INTRODUCTION

Longwall top coal caving (LTCC) mining is the most efficient method to extract thick or extra-thick coal seam and extensively used in western China.\textsuperscript{1-5} With high productivity and efficiency, LTCC mining plays an ultimate important role in the development and reform of the traditional coal mining method. The prototype of LTCC could date back to the 1960s and 1970s, when some European countries, especially the French and Yugoslavia, used the total soutirage method to extract thick and irregular coal seams.\textsuperscript{6} The poor recovery has been a major problem for the early soutirage longwall caving mining.\textsuperscript{7} In the early 1980s, LTCC mining was first introduced in China.\textsuperscript{5,8,9} Since then, with significant modifications and improvements, the LTCC mining method has experienced rapid development and achieved great success in China.\textsuperscript{8} In addition, the past few years have witnessed a series of successful applications of LTCC mining in Australia, India, Russia and so on.\textsuperscript{2,10-12}

In LTCC mining, the recovery ratio and the mining efficiency depend on fragmentation and caving of the top seams.\textsuperscript{6}
Therefore, it is vitally important to improve the top coal cavability. It is well established that the strength and thickness of the coal play an important role in determining the top coal cavability. Generally, the intact hard thick top coal has poor cavability. In order to enhance the recovery ratio for the LTCC panel and solve the problem of poor cavability for the thick hard top coal, weakening techniques like hydraulic fracturing and blasting are usually adapted in the LTCC mining. With a great radius of fractured zone, the advanced deep hole blasting (ADHB) is the first choice for fragmenting the hard top coal. The fragmentation results of the ADHB are directly related to top coal cavability, which determines the advancing speed of the working face and the recovery ratio of top coal. Insufficient fragmentation of the ADHB could lead to a series of problems to the LTCC panel, such as low recovery ratio, blocking of the drawing window and machine halt of the scraper conveyor. Therefore, it has great theoretical significance and engineering value to evaluate the effectiveness of blasting to enhance fragmentation for the thick hard top coal.

There are many existing research results that show blasting can improve the top coal cavability. However, the evaluation method is still immature and ineffective to assess the blasting effectiveness for top coal fragmentation in practical application. The technique of borehole imaging could survey the blasting-induced fractures directly on the condition that the fissures intersect the observation borehole. The borehole TV could conveniently estimate the fragmentation effectiveness of blasting; however, it is a post-evaluation method. In addition, the observation scope of borehole TV is limited in the borehole, which makes it difficult to meet the observation requirements for top coal on a large scale. The numerical simulation could analyze the blasting-induced damage zone’s scope by tracking the crack propagation in the surrounding rock, and it is widely used to study the cracking effect of blasting. Using the ANSYS-DYNA, Liu et al. established a 3D numerical model and qualitatively explained the pre-splitting effect of blasting in top coal. However, the numerical methods did not take the areas far away from the blasting hole into consideration. Geophysical methods could prospect the physical and mechanical property of the geologic body on a large scale. With great detecting distance and strong immunity from interference, the seismic method is widely utilized in the mining industry.

As a new technology of seismic method, seismic tomography can gain the internal dot matrix data and reconstruct the internal structures. Therefore, it can obtain a clear image of the geological body. Hence, seismic tomography has the feasibility to estimate the effectiveness of blasting to assist fragmentation of top coal in the underground LTCC panel on a large scale. Recently, seismic tomography is extensively used in detecting water-bearing structures, caving range of the overburdened strata, and risk assessment of rock burst.

Although some efforts have been done to highlight the reliability and rational technical parameters of seismic tomography in laboratories or field scales, however, it is difficult to generalize in complicated geological conditions and different research field. Furthermore, the seismic tomography has not yet been used in the evaluation of the effectiveness of blasting for top coal ahead of the LTCC mining face. The present paper proposes to evaluate the effectiveness of ADHB for thick hard top coal quantitatively by introducing the P-wave velocity attenuation model into the data processing of seismic tomography. The velocity attenuation model is based on the corresponding relationship between acoustic wave velocity and broken degree of the coal sample under laboratory uniaxial and triaxial compression test. Furthermore, a field seismic tomography test to estimate the effectiveness of ADHB in enhancing the fragmentation for hard top coal is also introduced. By exporting the nephogram of the P-wave velocity attenuation for top coal, the seismic tomography could quantitatively evaluate the effectiveness of ADHB for hard top coal.

### Laboratory Acoustic Test and P-Wave Velocity Attenuation Model

#### 2.1 Laboratory acoustic test

#### 2.1.1 Hard coal samples

The coal samples were extracted from the 3# coal seam, an extra-thick hard coal seam, of Qianshuta Coal Mine. As shown in Figure 1, the standard cylindrical coal samples (with length 100 mm and diameter 50 mm) were cored from a block of hard coal. Three samples, coded U-1 to U-3, were randomly selected for laboratory acoustic testing.

**FIGURE 1** Photo of standard cylindrical hard coal samples
U-3, were used for the uniaxial compression acoustic test. For the triaxial compression acoustic test, the specimens were coded like T-5-3. The prefix letter of the code “T” indicates that the load type is triaxial compression. The number in the middle of the code demonstrates the level of the confining pressure, and the last number is the serial number of the sample under the same confining pressure. Moreover, there were three samples at each confining pressure level. Take the sample code “T-5-1” as an example, indicating that the sample was the first specimen under triaxial compression load with 5 MPa confining pressure.

