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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:

$$V_P = a\sigma^{\lambda} \tag{1}$$

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):

$$V_p = 662\sigma^{0.5823} \tag{2}$$

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.

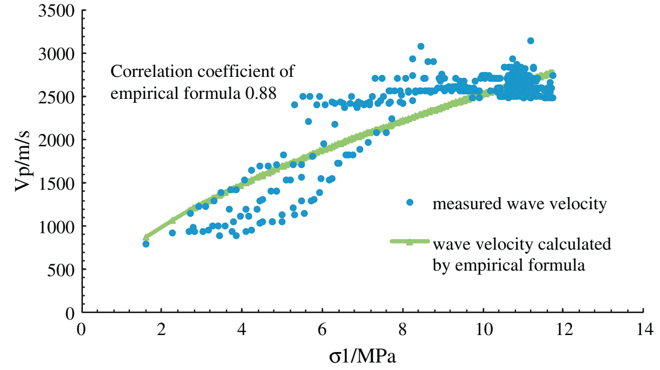

Fig. 1. Relationship between stress and *P*-wave velocity under uniaxial compression.

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):

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

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):

$$T_i = \sum_{j=1}^{N} a_{ij}S_j \tag{4}$$

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):

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

It can be expressed in the following matrix:

$$AS = T \tag{6}$$

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 equations one can obtain the slowness distribution thereby to achieve the velocity structure inversion in the research zones. It is noteworthy that in the process of seismic tomography the matrix A is often a large sparse matrix without obvious rules (that N elements in each row of A, while the ray-path only cross through a small part of all pixel), and the equation is often ill-conditioned, so repeat solution should be conducted in reality, the simultaneous iterative reconstructive technique shorted for SIRT (Tweeton, 1988; Friedel et al., 1996; Peterson et al., 1985; Saito, 1989) algorithm that characterized by quickly converging and small sensitivity of projection data error is widely used to reconstruct the velocity distribution, this method has been proved to be reliable and stable for seismic velocity tomography.

4. The early warning model and criterion of rockburst

The determination of the stress field state and concentration degree in coal seam is the basis of rockburst prediction. As we know from the experiments that the elastic wave velocity is positive anomaly at the areas with high stress and great concentration relative to the others, the anomaly index can be obtained as Eq. (7):

$$A_n = \frac{V_P - V_p^a}{V_p^a} \tag{7}$$

where V_p is the elastic wave velocity in the inversion area, and V_p^a is the average velocity.

The relation between the stress concentration degree and positive anomaly of elastic wave velocity as well as the criterion are established based on the experimental results, as shown in Table 1. Similarly, mining activities certainly produce cracks in the roof and floor strata form what called fractured and weaken zone, the extent of fracture and weaken of rock mass in this zone is related to the elastic wave velocity that provides an effect approach for assessment of weaken degree inducing by mining or artificial disturbances in the inversion area by negative anomaly index of elastic wav velocity, the evaluation criteria is shown in Table 2. The positive and negative anomaly of elastic wave velocity constitutes the assessment system of rockburst prediction by CT technology.

5. On-site application and verification of elastic wave CT technology

5.1. Introduction of longwall workface 16302C

The longwall workface 16302C, called LW16302C for short, is an island workface located in No. 16 mining district of 3_{lower} coal seam. LW16302C is 742.4 m long (advancing direction) and 135.5 wide with an average depth of 670 m. The designed terminal line and the center horizontal line of open-off cut are 80 m and 826 m fay away south from the center line of north district main return airway, respectively. The east and west side of LW16302C are LW16302 and LW16303 gobs. The open-off cut aligned at the center of LW16303 gob, bounded by the 2.0 m coal seam isopach and fault KF69. The terminal lines of these workfaces share the same straight line, as shown in Fig. 2.

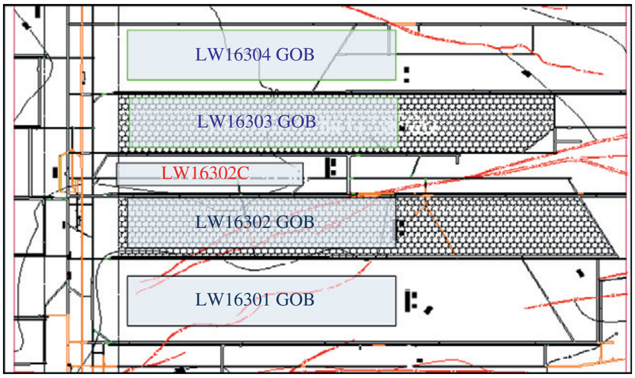

Fig. 2. Sketch map of LW16302C.

