In Situ Experiment and Analysis of the Attenuation Characteristics of Environmental Vibrations Based on Frequency Sweep Method

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Abstract. Analysis of the attenuation characteristics of environmental vibrations with different frequencies is of great benefit for preventing many vibration-related problems. This study carried out an in situ experimental study on the attenuation characteristics of a series of single frequency ground vibrations caused by harmonic excitations. An electromagnetic vibration excitation system was adopted to generate harmonic excitations at frequencies varying from 10 Hz to 80 Hz with steps 5 Hz. 5 low frequency, 1 component, 991 vibration sensors fastened on the ground surface were used for the measurement of the vertical velocity time histories of ground vibrations at 5 test points with different distances from the vibration source. The vibration level in terms of the vertical peak particle velocity of single frequency ground vibrations in general decayed monotonically but nonlinearly with distance, however, the attenuations of 15 Hz, 45 Hz, 65 Hz and 75 Hz ground vibrations were oscillatory due to vibration interference on the ground surface. The attenuation of single frequency ground vibrations was more rapid in the zone close to the vibration source than that in the zone far away. This study demonstrates that comparison of the attenuation characteristics of high and low frequency ground vibrations should take into account the difference in the amplitudes of the corresponding ground vibrations.

1. Introduction

Profound knowledge of the attenuation characteristics of environmental vibrations is of great significance in solving various types of vibration-related problems, i.e. damage to adjacent buildings and other structures [1-3], malfunctioning to vibration-sensitive equipment and instruments that are housed in the adjacent high-tech facilities [4, 5], and discomfort to people in the immediate vicinity [6, 7]. For the design of reliable, cost effectiveness and high efficiency measures to prevent such vibration-related problems, it is a great demand to conduct detailed investigations on the attenuation characteristics of ground vibrations by taking account of the difference in the amplitudes of ground vibrations with different frequencies.

The in situ vibration measurement is often adopted as a competitive method to obtain reliable information on the attenuation of ground vibrations. The various studies on the attenuation characteristics of ground vibrations from in situ measurements can be classified into three major categories: measurement and analysis of the attenuations of ground vibrations caused by human activities [8, 9], development of an empirical attenuation model taking proper account of geometric
and material damping of soil [10, 11], and comparison and analysis of the parameters of an empirical attenuation model for different vibration source types or soil types [12, 13].

The literature review reveals that: (1) the attenuation of ground vibrations with an increase in distance from vibration source is nonlinear; (2) the attenuation of high frequency ground vibrations is faster than that of low frequency ones; (3) the attenuation of ground vibrations is more rapid in the zone close to the vibration source than that in the zone far away [11, 14-16]. The attenuation of ground vibrations is caused by geometric and material damping of soil [8, 17]. Geometric damping attenuates the vibration level due to the fact that the same energy spreads over an increasingly larger volume as vibration propagates further from the vibration source [8, 18, 19]. Material damping transforms the vibration energy to internal energy as soil particles are moved by the propagating vibrations, and as the energy is converted and “lost” the vibration level decreases [8, 18, 19]. However, it is difficult to separate the geometric damping and the material damping effects.

A vast body of studies on the attenuation of ground vibrations has been performed based on the broad-band dynamic excitations generated by mechanized construction activities (blasting, dynamic and vibratory compaction, pile driving) [9, 20, 21] or vehicle traffic [22-24]. The attenuation characteristics of the corresponding broad-band ground vibrations were studied in terms of either the time domain amplitudes of the vibration signals (displacement, velocity or acceleration) or the frequency domain magnitudes obtained by transforming the time vibration signals to their conjugate frequency signals.

In situ experiment and analysis on the attenuation of ground vibrations with different frequencies caused by harmonic excitations are limited in literature. The objective of this study is to increase the knowledge and understanding in the field of ground vibration attenuation, and to provide a series of vibration data that researchers can use for further investigation and for the validation of numerical prediction models. This objective is achieved by carrying out in situ experiment on the attenuation characteristics of ground vibrations with different frequencies generated by harmonic excitations. First, the experimental program of the in situ experiment is briefly recapitulated. Second, the experiment results are analyzed and discussed.

