

## Research Article

# Model for Calculating Seismic Wave Spectrum Excited by Explosive Source

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To reveal the characteristics and laws of the seismic wavefield amplitude-frequency excited by explosive source, the method for computing the seismic wave spectrum excited by explosive was studied in this paper. The model for calculating the seismic wave spectrum excited by explosive source was acquired by taking the seismic source model of spherical cavity as the basis. The results of using this model show that the main frequency and the bandwidth of the seismic waves caused by the explosion are influenced by the initial detonation pressure, the adiabatic expansion of the explosive, and the geotechnical parameters, which increase with the reduction of initial detonation pressure and the increase of the adiabatic expansion. The main frequency and the bandwidth of the seismic waves formed by the detonation of the explosives in the silt clay increase by 23.2% and 13.6% compared to those exploded in the silt. The research shows that the theoretical model built up in this study can describe the characteristics of the seismic wave spectrum excited by explosive in a comparatively accurate way.

## 1. Introduction

Explosive is a common seismic source used for stimulating seismic waves artificially in seismic prospecting. It provides high-frequency and broad-frequency domain to achieve higher seismic resolution, aiming to satisfy the “smaller, thinner, and deeper” demands of seismic prospecting. Considering that the explosive source and the physical properties of the excitation medium have significant effects on seismic wave characteristics, the theoretical relationship between the explosive source and excitation medium parameters and the amplitude-frequency characteristics of the seismic waves can be established, thus to acquire the seismic waves satisfying the demands of seismic exploration by designing proper explosives excitation plan [1–6].

To study the seismic wave forming process induced by explosive source, Jeffreys et al. established a cavity vibration model in one-dimensional space, based on which a method for calculating the cavity size under spherical impact was given out [7–9]. Sharpe obtained the elastic wave analytical solution of the pressure on the wall of the spherical explosive

cavity [10]. Targeting at the theoretical model of point-source explosion and based on the research of Sharpe, Blake et al. obtained the analytical solution of the elastic waves in the viscoelastic medium models of Duvall and Ricker [11–13]. Meanwhile, Sharpe also took the influences of the detonation pressure of explosive source and the seismic wave attenuation with the increase of spreading distance into consideration when making the model. The calculation results of the model were similar to the true seismic waveforms. However, for the model, the way of directly loading the detonation pressure on the cavity wall actually lacked consideration about the dynamic explosion process. Jiang [14] established the model, whose results of the calculation were compared with Blake’s [11] model. For all these models, the impacts of the plastic regions on the seismic waves during the explosion process are simplified. Stevens et al. proposed the nonlinear model, which gave out a solution for explosive plastic regions [15–17]. These models can establish the relationship between explosives parameters and the seismic wave fields. However, since they all simplify the process that the explosive source excites the seismic

waves, it is impossible to establish the direct relationship between explosive source parameters and seismic wave field characteristics. Yu et al. improved the cavity source model for this problem, and established the theoretical model for the process that the explosive source excites the seismic wave field [18]. This method can be used to establish the cavity for explosive source, thus to describe the action process of the explosive source, the relationship between the initial parameters of the explosive source and the elastic wave field, and the whole-field seismic wave characteristics resulted by spherical explosives. However, these studies have not further studied the frequencies and bandwidths of the seismic waves.

Schenk and Červený studied the relationship between the density and proportion of sandy soil, and the frequency bandwidth of the seismic waves was formed during explosive detonation, based on which a fitting relationship model was acquired accordingly [19]. Through the test results of large-scale on-site tests, Wu studied the particle vibration velocity and its main frequency of the seismic waves formed by underground explosion at different positions. Wu et al. figured out, based on the above study, that the energy of high-frequency vibration attenuates sharply with the increase of distance [20]. Lin and Bai conducted time-frequency analysis on blasting vibration by the wavelet transform method, which provides a new method for the spectrum analysis of seismic waves [21]. Ling and Li analyzed the relationship between the explosive vibration band and the explosive source parameters by the wavelet method [22]. Stroujkova adopted on-site tests to analyze the seismic wave spectrum formed by different types of explosives and obtained the relationship between the low-frequency energy of the explosive seismic wave and the explosive expansion index [23]. It can be seen that the amplitude-frequency characteristics of the seismic waves are closely related to the explosive source parameters and the geotechnical medium parameters. However, these studies have not given a quantitative relationship between the seismic wave frequency characteristics and the explosive source and geophysical parameters.

If the relationship between the explosion characteristics and the amplitude-frequency of the seismic wave is established, the amplitude and frequency of the seismic waves can be controlled by selecting different types of explosives. To achieve goals of fine exploration and controlling of the seismic wave characteristics by changing the explosive source excitation plans, the model that explosive source excites amplitude-frequency characteristics of the seismic wave field must be established.

In this paper, the entire process in which the explosive source excites the seismic waves was analyzed firstly, and then, the theory that the spherical explosive source excites seismic wave field was described briefly, based on which the method for calculating the amplitude-frequency characteristics of the seismic wave field formed by explosive source was proposed accordingly. And, the applicability of this calculation model was verified through on-site experiments.

## 2. Creation of Seismic Wave

Explosive seismic wave is produced by the vibration of elastic cavity which is formed after medium blasting. At this stage, the seismic wave features are not related to the inelastic property of the medium. And, after being created, the seismic wave attenuates gradually with the increase of distance during the propagation process in geomaterial. Therefore, the study on frequency and amplitude rules of seismic wave field should be conducted from two perspectives: the creation of seismic wave and its propagation in medium.

The process from the explosives' detonation to the forming of seismic waves is accompanied with a series of chemical and physical changes. At the moment of blasting in geomaterial, the explosives produced abundant of gases with high velocity and pressure due to chemical reaction, which further formed the impact wave (Figure 1 (I)), directly applying on the geomaterial. Since the gas pressure is far greater than the geomaterial-confined deformation modulus, the geomaterial near the explosive source becomes liquefied under huge energy impact so that the blasting cavity can be deemed as the expansion in the incompressible fluid medium. With the development of the impact wave, the peak stress rapidly attenuates during the outwards propagation process. In this case, the impact wave converts into stress wave (Figure 1 (II) and (III)), the propagation velocity reduces sharply, and the elastic precursor with higher velocity than that of the failure wave can be separated and obtained from the plastic wave. The plastic wave peak and the wave velocity decrease with the increase of the propagation distance, but the elastic wave velocity remains unchanged. In this case, when the peak pressure of the stress wave decreases to below a certain value, the geomaterial would transform from the plastic state to the elastic state. Once the plastic wave disappears completely, the detonation wave completely turns to be an elastic wave (Figure 1 (IV)) at this moment, which is the seismic wave in general. The whole attenuation process of the blasting wave is as shown in Figure 1, in which  $y$ -direction refers to the changes of blasting wave pressure and  $x$ -direction refers to the one-dimensional detonation process.

The stress-strain curve in the geomaterial is as shown in Figure 2. The geomaterial state under the stress of the blasting wave can be divided into four parts. In the area close to the explosive, the blasting load stress is much greater than the confined deformation modulus of the geomaterial ( $\sigma > \sigma_c$ ). And, at this time, the geomaterial shows hydrodynamic properties with the propagation of impact wave in medium, and the peak stress descends gradually. When the geomaterial stress exceeds the extreme geomaterial strength ( $\sigma_c > \sigma > \sigma_b$ ), the geomaterial would exist in a broken form, the geomaterial deformation modulus ( $d\sigma/d\varepsilon$ ) still enlarges with the increase of stress, and the impact wave shows the elastic wave and turns to the unsteady impact wave. Under the condition that the stress value further decreases but is still greater than the yield point ( $\sigma_b > \sigma > \sigma_a$ ), the loading state evolves into a plastic state, having elastic-plastic waves. However, the geomaterial deformation modulus ( $d\sigma/d\varepsilon$ ) at

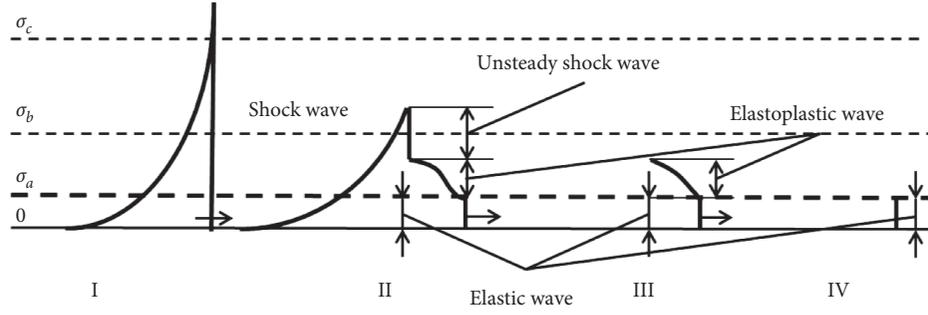


FIGURE 1: Blasting wave evolution with the attenuation of the peak stress.

