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Vibration Response of Soil under Low-Frequency Vibration Using the Discrete Element Method

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Abstract: The vibration response of soil is a key property in the field of agricultural soil tillage. Vibration components of tillage machinery are generally used to reduce tillage resistance and improve work efficiency, and the pressure variation under low-frequency vibration will affect the fragmentation and dispersion of farmland soil. However, the gradient of pressure variation, frequency domain response, and effective transmission range is unclear. A new method based on the DEM (discrete element method) is presented to study the vibration response and pressure transmission under low-frequency vibration. Bench test results have shown that peak pressure positively correlates with the vibration frequency and attenuates rapidly at a vibration distance of 100 to 250 mm. The resulting data were also selected to determine the simulation model's parameters. Amplitude, vibration frequency, and soil depth were used as test factors in single-factor simulation tests, and their effects on the peak pressure, frequency domain response, and effective transmission distance were analyzed. The results showed a positive relationship between the peak pressure and the test factors. The peak pressure increased with a maximum gradient of 19.02 kPa/mm at a vibration distance of 50 mm. The amplitude, vibration frequency, and soil depth positively correlated with the dominant frequency amplitude. The main frequency was independent of amplitude and soil depth. At a vibration distance of 250 mm, the dominant frequency was approximately twice the vibration frequency at 7–11 Hz and approximately equal to the vibration frequency at 13–15 Hz. Multiple exponential functions were used to fit the peak pressure attenuation function, obtaining an effective transmission distance range of 347.15 to 550.37 mm for the 5 kPa cut-off pressure. For a soil depth of 300 mm, the vertical shear wave diffusion angle was greater than the horizontal shear wave diffusion angle. This study clarifies the vibration response of soil under low-frequency vibration, which helps to design vibration-type, soil-engaging components of tillage machinery and match vibration parameters for energy-saving and resistance reduction purposes in soil tillage.

Keywords: soil; low frequency; discrete element method; vibration response; transmission



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1. Introduction

In recent years, the vibration response of soil has become a research hotspot due to the energy-saving and resistance reduction requirements of agriculture for soil tillage. Agricultural machinery with vibration components (vibration subsoilers, vibrating rotary tillers [1], root crop harvesters with vibrating shovels, etc.) is widely used in soil tillage. The driving torque is provided by the tractor output shaft, and the vibration frequency is generally less than 20 Hz [2,3]. Soil is a complex, semi-infinite, continuous, loose medium whose vibration response is irregular. As the vibration wave propagates through the soil layer, the soil particles produce a vibration response and are in an active state. Influenced by

the plasticity of the soil, the vibration energy is attenuated when the transmission distance of the vibration increases. In addition, the mechanical properties (cohesion, elasticity, friction, etc.) of soil significantly change when excited by the low-frequency vibrations of the components [4]. Therefore, studying the low-frequency vibration response of soil under different vibration conditions is crucial for designing vibration-type, soil-engaging components of tillage machinery and matching vibration parameters.

With a wide range of pertinent research and applications, the theoretical foundation for the vibration response of continuous rigid bodies is comparatively comprehensive [5–7]. In the vibration response analysis of the rice combined harvester frame, the vibration response is obtained and the dynamic model is verified by determining the excitation parameters of the dynamic model and analyzing its vibration signals [8]. The irregular contacts between discrete material particles lead to large calculating errors. Therefore, a corresponding test analysis is required depending on the material. In a vibratory impact drilling system, modeling enables the analysis of excitation and vibration frequency amplitude as a function of drilling speed and specifies the optimal loading parameters and strategies [9]. The unpredictable state of the soil under the action of vibration makes it possible to determine the maximum capacity of the soil by means of the vibration method, and to study the mechanisms that clarify the vibration and compaction of the soil for a given time, amplitude, and frequency [10]. Analyzing the vibration analysis method of continuous rigid bodies is helpful in clarifying the vibration response research method of discrete materials.

The discrete element method is a numerical simulation method used to model discontinuous media. With the ability to obtain data on the forces and movements of particles, it has been introduced into the study of the dynamic behavior of soils [11,12]. Huang et al. [13] proposed a DEM (discrete element method)-based method for studying ultrasonic propagation in agricultural soil media and analyzed the influence of excitation parameters on the time-domain and frequency-domain profiles of ultrasonic waves. Qiao et al. [14] investigated Brazil nut separation under vibration using the discrete element method and predicted both the final segregation degree and the segregation velocity. Amirifar et al. [15] used the discrete element method to present a numerical study on the self-assembly of mono-size granular spheres with periodic boundary conditions under uniform and non-uniform 3D vibration conditions.

Plant roots, farmyard litter, and other materials are frequently found in farmland soils with media diversity [16], which makes it difficult to collect reliable test results. Bench testing avoids the interference of unknown factors during field testing and facilitates the consistency of the test conditions. Liu et al. [17] constructed a ballast sensor by embedding a chip and built an impact hammer test rig to analyze the effect of vertical vibration and transmission characteristics of the ballast on the dynamic stability of railway track structures. Zhang et al. [18] used a support platform, hammer, and an acceleration sensor to build a large cabbage vibration test bench and used stepwise multiple linear regression methods to quantitatively and qualitatively analyze the cabbage quality. In this study, a low-frequency vibration transfer test bench with a parameter (amplitude, vibration frequency, soil depth) adjustment function was constructed. The bench test data were used to obtain response curves between pressure and the vibration frequency, as well as to verify the accuracy of the soil simulation model. Three sets of single-factor simulation tests were conducted. The peak pressure, frequency domain response, effective transmission distance, and vibration pressure transfer paths were studied to clarify the vibration response. The results can provide an essential reference for designing vibration-type, soil-engaging components of tillage machinery and matching vibration parameters for energy-saving and resistance reduction purposes in soil tillage.

2. Materials and Methods

2.1. Construction of Test Bench

A low-frequency vibration transfer test bench with amplitude, vibration frequency, and other parameter adjustment functions was constructed as shown in Figure 1. The test

bench consisted of a signal generator, a modal vibration exciter, a soil bin, a soil-pressure sensor, a power amplifier, a dynamic signal tester, and a PC. According to the pre-test results, the soil bin size was set to 1000 mm (length) $\times$ 600 mm (width) $\times$ 600 mm (height). The size of the vibration board of the modal vibration exciter was 50 mm (length) $\times$ 40 mm (width) $\times$ 5 mm (height).

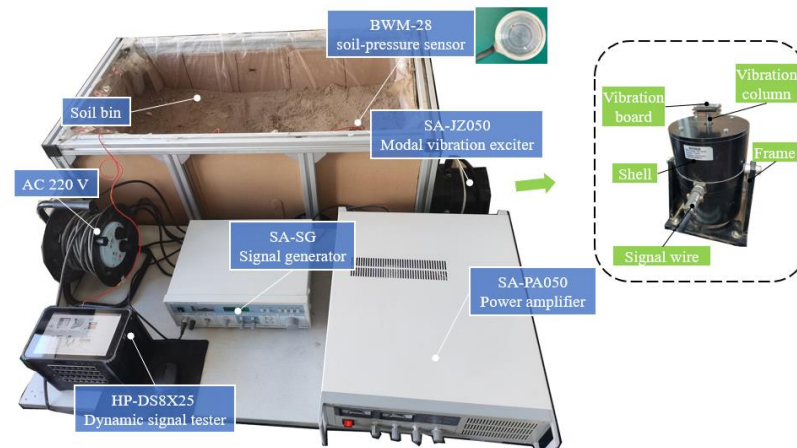


Figure 1. Composition of the low-frequency vibration transmission test bench.

