VIBRATION ISOLATION ANALYSIS OF THE SUBWAY STATION USING A SEMI-EXPERIMENTAL AND SEMI- NUMERICAL METHOD

Liu Changqing, Zhu Wenying, Xia Dan and Sun Xiaoming

Shanghai Academy of Environmental Sciences, Shanghai Engineering Research Center of Urban Environmental Noise Control, Shanghai, China
email: liucq@saes.sh.cn

With the rapid development of urban railway transit networks, subway induced vibration becomes an important aspect of the environmental impact. In this paper, several vibration isolation measures are studied to ensure the subway induced vibration in the building above it to meet the living requirements using a semi-experimental and semi-numerical method. Firstly, a measurement of vibration was carried out at the subway track bed to obtain the subway train induced source vibration strength. Then 3D finite element models of the whole structure including the layered soil, the subway track, the underground station hall and the building above it were established to calculate the vibration transmission loss from the track bed to the building floor, in which different vibration isolation measures were considered. By combining the source vibration data and transmission loss, vibration level in the building above the subway station was obtained and the effects of different measures were compared. The results show that: the measures of designing gap filled with vibration isolation material between the building and the subway platform structure have little effect on vibration isolation; floating slab track can effectively reduce indoor vibration to meet the relevant standards of vibration. The conclusions may be helpful for the engineering design of vibration isolation measures for subway induced vibration in building above.

Keywords: subway induced vibration; semi-experimental and semi-numerical analysis; building vibration isolation

1. Introduction

With the rapid development of economy and the expansion of city scale, the problem of urban congestion is becoming more and more serious. Subway has many advantages to effectively alleviate the ground traffic congestion. But at the same time, most of the subways are located in the downtown area, and many subway lines pass through the underground of the residential areas, schools, hospitals and other sensitive buildings, leading to environmental problems such as vibration and reradiated noise inside buildings, especially in big cities like Shanghai. In the past decade, researchers have done a lot of studies on subway induced vibration. These studies include the generation of subway vibration, the transfer of the energy, the building vibration prediction and isolation. The complexity of the subway induced vibration problems is high, and many research methods are proposed, such as the analytic method, numerical method, empirical method, experimental method and so on. Metrikine[1] studied the steady-state vibrations of an elastic beam on a viscoelastic layer under moving load using the analytic method. Sheng[2] studied the ground vibration generated by a load moving along a railway track using a semi-analytic method. Lou[3][4] studied the propagation of subway induced vibration in the surrounding buildings and ground with the numerical and experimental methods. Lombaert[5] proposed a numerical model for the prediction of railway induced vibration and validated it with experimental method. Lopes[6] proposed a comprehensive prediction model to analyse vibrations inside buildings due to subway railway traffic and validated it with experimental method. Sanayei[7] measured ground-borne vibrations due to surface trains and subways at a building foundation and analysed the vibration characteristics, which could provide reference for the design of vibration isolation in practical engineering. Ling[8] studied the influence of the vibration caused by the subway on the frame structure by taking a teaching building as an example and analysed the vibration isolation effect of steel spring vibration isolator on the building.

In this paper, a semi-experimental and semi-numerical method is presented and subway induced vibration isolation in adjacent building is analysed taking a building under construction in Shanghai as an example. The building is located in residential and commercial mixing zone with a subway station nearby. The subway line passes by the soil under the building and it is very close to the building foundation. The relative position between building and subway station is shown in Figure 1. In order to prevent excessive vibration caused by subway, two different vibration isolation design were proposed. First, a structure gap was designed between the building foundation and subway station, and the gap is filled with hard soil. Second, rubber blocks was added between the underground wall of the building and the subway station structure, as shown in Figure 2. The present paper aims to compare the vibration isolation effect of the two different design, and the building vibration with no gap designed is also calculated as comparison. In addition, vibration isolation effect of the steel spring floating slab track is also studied at last.

