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A coupled FE-TLE model for the prediction of Subway Train-induced Ground-borne Vibrations

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Abstract. A coupled finite element–thin layer element (FE-TLE) model for the prediction of subway induced vibrations was developed. With this model, the soil-tunnel system is divided into two parts, i.e., the tunnel structure and layered soil with a tunnel type hole. The tunnel structure is simulated by finite elements and the layered soils with hole by thin layer elements. The model fully accounts for the dynamic interaction between the tunnel and the soil. The numerical models for train-induced ground-borne vibrations were validated by in-situ experiments.

Introduction

With the rapidly growing population in metropolitan areas, mass rapid transit systems built underground have emerged as an effective transportation tool for relieving the saturated ground traffic in different parts of the world. Subway induced vibrations are a matter of growing concern in densely populated cities. The interaction between the wheels and the rails induces dynamic loads on the track, which generate waves that propagate through the tunnel and the surrounding soil into buildings. Residents in buildings may perceive these vibrations directly or indirectly in the form of re-radiated noise. Noise and vibration from underground railways is a documented disturbance to individuals living or working near subways. As such, the problem of train-induced ground-borne vibration and noise has received increasing attention from both engineers and researchers.

During the last decade various approaches with different accuracy have been performed to investigate for quantitative assessment and prediction of the vibration level from the line, and also to design tracks and constructional measures to reduce vibration level[2,3]. The methods can be classified as either numerical, analytical or (semi-)empirical method, such as thin layer method (TLM) [1] and (2) finite element -boundary element method (FEM-BEM) [4]-[6], etc.

In this article, a finite/ thin layer element approach is proposed to investigate the wave propagation behavior of a soil tunnel interaction system due to trains moving in underground tunnels. The governing equation of dynamic soil-tunnel interaction is established by flexible volume method and fundamental displacement solutions of the thin layer element method. The train moving underground is simulated by the coupled wheel-rail model and modeled as an infinite harmonic line load. The numerically obtained time and frequency responses of ground-borne vibrations from the method are found to be in good agreement with the corresponding experimental observations.

A Finite/ thin layer element model

Basic principles of thin-layer element method. The soil around of the tunnel is divided into n horizontal homogeneous layers in which properties and thickness of each layer can be different among the layers. The layers are numbered from the top to the bottom in order. The thin layer element method is far more efficient than the finite element method for analyzing the semi-infinite soil medium.

Assuming linear distribution of displacement along the thickness direction in the thin-layer element with h = thickness of the jth layer (Fig.1), displacements in the jth layer are expressed as

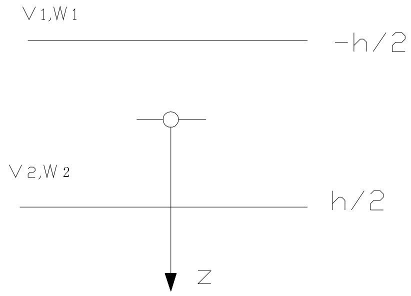


Fig.1: Distribution of displacement

$$\begin{Bmatrix} U \\ W \end{Bmatrix} = N_1 \begin{Bmatrix} u_1 \\ w_1 \end{Bmatrix} + N_2 \begin{Bmatrix} u_2 \\ w_2 \end{Bmatrix} \tag{1}$$

where, $N_1 = \frac{1}{2} - \frac{z}{h}, N_2 = \frac{1}{2} + \frac{z}{h}$ are shape functions.