The SA-SG signal generator provided output functions for sine, square, and triangle waveforms, and its sine signal frequency could be adjusted from 2 Hz to 2 kHz. The output waveform frequency was also visible through the LED window. The SA-PA050 power amplifier had a 500 VA rated input power, an AC input frequency response range of 20–50 k $\pm$ 1 dB, and less than 1% high-impedance nonlinear distortion. The maximum excitation force, amplitude, and acceleration for the SA-JZ050 modal vibration exciter were 500 N, 10 mm, and 49.5 g, respectively. Receiving signals from the SA-SG signal generator, the modal exciter generates different amplitudes and vibration frequencies. The BWM-28 soil-pressure sensor (BWM, Liyang, China), with a diameter of 28 mm, had an accuracy error of 0.1 kPa, a range of 0–100 kPa, and an overload capacity of 120%.

The soil was excavated in the experimental field of the Soil–Machine–Plant Key Laboratory (40°.01' N, 116.21' E), which has a northern temperate, semi-humid, continental monsoon climate with an average annual temperature of 9–19 °C and average annual precipitation of 470 mm to 660 mm. The soil type is cinnamon soil, and the soil particle density, as measured by the ring knife method, is 2600 kg/m³ (the volume of the particles was measured by the drying method and converted to calculate the particle density). After being transported back to the lab, the roots, stones, and farmland garbage were removed from the soil using a circular filter to obtain soil samples with consistent particle sizes. The soil and water quality were weighed separately using the moisture content of the deployment method [19] after being mixed evenly, covered with film, and left in place for 24 h (target moisture content 10%). The soil with the adjusted moisture content was poured into the soil bin, pressed down with an iron plate at each 50 mm point, filled to the desired volume, and then covered with film and left to stand for 72 h. Before the bench test, the soil firmness was measured using a spectrum firmness meter. The moisture content meter measured 1173 kPa and 9.7% moisture content.

2.2. Bench Tests of Low-Frequency Vibration

During the operation of agricultural plowing machinery, the vibrating earth-touching components can effectively reduce the working resistance and improve production efficiency. In the previous stage, we worked on the energy-saving and efficient harvesting of root rhizome crops (licorice, cassava, and potatoes) [20–22]. A lightweight harvester with novel oscillating shovel-rod components was developed. During the harvesting process, the shovel transmitted vibration energy in the horizontal direction and broke up the soil in

the vertical direction. The amplitude, vibration frequency, and soil depth used during the harvesting were in the ranges of 5 to 15 mm, 7 to 15 Hz, and 200 to 400 mm. In this study, a low frequency (7–15 Hz) was selected to clarify the vibration response, and a single-factor bench test was conducted. The study focuses on the vibration response in the horizontal direction. The soil depth (H_s) was set at 300 mm, and the area of the vibration board was 0.002 m^2 . Before the test, the soil bin was filled to a soil depth of 400 mm, and the distance between the vibration board and the bottom surface of the soil bin (H_b) was 100 mm (i.e., the soil depth for the bench test was 300 mm). The bottom soil reduced the reflection from the hard substrate. In order to prevent soil leakage from the vibration board action position, a layer of plastic film was placed inside the soil bin in advance.

The internal structure of a modal vibration exciter consists of a magnet exciting coil, a driving coil, a support spring, and a vibration column, which works according to the Faraday law of electromagnetic induction, as shown in Figure 2. The power amplifier supplies the driving coil with an electric current of variable frequency, and the driving coil is subjected to an electrodynamic force (F_e) proportional to the electric current, calculated by Equation (1). The amplitude of the vibration column is non-linearly related to the vibration frequency under the composite action of the elastic and electrodynamic forces. Within a slight vibration frequency variation, the rated amplitude (10 mm) value can be considered to be constant.

$$F_e = B \cdot I \cdot L \quad (1)$$

where B is the mean value of magnetic flux density, T; I is the output electric current value of modal vibration exciter, A; and L is the length of the driving coil wire, m.

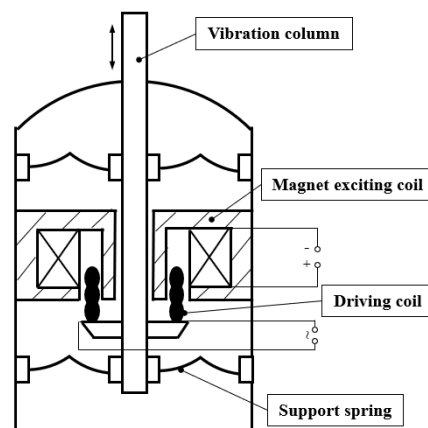


Figure 2. Internal structure of the modal vibration exciter.

Pile barriers buried in the soil had a significant effect on vibration attenuation [23,24]. The soil bin size was small, and only one soil-pressure sensor was buried to eliminate the influence on pressure value measurements (Figure 3). Before the test, the soil in the contact area was compacted to reduce the rebound effect. Burying the soil-pressure sensor could damage the test soil structure. A total of three vibration distances (L_V) were tested in the bench test in the sequence of 400, 250, and 100 mm. To minimize the reflection of vibrations from the sidewalls, a paper shell material with a thick honeycomb structure was used.

2.3. Simulation Modeling and Testing

2.3.1. Simulation Modeling and Parameter Determination

With the continuous optimization and advancement of discrete element technology, research scholars in the field of soil–machine interactions in agriculture usually use the discrete element method to simulate the workings of agricultural implements. They used spherical particles instead of actual soil particles in the simulations, and demonstrated the feasibility and accuracy of simulation tests using spherical particles to simulate soil particles in numerous published papers. The DEM simulation model ensured uniform soil conditions

among the test groups and extracted a wider range of test data. As shown in Figure 4, a 1:1 proportional 3D model of the soil bin, soil-pressure sensor, and vibration board was created using the Inventor 2018 software (Autodesk, San Francisco, CA, USA), saved as a .stl file, and then imported into the EDEM 2020 software (DEM Solution, Edinburgh, UK) for simulation modeling. In order to apply vibration to soil particles, sinusoidal translation kinematics to the vibration board can be added in the EDEM 2020 software, and reciprocation occurs based on the specified amplitude and vibration frequency.

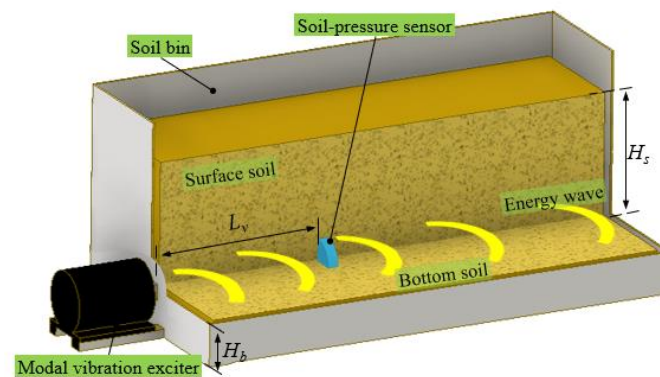


Figure 3. Diagram of low-frequency vibration horizontal transfer in soil.

