# Study on Metro Environmental Vibration Influence and Vibration Isolation Effect of Isolation Trench

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Vibration, caused by rail transit wheel-rail interaction, via rail system, tunnels (bridges or foundation), soil medium, ground buildings, propagates from source to structure, further induced the second vibration on buildings. The impact on the environment can last as long as 20 h, making many countries have to face the environmental vibration complaints caused by urban rail transit operation [1, 2]. Nowadays, as multi modal system gradually formed, part of rail lines have to pass through residential area, commercial center, or science park, in the form of ground line, underground line and elevated line. The minimum distance can be just a few meters from the buildings, and some lines may even underneath directly. All these make the effect of vibration and noise become increasingly serious, which rail transit construction unit should respond [3, 4].

For the ground rail transit, set vibration isolation in the propagation may be the common vibration propagation isolation, such as open trench, continuous hollow wall, continuous solid wall and WIB [5–10]. When vibration wave propagates to the vibration isolation, besides transmission and reflection, wave diffraction will happen in both ends and bottom of the vibration isolation. Vibration energy through the isolation is mainly composed of transmission wave and diffraction wave, generally less than the energy of the incident wave. Ground vibration can be reduced in this way. While wave reflection may lead to the ground vibration amplification effect ahead of the isolation [11, 12].

Compare to ground vibration source, there are few research on vibration propagation isolation underground. More than 10 m or dozens of meters tunnel depth makes open trench proves infeasible, continuous pile wall and in-filled trench are also limited [13]. Based on the test results of environmental vibration effect in

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Qingdao Jiayuan district, caused by Beijing Metro Daxing Line, 3-d simulation model is established to evaluate vibration isolation performance under different isolation vibration materials.

## Engineering Background

Qingdao Jiayuan district is located in the west of Beijing Metro Daxing Line, between Gaomidian North station and Gaomidian South station. These five-story cast-in-site structures, applying reinforced concrete strip foundation in 1.5–2 m depth. The shortest distance is only 12.5 m from Building 10 to Daxing right line (down line) center line, while to left (up line) center line is about 25.5 m. Metro tunnel structure with horseshoe shape composite lining, its soil depth is about 8.0–9.6 m. And the left line adopt type DTVI2 fastenings concrete track bed while the right line adopt ladder track, which laying length is 293 m. Residential district top view as shown in Fig. 1.


**Fig. 1** Qingdao Jiayuan district top view

Many vibration complaints from residents were received at the late stage of trial operation. For this situation, conducting simulation investigation of periodic row piles vibration isolation performance by means of filed survey and test is necessary.

## Environmental Vibration Influence

### *Evaluation Standard*

Qingdao Jiayuan district, as the function area sides main roads in Daxing district regional planning, its environmental vibration limit is 75 dB in the daytime and 72 dB in the nighttime according to "Standard of environmental vibration in urban area" (GB10070-1988) [14].

Based upon "Measurement Method of Environmental Vibration of Urban Area" (GB100071-1988) [15], plumb vibration acceleration grade should be measured. Setting time weight constant to be 1 s and extracting the maximum value when trains passing through. The average of 20 continuous sets of data, as the evaluation measure, is plumb vibration acceleration grade maximum VLzmax.

Environmental monitoring sites must be set outside the buildings 0.5 m far as "Technical Guidelines for Environmental Impact Assessment of Urban Rail Transit" (HJ453-2008) [16] required.

### *Test Point Arrangement*

For vibration complaints, a series of environmental vibration tests have done in tunnels, ground and buildings to analyze the structure vibration level and vibration energy band distribution. Sensors setting on both lines and tunnel walls in the same mileage, to measure vibration level and spectral distribution. Moreover, the ground half meters in front of buildings should be set for the vibration environmental effect.

### *Test Result Analysis*

The 1/3 octave band and Z vibration level in time domain are exploited to estimate environmental vibration effect caused by metro Daxing line.

Under the speed of 60 km/h, the 1/3 octave band acceleration level inside tunnel is shown in Fig. 2, and on the ground is shown in Fig. 3.

