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Original scientific paper

On Site Measurement and Evaluation of Environmental Vibration Caused by Ordinary Speed Train Operation

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Abstract: In order to study the environmental vibration characteristics and evaluation of the saturated soil site in the cold northern region caused by the train, vibration observation was carried out on a saturated soil site in a near railway area of the Harbin-Manzhouli Railway, and the environmental vibration caused by different trains at different operating speeds was analyzed in the time and frequency domains. The observation results were evaluated by using the 1/3 octave vibration acceleration level and the maximum weighted plumb vibration level as evaluation index. The results show that the acceleration decreases with the increase of distance, and the acceleration decreases rapidly from 10 m to 30 m, and slowly after 30 m. The vibration energy of the measurement points at 10 m and 20 m is concentrated in 15 - 60 Hz, and the vibration energy of the measurement points after 30 m is concentrated in 15 - 20 Hz. With the increase of the distance from the center of the track, the 1/3 octave vibration acceleration level and the maximum weighted plumb vibration level all show a trend of attenuation. The maximum weighted plumb vibration levels at 30 m are 70.8 dB and 71.3 dB for upward and downward trains, and 77.4 dB and 71.4 dB for upward and downward freight trains, respectively, which are greater than the weighted plumb vibration level limit for special residential buildings. The maximum value of vibration acceleration level at the 10 m measurement point is 88.6 dB, which exceeds the limit by 9.5 dB, and that of 30 m measurement point is 69.8 dB, which meets the specification requirements. The results of the study can provide basic data for the environmental vibration characterization of saturated soil sites caused by train operation and the environmental vibration design of residential, agricultural and water conservancy infrastructures in the near-railway area.

Keywords: environmental vibration; on site measurement; saturated soil; 1/3 octave band; the maximum weighted plumb vibration level

1 INTRODUCTION

By the end of 2022, China's railroad mileage reached 155000 kilometers, and at the same time, the problem of environmental vibration in the near railway area caused by railway operation is becoming increasingly prominent. Environmental vibration will affect the comfort of residential and industrial areas along the line, and various organs of the human body will have many adverse reactions when subjected to vibration. Coastal and riverside areas in the cold northern regions have shallow buried groundwater, and the saturation of the surface soil layer is often very high, which requires consideration of the effect of pore water on the propagation of environmental vibration [1]. With the expansion of cities, the construction of various buildings, structures, and agricultural water conservancy facilities on saturated soil sites along railroads are increasing. Before the construction of various infrastructures, it is necessary to observe and evaluate the environmental vibration of saturated soil sites along railways. In recent years, domestic scholars have conducted a lot of research on environmental vibration analysis and evaluation. Scholars [2-7] carried out vibration observation in the near railway area of different railways respectively, and analyzed the vibration propagation law based on the observation data. In 2008, Lei Xiaoyan et al. [8] firstly drew on the environmental vibration evaluation method in the United States to evaluate the environmental vibration caused by the train operation. Ma Kuikui et al. [9] conducted a study on the ground vibration characteristics of the Baoji-Lanzhou passenger dedicated line embankment section using on-site observation and numerical analysis methods. In 2017, Du Linlin et al. [10] proposed for the first time the effect of overlap coefficient on the maximum weighted plumb vibration level, and concluded that when the overlap coefficient reaches 3/4, the calculation result of weighted plumb vibration level tends to be stable. In 2020, Jia Chenyu et al. [11] carried out on-site observation in Longfeng Wetland of Daqing City, and launched a research on the evaluation of environmental vibration caused by Harbin-Qiqihar High Speed Railway. He Yulong et al. [12] chose to carry out vibration tests in an embankment section of the Chengdu-Chongqing High Speed Railway, and analyzed the vibration characteristics of the vibrated ground in three directions. 2021, Ma Kaiqiang et al. [13] evaluated the results of vibration observation of a rail transit superstructure using four different evaluation methods, and compared the weighting factors of the different evaluation methods. Zhang Yongfu et al. [14] conducted on-site observation of the embankment section and cut section of the Baolan High Speed Railway, and analyzed and evaluated the environmental vibration of the embankment section and cut section in terms of time domain, frequency domain, and the weighted plumb vibration level. Domestic scholars have conducted extensive research on the analysis and evaluation of vibration in the surrounding environment caused by train operation. However, there is relatively little research on vibration observation and evaluation of saturated soil sites in the cold northern regions, and there is a significant difference in vibration response between saturated soil sites dominated by fluid-solid two-phase media and unsaturated soil sites. Therefore, this paper chooses to carry out on-site observation in the saturated soil site in the near railway area of Binzhou Railway. Based on the observation results, the time history, root mean square value of acceleration, and power spectrum are studied. The observation results were evaluated by using the 1/3 octave vibration acceleration level and the maximum weighted plumb vibration level as evaluation index. It provides basic data for the theoretical analysis of the environmental vibration of saturated soil in the near railway area in the cold northern regions caused by train operation, and for the environmental vibration design of the infrastructure in the residential area and farmland and water conservancy projects.