2.1.2 | Experimental apparatus and testing scheme

In order to establish the correlation between the broken degree and the acoustic wave velocity attenuation, laboratory acoustic wave velocity tests of the hard coal samples under uniaxial and triaxial compression were implemented. The experiment apparatus was the RTR-1500 rock mechanics testing system of the China University of Petroleum-Beijing, and the experimental setup is shown in Figure 2. The wave velocity was measured by the penetration method, and the emissive and receive sensors were arranged at the ends of the sample. The acoustic wave velocity of the sample can be obtained by dividing the length of the coal sample by the time gap between the acoustic emitter and receiver. To improve the accuracy of the measurement, a minor compressive load is applied to the sample to ensure good coupling contact, and both ends of the sample are smeared with a little Vaseline. The acoustic signal amplification was set at 40 dB, and the noise threshold value was also set at 40 dB.

During the testing process, the acoustic acquisition system and the stress loading system were started simultaneously, and the acoustic information in the whole testing process was monitored in real time until the end of the test. In the loading process, an acoustic wave was generated at different axial strain and it propagated through the hard coal sample to the receiver at another end of the sample. The sensor of the receiver recorded the first break-time and energy amplitude information of the P-wave at different deformation stages of the coal samples. Four levels of confining pressures (2 MPa, 5 MPa, 8 MPa, and 10 MPa) were designed based on in-situ stress monitoring in the triaxial compression tests. During the triaxial compression tests, the axial stress and the confining pressures were loaded to the predetermined value simultaneously at a loading rate at 0.05 MPa per second. Subsequently, the axial stress was loaded until the coal sample broken.

2.2 | Results of the laboratory acoustic test

2.2.1 | Results of the acoustic test in uniaxial compression

Figure 3 shows the variation of elastic wave velocity vs axial stress and strain of coal samples under uniaxial compression. The elastic modulus, unconfined compressive strength (UCS), and residual strengths of coal sample U-1 are 2.7 GPa, 44.6 MPa, and 13.8 MPa, respectively. As shown in Figure 3A, the P-wave increases rapidly during the compaction of the void and cracks. In the elastic stage, with small fluctuation, the velocity of the P-wave keeps a slow growth vs the axial stress or strain. At the initial yield point, where the axial strain is 1.5%, the wave velocity decreases. During the strain hardening stage, the wave velocity experiences a stable fluctuation. A sharp fall of the wave velocity occurred closely after the peak value of axial stress. In the residual stage, as the axial stress drops to 13.8 MPa and the axial strain increases to 2.3%, the P-wave velocity drops to 1730 m/s and showed tiny fluctuation.

![Testing equipment and schematic diagram of the experiment setup](image-url)
Coal sample U-2 has a similar shape to the stress-strain curve (Figure 3B), with elastic modulus 2.2 GPa and UCS 44.3 MPa. The wave velocity declines from 2398 m/s to 2086 m/s when the axial stress surpasses the initial yield point. When axial strain increases from 1.2% to 1.8%, the coal sample experiences a strain hardening stage. The wave velocity undergoes a fluctuated rebound at this stage. After the sample break in the peak stress, wave velocity descends steeply again and the reduction amplitude is 20.8%. Subsequently, the wave velocity keeps slight fluctuating in the residual deformation stage with residual axial stress about 12.3 MPa. Sample U-3 has an early yield point and a long strain hardening stage (Figure 3C). The elastic modulus and UCS are 2.7 GPa and 28.5 MPa from the stress–strain curve. The first steep fall of wave velocity occurred on the heels of the initial yielding of the coal sample. The strain hardening stage witnessed a drastic fluctuation in the wave velocity. Similarly, a sharp drop of wave velocity follows the failure of the coal sample in the peak stress with decline amplitude of 28.7%.

2.2.2 Results of the acoustic test in triaxial compression

Considering the great compressive strength of the hard coal samples, four levels of confining pressures (2 MPa, 5 MPa, 8 MPa, are 10 MPa) are arranged in the acoustic test under the triaxial compression. At each confining pressure level, three coal samples are tested. Changes of the P-wave velocity and deviator stress vs strain of typical coal samples are shown in Figure 4. In general, the greater the confining stress, the higher the deviator stress that the coal sample could bear, and the sample could withstand great deviator stress in the residual stage. The P-wave velocity presents a rapid mounting at the early compaction stage, and then it fluctuates slightly in the elastic stage. Like the acoustic test under uniaxial compression, P-wave velocity decreases when stress exceeds the initial yield point. The greatest drop of the wave velocity follows closely to the failure of the coal sample in peak stress. The residual stage witnesses a moderate
fluctuation of the wave velocity. Take the coal sample T-2-2 as an example, the variation of P-wave velocity is illustrated in Figure 4A. With the closure of initial voids and micro-cracks, the P-wave velocity increases quickly from 2040 m/s to 2348 m/s. The biggest wave velocity is 2450 m/s and is located in the elastic stage. When the deviator stress approaches to 48 MPa (axial strain is 1.2%), i.e., the initial yield point, wave velocity began to decrease. In the peak stress of 56 MPa, the coal sample break, and the wave velocity fall from 2300 m/s to 1633 m/s, with reduction amplitude of 29.0%. With the axial strain increases to 3.4% in the residual stage, wave velocity descends to 1478 m/s.