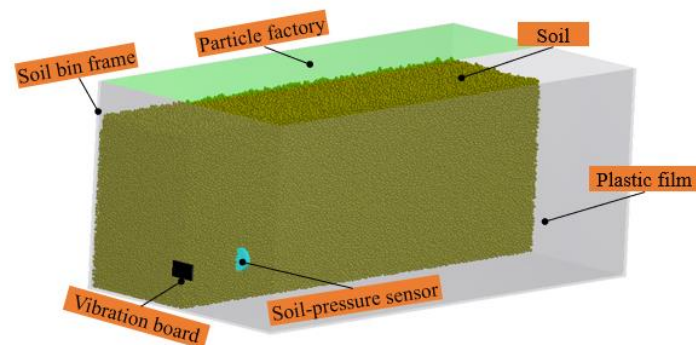


Figure 4. The DEM model of the simulation test (half sectional view of soil).

The calibration of the simulation model needs to take the actual test results as the target value, then continuously optimize and adjust the parameters of the simulation data until the relative error between the simulation results and the actual results reaches the permitted range. The simulation parameters of discrete elements can be divided into intrinsic parameters, contact parameters, and contact model parameters. In reference [25], the details introduced in our previous work can be found, where the soil's static stacking angle and the uniaxial confined compression were used to determine the intrinsic parameters and contact parameters of the soil model. These results were applied in this study, as shown in Tables 1 and 2.

The bonding contact model integrated into the EDEM 2020 software generated virtual cylindrical bonding bonds between particles, which have mechanical properties comparable to those of the finite element method. For the bonding contact model parameters, the parameter selection range was obtained by referring to the results of other scholars [26–28]. Then, the final parameter combinations were obtained through multiple simulations using the approximation method. The approximation method was used to run multiple iterations of the model parameters based on the reference parameter values. The internal material of the soil bin with the soil was plastic film, and the other parameters are shown in Table 3. The simulation software was EDEM 2020, which operates on a simulation platform with a Windows 10 64-bit system (CPU: Intel(R) Xeon(R) Gold 6226R, 2.90 GHz, dual CPU, 64

cores; GPU: NVIDIA GeForce RTX 3080). The simulation time step was set to 4.04486×10^{-5} s, 20% of the Rayleigh time step.

Table 1. Simulation parameters of the soil.

Parameters	Value	Parameters	Value
Soil particle radius	4 mm	Soil shear modulus	9.6×10^6 Pa
Soil density	2600 kg/m ³	Soil Poisson ratio	0.27

Table 2. Simulation parameters of the vibration board material.

Parameters	Value	Parameters	Value
Board density	7865 kg/m ³	Board Poisson ratio	0.35
Board shear modulus	7×10^8 Pa		

Table 3. Contact parameters of the simulation model.

Parameters	Value	Parameters	Value
The collision recovery coefficient between soil particles	0.25	The bond disk radius between soil particles (mm)	4.80
The static friction coefficient between soil particles	0.42	The collision recovery coefficient between soil and plastic	0.34
The rolling friction coefficient between soil particles	0.14	The static friction coefficient between soil and plastic	0.23
The normal stiffness per unit area between soil particles (Pa)	7.85×10^8	The rolling friction coefficient between soil and plastic	0.07
The tangential stiffness per unit area between soil particles (Pa)	7.42×10^8	The collision recovery coefficient between soil and steel	0.51
The critical normal stress between soil particles (N)	5.65×10^7	The static friction coefficient between soil and steel	0.32
The critical tangential stress between soil particles (N)	5.39×10^7	The rolling friction coefficient between soil and steel	0.09

2.3.2. Simulation Test

Considering the impact of soil-pressure sensors, only one sensor was buried for each simulation test. The vibration distance was between 0 and 600 mm, with a measurement interval of 50 mm. The simulation test investigated the differences in the low-frequency vibration response of soil for each test factor, setting the sampling frequency to 1000 Hz and the total simulation time to 1 s. Three sets of single-factor simulation tests were run in total, with the other two factors set to 0 levels whenever a single-factor test was performed for a factor (Table 4).

Table 4. Test factors and levels.

Level	−2	−1	0	+1	+2
Amplitude (mm)	5	7.5	10	12.5	15
Vibration frequency (Hz)	7	9	11	13	15
Soil depth (mm)	200	250	300	350	400

In addition, in the simulation process using EDEM software, the first to generate 200, 250, 300, 350, and 400 mm depth of soil was established. The particle factory finished generating the soil layer and then continued to simulate for 2 s until the particle movement was stable. The built-in save function of EDEM software was applied to save the finished file as a 0-moment file, which was able to clear the motion attributes of the particles and satisfy the requirement that the particles be at rest at the beginning of the simulation.

Finally, the motion parameters of the vibrating board in the 0-moment file were set, and each simulation test group was run in turn.

This study aimed to obtain the pressure at various vibration distances; analyze the characteristics of its time domain response and frequency domain response; determine the effective transmission distance; describe the soil vibration transfer path; and clarify the low-frequency vibration response of the soil. The indices and acquisition methods were as follows:

(1) Peak pressure (F): In the post-processing interface of EDEM 2020 software, the pressure data set of the soil pressure sensor was collected, and the peak pressure was calculated by the average of five groups' maximum pressure, as shown in Equation (2).

$$F = \frac{\sum_{i=1}^5 F_{Pi}}{5} \quad (2)$$

where F is the value of peak pressure, N , and F_{Pi} is a cycle's maximum pressure value in a stable section, N .

(2) Frequency domain response: Fourier transforms the time domain signal into the frequency domain signal, applies the findpeak function and plot function of MATLAB 2017 (MathWorks, Natick, MA, USA) software, and plots the peak curve of the frequency domain signal.

(3) Effective transmission distance: The scatter data of peak pressure and vibration distance are taken as the input; the peak pressure attenuation function was then fitted using MATLAB 2017 software, and the solve function was used to determine the corresponding distance under the cut-off pressure.

3. Results and Discussion

3.1. Analysis of Bench Test Results

Before the test, the soil-pressure sensor was set to 0 kPa and the signal acquisition frequency of the dynamic signal tester was set to 1000 Hz. The modal vibration exciter was set up with a vibration frequency of 7–15 Hz, an amplitude of 10 mm, and a vibration distance of 250 mm. Each set of tests was performed three times, and the test data were averaged. Figure 5a shows the response curve of peak pressure and vibration frequency. Using the vibration parameters of 10 mm amplitude and 11 Hz vibration frequency, Figure 5b shows the time domain response curve of pressure for each vibration distance.

