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Analysis of the influence of structural parameters on the vibration in buildings above the subway

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ABSTRACT

The rapid development of underground traffic network and lack of land resources are bringing more and more environmental vibration problems in buildings above the subway lines. To study the influence of the reinforced concrete and soil parameters on vibration in buildings caused by the subway below it, the semi-experimental and semi-numerical analysis method was considered. Firstly, a finite element model of the whole structure consisting of the subway station, the soil and the building above was established. Then the source vibration at the subway track bed was measured. At last, by combining the measured source vibration and the finite element model, vibration in the building above the subway was calculated with the initial designing value and fluctuating by ±20% of reinforced concrete and soil parameters. By comparing the results of vibration calculated in the building, the influence of the concrete and soil parameters on vibration of the building structure was analysed. It could be concluded that: the elastic modulus of the structures has more effect on structural vibration than the damping coefficient; the difference of soil parameters has less influence than that of the reinforced concrete. The conclusions may be helpful for vibration reduction design of buildings above the subway station.

Keywords: Vibration, Buildings above the Subway, Structural Parameters
I-INCE Classification of Subject Number: 76

1. INTRODUCTION

The problem of urban congestion is becoming more and more serious with the rapid development of economy and the expansion of city scale. Subway has many advantages to release ground traffic congestion. But 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. During the last 20 years, researchers have done a lot of research work on subway induced vibration, including the generation of subway vibration, the transfer of the energy, the building vibration prediction and isolation. As subway induced vibration problems are very complicated, many research methods are proposed, such as the analytic method,

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numerical method, empirical method, experimental method and so on. Sheng[1] developed a theoretical for predicting ground vibrations from trains generated by vertical track irregularities and studied the effects of track structure, vehicle speed and frequency range on the observed vibration levels. Lou[2][3] studied the propagation of subway induced vibration in the surrounding buildings and ground with the numerical and experimental methods. Lombaert[4] proposed a numerical model for the prediction of railway induced vibration and validated it with experimental method. Lopes[5] studied the influence of soil stiffness on building vibrations due to railway traffic in tunnels using the numerical method and found that soil stiffness plays a relevant role on the mechanisms of propagation of vibrations through the ground as well as on soil–structure interaction. Ling[6] 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. Liu[7] proposed a prediction method with artificial single-point pulse excitations for environmental vibration response induced by in-service metro train, which is suitable for accurately predicting vibrations in frequency domain before and after the construction of metro tunnel. Zou[8] measured field vibration of ground and over-track buildings induced by metro trains and calculated the structure radiated noise. Some important conclusions about environment protection were found.

In this paper, subway induced vibration in the building above it is calculated and the influence of structural parameters on the vibration is studied using the semi-experimental and semi-numerical method. The subway passes through the foundation of the building and the subway station is connected with the building basement structure. The building is in Shanghai and the relative position between building and subway station is shown in Figure 1. The present paper aims to compare the influence of the concrete and soil parameters on vibration of the building structure, which may be helpful for vibration reduction design of buildings above the subway station.