As shown in Fig. 2, compare to DTVI2 fastenings concrete track bed, train on the ladder track induced higher vibration acceleration level, even a differential of 20 dB in the frequency band of 30 Hz. In the frequency band of 3–40 Hz, only

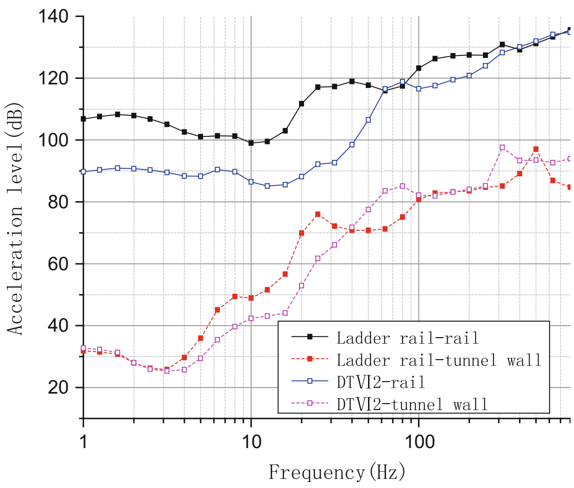



**Fig. 2** The 1/3 octave band acceleration level inside tunnel

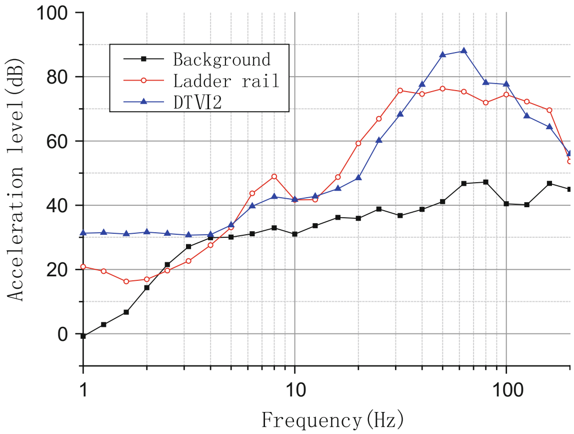



**Fig. 3** The 1/3 octave band acceleration level before the building half meter away

slightly higher than DTVI2 fastenings on tunnel walls, indicates vibration amplification effect caused by DTVI2 fastenings ladder track. The difference can be 15 dB around the frequency band of 25 Hz. While it turned out just the opposite in 40–110 Hz, shows that DTVI2 fastenings ladder track providing with the ability of reducing vibration. The difference can be 13 dB around the frequency band of 60 Hz.

Figure 3 indicates that in the frequency band of 4–200 Hz, trains running makes great contribution to ground vibration, in addition, the vibration acceleration level varies in different frequency bands. The main contribution frequency band of ladder track is about 30 Hz, the same as the vibration source dominant frequency, reached 38 dB. However for DTVI2 fastenings, the main contribution frequency band is about 60 Hz, reached 42 dB. Specifically, the ladder track induced higher vibration acceleration level than DTVI2 fastenings in the frequency band of 4–35 Hz, reaching 8 dB around 30 Hz. And it becomes lower in 35–200 Hz, with the maximum of 23 dB around 60 Hz.

Results are different in analyzing the 20 sets of the ground test point vibration data caused by trains, with Z vibration level maximum in time domain. Only 6 sets of right line data exceed the limit, with the total average of 70.7 dB, less than 72 dB limit. In contrast, 12 sets of left line data exceed the limit, and the total average is 76.5 dB, exceeding the vibration limit.

### *Reason Analysis of Overstandard Vibration*

Qingdao Jiayuan district vibration issue is building forced vibration caused by train. There is a difference of 6 dB between two lines, that the left line with the exceeding value of 76.5 dB has greater influence than the right, which values 70.7 dB below. And the maximum is almost over 15 dB between trains in good condition and out of condition, shows vehicle state makes significantly influence on ground environmental vibration.

## 3D Simulation of Vibration Propagation Isolation

### *3D Simulation Model*

The 3D finite element model is established based on the actual relationship with transit network. As shown in Fig. 4, this model with the dimension parameter of 31.5 * 60 * 40 m, setting the maximum size as 1 m for soil layer and tunnel elements. Its soil layer simplified to 4 according to soil distribution and soil layer shear wave velocity. The processed practical measured data can be input as the moving load on rails. The right line test section with 9 m in buried depth contains 5 ladder track, and its center line is 15 m away from building foundation which is 16 m wide. The distance between two center lines is 15 m, and the width of the isolation trench is 1 m.

