Prediction of Metro Train-Induced Vibrations on a Historic Building: The Case of the Round City and Chengguang Hall in Beijing

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Abstract. With the development of urban mass transit, the train-induced vibrations become a potential problem to historic buildings nearby. The protection and maintenance of historic buildings have aroused a great deal of public attentions. In this paper, the problem of environmental vibrations was analysed for the Round City and Chengguang Hall, a group of historic buildings in Beijing. The historic buildings are located close to a busy road and are near to a planning subway line. The natural frequencies and dynamic amplification factor of the timber structure were estimated by an empirical method. Then, a finite element model was built to predict the metro train-induced vibrations. The results show that, even if the floating slab track was used train-induced vibration can still be a potential problem against long-term protection for the timber structure.

1 Introduction

With the rapid development of urban mass transit system, more and more environmental concerns are focused on the vibrations induced by trains. When considering the long-term vibration effects on historic buildings, the potential architectural damage should be paid more attention. Bata (1971) and Clemente and Rinaldis (1998) reported the damage to some historic buildings caused by road traffic. Ellis (1987) investigated the link between vibration levels arising from road traffic and deterioration of historic buildings. Results showed that architectural damage was often of as much concern as structural damage to heritage buildings. In China, researchers made great efforts to protect historic buildings against vibrations from different types of traffic sources. In 1980s, the plan route of a railway line was changed to protect Longmen Grottoes (Wang and Su 1991). Zhou (2000) investigated the safety problem of Yunyan Pagoda (built between 959 and 961) against vibrations from Beijing-Shanghai high-speed railway lines. Li and Yu (2012) measured the road traffic-induced vibrations in the Hall of the Holy Mother (built between 1023 and 1032) and suggested a minimum safety distance from the road to protect the statues inside.

To learn about the dynamic behaviour of a building, the modal analysis is useful which can be performed by measurement and finite element (FE) analysis. Bazaco et al.

(1995) investigated the behaviour of XVth century Palacio de Sta. Cruz under road traffic loads. Bongiovanni et al. (2011) resumed some experiences in the field of experimental dynamic characterization of historical buildings.

To evaluate a historic building under the vibration environment, the in-situ measurement is the mostly used approach. Meng et al. (2008, 2009) performed experimental investigations of vibration induced by road traffic and evaluated the impact on an ancient city wall and the Bell Tower in Xi'an. Li et al. (2010) measured the metro-induced vibration effect on two sites of surrounding historic buildings. Min et al. (2013) performed an ambient vibration test on a heritage timber building in Seoul. Hinzen (2014) measured the subway train-induced vibrations in Cologne Cathedral.

To evaluate a historic building near a new built railway or subway lines, vibration prediction is an essential work. Most predictions were based on the numerical analysis. Liu et al. (2007) and Jia et al. (2008) predicted the vibration impact on the city wall and a historic railway station above a new-built underground railway line in Beijing. Breccolotti et al. (2011) predicted the vibration levels produced by railway traffic based on experimental measurements and FE modeling. Ma et al. (2016) analysed the vibration impact on a historic Bell Tower in Xi'an above two spatially overlapping metro lines.

Generally speaking, it is not difficult to build FE models for masonry structures. Nevertheless, it becomes a problem in dealing with the traditional Chinese timber structures. Firstly, all the wooden elements are constructed by the tenon-and-mortise work. In addition, most beams and columns are connected by *dougong* which is a unique structural element of interlocking wooden brackets, one of the most important elements in traditional Chinese architecture. Moreover, all columns just stand on the masonry bases, and the horizontal restraint for the columns is only provided by the friction between columns and bases. It can be found that the input parameters for contact element are difficult to determine. Accordingly, under all the difficulties, FE models may be not a good approach to deal with the prediction work. To learn the dynamic behavior of such unique timber structures, the empirical estimation or the in-situ measurement are another alternative choices.