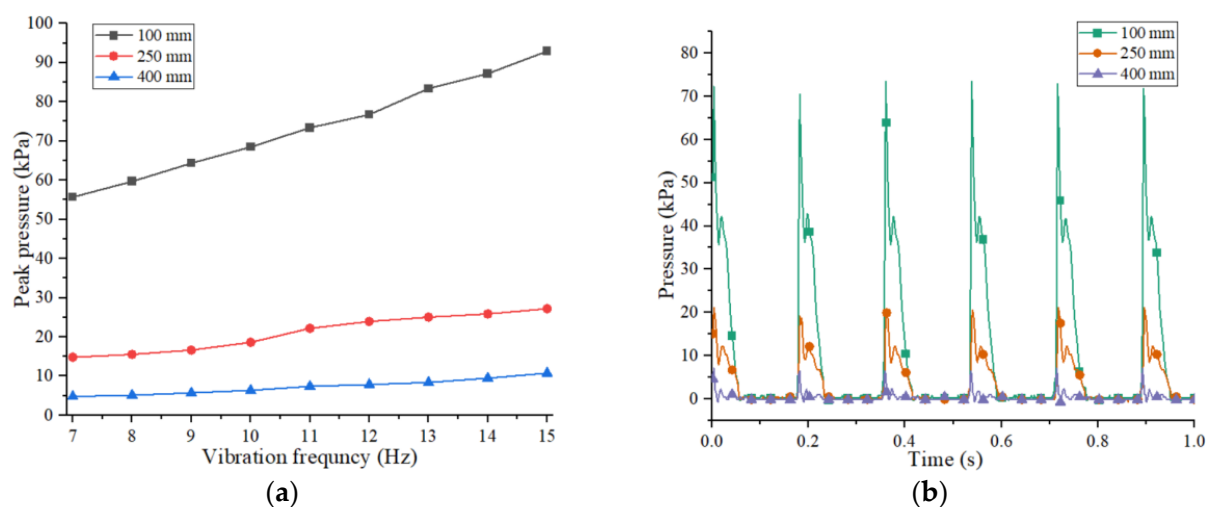


Figure 5. Results of the bench test: (a) Response curve of peak pressure and vibration frequency; (b) response curve of pressure, vibration distance, and time at 11 Hz.

Peak pressure was positively correlated with vibration frequency and negatively correlated with vibration distance (Figure 5a). The peak pressure increased by 4.66, 1.55,

and 0.74 kPa/mm at vibration distances of 100, 250, and 400 mm, respectively. Different vibration distances had the same response cycles for the peak pressure (Figure 5b), and the “sine-like” vibration waveform may have been related to the viscoelastic plasticity of the soil. The pressure rose rapidly during the loading stage, reached a transient peak, and formed a small wave during the unloading stage. In low-stiffness materials, the vibration energy attenuated rapidly [29,30]. The pressure attenuation gradient was approximately 0.34 kPa/mm when the vibration distance was less than 250 mm. The vibration pressure was low, in the range of 250 mm to 400 mm, and the attenuation gradient was approximately 0.099 kPa/mm.

3.2. Analysis of Simulation Model Accuracy

After determining the contact parameters for the soil particles, a set of comparative tests was carried out to verify the accuracy of the simulation model. The bench test was carried out to choose vibration frequencies of 9, 11, and 13 Hz, and the target values were the peak pressures at vibration distances of 100, 250, and 400 mm. As shown in Figure 6, the relative errors between the simulated and measured values were less than 8.64%, 10.03%, and 10.22% for the source distances of 100 mm, 250 mm, and 400 mm, respectively, at each vibration frequency. The peak pressure at the vibration distance of 250 mm and 400 mm was low, and relatively small differences can produce large relative errors. The model is considered to be accurate when the error between the simulated and actual values is about 10% [26]. The simulation results were generally consistent with the measured results, showing that the discrete element method can be used to simulate the low-frequency vibration response of the soil.

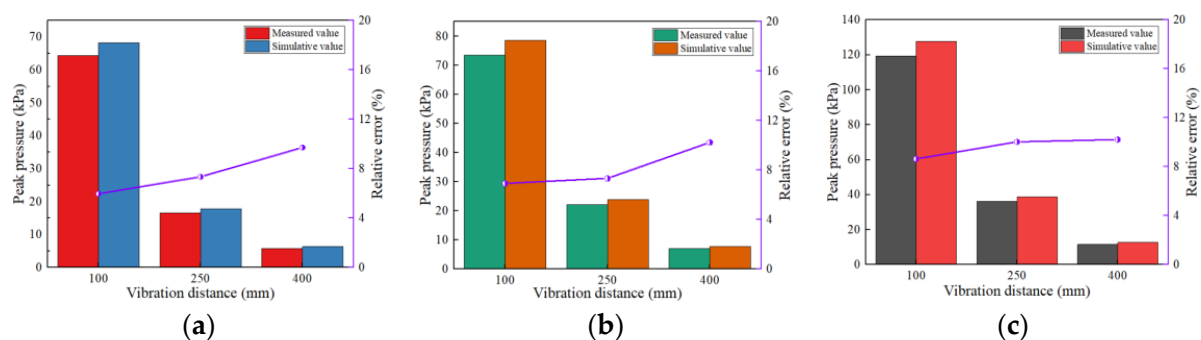


Figure 6. Comparison of measured and simulated values at different vibration frequency: (a) 9 Hz; (b) 11 Hz; (c) 13 Hz.

3.3. Analysis of Simulation Test Results

3.3.1. Peak Pressure

The response curve in Figure 7a shows that the peak pressure at each vibration distance gradually increased as the amplitude increased. This caused the amplitude to increase, the applied energy to gradually increase, and the soil particle movement to be more active, resulting in a gradual increase in the impact force on the pressure sensor. The largest increase gradient in peak pressure was 19.02 kPa/mm, measured at a vibration distance of 50 mm. The extreme difference in peak pressure at a vibration distance of 450 mm was 4.41 kPa, which was slightly influenced by the change in amplitude.

The response curve in Figure 7b shows that the peak pressure at each vibration distance gradually increased as the vibration frequency increased, which was consistent with the bench test results. Increased vibration frequency caused an impact on the soil particles more frequently. The soil obtained more elastic energy, the particles shook violently, and the peak pressure gradually increased. The largest increase gradient in peak pressure was 9.38 kPa/Hz, measured at a vibration distance of 50 mm. The extreme difference at a vibration distance of 400 mm was 5.12 kPa. When the vibration distance exceeded 400 mm, the effect of changes in vibration frequency was slight.

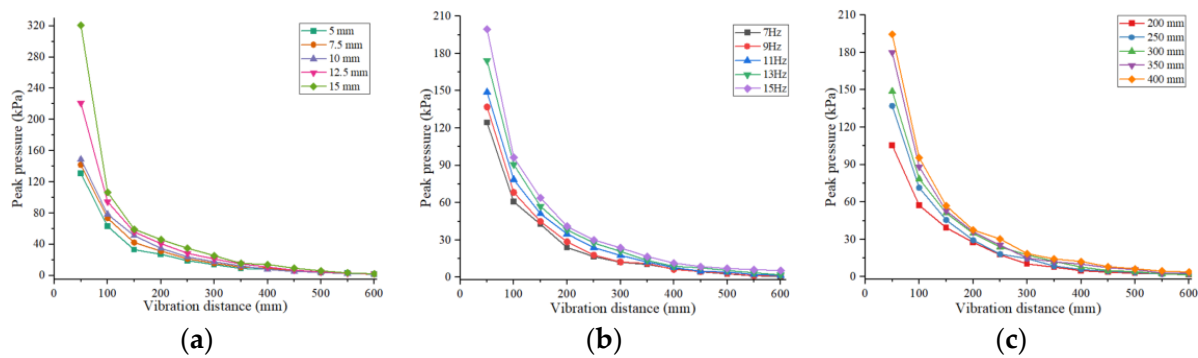


Figure 7. Response curve of peak pressure and vibration distance: (a) amplitude; (b) vibration frequency; (c) soil depth.

