Test and Analysis of the Influence of Curve Radius on Subway Vibration at a Speed of 120km/h

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Abstract. The environmental vibration problems caused by the operation of subway trains are becoming increasingly prominent. In order to master the influence of line conditions on the vibration characteristics of the subway under high-speed driving conditions, field test of track vibration on a curved section of the subway at a speed of 120 km/h was carried out. The vibration characteristics of ordinary tracks under different curve radius conditions were studied, and the vibration transmission laws were analyzed. The results show that the maximum Z-vibration level range of vertical vibration of the tunnel wall is 56.00dB~73.36dB when subway trains pass through a 750 m curve radius line. The maximum Z-vibration level range of vertical vibration of the tunnel wall is 51.18dB~63.32dB when subway trains pass through a 2000 m curve radius line. Compared with the 2000 m curve radius line, the amplitude of vertical vibration of steel rails and tunnel walls increases significantly in the low-frequency range when subway trains pass through the 750 m curve radius line, and the average value of the maximum Z-vibration level of vertical vibration of tunnel wall increases by 9.10dB.

Keywords: subway; test; curve radius; vibration

1 Introduction

With the rapid development of urban construction scale, the environmental vibration problem caused by the operation of subway trains along the line is also receiving more and more attention from people[1]. The vibration generated by subway trains during operation will be transmitted to the foundation of buildings above through tracks, tunnels, and soil. Not only will it affect the living and working comfort of residents inside the building, but it may also pose a potential threat to the structural safety of the building. For places sensitive to vibration, such as hospitals, laboratories, etc., subway vibration may cause instability in the operation of precision instruments, affecting the accuracy of experimental results or the normal operation of medical equipment. Therefore, some vibration control measures have to be taken. According to the vibration reduction needs of different sections, vibration reduction measures

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can be divided into general level vibration reduction, medium level vibration reduction, and high-level vibration reduction[2-3].

In order to solve these problems, it is necessary to carry out vibration reduction design in aspects such as subway vehicle type, track structure, and line conditions, in order to reduce the vibration generated by wheel rail contact and fundamentally reduce the impact of vibration on the surrounding environment. Zhang[4] compared the influence of subway operation on the surrounding environment in different soil sections. As the elastic modulus and density of the subway tunnel medium increase, the displacement and acceleration of tunnel bed and tunnel wall gradually decrease. Lin[5] conducted a comparative analysis of the vibration reduction effect of double layered nonlinear fasteners used in the vibration reduction turnout in the vehicle depot. Li[6] conducted a special study on the vibration problem of buildings along the subway line and proposed vibration reduction measures. Based on the existing circumstances that the North Palace Gate of the Summer Palace and Beijing Rail Transit Line 4，Ba[7] systematically studied the influence of the angle between the subway line and ancient buildings during subway operation, train speed and tunnel depth on the vibration of wooden ancient buildings. Gao[8] investigated the effects of various random irregularities of the track (height, level, track gauge, and track direction) on the vertical vibration acceleration and wheel rail force of subway tunnel walls at different train speeds.

Due to the small curve radius of urban rail transit lines, the interaction between vehicles and tracks is more intense, and the vibration characteristics are complex. Currently, little attention is paid to the impact of line types on subway vibration. Therefore, it is necessary and meaningful to study in detail the vibration characteristics of curved sections under high-speed driving conditions through on-site testing. In this article, the vibration characteristics of ordinary tracks under different curve radius line conditions were studied by conducting field test of track vibration in a curved section of a 120 km/h subway, and the vibration transmission law was analyzed. This study aims to provide valuable reference for subway line design.

2 Field Test

2.1 Test Section

Vibration testing research was conducted on shield tunnel subway lines. The cross-section of the shield tunnel is circular, the track type is ordinary track, and the steel rail is 60kg/m seamless steel rail, with a good surface condition. The train is an 8-car formation, A-type car, designed to operate at a speed of 120 km/h.

The test section parameters are shown in Table 1. Section 1 is a 750m curve radius line, and Section 2 is a 2000m curve radius line. When the train passes through the test section, the speed is about 100km/h.