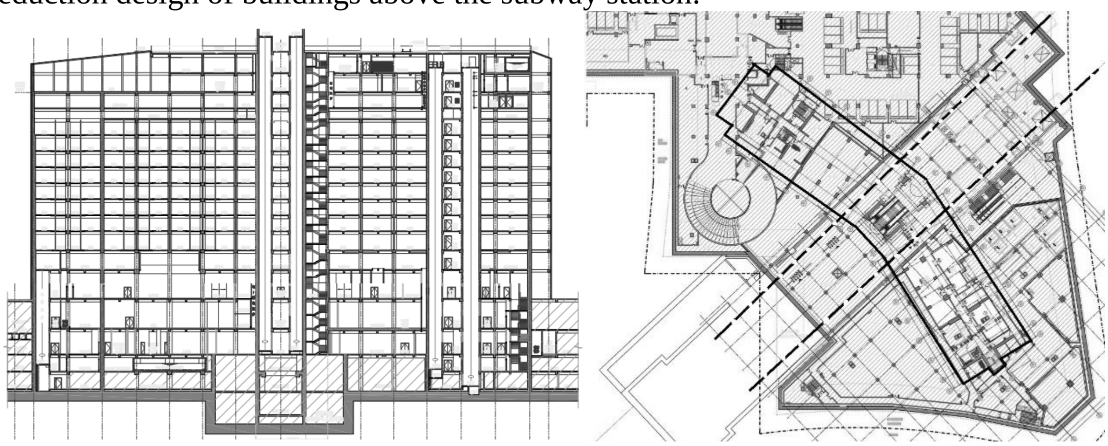

Figure 1: Relative position of the building and subway station

2. BASIC THEORY

The semi-experimental and semi-numerical method is a method combined by the experimental method and numerical method used to predict subway induced vibration. In this method, source vibration is obtained through the subway track vibration experiment, 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 basic theory of this method is shown below. The structural dynamic equations of the system can be written as:

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

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 $\{f(t)\}$:

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

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

$$X(\omega)=F(\omega)H(\omega) \qquad \text{Equation 3}$$

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

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

As the source vibration could be measured and the transfer function could be calculated, the vibration response in the buildings could be predicted.

3. SOURCE VIBRATION

An experiment was carried out at the subway track to get the source vibration under the building basement. Ten more subway trains passed the measured cross section and the vibration accelerations were recorded. The average 1/3 octave spectrum of the track acceleration level was obtained from the acceleration time domain data through fast Fourier transform method. The spectrum is shown in Figure 2.

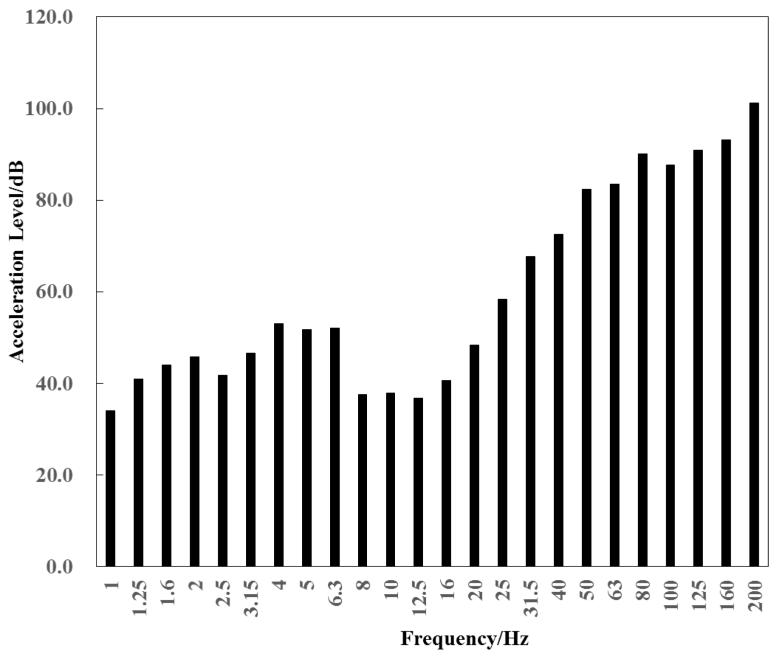

Figure 2: Source vibration acceleration level

4. NUMERICAL MODEL

To calculate the transfer function of the subway-soil-building system, a finite element model was established. Some assumptions were 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 (ε<10-4); second, elastic-plastic deformation (10-4<ε<10-2); third, destructive deformation (ε>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 3 is the finite element model.