2. Experimental Program

2.1. Site Characteristics

The experiment site locates in northeast Beijing. Many geotechnical and geophysical tests were conducted to characterize the soil. The experimental site is layered soil, as shown in figure 1. The surface is covered with artificial fill layer which are around 2.1 m deep. A compressible sandy gravel layer with a thickness of approximately 21.5 m was found under the artificial fill layer. The bedrock is at 25 m deep and is made of granodiorite.

![Figure 1. Site stratigraphy.](image-url)
The geotechnical parameters of the experimental site, which were determined by geotechnical and geophysical tests, are shown in table 1.

### Table 1. Geotechnical parameters of the experimental site.

| Layer           | Thickness (m) | Density (kg/m³) | Shear velocity (m/s) | Poisson ratio |
|-----------------|---------------|-----------------|----------------------|---------------|
| Artificial fill | 2.1           | 1630-2010       | 172-193              | 0.43-0.46     |
| Sandy gravel    | 21.5          | 2000-2200       | 291-571              | 0.41-0.44     |
| Granodiorite    | —             | 2210-2630       | 684-1200             | 0.4-0.43      |

#### 2.2. Dynamic Tests

A series of harmonic excitations at frequencies varying from 10 Hz to 80 Hz with steps of 5 Hz was provided using an electromagnetic vibration excitation system to generate ground vibrations. The duration of the harmonic excitation at each frequency was 40 s. The excitation system mainly contained four elements: a signal generator, a power control cabinet, an electromagnetic exciter, and an air-cooled machine, as shown in figure 2.

![Figure 2. The electromagnetic vibration excitation system.](image)

The harmonic excitations with different frequencies were generated by the up-down movement of the exciter actuator with one on-board accelerometer. The accelerometer, which was connected to a data acquisition unit, was used to record the acceleration time history of the exciter actuator. This allowed for calculation of the dynamic forces of the harmonic excitations with the mass of the exciter actuator. The mass of the exciter actuator is 750 kg.

Under the dynamic forces that were directly imposed on the ground surface by the electromagnetic exciter, ground vibrations were generated and propagated through the soil. 5 low frequency, 1 component, 991B vibration sensors were used to simultaneously record the vertical velocity time histories of ground vibrations at 5 test points (P₁-P₅) at different distances from the vibration source: 10m, 20m, 40m, 60m and 100m, see figure 1.

### 3. Results and Discussion

#### 3.1. Peak Dynamic Force

One of the aims of the in situ experiment was to provide a series of vibration data that researchers could use for the validation of numerical prediction models. One key input parameter used for vibration modelling is the time history of excitation force. For a harmonic excitation, once its peak dynamic force \( F_p \) is known, its force time history \( F \) can be obtained as:

\[
F = F_p \sin(\omega t)
\]
where $\omega$ is the frequency of the harmonic excitation, and $t$ is the time.

The peak forces $F_p$ of harmonic excitations with different frequencies were calculated as:

$$F_p(\omega) = m \cdot \max |a(\omega, t)|$$  \hspace{1cm} (2)

where $m$ and $a(\omega, t)$ are the mass and the acceleration time history of the exciter actuator.

The peak forces of harmonic excitations with different frequencies are shown in figure 3. It should be noted that the vibration excitation system employed in this study contained no feedback system used to in real time adjust the output energies of dynamic excitations based on vibration responses. Thus, the peak forces as shown in figure 3 are incoordinate in the respect of achieving the velocity amplitudes of ground vibrations with different frequencies at test point $P_1$ are the same.

With knowledge of the incooordination in the peak forces of the harmonic excitations, it will become more rational and rigorous to analyze the attenuation characteristics of ground vibrations.

![Figure 3. Peak dynamic forces of harmonic excitations.](image)

3.2. Peak Particle Velocity

The 'peak particle velocity' (PPV) has long been the principal indicator for test and evaluating ground vibrations. The vertical PPVs of ground vibrations at the 5 test points were calculated to evaluate the vibration levels at different distances from the vibration source. The relationship between the distance and the vertical PPVs is plotted in figure 4. The PPVs were calculated from the vertical velocity time histories as:

$$PPV(\omega) = \max |v(\omega, t)|$$  \hspace{1cm} (3)

where $v(\omega, t)$ is the vertical velocity time history of ground vibrations with frequency $\omega$.

