PAPER

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Ground microtremor test in shaking table experimental investigation on the steel corrugated utility tunnel

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Abstract. Shaking table test is an important method to study the seismic performance of structures. The accuracy of the test model which is designed based on the similarity ratio theory has a crucial impact on the reliability of the shaking table test results. In this paper, a steel corrugated utility tunnel model was made. Before it was fixed to the shaking table, the natural frequency of the model structure was measured by ground microtremor test, and the natural frequency of the prototype structure was obtained by numerical simulation. The ratio between test value and simulate value was calculated and compared with a pre-set similarity ratio to verify the accuracy of the model. The results demonstrate that the natural frequency of the model structure could be effectively obtained by ground microtremor test. The method of comparing frequency can comprehensively evaluate whether there gets some problem in designing and manufacturing the model structure. This paper can provide some references for the preliminary model design and preparation of the shaking table tests.

1. Introduction

In the field of earthquake engineering, the main experimental methods for seismic performance of structures include the following categories: 1. Monotonic loading static test; 2. Low cycle repeated loading static test; 3. Pseudo-dynamic test; 4. Shaking table test; 5. In-situ test. The shaking table test could reproduce the earthquake process well and therefore, it is the most direct way to examine the seismic responses and mechanic properties of the structure [1]. The principle of shaking table test is that firstly, the model structure is designed and made according to the similarity ratio, after it is fixed to the shaking table, under the input of seismic records or artificial waves, the dynamic responses of the model structure can be collected by different kinds of sensors. Finally, results tested by the model structure can be reversed to the prototype structure based on the similarity ratio. According to what mentioned above, the similarity ratio using for designing the test model is an important parameter that determines the reliability and authenticity of the shaking table test results. After years of research, the most commonly used similarity theory is Dimensional Analysis Method [2]. There are three basic control parameters, the first one is called similarity ratio of length, symbolized as S_l, which is used to control the size of the model structure; The second one is similarity ratio of elastic modulus, symbolized as S_E, which is determined according to the material of the model and prototype structure; The last one is similarity ratio of acceleration, symbolized as S_a, which is used for controlling the dynamic factors of model structure and shaking table tests, such as frequency, symbolized as S_ω, could be obtained as follows:

$$S_\omega = S_l^{-0.5} \cdot S_a^{0.5} \quad (1)$$

When designing and making a model structure, it is obviously very difficult to satisfy all similarity relations. Focusing on several key parameters, it is important to verify the accuracy of the test model. Natural frequency, which is only related to the stiffness and mass, is an intrinsic property of the structure. It can reflect the overall characteristics of the structure.

The microtremor was first observed and proposed by omori [3]. It is defined as the stable non-repetition random vibration of the ground. The ground microtremor is mainly produced by natural sources, such as the wind, ocean waves, volcano activities, and artificial sources such as traffic and machinery. It usually includes short-period micromotion and long-period micromotion [4]. Because of the richness of the period of the micro-vibration, the natural frequency of the structure could be excited and tested. At the same time, the displacement caused by ground microtremor is usually limited to a few microns, therefore, using ground microtremor to test the natural frequency of the structure would not cause any damage to the structure.

In this paper, a method to evaluate the accuracy of the model structure was proposed. Based on the shaking table test of steel corrugated utility tunnel, the natural frequency of the model structure was measured by ground microtremor test before it was fixed on the shaking table. The prototype structure's natural frequency was calculated through numerical simulation. By comparing the frequency ratio between test and simulation with the pre-set similarity frequency ratio, the accuracy of the model structure was evaluated.

2. Experimental setup

2.1. Model similarity ratios

The similarity ratio of length was determined according to the following factors: 1. One circular section urban utility tunnel with a diameter of 5m (marked as D_p) under construction in China; 2. The single shaking table with both sides length of 2m; 3. The bearing capacity and the power output limitation of single shaking table. Finally, the model structure was determined as a circular section utility tunnel with a diameter of 400mm (marked as D_m). Therefore, S_l was determined as follows:

$$S_l = D_m/D_p = 1/8 \quad (2)$$

The model structure was made of Q235 steel plate, the material was same as that used in prototype structure, so S_E was determined as follows:

$$S_E = 1 \quad (3)$$

According to the characteristics of urban utility tunnel [5-7], which is the long linear underground structure, and the dynamic parameters of the shaking table, S_a was taken as 2.

