrational acceleration along the depth is represented by an exponential function. The vertical acceleration spectrum is gradually attenuated along the depth, and the spectral density significantly increases because of the track irregularity, and the principal frequency of dynamic stresses was not affected.

Introduction

In the construction projects of high-speed railways, ballastless track structures are increasingly used. Under long-term repeated high-speed train loads, the subgrade should maintain the stability of the soil skeleton without additional deformation so that the rail system can not afford [1]. The long-term stability of the subgrade structure is the prerequisite for the durability of the ballastless track system. Vibration velocity or acceleration can be used as important load parameters to analyze long-term dynamic stability of the subgrade. However, the magnitude of vibration acceleration of ballastless track subgrade caused by high-speed train is much larger than that of vibration speed, it is sensitive to the external loads and has high measurement accuracy. So, it is more commonly used to investigate practical engineering[2], and vibration acceleration is usually used as an indicator to measurement the vibration of the environment caused by train operation[3]. Therefore, domestic and foreign researchers have studied the vibration characteristics of high-speed railway ballastless track subgrade in the aspect of theoretical analysis [4-5], field tests [6-7], numerical calculations [8-9], and have achieved many achievements. Research results has shown that track irregularity is the root cause of increased wheel-rail contact force, and it is the main cause of train vibration [10]. Researchers have also conducted some research about the vibration characteristics of subgrade under the condition of track irregularity [11-12]. Due to the complexity of the vibration characteristics of the ballastless track subgrade of high-speed railways, the existing research work still lags behind the engineering practice.

Currently, the finite element method is used to analyze the vibration characteristics of the subgrade of high-speed railway in view of the vibration problem. There are still two major problems: (1) The numerical model is not perfect. For example, a symmetric model cannot fully reflect the spatial propagation effects of fluctuations. (2) The train load is unreasonable. For example, the dynamic stress of the subgrade is investigated under the loading conditions of a single axle, bogie or single carriage, so that the load superposition effect between the axes of the train cannot be considered, thus...
calculation result of vibration characteristics of the subgrade cannot be objectively reflected during the running of the train. In addition, there are few studies on the frequency characteristics of vibration characteristics of structural layer of high-speed railway ballastless track subgrade. In view of the above problems, a three-dimensional finite element dynamic analysis numerical model of CRTSII slab ballastless track-subgrade system was establish by APDL language based on the ANSYS finite element platform, and high-speed moving load simulation technology was adopted to simulate the operation process of a CRH380A train with eight cars. The temporal and spatial variation of the vibration acceleration of the subgrade structure and its frequency spectrum characteristics were studied under the condition of constant speed load or track irregularity load.

Ballastless track subgrade numerical analysis model

Finite element model building. According to the standard single line cross section of ballastless track embankment[2], a 3D finite element model of CRTSII slab type ballastless track subgrade was established. The calculated length of finite element model was 26 m, and the calculated depth was 9.7 m below the surface of the subgrade. Because the main research object was the subgrade structure, the rails were simplified as a continuous beam with elastic point support, the gauge was 1.435 m, and the spacing between rail fulcrums was the same as the fastener spacing, and the value was 0.65m. The fasteners and pads under rail were equivalent linear elastic elements and the element type of fastener were COMBIN 14 spring-damping elements. In the calculation, a linear elastic constitutive model was used for the track structure. The calculation parameters are shown in Table 1. Damping effect of the soil in the subgrade structural layer was considered, and effect of plastic deformation characteristics of soil was not considered, so the dynamic properties of the soil were simulated by a viscoelastic constitutive model with a constant damping ratio. The calculation parameters are shown in Table 2.

Table 1 Parameters of track system

<table>
<thead>
<tr>
<th>material</th>
<th>Elastic Modulus [GPa]</th>
<th>Poisson's ratio</th>
<th>Density [kg.m$^{-3}$]</th>
<th>Height [m]</th>
<th>Width [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>steel rail</td>
<td>210</td>
<td>0.3</td>
<td>7830</td>
<td>0.2</td>
<td>2.55</td>
</tr>
<tr>
<td>track</td>
<td>35</td>
<td>0.167</td>
<td>2500</td>
<td>0.2</td>
<td>2.55</td>
</tr>
<tr>
<td>CA mortar</td>
<td>4.5</td>
<td>0.2</td>
<td>2000</td>
<td>0.2</td>
<td>2.55</td>
</tr>
<tr>
<td>supporting layer</td>
<td>27</td>
<td>0.2</td>
<td>2400</td>
<td>0.3</td>
<td>2.95-3.25</td>
</tr>
</tbody>
</table>