Table 1. Test section parameters.

section	Curve Radius (m）	Curve superelevation (mm）
1	750	150
2	2000	75

2.2 Layout of Measurement Points

To record the track vibration generated by subway trains passing through, acceleration sensors are fixed on measuring points on steel rail, track bed, and tunnel wall. The vertical vibration measurement point of the steel rail are arranged at the bottom of the steel rail. The vertical vibration measurement points of the track bed are arranged in the middle position of the track bed. The vertical vibration measurement points on the tunnel wall are arranged at a height of 1.25m from the rail surface. The layout of measurement points is shown in Figure 1.

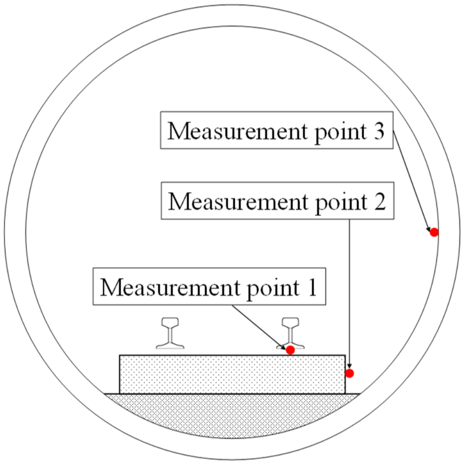


Fig. 1. Schematic diagram of measurement point layout.

2.3 Test Instrument

The test instrument consists of three acceleration sensors, a data acquisition system, and a computer. The acceleration sensor adopts piezoelectric acceleration sensors, and the data acquisition system is a multi-channel data acquisition instrument. Different range acceleration sensors are selected based on the measurement point position. The vertical vibration of the steel rail adopts an acceleration sensor with a range of 700g, the vertical vibration of the track bed adopts an acceleration sensor with a range of 50g, and the vertical vibration of the tunnel wall adopts an acceleration sensor with a range of 3g. During the normal operation of the subway, collect daily traffic data on regular working days.

3 Z-Vibration Level Analysis

3.1 Z-Vibration Level

In the "Measurement Method for Environmental Vibration in Urban Areas GB10071-1988", the vibration acceleration level obtained by adjusting the Z-weighting factor of the whole body vibration is used for vibration evaluation, namely Z-vibration level (VL_Z). The Z-vibration level reflects the weighted vibration energy of the vertical vibration acceleration within the center frequency range of one-third of the octave range of 1Hz~80Hz. The formula for calculating the Z-vibration level is

$$VL_Z = 10\log\left(\sum 10^{(VL_i+\lambda_i)/10}\right) \tag{1}$$

In the formula: VL_i is the vibration acceleration level (dB) of the i-th frequency band; λ_i is the weighting factor (dB) of the i-th frequency band. The weighting factor adopts the Z-weighting factor specified in ISO 2631/1-1985, as shown in Table 2.

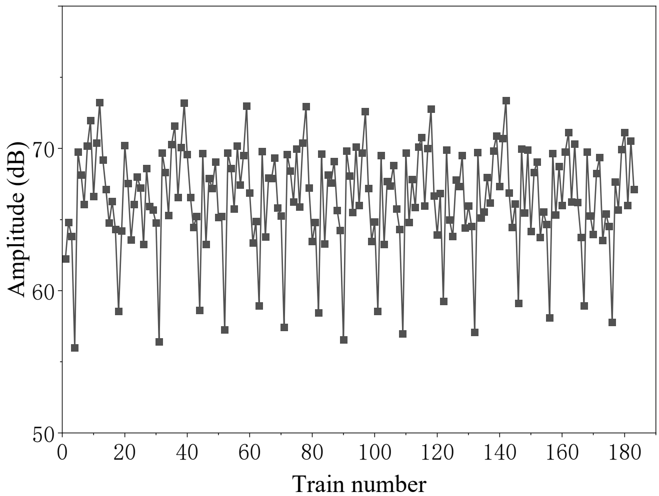
Table 2. Z-weighting factors specified in ISO 2631/1-1985.

