IOP Conf. Series: Materials Science and Engineering **735** (2020) 012067 doi:10.1088/1757-899X/735/1/012067

Experimental Study on the Damping Effects of Various Vibration Reduction Measures

Tanghui Liu [1], Rui Rao [2 *], Jianwu Liu [2], Mao Ye [2] and Yue Huang [2,]**

1. Guangzhou Metro Design and Research Institute Co., Ltd, Guangzhou, 510000
2. Tamkang University- Guangzhou University Joint Research Center for Engineering Structure1, Guangzhou 510006

Abstract. Field measurements are the most effective and direct way to evaluate the effects of vibration reduction measures. Through field measurements, this study examined the actual damping effects and vibration transfer characteristics of five vibration reduction measures for subway systems, namely, steel spring floating slabs, resilient short crossties, double-layer nonlinear damping fasteners, Vanguard fasteners and rubber floating slabs. The vibration level and 1/3 octave frequency division vibration level was used as vibration evaluation indices for analysis. This study aimed to provide a reference for the actual damping effects of vibration reduction measures. The results show the following: steel spring floating slabs outperformed resilient short crossties by 23.2 dB. Double-layer nonlinear damping fasteners outperformed Vanguard fasteners and rubber floating slabs by 1.6 and 2 dB, respectively. Resilient short crossties, Vanguard fasteners and double-layer nonlinear damping fasteners were effective in reducing vibration from steel rails to track beds (floating slabs). Steel spring floating slabs and rubber floating slabs were effective in reducing vibration from track beds (floating slabs) to tunnel walls.

1. Introduction

China has been developing subway transit systems for over 50 years. By the end of December 2016, 193 subway lines (including extensions), with a combined length of over 4,700 km, were under construction in full swing in 41 cities in China. With strong support from the government, more Chinese cities will have subway transit systems in future [1]. Unlike automobiles, subway systems neither take up ground space nor emit exhaust that pollutes the air. Additionally, subway systems can effectively relieve the pressure caused by shortages of ground space and are more environmentally friendly. By transporting passengers, subway systems can efficaciously mitigate urban ground traffic congestion.

Field measurement is the most effective and direct way to evaluate the effects of vibration reduction measures. Researchers in China and elsewhere have extensively measured subway train-induced vibrations in the field. By regression analysis of field-measured data, Japanese researchers Okwnura and Kuno [2] found that the types of train, train length, distance from the centerline, train speed, track structure and background vibration are the primary factors affecting vibrations. Through field measurements of the sources of train-induced vibrations on the ground and inside the surrounding buildings, Danish researcher Jakobsen [3] determined the patterns of vibration attenuation with distance in soils of various textures. Through field measurements, Saurenman and Philips [4] found that a resilient short crosstie track structure was less effective in reducing vibrations than expected. These researchers recommended testing of the performance of softer subgrades. Additionally, researchers in other countries, including Spain, the Czech Republic and the Netherlands, have conducted extensive field measurements, surveys and studies to examine environmental vibrations induced by rail traffic. Through field measurements and an analysis of Line 5 of the Beijing Subway, Li et al. [5] found that type III rail vibration absorbers and steel spring floating slab tracks outperformed ordinary fasteners in reducing vibrations by 10–15 and 15–25 dB, respectively. Through field measurements of Line 1 of the Guangzhou Metro, Yu [4] discovered a vibration amplification zone in the ground vibration propagation process. By field measurements of Line 3 of the Guangzhou Metro, Huangfu [7] found that acceleration first increased and then decreased as the distance from the centerline of the train increased.

In summary, subway train-induced vibration remains a focal topic of recent research. However, most studies examined only two or three vibration reduction measures and were therefore unable to provide comprehensive understanding of the damping effects of various vibration reduction measures. Track vibration reduction is a complex systematic problem that involves a multitude of factors, including geological conditions, track structure, vehicle system and building structure. Therefore, there are limitations in the available results obtained from field measurements. This study examined subway train-induced environmental vibrations. Five vibration reduction measures, namely, resilient short crossties, steel spring floating slabs, Vanguard fasteners, rubber floating slabs and double-layer nonlinear fasteners, were investigated through field measurements. The relative damping effects and vibration transfer characteristics of the five vibration reduction measures when used on the same line were compared using three indices, namely, vibration level, 1/3 octave frequency division vibration level and frequency spectrum. By increasing the number of vibration reduction measures investigated, a more comprehensive understanding of the damping effects of vibration reduction measures can be obtained.

