A Study of the Suitable Measurement Location and Metrics for Assessing the Vibration Source Strength Based on the Field-Testing Data of Nanchang Underground Railway

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Underground railway vibration source strength is one of the key values used for environmental impact assessment and the evaluation of mitigation measure's performance. However, currently there is no international standard of measuring the underground railway vibration source strength for such purposes. The available local standards and industrial guidelines do not agree on measurement locations as well as the metrics for presenting the source strength. This has caused many confusions. This paper aims to study the suitable measurement location and metrics using the data from a large scale field-testing carried out at the Nanchang underground railway (Metro Line 1, China) in 2017. 200 passing trains were recorded during the test at two different sections of the railway line, one with the spring floating slab installed and the other without. Three locations were chosen at each section, including one in the middle of the track and two on the tunnel wall at different heights. Based on the results of statistical analysis, the maximum of z-weighted vertical vibration level (VLzmax) obtained at a lower measurement location on the tunnel wall is the best for representing the underground railway vibration source strength, which is 76.66 dB obtained from this study.

Keywords: Underground railway tunnel, vibration source strength, floating slab, statistics analysis.

1 Introduction

Urban underground railway system in Chinese cities has developed rapidly in recent years as a reliable and cost effective public transportation solution. However due to the high level of vibration induced by the passing trains, it is also considered as a major vibration source causing many environmental problems. In order to assess the environmental impact of the induced vibration and to predict the vibration level at certain locations, the vibration source strength of the underground railway system must be known in advance. Although numerical simulation can be used to predict the source strength level, due to the complicity of the underground railway structure and the variation of geological conditions at difference cities, field-testing is still one of the most reliable and widely used methods. Many projects have been conducted at several cities in China to measure the vibration source strength level[1-5]. For example, Gu[1] carried out the field testing for several underground railway lines at Beijing, Shanghai and Guangzhou, and assessed the environmental impact based on the vibration source measurements. The performances of three vibration mitigation measures were also investigated. He[2] carried out similar test at Ningbo to investigate the influences of rail fastening and train speed on the vibration source characteristics. The vibration source strength obtained was 70.41 dB in his study. Li[3] carried out the measurement at a few locations inside the tunnel of Beijing underground railway (with more than 200 trains passing during the test) and concluded that the measurement obtained from the tunnel wall can provide the most reliable results for further environmental impact assessment. Liu[4] also carried out similar measurement in Beijing in order to investigate the performance of mitigation measures in a wide frequency range. Wu[5] investigated the performance of vibration reduction fastenings, short elastic sleeper and floating slab by comparing the measurement of vibration source strength before and after applying these measures.

Although all these studies[1-5] have measured the vibration source strength of the underground railway, the measurement locations and metrics used are not always the same.