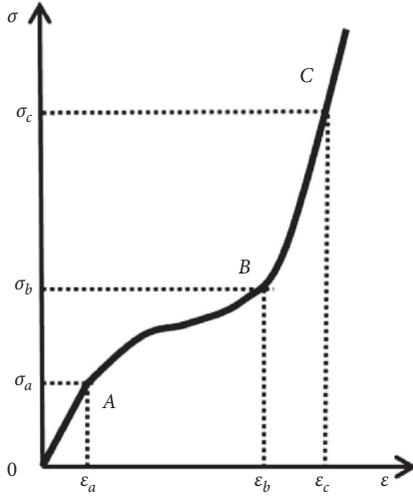


FIGURE 2: Stress-strain curve in the geomaterial.

that time decreases with the increase of stress. When the stress drops below the extreme elastic value ( $\sigma < \sigma_a$ ),  $(d\sigma/d\varepsilon)$  is a constant while the stress wave exists in the form of the elastic wave. Therefore, in terms of energy transformation direction, the explosive source forms the blasting cavity area, inelastic area, and elastic area in sequence at the moment of explosion.

### 3. Analysis on Process of Explosive Source Exciting Seismic Waves

The spherical cavity seismic source model can be used to describe the relationship between the explosive source and the seismic wave field. For this model, it is supposed that when the explosion happens, the shock wave pressure excited by the explosive source for an instant would destroy the mediums in regions nearby. In the region adjacent to the explosive loading area, the energy released by explosion is far greater than the soil medium pressure and the geotechnical strength. The geomaterial shows fluid property under such high pressure. The soil medium particles will displace with the explosion shock wave, while the water and gas in the soil

medium will be extruded out, forming an explosion cavity. As the spread and attenuation in the excitable medium occur, the shock wave pressure would keep attenuating till it is below the breaking strength of the medium at position which is a certain distance away from the shocking source. However, the excitable medium still has the elastic property. Yu established the spherical satchel charge seismic wave field model under the assumption that the soil medium is not compressible, the explosion process and the cavity are formed for an instant, and the changes to the soil medium is neglected. Based on the above model, the spherical explosive blasting cavity radius and the plastic zone radius can be obtained accordingly.

The blasting cavity radius is

$$b_* = a_0 \left( \frac{P}{-(c/\varphi) + (\sigma_* + (c/\varphi))L^{4f/3(1+f)}} \right)^{1/3\gamma} \sqrt[3]{\frac{2\mu}{3\sigma_*}} \quad (1)$$

where

$$L = \frac{\mu}{\sigma_* [1 + \ln(\sigma_*/\sigma_0)]} \quad (2)$$

Plastic zone radius is

$$b_0 = \left( \frac{\sigma_*}{\sigma_0} \right)^{1/2} b_* \quad (3)$$

where  $a_0$  is the explosive radius,  $P$  is the initial blasting pressure of the explosive,  $\gamma$  is the adiabatic expansion,  $\varphi$  is the cohesion of the soil medium,  $c$  is the internal friction angle of soil medium,  $\sigma_*$  is the compressive strength of the soil medium,  $\sigma_0$  is the tensile strength of the soil medium, and  $\mu$  is the lame coefficient.

Introduce the linear radial strain and hoop strain, and simply the motion equation as follows:

$$\frac{\partial^2 u}{\partial r^2} + \frac{2}{r} \frac{\partial u}{\partial r} - 2 \frac{u}{r^2} = \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2} \quad (4)$$

The solution of this equation can describe the forced vibration of the particle under viscous damping, and its general form is

$$U(r, t) = e^{(-\eta^2 \tau / \rho_{\text{soil}} c b_*)} \left[ \left( \frac{P b_*^2 c}{\eta \kappa r^2} - \frac{\eta P b_*}{\kappa \rho_{\text{soil}} c r} \right) \sin \frac{\eta \kappa \tau}{\rho_{\text{soil}} c b_0} + \frac{P b_*}{\rho_{\text{soil}} c r} \cos \frac{\eta \kappa \tau}{\rho_{\text{soil}} c b_0} \right], \quad (5)$$

where

$$\begin{aligned} \eta^2 &= \frac{2(1-2\sigma)\rho_{\text{soil}}c^2 + 3(1-\sigma)\gamma P}{2(1-\sigma)}, \\ \kappa^2 &= \frac{2\rho_{\text{soil}}c^2 - 3(1-\sigma)\gamma P}{2(1-\sigma)}, \\ \tau &= t - \frac{r - b_0}{c}. \end{aligned} \quad (6)$$

Seismic exploration analyzes the spectral characteristics of seismic waves from the perspectives of main frequency and bandwidth. Schenk proposed to use the mean value of the frequency at which the 0.7-times vibration amplitude value is located as the main frequency of the vibration signal, that is,  $f = ((f_2 + f_1)/2)$ , bandwidth  $f_a = f_2 - f_1$ , where  $f_2$  and  $f_1$  are, respectively, the frequencies at which 0.7 times of maximum vibration amplitude is located. To analyze the spectral characteristics of seismic signals, the Fourier transform can be used to quickly process time-domain signals and convert them into frequency-domain signals.

The motion velocity field of the particle of the seismic waves excited by the spherical explosive source is simplified as

$$U(t) = e^{-at} (A \cos(\omega_0 t) + B \sin(\omega_0 t)), \quad (7)$$

where

$$\begin{aligned} a &= \frac{\eta^2}{\rho_{\text{soil}} c b_*}, \\ A &= \frac{P b_*^2 c}{\eta \kappa r^2} - \frac{\eta P b_*}{\kappa \rho_{\text{soil}} c r}, \\ B &= \frac{P b_*}{\rho_{\text{soil}} c r}, \\ \omega_0 &= \frac{\eta \kappa}{\rho_{\text{soil}} c b_*}. \end{aligned} \quad (8)$$

Conduct the Fourier transform to formula (7):

$$F(\omega) = \int_0^{\infty} e^{-at} (A \cos(\omega_0 t) + B \sin(\omega_0 t)) \cdot e^{-i\omega t} dt. \quad (9)$$

That is,

$$F(\omega) = \frac{\sqrt[3]{A^2 + B^2} \omega_0}{(a + i\omega)^2 + \omega_0^2}. \quad (10)$$

The velocity spectrum is

$$|F(\omega)| = \frac{\sqrt[3]{A^2 + B^2} \omega_0}{|(a + i\omega)^2 + \omega_0^2|}, \quad (11)$$

$$|F(\omega)| = \frac{\sqrt[3]{A^2 + B^2} \omega_0}{\sqrt{(a^2 - \omega^2 + \omega_0^2)^2 + 4a^2 \omega^2}}. \quad (12)$$

## 4. Discussion

According to formula (12), it can be deemed that  $a$  and  $\omega_0$  are the main parameters affecting the spectral characteristics of the vibration at the elastic wave radius. In order to analyze the relationship between bandwidth and the parameters of  $a$  and  $\omega_0$ , normalization was conducted to vibration amplitude, based on which it could be seen that when  $\omega_0$  was maintained unchanged and  $a$  increased from 50 to 150, the main frequency had no change, while the bandwidth increased from 25 Hz to 35 Hz; when  $\omega_0$  increased from 50 to 100, the main frequency of the seismic waves increased from 50 Hz to 165 Hz, while the bandwidth was remained unchanged. The laws of changes are as shown in Figure 3. This means that  $a$  affects the bandwidth, and the greater the  $a$ , the wider the bandwidth;  $\omega_0$  affects the main frequency, and the greater the  $\omega_0$ , the higher the main frequency. Since  $a$  and  $\omega_0$  are closely related to explosive parameters and geotechnical medium parameters, it is necessary to analyze the influences of each explosive parameter and geotechnical medium parameter on the seismic wave frequency spectrum.

