Research Article

The Ultrasonic P-Wave Velocity-Stress Relationship and Energy Evolution of Sandstone under Uniaxial Loading-Unloading Conditions

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As shallow resources are exhausted, deep resources are gradually being exploited; consequently, mining disasters and accidents have increased significantly over time. During mining, a deep rock mass experiences complex mining-induced stress evolution, damage accumulation, and deformation failure processes, and the mechanical and acoustic properties of the rock constantly change. To better understand the variation in the mechanical and acoustic properties of rock under loading and unloading conditions, uniaxial loading-unloading experiments with real-time ultrasonic P-wave velocity monitoring were conducted on sandstone specimens drilled from a coal seam roof. The test results show that the axial stress level is directly related to the P-wave velocity. A logarithmic relationship exists between the ultrasonic P-wave velocity and stress in the tested sandstones. The wave velocity increase caused by the unit axial pressure increase is significantly lower than that at the initial loading stage after entering the higher stress level. The energy evolution of sandstone during loading and unloading is closely related to the stress loading history and reflects the damage accumulation in the rock. Under elastic loading, the energy accumulation is mainly reflected by an increase in elastic energy, and less energy is dissipated during the elastic loading period. Stress unloading causes high energy dissipation, resulting in irreversible strain and damage accumulation, which provides a good basis for using ultrasonic testing to preliminarily judge the failure of a specific rock and formulate corresponding engineering measures.

1. Introduction

Coal is the major energy source in China, and coal mining practices have been accelerating due to the rapid decline in shallow coal resources, resulting in a significant increase in coal mine disasters and accidents. Deep rock masses with significant stress sensitivity have experienced complex mining stress evolutions during the mining process and disasters, resulting in damage accumulation and deformation failure [1, 2]. The mechanical and acoustic properties of these rock masses constantly change, which undoubtedly increases the difficulty of coal mine disaster prevention and control.

Compared with seismic methods, ultrasonic testing has the advantages of a high operation frequency, good data resolution, easy control of the vibration source, and no specimen damage, so it is widely used in geological engineering, hydraulic engineering, coal mining, petroleum engineering, and many other engineering fields [3]. In petroleum engineering, ultrasonic testing technology is widely used for formation evaluation, and acoustic logging tools have been developed and applied systematically [4–6]. In the
field of coal mining, an accurate understanding of the acoustic characteristics of a rock under loading is the basis of using ultrasonic testing technology to detect the deterioration degree and mechanical properties of rocks [7, 8]. The study of the acoustic characteristics of rock can help to further develop the practical application of ultrasonic testing technology to solve complex rock mechanical problems in mining.

Therefore, many studies have been devoted to exploring the P-wave velocity-stress relationship of rock to promote the development of mining disaster prevention and monitoring. Birch [9] proposed that the elastic wave increases with increasing confining stress before it reaches a certain value. Walsh and Brace [10] suggested that a change in the microcracks in rocks affects the mechanical properties of rocks and changes the propagation velocity of elastic waves in rocks. The same conclusion was obtained by Simmons [11] when studying the shear wave velocity of various minerals. During stress evolution, the inner structure of the rock changes, e.g., due to crack opening or closure, introducing a corresponding change in the wave velocity. Sayers [12, 13] conducted research on the stress-dependent P-wave velocity under triaxial stress conditions and revealed the anisotropic characteristics of the P-wave velocity considering the impact of the stress distribution in a fractured rock mass. Yong et al. [14] discussed the spatial evolution of the P-wave velocity field in deformed rocks. Additionally, researchers have established a stress-wave velocity relationship based on a microcrack model [15–17]. Nur [18] studied the variation in the anisotropy characteristics of the equivalent compliance coefficient with stress by acoustic testing. Notably, this relationship is only applicable to the compaction stage of rock. On this basis, Su et al. [19] described the relationship between the P-wave velocity and stress as a quadratic function and carried out calibration experiments on various rock types. Zheng et al. [20] carried out experimental research on the changing law of the P-wave velocity throughout the loading process. It was considered that the change in the P-wave velocity was mainly caused by the change in the density. The development, closure, and penetration of cracks affect the variation in the stress-dependent P-wave velocity. Other researchers [21–23] have obtained a theoretical model of the rock P-wave velocity-stress relationship based on mesostructure analysis by correlating the rock micromechanical parameters with the ultrasonic P-wave velocity. In this previous research, it was generally proven that the propagation velocity of ultrasonic P-waves in a rock matrix is not directly affected by stress, i.e., the velocity of P-wave propagation in a specific medium is determined by the properties of the medium material itself and a constant, and the P-wave velocity evolution is a reflection of the crack development and change in the crack distribution in the rock. Applying an external force to rock can change the state and distribution of cracks in the rock, resulting in a change in the velocity of the P-wave.