In this paper, the prediction of metro train-induced vibrations on Chengguang Hall, located on the Round City, was studied. Firstly, the dynamic characteristic of the timber structure was estimated by an empirical method. Then, two 3D finite element (FE) models for calibration and prediction were built. Finally the vibration responses were analysed.

2 Problem Outline

2.1 Introduction of the Historic Building

Chengguang Hall (the Hall of Receive Light) was originally built in 1264 and reconstructed in 1743. As a typical Chinese timber structure, it is a spacious building with a double-eaved roof made of yellow glazed titles bordered in green (Fig. 1). Chengguang Hall is the main structure on the Round City, a mini castle with the area of only 4,553 m^2 and a round brick wall with about 4 m height on a island in the south of
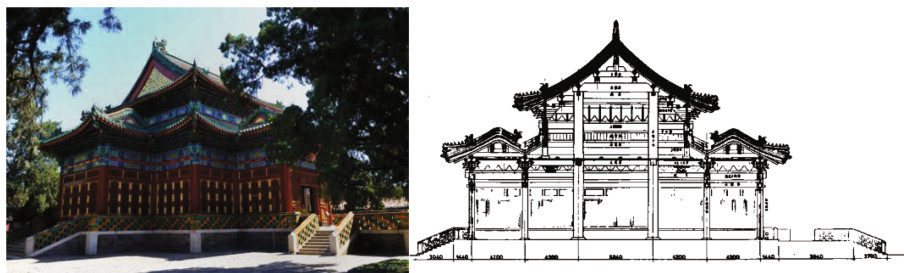
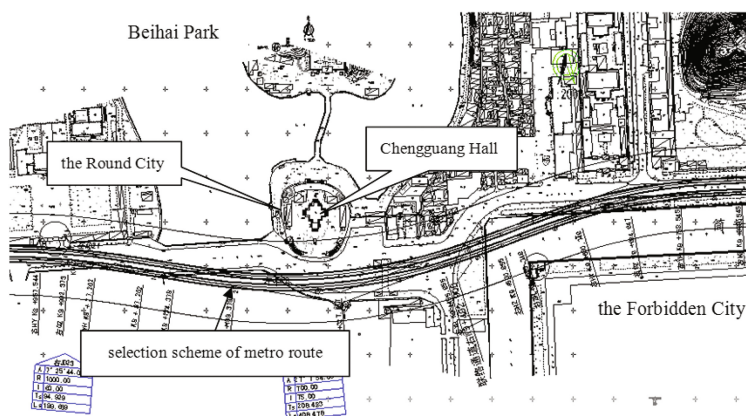**Fig. 1.** A picture and the cross-section of Chengguang Hall

Fig. 2. Layout of planned metro route near the Round City

Beihai Park (Fig. 2). Together with Beihai Park, Chengguang Hall and the Round City were listed as the first batch of national key cultural relics protection units of China in 1961.

2.2 Estimation of Dynamic Characteristic

In order to learn about the dynamic characteristic of a historic building, three methods can be employed: in-situ measurement, numerical simulation and empirical estimation. Here an empirical method was used according to Chinese national code GB/T50452 (2008). The first, second and third natural frequencies f_i can be estimated by:

$$f_i = \frac{1}{2\pi H} \lambda_j \psi \tag{1}$$

where H is the total height of a core column; ψ is a stiffness factor, and for a timber frame hall built on a massive platform foundation, a statistical value suggests $\psi = 43$ m/s; λ_j is a calculation factor for the j-th natural frequency, which depends on the

structural dimension and can be determined by an empirical table from GB/T50452 (2008). According to the surveying and mapping of Chengguang Hall by Ma et al. (1987), the calculation factors can be determined as $\lambda_1 = 1.79$, $\lambda_2 = 4.76$ and $\lambda_3 = 7.76$, and the natural frequencies can be calculated as $f_1 = 1.16$ Hz, $f_2 = 3.09$ Hz, $f_3 = 5.03$ Hz.