2.3 P-wave velocity attenuation model and analysis

2.3.1 P-wave velocity attenuation model

Elastic wave velocity and transmission characteristic could forecast integrity, density, crack density, and damage degree of the core sample. Recently, the elastic wave velocity test has been used to study the characteristics of damage evolution for rock. The effectiveness of blasting can be represented by the number and size of fractures (termed crack density) in the top coal. The crack density follows the characteristics of the elastic wave velocity. Therefore, the acoustic wave velocity method is put forward to estimate the fragmentation effectiveness of ADHB for top coal quantitatively, and the acoustic wave velocity attenuation, $A$, can be calculated with

$$A = 1 - \left( \frac{V_r}{V_0} \right)^2$$

(1)

where $A$ is the wave velocity attenuation for top coal, $V_r$ and $V_0$ are the residual wave velocity and the initial wave velocity, respectively.

The initial wave velocity $V_0$ could be the wave velocity when axial stress equals the in-situ vertical stress or obtained from the field acoustic monitoring. The residual wave velocity $V_r$ takes the smallest acoustic wave velocity in the residual deformation stage.
2.3.2 P-wave velocity attenuation analysis

The distribution of the P-wave velocity of each coal sample and the P-wave velocity attenuation is illustrated in Figure 5. Owing to the initial stress field, the underground coal seam is in a state of compression. Hence, we take the P-wave velocity at the end of the compaction stage in the acoustic test as the initial wave velocity \(V_0\). The residual wave velocity \(V_r\) takes the lowest velocity in the residual stage of the coal sample. Under uniaxial compression, the initial P-wave velocity of the coal samples ranges from 2142 m/s to 2235 m/s. The triaxial compression test witnesses a greater initial wave velocity. However, the residual wave velocity of the coal sample in triaxial compression acoustic test is drastically lower than that of the coal sample in uniaxial compression acoustic test. This phenomenon can be attributed to the different failure mode of coal sample with or without the confining pressure.

The typical coal specimen after the breakage is shown in Figure 6. The failure mode of coal sample, under the uniaxial compression, is split failure with the fractures nearly parallel to axial. In the triaxial compression test, the coal specimens exhibit the shear failure mode. After failure of the coal sample, the number of cracks, crack direction, and crack size have great influence on the propagation and attenuation of the elastic wave.\(^{35}\) When the crack is perpendicular to the wave propagation direction, the attenuation effect is the greatest, while the attenuation effect is the minimum when the crack is parallel to the wave propagation direction. As shown in Figure 6, the crack direction gradually transformed from the axial direction, which is the wave propagation direction, to obliquely intersecting the axial direction with the confining pressure increasing. Furthermore, with the increasing confining pressure, the range of the fractured zone and the degree of crack sliding become larger, leading to great size and number of cracks in the coal sample. Therefore, the coal samples in the triaxial compression test experience a greater wave velocity fall.

The P-wave velocity attenuation of each sample after failure, calculated use Equation (1), is also illustrated in Figure 5. More fractures were generated in the failure process with greater confining pressure, and the cracking mode transforms from axial split cracking to obliquely intersecting shear crack. Hence, the P-wave velocity attenuation appears an escalating trend with the mounting confining pressure. The uniaxial acoustic test acquires a lower P-wave velocity attenuation than the triaxial acoustic test. The greatest P-wave velocity attenuation of the sample under uniaxial compression is 0.47, the smallest value is 0.39, and the average value is 0.44. The P-wave velocity attenuation of the coal samples under triaxial compression is ranging from 0.57 to 0.71 with an average value 0.63.

Generally, the coal sample will exhibit a great P-wave velocity attenuation when large numbers of fractures generated in the coal sample after its breakage. Furthermore, the broken and damage degree of the coal sample can be easily classified using the value of P-wave velocity attenuation. Therefore, if the distribution of the elastic wave velocity of the hard top coal before and after the fracturing blasting can be obtained on a large scale, the P-wave velocity attenuation distribution of top coal could be calculated through data processing. Based on the calculated P-wave velocity attenuation distribution, the effectiveness of blasting to assist fragmentation for hard top-coal ahead the LTCC panel could be quantitatively evaluated.

3 ACOUSTIC WAVE METHOD AND FIELD TEST

3.1 Acoustic wave method for assessing the effectiveness of blast

3.1.1 Inversion of P-wave velocity in seismic tomography

Seismic tomography can acquire the transmission characteristics of P-wave in geologic body through wave impedance inversion and seismic data reconstruction. Due to various advantages like high resolution, intuitional images, and great reliability, it could obtain a clear internal structure image of the geologic body.\(^{27,29}\) It is assumed that the P-wave propagates along a ray in
the coal seam. As shown in Figure 7, the study area can be split into numerous small independent areas called grid cells or pixels. Assume that the total number of ray path is $M$, the total pixel is $N$, seismic wave slowness of pixel number $j$ is $f_j$, the length of ray path number $i$ is $L_i$, and the path in pixel number $j$ is $d_{ij}$, then the travel time of the seismic wave pass through path $i$ can be expressed by Equation (2) through high-frequency approximation.\(^{27,36}\)

$$t_i = \int i.f(x,y)ds = \sum_{j=1}^{N} d_{ij}f_j$$  \hspace{1cm} (2)

where $t_i$ is the travel time of path number $i$, and $f_j$ is wave slowness of pixel number $j$.  

