Characterization of Dynamic Mechanical Parameters of Rock Fracture Evolution Based on Dry Coupling Point Contact Ultrasonic Technology

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Abstract. The nonlinear characteristics of deep rock masses are very prominent. Accurately obtaining the dynamic mechanical parameters of rock masses and crack damage evolution can provide the necessary data basis for studying the nonlinear behavioral changes of the stress release core during the pressure relief of rock masses. An ultrasonic acquisition system based on a compact dry-coupled acoustic wave probe can adapt to the surface of the rock being monitored with various curvatures. It can monitor the ultrasonic wave at multiple locations during the entire process of uniaxial failure from the field sandstone standard sample. It can also comprehensively collect the ultrasonic wave changes in different areas of the rock during the entire process of failure. Furthermore, the evolution of cracks characterized by dynamic mechanical parameters of sandstone samples is analyzed. The results show that the dynamic Poisson ratio is relatively stable at the beginning and then gradually increases during crack development. While the dynamic elastic wave begins to accelerate down during crack development, the wave speed increases with the increase of stress. This can serve as a precursor to damage, providing certain feasibility for the characterization of onsite rock damage.

1. Introduction
In situ stress is the natural stress existing in rock mass and the most important factor that determines the excavation, design, and stability analysis of underground engineering [1]. As geotechnical engineering, water conservancy, and mining engineering gradually develop ability into the exploration of the deep strata, in situ stress effects become increasingly obvious. As such, it is necessary to obtain the in situ stress parameters of the stress environment of the deep rock mass [2].

At present, the determination of rock mechanical parameters is mainly based on two methods [3]. The first is by conducting indoor mechanics experiments, and the other is by calculation based on elastic wave theory. Results of laboratory tests often contain large experimental errors when compared with actual rock parameters. This is because of time effects and data fitting methods. The propagation characteristics of acoustic waves in rocks are closely related to their elastic properties. Unlike strain gauges, which can only monitor the local deformation of the surface, acoustic waves can better characterize the evolution of the internal cracks of the rock based on permeability. Rock damage directly affects the propagation speed and amplitude–frequency characteristics of sound waves. Ultrasonic testing, as a non-destructive testing method, is less affected by environmental noise than acoustic emission testing. It is convenient and feasible in engineering rock mass damage testing. The wave speed increases with the increase of stress. The main reason is that the micro-pores and micro-fissures inside the rock are closed, which causes the rock to become denser [4].

Research has been conducted on rock damage based on ultrasonic waves. Liu et al. [5] studied the P-wave velocity in dry and water-saturated rocks with different porosities under different confining pressures. They pointed out that the pore fluid will reduce the P-wave velocity, but the shear wave velocity has little effect when temperature is increased under low confining pressure.

A single wave velocity measurement will miss considerable important information. McCann et al. used ultrasonic waves of a certain frequency to study the P- and S-wave velocities as well as the
attenuation characteristics of sandstone and limestone. They reported the rock’s attenuation and absorption mechanism for sound waves [6]. Li et al.’s [7] study concluded that the confining pressure, crack angle, and number of cracks will all have a certain effect on the propagation speed and attenuation degree of elastic waves. For a limited size of indoor test rock sample, the traditional transceiver probe cannot be regarded as a point measurement method. In addition, it is difficult to determine the actual ultrasonic propagation distance, and this causes deviations in the wave speed measurement. Therefore, it is necessary to obtain real-time, high-frequency, accurate and convenient rock mass mechanical parameters. This paper focuses on an ultrasonic-based rock damage measurement method to determine the rock wave velocity characteristics in a single direction and using a single waveform. The method lacks the sound of rock in multiple directions and multiple waveforms. Spectral feature analysis.

2. Sandstone uniaxial loading process of ultrasonic multi-position multi-parameter sound spectrum characteristics

2.1. Test system and sample preparation
Considering the size limitation of small in situ stress boreholes and the design requirements of the acoustic probe, the acoustic digital acquisition plate, shown in Figure 1, is the third generation product after continuous research and development and improvement. The excitation voltage module generates a 100 V pulse wave and provides an excitation signal for the piezoelectric ceramic through the control system. A DC/DC isolated power supply module was provided to isolate the transmitting circuit from the receiving circuit. This reduces interference in the received signal. The algorithm for enhancing the signal-to-noise ratio of the received waveform combines the Fourier transform, low-pass filtering, wavelet denoising, and peak-finding algorithms. The MTS815 test machine is selected as the test loading system. A schematic diagram of the experimental mechanical loading and acoustic monitoring system is shown in Figure 2.
In this paper, the Sichuan yellow sandstone is selected. The dry coupling velocity measurement equipment is used to test the three-way wave velocity of the two rocks. The rock with the lower wave velocity anisotropy was selected to reduce the effect of the material itself on the data dispersion. It is processed into six standard rock samples with φ50×100mm and is as shown in Figure 3. Its verticality meets ISRM requirements.

