Study on elevated light rail induced vibration attenuation along the surrounding ground

Changqing Liu[1]; Yude Zhou[2]; Ying Tu[3]; Weimin Xu[4]

Shanghai Academy of Environmental Sciences

508 Qinzhou Rd, 200233 Shanghai, China

ABSTRACT

In this paper, the elevated light rail induced vibration attenuation along its surrounding ground is studied. A finite element vibration analysis model is established to compute the vibration response of the surrounding ground with different soil conditions, and the effects of soil parameters on the ground surface on vibration attenuation is analyzed. Vibration measurements were conducted at the surrounding ground of elevated light rail with different soil conditions, which verified the feasibility of FEA (finite element analysis). By the combination of FEA and vibration measurement results, a fast prediction method of the ground vibration is put forward. It is concluded that soil parameters have great effect on the attenuation of ground vibration and environmental vibration caused by the elevated rail could be predicted through finite element method. The conclusion is meaningful to the control and prediction of environmental vibration around the elevated light rail.

Keywords: elevated light rail; finite element analysis; ground vibration prediction

I-INCE Classification of Subjects Number(s): 75.3

1. Introduction

With the rapid increasing of population, urban traffic problem becomes more and more serious. Elevated highways, subway, light rail and other modern traffic are growing into a three-dimensional space transportation system, which alleviates the urban traffic problem effectively. But the vibration and noise caused by the high speed traffic badly impact the environment. In urban such as Beijing, Shanghai and Guangzhou, the elevated traffic line is only a few meters away from the house, leading to violent vibration in house. The government has to pay attention to the environmental vibration problems.

In recent years, research on viaduct vibration could be summed up in four aspects: vibration source, vibration propagation and attenuation, structural vibration response in the building along the line, and vibration control of rail traffic and building(1). Szurgott studied the dynamic response of bridges under moving loads through experimental analysis in his paper(2). Kim analyzed the vibration response of elevated bridge with different materials through comparison of steel structures and concrete structures in literature(3). Dinh studied dynamic response of the bridge under moving loads with the 3D model of wheel and rail in literature(4). Bian did research on dynamic characteristics of roadbed under dynamic load in literature(5). CHANG Le studied the impacts of viaduct vibration on surrounding ground and buildings through experimental method in literature(6). HUANG Mao-song analyzed the attenuation characteristics with depth of Rayleigh wave in layered ground in his paper(7). All in all, most of the researches are based on experimental study only or theoretical analysis only.

In this paper, the relevant research results at home and abroad are referred to, and FEM is used to study the environmental vibration at the surrounding ground of viaduct. Besides, experimental analysis is included for the validation of FEM. By the combination of FEM and vibration measurement, a method for prediction of the ground vibration is proposed and validated.

[1] liu-chq@163.com

[2] zhouyd@saes.sh.cn

[3] tuy@saes.sh.cn

[4] xuwm@saes.sh.cn

2. Theory of finite element analysis

The basic thinking of FEM used in dynamic analysis is dispersing a continuous region into a limited unit assembly whose units are linked with a certain way. Then the unknown field function in the whole solution domain could be expressed by the interpolating functions in the units. And through the differential equations of dynamics, the vibration modes and responses could be worked out.

Structural dynamics finite element equation is as follows:

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

$[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $\{F(t)\}$ is the node load vector, $\{q\}$ is the node displacement vector.

(1) could be solved by modal superposition method. Under the effect of single-frequency excitation $\{F_{(t)}\}=\{F\}\cdot e^{j\omega t}$, the response of the system can be defined as:

$$\{q\}=[\Phi]\{P\}\cdot e^{j\omega t} \tag{2}$$

$[\Phi]$ is the modal matrix consisting of the eigenvectors, $\{P\}$ is the modal coordinate vector. So (1) could be written as

$$-\omega^2[M][\Phi]\{P\}+j\omega[C][\Phi]\{P\}+[K][\Phi]\{P\}=\{F\} \tag{3}$$

Multiply both sides of (3) with $[\Phi]^T$, (4) is deduced

$$-\omega^2[\Phi]^T[M][\Phi]\{P\}+j\omega[\Phi]^T[C][\Phi]\{P\}+[\Phi]^T[K][\Phi]\{P\}=[\Phi]^T\{F\} \tag{4}$$