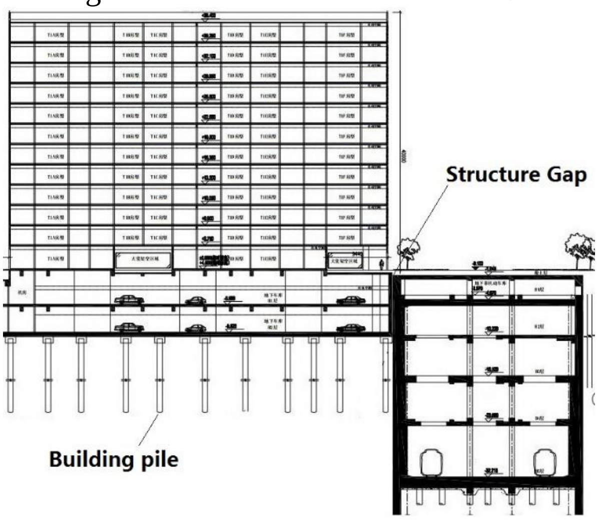

Figure 1: Cross section of the building and subway station

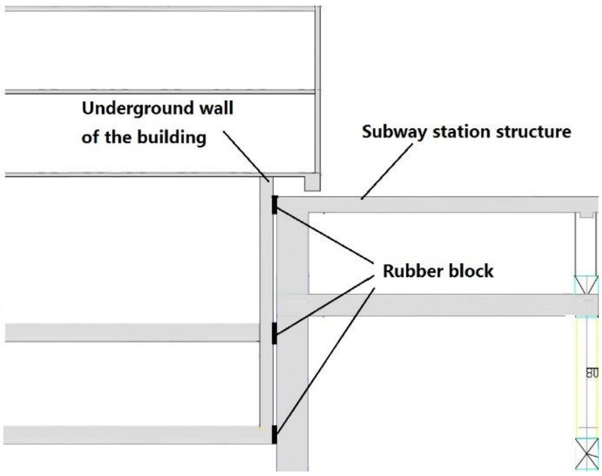

Figure 2: Rubber block between the building underground wall and the subway structure

2. Semi-experimental and semi-numerical method

The semi-experimental and semi-numerical method is a combination of experiment method and numerical method used to predict subway induced vibration. In this method, source vibration is obtained through experimental method, and the transfer function of the building structure is analysed through numerical method. Then the vibration response in the building could be calculated by the combination of source vibration data and transfer function. The structural dynamic equations of the system can be written as:

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=\{f(t)\} \tag{1}$$

Where $[M]$ is the mass matrix of the system, $[C]$ is the damping matrix of the system, [K] is the stiffness matrix of the system. $\{f(t)\}$ is a time varying load vector, which is the source excitation force. $\{x(t)\}$ is the vibration response vector of the system.

The frequency spectrum of source excitation load can be obtained by Fourier transform from the measured $\{f(t)\}$:

$$F(\omega) = \int_{0}^{+\infty} f(t) e^{-j\omega t} dt \quad (2)$$

Where ω is the circular frequency. The vibration frequency response and time domain response of the building could be expressed through equation (3) and (4).

$$X(\omega) = F(\omega) H(\omega) \quad (3)$$

$$x(t) = \frac{1}{2\pi} \int_{0}^{\omega_0} F(\omega) H(\omega) e^{j\omega t} d\omega \quad (4)$$

Where ω_0 is the cut-off frequency, $H(\omega)$ is the transfer function of the system, which could be calculated through numerical method.

3. Source vibration experiment

To get the source vibration acceleration, an experiment was carried out at a subway track in Shanghai, where the basement and structure of the subway station is similar with the one under construction. The vertical vibration acceleration of the track was recorded with an ICP acceleration sensor and data acquisition instrument during 10 subway trains passed. The time domain curves of the 10 subway trains induced vibration are shown in Figure 3. Then 10 1/3 octave spectrum of track acceleration level were obtained from the acceleration time domain data through fast Fourier transform method. The average spectrum of all the 10 1/3 octave spectrum of acceleration levels at the subway track bed is shown in Figure 4, which indicates the subway induced vibration energy mainly focuses on frequency above 20Hz.