The parametric analysis is presented for the filled material but not location, width, length and so on in case of the execution conditions. The isolation trench horizontal distance is 4.5 m from the right line tunnel boundary, and 15.6 m in depth, 1 m in thickness, 16 m in width. 5 kinds of materials filled are fly ash, rubber pieces, foam, sandy gravel, aerated concrete and lightweight aggregate concrete.

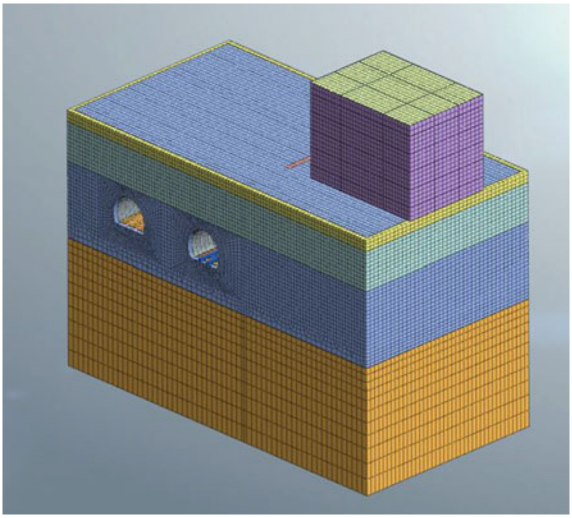


**Fig. 4** 3D dynamic simulation model

## *Modeling Parameter*

Based on the actual formation parameter and shear wave velocity, the soil layers are simplified to 4. The formation parameter is shown in Table 1.

For tunnel elements, dynamic elastic modulus is 29.0 GPa, dynamic poisson's ration is 0.2, and bulk density is 24 kN/m$^3$.

## *Boundary Condition*

Viscoelastic artificial boundary, a kind of local artificial boundary, has been widely used in dynamic finite element analysis, with the advantage of no low-frequency drift, semi-infinite medium elastic recovery capacity, good frequency stabilization, and application convenience in finite element software. It can be divided into spring-damper artificial boundary and 3D coherence artificial boundary according

**Table 1** Formation parameters of the model

| Soil layer | Thickness (m) | Bulk density (kN/m$^3$) | Dynamic poisson's ration | Dynamic elastic modulus (kPa) | Shear wave velocity (m/s) | Compressive wave velocity (m/s) |
|---|---|---|---|---|---|---|
| 1 | 1.8 | 18.5 | 0.37 | 1.4E5 | 165 | 362 |
| 2 | 6.2 | 19.5 | 0.35 | 2.6E5 | 220 | 458 |
| 3 | 12 | 20 | 0.3 | 6.0E5 | 336 | 629 |
| 4 | 20 | 21 | 0.26 | 7.8E5 | 380 | 668 |

to elements form. In this paper, 3D coherence artificial boundary is chosen, that the solid element is established along boundary normal, with outside nodes fixed.

### *Filling Materials Parameter*

Filling materials are two categories, flexible material and rigid material, according to the shear wave impedance ratio. Flexible material included fly ash, rubber pieces and foam, while the rigid included the others. Physical property indexes such as shown in Table 2.

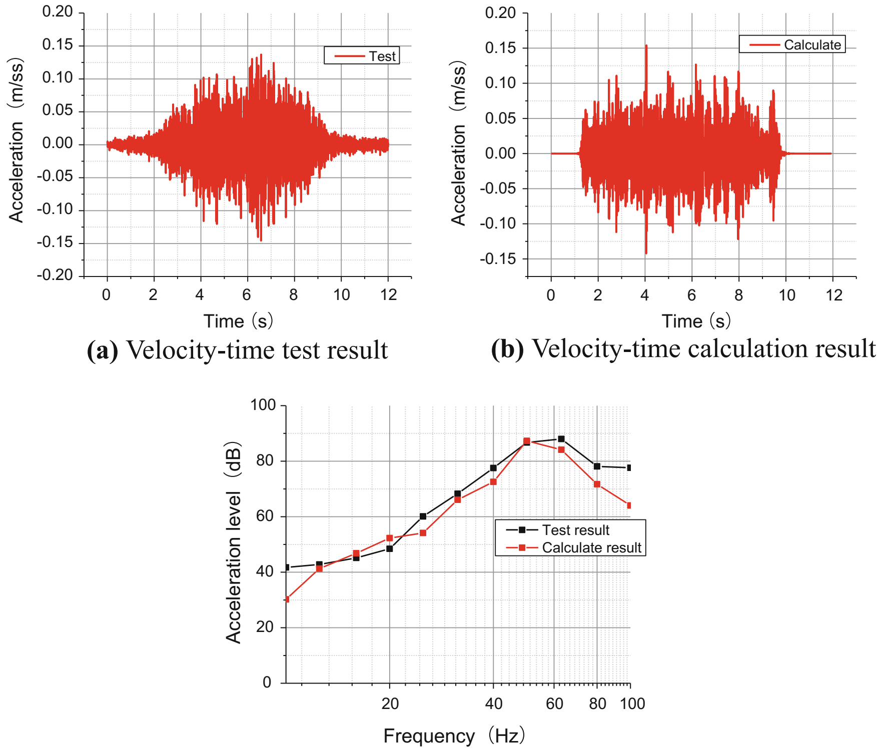
## Vibration Isolation Analysis of Various Isolation Trench Materials