![Figure 1. Digital multi-functional integrated circuit board.](image-url)
2.2. Experimental Method

The propagation path of ultrasonic waves is unpredictable. This is because of imbalances in the crack initiation position and the degree of development during the loading process. The arrangement scheme of multi-transmission and multi-reception probes has the problem where the location of the damaged area based on ultrasound measurements can be misjudged. In this study, a single-transmission and multi-reception ultrasonic probe arrangement is adopted. As shown in Figure 4, an ultrasonic transmission probe is arranged at position CH1 of the rock sample. The ultrasonic reception probes are arranged at positions CH2, CH3, and CH4. The essence of having the sonic probe transmitting pulses is to convert electrical signals into mechanical vibration signals. This means the inverse of the piezoelectric effect, while the principle of the receiving probe is the opposite. After the longitudinal wave transmitting probe generates a pulse on the rock, a compression or longitudinal wave is generated in the pulse direction, and a shear wave or transverse wave is generated in the vertical direction. The particle vibration caused by the transverse wave is perpendicular to the surface of the rock block and can be received by the longitudinal wave probe [8]. Therefore, in this study, CH2 and CH4 are used as longitudinal wave receiving sensors. Conversely, CH3 is used as a transverse wave sensor. CH1–CH2 is the local opposite longitudinal wave monitoring of the rock, while CH1–CH4 is the oblique longitudinal wave monitoring of the whole rock, and CH1–CH3 is the unilateral shear wave monitoring of the rock. The ultrasonic frequency is set to 125 KHz, and the automatic transmission and reception of ultrasonic waves are realized through the control circuit. The waveform sampling rate is 25 MHz, and the sampling interval between waveforms is 2 s. The load loading rate is 50 N/s. Before the start of the test, the fit between the dry-coupled acoustic wave head and the surface of the rock sample is checked. Only after everything is normal can the test be conducted.
2. Test results and analysis

2.1. Damage evolution characterized by stress and strain data

The typical stress–strain curve of the deformation and failure process of the sandstone specimen under uniaxial loading is shown in Figure 5. For brevity, this study focuses on sample 1 as the example used for analysis. The four typical stages of sandstone are distinguished by characteristic stresses related to microcracks [9], namely closing stress, crack initiation stress, crack instability propagation stress, and peak strength. To calculate the total volume strain of the rock sample, the following expression was used:

\[ \varepsilon_v = \varepsilon_1 + 2\varepsilon_3 \]  

(1)

where \( \varepsilon_v \) is the total volumetric strains, \( \varepsilon_1 \) is the axial strain, and \( \varepsilon_3 \) is the lateral strain.

\[ \varepsilon_v^{\text{true}} = \varepsilon_v - (1 - 2\nu)\sigma/E \]  

(2)
Figure 5. Stress–strain curves of sandstone under uniaxial loading.

The process of deformation and failure of the sandstone specimen in Figure 6 under uniaxial loading can be divided into four stages: the compaction stage, elastic stage, fissure stable development stage, fissure unstable development stage.

(i) Compaction stage: Axial stress 0- The original crack of the rock is gradually closed under load, and the crack volume strain is gradually closed to zero under compression. (ii) Elastic stage: The friction generated by the closed crack surface limits the sliding of the crack surface, resulting in the failure of the initiation and development of new fractures. Furthermore, the rock macroscopically and elastically deform at this stage. (iii) Fracture stabilization and expansion stage: When the initiation stress corresponding to the initial expansion of the rock was 21.84 MPa, new cracks began to initiate. There was an increase in the fracture volume. An increase in the total volumetric strain gradually decreases to the point of reversal that corresponds to the damage stress. (iv) Crack instability propagation stage: With the axial stress gradually increasing, the crack propagation speed is significantly accelerated. When the axial stress reaches the peak strength, the crack forms a macroscopic fracture surface, which quickly leads to the ultimate destruction of the rock style.

2.2. Damage evolution characterized by dynamic mechanical parameters

Damages such as rock voids and fissures can cause diffraction, transmission, and reflection of ultrasonic waves. These result in ultrasonic energy loss. The energy of the rock mass can reflect the degree of damage inside the rock mass, and the calculation of the rock mass energy depends on the measurement of the dynamic mechanical parameters in the rock mass. The mechanical parameters of the rock mass reflect its internal structure, and the elastic parameters of the infinite solid can be calculated by the following equations:
\[ E_d = \rho V_e^2 \left( \frac{1 + \mu}{1 - 2\mu} \right) \times 10^{-3} \] (1)

\[ \mu = \frac{\left( \frac{V_e}{V_s} \right)^2 - 2}{2 \left( \frac{V_e}{V_s} \right)^2 - 1} \] (2)

**Figure 6.** Evolutionary law of dynamic elastic modulus during uniaxial compression.

Figure 6 shows that in the compaction and elastic stages (i, and ii, respectively), the dynamic elastic modulus remains basically stable, and enters the crack stable development stage (iii). The dynamic elastic modulus begins to decrease slightly, until the crack unstable development stage (iv). In mid-term, the dynamic elastic modulus decreased by 23.1%, and the dynamic elastic modulus decreased by 89%. When the dynamic elastic modulus enters the stable development stage of fracture, it shows obvious stage transformation, and it has obvious descending mutations on the eve of rock failure.

**Figure 7.** Evolutionary law of dynamic Poisson ratio during uniaxial compression.
Figure 7 shows that the dynamic Poisson ratio in the compaction and elasticity stage approximates the dynamic elastic modulus, which is basically stable. On the eve of the fissure stable development stage (iii), the dynamic Poisson ratio increases by 41%. On entering the fissure unstable development stage (iv), the dynamic Poisson ratio increases by 83.9% compared with that in the elastic stage (ii).

3. Conclusion

This study investigated the evolution of the dynamic mechanical parameters of sandstone specimens based on the dry-coupled acoustic wave monitoring system. The uniaxial compression damage evolution was found to occur in four stages. The main conclusions are as follows:
(1) On the eve of failure of the sandstone sample studied, the dynamic elastic modulus decreased by 89%. The dynamic elastic modulus showed obvious phase transition on entering the stage of fissure stable development, and obvious abrupt decline before the rock failure occurred.
(2) The dynamic Poisson ratio approximates the dynamic elastic modulus and remained essentially stable in the compaction and elastic stages. In stage iv of the fissure instability development, the dynamic Poisson ratio increased by 83.9% compared with that in the elastic stage.

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Acknowledgments

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