frequency（Hz）	1	1.25	1.6	2	2.5	3.15	4	5	6.3	8
Weighting factor（dB）	-6	-5	-4	-3	-2	-1	0	0	0	0
frequency（Hz）	10	12.5	16	20	25	31.5	40	50	63	80
Weighting factor（dB）	-2	-4	-6	-8	-10	-12	-14	-16	-18	-20

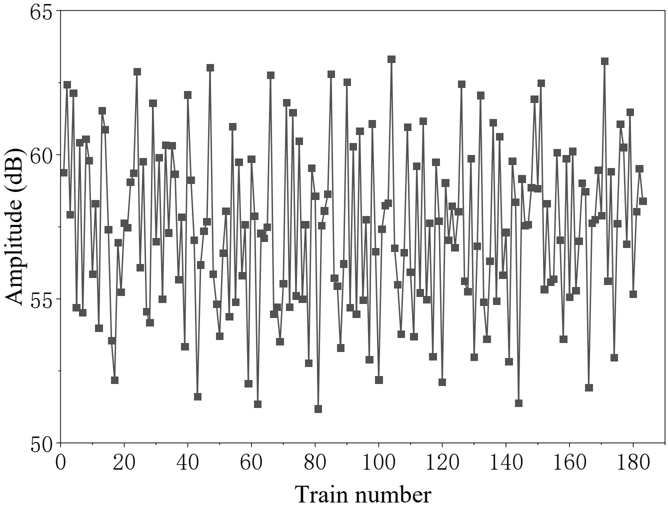
The maximum Z-vibration level ($VL_{Z,max}$) is the maximum value of the Z-vibration level during the train's passage. The Z-vibration level during the train passing time was calculated, with a time integration constant of 1 second and an overlap coefficient of 7/8. Based on this, the maximum Z-vibration level for each train passing through was obtained.

3.2 Analysis of Test Results

Figure 2 shows the maximum Z-vibration level of vertical vibration of tunnel wall. It can be seen that for different train numbers, the distribution of the maximum Z-vibration level is relatively discrete. When different subway trains pass through a 750m curve radius line, the maximum value of $VL_{Z,max}$ is 73.36dB, and the minimum value of $VL_{Z,max}$ is 56.00dB. When different subway trains pass through a 2000m curve radius line, the maximum value of $VL_{Z,max}$ is 63.32dB, and the minimum value of $VL_{Z,max}$ is 51.18dB.



(a) A curve radius of 750m.



(b) A curve radius of 2000m.

Fig. 2. The maximum Z-vibration level of tunnel wall.

Box plots were used for statistical analysis of test results. It is a statistical chart used to display the dispersion of a set of data, commonly used to identify data distribution and detect abnormal data. The box plot mainly consists of mean, lower quartile (25th percentile), median (50th percentile), upper quartile (75th percentile), lower margin (lower limit), upper margin (upper limit), and outliers.

The interquartile range is

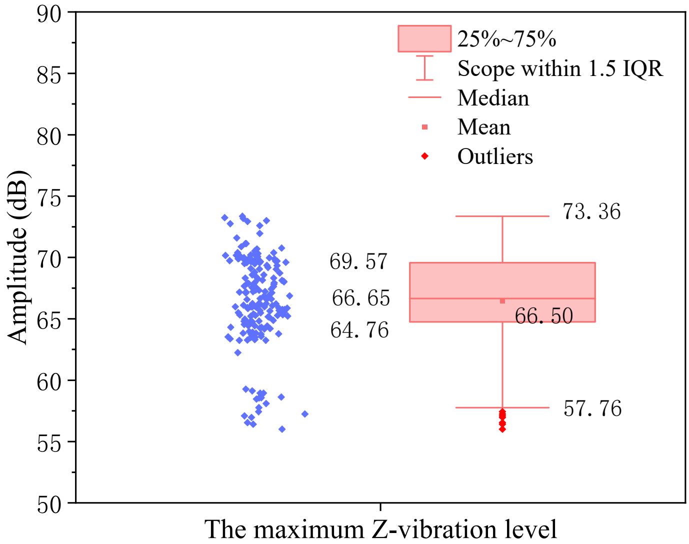
$$IQR = Q_3 - Q_1 \tag{2}$$

The interquartile range is used to determine the lower and upper limits, which are

