Physical Modelling in Geotechnics

Centrifuge modelling of vibration propagation via pile foundations in sand ground

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ABSTRACT: With the rapid development of urban traffic, the negative impact of traffic-induced vibration on human life and urban activities has become increasingly prominent. The vibration generated by the overhead traffic propagates into the deep ground through the pile foundation, which will impact the underground structure and the facilities it contains. This paper presents an experimental study using centrifuge model tests undertaken at a beam centrifuge at 80 g to provide insight into the vibration propagation via pile foundation in sand. The vibration acceleration and coherence coefficient at some particular point in the model is compared and analyzed. The results show that at pile toe, the energy of the vertical vibration decreases with the increase of the propagation distance, and the attenuation of the vertical vibration higher than 40 Hz is faster than that with vertical vibration lower 40 Hz portion. If there is a tunnel near the pile, the vertical vibration generated by the pile will be attenuated to a certain extent during propagating from the sand outside the tunnel to the tunnel's floor. The high-frequency part attenuates more than the low-frequency part. The insights obtained from this study can provide a valuable reference for the vibration reduction design of underground structures.

Keywords: Vibration propagation, Pile foundations, Underground structures, Centrifuge modelling.

1 INTRODUCTION

Vibration is inevitable in the operation of urban traffic systems. With the development of urban traffic, traffic-induced vibration has become one of the factors affecting the urban environment. Traffic-induced vibration will affect the natural environment, building structures, and machinery equipment and harm people's physical and mental health. In geotechnical engineering, traffic-induced vibration is transmitted into the ground as ground-borne vibration, affecting the underground structure and internal facilities it contains.

Many centrifuge tests have been conducted to model traffic-induced vibration and examine the effectiveness of vibration countermeasures. The key of this kind of test is vibration source simulation, noise control, and data acquisition. Luong (1994) developed an in-flight ball-dropping system to study surface wave propagation. A steel ball was pushed and fell vertically on the soil surface to generate surface waves. Based on the above method, Itoh et al. (2002) developed a multiple ball-dropping system to simulate the vibration from the high-speed train, which could realize the simultaneous generation of vibration at a single or multi-point in-flight. Sponge rubber was laid on the sides and bottom of the container to reduce wave reflection from the rigid boundaries of the model.

Murillo et al. (2009) added an optical sensor to capture the position of the steel ball based on the ball-dropping system and began to collect data when the steel ball reached a specific position to reduce the amount of data collected. Murillo also tested the noise in the container while the centrifuge was running, Fourier transform was applied to obtain and filter the main frequency ranges of the noise.

The ball-dropping system can simulate different vibration sources by adjusting the steel ball's mass, falling height, and inclination. However, it cannot accurately control the frequency range of the vibration source. Itoh et al. (2005) used a vibration shaker to simulate high-speed train-induced vibration and studied wave propagation characteristics in a shallow circular foundation in sand. The vibration amplitude, frequency range, and duration can be easily controlled using the shaker to simulate the traffic-induced vibration realistically.

Yang W (2012) used an electromagnetic shaker to simulate traffic-induced vibration and placed 20mm thick Duxseal on the sides and bottom of the model container. Duxseal, a material used to seal out water, dust, and air, is considered by some scholars to be an effective material for absorbing stress waves near model boundaries.

In the above studies, the vibration of ground traffic is transmitted from shallow foundation to underground. The vibration of overhead traffic goes deep into the ground through pile foundation, and its propagation may be different from that of shallow foundation.

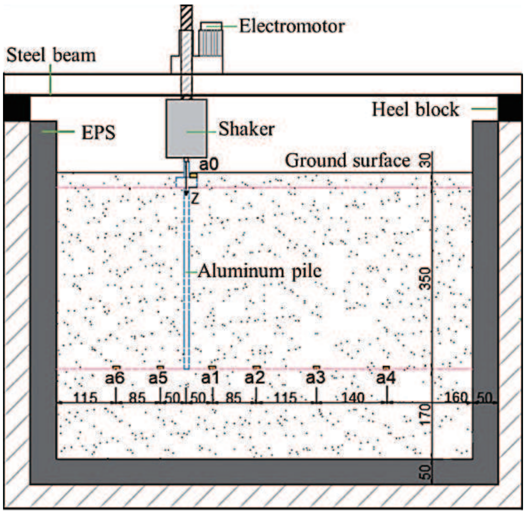

Fig. 1. The model layout of Test I (dimensions in mm).