According to those three basic parameters, other similarity ratios were calculated and listed in table 1.

Table 1. Similarity ratios of the model structure.

Types	Physical Quantities	Similitude Relations	Model Structure
Geometry Properties	Length	S_l	1/8
	Linear displacement	$S_r = S_l$	1/8
Material Properties	Equivalent density	$S_\rho = S_E/(S_a \cdot S_l)$	4
	Elastic modulus	S_E	1
Dynamic Properties	Mass	$S_M = S_\rho \cdot S_l^3$	1/128
	Frequency	$S_\omega = S_l^{-0.5} \cdot S_a^{0.5}$	4
	Acceleration	S_a	2
	Duration	$S_t = 1/S_\omega$	0.25

2.2. Utility tunnel model

According to the similarity theory, the experimental model structure was designed and fabricated by prefabrication method. It consisted of three parts, each of which was connected by 13 high-strength 8.8 M16 bolts. The model structure is shown in figure 1.

Figure 1. Model Structure.

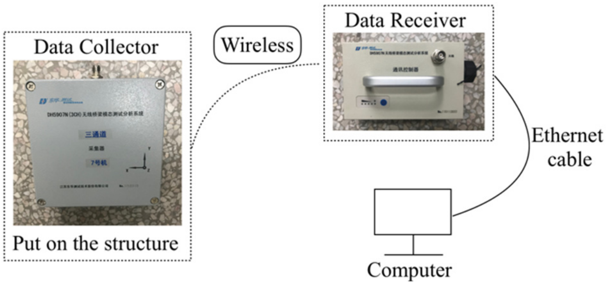


Figure 2. Sensor and data collection system.

2.3. Data collection and processing

Since the ground microtremor is very weak, it is necessary to use a high-precision sensor to capture the response signal of the structure under the excitation of ground microtremor. Compared to accelerometer, velocity sensor could measure tiny motion signal more precise.

The data was collected and analyzed by DH5907N Wireless Bridge Modal Test and Analysis System produced by Donghua Testing Technology Co., Ltd. It consists of a data collector and a data receiver. The data collector can separately acquire velocity signals in horizontal and vertical directions. The sensor has two sensitivity levels, the specific parameters are shown in Table 2.

Table 2. Sensitivity parameters of the sensor.

Types	High Sensitivity	Low Sensitivity
Velocity Range (mm/s)	6mm/s-600mm/s	0.12mm/s-12mm/s
Frequency Range (Hz)	0.13Hz-39Hz	0.8Hz-39Hz

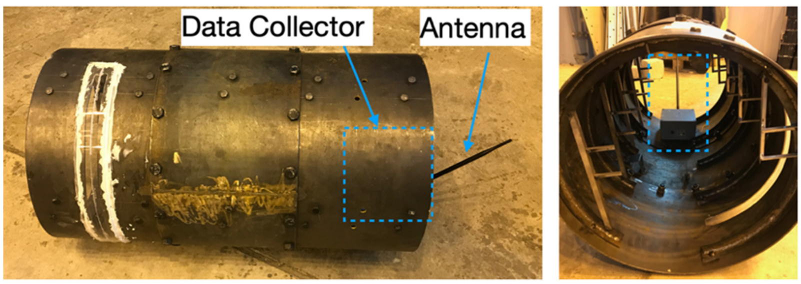
The ground microtremor tests were divided into two conditions. The first condition (Case 1) was directly put the model structure on the ground (see figure 3 (a)). The second condition (Case 2) was that measure the natural frequency after the model buried into the soil container (see figure 3 (b)). The completed models are illustrated in figure 3.

For the acquired velocity signal, it was converted into an acceleration signal by using Central Difference Method [8]:

$$y(k) = \frac{x(k+1) - x(k-1)}{2\Delta t} \quad (k = 1, 2, 3, \dots, N) \tag{4}$$

Where $\{x(k)\}$ $(k = 1, 2, 3, \dots, N)$ is the discrete data of velocity signal, $y(k)$ is the acceleration signal, Δt is the time step.

