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# Active velocity tomography for assessing rock burst hazards in a kilometer deep mine

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ABSTRACT

Active velocity tomography was used to determine the stress state and rock burst hazards in a deep coal mine. The deepest longwall face, number 3207 in the Xingcun colliery, was the location of the field trials. The positive correlation between stress and seismic velocity was used to link the velocity data with stratum stresses. A GeoPen SE2404NT data acquisition system was used to collect seismic data from 300 g explosive charges fired by instantaneous electric detonator and located in the tail entry. The geophones were installed on the rock bolts in the head entry of LW3207. Velocity inversion shows an inhomogeneous distribution of stress in the longwall face that could not be obtained from theory or numerical simulations. Three abnormally high P-wave velocity regions were identified that were located on the corners of the two roadways and at the face end near the rail entry side. The maximum velocity gradient is located at the open cut off near the rail entry and is the area most dangerous for rock burst. Mining-induced tremors recorded by a micro-seismic monitoring system demonstrated that the position of energy release during mining coincides with the high velocity gradient area. This technology aids technicians in the coal mine as they design measures to weaken or eliminate potential danger during subsequent mining.

## 1. Introduction

More and more mines in eastern China, and elsewhere, reach depths exceeding 1 km. At these depths new issues arise from the underground pressure including new rules for the mining induced stress field as well as new catastrophic dynamic phenomena, rock burst being the most unpredictable and violent of these [1–3]. Possible effects from rock burst include injuries and fatal accidents, damage to equipment, construction and production delays, and higher costs of construction and operation. Hence it is a topic of great research interest for mining engineers around the world [4].

A variety of countermeasures are in use to monitor and predict the danger from rock burst but no method has been entirely reliable because of various limits and poor field information [5]. Today, velocity tomography is being developed to ascertain the stress distribution and to determine the seismic zones over a large scale. This method is based on the fact that seismic wave velocity usually increases linearly with stress at lower stress levels and then plateaus at higher stress levels, which has been proven by many authors [6,7]. Since it provides the advantage of rapid, effective, and accurate hazard assessment tomography has rapidly become a research frontier at home and abroad [8–10].

## 2. Theory of velocity tomography

Velocity tomography falls into two main categories, active or passive, according to the seismic source [11]. Active sources, such as hammer strike, controlled blasting, or other sources of vibration, in known positions are advantageous since the seismic location is predictable and the energy relatively intense. This allows accurate coordinates to be obtained and can eliminate secondary errors. Active tomography also provides assessment results before the coal seam extraction that allows the technical staff to develop necessary preventive methods. Passive tomography usually uses micro-seismic events induced by mining activities that may be characterized as remote and that occur several times during the longwall face extraction. Nevertheless, passive tomography is challenging because of imprecise source location, inadequate knowledge of ray paths, and limited inversion areas; the latter being true because most mining-induced seismic events are adjacent to the exploitation zone.

We chose active tomography to find the velocity structure and then deduce the stress field state. From this an evaluation of areas with high rock burst hazard can be made.

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Arrays of seismic sources and geophones are arranged around the longwall face, the arrival time of the received wave, which is always the P-wave, can be easily determined. The seismic velocity along a ray is given by the ray-path distance divided by the time to travel between the source and receiver, as indicated in Fig. 1. The time is the integral of the inverse velocity, $1/V$, or the slowness, $S$:

$$T_i = \int_{Li} \frac{ds}{V(x,y)} = \int_{Li} S(x,y)ds \tag{1}$$

where $T_i$ is the travel time, $L_i$ is the spread path of the $i$'th seismic wave, $ds$ is an infinitesimal arc, $V$ is the velocity, and $S$ is the slowness. This equation is actually a typical nonlinear problem. For infinitesimal changes in the velocity structure the ray-path, $L_i$, can be treated as a straight line. However, the path is typically a curve due to complexity in the rock mass. The inversion area is decomposed into $N$ grids and the travel time in the $i$'th grid is:

$$T_i = \sum_{j=1}^{N} a_{ij} s_j \tag{2}$$

where $a_{ij}$ is the length of the $i$'th ray crossing the $j$'th grid. A matrix is used to describe the collected seismic ray paths passing through the grid cells. The matrix includes travel time, distance, and slowness for each grid element. The velocity can be determined by inversion as shown in Eq. (3):

$$AS = T \tag{3}$$

$$A = (a_{ij})_{M\times N} \tag{4}$$

where $A$ is the distance matrix, $(M \times N)$, $S$ is a $1 \times M$ matrix, and $T$ is a matrix holding the travel time per ray $(1 \times N)$. $a_{ij}$ is the length of the $i$'th ray crossing the $j$'th grid. Solving these equations one obtains the slowness distribution and thus an inversion of the velocity structure in the zone being studied.

