文章编号:1671-8879(2017)04-0018-07

Vibration impact of trains on thawed soil subgrade

PETRIAEV A

(Construction of Roads Transport Complex Department, Emperor Alexander Ⅰ St. Petersburg State Transport University, St. Petersburg 190031, Leningrad, Russia)

Abstract: This paper mainly presents the field studies of vibration impact from passing trains on the roadbed melting ground. The movement of railway rolling stock may cause oscillations on track superstructure, which manifest themselves in the form of noise and vibration. The increasing loads and speeds of trains lead to significant increases of dynamic vibration effects on the roadbed. The accumulated intensity of uneven residual deformation of railway track increases as a result that affects not only on roadbed, but also on constructions of buildings. The geosynthetics were used to design the superstructure for reducing the negative impact of vibration. The results show that during the passage of long train, the vibration process of railway subgrade soil has complex randomness, and it is accompanied by strong low harmonic and mid harmonic in all three components. Two trains passing by each other may cause preferential oscillation on the vertical plane of thawing subgrade. Compared with summer, subgrade thawing layer and boundary humidity lead to the average amplitude of vibration increasing 1.5 to 2 times, this part of significant growing vibration effect must be pay attention to when calculating the bearing capacity of subgrade. Compared with the melted soil, vibration distributions of inside and outside of subgrade can be described by means of a less attenuated exponential correlation. At the distance from 5 to 7 m to the track axis, the damping rate of vibration amplitude is 72% to 84% in the horizontal transverse direction. It is found for the first time that the damping amplitude of subgrade at the embankment is less than that in the cut. 4 figs, 9 refs.

Key words: subgrade engineering; dynamic vibration impact; vertical and horizontal stresses; thawing subgrade; attenuation of oscillation amplitude

CLC number: U211.3 **Document code**: A

列车对融土路基的振动影响

PETRIAEV A

(亚力山大一世圣彼得堡国立交通大学 道路运输综合研究所,列宁格勒州 圣彼得堡 190031)

摘 要:主要介绍了现场实测得到的列车交会对融土路基的振动影响。铁道机车车辆的活动可能引起轨道上部结构的振动,并以噪声和振动的形式表现出来。列车荷载和速度的增加将会导致路基动态振动效应的显著增长。由于这种接触引起的铁路轨道不均匀残余变形累积强度的增加,不仅会影响路基,也会对建筑及构筑物结构产生影响。采用土工合成材料设计轨道上部结构的目的

Received date: 2017-03-21

Author resume: PETRIAEV A, PhD, E-mail: pgups60@mail.ru.

是为了减少振动的消极影响。根据现场研究的结果和分析研究，可以得到以下结论：在长列车通过期间，铁路路基土体的振动过程具有复杂的随机性，并在其全部 3 个组件中伴随有很强的低谐波和中谐波；交会列车在垂直平面上引起解冻路基的优先振动；与夏季相比，路基内部正融层和边界处湿度的存在导致了振动幅值平均增大 1.5～2 倍，在路基承载能力计算时，必须注意这部分显著增长的振动影响；与融化的土体相比，路基内部和外部的振动分布通过一个衰减不太激烈的相关性指数 δ_2 进行描述；在距离轨道轴线 5～7 m 的位置，振动幅值的阻尼在水平横向上的发生率为 72%～84%；该研究首次发现，路堤处路基振动幅值的阻尼小于路堑处。

关键词：路基工程；动力振动影响；垂直和水平应力；融土路基；振幅衰减

0 Introduction

The increase of the railways carrying capacity should be decided by the intensification of the existing rail network. Firstly, it is planned to increase the weight of trains by increasing the linear load on the track and the length of trains. For these purposes, the railways acquire heavy-duty eight-axle wagons with axle load up to 250 kN and powerful locomotives with loads up to 270 to 300 kN per axle.