2 FIELD OBSERVATION TESTS

2.1 Test Overview

In order to avoid interference from other vibrations during on-site testing, on-site vibration observations were conducted in the near railway area of a certain roadbed section of the Harbin-Manzhouli Railway, the slope of the roadbed slope rate of 1:1.5, the embankment height of 2 m. The measurement section of the line is a straight section, using P60 steel rails and a crushed stone track bed. The measurement team obtained the acceleration time history data of 24 passenger trains, 32 freight trains, and 6 locomotives passing through the observation site, and selected some of the observed data of passenger trains and freight trains for vibration analysis, and the relevant test conditions of passenger trains freight trains are shown in Tab. 1. The on-site observation is in line with the requirements of the specification TB/T 3152-2007 Railway Environmental Vibration Measurement. The on-site observation when the train passed is shown in Fig. 1.

Table 1 Train testing conditions

No.	Train type	Formation / sections	Speed / km/h
1	Upward passenger train	17	100
2	Upward passenger train	14	103
3	Upward passenger train	15	95
4	Downward passenger train	19	126
5	Downward passenger train	15	120
6	Downward passenger train	16	115
7	Upward freight train	67	78
8	Upward freight train	34	81
9	Upward freight train	56	43
10	Downward freight train	67	65
11	Downward freight train	67	69
12	Downward freight train	67	83

(a) Passenger train

(b) Freight train

Figure 1 On-site observation during train passage

2.2 Observation Program

2.2.1 Observation Instrumentation

The signal acquisition instrument used in this observation is DH5922D dynamic signal tester (32 channels), which can simultaneously measure the data in the *X*, *Y* and *Z* directions of each measurement point, and the sampling frequency is set at 500 Hz. The sensor is chosen to be 2D001 magnetoelectric vibration sensor, with the acceleration sensitivity of 0.3V·s/m and the maximum range of acceleration of 20 m/s^2. The software acquisition system adopts DHDAS dynamic signal acquisition and analysis system. 2D001 magnetoelectric vibration sensor is connected with DH5922D dynamic signal tester through coaxial cable, and the DH5922D dynamic signal tester transmits the collected signals to the computer through a USB interface. The actual running speed of the train was measured using the STALKER PRO handheld radar speedometer from the United States. The experimental equipment met the observation requirements, and the experimental instrument is shown in Fig. 2.

Figure 2 Test instrument

2.2.2 Layout of Measurement Points

In the near railway area of Harbin-Manzhouli Railway, it is selected as the observation site, and the measurement points are set perpendicular to the track direction, with 7 measurement points and a spacing of 10 m between the points. The horizontal perpendicular to the track is specified as the **X** direction, the horizontal parallel to the track is specified as the **Y** direction, and the vertical plumbing to the ground is specified as the **Z** direction. The positional relationship between the measurement points and the track is shown in Fig. 3.