The peak pressure at each vibration distance gradually increased as the soil depth increased, according to the response curve in Figure 7c. As the soil depth increased, the discrete nature of the soil medium decreased, and the transmit pressure ability of soil particles increased, resulting in a gradual increase in peak pressure. The largest increase gradient of the peak pressure was 0.45 kPa/mm, at a vibration distance of 50 mm. The extreme difference in the peak pressure at the vibration source of 450 mm was 4.42 kPa. The variation in soil depth slightly influenced the peak pressure when the vibration distance was above 450 mm.

3.3.2. Frequency Domain Response

In the response of a nonlinear system, the primary resonances are the excitation frequency, close to the natural frequency, and the sub-harmonic resonance, close to an integer multiple of the natural frequency [31]. The frequency domain signal of the soil is very complex after being vibrated. The frequency domain signal at a vibration distance of 250 mm was processed using MATLAB 2017 software, with the minimum peak prominence of the findpeaks function set to 0.08 to visually compare and analyze the differences in the components of the frequency domain signal, as shown in Figure 8. The y-coordinate of the frequency domain signal was the magnitude, from which the main frequency and main frequency amplitude were extracted, as shown in Tables 5–7.

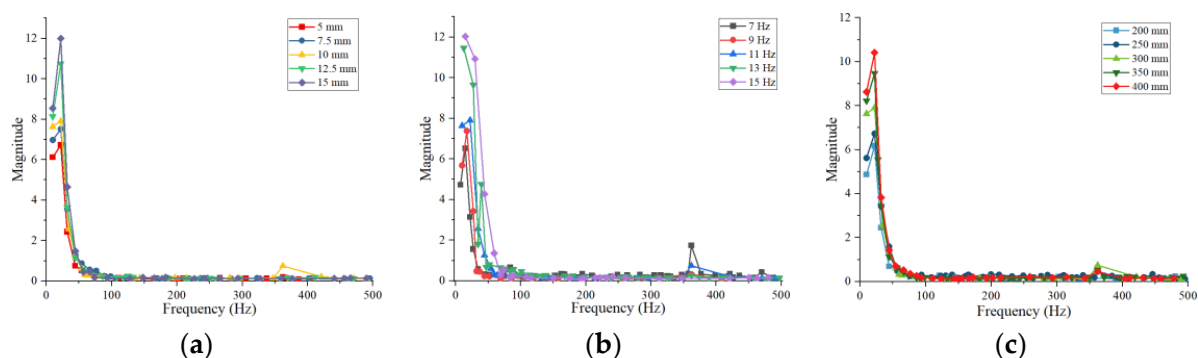


Figure 8. The frequency domain response of pressure values: (a) amplitude; (b) vibration frequency; (c) soil depth.

Table 5. Dominant frequency and dominant frequency amplitude at different amplitudes.

Amplitude/mm	5	7.5	10	12.5	15
Dominant frequency/Hz	22.17	22.17	22.17	22.17	22.17
Dominant frequency amplitude/kPa	6.73	7.51	7.91	10.75	11.99

Table 6. Dominant frequency and dominant frequency amplitude at different vibration frequencies.

Vibration Frequency/Hz	7	9	11	13	15
Dominant frequency/Hz	14.78	17.24	22.17	12.31	14.78
Dominant frequency amplitude/kPa	6.52	7.37	7.91	11.45	12.03

Table 7. Dominant frequency and dominant frequency amplitude at different soil depths.

Soil Depth/mm	200	250	300	350	400
Dominant frequency/Hz	22.17	22.17	22.17	22.17	22.17
Dominant frequency amplitude/kPa	6.17	6.72	7.91	9.48	10.41

In the frequency range from 0 to 50 Hz, the frequency multiplication and frequency division signal values were positively correlated with the amplitude, as shown in Figure 8a. The dominant frequency amplitude showed increased gradients of 0.16/mm and 1.14/mm for the amplitudes of 10 mm and 12.5 mm, respectively, which were the minimum and maximum values. The dominant frequency was approximately twice the vibration frequency, as shown in Table 3. The dominant frequency amplitude gradually increased with the amplitude, reaching a maximum value (11.99/kPa) at 15 mm. When the vibration frequency was 11 Hz, the dominant frequency was relevant to the elastic hysteresis of the soil (the elastic deformation took some time to return to its normal value after loading and unloading), which caused the soil to be positively vibrated by the vibration board during the rebound cycle, resulting in a dominant frequency of approximately twice the vibration frequency. When the amplitude was in the range of 5 to 15 mm, increasing the amplitude only improved the pressure, and the frequency response of the soil was unaffected.

In the frequency range from 0 to 100 Hz, the frequency multiplication and frequency division signal values were positively correlated with the vibration frequency, as shown in Figure 8b. The dominant frequency amplitude had increased gradients of 0.27/Hz and 1.77/Hz for vibration frequencies of 9 Hz and 13 Hz, respectively, which were the minimum and maximum values. The dominant frequency was approximately twice the vibration frequency at 7–11 Hz and approximately equal to the vibration frequency at 13–15 Hz, as shown in Table 4. The dominant frequency amplitude reached its maximum (12.03/kPa) at 15 Hz. The vibration impact response time between soil particles was shortened at a vibration frequency greater than 13 Hz, potentially eliminating vibration hysteresis. When the vibration frequency was between 13 and 15 Hz, increasing the vibration frequency enhanced the pressure and changed the frequency response of the soil.

In the frequency range from 0 to 50 Hz, the frequency multiplication and frequency division signal values were positively correlated with the soil depth, as shown in Figure 8c. The amplitude difference between the frequency multiplication and frequency division signal was minimal at frequencies greater than 50 Hz. As the soil depth increased, the least significantly increasing gradient (0.011/mm) of the dominant frequency was found at a soil depth of 250 mm, and the most (0.0314/mm) at 350 mm. The dominant frequency amplitude gradually increased with the increasing soil depth, reaching a maximum value (10.41/kPa) at 400 mm, as shown in Table 5. The dominant frequency of the soil was approximately twice the vibration frequency at various soil depths. As the soil depth increased, the soil's ability to store and transmit pressure increased with depth, while the frequency response rule remained constant.

Analyzing the resulting data, the generation of the dominant vibration frequency may have been affected by the soil's viscoelastic plasticity, and the dominant frequency's magnitude was obtained as 1/2 of the applied vibration frequency. The frequency domain component of 300–400 Hz may have been related to the reflection effect of the soil bin on the vibration.

3.3.3. Effective Transmission Distance

The vibration applied to the soils changed its physical characteristics, such as porosity, cohesion, and elastoplastic. The effective transmission distance is one of the most important indexes for studying the vibration response of soil. An accurate attenuation model can characterize soil vibration propagation and attenuation characteristics [32–34]. The vibration distance L_V was used as the independent variable, the peak pressure F as the dependent variable, and MATLAB 2017 software was used to model the peak pressure attenuation function. The effective transmission distance of the pressure was determined by solving the function. The confidence R^2 values of the multiple exponential function fitting methods were greater than 0.9874, a value which can accurately characterize the attenuation of peak pressure. When the peak pressure is less than 5 kPa, it decreases very slowly with increasing vibration distance, as shown in Figure 9. Thus, the cut-off pressure was selected at 5 kPa.