Equation (2) can be rewritten into a matrix equation as:

$$\begin{pmatrix} t_1 \\ t_2 \\ \vdots \\ t_i \\ \vdots \\ t_M \end{pmatrix} = \begin{pmatrix} d_{11} & d_{12} & \cdots & d_{ij} & \cdots & d_{1N} \\ d_{21} & d_{22} & \cdots & d_{2j} & \cdots & d_{2N} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ d_{i1} & d_{i2} & \cdots & d_{ij} & \cdots & d_{iN} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ d_{M1} & d_{M2} & \cdots & d_{Mj} & \cdots & d_{MN} \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_j \\ \vdots \\ f_N \end{pmatrix}$$  \hspace{1cm} (3)

or

$$\mathbf{T} = \mathbf{D} \cdot \mathbf{F}$$  \hspace{1cm} (4)

where $\mathbf{T}$ is the vector of the travel time, $\mathbf{D}$ is the matrix of the geometric path for the pixel, and $\mathbf{F}$ is the vector of wave slowness.

In the seismic exploration, the vector of the travel time $\mathbf{T}$ can be obtained by observing. As the seismic ray only passes through a small part of the matrix of the pixel, the matrix of the geometric path $\mathbf{D}$ is extremely sparse. Generally, the iterative method is used to calculate the field distribution of the seismic wave. The commonly used iterative approaches include the algebraic reconstruction technique (ART), simultaneous iterative reconstruction technique (SIRT), and least square with QR decomposition (LSQR).\(^{37}\) Considering the good convergence, the SIRT method is utilized to inverse the distribution of the P-wave velocity for the study area.

3.1.2 | Acoustic wave method based on seismic tomography

Before and after the fracturing of ADHB, the distribution of the P-wave velocity of the hard top coal can be reconstructed using seismic tomography. Furthermore, the distribution of P-wave velocity attenuation, representing the
degree of fragmentation of the top coal, could be calculated by introducing the attenuation model into the data processing of the seismic tomography. Therefore, an acoustic wave velocity attenuation method, based on seismic tomography, is proposed to estimate the effectiveness of ADHB to enhance fragmentation in top coal of the LTCC face. As shown in Figure 8, the acoustic wave is generated in one roadway, and the geophones are installed in another roadway. The seismic tomography is implemented before and after the ADHB operation. After the impedance inversion and data processing, the P-wave velocity attenuation nephogram of the top coal could be exported for illustrating the effectiveness of blasting for the top coal quantitatively.

3.2 | Field seismic tomography test

3.2.1 | Engineering background

The case study takes the 11303 LTCC panel of Qianshuta Coal Mine, which is located in Yulin District, Shanxi Province, China, as shown in Figure 9. The Qianshuta Coal Mine is in the Yuyang mining area of Shengfu coalfield, the largest coalfields in China. The LTCC mining method is used to extract the 3# coal seam in Yan’ a Formation of Jurassic, and the average thickness of the coal seam is 10.48 m. The buried depth of the coal seam is about 190 m, and the top coal cavability is poor due to the intact and hard characteristic of the coal.

The 11303 LTCC panel is 240 m in width and 1900 m in length. From the core logging data, the lithology of the LTCC panel is displayed in Table 1. The immediate roof is mudstone with thickness from 0.59 m to 0.69 m, and the main roof is feldspathic sandstone with thickness from 10.67 m to 22.65 m. The coal floor is silty mudstone with thickness from 1.10 m to 2.26 m. The thickness of the coal seam is ranging from 9.75 m to 11.21 m. With a cutting height of 4.0 m, the residual top coal is 6.61 m in thickness. The uniaxial compressive strength of coal samples from 3# coal seam is more than 25 MPa, some even reach 40 MPa. Owing to the high strength of the coal, the advanced deep hole blasting (ADHB) fracturing method is used to improve the fragmentation of the top coal ahead of the LTCC panel.

To implement the advanced deep hole blasting (ADHB) technique for fracturing the hard top coal, two technical roadways were excavated in the top coal layer. The technical roadways provide the working place for the borehole drilling and blasting. As illustrated in Figure 10, the ADHB boreholes are perpendicular to the advanced direction of the LTCC panel. The depth of the boreholes is 42 m when
FIGURE 9  Location of the study area of Qianshuta coal mine

| Rock formation | Lithology          | Rock stratum   | Thickness (m) | Average thickness (m) |
|----------------|--------------------|----------------|---------------|-----------------------|
| Main roof      |                    | Feldspathic sandstone | 10.67-22.65   | 16.66                 |
| Immediate roof |                    | Mudstone       | 0.59-0.69     | 0.64                  |
| Coal           |                    | 3# coal        | 9.75-11.21    | 10.48                 |
| Immediate floor|                    | Mudstone       | 1.1-2.26      | 1.68                  |
| Main floor     |                    | Siltstone      | 1.41-4.7      | 3.06                  |

TABLE 1  Lithology of the LTCC panel
they point to the headgate or tailgate. When the boreholes point to the middle of the panel, it is 50 m in depth. The diameter of the boreholes is 94 mm, and all the boreholes are uniformly arranged in the technical roadways with a boreholes space of 3.0 m. The emulsion explosive is used in the ADHB, and the sealing length is 6.0 m.