### *Model Verification*

The test point half meter in distance from the building is chosen for the vibration response of the soil layer and the building, in the condition of in no-filling material to prove the model correctly. As shown in Fig. 5, the comparison between the measured result and calculate result in the 1/3 octave band had good similarity, indicates the accuracy of the model.

**Table 2** Filling materials dynamic character

| Material type | Density ($kg/m^3$) | Elastic modulus ($\times 10^6$ $N/m^2$) | Poisson's ratio | Shear wave velocity (m/s) | Shear wave velocity ratio | Wave impedance ratio |
|---|---|---|---|---|---|---|
| Fly ash | 500 | 25 | 0.35 | 136.08 | 0.5917 | 0.1509 |
| Rubber pieces | 1480 | 4.5 | 0.48 | 32.05 | 0.1393 | 0.1052 |
| Foam | 80 | 11.8 | 0.4 | 229.5 | 0.998 | 0.0407 |
| Aerated concrete | 650 | 1900 | 0.2 | 1103.6 | 4.7983 | 1.5913 |
| Lightweight aggregate concrete | 1800 | 14,000 | 0.2 | 1800.2 | 7.827 | 7.1880 |




**(a)** Velocity-time test result **(b)** Velocity-time calculation result

**(c)** 1/3 octave band

**Fig. 5** Comparison of test and calculation result

## ***Floor Vibration Response Analysis***

Each floor vibration acceleration spectrum and Z vibration level in the condition of no vibration isolation just as shown in Figs. 6 and 7. It indicates that:

1. The vibration amplification occurs in this band that each floor resonant frequency is about 30 Hz.
2. The Z vibration level decreased first and then increased along with higher floors. The minimum is 77.76 dB in the second floor, and the maximum is 79.15 dB in the sixth floor.

**Fig. 6** Vibration acceleration-frequency of each floor

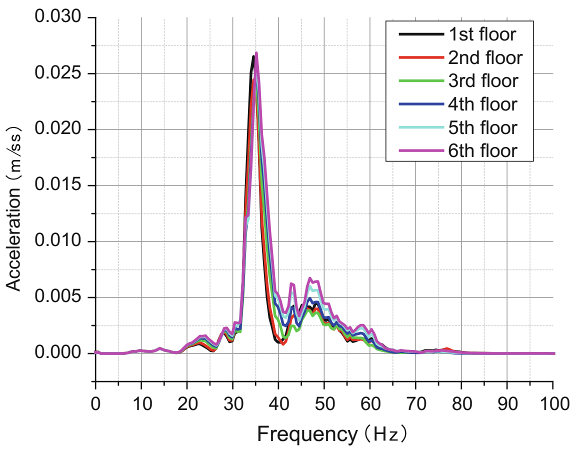
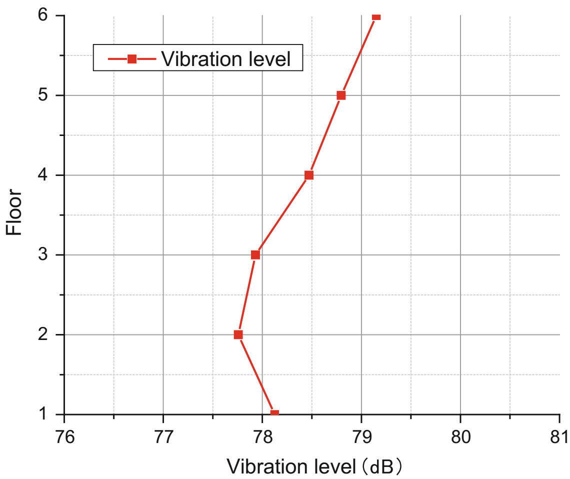