Studies have shown that the crack initiation-propagation process and the mechanical behavior of a deep rock mass are responses to the energy transformation drive [24, 25], the catastrophic failure of a rock mass under deep engineering disturbance is essentially a state mutation instability phenomenon driven by energy, and the energy dissipation and release mechanism are the core driving factors of the damage evolution [26]. Energy is the essential characteristic of a physical reaction and the internal factor of material failure. The damage and failure process of rock is closely related to the energy evolution. The deformation and failure of a deep rock mass is always accompanied by the process of energy accumulation, dissipation and release, which is represented by the mutual transformation of the strain energy, internal energy, radiation energy, and kinetic energy of the rock mass. It is difficult to fully and accurately explain the change in the inner structure and the disaster-causing mechanism of rock mass disaster phenomena (such as rock burst, plate crack, and partition fracture) due to deep engineering disturbance from the perspective of static mechanics. It is necessary to study the energy transformation mechanism of the rock damage under various mining-induced-stress loading modes.

In fact, the stresses in rock masses are constantly adjusting with mining at different depths [27–30], resulting in complex stress loading and unloading processes, rock mass damage accumulation, and significant mining-induced deformation and damage, which seriously affect crack propagation and distribution in mining-induced coal and rocks [31]. Xie et al. [32] explored the distribution law of the abutment pressure in a coal seam, analyzed the mining dynamic characteristics of the peak value and position of the abutment pressure in front of the working face under the influence of mining, obtained the dynamic stress conditions due to mining of the coal body in front of the working face, and further carried out experimental research on the dynamic behavior of rock during coal mining. Wu et al. [33, 34] described the entire creep process of salt rock under triaxial loading, especially the creep characteristics in the accelerated creep stage, by replacing the Newtonian dashpot in the Maxwell model with the variable-order fractional derivative component and extending it from one to three dimensions. Zhang et al. [35] further established an anisotropic coal permeability model considering the mining stress, fracture evolution, and gas adsorption-desorption effect. The definition of rock damage based on microcrack propagation has certain theoretical significance, but in practice, it is fairly difficult to obtain microcrack scale parameters. Therefore, it is necessary to develop a real-time detection and evaluation method for rock damage based on ultrasonic testing. By exploring the relationship between the stress and wave velocity of rock during the loading and unloading processes, the damage accumulation and energy transformation mechanism of rock can be quantitatively analyzed, which provides a theoretical basis for systematically analyzing the damage accumulation process of rock during mining-induced stress loading and unloading conditions with ultrasonic testing technology.

Therefore, to obtain a better understanding of the damage and failure of mining-induced rock, a study of the P-wave velocity-stress relationship and energy evolution of rock is presented here. Based on laboratory tests of the deformation damage and P-wave velocity of the roof
sandstone under uniaxial loading-unloading conditions, the dynamic elastic mechanical parameters of this rock are obtained. Then, the energy-driven damage evolution of rock under different stress levels is qualitatively analyzed, and the model of the relationship between stress and P-wave velocity of sandstone is also established, which can provide a good basis for using ultrasonic testing to preliminarily judge the failure of a specific rock and formulate corresponding engineering measures.