2. Test Overview

Line 1 of a certain urban subway system has a total length of 18.497 km, of which 2.048 km are aboveground and 16.499 km are belowground. The maximum train speed on this line is 80 km/h. Line 3 of this subway system has a total length of 64.41 km. The maximum train speed on this line is 120 km/h. Indeed, there is a relatively large difference between the train speeds of Lines 1 and 3 during operation. To reduce errors, the vibration reduction measures implemented on the same line were jointly analyzed. Two vibration reduction measures, namely, resilient short crossties and steel spring floating slabs, were implemented on the underground section of Line 1. Three vibration reduction measures, namely, Vanguard fasteners, rubber floating slabs and double-layer nonlinear fasteners, were implemented on Line 3. The vibration responses of the steel rails, track beds (floating slabs) and tunnel walls on both Lines 1 and 3 were measured.

3. Test Equipment

A LAN-XI 3050-A-040 data acquisition system (manufactured by Brüel & Kjær Sound & Vibration Measurement A/S, Denmark) and a DH8303 data acquisition system (manufactured by Jiangsu Donghua Testing Technology Co., Ltd, China) were used as the acquisition instrument, shown as Figure 1. The PULSE professional data acquisition and analysis software package was used to acquire and analyse the data. Integrated electronic piezoelectric (IEPE) accelerometers (manufactured by YMC Piezotronics Inc., Yangzhou, China) and piezoelectric accelerometers (manufactured by Jiangsu Donghua Testing Technology Co., Ltd, China) were used as sensors. Table 1 summarizes the relevant sensor parameters.

4. Test Arrangement

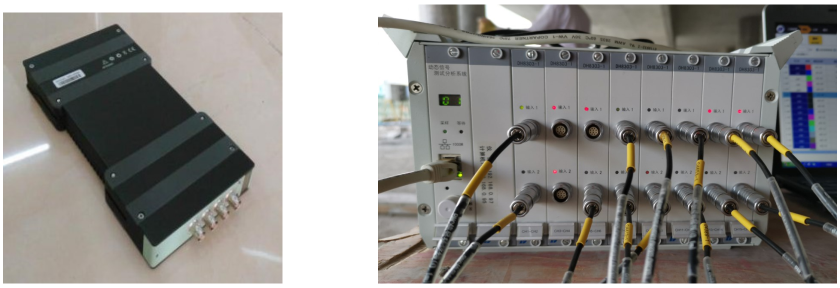
The vibration evaluation indices and test and data processing methods were selected according to Measuring Methods for Environmental Vibration in Urban Areas (China GB 10071-88) [8] and Standards for Environmental Vibration in Urban Areas (China GB 10070-88) [9]. Regarding the arrangement of the measuring points, the above two specifications stipulate that the measuring points should be placed at locations sensitive to vibrations. Thus, measuring points were set on the steel rails, track beds (floating slabs) and tunnel walls. One vibration pickup was placed at each measuring point. Because subway train-induced vibration is primarily vertical [10, 11], only vertical vibration signals

IOP Conf. Series: Materials Science and Engineering **735** (2020) 012067 doi:10.1088/1757-899X/735/1/012067

were picked up in this study. One IEPE accelerometer was placed at each of the three measuring points, as shown in Figure2. Based on the actual field conditions, the data were continuously collected 20 times from each measuring point.