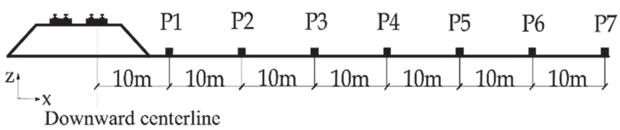
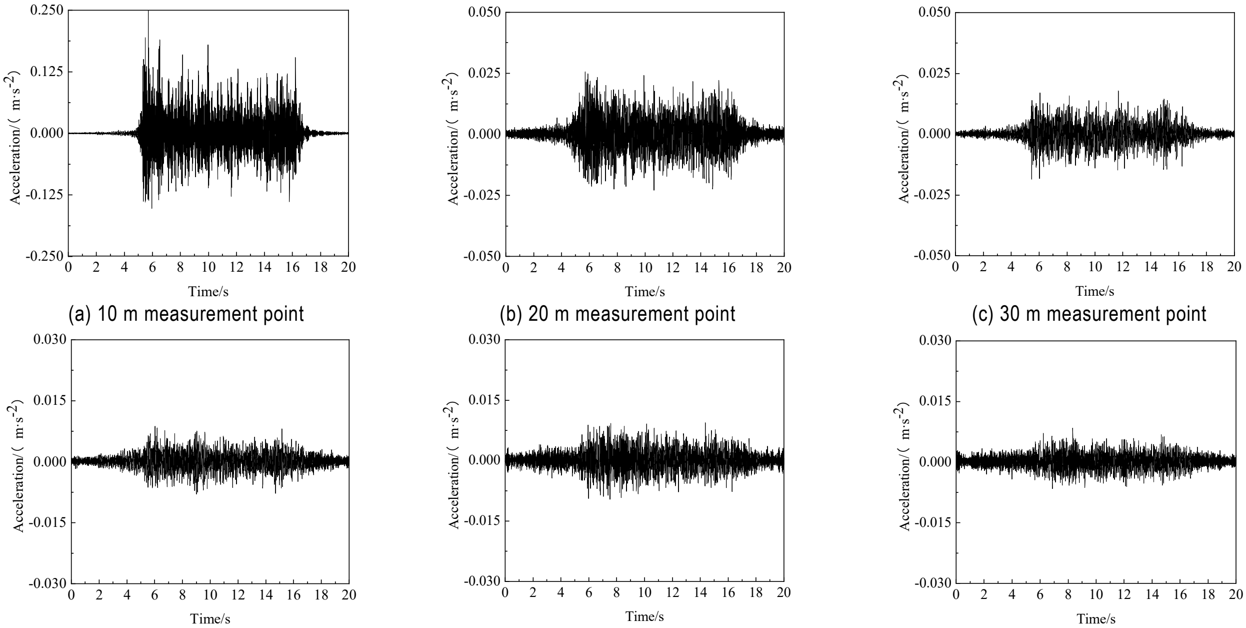


Figure 3 Layout cross-section of experimental observation points

3 ANALYSIS OF TEST RESULTS

3.1 Time Domain Analysis

The observation data of the No. 5 train with standard grouping (15 sections) and standard speed (120 km/h) is selected as a representative to be analyzed in terms of time and frequency domains. Drawing the acceleration time history curve based on the observation results is shown in Fig. 4.



(a) 10 m measurement point (b) 20 m measurement point (c) 30 m measurement point

(d) 40 m measurement point (e) 50 m measurement point (f) 60 m measurement point

Figure 4 Acceleration time history curve in the *z*-direction of each measuring point

In order to reduce the influence of the uncertainty of the acceleration peak selection on the vibration evaluation, the paper utilizes the acceleration root mean square (*RMS*) value as a statistical quantity for analyzing the variation of the vibration acceleration with the distance between the measurement point and the track [15], and the acceleration root mean square (*RMS*) value is shown in Eq. (1).

$$a_{\mathrm{rms}}=\sqrt{\frac{\sum a_i^2}{\mathrm{n}}} \tag{1}$$

where: a_{rms} is the root mean square value of acceleration; a_i is the measured *i* acceleration data; *n* is the number of samples in the measured time period.

According to Eq. (1), the root mean square value of acceleration in the *Z* direction at each measurement point is obtained, and its calculation results are shown in Fig. 5. and Fig. 6 demonstrates the trend of the peak acceleration in the *Z* direction at each measurement point.