A construction of rolling stock and track superstructure has undergone substantial changes in recent years, which, of course, is reflected in the subgrade. At the same time, constructive solutions of roadbed remain essentially unchanged, but its operational state, in some cases, is characterized by a decrease of elastic properties and bearing capacity. Operating experience of a roadbed and special observation of its work, has convincingly shown that with increasing weight standards and train speeds, even with constant axial load, the increasing number of crippled places in the subgrade, there is depression of track in those areas, in which they have not been, and in some cases recorded the creep of slopes[1]. Reported subgrade defects in most cases are the result of the influence of vibrodynamic impacts from passing trains on the strength and deformation characteristics of soils.

Strength and deformation properties of thawed soil have the lowest values in the spring. Wet soils during thawing reduce its properties in comparison with the frozen state, as well as their initial states before the freeze. One reason for this is the migration of moisture from the body of the subgrade to the zone of freezing. The thawing clayey soils decrease their bearing capacity under enough minor vibration exposure and transform into a liquid mass.

The implementation of planned measures causes a significant increase in the dynamic vibration impacts transmitted on the railway track, including the roadbed. Especially much, they will increase when the introduction of eight-axle wagons and composite long freight trains, which increases the distribution zone of stresses with depth, causing an increase in the oscillation amplitude of subgrade soil[2-3].

The researches include the basic characteristics of the oscillatory process of the subgrade. Interaction of track and subgrade is occurring pulsation of stresses and displacements of soil particles, which are distributed in the body of the subgrade in the form of elastic waves. The forces appearing in the contact of the wheel with the rail and soil vibration are stochastic in nature.

1 Experiment scheme

The oscillations of thawing soils are complicated by the difference in their properties and state, which are changed under the influence of a large number of factors. Patterns of a random process are identified using the theory of probability and mathematical statistics.

The nature of vibration in the subgrade soil depends on many factors, however, mostly from a moving load, the driving speed, the location of the studied point with respect to the source of vibrations and the condition of the soil, composing the roadbed[4]. In our experiments, the research of the nature of the oscillations in the soil of the railway subgrade was carried out according to the waveform of the oscillations, recorded during passage of trains at different speeds and weight standards and different values of thawed layer.

In the result, we selected two experimental section. The first section, represented by cut, was located in a curve with radius 2 500 m, the rail elevation of 40 mm. The second section, represented by embankment, was located on the tangent track. The superstructure was represented by rails R65 with long-welded rails and concrete sleepers number with a layout diagram of 1 840. Ballast consisted of 40 cm crushed stone under the sleeper. The substructure was presented by clayey soil.

The seismic sensors CM-3 carried out registration of oscillations. Sensors CM-3 allow to register amplitude of oscillation up to 1 mm with a frequency from 0.5 to 200 Hz, which have a device for temperature compensation, registering both the vertical and the horizontal component of oscillations. Two sets of sensors on three devices (for registering vibrations along and across track axis and the vertical) were placed at four sites (K1 to K4 in Fig. 1).

The first set was placed in the butt end of sleeper at the different levels from the sleeper bearing surface. The second set was near the same sleeper at the sod line of roadbed. The third set was located in the same cross section at the slope. The fourth set located at the base of slope.

Registration of oscillations was carried out by sensors tuned to a natural frequency of 0.5 Hz and set in the open pit. The possibility of conducting researches in the pits was substantiated earlier[1]. The cross-section was chosen in the butt section of the expansion joint due to the fact that in this area occurs the high level of vibrodynamic impact from trains and there is more intensive accumulation of vertical and horizontal deformations of the rodding, than in the middle of the section or the string of welded rails[5]. The magnitude of a joint gaps, during the testing, ranges from 10 to 20 mm.

Experiments were carried out in spring in the

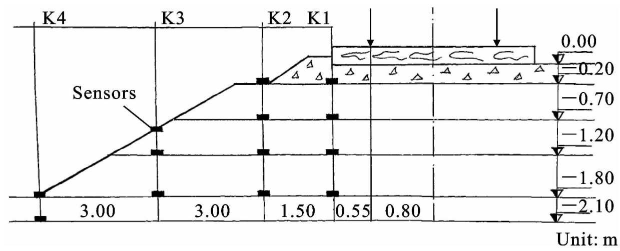

Fig. 1 Layout of sensors in body of subgrade on the second site

图 1 第 2 场地路基主体的传感器布置

period of intensive thawing of soils. The depth of frozen layer was determined by periodic drilling of wells in the body of the subgrade[6].