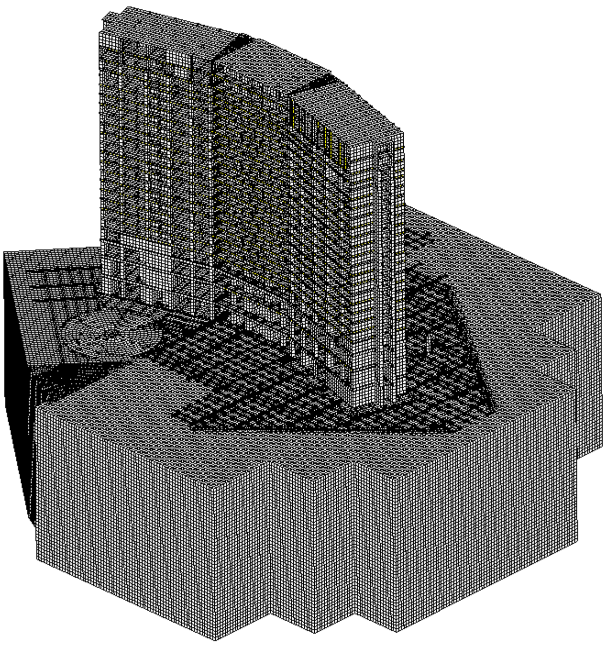

Figure 3: Finite element model of the whole system

The material parameters of the structure are shown in Tab 1, in which E is elastic modulus, μ is poisson's ratio, ξ is structural damping coefficient, ρ is density. The soil types are simplified according to the geological survey report. The equivalent parameters of the soil are shown in Table 2, in which Ed is dynamic elastic modulus, μ is poisson's ratio, ξ is structural damping coefficient, ρ is density, Vs is the shear wave velocity.

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 beam	Reinforced concrete	32.5	0.2	0.02	2500
Building column	Reinforced concrete	36	0.2	0.02	2600

Structure name	Material	E/GPa	μ	ξ	ρ/(kg.m^{-3})
Building Floor	Reinforced concrete	30	0.2	0.025	2400
Building Shear Wall	Reinforced concrete	32.5	0.2	0.02	2500
Building Block Wall	Reinforced concrete	28	0.2	0.03	2400

Table 2: Equivalent parameters of the soil

Soil type	Thickness	E_d/MPa	μ	V_s（m/s）	ρ/(kg.m^{-3})	ξ
Clayey silt	5	90.1	0.3	138	1820	0.1
Muddy clay	8	119.2	0.42	159	1660	0.1
Silty clay	8	213	0.3	214	1790	0.1
Silty clay	4	423.5	0.3	289	1950	0.15
Sandy silt	6	493	0.3	320	1850	0.15
Silty sand	25	527.3	0.3	325	1920	0.15

5. CALCULATION RESULTS

Unit load was applied to track bed and vibration responses with different structural parameters were analysed. Then the vibration transmission loss from the track bed to the building floor was calculated. The present paper mainly analyses vibration in rooms above the subway station, as shown in Figure 4. The analysed floors are L3~L10, as other floors are not residential floors.