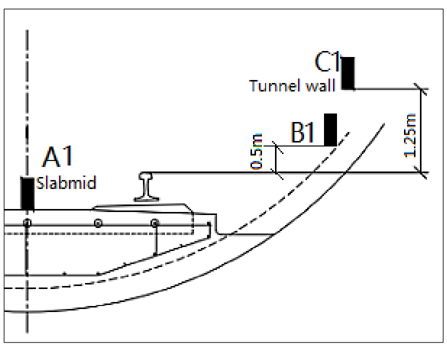
Gu[1] and He[2] used the Z-weighted[11] vertical acceleration level (VLz) which was averaged other the time period when the train was passing to represent the source strength. Li[3] and Liu[4] used the maximum vertical acceleration level (VLzmax) which was the maximum value of the Z-weighted vertical acceleration level averaged very second over the time period when the train was passing. All of these four projects measured the vibration on the tunnel wall, but none of them gave any further details of where exactly the accelerators were mounted. Wu[5] is the only one mentioned that the measurement location was 1 m above the truck on the tunnel wall. He calculated the Z-weighted vertical acceleration level in each 1/3 octave band and used the maximum value in the frequency domain (VLzmaxf) to represent the south strength level. This variation of using different measurement location and metrics is due to the fact that no international standard of measuring underground railway vibration source available at the moment. The local standards and industrial guidelines do not agree on the measurement locations as well as the metrics. The most relevant standard is a Chinese national standard, HJ453-2008[7], which is for assessing building vibration level caused by urban trains. It mentioned VLz should be used to represent the source strength level and it should be measured on the side 0.5-1.0 m away from the track, but no exact location was given. There is one international standard, ISO 10815: 1996[6], for measuring underground railway vibration level; however, it is for assessing the mechanical vibration inside in the railway tunnel rather than providing a source level which can be used to investigate the vibration outside the tunnel. It states that the test point should be located on the side wall of the tunnel, 1.2 m away from the track surface. No metrics for source strength level was specified. A local standard used in Beijing area, DB11/T 838-2011[8] requires that the measurement point to be at the tangent point on the near tunnel wall and perpendicular to the ground. If there is no tangent point in the tunnel, the location is chosen to be 1.9 m from the top of the track. VLzmax should be used to represent source strength. Finally there is a local industry standard (used in Beijing) for installing spring floating slab in urban underground railway, QGD-001-2009[9], mentioned that if the vibration source level needs to be measured for the purpose of assessing the performance of spring floating slab, the measurement location should be located at 1m high from the bottom of the tunnel side wall, and the metrics used should be VLzmaxf.

The disagreement between these standards/guidelines on measurement location and metrics has already caused many confusions, as the results can vary significantly. This also makes it very difficult to compare the results from individual projects. This paper aims to gain a better understanding of the suitable measurement location and source strength metrics by carrying out statistical analysis of the field testing data collected at Nanchang Metro Line 1. Details of the measurement set-up are introduced in Section 2, followed by statistical analysis of the data in Section 3. Conclusions are given in Section 4 at the end.

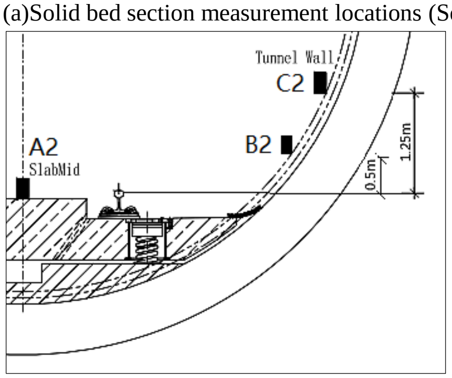
2 Measurement Set-up

The measurement was carried out at two different test sections of the railway line, one with spring floating slab installed, section 1, and the other without, Section 2. The two sections are 20 m apart. The tunnel has circular cross section with single track installed in the middle. Three measurement locations were chosen at each section: A) In the middle of track on the slab, B) 0.5 m from the top of the rail on the tunnel wall, and C) 1.25 m from the top of the rail on the tunnel wall, as showed in Figure 1.

The accelerometers used have a dynamic range between -490 m/s^2 and 490 m/s^2 and a usable frequency range from 0.5 Hz to 3000 Hz. The sampling frequency used was 2500 Hz. The test was carried out continuously for a whole day. The data acquisition system was triggered automatically when the train was passing. 6 locations (3 at each section) were measured simultaneously. Each record lasts 2 minutes. There were 200 trains recorded during that day. The train used at Nanchang underground is CCRC-B (manufactured by Changchun Railway Vehicles) with 6 carriages. The maximum passenger number on each direction is between 30000 and 55000 per hour. The maximum designed speed is 80 km/h, though the train-speeds recorded during the test were all around 70 km/h.



(a)Solid bed section measurement locations (Section 1)



(b) Floating plate section measurement locations (Section 2)

Figure 1. Measurement points on two test sections.

3 Statistical Analysis

The recorded vertical accelerations data were analyzed in the time domain and the frequency domain.