The horizontal maximum peak particle velocity (PPV) of a timber structure can be estimated by

$$V_{\max} = V_r \sqrt{\sum_{j=1}^{3} \left(\gamma_j \beta_j \right)^2} = V_r D \qquad (2)$$

where V_r is the horizontal PPV at the foundation of the building, γ_j and β_j are the participating factor and dynamic amplifying factor of the j-th vibration mode, respectively. D is the total dynamic amplification factor, which can be determined as 2.565 by empirical table from GB/T50452 (2008).

3   Prediction of Train-Induced Vibration

As a selection scheme of a metro route is planed to be built near to the Round City (Fig. 2). To predict the vibration responses of both the Round City and Chengguang Hall, two 3D FE models were built - one used for calibration and the other used for prediction. The prediction model includes the twin tunnels, soil layers, the Round City and the foundation of Chengguang Hall. Nevertheless, the timber structure of Chengguang Hall was not taken into account, due to the difficulties to model the timber structures which mentioned in introduction. Instead, the estimated dynamic amplification of the structure was used here.

3.1   3D FE Models

Two 3D FE models were built (Fig. 3). One was used for calibration, whose model dimension and input soil parameters were from Beijing metro line M4. The other was used for prediction, whose input soil parameters were from the core drilling data near the Round City. The input wave velocities for both models were plotted in Fig. 4. In the Beijing M4 where the calibration measurement was performed, the train speed is approximately 40 km/h, and the floating slab track (FST) with steel springs is installed. In the planned metro line near the Round City, the train speed and the parameters of FST keep the same. A train-FST track model was built, from which the supporting forces of the steel springs were obtained, and then applied on the concrete invert in tunnels.

3.1.1   Simulation of Moving Train Loads
To calculate the moving train loads, a MATLAB based program STFSTI (Simulation of Train/Floating Slab Track Interaction) was used. This program was developed by
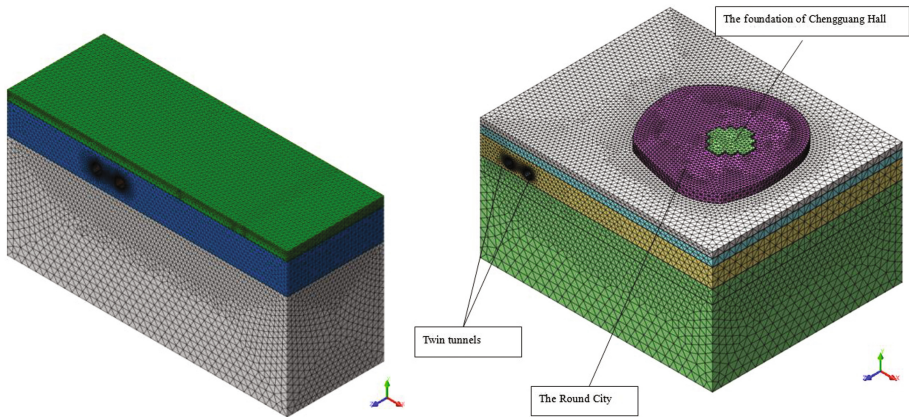
Fig. 3. Calibration model (left) and prediction model (right)
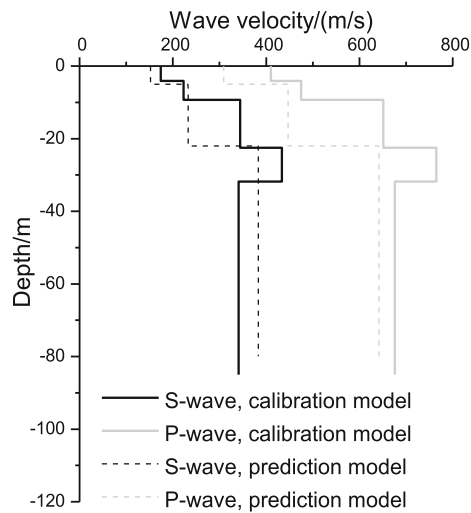
Fig. 4. The input wave velocities for FE models