Analysis of the nature of the vibration shows that the evaluation of the oscillation amplitude can be generated through the resultant and the components of vibration amplitude. The horizontal components is along and across the track and the vertical component. The value of each component is defined as the sum of the amplitudes of the main and superimposed harmonics in the places of maximum amplitudes. The value of each component is the sum of the amplitudes of the main and superimposed harmonics in the places of their greatest amplitudes.

The freight trains were presented by standard wagons with locomotives VL-23 at the speed of 30 to 80 km/h and the passenger trains were presented by locomotives CHS-6 and CHS2T at the speed of 50 to 160 km/h.

Analysis of the nature of the oscillatory process of the soil massif was conducted on the waveforms, recorded at sites during passage of different types of passing load.

There is a significant difference between the value and shape of the oscillations, depending not only from the speed of passing loads and depth of thawed layer, but also from the orientation of the sensors.

Results analysis of waveforms shows that each component of the oscillations can be symbolically sorted into three components: low frequency (1.0 to 3.0 Hz), medium frequency (10 to 25 Hz) and high frequency (30 to 100 Hz).

High frequency component has small amplitude on the order of 5 to 10 μm and the most clearly visible in places of maximum and minimum, where the least distorted. The occurrence of high frequency component is due to the influence of unsprung mass of the rolling stock in case of unevenness rails and wheels. Due to the high frequency and low amplitude, this component has no significant effect on soils and decays rapidly with the distance from source of impact.

Mid-frequency component is characterized by significant values of amplitudes of vibrations that depend on the speed of the train and the static axle load. This component appears during passage axis of the bogie and is registered in the form of sharp peaks and spikes. This component decisively influences the stability of the slopes of the subgrade, spreading to a distance up to 300 m.

The amplitude of the low frequency harmonics is comparable to the value of the mid-frequency harmonics, and sometimes surpasses it. This component represents the overall deformations of the embankment under the influence of a passing load. Low frequency component of the vertical oscillations in the thawing soil subgrade appears when the speed of freight trains is 50 km/h or more, and passenger trains at the speed exceeding 60 km/h and this component is characterized by the significant amplitude. According to Stoynovich, et al. the appearance of this component for thawed soil, respectively, occurs at speeds of 80 and 110 km/h. The low frequency component appears subjected to rapid rise of load and a high strain rate[2]. At low speed the increase in deformation is small and the sensors do not register it.

The maximum value of amplitude is fixed at the time of matching the phase of low frequency and mid frequency components of the oscillatory process.

The difference should be noted in character of the components of the ground oscillations of the top of subgrade. The horizontal component along the track does not depend on the axle load or the speed of the train. It has great stability and it has not an abrupt surges. The amplitude of the vertical component of vibrations characterized by considerable values and mostly depends on the train speed, axle load, location, depth of the thawed layer of soil and condition of the track.

The horizontal component of the oscillations across the track occupies an intermediate position and is characterized by the absence of patterns in the manifestation of the maximum amplitudes. The maximum amplitude usually occurs at the time of the passage of the bogies. At speeds over 80 km/h, the horizontal component has the low frequency harmonics with a frequency of 0.5 to 2 Hz that indicates a change in the character of the wave process in the thawing ground. The increase of train speed leads not only to an increase in the oscillation amplitude, but also to the continuous change in the frequency spectrum.

The resulting oscillations, as components have complex nature, differ sharply from harmonic oscillations, and in general, are stochastic processes. The comparison of the nature of the oscillations of the soil in different directions allows to obtain a qualitative picture of the ratio of the amplitudes of the various components.

2 Analysis of test results

To determine the bearing capacity of the subgrade during thawing, it is necessary to define the dependence of oscillations distribution in the horizontal and vertical planes.

The identification of vibration amplitude attenuation along the depth of the subgrade was carried out due to the waveforms, which are recorded by the sensors and located in the pit near the end of the sleepers at different depths from the sleeper bearing surface. The results of our experiments to determine the dependence of oscillation distribution along the height of the embankment is shown in Fig. 2.