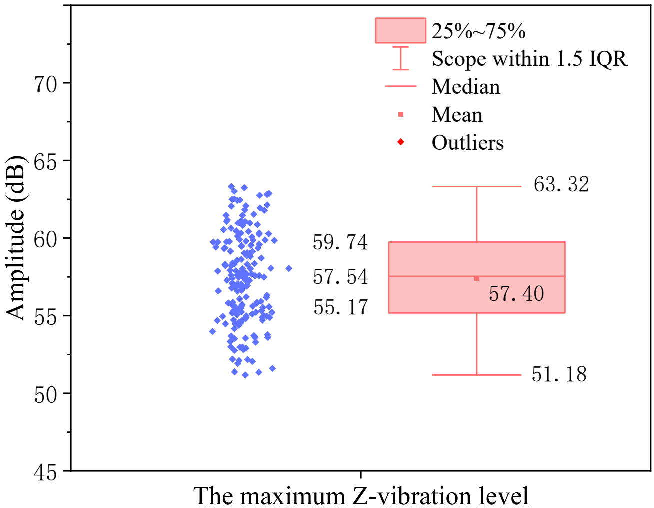
$$T_{\min} = Q_1 - 1.5 \times IQR \tag{3}$$

$$T_{\max} = Q_3 + 1.5 \times IQR \tag{4}$$

The box plot of statistical results of the maximum Z-vibration level of vertical vibration of the tunnel wall is shown in Figure 3. The average and median values of $VL_{Z,max}$ are 66.50dB and 66.65dB, respectively, when the subway trains pass through a 750m curve radius line. The average and median values of $VL_{Z,max}$ are 57.40dB and 57.54dB, respectively, when subway trains pass through a 2000m long curve radius line. Compared with the 2000m curve radius line, when subway trains pass through the 750m curve radius line, the average value of the maximum Z-vibration level of vertical vibration of tunnel wall increases by 9.10dB.



(a) A curve radius of 750m.



(b) A curve radius of 2000m.

Fig. 3. The maximum Z-vibration level of tunnel wall.

4 Analysis of Vibration Characteristics

Due to the fact that the frequency of environmental vibrations caused by subways is mainly within 200Hz, the high-frequency range will rapidly decay with increasing distance. Therefore, when conducting frequency domain analysis, the one-third octave frequency range of 1Hz-200Hz should be considered.

The typical one-third octave frequency spectrum of vertical vibration acceleration of steel rails, track beds, and tunnel walls under different curve radius line conditions is shown in Figures 4~6.

It can be seen that compared with the 2000m curve radius line, when subway trains pass through the 750m curve radius line, the vertical vibration of the steel rail increases in the 1Hz~6.3Hz low-frequency range and slightly decreases in the 8Hz~200Hz high-frequency range. The vertical vibration of the track bed increases in the 1Hz~200Hz full frequency range, and the vertical vibration of the tunnel wall increases in the 1Hz~8Hz low-frequency range and slightly decreases in the 10Hz~200Hz high-frequency range.

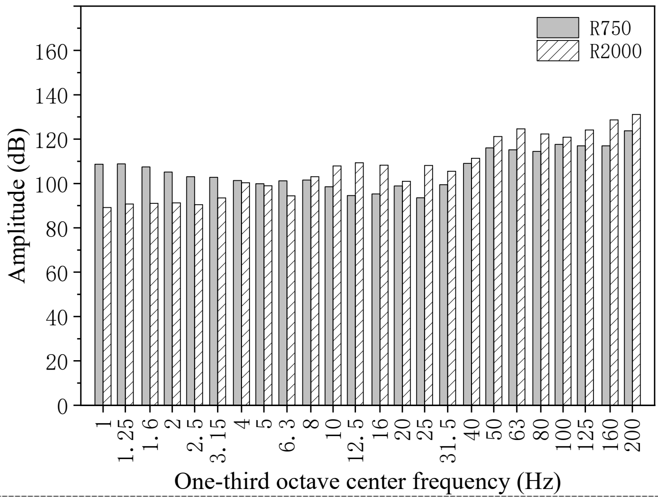


Fig. 4. Vertical vibration of steel rails.

