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Rockburst hazard determination by using computed tomography technology in deep workface ☆

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ABSTRACT

The rockburst in mines results from the dynamic load coupled with static one in coal seams around workface zones, so it is essential to learn the stress distribution of the coal and surrounding rock for determination of rockburst risk areas. The relationship between the elastic wave velocity and stress applied on coal sample was investigated systematically by laboratory testing, theoretically analysis, as well as on-site observation, and a positive correlation between them under uniaxial compression was put forward. Furthermore, it is drawn that the anomaly of elastic wave velocity reflects the stress changes: the positive anomaly ascertains the stress concentration while the negative anomaly estimates the mining destress and weaken degree, and corresponding assessment criterions and parameters were established respectively. The hazard areas and degree of an island longwall face 16302C were forecasted before coal winning based on the elastic wave anomaly distribution rules using active tremor velocity inversion, monitoring results of mining shocks during exploitation indicate that the consistency between locations of big tremors and where forecasted by computed tomography (CT) exceed 80%. The successful application of this technology achieved remarkable economic and social benefits for disaster control in rockburst mines.

1. Introduction

As the depth of coal mine increases sharply year by year, the initial stress in rock mass rises correspondingly, as a result, more and more dynamic disasters, i.e. rockburst and roof caving have been induced, rockburst, a special underground behavior characterized by obvious dynamic features, which is considered as a natural disaster caused by elastic energy emitted, in a sudden, rapid, and violent way from coal-rock mass, when the static stress exceeds the strength limit and triggered by dynamic stress wave, and the coal seam is damaged rapidly and thrown into roadways. Meanwhile, it leads to vibration and destruction of the rock mass, furthermore destroys the supports and equipments, causes miners causalities (He and Qian, 2010; Dou et al., 2009; Dou and He, 2001, 2007).

The rockburst in deep mines is the result of static stress (abutment stress) coupled with dynamic loads (seismic wave) in coal seams around mining areas, the greater the abutment stress, the higher likelihood the rockburst. So it is essential to study the stress distribution and find out the high stress location of the coal and surrounding rock around the workface, to determine rockburst risk areas and prevent the rockburst accidents.

The computer simulation and on-site measurement are common methods used to study the stress distribution in the coal seam and surrounding rock mass, both of which have inherent drawbacks (Dou and He, 2001). For instance, the computer simulation at present is just a development trend that enable match the real stress condition closely after the overburden strata because of the complex geological conditions, meanwhile the observation in field approach can only obtain the changes of stress, also called relative stress, within a limited scope, if definite stress is needed this method will be powerless (Dou and He, 2007). In order to overcome previous technical defects, we put forward the computed tomography technology, which is called computed tomography (CT) for short, to measure stress distribution based on the theory that elastic wave velocity changes positively with stress state in

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the coal/rock mass, using elastic wave velocity inversion throng the workface to determine the stress state and divide the rockburst danger to different degrees and regions of the whole workface scope. This technology can provide a solid foundation for rockburst prevention and control effectively.

2. Experiment on the relationship between *P* wave velocity and stress applied on the coal sample

The experimental relationship between elastic wave velocity and stress level applied on the coal sample is the prerequisite for CT technology used to analyze and assess the stress distribution in the workface as well as establish the theoretical foundation for rockburst danger forecasting. Hence, a series of experiments that uniaxial compression of coal sample until damage were designed that the loading rate was 5 MP/min and the *P* wave velocity was tested every 3 s. These experiments were carried out at College of Hydraulic and Hydra-electric Engineering, Sichuan University, using MTS815 Flex Test GT of rock and concrete material properties testing machine with the maximum axial load of 4600 kN, the horizontal and vertical measure range of the uniaxial extensometer are 4 mm and −2.5 to +12.5 mm, respectively. This machine is able to achieve triaxial tests, the horizontal measure range of triaxial extensometer is −2.5 to +8 mm, the confining and osmotic pressure are the same, 140 MPa, and the osmotic pressure difference is 30 MPa. The maximum direct tensile load can reach 2300 kN, the vibration frequency of the axial, confining and osmotic load is more than 5 Hz, the accuracy of each testing sensor equals to 0.5% of the geometric calibrated span. TDS3014, 5077PR, and 34099B system are used to test *P*-wave velocity, real-time monitor, record and display the experimental process. These ultrasonic testing systems combined with MTS815Flex test GT together constitute the *P* wave monitor and record during the Rock mechanics experimental test.