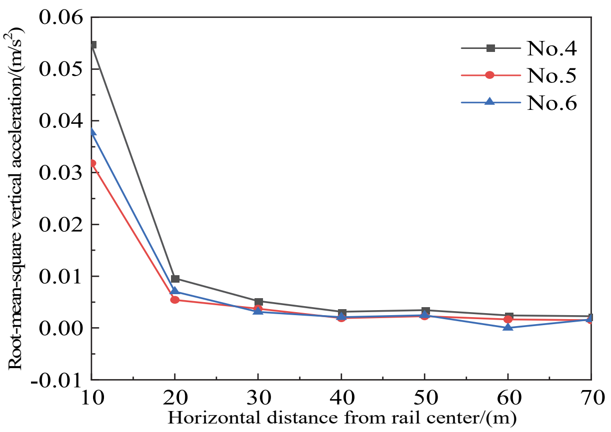


Figure 5 The trend of the root mean square value of acceleration in the *z*-direction

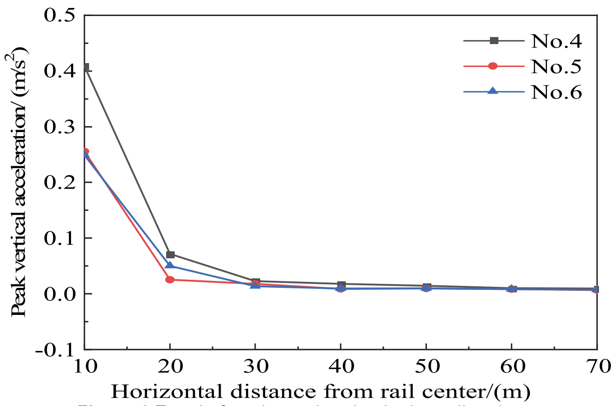


Figure 6 Trend of peak acceleration in the *z*-direction

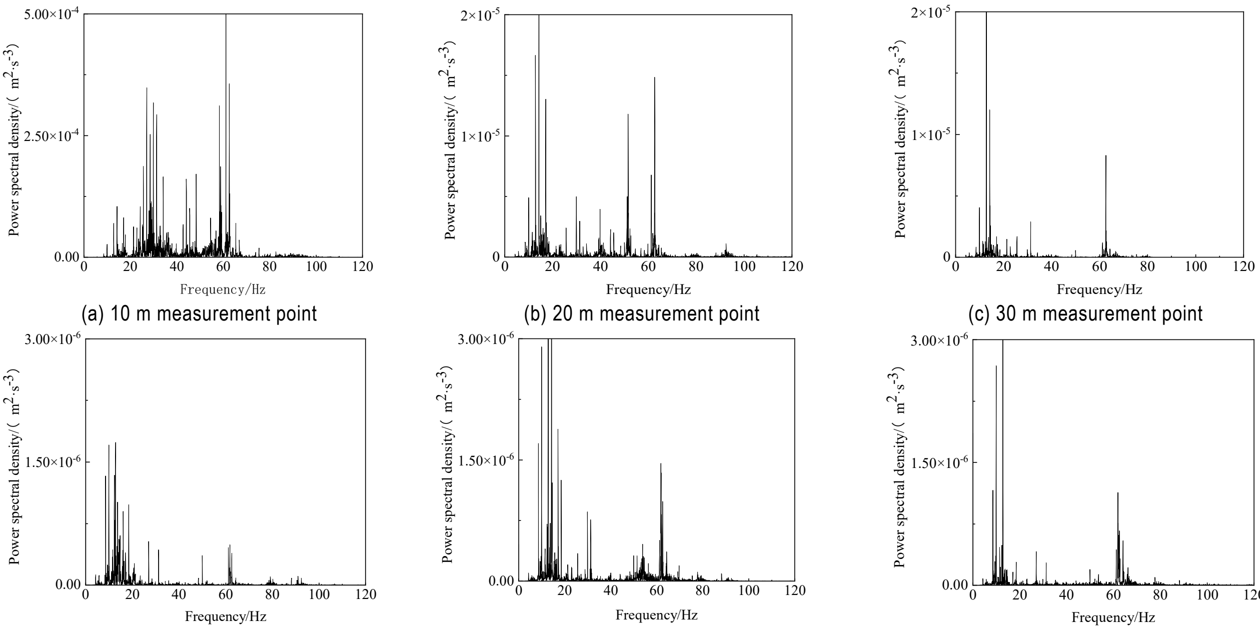
As can be seen from Fig. 4, the acceleration amplitude at the 10 m measurement point has a large range of variation, showing a periodic peak, lasting about 12 s. With the increase of distance, the acceleration value shows a trend of attenuation. Compared with the unsaturated soil site, the saturated soil site is full of water, the water flow rate is hindered, and the damping coefficient is larger, so that the vibration energy is constantly dissipated in the propagation process. The acceleration value in the interval of 10 m to 20 m decays rapidly, and the acceleration value tends to decay gently after 30 m, which is close to the background vibration. From Fig. 5 and Fig. 6, it can be seen that with the increase of distance, the root mean square value of acceleration and peak acceleration in *Z* direction show a decreasing trend, the root mean square value of acceleration in the interval of 10 m to 20 m accounts for 86% of the total decay value, and the peak acceleration value accounts for 85% of the total decay value. The root mean square value of acceleration at the measurement point of 50 m is improved compared with that at the measurement point of 40 m, and the three passenger trains improve by 15%. The local amplification zone vibration appeared at the 50 m measurement point, and the formation of the amplification zone was affected by the wave impedance ratio of the velocity interface, the thickness of the cover layer, the damping ratio, and the excitation frequency, etc [16].