Cui G (2018) applied the excitation force to the top of an aluminum pile by using a shaker to model the vibration of the pile foundation caused by the train. Cui G's research focused on improving the signal-to-noise ratio of the test model by adopting a variety of methods rather than vibration propagation via pile foundation.

In this study, centrifugal model tests were used to study the propagation of traffic-induced vibration via pile foundation in the sand ground. On this basis, a model tunnel was buried into the foundation to study the influence of the existence of the tunnel on the propagation of ground-borne vibration.

2 EXPERIMENTAL SETUP

2.1 Centrifuge modelling

The tests presented in this paper were carried out at an acceleration level of 80 g. The geotechnical centrifuge used belongs to Tongji University in China. The substantial container designed for the centrifuge has an internal dimension of 0.9 m × 0.7 m × 0.7 m (length × width × height). To reduce the reflection of the wave from the rigid boundaries of the model container, 5cm thick Expanded Polystyrene (EPS) was attached on the sides and bottom of the container.

Fujian standard sand, one type of quartz sand widely used in laboratory experiments in China, was used to ensure the comparability of the test results with other studies. The sand was dry pluviated to achieve a relative density of 80% using a sand pourer.

2.2 Model configuration

Two centrifugal model tests were carried out in this study. The model layout and instrument location of Test I are shown in Figure 1.

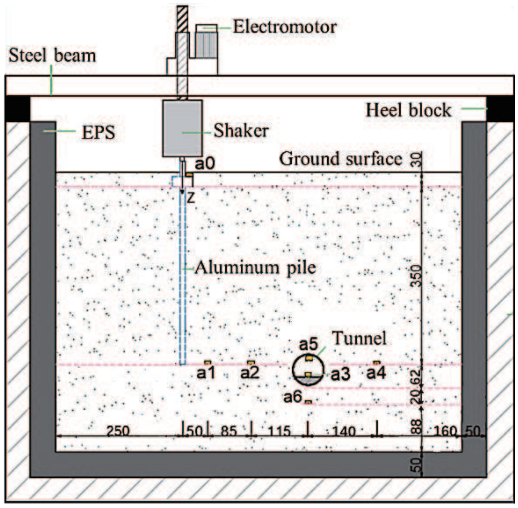

Fig. 2. The model layout of Test II (dimensions in mm).

An aluminum model pile, 350 mm in length, 10 mm in diameter, and 20 mm in the height of the cap (28 m, 0.8 m, and 1.6 m at prototype scale) was used to simulate the pile foundation of overhead traffic. The electromagnetic shaker generated the excitation force, which propagated from the top of the aluminum pile into the sand foundation.

The sand in this model compressed in the centrifugal field, which would drag the aluminum pile to move downward. If the position of the shaker was fixed, the end of the force lever of the shaker would be separated from the top of the aluminum pile so that the input of excitation force cannot be realized. To solve this problem, an electromotor fixed on the steel beam was introduced into the system, and the shaker was set on the movable rod powered by the motor. By controlling the motor to push the rod down, the force lever of the shaker can maintain contact with the pile top in-flight.

Seven sensors were employed to measure the vertical acceleration of the pile in Test I. One acceleration sensor was buried on the cap of the aluminum pile to measure the vibration input of the system, marked as a_0. The other acceleration sensors were buried on the horizontal plane of the pile toe and marked as $a_1 \sim a_6$, respectively. The acceleration sensors a_1, a_5, a_2, and a_6 were buried symmetrically about the aluminum pile, respectively, to analyze the wave reflection from the boundary.

In Test II, an aluminum model tunnel was embedded to the sand with a burial depth of 360 mm (28.8 m at prototype scale) and a distance of 250 mm (20 m at prototype scale) from its central axis to the pile, as shown in Figure 2. The model tunnel was designed with an outer diameter of 82 mm (6.56 m at prototype scale), an inner diameter of 78 mm, a length of 200 mm, and a floor height of 20 mm. The position of the acceleration sensors

a_1, a_2, and a_4 was still the same as that in Test I. To test the vibration inside the tunnel, a_3 and a_5 were arranged at the floor and top center of the tunnel, respectively.

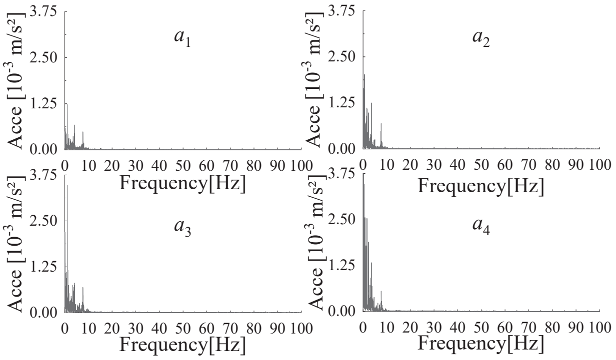

Fig. 3. The frequency range of background noise.