In general terms, the nature of the reduction of the amplitudes along the vertically has the exponential dependence

$$A_z = A_0 e^{z\ln(\delta_1)} \tag{1}$$

where A_z is resultant oscillation amplitude in the

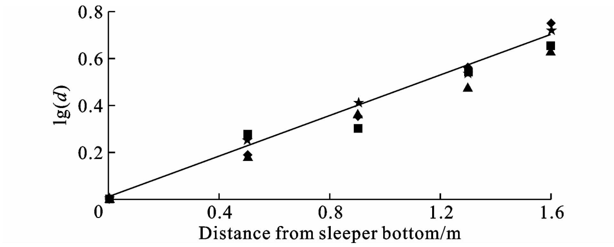

Fig. 2 Dependence of coefficient of oscillation damping along height of embankment

图 2 路基振动阻尼系数与高度的相关性

point with coordinates z(μm); A_0 is resultant oscillation amplitude (μm); δ_1 is oscillation depth decrement factor.

Decrement factor for the thawing embankment soils is 0.64.

The comparison of calculation results of oscillation amplitudes according to Eq. (1) with values obtained in experiments at different train speeds with different axle loads presents a good coincidence.

The experiments performed in the cut indicate that the intensity attenuation of vibration amplitudes in natural soils is more than that in soil of embankment. It is obvious that soils of a natural condition have a slightly higher uptake capacity of vibration energy. Therefore, the value of the d ratio for undisturbed soil addition is slightly less than that for the soils of the embankment and it is 0.59.

When we compare the obtained coefficients of damping oscillations with the same in thawed soils, it should be noted that the values of the latter is smaller, which indicates less intensive damping of amplitudes in the soil of thawing subgrade[1]. Thus, during the thawing, high vibrodynamic influence is transmitted to the larger depth, causing the reduction of strength characteristics of the soil and the increasing possibility of occurrence deformation.

To assess the stability of the subgrade and nearby structures, it is important to know the dependence of distribution of the oscillations in the cross section of the subgrade. Analysis of the records obtained with the installation of sensors on the surface of subgrade at different distances from the axis of the track shows that there is a sharp change in the character of the oscillations. First of all, it should be noted that the smoothing shapes of all components with increasing the distance from the train in a direction perpendicular to the axis of the track.

The oscillatory process caused by the passing trains at a distance of over 7 m from the rail head becomes smoother. Neither high frequency nor low frequency components is not recorded at this distance. The nature of the oscillation in the slope of the subgrade is analogous to that of harmonic oscillations with frequency 16 to 32 Hz. At a distance of 10 m (zone Ⅰ) from the axis of the track there is a strong attenuation of low and high frequency components of oscillations. The attenuation intensity of these frequencies at the vertical component is slightly larger than the attenuation intensity at the horizontal one. Thus, in the thawing soil, the nature of wave propagation in vertical and horizontal planes is different. This is indicated by the ratio of the amplitudes of these components that are continuously changing as the distance from the axis of the track.

Typical graphs for the components of the vibration amplitudes are shown in Fig. 3.

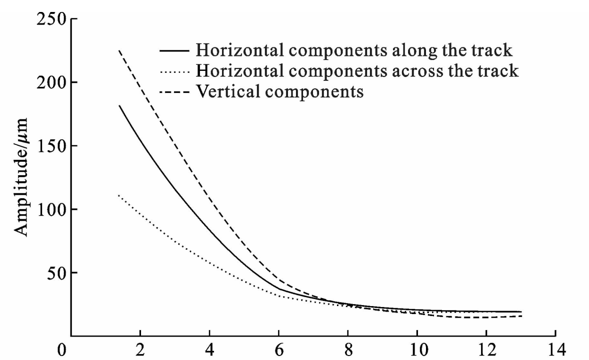

Fig. 3 Dependence of oscillation damping across track

图 3 轨道上的振荡阻尼关系

A noticeable predominance of the vertical component over the horizontal one (in 1.5 to 2 times) appears at a distance of 2 to 4 m from the axis of the track. However, as the distance from the center of the track, there is an equalization of the absolute values of the amplitudes in both directions. On the basis of experimental data, we can assume that equalization of the amplitudes occurs at a distance of 8 to 12 m from the center of the track.