3.2.2 | Seismic tomography scheme and its instruments

1. Field testing area

As the top coal fragmentation is closely associated with safe and efficient coal extraction, it is necessary to evaluate the effectiveness of the ADHB. Furthermore, the field seismic tomography test is adapted to obtain the P-wave velocity distribution of the top coal before and after the ADHB implementation. The test area is located between the two technical roadways with 74 m in width and 123 m in length, as shown in Figure 11. Before the blasting, the first seismic tomography is conducted to obtain the initial distribution of the P-wave velocity of the top coal. Furthermore, the distribution of the P-wave velocity of the top coal after the blasting can be gained from the secondary seismic tomography.

2. Seismic tomography scheme

In the field seismic tomography test, the seismic wave was generated in the 1# technical roadway, and the geophones were installed in the 2# technical roadway. The layout diagram of the seismic tomography is illustrated in Figure 12. The PASAT-M seismic tomography system Figure 13 was utilized in the field test with the advantages of small volume and convenience of installation. The seismic sources use artificially excited seismic waves. The excitation of the seismic wave using the safe emulsion explosives, and the schematic diagram of the borehole and charge structure is illustrated in Figure 14. Moreover, the two-component geophones were installed with a horizontal gap of about 10 m, and their total number is 11. The operating frequency band of the geophone is ranging from 5 Hz to 10 000 Hz. The sampling frequency is set at 2000 Hz, and the sampling interval is 0.5 s.

3.3 | P-wave velocity attenuation distribution of the top coal

3.3.1 | Typical waveforms and inversion method analysis

For each seismic source generated in the 1# technical roadway, there were 11 geophones to receive the P-wave in the 2# technical roadway. Before the ADHB, 19 effective seismic sources were generated, and 209 seismic signals were gained in the first seismic tomography. After the ADHB, the field tomography test obtains 22 effective generation sources and 242 channels of seismic signals. The scatter plot of the first-arrival travel time vs the source-receiver distance is illustrated in Figure 15. The average seismic wave velocity is 2.38 m/ms and 1.93 m/ms before and after the ADHB implementation, which was used as the initial velocity for the primary iteration. The field study area was divided into small pixel cells, and the direct ray tracing technology and SIRT method were utilized to inverse the distribution of the elastic wave velocity for the study area.

Traditionally, the first breaks of the seismic wave were picked up manually according to the change of seismic amplitude and waveform. It is hard to avoid the deviations
and inconsistencies caused subjectivity in the manual picking process. Nowadays, most of software packages provide interactive pickup tools. In the field seismic tomography test, the distance to source is small, the first arrival wave is the direct wave propagated in the coal seam. A typical first-breaks picking up results of the seismic data after the ADHB is illustrated in Figure 16. The first breaks of the seismic wave were automatically picked up using the time window method firstly. Furthermore, small modification is achieved by carefully manual checking.

3.3.2 P-wave velocity distribution before and after the ADHB

Figure 17 shows the distribution of the P-wave velocity of the top coal obtained by seismic tomography before and after the fracturing ADHB. As shown in Figure 17A, the seismic P-wave velocity ranges from 2400 m s⁻¹ to 2600 m s⁻¹ in the majority area of the top coal before the implementation of ADHB. In areas close to the technical roadway, the seismic P-wave velocity is less than
2100 m s$^{-1}$. This phenomenon could be attributed to the excavation damaged zone, leading to a wave velocity decline of the technical roadway. In a word, before the fracturing blast, the average seismic P-wave velocity of hard top coal in the study area surpass 2200 m s$^{-1}$. The distribution of the seismic P-wave velocity after the ADHB is illustrated in Figure 17B, the greatest wave velocity is 2068 m s$^{-1}$, less than the smallest value of the P-wave velocity before the fracturing blast. After the ADHB, the areas where the seismic wave velocity less than 2000 m s$^{-1}$ occupy 82% of the study area of the top coal.

3.3.3 | P-wave velocity attenuation distribution of the top coal

Take the P-wave velocity before the fracturing ADHB as the initial wave velocity $V_0$, and the P-wave velocity after the fracturing ADHB as the residual wave velocity $V_r$. The value of P-wave velocity attenuation of every pixel could be calculated by introducing the P-wave velocity attenuation model into the data processing. Then, the nephogram of the P-wave velocity attenuation for top coal in the study area is exported in Figure 18, which could
quantitatively estimate the fragmentation degree for the top coal. It can be drawn from the nephogram that the areas whose P-wave velocity attenuation value surpasses 0.6 occupy 5.8% of the total test area. In those zones, the hard top coal is fully fractured during the ADHB and hence has greater cavability. With P-wave velocity attenuation ranging from 0.3 to 0.6, the moderately fractured zones occupy 82.7% of the total test area. This portion of the top coal has medium fragmentation in the ADHB and will be re-crushed by the subsequent abutment pressure caused by the LTCC mining. The insufficient fragmentation zones, where the P-wave velocity attenuation value less than 0.3, occupy about 11.5% of the total test area. In the insufficient fragmentation zones, the hard top coal is partially fractured by the ADHB. The low P-wave attenuation zone is adjacent to the technical roadway, which could be attributed to the following two reasons: firstly, the fracturing effect is poor in the sealing section of the blasting borehole as large sealing length (6.0 m in the field test) is needed in the ADHB; then, the roadway support system also facilitates reducing the damaging effect in the surrounding rock of the technical roadway. As the P-wave source of the seismic tomography is blasting in the 1# technical roadway, leading a greater P-wave attenuation effect in zones along the 1# technical roadway than that of the 2# technical roadway.