Beijing Jiaotong University (BJTU) (Ma 2014; Liu et al. 2016). The modeling in STFSTI is restricted in two dimensions. The vehicles are modeled by a mass-spring system that consists of one car body, two bogies and four wheels, all of which are rigid bodies and connected to each other by the secondary and primary suspensions. The floating slab track model is based on periodic-infinite structure theory. The rail is modeled by an infinite Euler beam, and the floating slab is modeled by Euler beam with finite length. Within each length of a floating slab, there are N_r fasteners and N_s steel springs, with a distance of d_r and d_s (Fig. 5). The calculation of this program is performed in frequency domain and the output is analytical solution. The contact wheel/rail forces are modeled by a Hertzian contact spring.
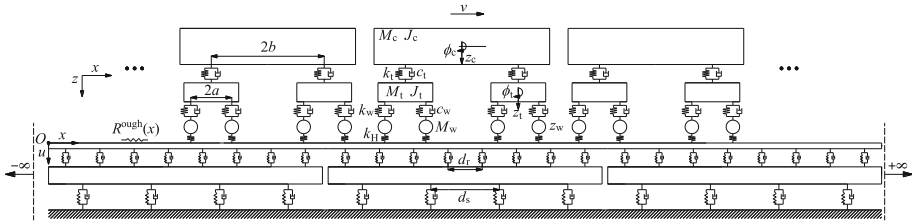
Fig. 5. Schematic of dynamic train-track model

The dynamic forces under the p-th steel spring of j-th floating slab can be calculated by:

$$\hat{F}_{j,p}(\omega, \omega_l) = \frac{(k_s + ic_s\omega)}{2}\hat{u}_s(x_{j,p}, \omega, \omega_l) \tag{3}$$

where $\hat{u}_s(x_{j,p}, \omega, \omega_l)$ is the displacement response at the p-th steel spring of j-th floating slab; $x_{j,p}$ is the coordinate of the $\hat{u}_s(x_{j,p}, \omega, \omega_l)$; k_s and k_p are the stiffness and damping of the spring, respectively.

According to the periodic-infinite structure theory, the displacement can be expressed as:

$$\hat{u}_s(x_{j+1,p}, \omega, \omega_l) = e^{i(\omega_l-\omega)L/v}\hat{u}_s(x_{j,p}, \omega, \omega_l) \tag{4}$$

Then, under the wheel/rail forces $\bar{Q}_k^{wr}(\omega_l) = e^{it\omega_l}$ ($k = 1, 2, \ldots, m_w$), the forces are also abided by the periodic condition:

$$\hat{F}_{j+1,p}(\omega, \omega_l) = e^{i(\omega_l-\omega)L/v}\hat{F}_{j,p}(\omega, \omega_l) \tag{5}$$

Finally, by the principle of superposition, the total force can be expressed as:

$$\hat{F}_{j,p}(\omega) = \sum_{l=0}^{N_R} \hat{F}_{j,p}(\omega, \omega_l) \tag{6}$$

### 3.1.2   In-Situ Measurement and Model Verification

Figure 6 shows the comparison of measurement and calculation results, in time history and in one-third octave bands. The measurement results are chosen from BJTU's database of railway vibration, which is the vertical ground velocity 30 m away from the central line of the shield tunnel of M4. The train speed was approaching 40 km/h and the track is steel spring FST.
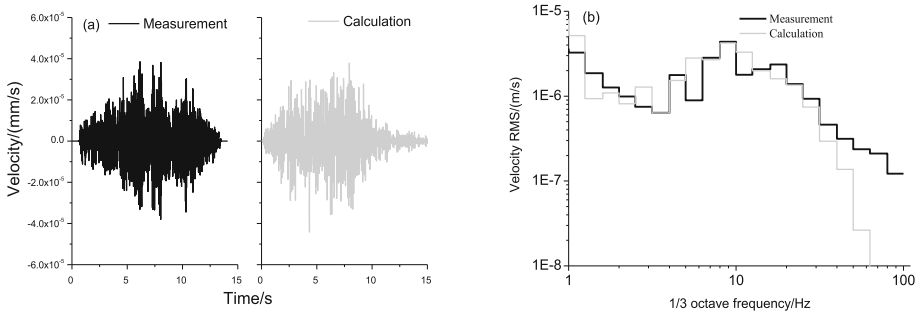
Fig. 6. Comparison of measured and calculated results: (a) time history; (b) 1/3 octave band