![Figure 4. Vertical PPVs plotted against distance.](image)
It is clearly shown in figure 4 that the vibration level of single frequency ground vibrations in general decays monotonically but nonlinearly with an increase in the distance from test point $P_1$. This was as expected and was due to the geometric and material damping effects of soil in this experiment site. It was believed that the geometric damping effect is related with vibration source type and is independent of soil type along the propagation path [14], and the material damping effect is related with the vibration amplitude and soil type [25]. The vertical PPVs of ground vibrations with different frequencies were obviously different at test point $P_1$ due to the incoordination in the corresponding peak dynamic forces. However, the difference in the vertical PPVs was found to decrease with distance from test point $P_1$.

In the in situ experiment, the vibrations caused by the interactions between the exciter and the ground propagated simultaneously along the ground surface and the soil depth. When the vibrations propagated along the depth to the soil interfaces, part of the vibrations was reflected back to the ground surface. Therefore, the measured vibration response at the ground surface was the result of the interference between the propagated vibrations along the ground surface and the reflected vibrations. Such kind of vibration interference was believed to have more or less effect on the attenuation characteristics of ground vibrations [16]. In this in situ experiment, the effect of vibration interference clearly manifested as such an experiment phenomenon that the attenuations of 15 Hz, 45 Hz, 65 Hz and 75 Hz ground vibrations were oscillatory but not monotonic (figure 4).

### 3.3. Attenuation Rate

For the purpose of analyzing and comparing the attenuation characteristics of high and low frequency ground vibrations, the vertical PPV attenuation rates of ground vibrations with different frequency were calculated and shown in table 2. The vertical PPV attenuation rate is defined as:

$$R_{i+1}(\omega) = \frac{PPV_{i+1}(\omega) - PPV_i(\omega)}{D_{i+1} - D_i} (i = 1, 2, 3, 4)$$

where $D_i$ and $D_{i+1}$ are the distances of test points $P_i$ and $P_{i+1}$ from the vibration source.

| Freq. (Hz) | PPV$_1$ (mm/s) | R$_{12}$ ($P_1$-$P_2$) (10m-20m) | R$_{23}$ ($P_2$-$P_3$) (20m-40m) | R$_{34}$ ($P_3$-$P_4$) (40m-60m) | R$_{45}$ ($P_4$-$P_5$) (60m-100m) |
|------------|----------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 10         | 0.020          | -0.713                        | -0.336                        | -0.0425                       | -0.0358                       |
| 15         | 0.072          | -3.87                         | -0.728                        | 0.027                         | -0.1213                       |
| 20         | 0.110          | -4.807                        | -0.9105                       | -0.952                        | -0.286                        |
| 25         | 0.164          | -8.521                        | -1.9175                       | -0.993                        | -0.2463                       |
| 30         | 0.162          | -7.159                        | -1.215                        | -2.2845                       | -0.4825                       |
| 35         | 0.221          | -17.338                       | -1.1835                       | -0.518                        | -0.238                        |
| 40         | 0.197          | -12.512                       | -2.9155                       | -0.247                        | -0.0443                       |
| 45         | 0.141          | -6.342                        | -3.313                        | 0.2085                        | -0.1745                       |
| 50         | 0.179          | -9.929                        | -2.8515                       | -0.5274                       | -0.2101                       |
| 55         | 0.130          | -8.925                        | -0.5215                       | -1.169                        | -0.1088                       |
| 60         | 0.186          | -10.413                       | -0.1155                       | -2.512                        | -0.4905                       |
| 65         | 0.189          | -12.823                       | 0.5415                        | -1.8295                       | -0.6968                       |
| 70         | 0.150          | -4.505                        | -0.8425                       | -3.5065                       | -0.1893                       |
| 75         | 0.143          | -4.104                        | -3.9275                       | 0.0815                        | -0.4068                       |
| 80         | 0.159          | -7.75                         | -1.6455                       | -1.682                        | -0.2778                       |
The definition (4) of attenuation rate indicates that a minus attenuation rate \( R_{ii+1} \) means the vibration level decays when ground vibrations propagate from test point \( P_i \) to test point \( P_{i+1} \), explaining the vertical PPV of ground vibrations at test point \( P_{i+1} \) is smaller than that at test point \( P_i \). Furthermore, the absolute of a minus attenuation rate represents the damping ability of soil to attenuate ground vibrations, thus the greater the absolute of a minus attenuation rate, the more rapid the attenuation of ground vibrations.