2.3 Vibration input and output

The frequency of traffic-induced vibration is mainly in the range of 0-100 Hz (0-8000 Hz in model scale), so a shaker with a maximum working frequency of 15 kHz was introduced in this study. Excitation force was applied to the model only when excitation signals were given to the shaker. The commonly used excitation signals in the research include burst random, pseudo-random, and sine chirp (Avitabile, 2001). A sine chirp signal was adopted in this experiment to avoid spectrum leakage during data transformation. When the model was loaded to 80 g, the signal source was controlled to provide the shaker with 160 seconds (the duration and the excitation voltage provided are reasonable values confirmed by pre-experiment) sweep signal in the range of 0-8000 Hz, and the data of the sensor was recorded at the same time. A National Instruments acquisition card (NI-9231) was used to provide up to 8 synchronous acquisition channels, and the capable sampling rate of a single channel was 51.2 kHz, exceeding Nyquist frequency.

To reduce background noise interference to test results, a preliminary experiment was conducted based on Test I without applying exciting force. The acceleration measured is shown in Figure 3 after the discrete Fourier transform (the frequencies in the figures are all prototype values). The frequency range of background noise is concentrated within 10 Hz (800 Hz in model scale). Therefore, the cut-off frequency of the high-pass filter was set as 800 Hz in formal tests.

3 TEST RESULTS

The frequency response functions (FRFs) of the symmetrical position on both sides of the aluminum pile in Test I are shown in Figure 4. The FRFs of a_1 and a_5 almost coincide, while the FRFs of a_2 and a_6 coincide well in most frequency ranges, which indicates that the boundary wave reflection of the model container is weak and EPS could well absorb vibration.

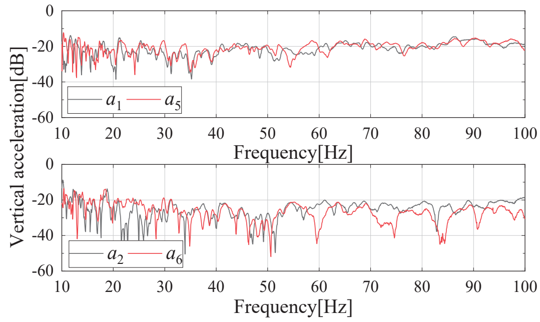

Fig. 4. FRFs comparison of symmetric positions for Test I.

The coherence coefficient between the vibration input (a_0) and accelerations in the soil (a_1 to a_4) are shown in Figure 5. The coherence values of most frequency range from a_1 to a_4 is close to 1, indicating that the signal-to-noise ratio (SNR) is high, and the closer the sensor to the vibration source, the higher the SNR. Even the most remote sensor, a_4, has low SNR only at a few frequencies above 70 Hz.

The FRFs at each measuring point in Test I are shown in Figure 6. Taking the vibration at a_0 as the comparison benchmark, the vertical vibration attenuates about 20 dB when it propagates from pile toe to a_1 (4 m at prototype scale) and 25 dB when it propagates to a_2. At a_3, the vibration frequency below 40 Hz is attenuated by about 25 dB, and the frequency above 40 Hz is attenuated by about 28 dB. At a_4 (31.2 m at prototype scale), the vibration frequency below 40 Hz is attenuated by about 25 dB, and the frequency above 40 Hz is attenuated by about 30 dB. The above results show that when the vertical vibration transmitted by the pile propagates along the pile toe plane in the sand foundation, the vibration gradually attenuates with the propagation distance, and the high-frequency part attenuates faster than the low-frequency part.

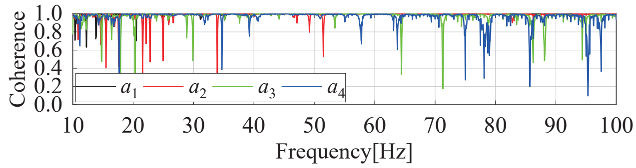

Fig. 5. Coherence values between a_0 and a_1-a_4 in Test I.

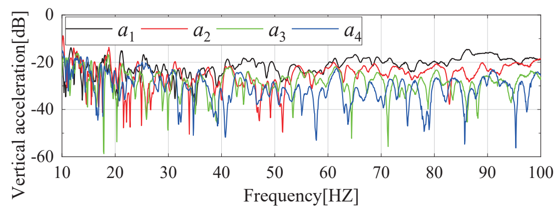

Fig. 6. FRFs of a_1-a_4 in Test I.