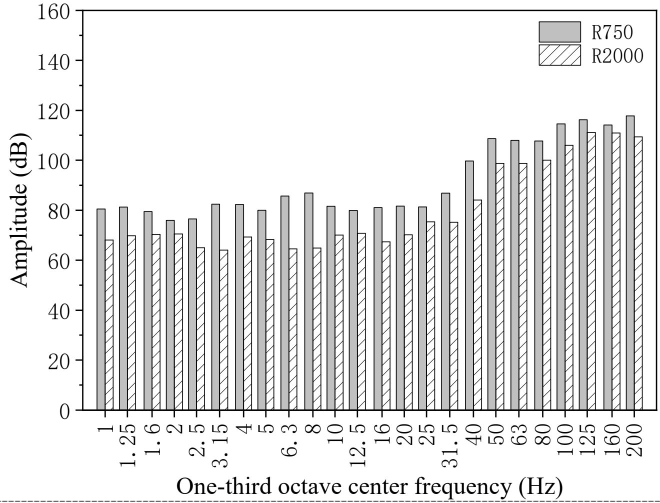


Fig. 5. Vertical vibration of track beds.

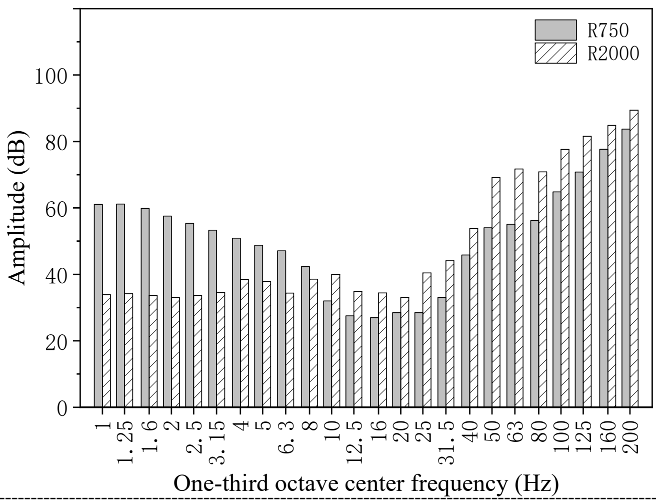


Fig. 6. Vertical vibration of tunnel wall.

5 Conclusion

(1) When subway trains pass through a 750m curve radius line, the maximum Z-vibration level range of vertical vibration of the tunnel wall is 56.00dB~73.36dB, with an average value of 66.50dB.

(2) When subway trains pass through a 2000m curve radius line, the maximum Z-vibration level range of vertical vibration of the tunnel wall is 51.18dB~63.32dB, with an average value of 57.40dB.

(3) Compared with the 2000m curve radius line, when subway trains pass through the 750m curve radius line, the average value of the maximum Z-vibration level of vertical vibration of tunnel wall increases by 9.10dB.

(4) Compared with the 2000m curve radius line, when subway trains pass through the 750m curve radius line, the vertical vibration amplitude of the steel rail and tunnel wall increases significantly in the low-frequency range.

(5) This study provides a reference for alleviating environmental vibration problems caused by subway operation. However, factors such as the diversity of geological conditions and differences in subway vehicle types may not be comprehensively and meticulously considered in this study. In the future, it is necessary to further study the propagation mechanism of subway vibration, in order to reveal more potential influencing factors, and provide more comprehensive and scientific basis for the optimization design, effective maintenance, and comprehensive mitigation of environmental impacts of subway infrastructure.

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