Study on Changes in Wave Velocity in Surrounding Tunnel Rock under Different High In-situ Stresses

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Abstract: Studies have indicated that in the tunnel’s surrounding rock, high in-situ stress influences the wave velocity changes. Under different ground stresses, an underground model system is used to study the propagation characteristics of the blasting seismic wave velocity. The electric spark was used to recreate explosive blasting by employing a model loading system to simulate gradient loading under high in-situ stress in the tunnel. The DH5983 dynamic signal analytical system was used to collect the vibration acceleration and calculate the average velocity. The average radial and axial wave velocities gradually increased with increasing in-situ stress, and the increase in the average radial wave velocity was greater than the axial wave velocity, according to the test results. The growth rate of the average wave velocity gradually slowed down under various high in-situ stressors, with that in the low in-situ stress stage being greater than in the high in-situ stress stage. A logarithmic growth trend is seen when the wave velocity gradually becomes constant. The average decay growth rate of the radial wave velocity was larger than the rate of axial velocity, which was approximately 1.5 times.

Key words: high in-situ stress; blasting; average wave velocity; model test

1. Introduction
The effect of tunnel blast disturbance on the surrounding rock and the energy transmission in the rock mass are received in the form of blasting seismic waves. The tunnel is affected by increasing levels of high in-situ stress. The interaction of blasting seismic wave and high in-situ stress have a series of effects on the changes of wave velocity in the tunnel surrounding rock. The wave velocity is reflection of the physical and mechanical characteristics of the surrounding rock. Therefore, blasting design and construction safety must be regulated to investigate the changes in blasting seismic wave velocity in the surrounding rock under high in-situ stress.

Many studies have been conducted on the changes of wave velocity in the tunnel surrounding rock. Zhao et al. [1] conducted an indoor saturated soil test on a plane wave loader and an in-depth analysis of the changing law of the wave velocity of the explosion wave load. Fan et al. [2] analyzed the effect of initial stress on the rock elastic wave velocity by using theoretical models and test results. Tao [3] used wave velocity as a representative parameter through theory and experimental methods to study the transmission mechanism and control theory of stress waves in the initial stress under dynamic disturbance. Li et al. and Wang et al. [4-5] analyzed the influence of confining pressure on the acoustic wave velocity of rocks through indoor tests and on-site testing. In terms of on-site testing, Wang et al.
analyzed and discussed the problem of abnormal wave velocity changes before and after the blasting excavation of rock mass. Xiao et al. [7] based on field tunnel blasting test results and studied the change law of sonic wave velocity along the hole depth and the effect of cyclic blasting on the wave velocity in the survey area. Liu et al. [8] based on the measured tunnel seismic wave velocity, analyzed the measured seismic wave velocity distribution and the anisotropy of the surrounding rock. Xie et al. [9] through an analysis of the changes in the coal stress and longitudinal wave velocity in different blasting ranges, conducted a series of controllable pre-splitting blasting tests at the Coal Mine. Ma [10] carried out the engineering practice of rock column ground blasting by collecting the wave velocity in the coal and rock mass media before and after blasting, utilizing a micro seismic monitoring system. Then, they analyzed the effect of rock column ground blasting. Chen et al. [11] studied the attenuation law and related influencing factors of blasting seismic wave propagation velocity during mining. Cong et al. [12] analyzed the qualitative relationship between the wave velocity and the stress of the slot wave and evaluated the effect of blasting pressure relief on the coal face. Liang et al. [13] used LS-DYNA to simulate the process of rock crack growth in single-hole blasting on slopes and analyzed the crack growth based on the relationship between the rate of change of blasting wave velocity and the average stress of the crack unit and the attenuation law of the blasting stress wave. In theory, Lei et al. [14] solved the wave propagation in a circular hole under double exponential blasting load using the characteristic curve method and presented the wave velocity calculation result.

In conclusion, the blasting seismic wave velocity is difficult to test and study under different high in-situ stress conditions at the engineering site and existing laboratory conditions. There is a scarcity of research on theoretical and numerical simulations. At present, no model test research is available on the changes in blasting seismic wave velocity under different high in-situ stresses. In this study, a 3D underground engineering comprehensive model test device with dynamic loading function and electric spark initiation of non-explosive rolls was used to simulate tunnel blasting excavation. A blasting mechanical model test was carried out to study the changes in blasting seismic wave velocity in the tunnel surrounding rock under different high in-situ stresses. This research introduces a new method for the study of blasting seismic wave velocity, and the test results provide a reference for tunnel blasting design.