5.2. Analysis of elastic wave velocity CT inversion results

Fig. 3 shows the results of elastic wave velocity CT inversion in the coal seam, different colors represent different level of velocity that from high to low corresponding to color of red, yellow, green and blue, the red area is in accord with the highest velocity that is high stress zone, while blue represents low-velocity and low stress. Three high stress zones are determined separately that one locates near the middle entry along the open-off cut, marked A in Fig. 3, and the other at the right band of a fault at the center of workface, as marked B in Fig. 3, the last one is nearby terminal line along the tailentry side, marked C in Fig. 3. Stress concentration near the open-off cut that is region A is larger relative to the other two regions, additionally, compare the isopach of coal seam in this area, we find that the thickness contours is very intensive which indicates great changes of coal thickness, so high stress concentration of area A is attributed to the great change of coal thickness as it is known that stress concentration area is always consistent with the maximum gradient direction of thickness changes. But for the other two high tress zones that locate in the middle of the workface and near the terminal line, represented by B and C

Table 1
Relationship between positive anomaly of elastic wave and stress concentration degree.

Rockburst danger index	Stress concentration degree	Positive anomaly A_n (%)	Stress concentration probability
0	No	<5	<0.2
1	Weak	5–15	0.2–0.6
2	Moderate	15–25	0.6–1.4
3	Strong	>25	>1.4

Table 2
Relationship between negative anomaly of elastic wave and weaken degree.

Weaken index	Weaken degree	Negative anomaly A_n (%)	Stress reduce probability
0	No	0 to −7.5	<0.25
1	Weak	−5 to −15	0.25–0.55
2	Moderate	−15 to −25	0.55–0.8
3	Strong	>−25	>0.8

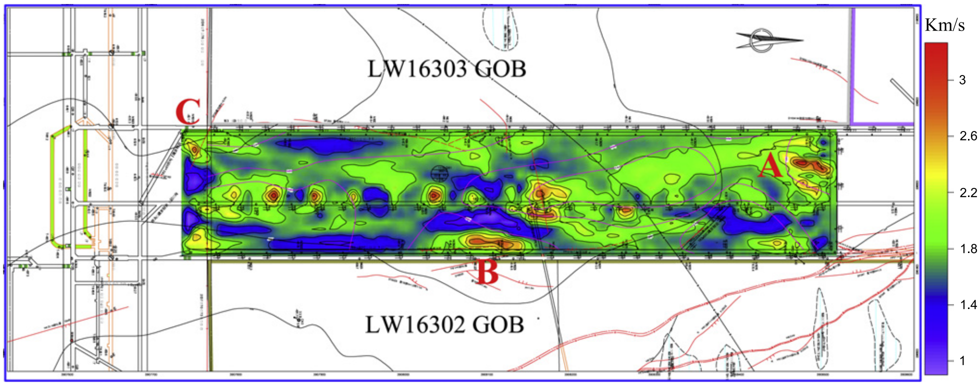

Fig. 3. Inversed velocity distribution of LW16302C.

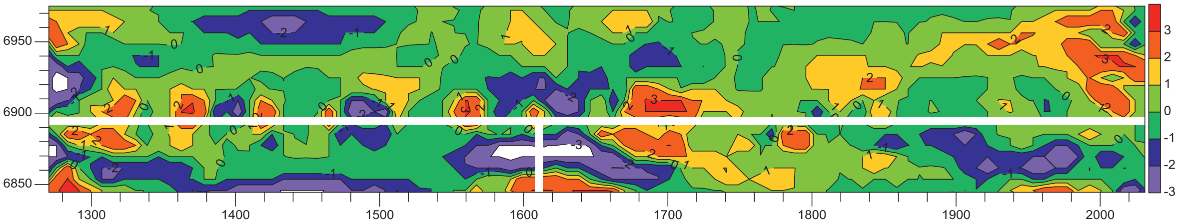

Fig. 4. Rockburst hazard identify by the elastic wave velocity anomaly.

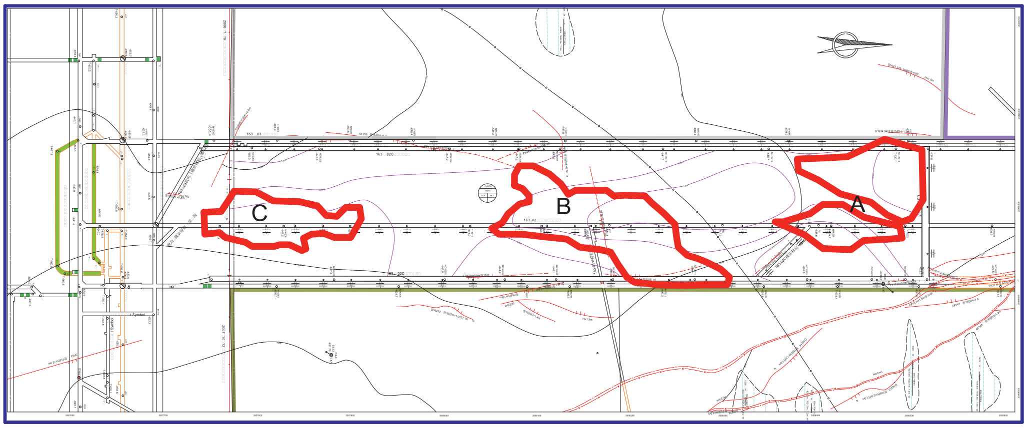

Fig. 5. Classification of the rockburst hazard area of LW16302C.