When subway trains moves, the vibration source can be approximated as a line load.When one point $\mathrm{m}(x_0, y_0)$ on the layer surface S in the layered soil foundation was loaded one harmonic line load $(\mathrm{p_x} \quad \mathrm{p_z})_s^T$, the displacement of the point $\mathrm{n}(x, y)$ on the layer surface R can be calculated using mode superposition method:

$$\begin{Bmatrix} \mathrm{u_x} \\ \mathrm{u_z} \end{Bmatrix} = \begin{bmatrix} -\mathrm{i}\sum\limits_{\mathrm{k=1}}^{\mathrm{2N}} \mathrm{X_{rk}} \frac{\mathrm{X_{sk}} \kappa_{\mathrm{k}} \mathrm{F_1(R)}}{\mathrm{D_\kappa}} & -\mathrm{sgn(x-x_0)} \sum\limits_{\mathrm{k=1}}^{\mathrm{2N}} \mathrm{X_{rk}} \frac{\mathrm{Z_{sk}} \kappa_{\mathrm{k}} \mathrm{F_1(R)}}{\mathrm{D_\kappa}} \\ \mathrm{sgn(x-x_0)} \sum\limits_{\mathrm{k=1}}^{\mathrm{2N}} \mathrm{Z_{rk}} \frac{\mathrm{Z_{sk}} \kappa_{\mathrm{k}} \mathrm{F_1(R)}}{\mathrm{D_\kappa}} & -\mathrm{i}\sum\limits_{\mathrm{k=1}}^{\mathrm{2N}} \mathrm{Z_{rk}} \frac{\mathrm{Z_{sk}} \kappa_{\mathrm{k}} \mathrm{F_1(R)}}{\mathrm{D_\kappa}} \end{bmatrix} \begin{Bmatrix} \mathrm{p_x} \\ \mathrm{p_z} \end{Bmatrix} \tag{2}$$

where $R = |x - x_0|, F_1(R) = \exp(-i\kappa_k R), D_k = \kappa_k^2 \{X_k\}^T [A_p] \{X_k\} + \kappa_k^2 \{Z_k\}^T [A_s] \{Z_k\}$

$$-\{X_k\}^T [A_p] \{X_k\} - \{Z_k\}^T [E_p] \{Z_k\}, \mathrm{sgn}(x - x_0) = \begin{cases} 1 & x > x_0 \\ 0 & x = x_0 \\ -1 & x < x_0 \end{cases}.$$

This can be illustrated in Fig.2.

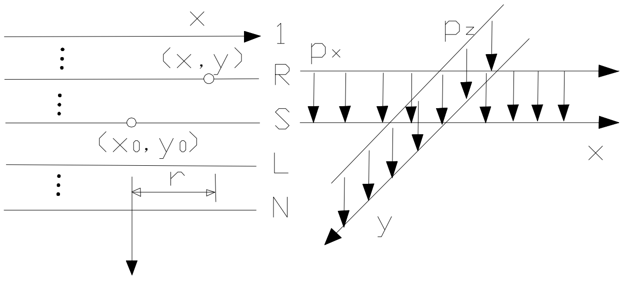


Fig. 2: Green function of line loading

More details of the derivation refer to [1].

Formulation for soil-tunnel interaction. The soil-tunnel system is divided into two parts, i.e., the tunnel structure and layered soil with a tunnel type hole. The tunnel structure is simulated by finite elements and the layered soils with hole by thin layer elements. The governing equation of dynamic soil-tunnel interaction is established by flexible volume method and fundamental displacement solutions of the thin layer element method. A coupling soil-tunnel model using FE-TLE method is shown in Fig.3. The dynamic stiffness of soil-tunnel interaction is given below:

$$K=K_b-K_s+K_t-\omega^2(M_s-M_t) \tag{3}$$

where K_b is the stiffness matrix of the whole half-space assembled by k_b, K_s is the stiffness matrix of the dredged soils[7,8], K_t is the stiffness matrix of the tunnel, M_s is the mass matrix of soil, M_t is the mass matrix of the tunnel.