Further，the ratio of the components depends on the speed of trains，lines plan，design of substructure and the depth of thawed soil.

The reduction of zone Ⅰ of 3 to 4 m is in curvilinear part of the track，under the action of horizontal forces during passing of a freight train. The evaluation in vibration amplitude depends on the distance from the source of vibrations made by total attenuation coefficient δ_2，which is determined by

$$\delta_2 = \frac{A_y}{A_0}$$

where A_y is resultant oscillation amplitude at distance y (m) from the center of track (μm)；A_0 is resultant oscillation amplitude at the end of sleeper (μm).

The change in the oscillation decrement factor depending on the distance from the source of vibrations with the same depth of the thawed layer is shown in Fig. 4. The resulting curves can be approximated by exponential dependence with two zones according to intensity of amplitude change.

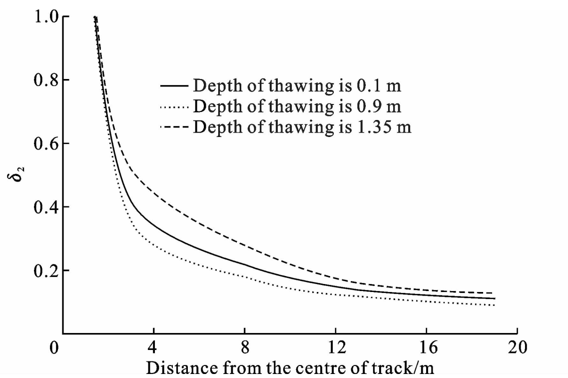

Fig. 4　Dependence of oscillation damping of resultant amplitude across track

图 4　轨道上振幅的振荡阻尼关系

In the first zone at a distance of 4 to 8 m from the center of track occurs the most intense attenuation in the horizontal plane. In this zone，the amplitude decreases by 72% to 84%. In the first zone，quite large vibrations are transmitted to the sod line，the bottom of slopes of the cut and slopes of embankments. The level of the amplitudes in these zones reaches 60 to 80 μm，as shown in previous researches，causing the decrease of the strength characteristics of the soil by 12% to 25%[2]. The decrease of the strength characteristics of soil，the high humidity of these areas during the period of thawing and the increase of vibration impact lead，are shown by field observations，to the appearance and development of zones of shear of soil at the bottom of the slope[5-6].

In our opinion，in the first zone there is the damping of pulsations in the soil subgrade under the influence of moving load. Furthermore，the intensity attenuation is negligible and the damping factor asymptotically approaches to zero. Within the second zone，the damped oscillations are close to the waves of Rayleigh and Love，which are distributed over large distances with a very small damping factor.

Thus，at a distance of 4 to 8 m from the axis of the path，there is the damping of the oscillations arising from both actions：surge of power factor and actions of the oscillations of the sprung masses. Beyond the distance of 8 m，surface waves，arising under the influence of vibrations of the sprung masses，gradually disappear.

To determine the oscillation decrement factor，dependence of coefficient δ_2 of the distance at the center of track was rebuilt in semi-logarithmic coordinates，which allowed us to obtain a linear dependence with different angular coefficients within each zone.

Changing values of horizontal amplitudes in the cross direction of the subgrade can be described by the following expression[7-9].

$$A_y = A_0 \mathrm{e}^{\ln(\delta_2^1)\varphi(y) + \ln(\delta_2^2)\varphi'(y)} \tag{2}$$

$$\varphi(y) = \begin{cases} 0 & 0 < y \leqslant 1.35 \text{ m} \\ y - 1.35 & 1.35 \text{ m} < y \leqslant 8 \text{ m} \\ 6.65 & y > 8 \text{ m} \end{cases}$$

$$\varphi'(y) = \begin{cases} 0 & y \leqslant 8 \text{ m} \\ y - 8 & y > 8 \text{ m} \end{cases}$$

where δ_2^1 is oscillation decrement factor in the first zone (1/m)；δ_2^2 is oscillation decrement factor in the second zone (1/m).