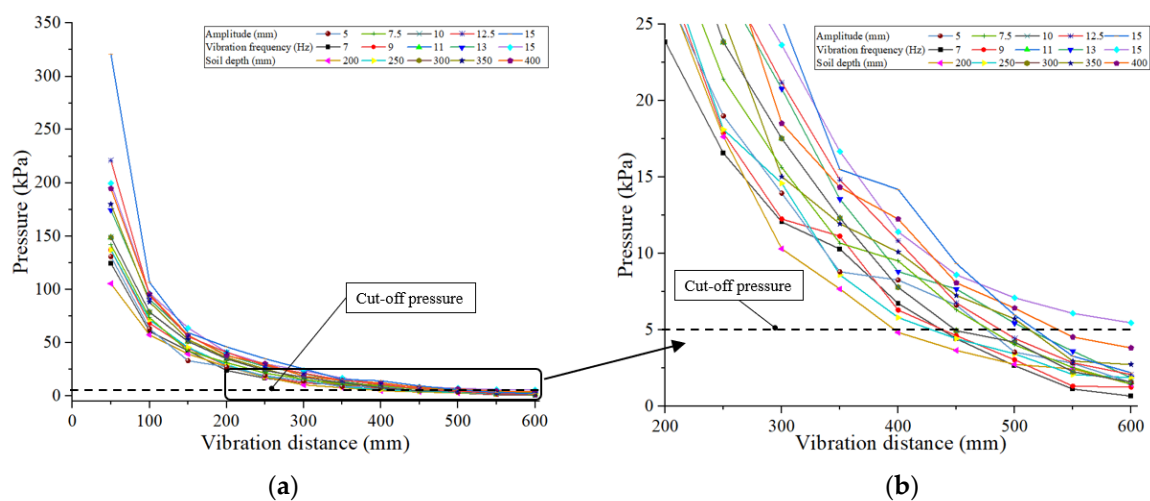
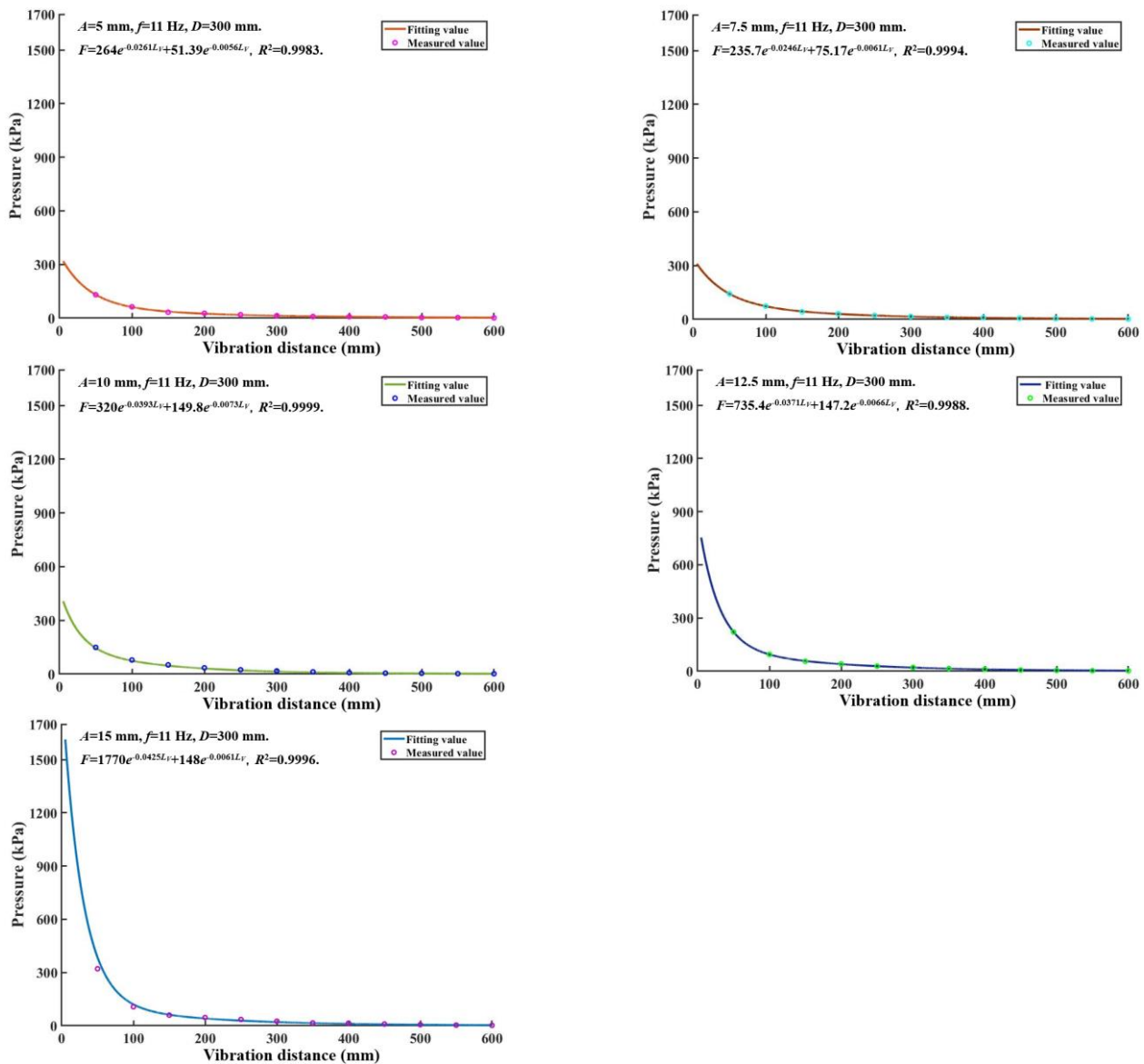


Figure 9. Diagram of the cut-off pressure selection: (a) shows the pressure value versus vibration frequency response curve for each condition, and (b) shows an enlarged view of the key area.

When the amplitude increased, the coefficient of the peak pressure attenuation function gradually increased, and the variation gradient of pressure increased (Figure 10a). Observing the characteristic points of the curve and read the exact data values within the software, at amplitudes of 5 mm and 15 mm, minimum and maximum peak pressures of 320 kPa and 1610 kPa were obtained at the vibration board–soil interface, respectively. The effective transmission distances of the pressure to the low-frequency vibration were 416.25, 444.45, 465.73, 512.48, and 555.37 mm for each amplitude (5, 7.5, 10, 12.5, and 15 mm). The attenuation gradient of pressure increased slightly as the vibration frequency increased, as shown in Figure 10b. At vibration frequencies of 7 Hz and 15 Hz, minimum and maximum peak pressures of 200 kPa and 520 kPa were obtained at the vibration board–soil interface, respectively. The effective transmission distance was calculated by inputting the cut-off pressure into the function for each vibration frequency (7, 9, 11, 13, and 15 Hz). These values were 347.15, 424.31, 465.73, 502.48, and 550.21 mm, respectively. As the soil depth increased, the peak pressure decreased, and the coefficient of the peak pressure attenuation function gradually increased (Figure 10c). At soil depths of 200 mm and 400 mm, minimum and maximum peak pressures of 155 kPa and 450 kPa were obtained at the vibration board–soil interface, respectively. For each soil depth (200, 250, 300, 350, and 400 mm), the cut-off pressure values were calculated to be 370.81, 422.88, 465.73, 487.97, and 531.58 mm, respectively.