It is clearly seen in table 2 that almost all the attenuation rates \( R_{ii+1} \) \((i=1, 2, 3, 4)\) are minus explaining the vertical PPV of ground vibrations at test point \( P_{i+1} \) was smaller than that at test point \( P_i \). For 15 Hz, 45 Hz, 65 Hz and 75 Hz ground vibrations, positive attenuation rates existed because of the oscillation in the attenuations of the corresponding ground vibrations. The attenuation rate \( R_{23} \) of 65 Hz ground vibrations, for instance, was positive explaining such an experiment phenomenon that the PPV of 65 Hz ground vibrations at test point \( P_3 \) was greater than that at test point \( P_2 \).

In the four attenuation rates \( R_{ii+1} \) \((i=1, 2, 3, 4)\) of single frequency ground vibrations, the absolute of the attenuation rate \( R_{12} \) was the greatest one, and the absolute of the attenuation rate \( R_{45} \) was the smallest one. The greater attenuation rate \( R_{12} \) and the smaller attenuation rate \( R_{45} \) demonstrated that the attenuation of single frequency ground vibrations was more rapid in the zone close to the vibration source than that in the zone far away. This might be attributed to the fact that the vertical PPV of single frequency ground vibrations in the zone close to the vibration source was greater than that in the zone far away. Thus, the attenuation effect of soil on ground vibrations, which is amplitude-dependent, was greater in the zone close to the vibration source than that in the zone far away.

The absolute of any one of the four attenuation rates \( R_{ii+1} \) \((i=1, 2, 3, 4)\) of ground vibrations with different frequencies had no specific relationship with vibration frequency. This result indicated that the phenomenon that the attenuation of high frequency vibrations is faster than that of low frequency vibrations was not observed in this study. It may well be that because there was no specific relationship between the vertical PPV and the frequency of ground vibrations at any one of the 5 test points \( P_i \) \((i=1, 2, 3, 4, 5)\), the amplitude-dependent attenuation effect of soil on ground vibrations had no specific relationship with vibration frequency. This result illustrates that future efforts are required to accurately study the relationship between attenuation rate and vibration frequency by maintaining the amplitudes of ground vibrations with different frequencies are the same.

4. Conclusions

Using the harmonic excitations at frequencies varying from 10 Hz to 80 Hz with steps of 5 Hz generated by an electromagnetic vibration excitation system as dynamic loadings, study and analysis on the attenuations of ground vibrations with different frequencies were conducted based on in situ experiment in this study. It can be concluded that:

(1) In general, the vibration level in terms of the vertical PPV of single frequency ground vibrations decayed monotonically but nonlinearly with an increase in the distance from the first test point.

(2) The attenuations of 15 Hz, 45 Hz, 65 Hz and 75 Hz ground vibrations were oscillatory, which indirectly demonstrated that the interference effect between the propagated vibrations along the ground surface and the reflected vibrations existed and influenced the attenuation characteristics of ground vibrations more or less.

(3) In the zone close to the vibration source where large vibration amplitudes were experienced, single frequency ground vibrations decayed more rapidly than in the zone far away where the vibration amplitudes were relatively small.

(4) A notable finding was that there was no specific relationship between any one of the four attenuation rates of ground vibrations with vibration frequency. In other words, the phenomenon that the attenuation of high frequency vibrations is faster than that of low frequency vibrations was not supported by the measurement results in this study.

Because of the amplitude-dependency of the damping effect of soil on ground vibrations, further research needs to be focused on the analysis and comparison of the attenuation characteristics of high
and low frequency ground vibrations by maintaining the amplitudes of ground vibrations with different frequencies the same.

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