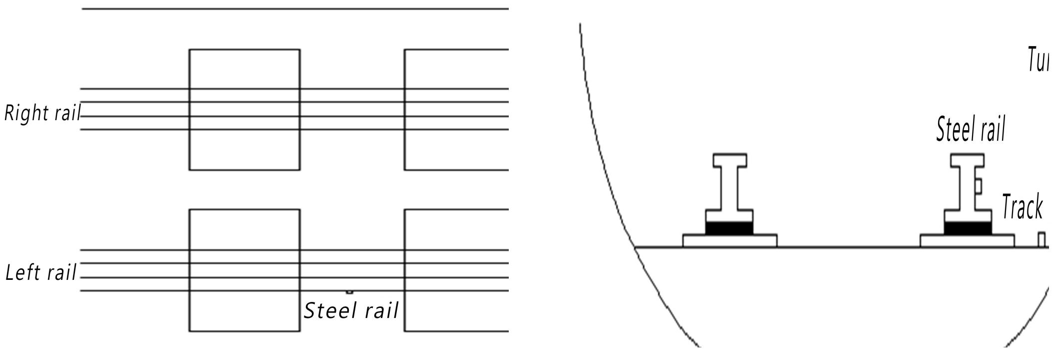
Table 1. Sensor Parameters

Type	Parameter range	Application
121A100 IEPE accelerometer	Measuring range: -50–50 g Frequency range: 1 Hz–10 kHz Sensitivity: 9.9 mV/ms-2	Acceleration sensors on track beds and tunnel walls
121A05 IEPE accelerometer	Measuring range: -1,000–1,000 g Frequency range: 1 Hz–10 kHz Sensitivity: 5.28 mV/ms-2	Acceleration sensors on steel rails
1A102E piezoelectric accelerometer	Measuring range: -500–500 g Frequency range: 1 Hz–10 kHz Sensitivity: 1mV/ms-2	Acceleration sensors on steel rails



（a）LAN-XI 3050-A-040 (b) DH8303

Figure 1. Data acquisition system

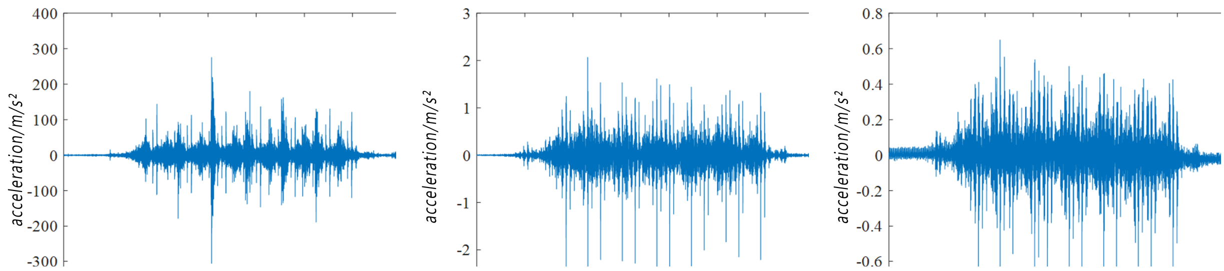


(a) Planar view (b) Sectional view

Figure 2. Schematic Diagram of the Arrangement of Measuring Points

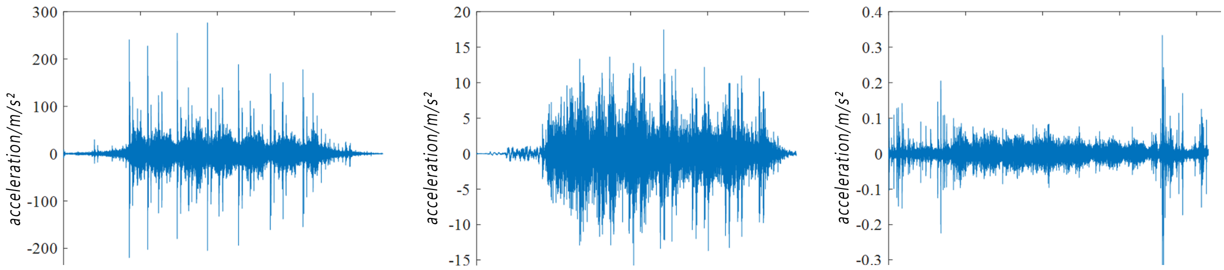
5. Test Results

The peak acceleration and vibration level are important parameters in environmental vibration research [12]. Tests were performed during day-time rush hours. In the field tests, the vertical acceleration time histories were recorded for at least 20 trains passing through each test section to ensure that the data were reliable. Due to the limited length of this article, a relatively good typical acceleration history for one pass is presented. Figure 3–7 show the time histories at the steel rails, track beds and tunnel walls recorded when a train passed the sections where resilient short crossties, steel spring floating slabs, Vanguard fasteners, rubber floating slabs and double-layer nonlinear fasteners were implemented, respectively. As demonstrated in Figure 3-7, the peak acceleration at the steel rails was the highest, followed by that at the track beds and that at the tunnel walls.