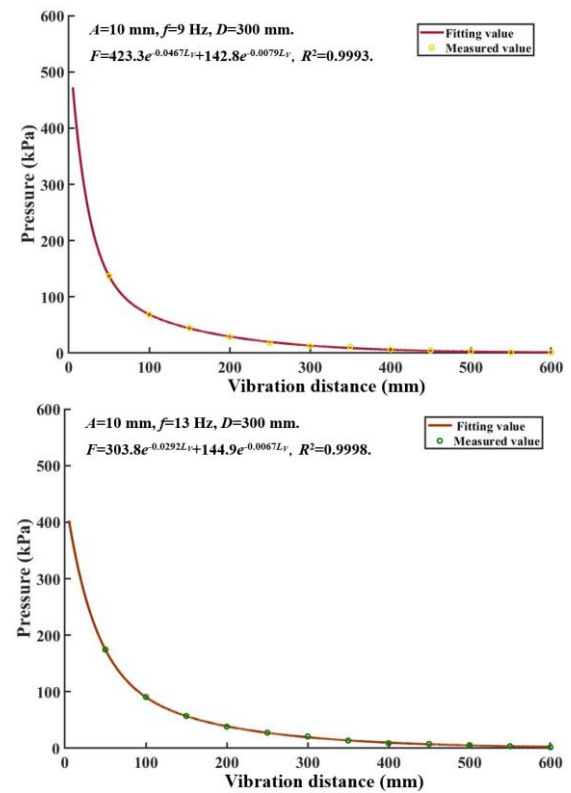
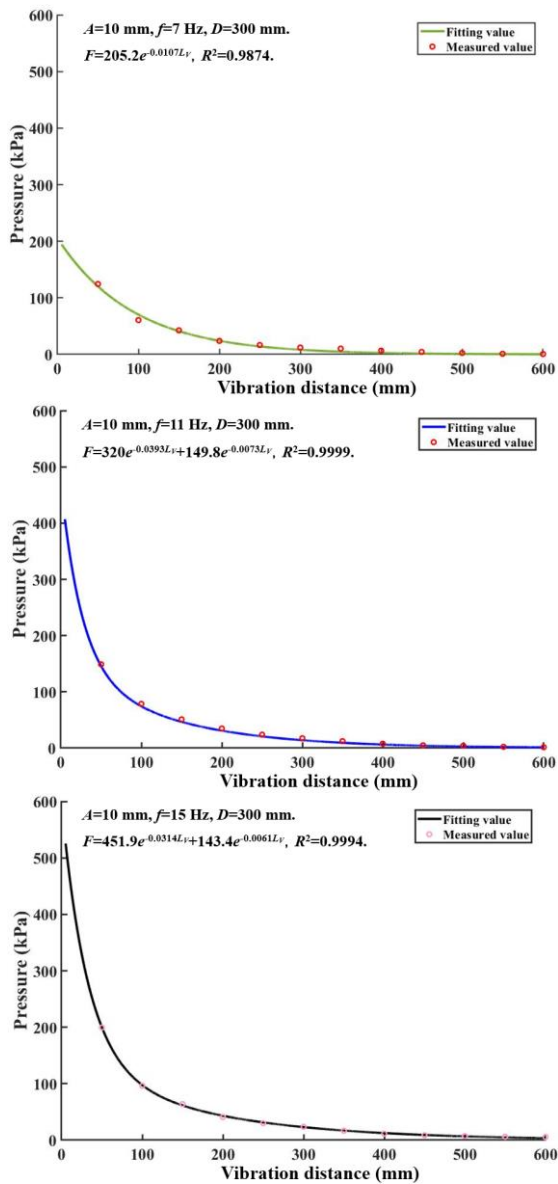
3.3.4. Vibration Pressure Transfer Path

Obtaining the forces and movements of the soil particles is helpful for clarifying the vibration pressure transfer paths. A test group with the vibration parameters of 10 mm amplitude, 11 Hz vibration frequency, 300 mm soil depth, and 100 mm vibration distance was selected for the simulation analysis. The soil particle properties were set to vector in the post-processing interface of the EDEM 2020 software, and the clipping command was used to obtain front and vertical views of the soil bin, as shown in Figure 11.



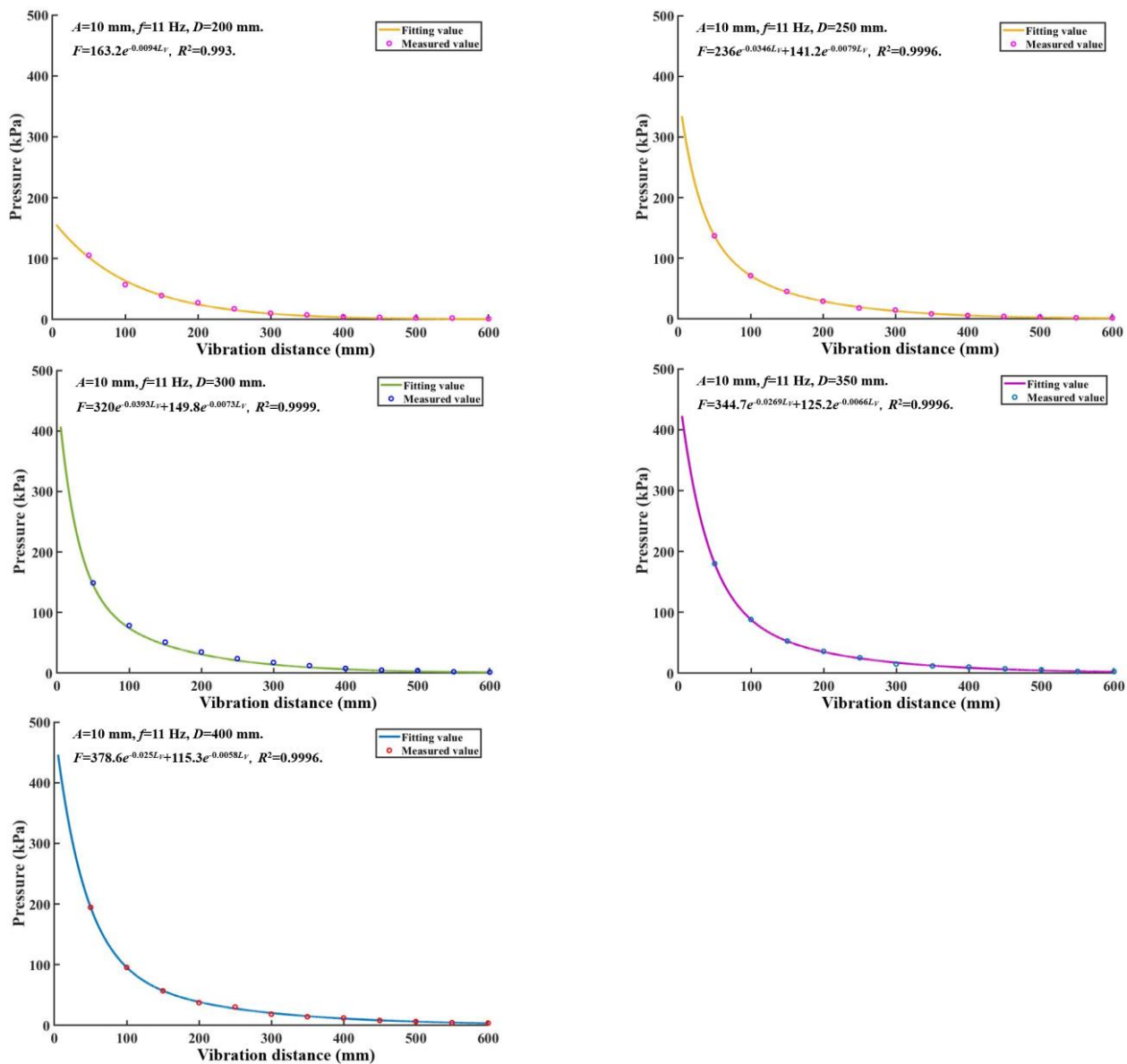
(a)

Figure 10. Cont.