Define $[M_1]=[\Phi]^T[M][\Phi]$, $[C_1]=[\Phi]^T[C][\Phi]$, $[K_1]=[\Phi]^T[K][\Phi]$, $\{F_1\}=[\Phi]^T\{F\}$

$[M_1]$, $[C_1]$, $[K_1]$ are all diagonal matrices because of the orthogonality between $[\Phi]$ and $[M]$、$[C]$、$[K]$. So (4) becomes:

$$(-\omega^2[M_1]+j\omega[C_1]+[K_1])\{P\}=\{F_1\} \tag{5}$$

$$[M_1]=\begin{bmatrix} m_1 & & & \\ & m_2 & & \\ & & \ddots & \\ & & & m_n \end{bmatrix},\quad [C_1]=\begin{bmatrix} c_1 & & & \\ & c_2 & & \\ & & \ddots & \\ & & & c_n \end{bmatrix},\quad [K_1]=\begin{bmatrix} k_1 & & & \\ & k_2 & & \\ & & \ddots & \\ & & & k_n \end{bmatrix},\quad \{F_1\}=\begin{Bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{Bmatrix}.$$

The following equation could be deduced from (5):

$$(-\omega^2 m_r + j\omega c_r + k_r)p_r = f_r \quad (r = 1,2,3,...,n) \tag{6}$$

$$p_r = \frac{f_r}{(-\omega^2 m_r + j\omega c_r + k_r)} \qquad (r = 1,2,3,...,n) \tag{7}$$

From (2) and (7), the vibration response under the frequency ω could be obtained

3. Numerical study

3.1 Finite element model

As the viaduct structural system is too complex to analyze through the finite element method, 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 of the structure;

(2) The soil around the viaduct 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 elevated light rail induced vibration is less than 10^{-5}. So the vibration wave in the soil is elastic wave as reported by Xia (8);

(3) In the condition of small deflection, the pile foundation and surrounding soil will not be separated from each other, so they are considered to be synergy deformation as reported by Ma (9).

The material parameters of the viaduct is shown in Tab 1, in which E is modulus of elasticity, μ is poisson's ratio, ξ is structural damping coefficient, ρ is density.

Tab 1- Material parameters of the viaduct

Structure name	Material	E/GPa	μ	ξ	ρ/(kg . m$^{-3)}$
Elevated bridge	Reinforced concrete	38	0.2	0.015	2700
Elastic support	steel	216	0.27	0.001	7850
Pile foundation	Reinforced concrete	38	0.2	0.015	2700

In this paper, modulus of elasticity and structural damping coefficient of the soil are the main parameters to be studied. The density and poisson's ratio are respectively ρ=2000kg/m3 and μ=0.4, which are commonly used in Shanghai. The values of elastic modulus and damping coefficient in this paper to study are shown in Tab 2.

Tab 2- Material parameters of soil

Soil	1	2	3	4	5	6
E/GPa	0.06	0.2	1	24	0.2	0.2
ξ	0.15	0.15	0.15	0.15	0.1	0.05

Based on the assumptions and material parameters above, the finite element model of the elevated light rail structural system is established. The system consists of elevated bridge, elastic supporting, pile and ground around the viaduct. The FE model is shown in Fig 1.