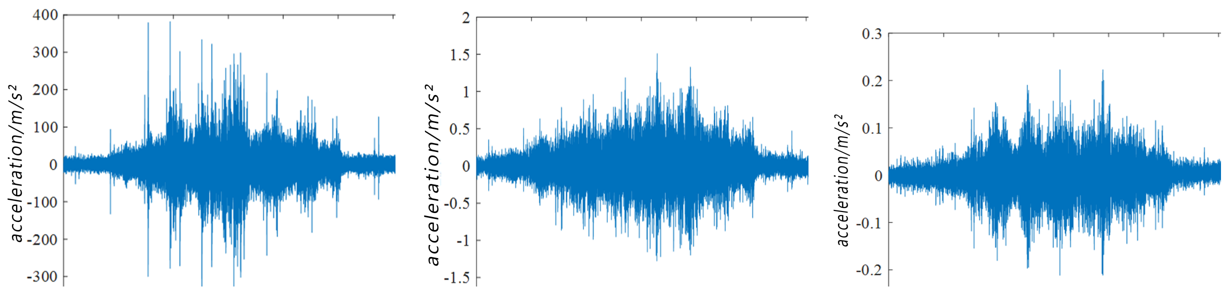
(a) At the steel rail (b) At the track bed (c) At the tunnel wall

Figure 3. Acceleration Time Histories Recorded at the Section where Resilient Short Crossties were Implemented (speed: 120 km/h)



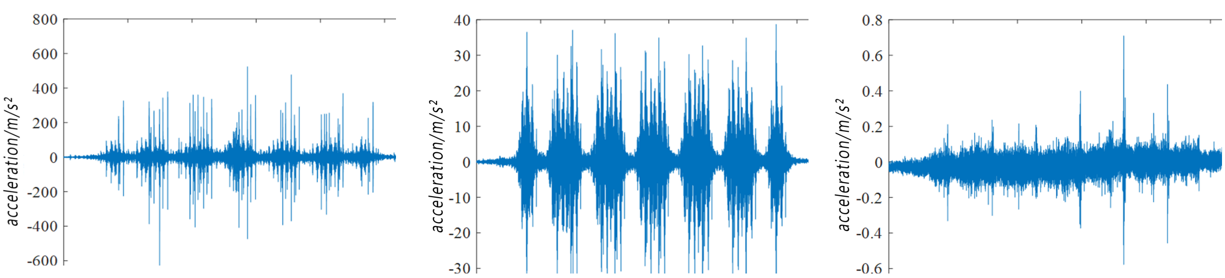
(a) At the steel rail (b) At the track bed (c) At the tunnel wall

Figure 4. Acceleration Time Histories Recorded at the Section where Steel Spring Floating Slabs were Implemented (speed: 120 km/h)



(a) At the steel rail (b) At the track bed (c) At the tunnel wall

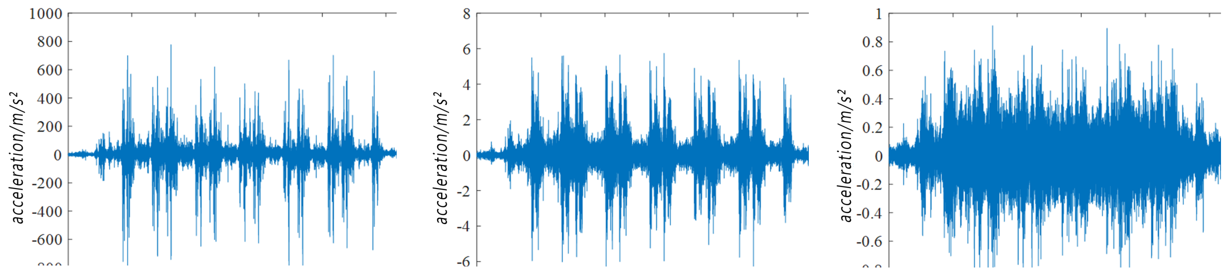
Figure 5. Acceleration Time Histories Recorded at the Section where Vanguard Fasteners were Implemented (speed: 80 km/h)