3.1 Maximum Peak Value of Time Domain Series

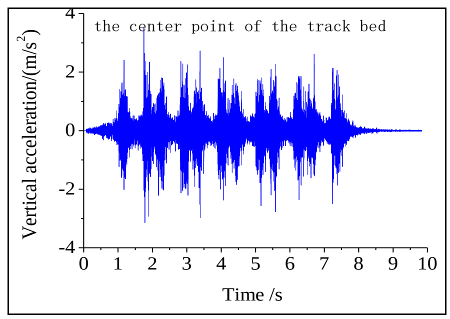
Figure 2 shows a typical time domain result at the 6 measurement locations when a train was passing. The impacts from each passing wheel pair can be identified clearing from the peaks of vertical acceleration. At both sections, measurement location A recorded the highest vertical acceleration and the measurement location C recorded the lowest. For some cases, the result from measurement location C cannot be used to identify the wheel impact, such as Figure 2C. Comparing the results recorded at the two sections, the section with floating slab installed showed a much lower acceleration on the tunnel wall, but a much larger value in the middle of the track slab. It is well known that the floating slab can reduce the vibration level in the tunnel by increasing its own vibration level. But it also means that using the measurement obtained from the middle of the track slab to represent the source strength level may not be appropriate when floating slab is installed.

Statistical analysis was carried out to investigate the maximum peak value of acceleration associate with each train (200 trains in total) at the 6 measurement location. Results were fitted with Gaussian probability density curve and showed in Figure 3. The Gaussian probability density function used was:

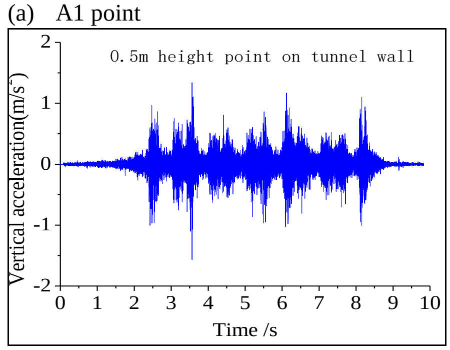
$$y = y_0 + Ae^{-\frac{(x-x_c)^2}{2w^2}} \quad (1)$$

where, $A = 1/w\sqrt{2\pi}$, x_c is the mean value, and w is the standard deviation.

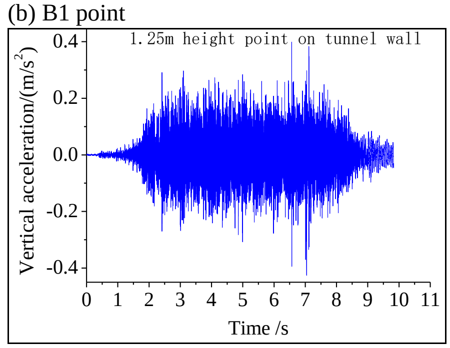
The mean value, standard deviation and coefficient of variance are listed in Table 1.