3.2 Prediction of Vibration Responses

Two conditions are considered herein: one is a train running in the tunnel near the Round City, and the other is two trains running in both tunnels at the same time. Figure 7 shows the vertical velocities of the foundation of Chengguang Hall and the Round City when the two trains operate in the both tunnel at the same time. It shows the maximum PPV is 0.146 mm/s. Besides, on the top of the city wall, vibrations do not attenuate monotonously with the distance to the source. The existence of the foundation affects the vibration field around it.
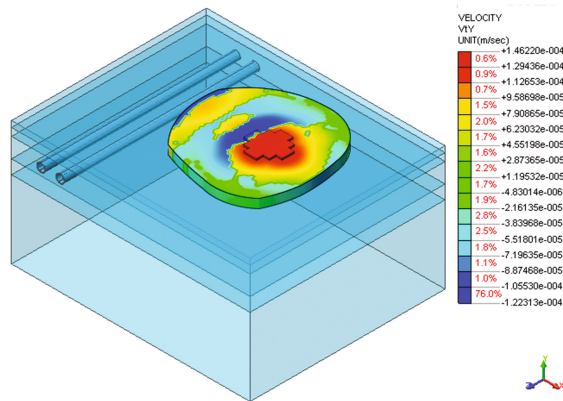
Fig. 7. Vertical velocity of the foundation of the hall and the Round City

Figure 8 shows the predicted PPVs. According to GB 50452, the guidance limit for the Round City and Chengguang Hall are 0.20 and 0.15 mm/s, respectively, considering the building protection against architectural damages. When predicting the vibration of timber structure, the total dynamic amplification factor D is introduced. It can be found that, the vibration response can satisfy the protection limit of the Round City. Nevertheless, the horizontal vibration of the timber structure exceeds the limit
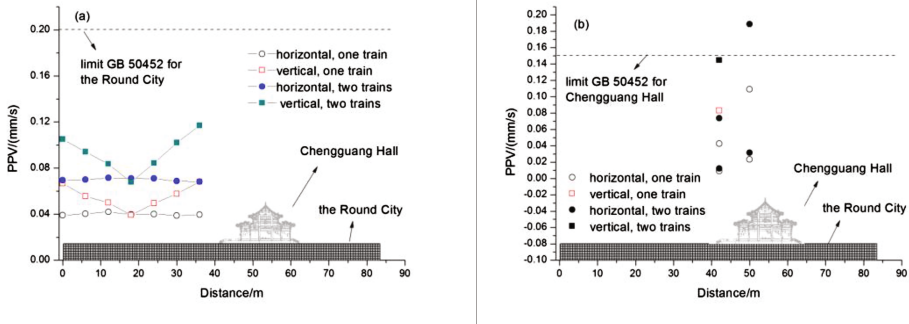
Fig. 8. Vibration responses of (a) the Round City and (b) Chengguang Hall

under condition of two-train operation. In reality, the predicted responses are only the vibration induced by metro trains. If the contribution of road traffic is considered, the total responses will be larger.

4 Conclusions

In this study, a case study of train-induced vibration impact on historic buildings was introduced. By the empirical estimation of the dynamic behavior of the timber structure and numerical prediction, the following conclusions can be drawn:

(a) By comparison of the ground vibration of the calibration model, the FE model can be accepted;

(b) Even if the FST is used, train-induced vibration can still be a potential problem against long-term protection for the timber structure; it is suggested that the metro route should be optimized.

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