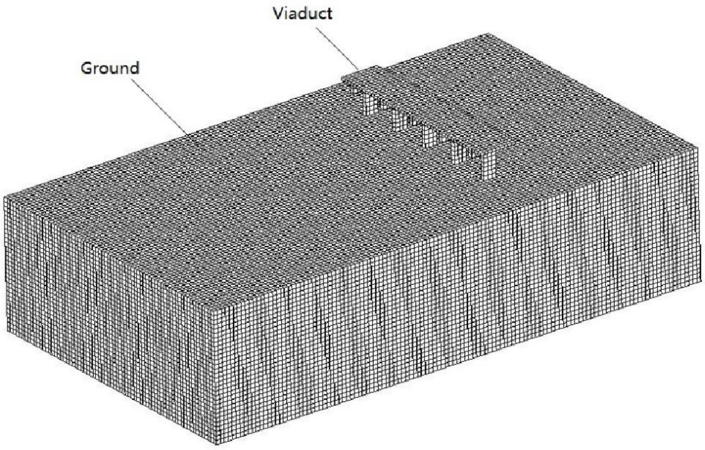

Fig 1- Finite element model of the overall structure.

3.2 FEA results

According to Shanghai local environmental vibration standard (DB31/T470-2009), the ground vibration is analyzed in the frequency range 1~80Hz. TL (transmission loss) is calculated to study the vibration attenuation along different soil.

Define the acceleration level La as

$$L_a = 10\lg\left(\frac{a}{a_0}\right)^2 \tag{8}$$

$a_0 = 10^{-6} m/s^2$ is the reference value of vibration acceleration. a is the ground vibration acceleration, and $a = \int_{\omega_1}^{\omega_2} \overline{a}(\omega)d\omega$. $\overline{a}(\omega)$ is the acceleration spectral density function.

On frequency band $\omega_1 \sim \omega_2$, the vibration transmission loss of the ground points is

$$TL = L_{as} - L_{ai} = 10\lg\left(\frac{a_s}{a_i}\right)^2 = 10\lg\left(\frac{\int_{\omega_1}^{\omega_2}\overline{a}_s(\omega)}{\int_{\omega_1}^{\omega_2}\overline{a}_i(\omega)}\right)^2, i = 1,2,... \tag{9}$$

a_s is vibration acceleration of the excitation point; a_i is vibration acceleration of the ground point.

3.2.1 Effect of soil modulus on the ground vibration transmission

Vibration response of the ground points of soil 1~4 is calculated, and the effects of soil modulus on the ground vibration transmission is analyzed. Shown in Fig 2~5 is the spectrum of vibrational translation loss of the points on ground with different soil modulus. It is seen from the comparison of the spectrum that:

1) The vibration transmission loss increases with distance in different soil;
2) For the soil with small modulus, the transmission loss of low frequency is little while that of high frequency is very large. As the modulus increases, the transmission loss of low frequency increases while that of high frequency decreases. The reason for this phenomenon is that the increasing modulus improves the stiffness of the soil, thus improving the natural frequency of the whole system.

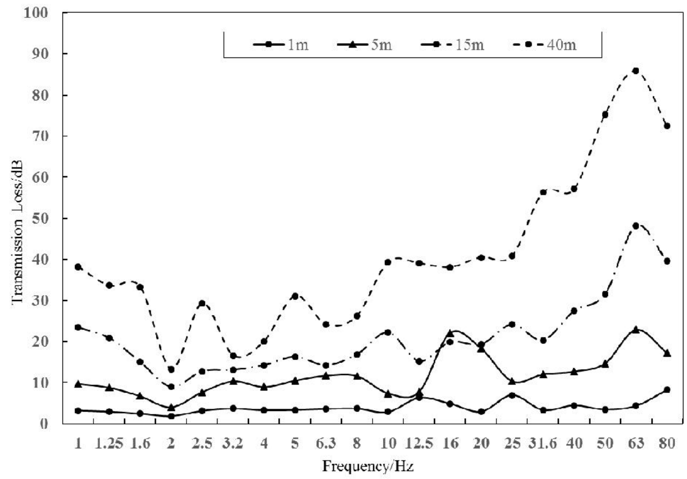

Fig 2 - Spectrum of vibrational translation loss of the points on ground (*E*=0.06GPa)