**Fig. 7** The Z vibration level of each floor




## *Filling Materials Vibration Effect Analysis*

Taking the test point half meter in distance from the buildings as example, Table 3 shows the maximum Z vibration level of each filling materials, and the comparison of the 1/3 octave band and Z vibration level just as shown in Figs. 8 and 9.

From the data above, it indicates that:

1. Isolation trench with different filling materials all have the capacity to induce the vibration effect, with the decrease of 1.5–3.5 dB in the Z vibration level peak value.

**Table 3** The Z vibration level of various filling materials

| Vibration isolation | Maximum of the Z vibration level (dB) |
|---|---|
| None | 77.52 |
| Fly ash | 74.43 |
| Aerated concrete | 76.00 |
| Foam | 74.47 |
| Lightweight aggregate concrete | 75.20 |
| Rubber | 73.93 |

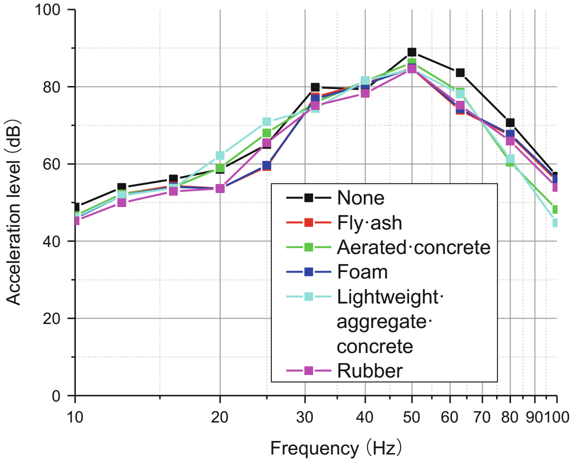



**Fig. 8** Vibration acceleration-frequency in the 1/3 octave band of various materials

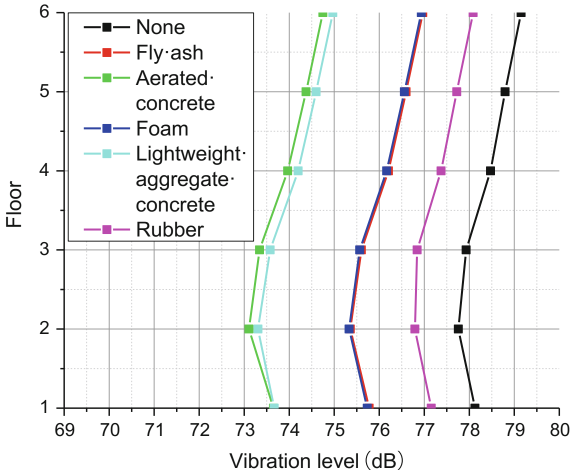



**Fig. 9** The Z vibration level of each floor with various materials

2. The rubber with small stiffness and high elasticity, provides positive effect in the system as a mass-spring vibration isolation structure, which can attenuate the vibration propagation.
3. Each floor Z vibration level all decreased first and then increased in different fillings. And the second floor reached the minimum, the sixth reached the maximum.

## Conclusions

1. Compared with DTVI2 fastenings, ladder track can provide vibration isolation effect in the band of 40–110 Hz, and it can reach 13 dB around 60 Hz. The up line played more of a role than the down line in the building vibration caused by rail transit, with the difference of 6 dB, its test point half meter in the distance from the buildings reached 76.5 dB which exceeds the 72 dB limit.
2. Vibration isolation with different filling materials all make good performance in reducing the vibration, by lower the peak of 1.5–3.5 dB in Z vibration level. The rubber with small stiffness and high elasticity, providing positive effect in the system as a mass-spring vibration isolation structure, achieves the best effect.
3. Z vibration level of each floor all decreased first and then increased, indicates the isolation method has little impact on the vibration propagation characteristics of building structures.

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