**4.1. The Influences of Explosive Source Parameters on Amplitude-Frequency Characteristics.** It can be figured out from formulas (1), (5), and (12) that the explosive parameters of detonation velocity  $D$ , initial detonation pressure  $P_0$ , and explosion adiabatic expansion  $\gamma$  will affect the seismic wave amplitude-frequency characteristics. In order to analyze the impacts of detonation velocity  $D$  and explosion adiabatic expansion  $\gamma$  on the amplitude-frequency characteristics of seismic waves in detail, the excitation of the explosive source in the geomaterial was taken as the basic data to verify the parameters in this paper. The explosive source is 1 kg TNT, and the geomaterial medium is silt clay. For the detailed parameters of TNT and silt clay, please refer to Tables 1 and 2.

Substitute data of Tables 1 and 2 into formulas (1), (3), (5), and (12), respectively, the data of detonation pressure, cavity, elastic area radius, and particle vibration velocity frequency and bandwidth at the elastic radius part, which are excited by the explosion of spherical explosive source in silt clay, can be obtained accordingly. In order to study the influencing laws of explosive source parameter changes on the amplitude-frequency characteristics, only a single parameter was changed while all others were maintained unchanged during the calculation process. Figures 4–9 show

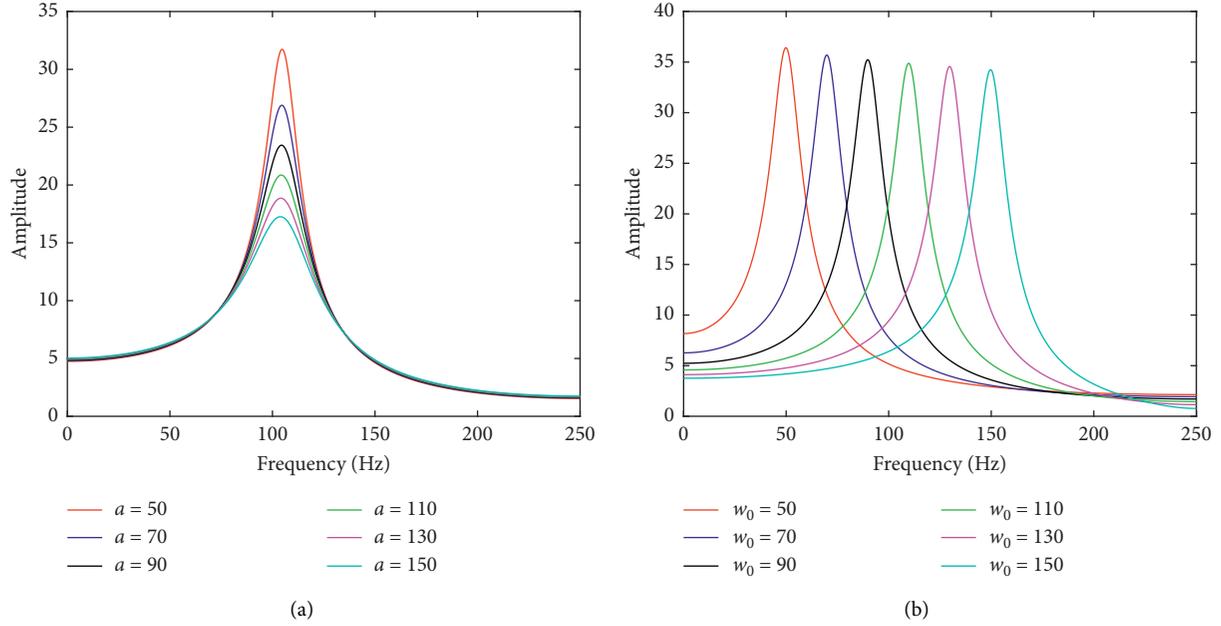


FIGURE 3: The influencing laws of  $a$  and  $w_0$  on the amplitude and frequency of seismic waves.

the changes of the amplitude-frequency characteristics of the seismic wave which was formed with the changes in the initial detonation pressure, adiabatic expansion, and geo-technical parameters of the explosive.

According to the research of Henrych, the detonation pressure range of conventional explosives is 5–10 GPa. In the prediction model, the detonation pressure was set to be 4, 8, and 12 GPa, and other parameters were maintained as shown in Tables 1 and 2. Figure 4 shows the frequency spectrum of the seismic wave changing with the initial detonation pressures: with the initial detonation pressure increases, the frequency of the seismic wave decreases and the frequency band becomes narrower. The size and wall pressure of the explosion cavity after the detonation is also closely related to the initial detonation pressure. The increase of the initial detonation pressure leads to an increase in the stress that the explosive source applied to the geomaterial medium at the time of detonation, thereby forming larger cavity. The greater the detonation cavity, the lower the cavity wall pressure. The enlargement of cavity size reduces the particle vibration frequency. When the initial detonation pressure increases from 4 GPa to 12 GPa, the main frequency decreases from 306.4 Hz to 240.6 Hz, and the bandwidth attenuates from 440 Hz to 350 Hz.

The adiabatic expansion of the explosives is the parameter characterizing the attenuation of the maximum stress state of the high pressure gas caused by explosion. The greater the index, the faster the attenuation. Opjehko figured out based on the relative research that the adiabatic expansion of conventional explosives is from 1.5–3.5. In the prediction model, the adiabatic expansion was set to be 1.5, 2.5, and 3.5, respectively, while all other parameters were maintained as shown in Tables 1 and 2. Figure 5 shows the impacts of adiabatic expansion changes

TABLE 1: Parameters of TNT.

$\rho$ ( $\text{kg}\cdot\text{m}^{-3}$ )	$D$ ( $\text{m}\cdot\text{s}^{-1}$ )	$P_0$ (GPa)	$\gamma$
1650	6930	9.82	3.15

TABLE 2: Parameters of soil.

$\sigma_*$ (MPa)	$\sigma_0$ (MPa)	$\mu$ (GPa)	$\rho_{\text{soil}}$ ( $\text{kg}\cdot\text{m}^3$ )	$K$ (MPa)	$q$
13	2	0.147	1840	245	2

on amplitude-frequency characteristics of the seismic waves. With the increase of the adiabatic expansion, the main frequency of the seismic wave enlarges and the bandwidth broadens. When the adiabatic expansion increases, the velocity of blasting pressure attenuation increases, the detonation cavity size reduces, and the seismic wave frequency increases. When the adiabatic expansion increased from 1.5 to 3.5, the main frequency of the seismic waves increased from 185 Hz to 350 Hz, while the bandwidth increased from 250 Hz to 510 Hz.

To increase the frequency and bandwidth of the explosive seismic waves, explosives having larger adiabatic expansion and higher detonation pressure can be considered to increase frequency while guaranteeing no reduction of energy. Meanwhile, adding volume of explosive can increase the bandwidth and enhance the proportion of low-frequency signals and reduce the energy dispersion of the seismic waves when spreading in the geomaterial medium. This is conducive for prospecting in deeper stratum.

4.2. *Impacts of Geomaterial Parameters on Amplitude-Frequency Characteristics.* By referring to the method of analyzing the impacts of explosive source parameters on seismic