(a) A1 point

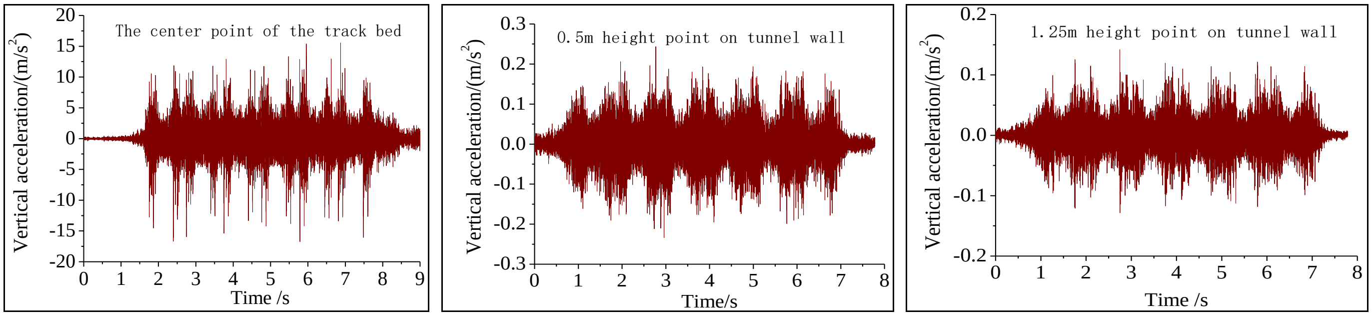


(b) B1 point



(c) C1 point

Solid bed section (Section 1)



(d) A2 point (e) B2 point (f) C2 point

Floating slab bed section (Section 2)

Figure 2. Vertical acceleration in time domain.

Table 1. Statistical results of vibration acceleration from 200 passing trains. SD: Standard Deviation; CV: Coefficient of Variance.

	A point			B point			C point		
	MEAN(m/s^2)	SD*(m/s^2)	CV*	MEAN(m/s^2)	SD(m/s^2)*	CV*	MEAN(m/s^2)	SD(m/s^2)*	CV*
Section 1	3.647	0.563	0.154	1.252	0.194	0.155	0.377	0.056	0.149
Section 2	17.874	2.263	0.127	0.249	0.065	0.261	0.147	0.014	0.095

From Table 1, for all the measurement locations, the coefficient of variance is quite small. This means although there are some uncertainties introduced by the train operations (such as the train speed and number of passengers) the results are relatively reliable.

The floating slab can reduce the vibration level on the wall. The lower measurement location, location B, shows a much obvious reduction than the higher measurement location, location C. Although location B and location C are only 0.75 m apart, the difference from the result is significant. The mean value at location B can be as large as 3 times of the mean value at location C. This again highlights the problem of using measurement at different locations for vibration impact assessment at a later stage.