Table 2 Parameters of embankment

<table>
<thead>
<tr>
<th>material</th>
<th>surface layer of subgrade</th>
<th>bottom layer of subgrade</th>
<th>subgrade body</th>
<th>foundation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Modulus [GPa]</td>
<td>0.20</td>
<td>0.14</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.27</td>
<td>0.32</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Density [kg.m$^{-3}$]</td>
<td>2250</td>
<td>2130</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>damping</td>
<td>0.028</td>
<td>0.035</td>
<td>0.040</td>
<td>0.045</td>
</tr>
<tr>
<td>Height [m]</td>
<td>0.4</td>
<td>2.3</td>
<td>2.0</td>
<td>5</td>
</tr>
<tr>
<td>Width [m]</td>
<td>6-7.2</td>
<td>7.2-14.1</td>
<td>14.1-21</td>
<td>30</td>
</tr>
<tr>
<td>ratio of slope</td>
<td>1:1.5</td>
<td>1:1.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In this paper, the element type of ballastless track slab, CA mortar, supporting layer and subgrade structure layers was solid45 element, The mesh of the 3D finite element model of CRTS II type slabless track-subgrade system is shown in Fig. 1, and the number of model units is 74,893 and the number of nodes is 80,676.
In the 3D finite element model, a three-dimensional viscoelastic boundary element[12] was applied to the two sides of the subgrade parallel to the direction of the line and subgrade bottom surface. At the same time, the displacement of the two boundary faces perpendicular to the line direction along the line is constrained.

**Train load application**

The main object of study in this paper was subgrade, so the coupling of the vehicle and the track was out of consider, the high-speed train loading was used as the external excitation input. Due to various complex factors, such as the dynamic performance of the locomotive, the smoothness of the line, and the stiffness of the subgrade[13], the problem that the loading act on steel rail is a hard work to conduct. In fact, the train is constituted by a series of cars with uniform carriage. As a whole, there are obvious periodic characteristics of the wheel load along the line [14-15]. For this reason, the loading model can be assumed that the train is infinite length, the vehicle dynamic load is regarded as a combination of four groups of single concentrated loads. Each group of vehicle dynamic loads is a periodic moving load whose period is the length L of the vehicle, as shown in Fig. 2.

According to the dynamic load of the first group of vehicles, the model assuming that the train operating speed is \(v\) and the vehicle dynamic load is located at time \(t\) at \(Z = vt\), so the vehicle dynamic load function is expressed as:

\[
P_1(t, z) = P_0 \delta(Z - vt) + F(t) \delta(Z - vt).
\]

Where, \(vt - L/2 < Z < vt + L/2\); \(P_0\) is the static load of the train; \(F(t)\) is the additional dynamic load caused by the vertical vibration of the vehicle; \(\delta(Z - vt)\) is about \((Z, t)\) Dirac's function.

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

Where, \(P_1, P_2, P_3\) are the vibration load amplitudes corresponding to a typical value of the control condition of the track geometry irregularity management values, \(P_i = M_0 a_i \omega_i^2\), where \(M_0\) is the
unsprung mass; \( a_i \) is the vector height corresponding to geometric irregularity under irregular control conditions; \( \omega_i = 2\pi v / L_i \), where \( L_i \) is the wavelength of the geometric irregularity curve. This paper selects the CRH380A train with eight-car with an axle weight of 140kN and a speed of 300km/h. In the track geometry irregularity management values, the wavelength and vector height values in the three control conditions are: \( L_1 = 10 \text{m}, a_1 = 2.0 \text{mm}, \) and \( L_2 = 2 \text{m}, a_2 = 0.38 \text{mm}; L_3 = 0.5 \text{m}, a_3 = 0.06 \text{mm}, \) the unsprung mass of the train is 750kg.

Vibrational characteristics of subgrade analysis

Among the three components of lateral, vertical and longitudinal response of the vibration acceleration of the subgrade, the analysis shows that the value of the vertical component is the largest. Therefore, the vertical vibration acceleration is analyzed in this paper. Under the action of train load, the typical time-history curves of vertical vibration acceleration of track subgrade structure are shown in Fig. 3.

![Fig. 3 surface layer of subgrade and surface acceleration time-histories](image)

From Fig. 3, it can be seen that the time-history curve of dynamic acceleration of subgrade under the train load has obvious periodicity. When the train wheels pass through the test section, the peak value of the dynamic acceleration has obvious mutability. Comparing Fig. (a) with Fig. (b) in Fig. 3, it can be seen that the internal vibration acceleration of the subgrade still shows obvious periodicity under the condition of track irregularity. Peak phenomenon occurs when the vehicle loads passes through the subgrade, and it shows obvious random vibration characteristics.

The vibration acceleration amplitude of the subgrade are shown in Table 3.

<table>
<thead>
<tr>
<th>Test position</th>
<th>Constant load[m/s²]</th>
<th>Irregularity[m/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>surface of the top of</td>
<td>1.96</td>
<td>4.46</td>
</tr>
<tr>
<td>the subgrade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>surface of the bottom</td>
<td>0.97</td>
<td>3.04</td>
</tr>
<tr>
<td>of the subgrade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>surface of the base</td>
<td>0.15</td>
<td>1.21</td>
</tr>
<tr>
<td>of the subgrade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bottom of the body</td>
<td>0.09</td>
<td>0.46</td>
</tr>
<tr>
<td>of the subgrade</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From Table 3, it can be seen that the vibration acceleration of subgrade caused by train load with track irregularity is more than 1 times of the acceleration by constant speed dead load, and the track irregularity significantly aggravates the vibration of the track subgrade system. Therefore, track irregularity should be strictly controlled to reduce the vibration of the track structure and the subgrade, so as improve the safety and comfort of vehicle operation.