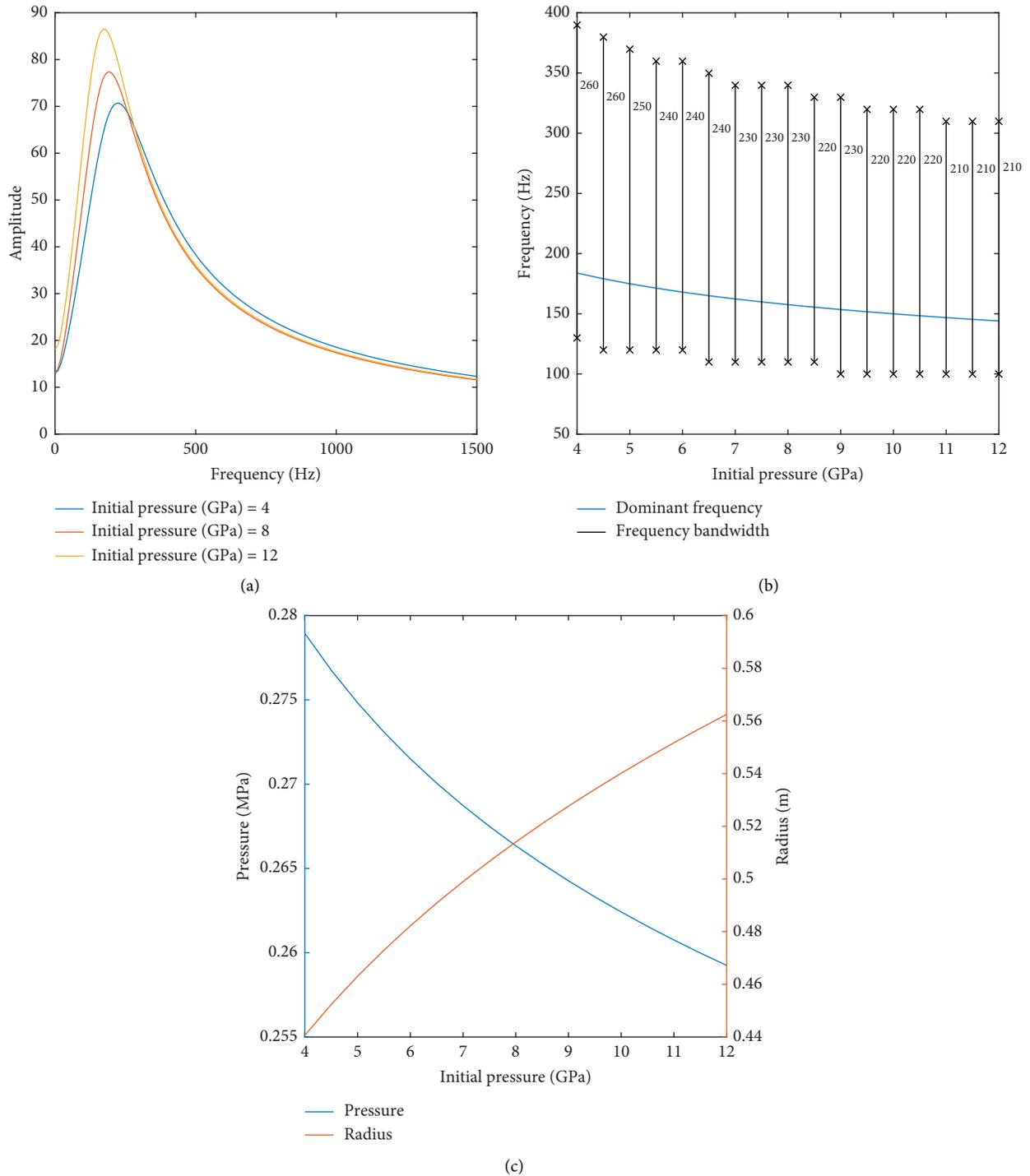


FIGURE 4: Impacts of initial detonation pressure changes on seismic wave frequency at elastic radius position. (a) Impacts of initial detonation pressure on velocity and frequency-amplitude characteristics of particle vibration. (b) Impacts of initial detonation pressure on velocity, main frequency, and bandwidth of particle vibration. (c) Impacts of initial detonation pressure on detonation cavity and its internal pressure.

wave spectrum, the way of changing a single parameter was adopted to analyze the impacts of geomaterial parameters on seismic waves formed by the explosive source. Among geomaterial parameters, the part having close relationship with amplitude-frequency characteristics of the seismic waves include density  $\rho_{soil}$ , compressive strength  $\sigma_*$  (Figure 6),

tensile strength  $\sigma_0$  (Figure 7), Lamé coefficient  $\mu$  (Figure 8), and shear modulus  $G$  (Figure 9).

When the compressive strength of the geomaterial increases, the frequency of the seismic waves increases, the detonation volume reduces, and the frequency of the seismic waves increases. When the compressive strength of the

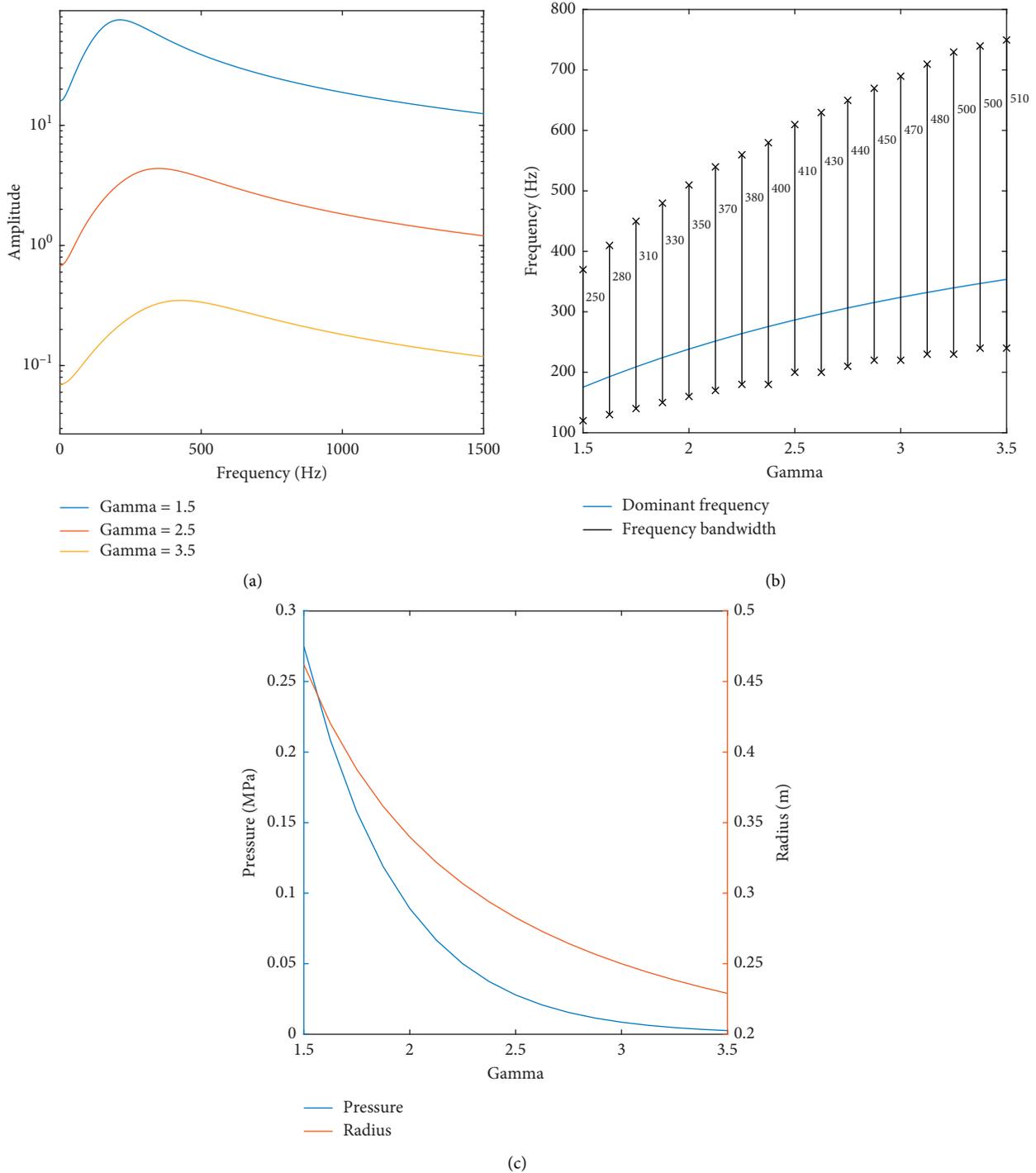


FIGURE 5: Impacts of adiabatic expansion changes on seismic wave frequency. (a) Impacts of adiabatic expansion on velocity and frequency-amplitude characteristics of seismic wave. (b) Impacts of adiabatic expansion on velocity, main frequency, and bandwidth of particle vibration. (c) Impacts of adiabatic expansion on detonation cavity and its internal pressure.

geomaterial increased from 6 MPa to 20 MPa, the main frequency of the seismic waves enlarged from 147 Hz to 252 Hz, while the bandwidth increased from 200 Hz to 320 Hz.