3.2 Frequency Domain Analysis

Spectral analysis can reflect the distribution of vibration energy and vibration frequency components [14]. The power spectrum is obtained by spectral transformation of the vibration test data of No. 5 trains, and its operational Eq. (2) is given in the following equation.

$$P_{ii}(f)=\frac{1}{N}\sum_{n=1}^{N}[R_{in}^{*}(f)*R_{in}(f)] \qquad (2)$$

where: $P_{ii}(f)$ is the self-power spectrum of the vibration of the ith measurement point, $m^2 \cdot s^{-3}$; $R_{in}(f)$ is the Fourier spectrum of the nth segment data of the *i*th measurement point, and ${R^*}_{in}(f)$ is the conjugate complex of $R_{in}(f)$. The train power spectrum is calculated as shown in Fig. 7.



(a) 10 m measurement point (b) 20 m measurement point (c) 30 m measurement point

(d) 40 m measurement point (e) 50 m measurement point (f) 60 m measurement point

Figure 7 Train power spectrum

From Fig. 7, the main frequency range of vertical vibration response is 0 - 80 Hz. with the increase of distance, the band width of the vibration response decreases gradually, the vibration energy in the aggregation area gradually attenuates, and the attenuation of the 10 m to 30 m interval is especially obvious. This is due to the damping and filtering effects of the saturated soil layer, where high-frequency vibrations have a short propagation distance in the soil layer and low-frequency vibrations have a long propagation distance in the soil layer. The vibration energy of the 10m measurement point is concentrated in 20 - 40 Hz, 55 - 65 Hz, the vibration energy of the 20 m measurement point is concentrated in 15 - 20 Hz, 40 - 65 Hz, the vibration energy of the measurement point of the 30 - 70 m interval is concentrated in 15 - 20 Hz, 55 - 65 Hz. Within the range of 15 - 20 Hz, there is a sudden change in energy accumulation at the 50 m measuring point, which is consistent with the analysis of local vibration amplification in the previous section.

4 ENVIRONMENTAL VIBRATION EVALUATION

4.1 The Weighted Plumb Vibration Level Evaluation

According to Urban Area Environmental Vibration Standard (GB 10070-88) [18] and Urban Area Environmental Vibration Measurement Method (GB 10071-88) [19], the maximum weighted plumb vibration level is used as an evaluation index to evaluate the environmental vibration of saturated soil site. In order to evaluate the environmental vibration of the saturated soil site more comprehensively, the observation data of upward and downward traveling passenger and feight trains are selected, and the maximum weighted plumb vibration level is calculated for different trains at different measurement points, as shown in Tab. 2. The variation curves of the maximum weighted plumb vibration level of the upward passenger trains are shown in Fig. 8, and the vibration curves of the maximum weighted plumb vibration level of the downward passenger trains are shown in Fig. 9. The vibration curves of the maximum weighted plumb vibration level of the upward freight trains is shown in Fig. 10, and the vibration curves of the maximum weighted plumb vibration level of the downward freight trains is shown in Fig. 11.