**Distribution of vertical vibration acceleration along depth.** The curves between the amplitude of dynamic acceleration caused by constant speed dead load along depth is shown in Fig. 4, and the curves of the attenuation coefficient along the depth is shown in Fig. 5. In this paper, R stands for
subgrade under the rail, C stands for subgrade center, S stands for under edge of the support layer, A stands for average value, Af stands for average fit value.

![Fig. 4 acceleration along depth distribution](image)

![Fig. 5 acceleration attenuation coefficient along depth distribution](image)

From Fig. 4 and Fig. 5, it can be seen that within the range of 1 m below the surface of the subgrade, the acceleration of subgrade is more than which is below the subgrade center and the edge of the supporting layer, and the distribution law of acceleration will approach below -1 m depth. The attenuation of acceleration mainly concentrated at -1.5 m depth, and the attenuation rate is close to 80%.

The vertical vibration acceleration at different locations of the subgrade decays rapidly along the depth. The distribution law is expressed as:

$$\phi(z) = 0.8891e^{0.0591z}$$  \hspace{1cm} (3)

where, $\phi(z)$ is the average value of the vertical acceleration attenuation coefficient of subgrade vibration along the depth $z$, and $z$ is the depth from the surface of the subgrade.

**Acceleration spectrum characteristics.** Apply fast Fourier transform on time-history curves of vertical vibration acceleration of the subgrade, the frequency spectrum curves under the action of constant speed dead load are obtained presented in Fig. 6, the frequency spectrum curves under the action of train load with track irregularity are obtained presented in Fig. 7.

![Frequency spectrum curves](image)

(a) Surface of the top of the subgrade  \hspace{1cm} (b) Surface of the bottom of the subgrade
Fig. 6 shows that the principal spectrum distribution of vertical acceleration are 0-60Hz and 80-120Hz along surface of the top of the subgrade to surface of the bottom of the subgrade, and it mainly distribute around 40Hz and 100 Hz, the distribution of frequency between 60-80Hz is small value and Less distribution. It is concluded that the spectral components in this range are gradually absorbed by the track and surface layer of subgrade. Fig.6 also shows that the principal spectrum
distribution of vertical acceleration is 0-20Hz along surface of the top of the subgrade to surface of the bottom of the subgrade, and frequency between 40-120 Hz are basically absorbed. The analysis shows that the frequency of the surface layer of the subgrade is dominated by high frequency vibration, and the subgrade structure below the surface layer of the subgrade is dominated by low frequency vibration.

Fig.7 shows that spectral distribution range of vertical vibration acceleration of the surface layer of the subgrade under the condition of track irregularity is basically the same as the constant speed dead load, but the vibration amplitude and peak distribution density are obviously increased, which could explain that the track irregularity exacerbates the subgrade vibration, and also shows that the track irregularity does not change the main frequency range of the vibration acceleration of the subgrade. Fig.7 also shows that the principal spectrum distribution of vertical acceleration are 0-15Hz, 30-50Hz, and 80-100Hz along the bottom surface of the subgrade to bottom of the subgrade body cased by track irregularity, however frequency component between 40-120Hz below surface of the base of the subgrade are basically absorbed. It is observed that the track irregular load has a relatively large frequency, and it can be transmitted to deeper subgrade structure resulting in a certain increase in the amplitude of high-frequency vibrations in the bottom of the subgrade and roadbed.

Conclusions

The contribution of this paper is to provide the spatial-temporal distribution and the frequency attenuation characteristics of the internal accelerations of the subgrade under constant speed dead load and track irregular load, several findings were made:

(1) The vertical vibration acceleration of the subgrade shows obviously periodic characteristics under the action of train load, and it also shows random vibration characteristics under the condition of track irregularity.

(2) Within the range of 1m below the surface of the subgrade, the acceleration of subgrade is more than which is below the subgrade center and the edge of the supporting layer, and the distribution law of acceleration will approach below -1 m depth. The acceleration attenuation along the depth can be represented by an exponential function.

(3) The vertical vibration acceleration amplitude of the subgrade under the condition of track irregularity is more than twice that of the constant speed load. The track irregularity significantly aggravates the vibration amplitude and spectral density of the subgrade structure, but it does not change the main frequency range of the subgrade vibration acceleration. The vertical acceleration spectrum is gradually attenuated along the depth, and the spectral density significantly increases because of the track irregularity, and the principal frequency of dynamic stresses was not affected.

(4) Under the action of constant speed dead load, with the increase of the subgrade depth, the frequency components within range of 60-80 Hz are absorbed firstly, and then 40-60 Hz and 80-120 Hz are gradually absorbed. Under the condition of train load with track irregular, the frequency components within range 0-15Hz, 30-50Hz, and 80-100Hz appear in each subgrade structure layer, and the frequency range of 15-30Hz are absorbed, and then 60-80Hz are absorbed.

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