(a) At the steel rail (b) At the track bed (c) At the tunnel wall

Figure 6. Acceleration Time Histories Recorded at the Section where Rubber Floating Slabs were Implemented (speed: 80 km/h)

IOP Conf. Series: Materials Science and Engineering **735** (2020) 012067 doi:10.1088/1757-899X/735/1/012067



(a) At the steel rail (b) At the track bed (c) At the tunnel wall

Figure 7. Acceleration Time Histories Recorded at the Section where Double-layer Nonlinear Fasteners were Implemented (speed: 80 km/h)

6. Analysis of Damping Effects and Vibration Transfer Characteristics

6.1 Vibration Level Analysis

Environmental vibrations have complex effects on the human body. The vibration acceleration level is the most common evaluation index for environmental vibrations. Chinese Standard GB 10070-88 stipulates the following. The evaluation range is 1–80 Hz. For the effects of environmental vibration on the human body, effective acceleration must be corrected based on frequency. By vertically weighting the vibration level, an evaluation quantity—the vibration level VLz—is obtained. This quantity is the human body vibration evaluation index, which is referred to as the Z vibration level for short (unit: dB). VLz is calculated using the following equation.

$$VLz = 20\log\frac{a_{\omega}}{a_0} \tag{1}$$

Where αo is the reference acceleration (αo=10-6 m/s2) and α is the vibration acceleration (unit: m/s2) obtained after correction based on the full-body-vibration Z-weighting factor stipulated in the International Organization for Standardization 2631/1-1985 Standard.

Tables 2 and 3 summarize the peak acceleration and VLz values for the steel rails, track beds (floating slabs) and tunnel walls when 20 trains passed sections with various vibration reduction measures. Fig. 7 shows the decrease in the VLz value from the steel rails to track beds (floating slabs) and from the track beds (floating slabs) to tunnel walls.

The peak acceleration and VLz values in Tables 2 and 3 and the decrease in VLz value in Figure 8 demonstrate the following.

(1) On Line 3 of the subway system (speed: 120 km/h), the VLz value at the tunnel walls where steel spring floating slabs were implemented was 23.2 dB lower than that at the tunnel walls where resilient short crossties were implemented. Evidently, steel spring floating slabs were more effective in reducing vibrations.

(2) On Line 1 of the subway system (speed: 80 km/h), the average VLz values at the tunnel walls where double-layer nonlinear fasteners were implemented were 1.6 and 2 dB lower than that at the tunnel walls where Vanguard fasteners were implemented and that at the tunnel walls where rubber floating slabs were implemented, respectively. The double-layer nonlinear fasteners performed the best in reducing vibrations, followed by the Vanguard fasteners and rubber floating slabs. The less-than-ideal damping effects of the Vanguard fasteners and rubber floating slabs might be a result of the reduction in the damping effects of these components due to the relatively significant wear on this line.

(3) Resilient short crossties, Vanguard fasteners and double-layer nonlinear damping fasteners were more effective in reducing the vibrations from the steel rails to track beds than the vibrations from the track beds to tunnel walls. The steel spring floating slabs and rubber floating slabs were more effective in reducing vibrations from the floating slabs to tunnel walls than vibrations from the steel rails to floating slabs.