According to the analysis of Section 2, the spherical satchel charge would leave spherical detonation cavity in the homogeneous medium after explosion. The stress on radial direction on the cavity wall and the geomaterial

compressive strength are in a balanced status; the stress on circumferential direction and the geomaterial tensile strength are in a balanced status. This is the result of co-action of tensile strength and compressive strength. Therefore, the laws of tensile strength influencing the amplitude-frequency characteristics of seismic waves are similar to those of the compressive strength. The greater

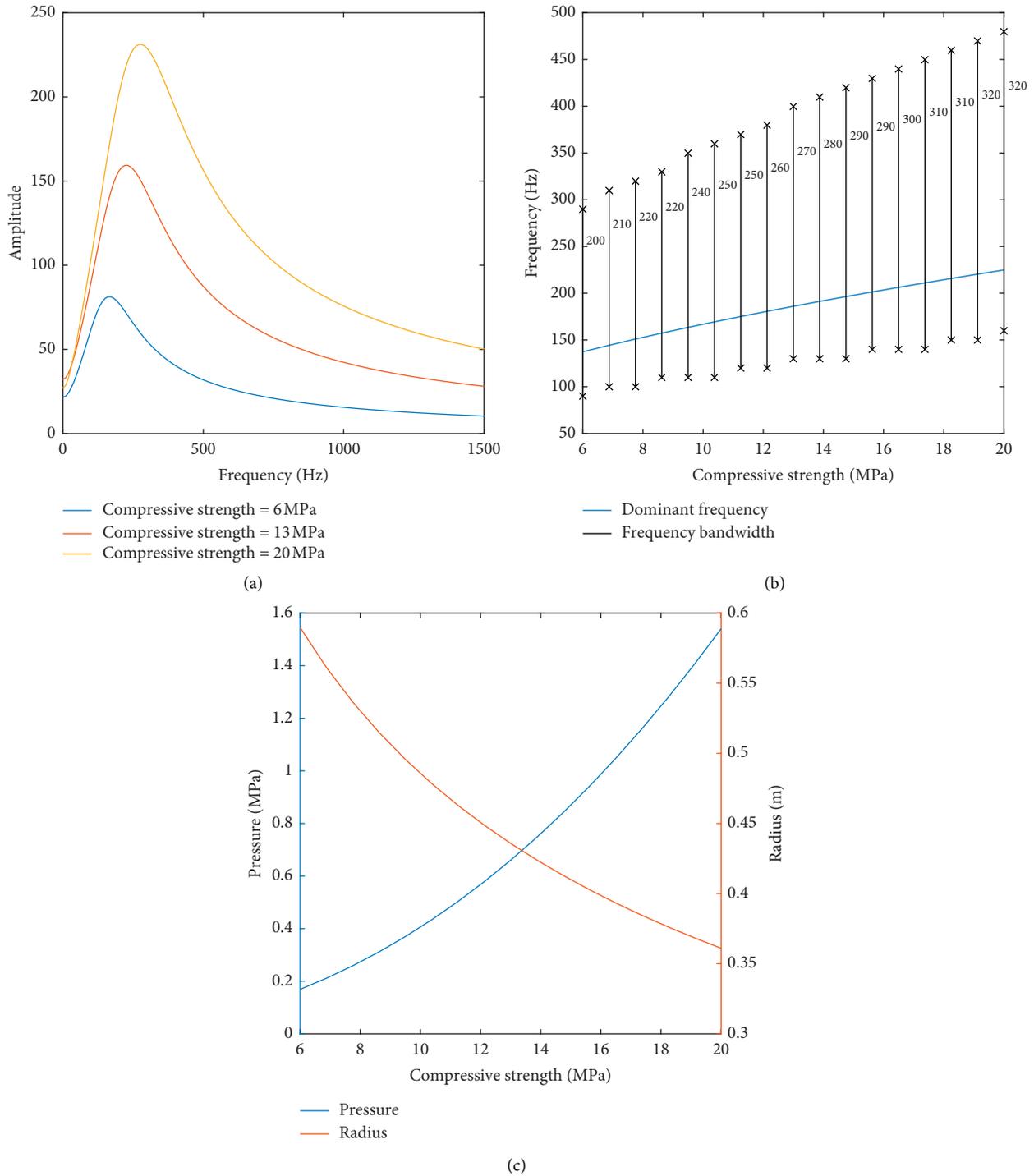


FIGURE 6: Impacts of geomaterial compressive strength on amplitude-frequency characteristics of seismic waves. (a) Impacts of geomaterial compressive strength on velocity and frequency-amplitude characteristics of particle vibration. (b) Impacts of geomaterial compressive strength on velocity, main frequency, and bandwidth of particle vibration. (c) Impacts of geomaterial compressive strength on detonation cavity and its internal pressure.

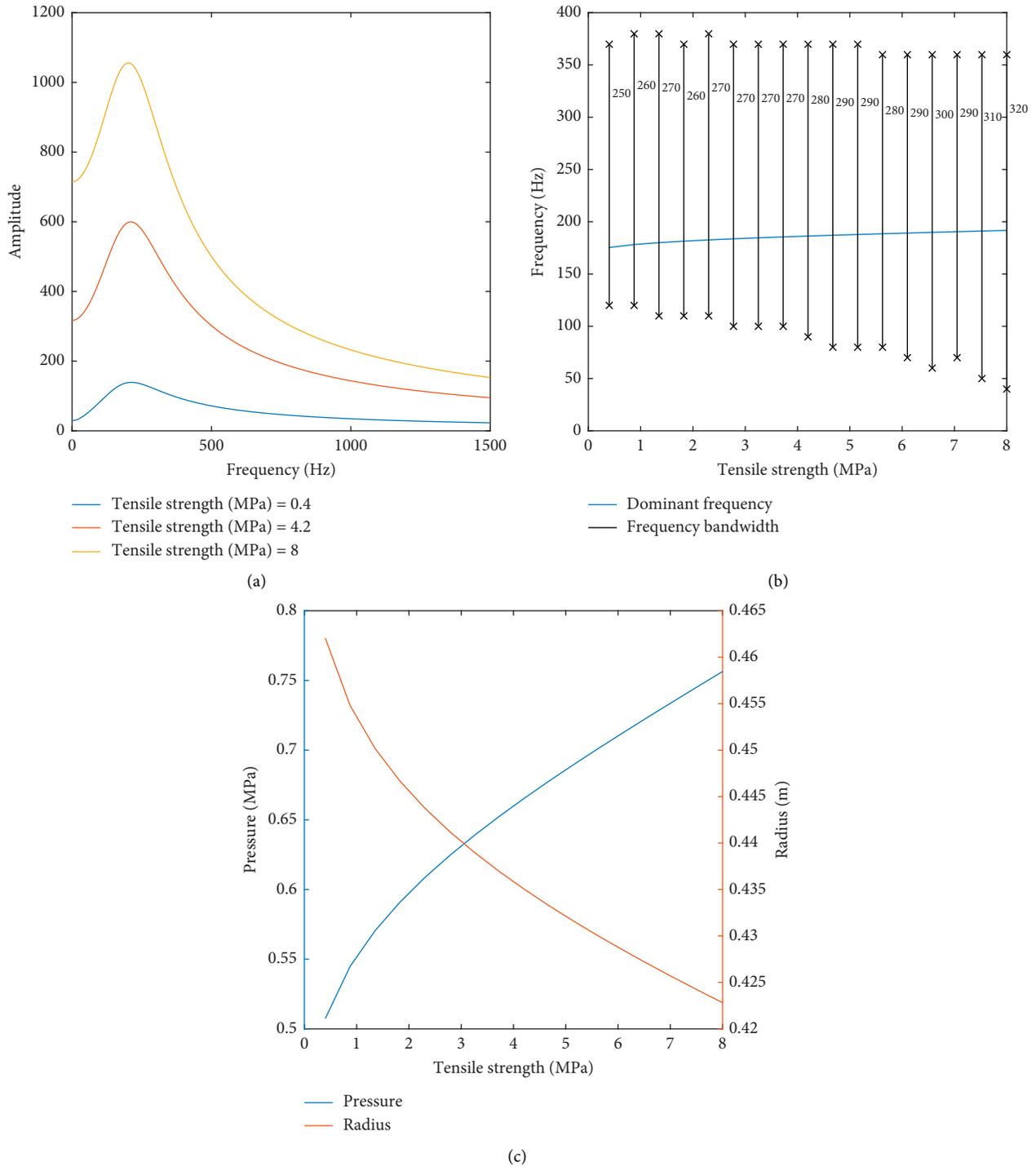


FIGURE 7: Impacts of geomaterial tensile strength on amplitude-frequency characteristics of seismic waves. (a) Impacts of geomaterial tensile strength on velocity and frequency-amplitude characteristics of particle vibration. (b) Impacts of geomaterial tensile strength on velocity, main frequency, and bandwidth of particle vibration. (c) Impacts of geomaterial tensile strength on detonation cavity and its internal pressure.

the compressive strength, the smaller the detonation cavity (Figure 8(c)) and the larger the seismic wave frequency. When the tensile strength of the geomaterial increased from 0.4 MPa to 8 MPa, the main frequency of the seismic waves enhanced from 175 Hz to 190 Hz, while the bandwidth increased from 250 Hz to 320 Hz.