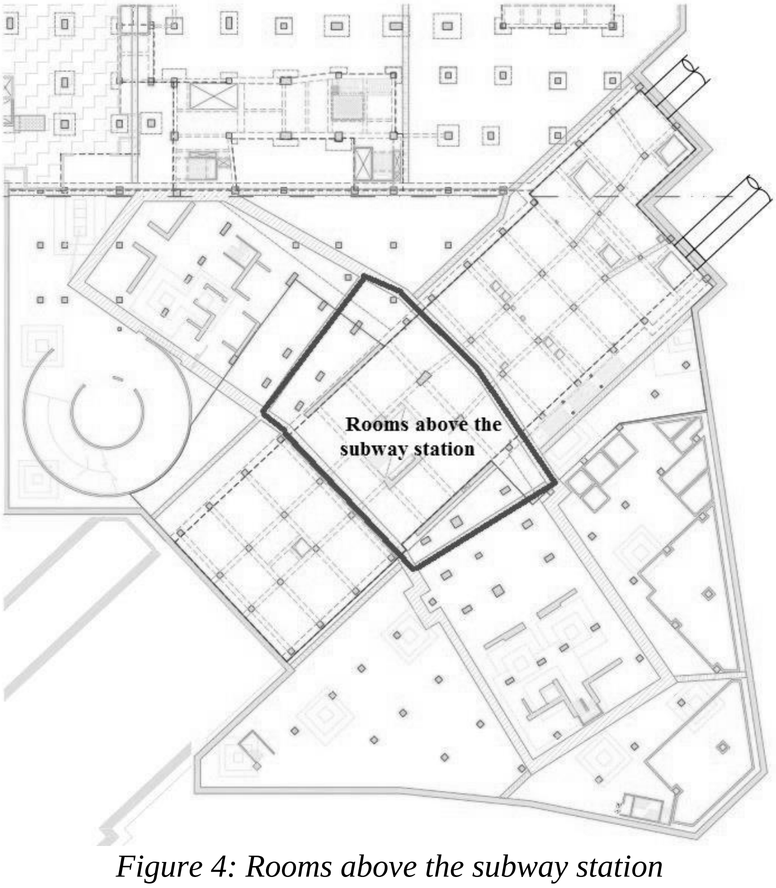

Figure 4: Rooms above the subway station

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)*[11]* with a weighted network shown in Table 3.

Table 3: Acceleration level frequency weighting factors in DB 31/T470-2009[11]

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

The effects of different structural parameters including elastic modulus and structural damping coefficient fluctuating by ±20% were analyzed.

The results are shown in the following subsections.

5.1 Influence of the Reinforced Concrete Parameters

The difference of elastic modulus and structural damping coefficient of the reinforced concrete was calculated respectively. Shown in Figure 5~6 are the largest total vibration level of each floor with the E and ξ fluctuating by ±20%. Shown in Table 4~5 are the relative deviation of vibration at each floor with the E and ξ fluctuating by ±20%.

The results show that:

1) The subway induced vibration level doesn’t always decrease with the rise of floors. Some of the higher floors show larger vibration level than the lower floors;
2) The fluctuation of elastic modulus has more influence on vibration response of the floors than that of the structural damping coefficient;
3) The vibration in building can be reduced by increasing the structural damping coefficient while the change of elastic modulus doesn’t show obvious law of vibration reduction.

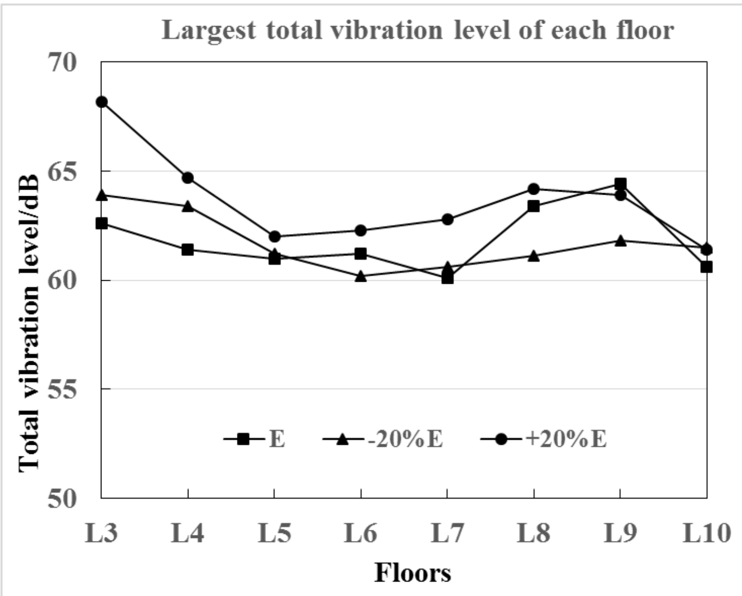

Figure 5: Largest total vibration level of each floor with the E fluctuating by ±20%