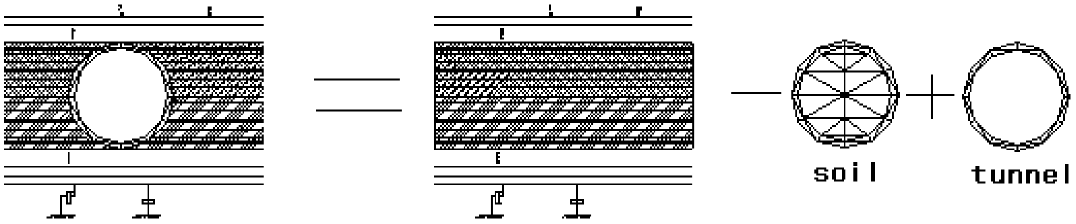


Fig.3: A coupling soil-tunnel model

In the calculation, element division of the tunnel is completed by selecting n nodes. M nodes on the surface of the ground can be selected according to the measured data. Each node has two degrees of freedom, then K_b is a matrix of size 2(m+n)×2(m+n). The boundary condition of soil is paraxial boundary. The size of the stiffness and mass matrix of the tunnel and dredged soils is 2n×2n, and they can be calculated using the finite element method. The result can be transferred to matrix of the same dimensions as K_b using the transformation matrix. Taking the matrix inversion of K, flexibility matrix of the model can be obtained. The displacement response of desired nodes now can be obtained when apply loads on any other nodes.

Numerical results

The tunnel of this metro line was a shield tunnel with the precast reinforced concrete lining at 15 m below the free ground surface (Fig.4). It has an outer radius of 3.1m and a wall thickness of 0.35m.The tunnel lining consists of six circumferential segments connected by bolts for each ring. The reinforced concrete lining has a Young's modulus $E=3.45\times10^{10}MPa$, a Poisson's ratio $\nu=0.2$, a density $\rho=2500kg/m^3$ and damping ratio $\beta=0.05$.

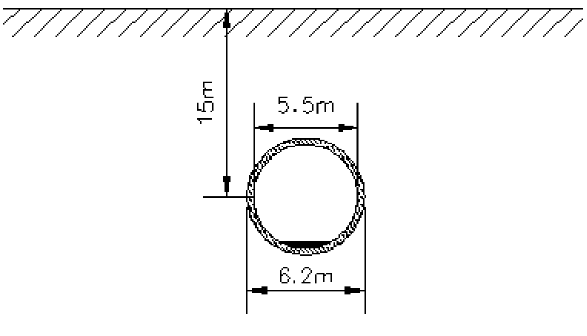


Fig. 4: Location of the tunnel

The dynamic soil characteristics are summarized in the Table 1.

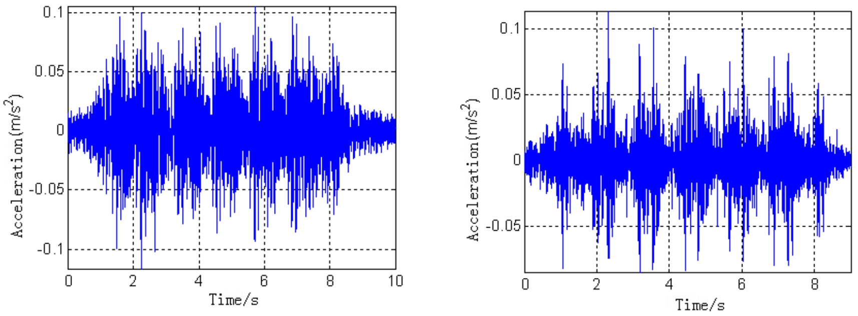
Table.1: Dynamic soil characteristics

Layer number	soil thickness [m]	Bottom buried deep[m]	Poisson's ratio	average density [$10^3 kg/m^3$]	Vsm [m/s]	Average shear modulus [Mpa]
1	6.4	6.4	0.4	1.86	85.34	13.5
2	11.26	17.66	0.4	1.80	108.43	21.2
3	26.4	44.06	0.4	1.82	220	88.1
4	7.4	51.46	0.4	1.98	192.30	73.2
5	8.05	59.51	0.4	1.92	230	101.6
6	16.96	76.47	0.4	1.95	220	94.4
7	23.53	100	0.4	1.95	288.77	163