2. Materials and Methods

2.1. Specimen Preparation and Experimental Scheme. The sandstone specimens were obtained from the Tashan Coal Mine (113°6', 39°55'N). The cylindrical sandstone specimens for the uniaxial loading-unloading tests were drilled from different sandstone strata in the coal seam roof but at approximately the same depth of 500 m and prepared according to the suggested method of the ISRM [36].

The basic physical information and experimental results of the sandstone specimens are shown in Table 1. $E$ and $\nu$ in Table 1 are Young’s modulus and Poisson’s ratio, respectively.

To simply simulate the mining-induced stress disturbance conditions of the roof sandstone near the mining face, the testing scheme was carried out during the loading and unloading processes. Two stages of cyclic loading and unloading were adopted first and then loading was applied to failure. The restarting point of the loading cycles was set as 5 MPa, and the maximum cyclic load was set as 60–70% of the uniaxial compressive strength (UCS) of the sandstone specimens determined from a direct uniaxial compression test, i.e., the average UCS was 100 MPa, close to the crack initiation stress level. The specific selection of the maximum cyclic load was based on the real-time change in wave velocity. The stress corresponding to the appearance of the wave velocity platform was selected as the peak stress of the loading and unloading cycle. During loading and unloading, the loading rate was set as 60 kN/min. In the final loading stage, the loading rate of the specimens was controlled at a circumferential deformation rate of 0.04 mm/min to obtain a complete stress-strain curve and a possible postpeak P-wave stress relationship.

Throughout the testing process, the ultrasonic P-wave velocity of the sandstone specimens was tested every 3 seconds. The propagation time of the P-wave in the specimen before it is loaded ($T_p$); and the P-wave starts to propagate ($T_{p1}$) is the time when

$$\frac{L}{T_p} \left(1 - \frac{\epsilon_1}{\epsilon_2}ight) = \frac{L}{T_{p2}}.$$

where $V_p$ is the P-wave velocity (m/s); $T_{p1}$ is the time when the P-wave starts to propagate; $T_{p2}$ is the time when the receiving probe receives the P-wave; $L$ is the length of the specimen before it is loaded (m); and $\epsilon_1$ is the strain along the P-wave propagation direction produced in the test specimens during loading.

3. Results and Discussion

3.1. The Mechanical Behavior of Sandstone under Loading and Unloading Conditions. The complete stress-strain curves of the sandstone specimens are shown in Figure 2. During the initial loading stage, the sandstone samples show obvious nonlinear deformation characteristics when the axial stress level is within approximately 30% of the peak strength. During uniaxial loading-unloading, the specimen is always in a state of compression in the axial direction and in a state of expansion in the circumferential direction. The testing results shown in Table 1 also indicate that the UCS of sandstone is highly correlated with its elastic modulus. The greater the elastic modulus of sandstone specimens is, the greater the UCS is. The loading and unloading results remain...
Table 1: Basic information and testing results of roof sandstone specimens.

| Specimens | Diameter (mm) | Length (mm) | Density (g/cm³) | σc (MPa) | E (GPa) | ν  |
|-----------|---------------|-------------|-----------------|----------|---------|----|
| US1       | 49.36         | 94.97       | 2.553           | 82.058   | 23.927  | 0.283 |
| US2       | 49.25         | 96.34       | 2.566           | 143.673  | 33.986  | 0.154 |
| US3       | 49.88         | 92.86       | 2.647           | 68.644   | 12.259  | 0.283 |

Figure 1: Schematic diagram of the coupling of the acoustic testing system and MTS815 system.

Figure 2: Continued.
in the elastic loading section, so the stress-strain curve loops corresponding to these two cycles coincide. However, axial stress unloading still causes damage to the sample, so the initial loading curve and reloading curve do not coincide.

During the loading and unloading processes, when the stress is less than approximately 30% of the peak strength, nonlinear deformation of sandstone the samples arises, similar to that in the initial loading section, which indicates that the compressibility of the pores and fractures in the sandstone samples is nonlinear. During the loading process, the extents of the compression of the sandstone pores and fractures are different under different stress levels, which directly leads to the differential evolution of the acoustic characteristics of roof sandstones.