The results of *P*-wave velocity test during the whole process of uniaxial compression indicate that *P*-wave velocity increases positively with stress increasing. Increasing gradient of *P* wave velocity is usually highest at the beginning of the compression, and then the gradient decreases as the stress arises to the elastic limit of the coal sample, gradually *P* wave velocity reaches and maintains its maximum. The evolution of the velocity demonstrates that the affected factors no longer adjust as the stress state reaches to a certain stage of plastic in most cases. A power function is put forward to describe the relationship between stress and velocity as follow:

$$V_P = a\sigma^{\lambda} \quad (1)$$

where V_P is the *P* wave velocity, σ is the stress, a and λ are fitting and selected parameters, respectively.

Fig. 1 shows the fitted curve of the stress and velocity based on Eq. (1) and the actual data during experiments, and the correlation coefficient of this model reaches to 0.88, so we can obtain the expression of the curve as Eq. (2):

$$V_p = 662\sigma^{0.5823} \quad (2)$$

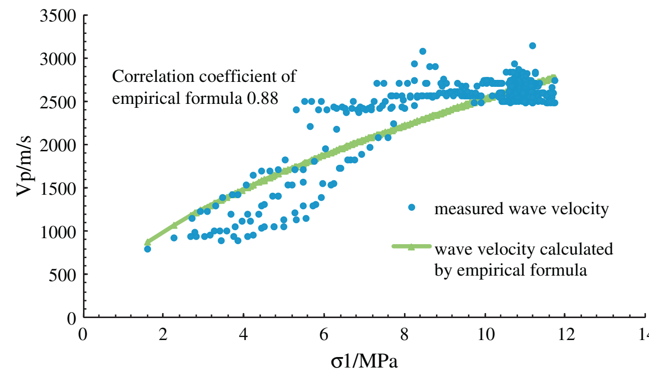

Fig. 1. Relationship between stress and *P*-wave velocity under uniaxial compression.

3. The theory of elastic wave computed tomography

Elastic wave CT technology as one of the mining geophysics methods is in essence seismic tomography. The basic principle of this method is seismic velocity inversion of the coal seam by investigating the travel time and energy attenuation of the seismic rays throughout the workface (Zhang et al., 2004; Young and Maxwell, 1992; Nur and Simmons, 1969; Jackson et al., 1995). The higher initial stress, the faster seismic velocity is when the rays propagate in the coal and rock mass (Lurka and Swanson, 2009; Lurka, 2008). The distribution of velocity field can be determined by inversion algorithm, consequently the stress field can be identified based on the theoretical and experimental relation established, the anomalous high stress and rockburst danger zones will be targeted, so as to provide a basis and guidance for prevention of this kind of rockburst.

The CT technique is implemented in roadways of the workface that arranges series of seismic source usually using blasting in one entry and geophones for seismic wave receiving were mounted to the existing rock bolts in the other entry. The most important data for velocity inversion and reconstruction is the first arriver time of different sources to different receivers which used for establish equation. Elastic wave CT technology depends on the relationship between travel time and seismic velocity $\upsilon(x,y)$ or slowness $S(x,y) = 1/\upsilon(x,y)$ along a ray-path, suppose the propagation path of the *i*th seismic wave is L_i with the travel time of T_i, one can obtain travel time equation, as shown in Eq. (3):

$$T_i = \int_{L_i} \frac{ds}{V(x,y)} = \int_{L_i} S(x,y)ds \quad (3)$$

where T_i is the travel time, L_i the spread path of the *i*th seismic wave, *ds* the infinitesimal arc, *V* the velocity, and *S* the slowness.

It is known that $\upsilon(x,y)$ and T_i are variables, so this equation is nonlinear, if little change occurs for the velocity structure, the ray-path L_i can be treated as a straight line, however the path is usually a curve in fact due to complexity of the rock mass, we need discrete the inversion area to *N* grids, so the travel time in the *i*th grid can be presented as Eq. (4):

$$T_i = \sum_{j=1}^{N} a_{ij}S_j \quad (4)$$

where a_{ij} is the length of the *i*th ray crossing the *j*th grid.

When massive seismic ray-paths pass through the grid cells, arranging the travel time, distance, and slowness for each grid into matrices, the velocity can be determined through inverse theory as shown in Eq. (5):

$$\begin{cases} T_1 = a_{11}S_1 + a_{12}S_2 + a_{13}S_3 + L + a_{1j}S_j \\ T_2 = a_{21}S_1 + a_{22}S_2 + a_{23}S_3 + L + a_{2j}S_j \\ \ldots\ldots \\ T_i = a_{i1}S_1 + a_{i2}S_2 + a_{i3}S_3 + L + a_{ij}S_j \end{cases} \quad (5)$$

It can be expressed in the following matrix:

$$AS = T \quad (6)$$

where $A = (a_{ij})_{M\times N}$ is the distance matrix ($N \times M$), *S* the matrix ($1 \times M$), and *T* the travel time per ray matrix ($1 \times N$). Solving the