The damping of the oscillations in the body of the subgrade occurs at the exponential dependence at the same time in vertical and horizontal planes, so we can determine the vibration amplitude at any point on the subgrade by the follow equation

$$A_{zy}=A_{O}e^{z\ln(\delta_1^1)+\ln(\delta_2^1)\varphi(y)+\ln(\delta_2^2)\varphi'(y)+\delta_3 h_i}$$

$$\varphi(y)=\begin{cases}0 & 0<y\leqslant 1.35\ \text{m}\\ y-1.35 & 1.35\ \text{m}<y\leqslant 8\ \text{m}\\ 6.65 & y>8\ \text{m}\end{cases}$$

$$\varphi'(y)=\begin{cases}0 & y\leqslant 8\ \text{m}\\ y-8 & y>8\ \text{m}\end{cases}$$

where A_{zy} is resultant oscillation amplitude in the point with coordinates z and y (μm); h_i is altitude of the slope over the calculation point(m); δ_3 is oscillation decrement factor in the slope of the roadbed (1/m), and

$$\delta_3=\frac{\ln(\delta_1)}{1.5\cot(\alpha_1)}$$

where α_1 is slope inclination angle of embankment or cut(℃).

Using the obtained dependency of the distribution of oscillations in the subgrade, the designer can determine the bearing capacity of the subgrade. In the case of insufficient bearing capacity, it is necessary to develop constructive solutions to prevent possible deformation of the rail track. Such constructive solutions are the installation of protective layers of polystyrene or geogrids. In this case the main technical solutions are as follows.

Ballast is being cleared to the required depth under the roadbed with laying geogrid ore plates of XPS at a width of 4 m. Tests in this paper are performed without removing the track by machines RM-80 or SCHU-800-600. The cleaned ballast is laid directly on the plates of XPS ore on the geogrid, which is unwound from a roll assigned to the machine pit chain. Roll length is 30 to 50 m and the overlap of the next rolls must not be less than 0.5 m.

The advantage of the above technical solutions is the possibility of its realization in complexity with the overhaul or track maintenance, and on the separate local area requiring reinforcement. The technological process of reinforcing the roadbed and ballast with geogrids is combined with other design solutions of railway roadbed improvement.

3 Conclusions

(1) Oscillatory process of soil railway subgrade, during passage of long trains, is complex stochastic nature with strongly low and midrange harmonics in all three of its components.

(2) Passing trains cause preferential oscillations of the thawing subgrade in the vertical plane.

(3) The presence of the thawing layer in the body of the subgrade and humidity on the boundary leads to the increase of oscillation amplitudes on average 1.5 to 2 times compared with the summer. It is necessary to discuss the significantly rising vibration impact on subgrade during calculation of its bearing capacity.

(4) The distribution of vibrations in the body and outside of the roadbed, is described by the exponential dependence with the less intense nature of the attenuation, compared with thawed soil. Damping of the oscillation amplitude in horizontal transverse direction occurs up to 72% to 84% at a distance of 5 to 7 m from the axis of the track.

(5) For the first time reveals that in the thawing subgrade of embankment, the intensity of damping of oscillation amplitudes is less than that in the cut.

References:

[1] PUPATENKO V V. Subgrade strength of narrow gauge railways under the influence of rolling stock [D] St. Petersburg: St. Petersburg State Transport University, 1993.

[2] STOYNOVICH G M. In situ study of the dynamic vibration magnitude of the impact of a moving load on the ground[M]. Khabarovsk: Khabarovsk Book Publishers, 2005.

[3] PETRYAEV A, MOROZOVA A. Railroad bed bearing strength in the period of thawing and methods of its enhancement[J]. Sciences in Cold and Arid Regions, 2013, 5(5): 548-553.

[4] WANG Zi-yu, LING Xian-zhang, ZHANG Feng, et al. Field monitoring of railroad embankment vibration responses in seasonally frozen regions[J]. Sciences in Cold and Arid Regions, 2013, 5(4): 393-398.

(下转第 33 页)