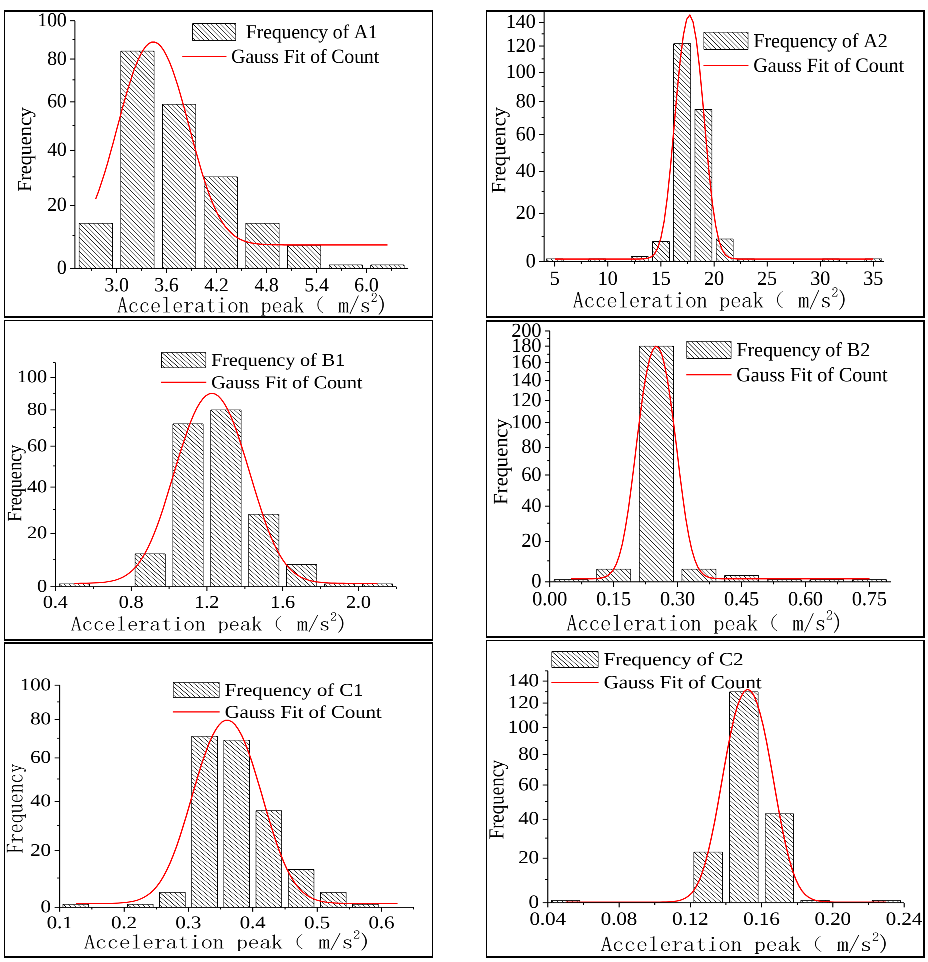


Figure 3. Statistical distribution of the peak vibration acceleration at two sections.

3.2 Analysis of Source Strength in Frequency Domain

Mean values of the Un-weighted vertical acceleration level (VAL) in each 1/3 octave band were calculated and showed in Figure 4 with error bars indicating scale of variance over the 200 records.

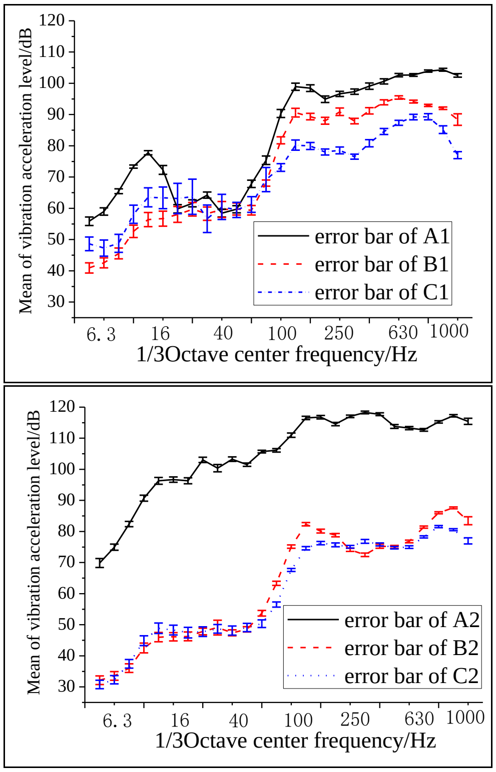
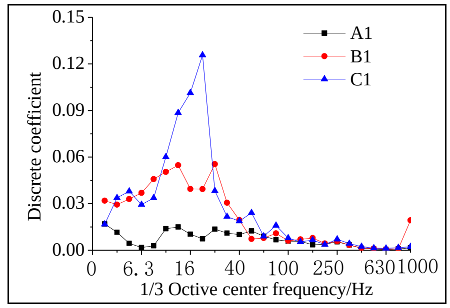


Figure 4. Mean values of the Un-weighted vertical acceleration level in frequency domain.

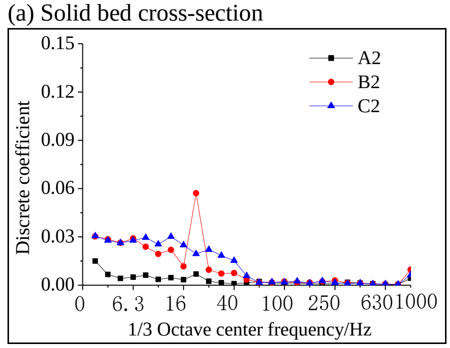
From Figure 4, although the VAL in different frequency bands can vary due to the uncertainties caused by train operation, the trend of the spectrum and the peak frequencies are nearly the same for all 200 trains. The variation of VAL on the wall is larger than in the middle of the track, especially for frequency bands lower than 63 Hz. For both sections, the higher measurement location on the wall, location C, shows an even larger variation than the lower measurement location, location B.