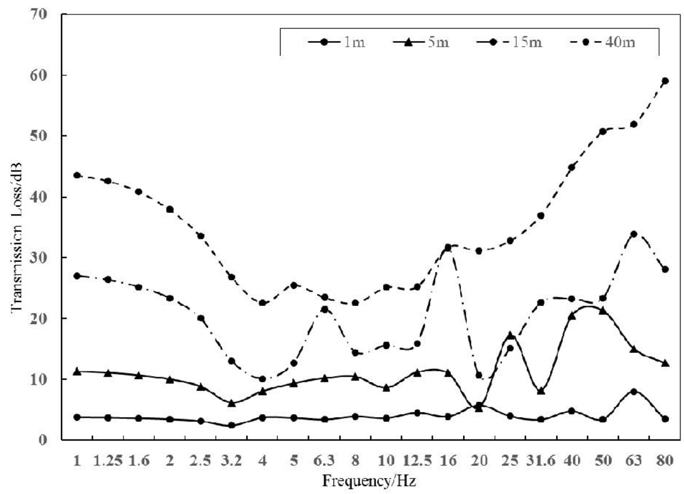

Fig 3 - Spectrum of vibrational translation loss of the points on ground (*E*=0.2GPa)

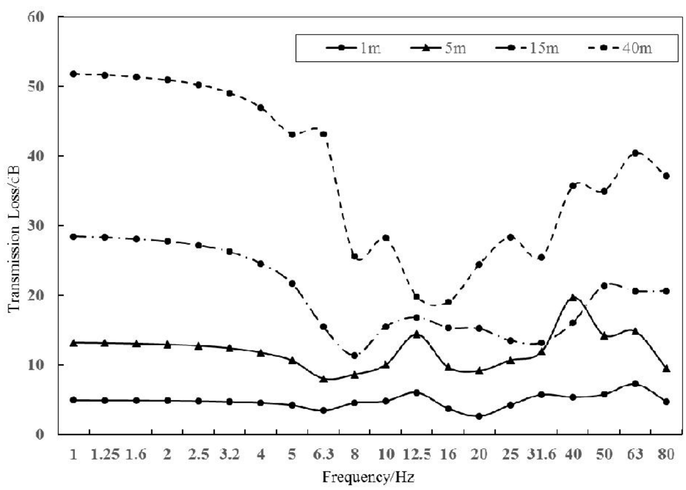

Fig 4 - Spectrum of vibrational translation loss of the points on ground (*E*=1GPa)

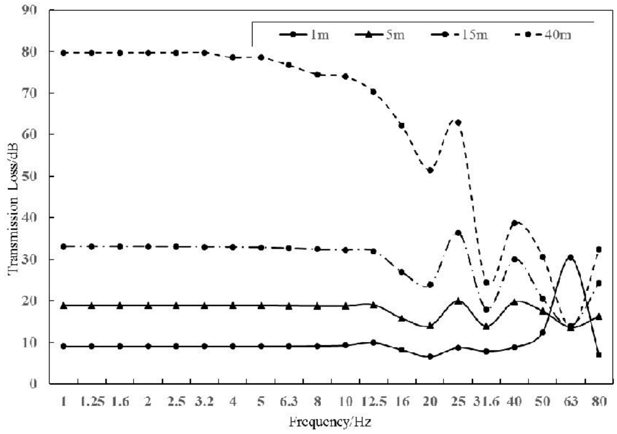

Fig 5 - Spectrum of vibrational translation loss of the points on ground (*E*=24GPa)

3.2.2 Effect of damping coefficient of soil on the ground vibration transmission

Vibration response of the ground points of soil 2, soil 5, and soil 6 is calculated, and the effects of soil damping coefficient on the ground vibration transmission is analyzed. Shown in Fig 6~8 is the spectrum of vibrational translation loss of the points on ground with different soil damping coefficient. It is seen from the comparison of the spectrum that:

(1) The effect of soil damping coefficient on vibration attenuation mainly focuses on high frequency, and little effect is observed in low frequency.

(2) As the distance of the ground points increases, vibration in high frequency decreases fast. And vibration in soil with larger damping coefficient decreases faster.