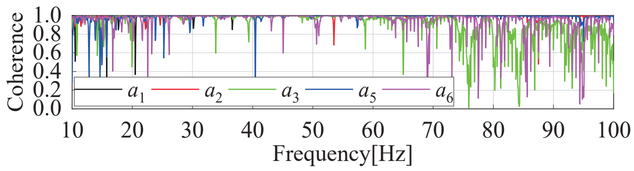

Fig. 7. Coherence values between a_0 and a_1-a_6 in Test II.

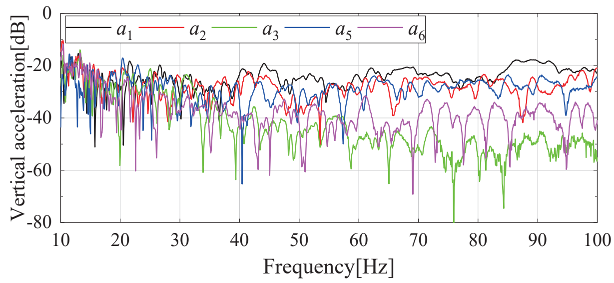

Fig. 8. FRFs of a_1-a_6 in Test II.

Similar to test I, the processed results of Test II are shown in Figures 7 and 8. Sensor a_4 failed in the experiment, so there is no corresponding data. As shown in Figure 7, sensors a_1, a_2, and a_5 have high SNR, while sensors a_3 and a_6 have low SNR at frequencies higher than 65 Hz. As background noise and model boundary hardly affect the vibrations, the significant difference in the SNRs of a_3, a_5 and a_6 indicates that the existence of the tunnel affects the vibration propagation at different positions around and inside the tunnel to varying degrees.

The vibration propagation outside the tunnel (at positions a_1, a_2, and a_6) shown in Figure 8 is similar to Test 1: the vibration gradually attenuates as the distance increases, and the high-frequency part attenuates faster than the low-frequency part. When the vibration propagates into the tunnel, the vibration acceleration of a_5 (at the top of the tunnel) is closer to a_2. In contrast, a_3 (at the tunnel floor) has a more considerable vibration attenuation: about 25 dB in the frequency range of 10-35 Hz, about 40 dB in 35-60 Hz, and about 50 dB in 60-100 Hz. The above results show that when the vibration transmitted by the pile propagates into the tunnel near the pile toe plane in the sand foundation, the vibration is basically uninfluenced at the top of the tunnel compared with that at the vicinity of the tunnel. In contrast, the vibration at the tunnel floor is more seriously attenuated.

The FRFs of a_3 versus a_1 are plotted for both tests, as shown in Figure 9. Most of the curves fit well in the 10-40 Hz frequency range, while in the 40-100 Hz, the FRF curve of Test I is above that of Test II, and the difference between the two is about 20 dB. This shows that the tunnel near the pile toe plane and 20 m away from the pile toe will hardly affect the vibration below 40 Hz transmitted by the pile. Still, at the tunnel floor, the existence of the tunnel will reduce the 40-100 Hz vibration transmitted by the pile to one percent of that without the tunnel.

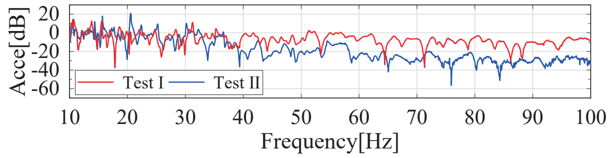

Fig. 9. FRFs of a_3 / a_1 for Test I and Test II.

4 CONCLUSIONS

This paper presents an experimental study to provide insight into the vibration propagation via pile foundation in the sand. The main conclusions drawn in this study are:

1. When the vertical vibration transmitted by the pile propagates along the pile toe plane in the sand foundation, the vibration gradually attenuates with the increase of the propagation distance, and the attenuation of the vertical vibration higher than 40 Hz is faster than the lower 40 Hz portion.

2. When the vibration transmitted by the pile propagates into the tunnel near the pile toe plane in the sand foundation, the vibration is almost not attenuated at the top of the tunnel compared with the vicinity of the tunnel. In contrast, the vibration at the tunnel floor is more seriously attenuated.

3. The tunnel near the pile toe plane and 20 m away from the pile toe will hardly affect the vibration below 40 Hz transmitted by the pile. Still, at the tunnel floor, the existence of the tunnel will reduce the 40-100 Hz vibration to one percent of that without the tunnel.

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