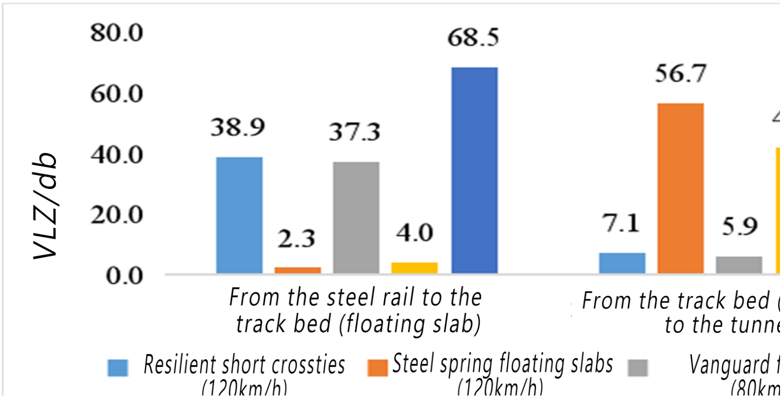


Figure 8. Decreases in *VLz* Values

Table 2. Peak Acceleration Values under Various Vibration Reduction Measures

Vibrati on reduction measure	Steel rail Acceleration (m/s2)		Track bed (floating slab) Acceleration (m/s2)		Tunnel wall Acceleration (m/s2)	
	Average	Range	Average	Range	Average	Range
Resilient short crossties (120 km/h)	245.4	177.6–340.8	2.8	2.2–3.5	0.9	0.7–1.1
Steel spring floating slabs (120 km/h)	313.6	168.8–455.9	17.2	13.9–23	0.5	0.4–1.0
Vanguard fasteners (80 km/h)	324.1	163.8–417.1	1.9	0.9–3.9	0.3	0.2–0.5
Rubber floating slabs (80 km/h)	632.9	487.7–781.1	44.9	34.9–59.0	0.6	0.3–1.2
Double-layer nonlinear fasteners (80 km/h)	831.0	657.9–1142.3	7.5	6.4–9.6	1.1	0.8–1.9

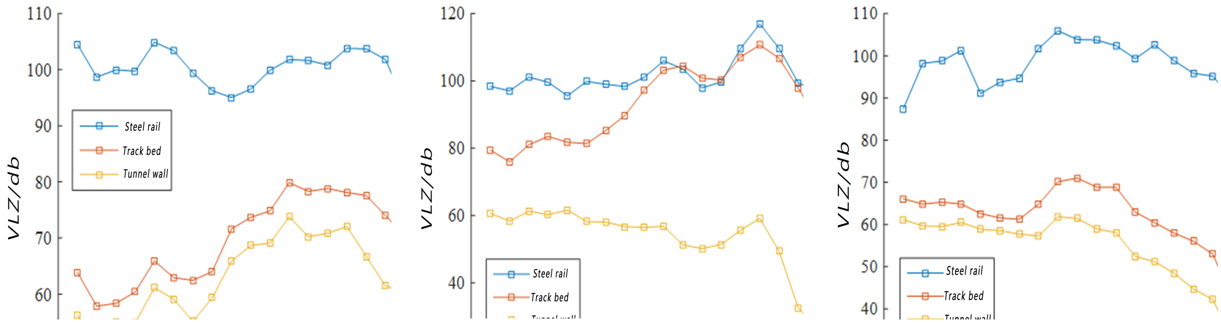
Table 3. VLz Values under Various Vibration Reduction Measures

Vibration reduction measure	Steel rail VLz (dB)		Track bed (floating slab) VLz (dB)		Tunnel wall VLz (dB)	
	Average	Range	Average	Range	Average	Range
Resilient short crossties (120 km/h)	122.4	109.9–143.7	83.5	80.8–89.9	76.4	74.0–83.4
Steel spring floating slabs (120 km/h)	112.2	108.2–114.4	109.9	105.9–111.2	53.2	52.7–54.0
Vanguard fasteners (80 km/h)	109.9	107.6–116.4	77.3	73.2–81.0	71.1	68.8–74.7
Rubber floating slabs (80 km/h)	113.2	110.7–116.0	109.7	107.6–114.1	71.5	68.9–75.2
Double-layer nonlinear fasteners (80 km/h)	142.3	138.5–144.9	73.8	72.3–76.4	69.5	68.4–70.9

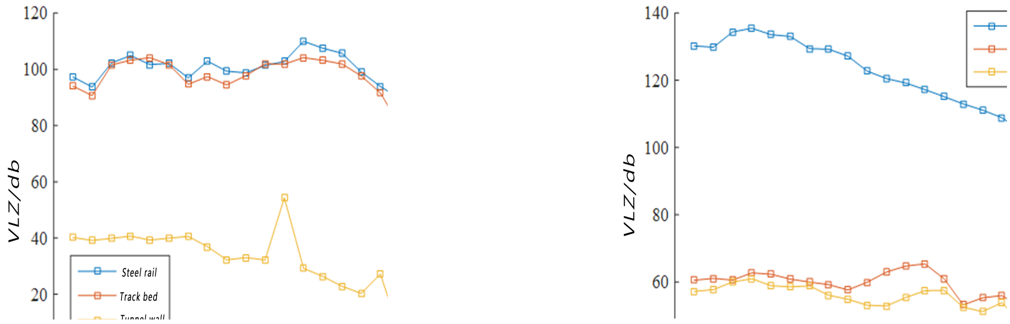
6.2 One-third Octave Frequency Division Vibration Level Analysis