In addition, the parts of the stress-strain curves corresponding to the last loading process are similar to those of a typical rock specimen under uniaxial loading, which can be generally divided into four stages [38], i.e., compaction, elastic deformation, plastic deformation, and failure. During the loading and unloading, a hysteretic effect is generated and results in a plastic hysteretic loop in the stress-strain curve, accompanied by the dissipation of energy in the specimens.

3.2. The P-Wave Velocity-Stress Relationship of Loaded Roof Sandstone

3.2.1. Evolution of the P-Wave Velocity of Sandstone under Uniaxial Loading-Unloading Conditions. The relationships between the P-wave velocity and the stress of the specimens during uniaxial loading-unloading are shown in Figure 3 and can be divided into 5 stages according to the branch of each loop, namely, the L1, U1, L2, U2, and L3 stages. The P-wave velocity of sandstone is directly related to the axial stress. During the initial loading of the specimen, the P-wave velocity increases rapidly. With an increase in the axial stress, the increase in the P-wave velocity slows. During unloading, the P-wave velocity decreases with the decrease in axial stress, and then during reloading and unloading, the wave velocity changes with the increase and decrease in axial stress, similar to the previous observations. The P-wave velocity changes slowly at high stress levels and rapidly at low stress levels. When the axial stress continues to increase beyond the maximum stress of the previous loading process, the P-wave velocity exhibits a certain increase from the previous highest P-wave velocity, but the increment of the P-wave velocity is small.

The influence of stress on ultrasonic P-wave velocity during uniaxial compression is mainly due to the closure and expansion of microcracks. In the initial stage of the load increase, the microcracks in the specimen quickly close, and the P-wave velocity increases greatly. As the axial stress increases, the microcracks are further compacted and closed, and the P-wave velocity further rises. However, the decrease in the extent of crack closure causes the rate of increase in the P-wave velocity to slow. In the L3 stage, when the axial stress level exceeds 50~85% of its UCS, the structure, such as the cracks in the test piece, cannot be further compressed, the P-wave velocity basically reaches the maximum value, and the peak value changes little afterward. The P-wave velocity reaches the maximum value shortly before the loading stress reaches the maximum value, and there is a stage with a constant velocity. In the unloading stage, due to the decrease in axial stress, the originally closed pores and cracks reopen, and the compactness between particles weakens. This results in a decrease in the P-wave velocity. However, the specimen has a certain memory effect on the load cycle process, so the P-wave velocity at the beginning of the second cycle is significantly higher than that at the beginning of the first cycle. This behavior is caused by the permanent closure of some of the fractures and pores during the compression stage, which cannot be opened after the stress is reduced.

During uniaxial loading-unloading, when the axial stress reaches its maximum and minimum values, the P-wave velocity also reaches its maximum and minimum values. The peaks of the P-wave velocities of the L1 and L2 stages of US1 and US3 remain approximately the same. This result shows that the pores and fractures that were closed in the loading stage reopen in the unloading stage, and the close contact state between particles is relieved to some extent, while the cyclic load has no great influence on the recovery of opening and closing. For US2, the peak value of the P-wave velocity
in the L2 stage is smaller than that in the L1 stage, indicating that the first loading and unloading cycle caused irreversible damage to the sample and that the pores and fractures that opened in the L1 stage do not completely recover in the U1 stage.

3.2.2. Nonlinear Relationship between the Ultrasonic P-Wave Velocity and Stress. According to the previous analysis results, in the initial stress loading stage, the variation in the P-wave velocity is considerable, but as the stress level reaches a certain value, the increase in the P-wave velocity slows and becomes stable. This phenomenon shows that the relationship between the stress and P-wave velocity can be fitted by a logarithmic function:

$$ V_p = k \ln(\sigma + 1) + V_{p0} $$  \hspace{1cm} (2)

where $k$ is the fitting parameter and $V_{p0}$ is the initial P-wave velocity of the sandstone specimen.