The greater the Lamé Coefficient, the larger the detonation radius and the lower the seismic wave frequency. When the geomaterial Lamé Coefficient increased from 0.2 GPa to 0.4 GPa, the main frequency of the seismic wave decreased from 175 Hz to 149 Hz and the bandwidth decreased from 250 Hz to 210 Hz.

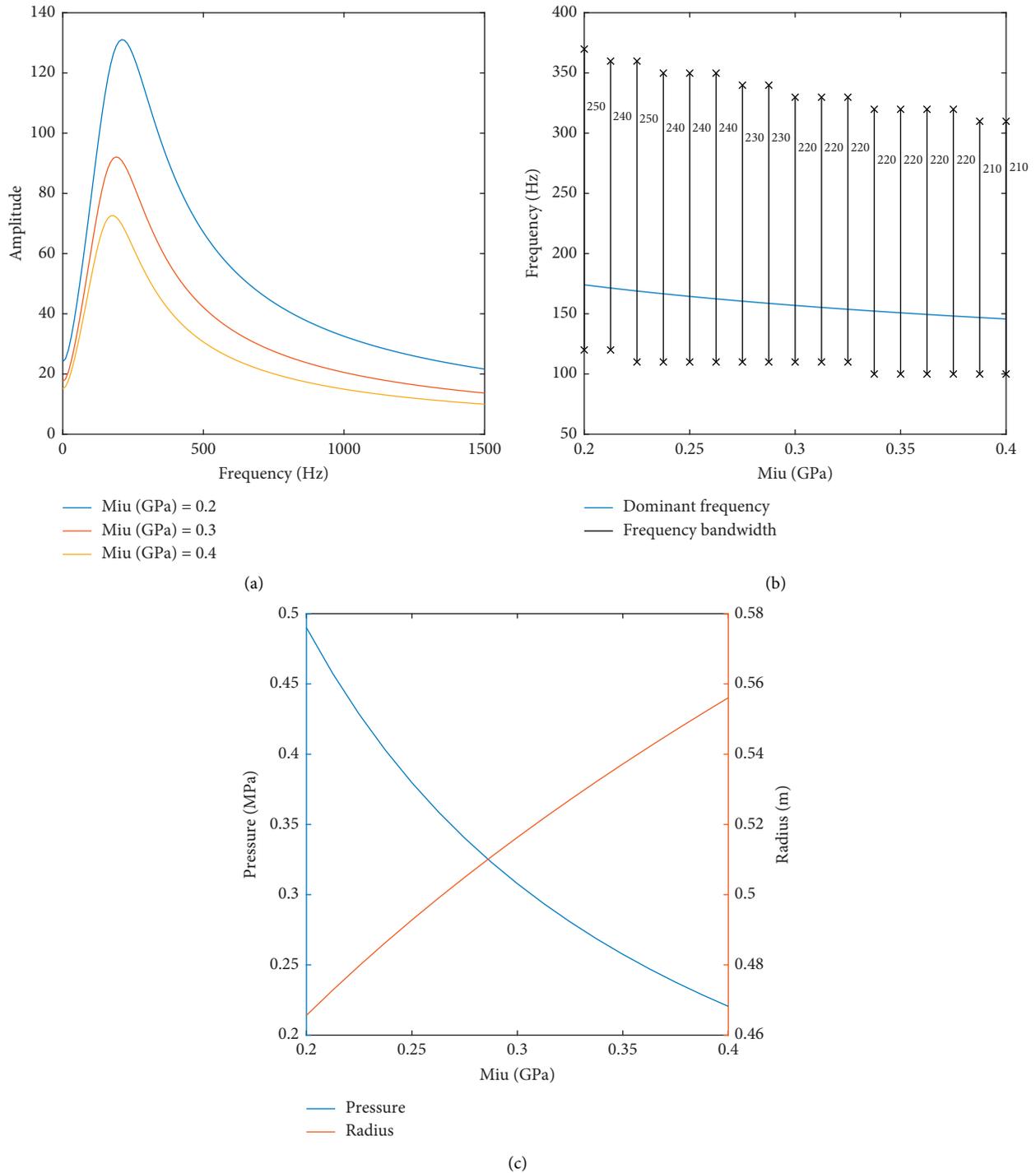


FIGURE 8: Impacts of geomaterial Lamé coefficient on amplitude-frequency characteristics of seismic waves. (a) Impacts of geomaterial Lamé coefficient on velocity and amplitude-frequency characteristics of particle vibration. (b) Impacts of geomaterial Lamé coefficient on velocity, main frequency, and bandwidth of particle vibration. (c) Impacts of geomaterial Lamé coefficient on detonation cavity and its internal pressure.

Although the longitudinal wave velocity of the geomaterial affects the mechanics parameters, it has nothing to do with the geomaterial strength. So, the wave velocity changes will not change the detonation cavity and its internal pressure. Under

the same stress conditions, the greater the geomaterial wave velocity, the larger the elastic modulus. Under the same stress conditions, it results in smaller particle strain, shorter time required for particle rebound, and shorter vibration period,