The vibration acceleration time history data measured were processed using the 1/3 octave frequency division vibration level [13]. The distribution figures of the 1/3-octave central frequency vibration levels at the measuring points were compared. Based on the energy attenuation in each frequency band at the steel rails, track beds and tunnel walls, the damping effects of various vibration reduction measures were analyzed. The Standard for Limits and Vibration Test Methods for Building Vibration and Secondary Radiation Noise Caused by Urban Rail Transit (JGJ/T 170-2009) [13] stipulates that 1/3-octave central frequencies should be corrected based on various Z-weighting factors for frequencies within the range of 4–200 Hz.

Figure 12–16 show the 1/3-octave curves of the vibration acceleration responses under each vibration reduction measure.



(a) under resilient short crossties (b) under rubber floating slabs (c) under Vanguard fasteners



(d) under steel spring floating slabs (e) under double-layer nonlinear fasteners

Figure 9. Frequency Division Vibration Levels

The following can be found from Figure 9.

(1) Within the frequency range of 4–200 Hz, on Line 3 of the subway system (speed: 120 km/h), the vibration level value decreased by approximately 20–40 and 3–12 dB from steel rails to track beds and from track beds to tunnel walls, respectively, in the sections where resilient short crossties were implemented. In the sections where steel spring floating slabs were implemented, the vibration level values at the steel rails and floating slabs were basically the same. Additionally, in these sections, the vibration level values decreased by approximately 50–80 dB from the floating slabs to tunnel walls. The resilient short crossties were more effective in reducing the vibrations from the steel rails to track beds (floating slabs) than the steel spring floating slabs. The steel spring floating slabs were more effective in reducing the vibrations from the track beds (floating slabs) to tunnel walls.

(2) Within the frequency range of 4–200 Hz, on Line 1 of the subway system (speed: 80 km/h), the vibration levels decreased by 20–45 and 3–11 dB from the steel rails to track beds and from the track beds to tunnel walls, respectively, in the sections where the Vanguard fasteners were implemented. In the sections where the rubber floating slabs were implemented, the vibration levels decreased by approximately 8–20 dB from the steel rails to floating slabs within the frequency range of 4–20 Hz. Additionally, in these sections, the vibration levels at the steel rails and floating slabs were basically the same within the frequency range of 20–200 Hz. Moreover, the vibration levels decreased by approximately 20–65 dB from the floating slabs to tunnel walls in the sections where the Vanguard fasteners were implemented. In the sections where double-layer nonlinear fasteners were implemented, the vibration levels decreased by approximately 50–70 dB from the steel rails to track beds, and the

vibration levels at the track beds and tunnel walls were basically the same. The double-layer nonlinear fasteners were the most effective in reducing the vibrations from the steel rails to track beds (floating slabs), followed by the Vanguard fasteners and rubber floating slabs. The rubber floating slabs were the most effective in reducing the vibrations from the track beds (floating slabs) to tunnel walls, followed by the Vanguard and double-layer nonlinear fasteners.

(3) Within the frequency range of 4–200 Hz, the vibration levels decreased to varying extents from the steel rails to track beds (floating slabs) and from the track beds (floating slabs) to tunnel walls under various vibration reduction measures.

(4) The frequency at which the peak acceleration value in each structure appeared varied between the five vibration reduction measures examined in this study. This result is related to the properties of each structure. These five vibration reduction measures were effective in reducing the vibrations in different frequency bands.

7. Conclusions

In this study, through field measurements of track structures within a subway system under various vibration reduction measures, the vibration responses of steel rails, track beds and tunnel walls on the same line under various vibration reduction measures were determined. Additionally, the vibration level and 1/3 octave frequency division vibration level was analyzed. The test results show the following:

(1) On Line 3 of the subway system (speed: 120 km/h), the steel spring floating slabs outperformed the resilient short crossties in reducing vibrations by 23.2 dB. The steel spring floating slabs were more effective in reducing vibrations. The resilient short crossties were more effective in reducing the vibrations from the steel rails to track beds (floating slabs). The steel spring floating slabs were more effective in reducing the vibrations from the track beds (floating slabs) to tunnel walls.