The mean VAL on the wall was reduced by introducing floating slab into the system, in return of an increase of mean VAL in the middle of the track. Using the results at 80 Hz band as an example, the insertion losses introduced by the floating slab are 8.2 dB at location B and 5.7 dB at location C. However, there is an increase of 17.6 dB at location A. As a result, the impact of increased vibration level on the train body should be taken into account when the floating slab is used for the purpose of reducing the vibration level outside the tunnel.

The coefficient of variation (CV) is calculated in each frequency bands at each measurement location and showed in Figure 5. The frequency bands lower than 63 Hz has a larger CV comparing the higher frequency bands. The CV for the section with floating slab is relatively smaller than the one without. At section1, where no floating slab was installed, the CV for higher measurement location, location C1, is a lot larger than lower measurement location, location B1, at some lower frequency bands.



(a) Solid bed cross-section



(b) Floating slab bed cross-section

Figure 5. Coefficient of variation diagram at each measuring point.

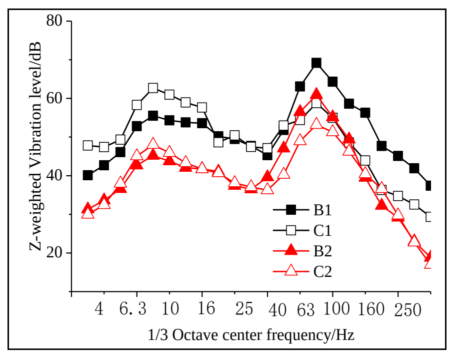


Figure 6. Mean value of Z-weighted vibration level in 1/3 octave bands.

The mean values of VLz in 1/3 octave bands at all four locations on the wall are showed in Figure 6. From Figure 6, floating slab provided a good vibration reduction. This can be observed from both locations (B and C). For both sections, comparing to the location C, location B shows a much larger vibration level at the frequencies (<63 Hz) but lower vibration levels at frequencies (>63 Hz). This indicates that after propagating through the interior of the tunnel, the high-frequency components of the vibration have experienced a more rapid attenuation during the transmission. Similar results were obtained from other study[14].

3.3 Analysis of Source Strength Metrics

As mentioned in Section 1, there are a few metrics used for representing source strength level, including the maximum Z-weighted vertical vibration level (VLzmax), the maximum value of Z-weighted vertical vibration level in frequency domain (VLzmaxf) and the averaged Z-weighted vertical vibration level (VLz).

In order to gain a better understanding of these levels, and find out which is better to use, all of them were calculated for the 200 passing trains. The statistical distributions of the results are showed in Figure 8. The mean value, standard deviation and coefficient of variance were showed in Table 2.

Table 2. Statistical results for Z-weighted vibration level at two sections.

		VLzmaxf (dB)	VLz (dB)	VLzmax (dB)
B1	MEAN	69.33	72.33	**76.66**
	SD	1.05	**0.72**	0.79
	CV	0.015	0.010	0.010
C1	MEAM	62.88	68.89	**70.38**
	SD	3.09	2.58	**1.98**
	CV	0.049	0.037	0.028
B2	MEAN	60.98	63.64	**66.48**
	SD	0.44	**0.30**	0.35
	CV	0.007	0.005	0.005
C2	MEAN	53.24	58.46	**60.81**
	SD	0.57	0.46	**0.46**
	CV	0.011	0.008	0.008