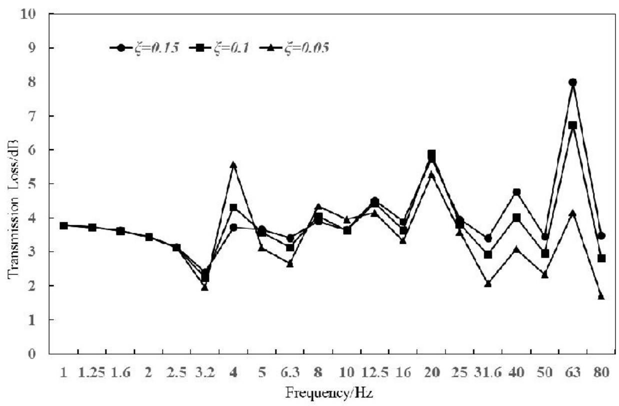

Fig 6 - Spectrum of vibrational translation loss of the point 1m away from the pile foundation

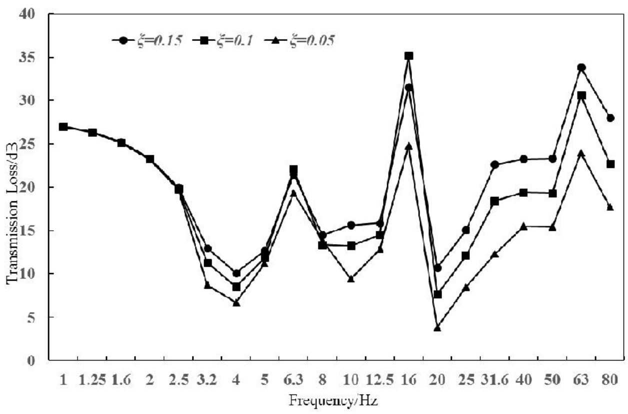

Fig 7 - Spectrum of vibrational translation loss of the point 15m away from the pile foundation

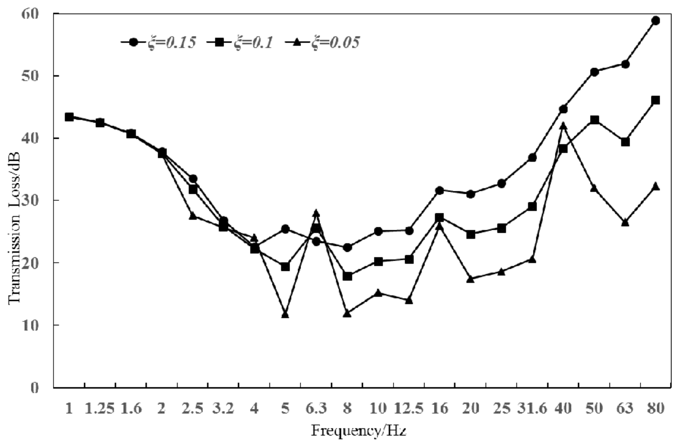

Fig 8 - Spectrum of vibrational translation loss of the point 40m away from the pile foundation

4. Measurement and prediction

4.1 Environmental vibration measurement

In order to validate the accuracy of finite element analysis and its feasibility of application in practical engineering, vibration measurement was carried out at a section of viaduct in Shanghai. The ground in the area chosen to test is covered by concrete. During the measurement, the train passed at a constant speed. The vibration acceleration of point at the pile foundation (0m), and the ground point 5, 15, 40m away from the pile respectively was measured when the train passed through. The background vibration was also measured at each point. The location of all the measurement points is shown in Fig 9.

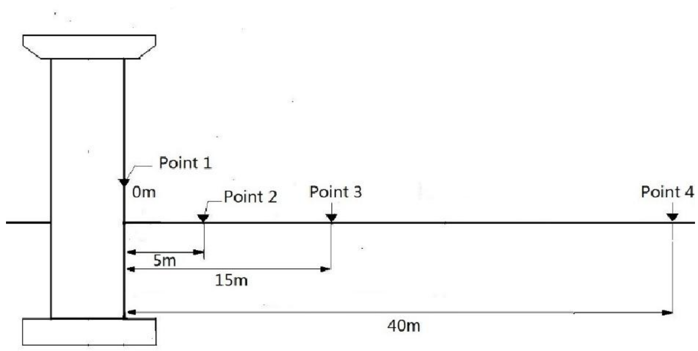

Fig 9 - Location of the measurement points

Shown in Fig 10 is the time domain curves of point 1 and point 4. Shown in Fig 11 and Fig 12 are the spectrum of light rail induced vibration and background vibration at point 1~4 in frequency range 1~80 Hz. It could be observed from Fig.10~12 that:

(1) When the train passes through, the amplitude of vibration acceleration of point 1 is over ten times larger than that of point 4, indicating a great attenuation of vibration surround the light rail transit.