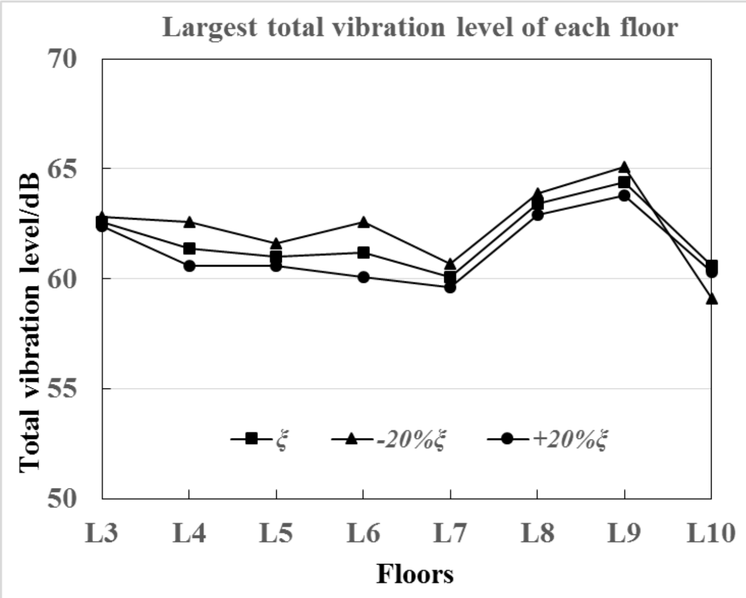

Figure 6: Largest total vibration level of each floor with the ξ fluctuating by ±20%

Table 4: Relative deviation of vibration at each floor with the E fluctuating by ±20%

Relative deviation of vibration	L3	L4	L5	L6	L7	L8	L9	L10
-20%E	2.08%	3.26%	0.33%	-1.63%	0.83%	-3.63%	-4.04%	1.49%
+20%E	8.95%	5.37%	1.64%	1.80%	4.49%	1.26%	-0.78%	1.32%

Table 5: Relative deviation of vibration at each floor with the ξ fluctuating by ±20%

Relative deviation of vibration	L3	L4	L5	L6	L7	L8	L9	L10
-20%ξ	0.32%	1.95%	0.98%	2.29%	1.00%	0.79%	1.09%	-2.48%
+20%ξ	-0.32%	-1.30%	-0.66%	-1.80%	-0.83%	-0.79%	-0.93%	-0.50%

5.2 Influence of the Soil Parameters

The difference of elastic modulus and structural damping coefficient of the soil was calculated respectively. Shown in Figure 7~8 are the largest total vibration level of each floor with the E and ξ fluctuating by ±20%. Shown in Table 6~7 are the relative deviation of vibration at each floor with the E and ξ fluctuating by ±20%.

The results show that:

1) The fluctuation of elastic modulus has more influence on vibration response of the floors than that of the structural damping coefficient;
2) The structural damping coefficient has little influenc on vibration response in the building. The ξ fluctuating by ±20% causes less than 1% relative deviations of vibration level in the rooms even most of them are less than 5%;
3) The difference of soil parameters has less influence than that of the reinforced concrete.