Then perform Fast-Fourier Transform (FFT) on acceleration signal and Frequency-Amplitude curve is obtained.



(a) Case 1.

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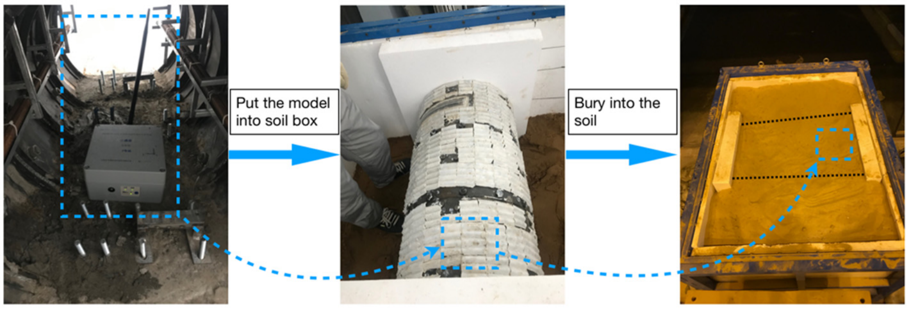


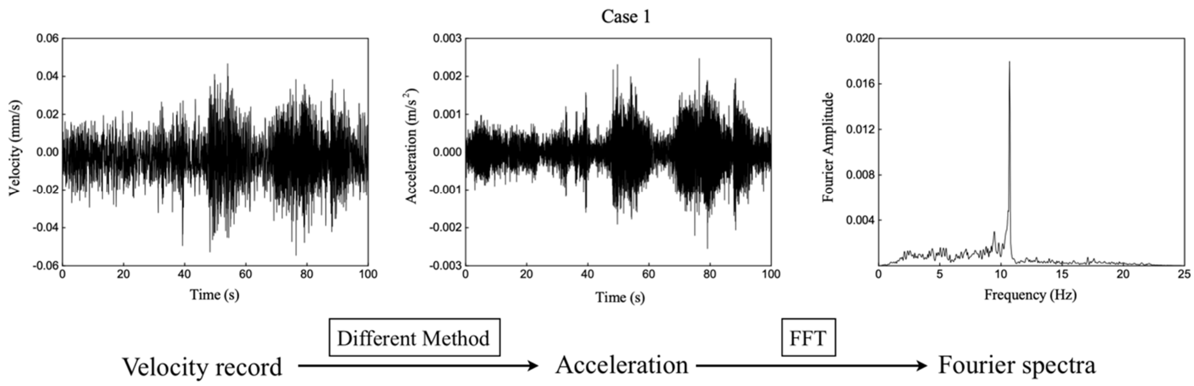
(b) Case 2.

Figure 3. Completed model site. (a) Case 1. (b) Case 2.

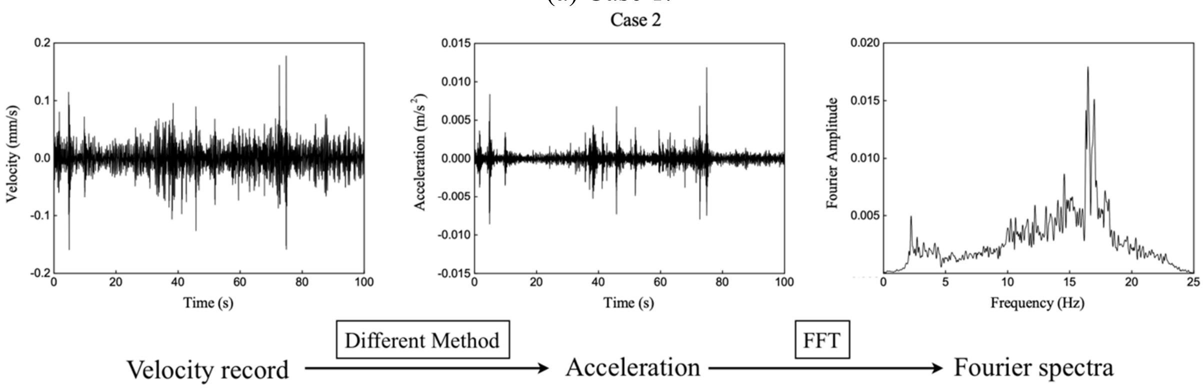
3. Results and discussion

3.1. Experimental results

The velocity record, acceleration signal and Fourier spectra of case 1 and case 2 are presented in figure 1 (a) and (b), respectively.