Based on (2), the relationships between the P-wave velocity and stress of the three sandstone specimens under uniaxial loading-unloading are shown in Table 2. Since the trend of the relationship in each stage is the same, only the relationship between the P-wave velocity and stress in the L1 stage is shown in Figure 4. Figure 4 shows that the P-wave velocity changes rapidly when the axial pressure is low, while it changes slowly when the axial pressure is high, and the fitting results are consistent with the experimental results. The minima observed in the velocity-stress curve in Figure 4(b) are likely related to the development of pores and fractures in the US2 sample during the initial loading process, which is also consistent with the test results of the relationship between the peak wave velocities corresponding to the peak stress levels during the two loading and unloading cycles.

The functions, parameter values, and correlation coefficients of each stage are all shown in Table 2 for all three specimens. The correlation coefficients of the fitting results of different rock specimens at different stages are all high, indicating that the logarithmic function can accurately reflect the relationship between the P-wave velocity and stress of the specimens. The parameter $k$ of the sandstone specimens is calculated. $V_{p0}$ is the P-wave velocity value of the rock specimens without loading, which has no relationship with stress and is related to the inherent properties of specimens. The parameter $k$ mainly reflects the sensitivity of

![Figure 3](image-url)
Table 2: Fitting results of the relationship between the P-wave velocity and stress of the sandstone specimens.

| Specimens | Stage | Relationship function | $R^2$ |
|-----------|-------|-----------------------|-------|
| US1       | $L_1$ | $V_p = 115 \ln (\sigma + 1) + 3805.5$ | 0.97  |
|           | $U_1$ | $V_p = 109.17 \ln (\sigma + 1) + 3844.8$ | 0.98  |
|           | $L_2$ | $V_p = 128.81 \ln (\sigma + 1) + 3762.1$ | 0.97  |
|           | $U_2$ | $V_p = 106.85 \ln (\sigma + 1) + 3849.2$ | 0.99  |
|           | $L_3$ | $V_p = 88.923 \ln (\sigma + 1) + 3881.7$ | 0.93  |
| US2       | $L_1$ | $V_p = 182.67 \ln (\sigma + 1) + 4190.0$ | 0.91  |
|           | $U_1$ | $V_p = 158.64 \ln (\sigma + 1) + 4338.3$ | 0.94  |
|           | $L_2$ | $V_p = 166.67 \ln (\sigma + 1) + 4265.0$ | 0.93  |
|           | $U_2$ | $V_p = 168.85 \ln (\sigma + 1) + 4278.8$ | 0.98  |
|           | $L_3$ | $V_p = 169.22 \ln (\sigma + 1) + 4288.1$ | 0.98  |
| US3       | $L_1$ | $V_p = 424.60 \ln (\sigma + 1) + 2217.4$ | 0.98  |
|           | $U_1$ | $V_p = 356.03 \ln (\sigma + 1) + 2534.4$ | 0.99  |
|           | $L_2$ | $V_p = 446.74 \ln (\sigma + 1) + 2146.3$ | 0.96  |
|           | $U_2$ | $V_p = 380.12 \ln (\sigma + 1) + 2449.0$ | 0.99  |
|           | $L_3$ | $V_p = 391.17 \ln (\sigma + 1) + 2322.5$ | 0.96  |

Figure 4: Relationship between the P-wave velocity and stress in the L1 stage of the sandstone specimens: (a) US1; (b) US2; (c) US3.
the P-wave velocity to stress. The greater the $k$ value, the faster the variation in the P-wave velocity and the stronger the stress sensitivity of the P-wave velocity in the sandstone specimens. According to the $k$ value corresponding to the three loading processes shown in Table 2, after two loading and unloading cycles, the wave velocity-stress sensitivity of sandstone samples decreases.

Notably, although the relationships between stress and P-wave velocity obtained here have the same form, the magnitudes vary greatly among the samples. Therefore, in the process of in situ rock acoustic testing, it is necessary to test specific samples to obtain the relevant parameters of the corresponding engineering rock masses.