From Tab. 2, Fig. 8 to Fig. 11, the maximum weighted plumb vibration level of upward and downward passenger trains at 30 m is 70.8 dB and 71.3 dB, while the maximum weighted plumb vibration level of upward and downward freight trains at 30 m is

77.4 dB and 71.4 dB. According to the strictest requirements of Urban Area Environmental Vibration Standard, the weighted plumb vibration level limit for special residential areas is 65 dB, and the maximum weighted plumb vibration level of passenger and freight trains at 30 m exceeds the standard value. With the increase of distance, the maximum weighted plumb vibration level of upward and downward traveling passenger and freight trains shows an overall decreasing trend, with a rapid attenuation in the interval of 10 m to 30 m, and a slow attenuation after 30 m.

Table 2 Maximum weighted plumb vibration level of different trains at different measurement points

Point	Z_{max} / dB			
	Upward passenger trains	Downward passenger trains	Upward freight trains	Downward freight trains
$P1$	84.1	86.7	83.7	82.7
$P2$	74.6	74.1	78.9	73.6
$P3$	70.8	71.3	77.4	71.4
$P4$	68.2	67.8	75.4	69.2
$P5$	67.2	67.8	75.1	68.7
$P6$	64.1	64.2	73.8	67.5
$P7$	61.8	62.1	72.8	65.6

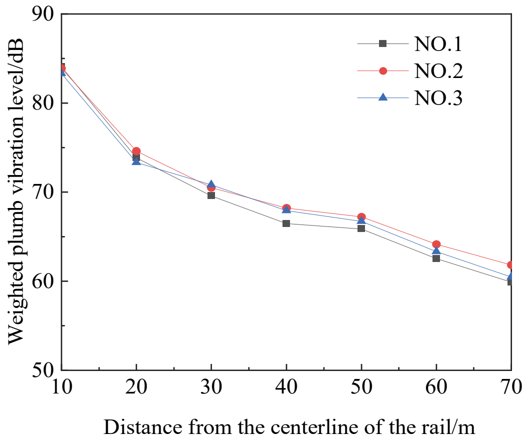


Figure 8 Weighted plumb vibration level curves of upward passenger trains

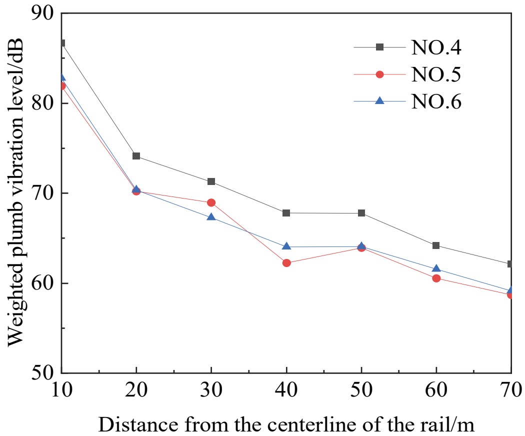


Figure 9 Weighted plumb vibration level curves of downward passenger trains

The number of carriages of upward freight trains No. 7 and No. 9 are much more than that of upward freight train No. 8, and the hourly speed of upward freight trains No. 7 and No. 9 is less than that of upward freight train No. 8, while the weighted plumb vibration level of freight train No. 8 is greater than that of freight trains No. 7 and No. 9. Freight trains No. 10, No. 11, and No. 12 each have 67 carriages. Freight train No. 12 has the fastest speed, and weighted plumb vibration level of freight train No. 12 is greater than that of freight trains No. 10 and No. 11. This indicates that the influence of the number of carriages on vibration intensity is not significant, while the influence of train speed on vibration intensity is significant. The distance between the upward and downward trains is 5 m, the distance between the center line of the upward train and $P1$ point is 15 m, and the distance between the center line of the downward train and $P1$ point is only 10 m.