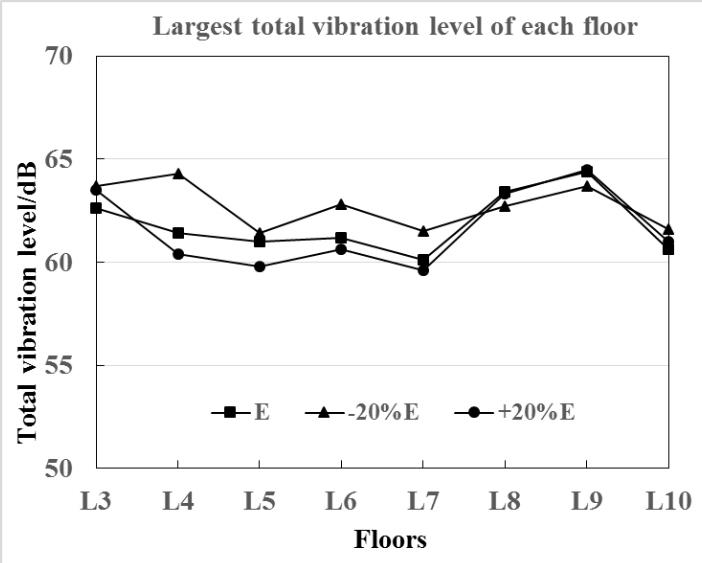

Figure 7: Largest total vibration level of each floor with the E fluctuating by ±20%

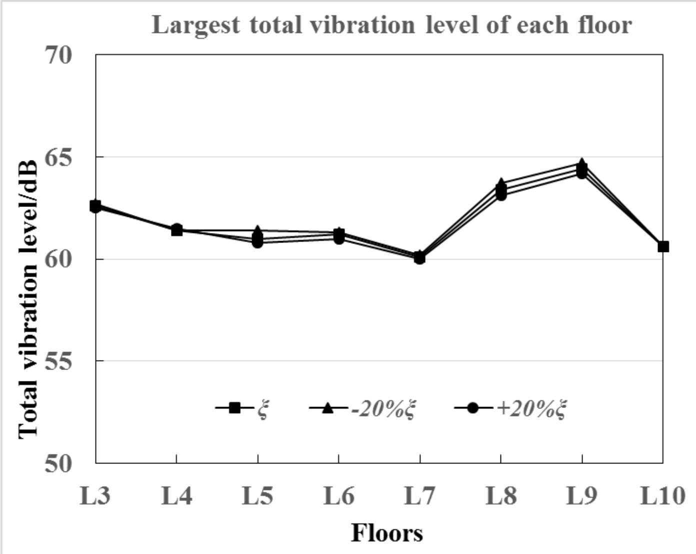

Figure 8: Largest total vibration level of each floor with the ξ fluctuating by ±20%

Table 6: Relative deviation of vibration at each floor with the E fluctuating by ±20%

Relative deviation of vibration	L3	L4	L5	L6	L7	L8	L9	L10
-20%E	1.76%	4.72%	0.66%	2.61%	2.33%	-1.10%	-1.09%	1.65%
+20%E	1.44%	-1.63%	-1.97%	-0.98%	-0.83%	-0.16%	0.16%	0.66%

Table 7: Relative deviation of vibration at each floor with the ξ fluctuating by ±20%

Relative deviation of vibration	L3	L4	L5	L6	L7	L8	L9	L10
-20%ξ	0.16%	0.00%	0.66%	0.16%	0.17%	0.47%	0.47%	0.00%
+20%ξ	-0.16%	0.16%	-0.33%	-0.33%	-0.17%	-0.47%	-0.31%	0.00%

6. CONCLUSIONS

The present paper focuses on the analysis of the influence of structural parameters on the vibration in buildings above the subway. The semi-experimental and semi-numerical method is considered and the vibration level in the building above the subway station is calculated under different conditions. The results show that: 1) the fluctuation of elastic modulus has more influence on vibration response of the floors than that of the structural damping coefficient; 2) the difference of soil parameters has less influence than that of the reinforced concrete; 3) the vibration in building could be reduced by increasing the structural damping coefficient of the reinforced concrete; 4) the soil damping coefficient has little influence on vibration response in the building, as the ξ fluctuating by ±20% causes less than 1% relative deviations of vibration level in the rooms even most of them are less than 0.5%. The conclusions may be helpful for the engineering design of vibration reduction for subway induced vibration in buildings above.

7. ACKNOWLEDGEMENTS

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