(2) The elevated light rail induced vibration mainly focuses on frequency above 20Hz, while the background vibration mainly focuses on frequency below 20Hz.

(3) The vibration with frequency above 20Hz and blow 5Hz both attenuate severely with the distance increases. The main reason for the attenuation of low frequency vibration is that the ground is

covered by thick concrete, which lead to high stiffness of the ground. While the attenuation of high frequency vibration is mainly caused by the damping of soil.

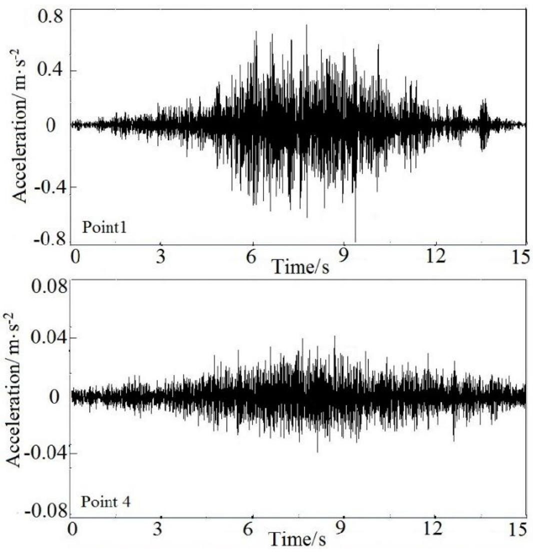

Fig 10 - Time domain waveform of vibration at point 1 and point 4

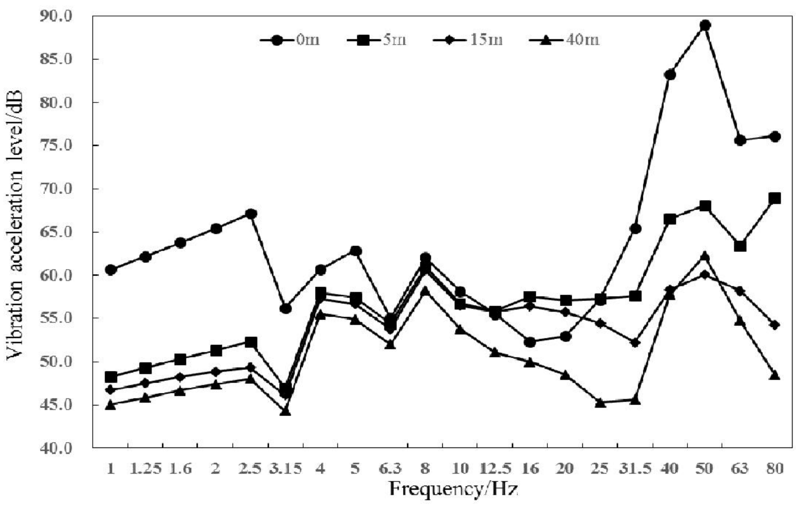

Fig 11 - Spectrum of light rail induced vibration at point 1~4

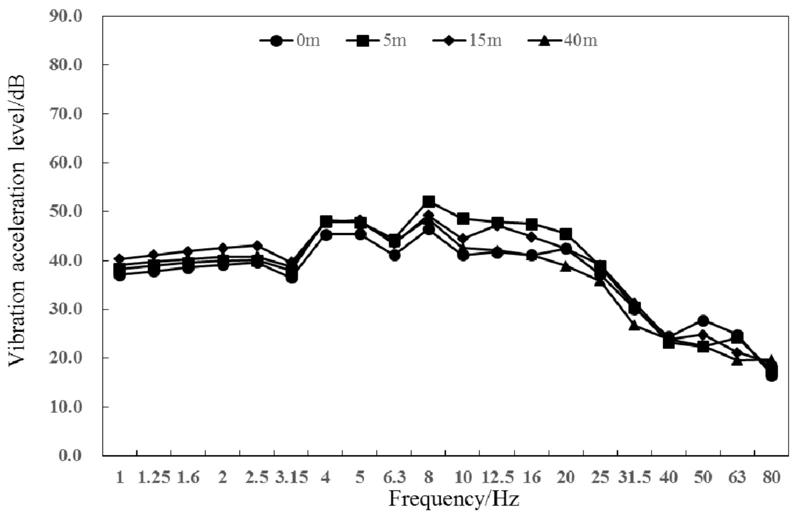

Fig 12 - Spectrum of background vibration at point 1~4

4.2 Vibration prediction

The vibration excitation of rail transit is very complex, and it is too difficult to simulate its spectrum through theoretical method. In order to predict environmental vibration caused by rail transit, vibration testing for the elevated bridge with similar structure should be carried out to get the vibration spectrum of pile foundation as well as the background vibration spectrum. Combining the measurement results with the vibration transmission loss along the ground calculated by finite element method, environmental vibration could be predicted.