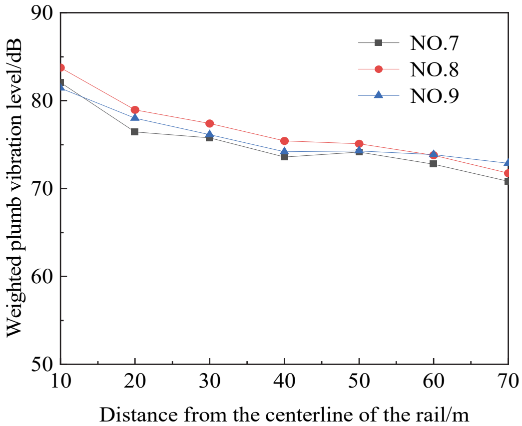


Figure 10 Weighted plumb vibration level curves of upward freight trains

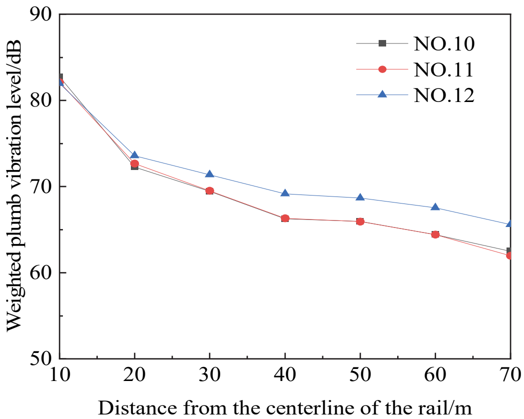


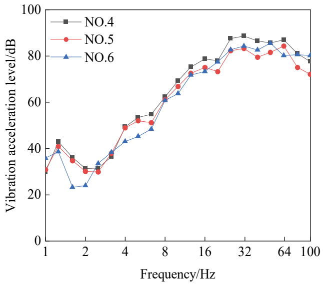
Figure 11 Weighted plumb vibration level curves of downward freight trains

The weighted plumb vibration level of the upward trains is generally larger than that of the downward trains, and the attenuation of the weighted plumb vibration level of the upward trains is slow. This may be due to the unloaded operation of the downward trains and the full load operation of the upward trains. The different axle loads of the upward and downward trains affect the vibration intensity.

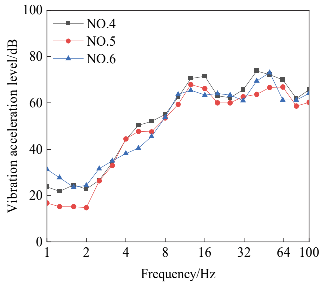
4.2 1/3 Octave Evaluation

In vibration testing, 1/3 octave is often used for frequency band division. The 1/3 octave can use fewer data points to describe the variation of vibration acceleration with frequency, and has the characteristics of wide frequency band and fewer spectral lines [20].

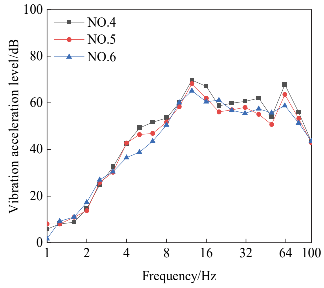
The 1/3 octave frequency evaluation method is used to evaluate the impact of ground vibration on human comfort caused by the operation of downward trains. The calculation results of vibration acceleration levels at each measurement point of downward trains are shown in Fig. 12.