Generally, the recovery rate of top coal is great in the area where the blasting effect is good, while a low recovery ratio has appeared in the area where the blasting effect is relatively poor. In the subsequent LTCC mining, the recovery ratio of the top coal for the study area was obtained by analyzing the raw coal production per day. As illustrated in Figure 19, the recovery ratio ranges from 44.7% to 79.4% in the study area. In the left side of the study area, the top coal recovery ratio is relatively low as the P-wave velocity attenuation is less than 0.3, while the recovery ratio exceeds 75% when the P-wave velocity attenuation is larger than 0.52. The statistical results of the top coal recovery ratio indicate that the P-wave attenuation could truly reflect the fragmentation degree of top coal. As the ADHB is not applied adjacent to the cut-through, which leads to a poor recovery ratio in those zones, supplementary split blasting or hydro-fracturing should be applied in the cut-through ahead of the LTCC face.
4 | DISCUSSION

4.1 | Effectiveness of the ADHB

In the laboratory acoustic test, the P-wave velocity attenuation of the hard coal sample was ranging from 0.39 to 0.71 after the failure of the coal sample. Before breakage, the coal sample has experienced a decline of P-wave velocity; however, the P-wave velocity attenuation is less than 0.3. When the P-wave velocity attenuation is larger than 0.6, the fragmentation degree is great. In addition, the field measurement of the top coal recovery ratio indicates a low recovery ratio in the left side of the study area, where the P-wave velocity attenuation is less than 0.3, as shown in Figures 18 and 19. Combining the laboratory acoustic test results and the field seismic tomography test, the effectiveness of ADHB for top coal ahead the LTCC face could be classified using the value of P-wave velocity attenuation.

From engineering experience in Qianshuta Coal Mine, the classification method based on P-wave velocity attenuation value (Table 2) was proposed to evaluate the effectiveness of ADHB to enhance fragmentation in hard top coal. The effectiveness of ADHB for top coal is well when the P-wave velocity attenuation surpasses 0.6. Under this condition, the top coal is desirably fragmented and could be smoothly caved and drawn. When the P-wave velocity attenuation lies in the range of 0.3-0.6, the top coal could be crushed again under the mining pressure, suggesting a medium fragmentation effectiveness of the ADHB. The effectiveness of ADHB of the top coal is poor when the P-wave velocity attenuation is less than 0.3. In this condition, some supplementary fracturing methods, like hydraulic fracturing, should be taken to avoid boulder yield and the occurrence of cantilever structure in top coal.

4.2 | Checkboard resolution test

It is necessary to examine the precision of the tomography results. Generally, the checkerboard resolution test (CRT) and the restoring resolution test (RRT) are conducted to ensure the reliability of obtained results. The CRT is well competent in the resolution analysis of the geologic body in medium and small scale, and the test results of the CRT are direct-viewing. Hence, the CRT is utilized to examine the precision of the field tomography results. Three grid intervals (5 m, 8 m, and 10 m) are used in the CRT, and the test results with the grid interval of 8 m are displayed in Figure 20. The synthetic input model is assigned with 5% perturbations. Furthermore, the velocity perturbation of each grid point is equal to that of the four surrounding points while with a different negative or positive sign, as shown in Figure 20A. The well-recovered areas, with the same sign of velocity perturbation in both the input and output models, are illustrated in Figure 20C. The test results show that most of the study areas, especially the middle parts, are located in well-recovered areas.

5 | CONCLUSIONS

In LTCC mining of thick hard coal seam, the technique of ADHB is one of the commonly used artificial weakening methods to improve the top coal fragmentation and cavability. The effectiveness of ADHB has great influence on the recovery ratio and drawing smoothness. Through an acoustic wave method based on P-wave velocity attenuation, this paper takes a rewarding exploration for quantitatively evaluating the effectiveness of ADHB to enhance

| P-wave velocity attenuation | Effectiveness classification | Notes |
|-----------------------------|-------------------------------|-------|
| A ≤ 0.3                     | Poor                          | Need supplementary fracturing method |
| 0.3 < A ≤ 0.6               | Medium                        | Need re-crush under the mining pressure |
| A > 0.6                     | Well                          | Good effectiveness of blasting and well cavability |
fragmentation in thick hard top coal. The following conclusions can be drawn:

1. The P-wave velocity attenuation model could well represent the broken degree of the hard coal sample. After failure, the P-wave velocity attenuation of the hard coal sample was ranging from 0.39 to 0.71. And the P-wave velocity attenuation of the sample under triaxial compression is greater than that of the sample under uniaxial compression.

2. The P-wave velocity attenuation of the top coal before and after the ADHB can be obtained by introducing the P-wave velocity attenuation model into data seismic tomography. As the fracture direction has a great influence on the P-wave velocity, it is recommended to increase the number of the excitation and reception points in field seismic tomography.

3. Based on seismic tomography, the acoustic wave method can quantitatively evaluate the fragmentation effectiveness of the ADHB technique for hard top coal ahead of the LTCC mining face. When the P-wave velocity attenuation surpasses 0.6, the effectiveness of ADHB is well; when the P-wave velocity attenuation is ranging from 0.3 to 0.6, the effectiveness of ADHB is medium; the effectiveness of ADHB is poor when the P-wave velocity attenuation is less than 0.3.

4. When the P-wave velocity attenuation is less than 0.3, the top coal recovery ratio is less than 50%, which is far below the requirements of standards, and some supplementary fracturing methods, like hydraulic fracturing, should be taken to assist top coal fragmentation.