2. Model test design

2.1. Model test system introduction

This test used an underground engineering model test system to study the changes in blasting seismic wave velocity in the tunnel surrounding rock under different high in-situ stresses. A model reaction force bench device (Figure 1a), a hydraulic loading system, a blasting simulation system and a test analytical system are the major components of the system.

The model reaction force bench device has an excavation perspective window, and a hydraulic loading system is used to provide the 3D dynamic gradient loading of the model. The accuracy of the pressure control was 0.1 MPa. The blasting simulation system consisted of a non-explosive seismic source device, an intelligent control initiation device and connection lines. The non-explosive seismic source is controlled by the CD-2 portable electric spark device to initiate detonation. Figure 1b shows a CD-2 portable electric spark source device. Wave absorbing plates were installed on the inner boundary of the model to prevent the shock wave from rebounding and to reduce the shock wave generated by the explosion, ensuring that the blasting dynamic boundary condition was met. Figure 1c shows a wave absorbing plate. The DH5983 dynamic signal analysis system was used to collect real-time dynamic physical quantities, including stress, strain, displacement, velocity, and acceleration of the tunnel’s surrounding rock. Figure 1d shows the DH5983 dynamic signal analytical system.
2.2. Determination of the similar proportions and materials

This model test simulated an underground circular tunnel with a diameter of 5 m, and the rock mass was homogeneous sandstone. Considering the size limitation of the model device, the size of the design model was 1500×1500×2000 mm (width × height × length). The cross-sectional shape of the tunnel was circular, and the diameter was 20 cm.

According to the similarity theory and dimensional analysis [15], static and dynamic similarities were considered in the experiment. Although there are numerous experimental parameters, only the parameters that have a significant influence on the model test were studied. The similarity ratios of the important physical parameters of the model are shown in Table 1, and the dynamic similarity ratios are shown in Table 2.

| Parameter               | Geometric (m) | Density (g/cm³) | Uniaxial compressive strength (MPa) | Elastic modulus (GPa) | Acoustic wave velocity (m/s) |
|-------------------------|---------------|-----------------|-------------------------------------|-----------------------|-----------------------------|
| Similarity ratio        | 1:25          | 1:1.2           | 1:30                                | 1:30                  | 1:5                         |

| Parameter     | Acceleration (m/s²) | Time (s) | Velocity (m/s) | Frequency (hz) | Quality (g) | Damping N/(m/s) | Rigidity N/m |
|---------------|---------------------|----------|----------------|----------------|-------------|-----------------|--------------|
| Similarity ratio | 1:1                 | 1:5      | 1:5            | 5:1            | 1:18750     | 1:3750          | 1:750        |

Fine sand, cement, gypsum, barite powder, water and borax were selected as similar materials based on the orthogonal test method [16]. The four physical parameters of similar material density, uniaxial compressive strength, elastic modulus, and acoustic wave velocity were subjected to sensitivity and regression analyses. The optimal mix ratio of the similar materials that satisfy the requirements of the tunnel blasting mechanical model test was finally obtained. The mix ratio of the similar materials was fine sand: cement: gypsum: barite powder: water = 8:0.2:0.5:0.3:1, respectively. The borax concentration in the water was 1%, and borax acts as a retarder. Similar materials are shown in Figure 2.

Figure 1. Model test system

Figure 2. Similar materials.

The basic physical and mechanical parameters of the prototype sandstone and similar materials are
shown in Table 3.

**Table 3. Physical and mechanical parameters of the prototype sandstone and similar materials**

| Material          | Uniaxial compressive strength (MPa) | Elastic modulus (GPa) | Density (g/cm³) | Acoustic wave velocity (m/s) |
|-------------------|-------------------------------------|-----------------------|-----------------|-------------------------------|
| Sandstone prototype | 39.43                               | 14.2                  | 2.39            | 2560                          |
| Similar material  | 1.31                                | 0.47                  | 1.99            | 512                           |

According to the criterion of in-situ stress (Standard for engineering Classification of rock mass [GB/T50218-2014]), the value of high in-situ stress is determined from Equation (1):

\[
\delta = \frac{\sigma_c}{\sigma_1},
\]

where \(\sigma_c\) is the uniaxial compressive strength of rock, MPa; \(\sigma_1\) is the maximum horizontal principal stress value of the vertical tunnel axis, MPa; \(\delta\) is the strength–stress ratio of the surrounding rock; when \(\delta \leq 4\), it is used as the criterion of high in-situ stress.