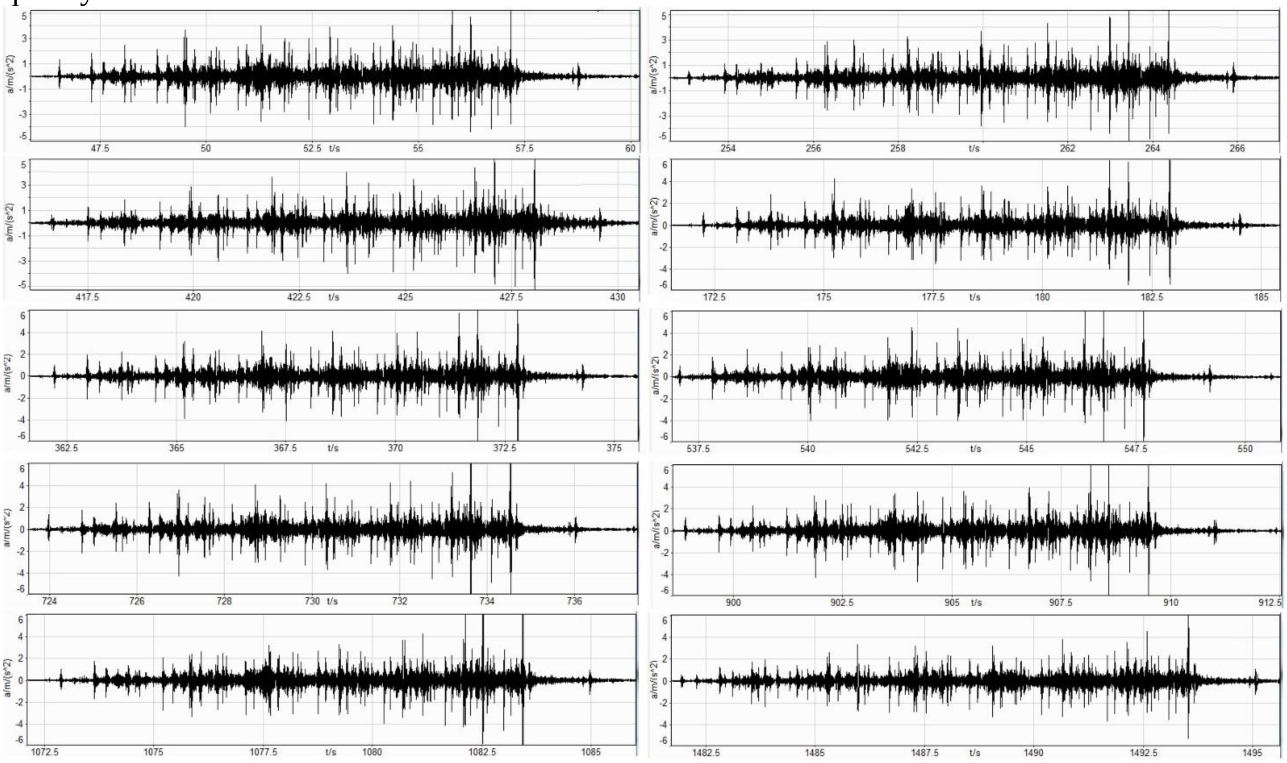

Figure 3: Time domain curves of the 10 subway trains induced vibration

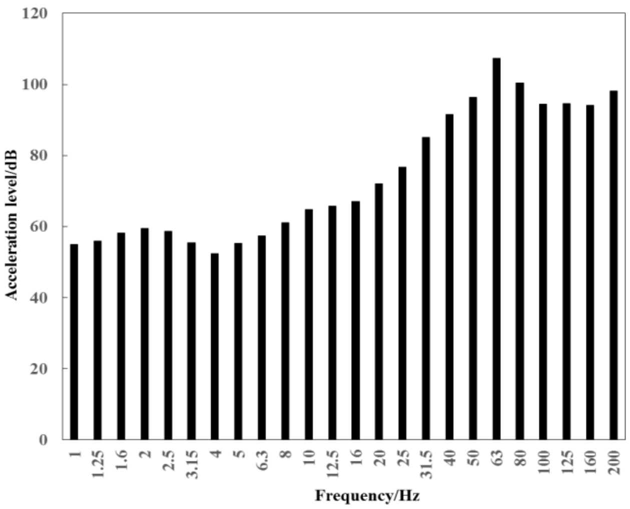

Figure 4: Average spectrum of acceleration level at the subway track bed

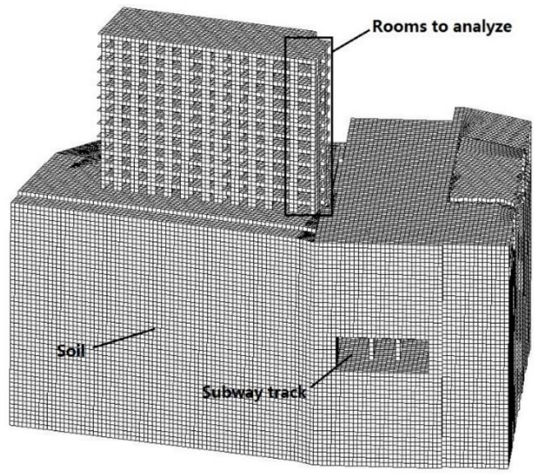

Figure 5: Finite element model of the system

4. Numerical model

As the subway-soil-building system is too complex to modelling, some assumptions are used to simplify the model as follows:

(1)The reinforced concrete structure is considered to be linear elastic structure because of the small deformation and low stress;

(2)The soil around the subway is considered to be viscoelastic. Natural soil is divided into three categories based on the strain value ε caused by the stress. First, elastic deformation ($\varepsilon<10^{-4}$); second, elastic-plastic deformation ($10^{-4}<\varepsilon<10^{-2}$); third, destructive deformation ($\varepsilon>10^{-2}$). The strain value of soil caused by subway induced vibration is less than 10^{-5}. So the vibration wave in the soil is elastic wave as reported by Xia[9];

(3)Under the condition of small deflection, the foundation raft and surrounding soil would not be separated from each other, so they are considered to be synergy deformation as reported by Ma[10].