CONFLICT OF INTEREST
The authors declare that they have no competing interest.

ETHICAL APPROVAL
This article does not contain any studies with human participants or animals performed by any of the authors.

ORCID
Yuliang Zhou https://orcid.org/0000-0001-7942-9296

REFERENCES
1. Vakili A, Hebblewhite BK. A new cavability assessment criterion for Longwall Top Coal Caving. Int J Rock Mech Min Sci. 2010;47(8):1317-1329. https://doi.org/10.1016/j.ijrmms.2010.08.010

2. Le T, Zhang C, Oh J, Mitra R, Hebblewhite B. A new cavability assessment for Longwall Top Coal Caving from discontinuum numerical analysis. Int J Rock Mech Min Sci. 2019;115:11-20. https://doi.org/10.1016/j.ijrmms.2019.01.006

3. Wang J, Zhang J, Li Z. A new research system for caving mechanism analysis and its application to sublevel top-coal caving mining. Int J Rock Mech Min Sci. 2016;88:273-285. https://doi.org/10.1016/j.ijrmms.2016.07.032

4. Le TD, Mitra R, Oh J, Hebblewhite B. A review of cavability evaluation in longwall top coal caving. Int J Min Sci Technol. 2017;27(6):907-915. https://doi.org/10.1016/j.ijmst.2017.06.021

FIGURE 20 Results of the CRT with a grid interval of 8.0 m
14. Zhang Q, Yue J, Liu C, Feng C, Li H. Study of automated top-coal caving in longwall top-coal caving mining method. *Int J Rock Mech Min Sci.* 2014;71:160-170. https://doi.org/10.1016/j.ijrmms.2014.04.024

15. Benech M, Colloid H. Soutirage mining used effectively for thick and irregular coal seams. *World Coal.* 1982;4(8):51-54.

16. Ghose AK. Underground methods of extraction of thick coal seams—a global survey. *Min Sci Technol.* 1984;2(1):17-32. https://doi.org/10.1016/S0167-9031(84)90171-3

17. Bai Q, Tu S, Wang F. Characterizing the top coal cavability with hard stone band(s): insights from laboratory physical modeling. *Rock Mech Rock Eng.* 2019;52(5):1505-1521. https://doi.org/10.1007/s00603-018-1578-y

18. Wang J, Wang Z, Li Y. Longwall top coal caving mechanisms in the fractured thick coal seam. *Int. J. Geomech.* 2020;20(8):6020017. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001722

19. Kurlenya MV, Mirenkov VE. Assessment of deformation of coal seam and longwall through the identification of top coal caving parameters. *J Min Sci.* 2020;56(4):505-511. https://doi.org/10.1134/S1062739120046799

20. Öge İF. Prediction of top coal cavability character of a deep coal mine by empirical and numerical methods. *J Min Sci.* 2018;54(5):793-803. https://doi.org/10.1134/S1062739118054903

21. Khanal M, Adhikary D, Balusu R. Prefeasibility study—geotechnical studies for introducing longwall top coal caving in Indian mines. *J Min Sci.* 2014;50(4):719-732. https://doi.org/10.1134/S1062739114040139

22. Wang Z, Wang J, Yang S. An ultrasonic-based method for long-wall top-coal cavability assessment. *Int J Rock Mech Min Sci.* 2018;112:209-225. https://doi.org/10.1016/j.ijrmms.2018.10.019

23. Zhang Q, Yue J, Liu C, Feng C, Li H. Study of automated top-coal caving in extra-thick coal seams using the continuum-discontinuum element method. *Int J Rock Mech Min Sci.* 2019;122:104033. https://doi.org/10.1016/j.ijrmms.2019.04.019

24. Huang B, Wang Y, Cao S. Cavability control by hydraulic fracturing for top coal caving in hard thick coal seams. *Int J Rock Mech Min Sci.* 2015;74:45-57. https://doi.org/10.1016/j.ijrmms.2014.10.011

25. He Q, Suurineni FT, Oh J. Review of hydraulic fracturing for preconditioning in caving mine. *Rock Mech Rock Eng.* 2016;49(12):4893-4910. https://doi.org/10.1007/s00603-016-1075-0

26. Liu J, Liu Z, Xue J, Gao K, Zhou W. Application of deep borehole blasting on fully mechanized hard top-coal pre-splitting and gas extraction in the special thick seam. *Int J Min Sci Technol.* 2015;25(5):755-760. https://doi.org/10.1016/j.ijmst.2015.07.009

27. Lai X, Shan P, Cao J, Sun H, Suo Z. Hybrid assessment of pre-blasting weakening to horizontal section top coal caving (HSTCC) in steep and thick seams. *Int J Min Sci Technol.* 2014;24(1):31-37. https://doi.org/10.1016/j.ijmst.2013.12.006

28. Suo Y. Study of pre-weakened method on the hard thick-top-coal in fully mechanized caving. *J Chin Coal Soc.* 2001;26(6):616-620. https://doi.org/10.13225/j.cnki.jccs.2001.06.011

29. Song Z, Konietzky H. A particle-based numerical investigation on longwall top coal caving mining. *Arab J Geosci.* 2019;12(18):556. https://doi.org/10.1007/s12517-019-4743-z