(a) Case 1.



(b) Case 2.

Figure 4. The velocity record, acceleration and Fourier spectra. (a) Case 1. (b) Case 2.

3.2. Numerical simulation

In order to estimate the prototype urban utility tunnel's natural frequency, 2D time domain analysis was conducted. The ground was modeled as 2D finite elements (CPE4), and the Mohr-Coulomb model was selected as constitutive model. The structure was modelled as a set of shell elements. The structure was set of circular section urban utility tunnel with a diameter of 4m, a wall thickness of 5mm and an overlying soil thickness of 1.5m. The natural frequencies of the structure simulated by ABAQUS are shown in Table 3, and the first-order mode is presented in figure 5.

Table 3. Natural frequencies from numerical simulation

Order	Natural Frequencies (Hz)
First-order	5.3795
Second-order	7.7825
Third-order	7.9254
Forth-order	8.3299
Fifth-order	10.0780

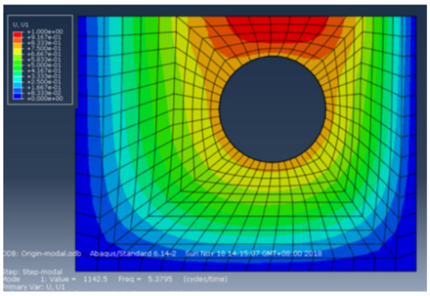


Figure 5. The first-order model

3.3. Discussion

Figure 4 (a) and (b) illustrate that the natural frequencies between structure itself and structure-surrounding soil are quite different. When put the model structure on the ground, the natural frequency equated to 10.8Hz and its amplitude was much larger than that of other frequency ranges. When put the model structure into the soil container and buried with soil, the natural frequency was 17.4Hz. It was because that the boundary condition and the surrounding environment changed. It should be noted that the result measured in case 2 was closer to the natural frequency of the soil container-soil-structure as a whole obtained by the white noise sweep in the shaking table tests. Therefore, for underground structures, simulating their boundary condition could make the result more precise when performing ground microtremor test.

Figure 4 (b) and figure 5 illustrate that the ratio of natural frequency of model structure and prototype structure equals to 3.23, compared with the similarity ratio of frequency, which equals to 4, considering the inevitable noise interference in ground microtremor test and the partial simplification of the modeling of structure in the numerical simulation, we think that the values of those two are similar. That means there was no obvious defect in the design and fabrication of the model structure, and the subsequent shaking table test results would be highly credible.

4. Conclusion

In this study, the accuracy of the model design and fabrication was verified by the ground microtremor test before the model was fixed to the shaking table. The conclusions are as follows:

（1）In the processing of model design, due to the complexity of the structure, it is usually difficult to fully satisfy all the similarity relations. Therefore, the method of comparing frequencies using ground microtremor test can comprehensively evaluate whether there is any problem in the design and manufacture of the model structure.

（2）The frequency ratio of the model structure measured by ground microtremor test in case 2 and calculated by numerical simulation equals to 3.24, that is close to the pre-set similarity ratio of frequency, which equals to 4, so the design of the model can be considered accurate in this test. In other words, if the frequency ratio between test and simulation is similar as the pre-set similarity frequency ratio, then the accuracy of the test model can be proved; else, the test model or design similarity relation needs to be adjusted. For example, increasing or decreasing the weight of the model, adjusting the pre-set acceleration similarity ratio and etcetera.

（3）The natural frequency obtained from the model inside the model box was much closer to the natural frequency from the shaking table test than when it was on the ground. This indicates that the boundary condition holds very crucial significance for this experiment. Hence, to improve the result accuracy of the ground microtremor test, boundary condition cannot be underestimated.

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