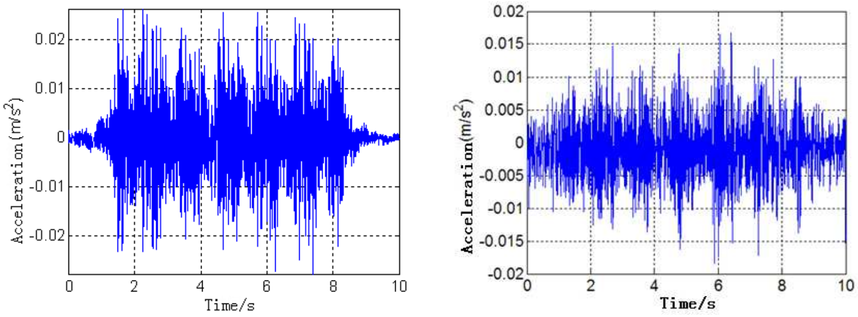
The metro vehicle is composed of 6 carriages with each length of 24.6 m. The bogie distance L on all carriages is 17.5 m, and the axle distance L is 2.5 m. The total mass of the train is $3.97\times10^5 kg$, $4.14\times10^5 kg$ and $5.69\times10^5 kg$ respectively according to three operation condition. The mass of the bogie and axle are $3.894\times10^3 kg$ and $1.42\times10^3 kg$, respectively. The primary suspension has the stiffness of $5.6\times10^6 N/m$ and the damping of $0 N\cdot s/m$. The second suspension has the stiffness of $4.7\times10^6 N/m$ and the damping of $1.1\times10^4 N\cdot s/m$.

There are various excitation mechanisms responsible for generating vibrations due to moving trains. In this study, the excitation due to rail unevenness on the track bed is modeled using the wheel-rail coupling model.

Fig.5 (left) shows the time history of vertical acceleration on the ground surface with different distance to the tunnel. The measured data (right) is also plotted for comparison. It can be found that the simulation results are consistent with measured data considering the amplitude.

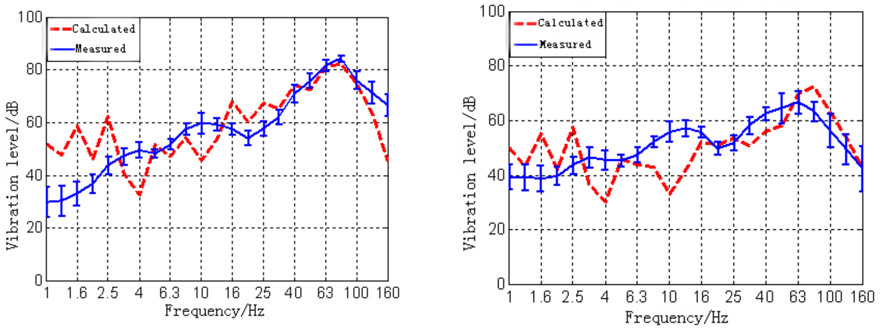


a. 2 m from the tunnel



b. 20 m from the tunnel

Fig. 5: Vertical acceleration at variable distance



a.2 m from the tunnel **b.20 m from the tunnel**

Fig. 6: One-third octave band spectra

Fig.6 illustrates the comparison of the one-third octave band spectra between simulation result and the measured data. The comparison of the one-third octave band spectra of the predicted and the measured results shows that the simulation fluctuates larger than the situ measurement. Up 10Hz, the correspondence between the predicted and experimental results is reasonably good.

Conclusions

In this paper, the experimental validation of a numerical model for the prediction of subway induced vibrations has been presented. The coupled FE-TLE model fully accounts for the dynamic interaction between the tunnel and the soil. The response to moving loads (trains) is computed by first estimating the excitation forces and then solving the tunnel–soil interaction problem to compute the vibrations in the tunnel and the free field. The vibrations in in the free field have been predicted and validated for the passage of a test train on the line 8 Shanghai metro. The correspondence between the predicted and experimental results is reasonably good.

This study demonstrates the applicability of the coupled FE-TLE model to make realistic predictions of the vibrations from underground railways.

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