The range of high in-situ stress calculated by Equation (1) is \(\sigma_1 \geq 0.33\). Hence, 0, 0.5, 1.0, 1.5, and 2.0 MPa were taken as the values of high in-situ stress, and the changes in blasting seismic wave velocity under five in-situ stresses were studied.

### 2.3. Layout of the acceleration measuring points for the model test

In this test, a small-sized acceleration sensor was selected to reduce the data errors caused by the velocity sensor’s size. In the tunnel’s surrounding rock, radial and axial acceleration sensors were arranged to test the vibration acceleration using the time difference technique of receiving blasting seismic wave signals at different acceleration measuring points to calculate the wave velocity in the surrounding rock under different high in-situ stresses. The acceleration sensors are arranged on one side of the tunnel surrounding rock due to the symmetrical layout of the tunnel model. Considering that the area closer to the source was an important research area, the measuring points should be densely arranged, and the corresponding areas farther away from the source should be sparsely arranged.

The acceleration sensors can only receive blasting seismic wave signals in one direction. Therefore, acceleration sensors \(a_1–a_3\) and \(a_5–a_7\) were arranged along the radial and axial directions of the tunnel surrounding rock to measure the acceleration waveform diagrams and data, respectively. The layout plan of the acceleration sensors is shown in Figure 3.

![Figure 3. Layout plan of the acceleration sensors](image)

### 2.4. Model test procedure

1. Install the wave absorbing plates on the inner boundary of the model, and weigh similar materials and mix them well according to the mix ratio. Fill similar materials into layers, and use jacks to
compact them. The height of each layer was 3 cm. Fill them to 80 cm.

(2) The acceleration sensors and a prefabricated blast hole were pre-buried at a height of 75 cm. The sensor wires on both sides were led out of the holes and connected to the DH5983 dynamic signal analysis system to check whether there were broken sensors. Continue to fill up to the design height of 150 cm. The upper surface of the model was covered with plastic wrap and fully cured for 30 days. Remove the plastic wrap, and close the upper boundary of the model. Figure 4 shows the acceleration sensors and prefabricated blast hole.

![Acceleration sensors and prefabricated blast hole](image1)

Figure 4. Acceleration sensors and prefabricated blast hole

(3) Excavate the circular cross section tunnel manually until the blast hole stopped. The tunnel’s diameter was 20 cm. Figure 5 shows the underground tunnel.

![Underground tunnel](image2)

Figure 5. Underground tunnel

(4) In the test, the model reaction force bench device and a hydraulic loading system were used to impose a triaxial load on the test model, as shown in Figure 6a. The test model was loaded in-situ stresses of 0, 0.5, 1.0, 1.5 and 2.0 MPa, and electric spark blasting was carried out in the pre-buried blast hole on the tunnel palm face. The blasting disturbance energy was taken to be 600 J. The electric discharge head instantly released saturated brine through the tip of the needle, filling the current evenly with saturated brine and producing a high-pressure explosion source. Record the vibration acceleration of the surrounding rock under different high in-situ stresses.

![Loading, non-explosive cylindrical roll and the installation of the blasting device](image3)

Figure 6. Loading, non-explosive cylindrical roll and the installation of the blasting device.

(5) Crush the model at the end of the test to recover various instruments and materials.

3. Underground engineering model test results and analysis

3.1. Vibration acceleration of the surrounding rock

The model test obtained the data and acceleration waveform diagrams of each measuring point under high in-situ stresses of 0, 0.5, 1.0, 1.5, and 2.0 MPa. The acceleration waveform diagrams of measuring points $a_1$–$a_7$ under the in-situ stress of 1.0 MPa are shown in Figures 7 and 8.
Figure 7. Radial acceleration waveform diagrams under the in-situ stress of 1.0MPa

Figure 8. Axial acceleration waveform diagrams under the in-situ stress of 1.0MPa

The reception time difference between the adjacent acceleration measuring points of the same cross section is shown in the acceleration waveform diagram of Figures 7 and 8, indicating that the blasting seismic wave signal received by the DH5983 dynamic signal analytical system is well synchronized. The acceleration waveform diagrams rise from zero fluctuation to the peak and then decay to zero after fluctuation. The acceleration waveforms are great.