(2) On Line 1 of the subway system (speed: 80 km/h), the double-layer nonlinear vibration reduction fasteners were the most effective in reducing vibrations, followed by the Vanguard fasteners and rubber floating slabs. The double-layer nonlinear vibration reduction fasteners outperformed the Vanguard fasteners and rubber floating slabs by 1.6 and 2 dB, respectively. The double-layer nonlinear fasteners were the most effective in reducing the vibrations from the steel rails to track beds (floating slabs), followed by the Vanguard fasteners and rubber floating slabs. The rubber floating slabs were the most effective in reducing the vibrations from the track beds (floating slabs) to tunnel walls, followed by the Vanguard fasteners and double-layer nonlinear fasteners.

To reduce errors, only the vibration reduction measures on the same line were compared. This limitation ensured consistent test conditions (e.g., tunnel structure, sectional form and burial depth). However, limited by the conditions, it was impossible to ensure a completely uniform train speed at the measuring points under each vibration reduction measure. Additionally, unpredictable external factors interfered with the test process. Conclusions were derived from this study while ignoring the aforementioned factors. While there are certain errors in the conclusions, the conclusions can, to a certain extent, demonstrate the relative damping effects of various vibration reduction measures and provide a certain reference and basis for implementation of vibration reduction measures in urban subway systems in future.

8. Acknowledgments

This work is supported by Guangzhou Education Bureau project (Project No. 1201610505) and the National Natural Science Foundation of China (No. 51608135)

9. References

[1] Research team for annual reports on urban rail transit traffic in China. Annual reports on urban rail traffic in China [M]. Beijing Jiaotong University Press (Beijing), 2017: 2-2.

[2] Okumura Y, Kuno K. Statistical analysis of railway noise and vibration field data collected in an urban area [J]. Applied Acoustics, 1991, 33(4):263-280.

[3] Jakobsen J. Ground Vibration from Rail Traffic [J]. Journal of Low Frequency Noise Vibration & Active Control, 1987:96-103.

IOP Conf. Series: Materials Science and Engineering **735** (2020) 012067 doi:10.1088/1757-899X/735/1/012067

[4] Saurenman H. In-service tests of the effectiveness of vibration control measures on the BART rail transit system [J]. Journal of Sound & Vibration, 2006, 293(3–5):888-900.
[5] Li K, Liu W, Xun X, et al. In situ test of vibration attenuation of underground line of Beijing Metro Line 5 [J]. Journal of the China Railway Society, 2011, 33(4): 112-118.
[6] Yu Z. Test on vibration caused by subway and response research of structure and pile-soil [D]. Guangdong University of Technology, 2015.
[7] Huangfu Chanyuan. Study on subway-introduced vibration response of ground surface and building structure [D]. South China University of Technology, 2014.
[8] Measuring methods for environmental vibration in urban areas (Chinese GB Standard 10071-88) [s]. Standards Press of China (Beijing), 1988.
[9] Standards for environmental vibration in urban areas (Chinese GB 10070-88) [s]. Standards Press of China (Beijing), 1988.
[10] Lou M, Jia X, Yu J. Field measurement and analysis of ground vibration induced by subway trains [J]. Journal of Disaster Prevention and Mitigation Engineering, 2009, 29(3): 282-288.
[11] Lou M, Li S. Evaluation research of building vibrations induced by subway running train [J]. Journal of Vibration and Shock, 2007, 26(8): 68-71.
[12] Zhang X. A study on viaduct traffic-induced vibration, building vibration reduction, and control methods [D]. Beijing University of Technology, Beijing, 2009.
[13] Wang J. Application of MATLAB in vibration signal processing [M]. China Water & Power Press (Beijing) and Intellectual Property Publishing House Co., Ltd. (Beijing), 2006.
[14] Standard for limits and vibration test methods for building vibration and secondary radiation noise caused by urban rail transit (JGJ/T 170-2009) [s]. China Architecture & Building Press (Beijing), 2009.