30. Zhu D, Chen Z, Du W, Zhang L, Zhou Z. Caving mechanisms of loose top-coal in longwall top-coal caving mining based on stochastic medium theory. *Arab J Geosci.* 2018;11(20):621. https://doi.org/10.1007/s12517-018-3987-3

31. Simsir F, Ozfirat MK. Determination of the most effective longwall equipment combination in longwall top coal caving (LTCC) method by simulation modelling. *Int J Rock Mech Min Sci.* 2008;45(6):1015-1023. https://doi.org/10.1016/j.ijrmms.2007.11.005

32. Xie H, Wang J, Chen Z, et al. Study on top-coal blasting technique of full-mechanized caving in the hard coal seam. *J Chin Coal Soc.* 1999;24(4):350-354. https://doi.org/10.1088/0256-307X/15/12/024

33. Zhu Z, Xie H, Mohanty B. Numerical investigation of blasting-induced damage in cylindrical rocks. *Int J Rock Mech Min Sci.* 2008;45(2):111-121. https://doi.org/10.1016/j.ijrmms.2007.04.012

34. Peng C, Li S, Hao W, et al. Numerical simulation for penetrating and blasting process of EPW based on CDEM. *J Vibat Shock.* 2017;36(13):11-18. https://doi.org/10.13465/j.cnki.jvvs.2017.13.002

35. Cai W, Dou L, Gong S, Li Z, Yuan S. Quantitative analysis of seismic velocity tomography in rock burst hazard assessment. *Nat Hazards.* 2015;73(3):2453-2465. https://doi.org/10.1007/s11069-014-1443-6

36. Peng S, Ling B, Liu S. Application of seismic tomography in longwall top coal caving face. *Chin J Rock Mech Eng.* 2002;21(12):1786-1790. https://doi.org/10.3321/j.issn:1000-6915.2002.12.008

37. Dou L, Cai W, Gong S, et al. Dynamic risk assessment of rock burst based on the technology of seismic computed tomography detection. *J Chin Coal Soc.* 2014;39(2):238-244. https://doi.org/10.13225/j.cnki.jccs.2013.2016

38. Zhang P, Liu S, Wu R. Observation of overburden failure of coal seam by CT of seismic wave. *Chin J Rock Mech Eng.* 2004;23(15):2510-2513. https://doi.org/10.3321/j.issn:1000-6915.2004.15.005

39. Yurikov A, Lebedev M, Pervukhina M. Ultrasonic velocity measurements on thin rock samples: experiment and numerical modeling. *Geophysics.* 2017;83:1-40. https://doi.org/10.1190/geo2016-0685.1

40. Yasar E, Erdogan Y. Correlating sound velocity with the density, compressive strength and Young's modulus of carbonate rocks. *Int J Rock Mech Min Sci.* 2004;41(5):871-875. https://doi.org/10.1016/j.ijrmms.2004.01.012

41. Inserra C, Biwa S, Chen Y. Influence of thermal damage on linear and nonlinear acoustic properties of granite. *Int J Rock Mech Min Sci.* 2013;62:96-104. https://doi.org/10.1016/j.ijrmms.2013.05.001

42. Byun JH, Lee JS, Park K, Yoon H-K. Prediction of crack density in porous-cracked rocks from elastic wave velocities. *J Appl Geophys.* 2015;115:110-119. https://doi.org/10.1016/j.jappgeo.2015.02.020

43. Schubnel A, Nishizawa O, Masuda K, Lei XJ, Xue Z, Guégen Y. Velocity measurements and crack density determination during wet triaxial experiments on Oshima and Toki granites. *Pure Appl Geophys.* 2003;160(5-6):869-887. https://doi.org/10.1007/PL00012570

44. Li X, Zhao H, Luo Y, et al. Experimental study of propagation and attenuation of elastic wave in deep rock mass with joints. *Chin J Rock Mech Eng.* 2015;34(11):2319-2326.
36. Letort J, Roux P, Vandemeulebrouck J, et al. High-resolution shallow seismic tomography of a hydrothermal area: application to the Solfatara, Pozzuoli. Geophys J Int. 2012;189(3):1725-1733. https://doi.org/10.1111/j.1365-246x.2012.05451.x

37. Neumann-Denzau G, Behrens J. Inversion of seismic data using tomographical reconstruction techniques for investigations of laterally inhomogeneous media. Geophys J Int. 2010;79(1):305-315. https://doi.org/10.1111/j.1365-246X.1984.tb02858.x

38. Wang Z, Zhao D, Gao R, Hua Yuanyuan. Complex subduction beneath the Tibetan plateau: a slab warping model. Phys Earth Planet Inter. 2019;292:42-54. https://doi.org/10.1016/j.pepi.2019.04.007

39. Wang Z, Li X, Zhao D, Shang X, Dong L. Time-lapse seismic tomography of an underground mining zone. Int J Rock Mech Min Sci. 2018;107:136-149. https://doi.org/10.1016/j.ijrmms.2018.04.038

40. Lévêque J, Rivera L, Wittlinger G. On the use of the checkerboard test to assess the resolution of tomographic inversions. Geophys J Int. 1993;115(1):313-318. https://doi.org/10.1111/j.1365-246X.1993.tb05605.x

How to cite this article: Zhao T, Zhou Y, Gao S. An acoustic wave method for evaluating the effectiveness of blast to enhance fragmentation in longwall top coal caving. Energy Sci Eng. 2022;10:64–80. https://doi.org/10.1002/ese3.1004