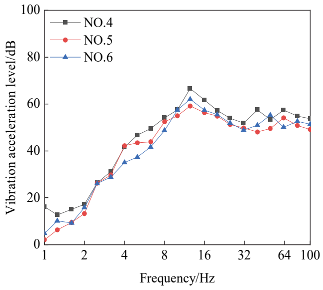
(a) 10 m measurement point



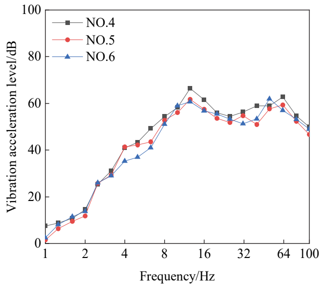
(b) 20 m measurement point



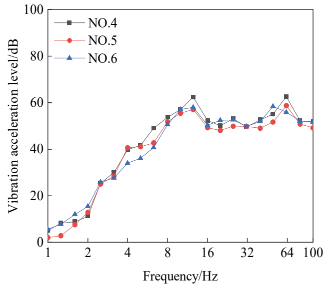
(c) 30 m measurement point



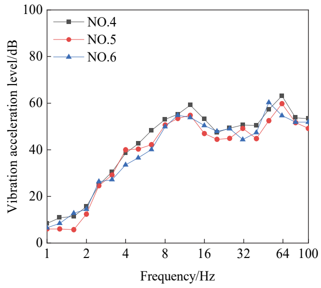
(d) 40 m measurement point



(e) 50 m measurement point



(f) 60 m measurement point



(g) 70 m measurement point

Figure 12 Vibration acceleration level curve of measuring points at different distances

From Fig. 12, it can be seen that the vibration acceleration level in the *Z*-direction of the downward passenger trains No. 4, No. 5, and No. 6 shows an overall trend of first increasing and then decreasing with the increase of frequency. Except for the 10 m measuring point, all other measuring points show a slight depression in the range of 12.5 Hz to 63 Hz. The vibration acceleration level at the 10 m measuring point reaches its maximum value at 31.5 Hz, with a maximum value of 88.6 dB. The vibration acceleration level at the 20 m measuring point reaches its maximum value at 40 Hz, which is 73.8 dB. The maximum vibration acceleration levels at measuring points 30 m, 40 m, 50 m, and 60 m occurred at 12.5 Hz, with maximum values of 69.8 dB, 66.7 dB, 66.4 dB, and 62.7 dB, respectively. The maximum vibration acceleration level at the 70 m measuring point appears at 63 Hz, with a maximum value of 63.1 dB. According to GB50355-2018 Standard for Indoor Vibration Limits and Their Measurement Methods in Residential Buildings [21], the 10m measurement point exceeds the specification limit by 9.5 dB. The 20 m measurement point exceeds the specification limit by 2.5 dB, and the rest of the measurement points meet the specification requirements. The vibration frequency of various organs in the human body is mainly between 1 and 80 Hz, so the vibration in this area can cause resonance in some organs, making the human body very sensitive to the vibration in this range, which has a significant impact and harm on the organs [22]. The vibration acceleration levels at each measuring point shown in the text exhibit extreme points at 12.5 Hz and 63 Hz, which have a significant impact on human comfort. Therefore, it is necessary to take control measures to reduce the impact of vibration on human comfort.

5 CONCLUSION

(1) With the increase of distance, the vibration acceleration and root mean square value of acceleration both show a decreasing trend. The attenuation is fast at 10 - 30 m, and slow after 30 m. A local vibration amplification zone appears near 50 m.

(2) The main frequency range of vertical vibration response is 0 - 80 Hz. As the distance increases, the frequency band width of vibration response gradually decreases. The vibration energy attenuation is significant in the frequency band above 40 Hz, while the vibration energy attenuation is relatively slow in the frequency band of 15 - 20 Hz.

(3) Train running speed and axle weight have obvious influence on the vibration intensity, while the number of carriages has no obvious influence on the

vibration intensity.

(4) The maximum weighted plumb vibration level of upward and downward passenger trains at 30 m is 70.8 dB and 71.3 dB, while the maximum weighted plumb vibration level of upward and downward freight trains at 30 m is 77.4 dB and 71.4 dB. According to the strictest requirements of the Urban Regional Environmental Vibration Standard, the weighted plumb vibration level limit for special residential areas is 65 dB, and the maximum weighted plumb vibration level of upward and downward passenger trains at 30 m exceeds the specification limit.

(5) According to the Standard for Indoor Vibration Limits and Measurement Methods of Residential Buildings, the maximum value at 31.5 Hz occurs at 10 m measuring point, with maximum value of 88.6 dB and the maximum value exceeding the limit of 9.5 dB. The maximum vibration acceleration level at the 30 m measuring point appeared at 12.5 Hz, with maximum value of 69.8 dB, which meets the specification requirements.

Acknowledgment

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