3.3. The Energy Evolution of Sandstone under Uniaxial Loading-Unloading Conditions. The deformation and failure process of rock is accompanied by the accumulation and release of energy. The law of conservation of energy in rock is as follows [26]:

\[ U = U^d + U^e, \]

where $U$ is the energy input from the outside; $U^e$ is the elastic energy accumulated in the rock; and $U^d$ is the energy dissipated in the process of rock deformation and failure.

Generally, the stress-strain curve corresponding to rock loading and unloading is used to calculate the elastic properties. For the convenience of calculation, the elastic energy $U^e$ is properly simplified. The energy of each part of the rock element in the principal stress space can be expressed as follows [28]:

\[ U = \int_0^{\epsilon_1} \sigma_1 \, d\epsilon_1 + \int_0^{\epsilon_2} \sigma_2 \, d\epsilon_2 + \int_0^{\epsilon_3} \sigma_3 \, d\epsilon_3, \]

\[ U^e = \frac{1}{2E_0} \left[ \sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1) \right], \]

where $E_0$ is the initial elastic modulus and $\nu$ is Poisson’s ratio. According to the energy evolution of the sandstones during
uniaxial loading-unloading in Figure 5, the loading and unloading of sandstone change in three stages: compaction (OA), elastic (AB), and crack growth (BC).

During the compaction stage, the energy in the loading stage increases slowly. The elastic energy stored in the compaction stage is small, and the energy dissipated during the initial pore compaction and fracture closure of the rock specimens is larger. The dissipated energy corresponding to point A represents the energy consumed by compacting the initial fractures and pores in the rock specimens. In the elastic stage, the total energy and absorbed elastic energy increase with the increase in loading. The curves of the total energy absorbed and elastic energy basically develop in parallel. The work done by external forces is mainly stored in the form of elastic energy. The curve of the dissipated energy in this stage plateaus or slowly increases. The dissipated energy of sandstone increases slowly in the process of loading, increases rapidly at the beginning of unloading, and tends to be stable in the later stage of unloading. When the stress reaches yielding point B, irrecoverable damage in the specimens accumulates. In the crack growth stage, the total absorbed energy continues to increase, and the elastic energy reaches the maximum at the peak strength. The most obvious feature of the crack growth stage is that the rate of increase in the dissipated energy becomes faster.

According to Figure 5, the unloading point of cyclic loading and unloading is approximately 60~70% of the UCS, which approximately corresponds to end point B of the elastic stage. The disturbance is mainly in the elastic stage, including a small part of the compaction stage. At point B, at the end of the elastic stage, the cyclic disturbance has already produced certain damage to the rock specimens but has not yielded. The greater the dissipated energy at point B is, the more the energy accumulation capacity decreases. Furthermore, in engineering practice, the state of the geostress determines the amount of energy released during excavation. With a high geostress, a considerable amount of elastic energy is stored before the excavation of the rock mass. After underground excavation, engineering-induced stress unloading and the release of energy may cause disasters such as rock bursts. Therefore, unloading or disturbing the rock mass ahead of such work can reduce the elastic energy stored in the rock, thereby reducing the strength of rock bursts.

P-wave velocity change caused by a unit of axial pressure increase is significantly lower than that in the initial loading stage. After previous loading and unloading processes, the wave velocity-stress sensitivity of sandstone decreases. In the later stage, corresponding to the destruction of the specimens, the wave velocity decreases obviously.

The energy evolution of sandstone during loading and unloading is closely related to the stress loading history and reflects the accumulation of damage in the rock. Under elastic loading, the energy accumulated is mainly elastic energy, and the energy dissipation is weaker during the elastic loading period. However, stress unloading will cause a strong energy dissipation process, resulting in irreversible strain and damage accumulation.

Through the accurate prediction of the nonlinear relationship of stress and P-wave velocity, the distribution of the regional stress field can be obtained directly through wave velocity measurement by using technical methods, which can guide the stress field adjustment and surrounding rock stability support measures based on energy theory and ensure engineering safety. The results of this research provide a good basis for using ultrasonic testing to preliminarily judge the failure of a rock mass and formulate corresponding engineering measures.

Data Availability
The data will be available according to the application.

Conflicts of Interest
The authors declare no conflicts of interest.

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