In this paper, vibration of the ground tested is predicted by the combination of measurement and FEM. As the ground is covered with continuous and thick concrete, the transmission loss of soil4 is used for prediction. Shown in Fig 13 is the comparison of the prediction results and measurement results of the total vibration acceleration level. It is seen from Fig 13 that the vibration attenuates exponentially with distance and that the predicted results agree with the measurement results, thus indicating the accuracy of the prediction method in engineering.

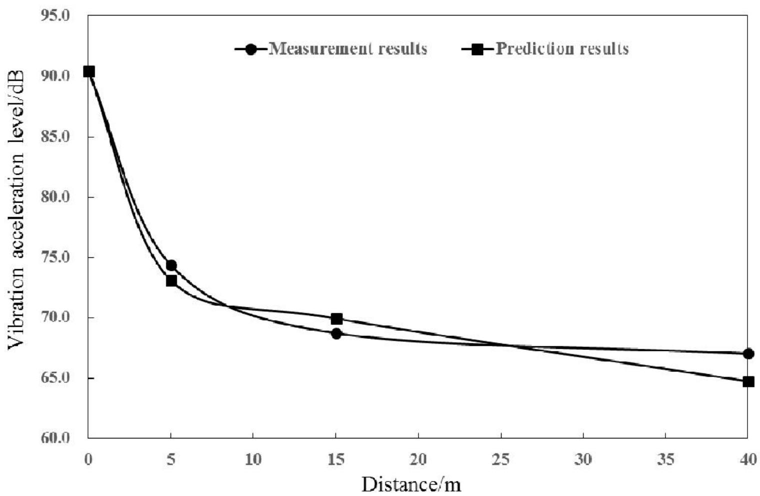

Fig 13 - Comparison of the prediction results and measurement results

5. Conclusions

(1) The vibration energy caused by the elevated rail transit attenuates with distance when transmitting along the surrounding ground. For the soil with small modulus, the transmission loss of low frequency is little while that of high frequency is very large. As the modulus increases, the stiffness of the soil is improved and the natural frequency of the whole system increases, thus making the transmission loss of low frequency increases while that of high frequency decreases.

(2) The effect of soil damping coefficient on vibration attenuation mainly focuses on high frequency. As the distance of the ground points increases, vibration with high frequency in soil with larger damping coefficient decreases faster, while vibration with low frequency in soils with different damping coefficient has no difference with each other.

(3) The elevated light rail induced vibration mainly focuses on frequency above 20Hz. The total acceleration level attenuates exponentially with distance. The elevated light rail induced vibration of the environment could be predicted accurately through the combination of FEM and experimental method.

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