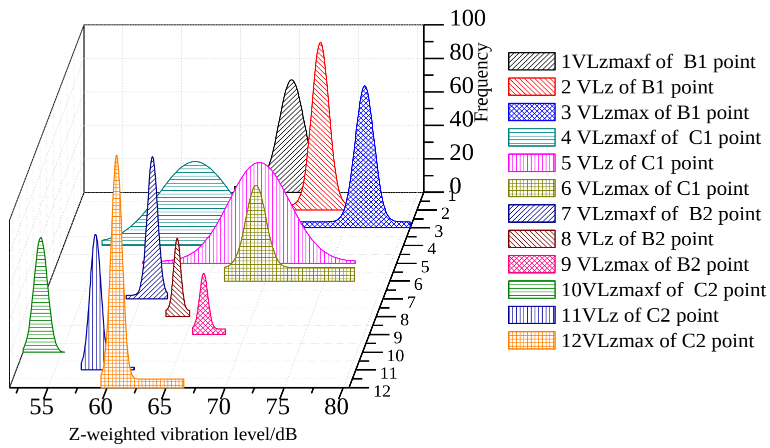


Figure 7. Statistical distributions of three types of Z-weighted vibration level.

At all four locations in Table 2, Vlzmax gave larger values comparing to the other two, with VLzmax>VLz>VLzmaxf. It also gave one of the lowest CV among these three, which indicating it is less influenced by the variance induced by the trains. Therefore VLzmax would be the best choice to be used for source strength assessment in this case.

From Table 2 and Figure 7, despite the difference from the 200 passing trains, the CVs are all relatively small. The largest CV is from the measurement location C1. But it is still less than 0.05. This indicates that the factor from passing train has limited influence on the Z-weighed vibration level of the vibration source. For both sections, location C has larger CVs, reflecting a relatively larger variance of the data recorded, and all three of metrics show larger values at location B than C, though they are all calculated in different ways. Considering both the level of the value and the variance between individual records, the location B would be a much better location for measuring the vibration strength level.

There was only 0.75 m difference between location B and location C, but the difference of VLzmax at these two locations in Section 1 was as large as 6.28 dB. Therefore the measurement location should be very carefully marked during the test. The source strength of the Nanchang Metro Line 1 is 76.7 dB which is the VLzmax value measured at location B.

Vibration reductions provided by the floating slab at location B and location C using these three levels are showed in Table 3.

Table 3. Approximate insertion loss of floating plate at high and low test points (Unit: dB).

	VLzmaxf	VLz	VLzmax
B1	8.35	8.70	10.18
C1	9.64	10.43	9.57

If VLzmax is used for the assessment, the floating slab's insertion loss is 10.18 dB for this case. The insertion loss term CL to be used in the vibration prediction formula suggested in[7] was between 20 dB to 30 dB. Clearly for this case, it would provide a much lower ground vibration level. The floating slab's insertion loss at Nanchang underground line is 10.18 dB.

4 Conclusion

From the statistical analysis of the field testing results obtained from underground Nanchang Metro Line 1, with 200 passing trains, following conclusions can be drawn:

1. The variation of trains has limited influence on the measured vibration strength level. Lower measurement location gave a much clearer signal in time domain. In frequency domain, the lower frequency bands (<63 Hz) showed a much smaller variance than higher frequency bands. Again, the lower measurement location gave a smaller variance. Considering both the level of the value and the variance among recorded data, the lower measurement location, B, is a much better choice for measuring vibration source strength in this study.

2. LVzmax gave a larger value comparing to LVzmaxf and LVz, and also is relatively more stable. Therefore LVzmax should be used to represent the source strength level here. The source strength measured at Nanchang Metro Line 1 is 76.66 dB.

3. The steel spring floating slab can reduce the vibration strength level measured on the tunnel wall significantly. However, the vibration of the floating plate itself would increase as a return. This can have a negative impact on the vibration level inside the train which should be carefully considered before using the floating slab to reduce the environmental impact.

4. The insertion loss provided by floating slab is 10.18 dB here. This value is much smaller that the suggested insertion loss used in the

calculation formula for environmental vibration impact prediction in 'Technical Guidelines for Environmental Impact Assessment in Urban Rail Transit" (HJ 453-2008)[7].

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