(b)

Figure 10. Cont.



(c)

Figure 10. Multinomial exponential function fitting curve for vibration distance and pressure: group (a) is for amplitude; group (b) is for vibration frequency; and group (c) is for soil depth.

After being vibrated by low-frequency vibration, pressures were transmitted in the soil as waveforms [35], forming compressional and shear waves on the free surface of the soil. During the pre-loading stage, the soil particles in the contact area tended to move diagonally downwards (point a to point b), as shown in the front view. These particles were under pressure and produce large velocities and displacements, while the soil particles outside the contact area only slightly changed. The vibration board compresses soil particles during the loading stage (points b to c). The soil particles in the contact area obtained greater force and displacement, and the direction of movement changed. At the further end, the force on the soil particles increased, but the displacement and direction of movement changed slightly. A possible reason is that the pressure increased by compression, and the movement of the vibration board was converted into the compression displacement of the soil. The red color of the soil particles in the lower half of the vibration board was more concentrated, indicating that its pressure was greater than the soil above. The shear wave diffusion angle in the vertical direction was approximately 103° , and was measured by the

angle between the two black dashed lines at point c. The soil particles suffered internal force during pre-unloading (points c to d), and internal elastoplastic pushed them back toward their original position.

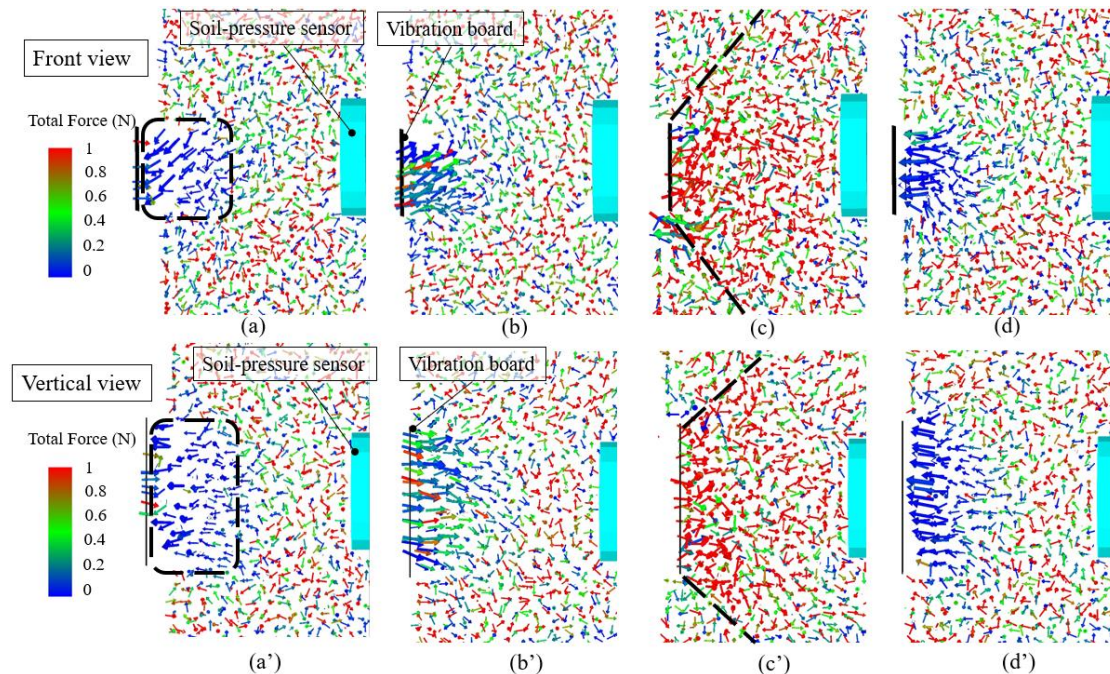


Figure 11. Vector model of soil particles. In the front view, points a–b are the pre-loading stage, points b–c are the loading stage, and points c–d are the pre-unloading stage. In the vertical view, points a'–b' are the pre-loading stage, points b'–c' are the loading stage, and points c'–d' are the pre-unloading stage. The black rectangular wire frame is the contact area. The black dashed line is the dividing line between the strong and weak pressure on the soil particles.

From the vertical view, soil particles in the pre-loading stage (points a' to b') were subjected to increased forces in the contact area, and the movement was ordered. The vibration board pressed the soil particles in the loading stage (points b' to c'), and the forces on both sides of the vibration board axis were uniform. The soil was vibrated, and the pressure diffused to both sides. The angle between the two black dashed lines at point c' is the horizontal diffusion angle of the shear wave, which was approximately 85°. The soil particles suffered internal force during the pre-unloading stage (points c' to d') and moved back toward the original position.

4. Conclusions

In this study, a low-frequency vibration transfer test bench was constructed, and a single-factor bench test was conducted. The bench test results were analyzed to obtain pressure response curves and were then used to determine the simulation model parameters. In addition, the influence of the test factors on the peak pressure, frequency domain response, and effective transmission distance was analyzed by simulation tests, while the vibration pressure transfer path of the soil was discussed.

- (1) The peak pressure positively correlated with the amplitude, vibration frequency, and soil depth. The pressure attenuated rapidly at a vibration distance of 0 to 250 mm. When the vibration distance was greater than 500 mm, the pressure was slightly affected by the parameters.
- (2) The dominant frequency amplitude positively correlated with the amplitude, vibration frequency, and soil depth. The main frequency was independent of the amplitude and soil depth. At a vibration distance of 250 mm, the dominant frequency was

approximately twice the vibration frequency at 7–11 Hz and approximately equal to the vibration frequency at 13–15 Hz.

- (3) Multiple exponential functions can be used to accurately fit the peak pressure attenuation curve. For a cut-off pressure of 5 kPa, the effective transmission distance ranged between 347.15 and 550.37 mm. Beyond the effective transmission distance, the gradient of pressure variations in the soil was slight, but the pressure signal extended over a long distance.
- (4) Pressure is transmitted by forward diffusion. In the loading stage, the soil particles outside the contact area were subjected to increased forces, but slight changes in movement. When the soil depth was 300 mm, the shear wave diffusion angle in the vertical direction was greater than that in the horizontal direction.

We tested the vibration response of the soil under low-frequency vibration using the soil bin test and described the vibration pressure transfer path for the effective distance, which is of great academic value in soil tillage studies. In future research, the influence of vibration transmission by the boundary reflection of the test device, the influence of soil moisture content on the test results, and the applicability of field and in situ tests will be discussed, which may further validate the accuracy of discrete element simulations and specify the factors affecting soil vibration. This will help to support the development of vibration response mechanisms for soils.

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