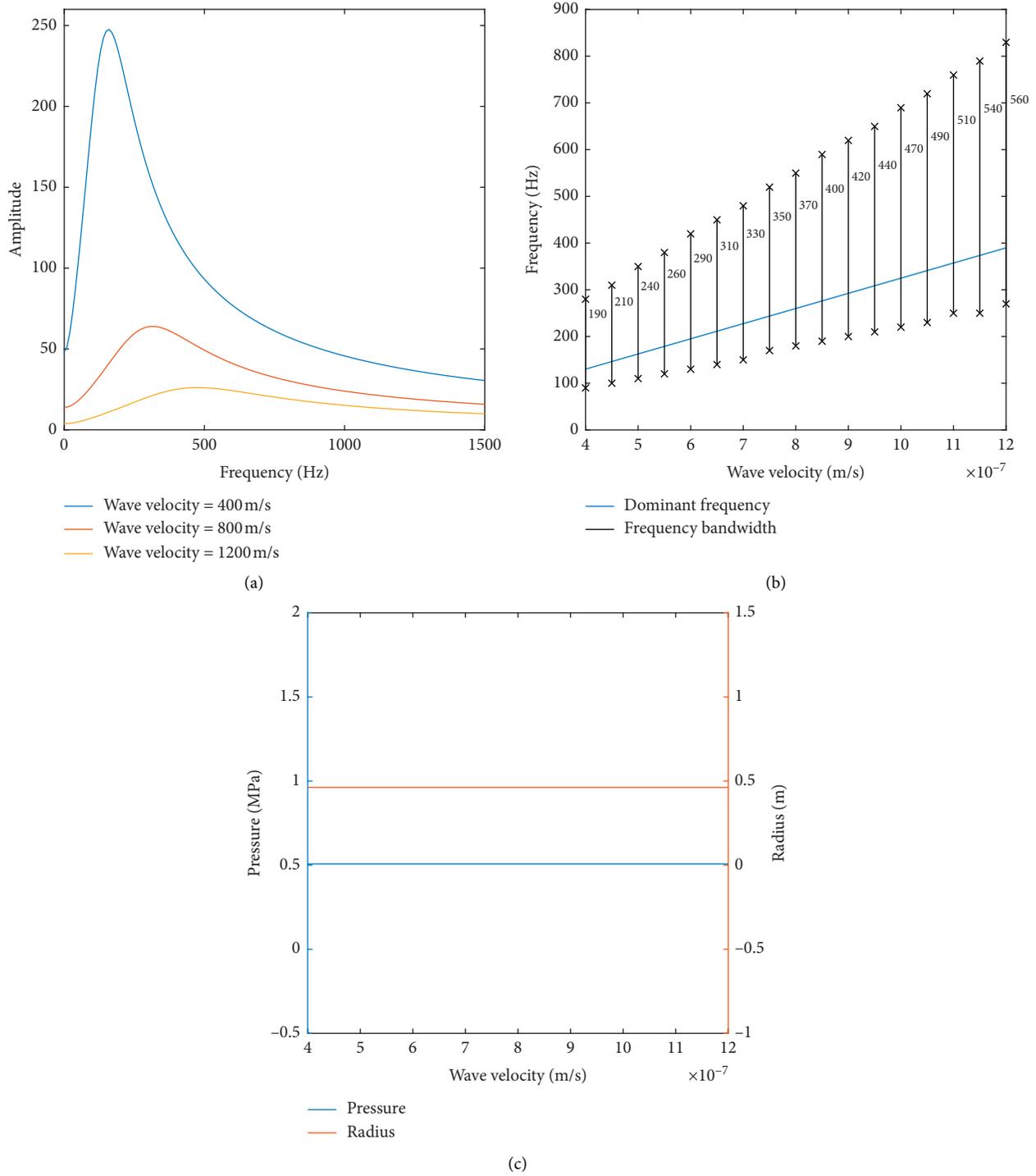


FIGURE 9: Impacts of wave velocity of geomaterial on amplitude-frequency characteristics parameters of seismic waves. (a) Impacts of wave velocity of geomaterial on velocity and amplitude-frequency characteristics of particle vibration. (b) Impacts of wave velocity of geomaterial on velocity, main frequency, and bandwidth of particle vibration. (c) Impacts of wave velocity of geomaterial on detonation cavity and its internal pressure.

but increased vibration frequency. Therefore, the greater the wave velocity in geomaterial, the higher the frequency of seismic waves. When the wave velocity increased from 400 m/s to 1200 m/s, the main frequency of the seismic wave increased from 130 Hz to 390 Hz, while the bandwidth increased from 190 Hz to 560 Hz.

4.3. *Experimental Results' Comparison.* The on-site experiment was conducted to verify the model for calculating spectrum of seismic waves excited by the explosive source. In the experiment, the AN-TNT, AN-TNT-AL, and AP-RDX-AL-G were used as seismic sources. The explosives were embedded 12 m below the ground surface. For all explosives,

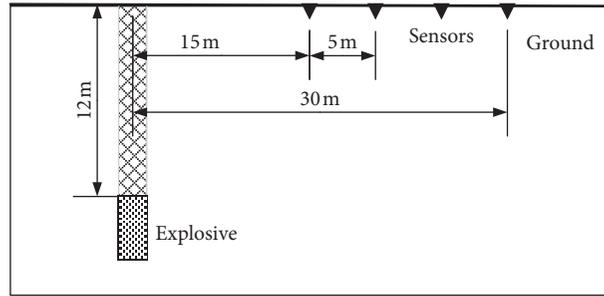


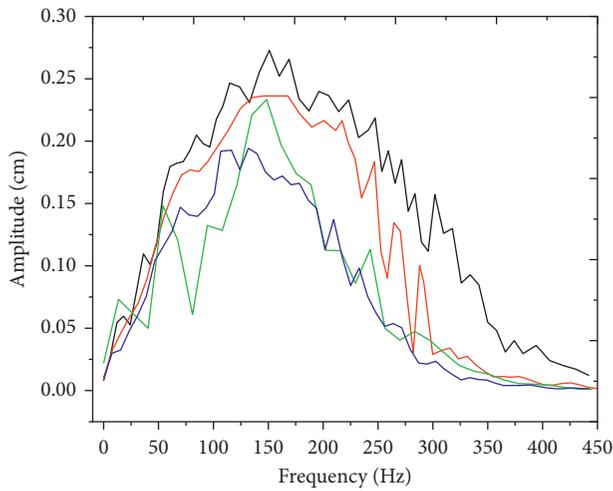
FIGURE 10: Layout plan of geophones.

TABLE 3: Initial detonation pressures and adiabatic expansion indexes of four explosives.

Explosive	Detonation pressure (GPa)	Adiabatic expansion index
AN-TNT	8.98	3.00
AN-TNT-AL	8.94	2.49
AP-RDX-AL-G	9.82	2.35
Emulsion	9.81	2.30

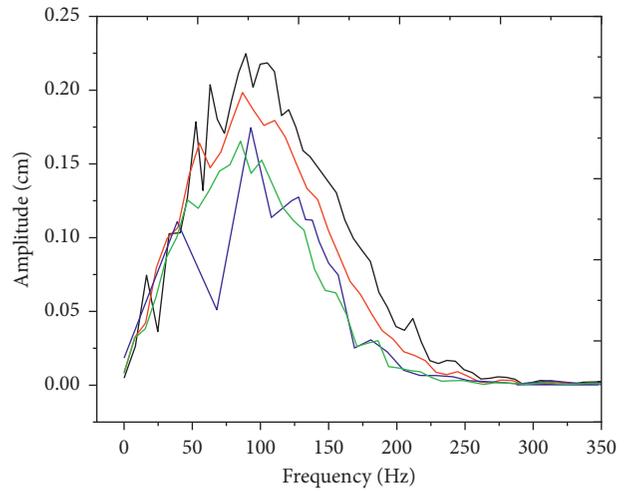
TABLE 4: Geomaterial parameters.

Geomaterials	$\sigma_*$ (MPa)	$\sigma_0$ (MPa)	$\mu$ (GPa)	$F$	$K$ (kPa)	$\rho_{\text{soil}}$ (kg/m <sup>3</sup> )	$\sigma$
Silt	6.2	0.8	0.09	0.38	25	1400	0.25
Silt clay	11.6	2	0.16	0.2	50	1600	0.25



15m  
 — APRDXALG      — ANTNT  
 — ANTNTAL      — Emulsion

(a)



20m  
 — APRDXALG      — ANTNT  
 — ANTNTAL      — Emulsion

(b)

FIGURE 11: Continued.

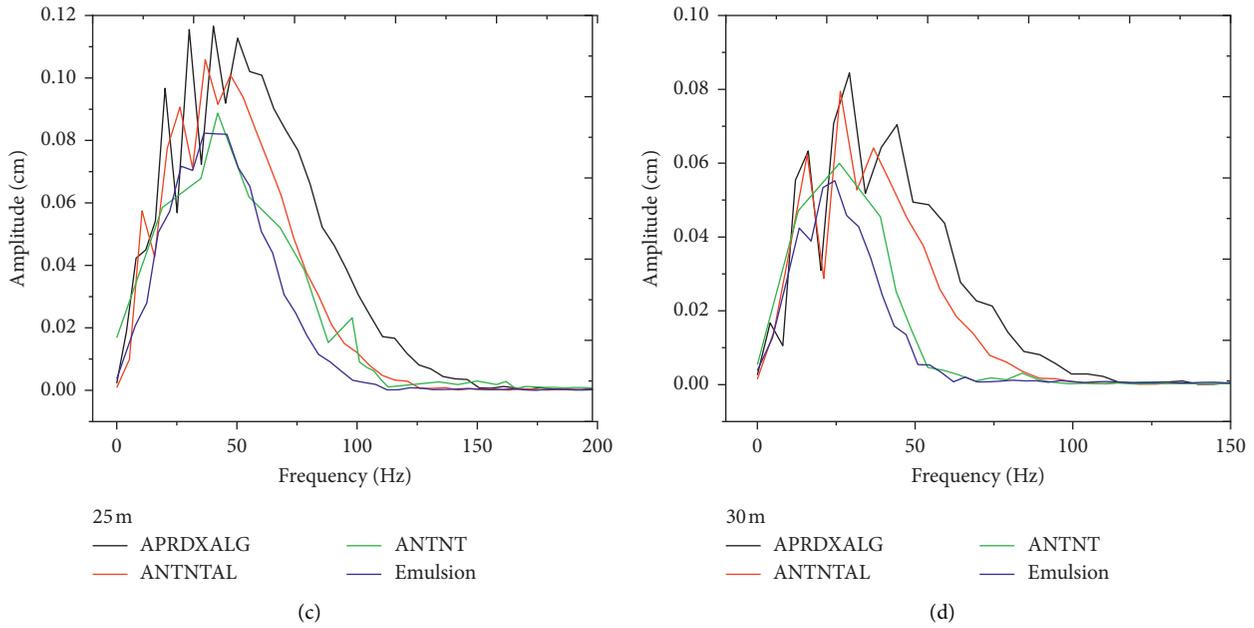


FIGURE 11: Spectrum of seismic waves excited by different explosives at different distances in geomaterials. (a) Spectrum comparison at 15 m position. (b) Spectrum comparison at 20 m position. (c) Spectrum comparison at 25 m position. (d) Spectrum comparison at 30 m position.