3.2. Wave velocity changes in the tunnel surrounding rock

Using the time difference technology of receiving blasting seismic wave signals from the adjacent acceleration measuring points, the time the first peak of each acceleration waveform diagram arrives was taken as the blasting seismic signal arrival time. Then the average wave velocity in the surrounding rock under different high in-situ stresses was calculated, as shown in Equation (2).

$$V_P = \frac{L}{\Delta t}$$  \hspace{1cm} (2)

where $V_P$ is the blasting seismic average wave velocity, m/s; $L$ is the distance between the adjacent acceleration measuring points, m; and $\Delta t$ is the time difference between the adjacent acceleration measuring points receiving the blasting seismic wave signals, s.

The calculated blasting seismic average wave velocity within the range of each acceleration measuring point under different high in-situ stresses is shown in Table 4.

Table 4. Calculated blasting seismic average wave velocity

| In-situ stress (MPa) | $a_1$–$a_2$ | $a_2$–$a_3$ | $a_3$–$a_4$ | $a_5$–$a_6$ | $a_6$–$a_7$ |
|---------------------|-------------|-------------|-------------|-------------|-------------|
| 0                   | 844         | 862         | 837         | 681         | 672         |
| 0.5                 | 1118        | 1131        | 1108        | 866         | 857         |
| 1.0                 | 1207        | 1219        | 1203        | 922         | 914         |
| 1.5                 | 1235        | 1241        | 1236        | 941         | 945         |
| 2.0                 | 1248        | 1247        | 1252        | 960         | 956         |

Figure 9 is plotted based on Table 4 to study the changes in the average wave velocity within the...
range of the same acceleration measuring point under different high in-situ stress.

Figure 9. Changes of the average wave velocity in the same acceleration measuring point range under different high in-situ stresses.

Figure 9 shows that when the high in-situ stress increases, the average radial and axial wave velocities within the same acceleration measuring point range gradually increase. The average radial and axial wave velocity increases are 47.3% and 41.5%, respectively. The increase in radial wave velocity is greater than that in axial wave velocity.

The average wave velocity growth rate gradually slows down. The wave velocity growth rate in the low in-situ stress stage (0–0.5MPa) is greater than that in the high in-situ stress stage (0.5–2.0MPa). The average radial wave velocity growth rate decreased from 543 m/s/Mpa to 23 m/s/Mpa, and the average axial wave velocity growth rate decreased from 370 m/s/Mpa to 30 m/s/Mpa. The wave velocity gradually becomes constant and shows a logarithmic growth trend.

The average decay rate of the growth rate of radial wave velocity is larger than the rate of axial wave velocity. The average decay rates are 260 and 170 m/s/MPa, which are approximately 1.5 times.

The main reason for this is that, as the high in-situ stress increases, the pores and cracks in the surrounding rock gradually compact, and the frictional stiffness between the particles of the surrounding rock gradually increases, reducing the energy loss of the blasting seismic waves in the surrounding rock. When the density gradually reaches the limit, the energy loss of the blasting seismic wave tends to be stable, and the wave velocity slowly tends to be constant.

4. Conclusions
A non-explosive seismic source device with an underground engineering model test system was used instead of traditional explosives. Arranging acceleration sensors in the radial and axial directions of the tunnel’s surrounding rock, a model test study on the changes in wave velocity in the surrounding rock was conducted. The main conclusions drawn in this research can be summarized as follows:

(1) The average radial and axial wave velocities within the same acceleration measuring point range gradually increased with the increase in in-situ stress under different high in-situ stresses. The increase in average radial wave velocity was greater than the increase in average axial wave velocity.

(2) The average wave velocity growth rate gradually slowed down with the increase in the in-situ stress within the same acceleration measurement range under different high in-situ stresses. The wave velocity growth rate in the low in-situ stress stage was much greater than in the high in-situ stress stage. The wave velocity gradually became constant, showing a logarithmic growth trend.

(3) The average decay rate of the growth rate of radial wave velocity was 1.5 times greater than the average decay rate of the growth rate of axial wave velocity.

(4) In the model test, the number of acceleration sensors was limited, and the distance between the acceleration measuring points was slightly larger. In the latter period, it is considered to increase the number of acceleration sensors and reduce the distance between the acceleration measuring points for further testing.
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