Based on the assumptions above and the structure design drawing, a 3D finite element model consisting of the subway, soil, and building was established, in which the frame structure of building and foundation were composed of plate elements and beam elements, the soil and subway structure were composed of solid elements. In order to reduce the influence of boundary reflection wave, viscoelastic artificial boundary was established for the model. Shown in Figure 5 is the finite element model.

The material parameters of the structure are shown in Tab 1, in which E is modulus of elasticity, μ is poisson's ratio, ξ is structural damping coefficient, ρ is density. The soil types are simplified according to the geological survey report and the Code for seismic design of buildings (GB50011-2010)[11]. The equivalent parameters of the soil are shown in Table 2.

Table 1: Material parameters of the structure

Structure name	Material	E/GPa	μ	ξ	ρ/(kg · m^{-3})
Subway track	concrete	36	0.167	0.015	2500
Subway frame	Reinforced concrete	38	0.2	0.01	2700
Building frame	Reinforced concrete	30	0.2	0.015	2700
Floor	Reinforced concrete	30	0.2	0.015	2700

Table 2: Equivalent parameters of the soil

Soil type	Thickness	E/MPa	μ	V_s （m/s）	ρ/(kg · m^{-3})
Soft soil	16.7	91.26	0.35	130	2000

Middle soft soil	10.2	296.24	0.4	230	2000
Middle hard soil	14.1	668.85	0.3	350	2100
Hard soil	14.1	1105.65	0.3	450	2100

5. Response of the building floor with different vibration isolation measures

Unit load was applied to track bed and vibration response with different vibration isolation measures was analysed. Then the vibration transmission loss from the track bed to the building floor was calculated. The present paper mainly analyses vibration in rooms neighbour to the subway station, as shown in Figure 5. By combining the measured source vibration data with the calculated transmission loss, vibration level in the building above the subway station was obtained. The total vibration level was computed according to Shanghai local standard "Limits and measurement methods for vibration and ground-borne noise in dwellings caused by the moving vehicles of urban rail transit" (DB 31/T470-2009)[12] with a weighted network shown in Table 3. In this standard, the limit of indoor total vibration level in the frequency range of 1~80Hz were provided, for 72dB in day time and 69dB in night. The effects of different vibration isolation design and floating slab track are shown in the following subsections.

Table 3: Acceleration level frequency weighting factors in DB 31/T470-2009

f /Hz	1	1.25	1.6	2	2.5	3.15	4	5	6.3	8
C_i /dB	-6	-5	-4	-3	-2	-1	0	0	0	0
f /Hz	10	12.5	16	20	25	31.5	40	50	63	80
C_i /dB	-2	-4	-6	-8	-10	-12	-14	-16	-18	-20

5.1 The effects of different vibration isolation design

Total vibration levels in the building are calculated under three conditions as mentioned above.

① Structure gap filled with hard soil.

② Rubber blocks was added in the gap.

③ No structure gap.

The results of different design are shown in Figure 6. It is dedicated that:

a) The three floor vibration level curves show the same trend with the rise of the floor;
b) The total vibration level of each floor on curve ② is less than that on curve ① and curve ③, indicating that design ② has better effect on vibration isolation;
c) Only the seventh ~ ninth floor on curve ① shows more serious vibration than that on curve ③, indicating that design ① has effect on vibration isolation but not very remarkable;
d) All vibration level on the three curves exceeds the limit 69 dB except the eighth floor on curve ②, which shows that the vibration isolation effect of the two measures is not good enough.