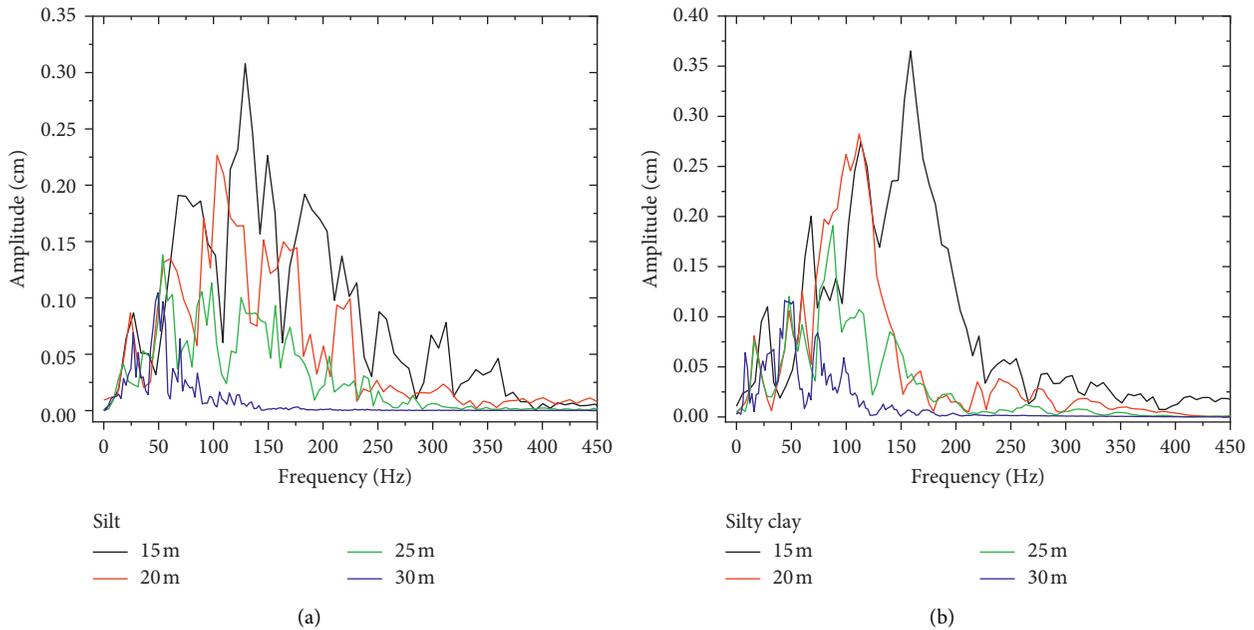


FIGURE 12: Spectrum comparison of seismic waves excited at different positions in different geomaterials. (a) Spectrum comparison of seismic waves excited in silt. (b) Spectrum comparison of seismic waves excited in silty clay.

the quantity of 4 kg was adopted. The sensors were embedded in 0.3 m depth with 5 m horizontal interval. And, for the deployment of the geophones, see Figure 10. The seismic waves were recorded by the 428XL digital seismograph produced by the French Sercel company. The adiabatic expansion index and the detonation pressure are as shown in Table 3. And, the geomaterial parameters are as shown in Table 4.

It can be figured out from Figure 11 that the seismic wave frequency excited by explosive with high detonation pressure is lower than the seismic wave frequency excited by conventional explosives, among which the AP-RDX-AL-G formed maximum seismic wave frequency, followed by AN-TNT-AL explosive. Besides, the AN-TNT and AN-TNT-AL showed basically the same initial detonation pressures, but the later's adiabatic expansion index is 25% higher than that

of the former, and the frequency of the later is significantly higher than that of the former, showing 11.1% main frequency increase and 9.38% increase of bandwidth. The experiment results have proved the correctness of the theoretical model, and explosives with low detonation pressure and low adiabatic expansion index excite seismic waves with higher frequency and broader bandwidth.

According to Figure 12, which shows the comparison results of the spectrum of the seismic waves excited in different geomaterials, the main frequency of the seismic wave excited in the silt clay is, respectively, 23.2%, 8.7%, 38.5%, and 10.74% higher at four positions of 15 m, 20 m, 25 m, and 30 m compared to those seismic waves excited in the silt. No matter whether it is geomaterial strength or Lamé Coefficient, the silt clay is better than the silt and can excite better seismic wave. This is in line with the results obtained by the theoretical model. Therefore, in practical engineering, the explosive source excitation can be conducted in silt clay or clay instead of silt.

## 5. Conclusions

In order to make clear the relationship between the explosive source and the amplitude-frequency characteristics of the seismic wave, the model for predicting the seismic wave spectrum excited by the explosive source was established in this paper, which overcomes the problems that the explosive source model cannot describe the explosive source parameters quantitatively, and the geomaterial parameters have insufficient impacts on the seismic wave spectrum excited by explosives, providing theoretical basis for guiding the fine exploration and production.

This model was applied to analyze the impacts of explosive source parameters on the seismic wave spectrum. The results show that when the initial detonation pressure of the explosive increased from 4 GPa to 12 GPa, the main frequency of the seismic waves decreased from 64.1 Hz to 52.3 Hz, while the bandwidth attenuated from 62 Hz to 48 Hz; when the adiabatic expansion increased from 1.5 to 4.5, the main frequency of seismic waves increased from 65.7 Hz to 124.7 Hz, while the bandwidth increased from 55 Hz to 132 Hz. Lower initial detonation pressure and higher adiabatic expansion can effectively increase the seismic wave frequency and frequency bandwidth, thereby improving seismic exploration resolution and facilitating the detection towards deeper stratum. When the geomaterial compressive strength increased from 6 MPa to 20 MPa, the main frequency of the seismic waves increased from 147 Hz to 252 Hz, and the bandwidth increased from 200 Hz to 320 Hz. When the geomaterial tensile strength increased from 0.4 MPa to 8 MPa, the main frequency of the seismic waves enhanced from 175 Hz to 190 Hz, and the bandwidth increased from 250 Hz to 320 Hz. When the Lamé coefficient increased from 0.2 GPa to 0.4 GPa, the main frequency of the seismic waves increased from 175 Hz to 149 Hz and the bandwidth increased from 250 Hz to 210 Hz. When the wave velocity increased from 400 m/s to 1200 m/s, the main frequency of the seismic waves increases from 130 Hz to 390 Hz, and the bandwidth increased from 190 Hz to 560 Hz.

The results indicate that the explosive source may excite higher seismic wave frequency and bandwidth in harder geomaterial.

In addition, on-site experiment was carried out to verify the prediction model. The detonation pressure decrease and adiabatic expansion increase of the explosives can lead to increases of the amplitude, frequency, and bandwidth. Moreover, it was also figured out from the experiment that compared to the seismic waves excited in silt, the main frequency of seismic waves excited in silt clay increased by 23.2%, 8.7%, 38.5%, and 10.74% at four positions of 15 m, 20 m, 25 m, and 30 m, while the bandwidth increased by 13.6%, 10.7%, 8.76%, and 14.3%, respectively. The experimental results show that the spectrum calculation model can describe the seismic spectrum characteristics excited by explosive blasting, which provides theoretical foundation for guiding the fine prospecting and production.

It should be noted that the prediction model in the paper simplifies the geomaterial parameters in order to quickly predict the seismic wave spectrum. However, the simplified parameters may affect the calculation of seismic wave frequency, for example, the explosion effects may result in density changes of mediums near the seismic source. Besides, the attenuation effect of seismic wave in geomaterial could also affect the amplitude-frequency characteristics of the entire seismic wave field. These factors need to be further studied in the future.

## Data Availability

The data used to support the findings of the study are available within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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