## 3. An in situ experiment

### 3.1. Coal mine

The study was conducted in a kilometer deep underground coal mine located in Shandong province in eastern China. Top coal caving will be used in LW3207, where the coal seam ranges in thickness from 5.1 to 6.5 m at a depth from 1260 to 1360 m. This is currently the deepest longwall face in China. Both sides of the longwall face are solid coal seam. Numerous mining tremors and rock bursts have occurred in the past during coal winning at the other faces and roadways of the mine.

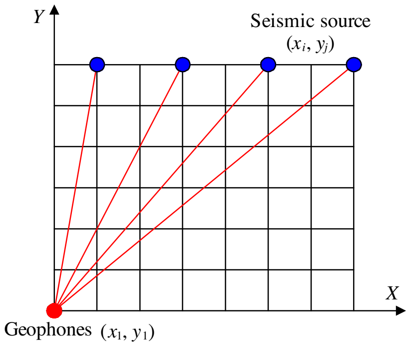

**Fig. 1.** Schematic diagram of velocity tomography.

### 3.2. Design of the experiment

The stress field was surveyed and a identification of the hazardous areas made by effective use of active tomography. Blasting is the seismic source and was located in the tail entry. Sources were spaced from Nos. 1001 to 1010 at 8 m intervals near the open cut off. This increases the ray path density. Additional sources were evenly spaced at 16 m intervals. A series of 54 geophones spaced at a uniform interval of 8 m were mounted to the existing rock bolts in the head entry. The layout of the design is illustrated in Fig. 2.

Data acquisition and analysis were done with a GeoPen SE2404NT and a host computer. Five acquisition stations and 54 channels of geophone signal were used. In this trial the array was moved ahead once to completely cover the inversion region.

The blasting holes were drilled 4 m into the coal seam and charged with 300 g of explosive fired by instantaneous electric detonators that were simultaneously triggered by the host computer. The wave data was recorded and an example of one set of data being as shown here as Fig. 3.

### 3.3. Inversion methods

The simultaneous iterative reconstructive technique (SIRT) algorithm is characterized by quick convergence and divergence. It is widely used to solve Eqs. (1)–(3) as a route to the reconstructed velocity distribution. This method has proved to be a reliable and stable technique for seismic velocity tomography. The study area was divided into a series of 10 m by 10 m grids. A total of 2379 rays crossed the study zone, as shown in Fig. 4. This size is sufficiently accurate for ascertaining the stress state in the strata. Bending curve rays are put into the inversion, which is favorable for the model portrayed. The average velocity of 3450 m/s is input as the initial velocity and a limiting range from a minimum of 1000 m/s to a maximum of 6000 m/s is also used to improve the algorithmic efficiency.

## 4. Velocity inversion

### 4.1. Velocity inversion results

Traditionally, only the gravitational stress in the vertical direction can be estimated. Then elastic theory is used to calculate the horizontal stress by using a coefficient called the side pressure coefficient. Alternately, a computer numerical model may be used to simulate the stress field before coal extraction but this stress field has been uniformly found to have a huge difference compared to reality.

In comparison, velocity tomography exhibits obvious strengths because of the link between seismic velocity and stress. Fig. 5 shows the P-wave velocity within the coal seam. The results are an uneven velocity field with a velocity distribution ranging from high to low speed. Three higher speed areas exist located along the corners of the tail gate and head gate, and at the face end of the tail gate side. The velocity near the corner of the tail entry is smaller than at the head entry because the coal has been broken there. The open-cut-off entry is an area of low speed so the velocity gradient is quite high at the face end where the most dangerous zones for rock burst exist. So care where rock burst might occur must be taken when mining begins. Extra high velocities are mainly caused by geological structures such as faults, folds, or the corners of the entries that abut stress concentrations. High stress is a sufficient condition for rock burst to occur. The longwall face was divided into different zones based on the stress distribution. This leads to a series of corresponding rock burst hazard zones