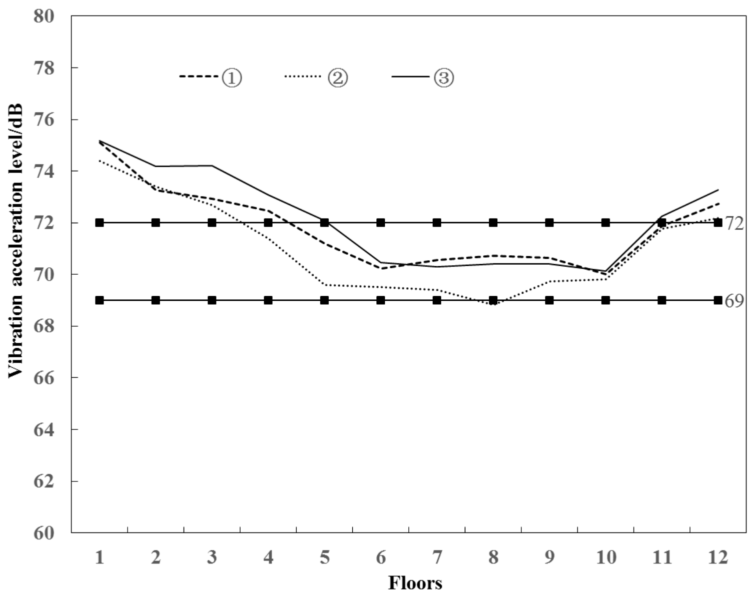

Figure 6: Vibration level of each floor under different design

5.2 Effect of special track isolation measure

As the vibration isolation designs show little effect, special track isolation measures such as floating slab track should be taken into consideration. Shown in Figure 7 is the acceleration vibration level insertion loss curve of floating slab track provided by the track vibration isolation design company. Shown in Figure 8 is the vibration level of each floor under different design with insertion loss of floating slab track considered. It could be concluded from the curves that:

a) The floating slab track mainly has effect on frequency above 20Hz, and vibration frequency below 10Hz would be enlarged in contrary;

b) After taking special track isolation measures, building vibration is greatly reduced to meet the local standard of Shanghai.

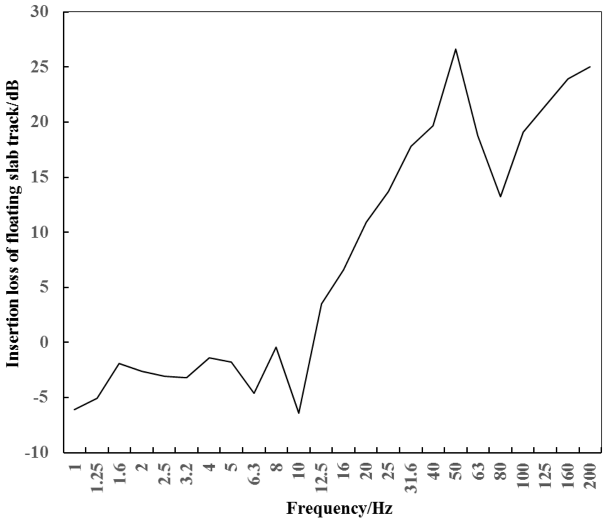

Figure 7: Insertion loss of floating slab track

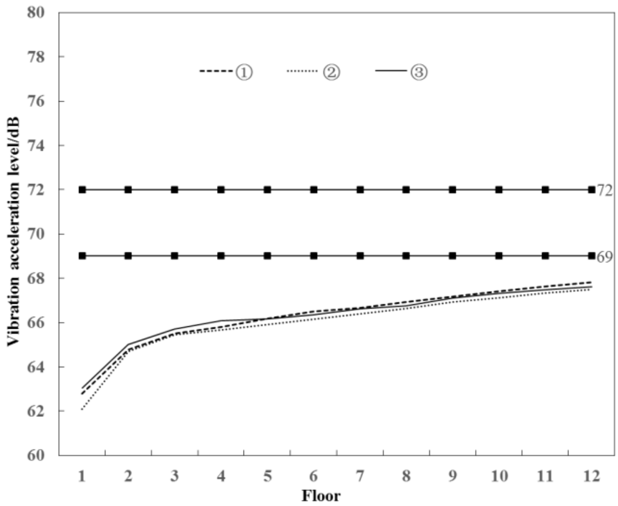

Figure 8: Vibration level of each floor under different design with floating slab track

6. Conclusions

The present paper focuses on the isolation of subway induced vibration. A semi-experimental and semi-numerical method is introduced and the vibration level in the building adjacent to subway station is calculated under different conditions. The results show that: the measures of designing gap filled with vibration isolation material between the building and the subway platform structure have little effect on vibration isolation; floating slab track can effectively reduce indoor vibration to meet the relevant standards of vibration. The conclusions may be helpful for the engineering design of vibration isolation measures for subway induced vibration in building above.

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