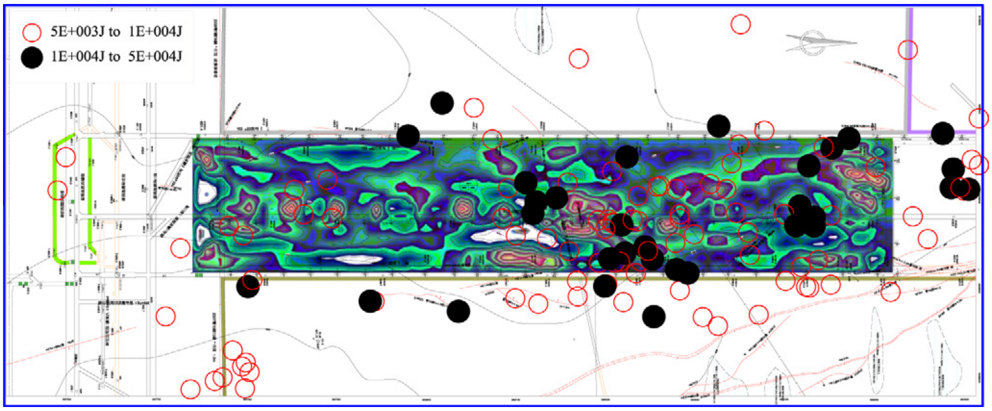

Fig. 6. Distribution of microseismic events in LW16302C.

respectively, are banded distribution and disaccord with the direction of small faults as well as maximum gradient of coal thickness change. Excluding the geological factors, we consider that the exited anomalous stress concentration is responsible for the high velocity of these two zones where would be attack by rockburst disaster easily. In summary, the reasons of the high tress in LW16302C are ascribed to gobs on both sides, changes of coal seam thickness and fault geology.

5.3. Identify of rockburst hazardous zones in LW16302C

The rockburst hazardous zones in LW16302C identified by elastic wave anomaly method are indicate in Fig. 4, the danger index relatively concentrates in several areas that nearby the open-off cut and terminal line, meanwhile obvious negative anomaly appears near both besides of the workface which reveals the roof has been fractured and destressd by the mining activities of previous workface and boundary faults so the velocity and stress are much lower. But around the faults internal the LW16302C, stress exhibits in contrary to those faults along the boundary. Distinct high stress and velocity exit closed to the crossheading and seam thinning area especially in the cliff of left contour indicate that rockburst hazard exits near the crossheading.

Based on the analyzed results above and combined with the actual production specification of LW16302C, we determine three rockburst zones finally that one is near the terminal line (C area in Fig. 5), the other at the crossheading (B area in Fig. 5) and the last nearby the open-off cut (A area in Fig. 5).

5.4. Microseismic monitoring tests of rockburst hazardous areas

Before the coal winning of LW16302C, not only the elastic wave CT technology was carried out, but also microseismic monitoring system was installed in the coal mine and sufficient geophones arranged around the workface. Therefore we can contrast the monitored microseismic event after the extraction with the results of hazard prediction by elastic wave CT fluoroscopy technology, so that they can mutually verify the accuracy of detection or monitoring. Fig. 6 shows the distribution of monitored microseismic events with energy greater than 10^3 J in LW16302C. The tremors are mainly located in the right half of the workface, that is in the region A and B, which have a strong correlation with the high velocity and the obvious velocity anomaly that indicates greater stress within the region. According to the theory of rockburst, the higher level of mining-induced tremors, the more easily lead to rockburst, and at the same time the stress is generally much more concentrated of high energy level of microseismic events. It can be seen from Fig. 6, mining tremors with energy over 10^4 J occurred mainly in zone A and zone B of LW16302C, and the consistency of the prediction hazard locations determined by elastic wave CT fluoroscopy technology and the results of microseismic monitoring is more than 80%. The above results verified the approach that using the elastic wave CT fluoroscopy technology to determine the high rockburst risk areas in workface is validity and reliability.

6. Conclusions

- The stress level of coal and elastic wave velocity are positively correlated. Experiments show that the elastic wave velocity rises with the increase of stress, and there is a power function relationship between stress and velocity when the coal samples are under uniaxial compression condition.
- The basic principle of elastic wave CT technology is seismic velocity inversion of the coal seam. High stress and high rockburst risk areas can be identified based on the distribution of velocity field within the workface.
- Relationship that anomalous changes of elastic wave velocity can reflect stress changes is proposed, and the positive anomaly of elastic wave velocity is used to determine the stress concentration, while the negative anomaly is used to determine degree of exploitation destress and weaken, moreover, corresponding assessment criterion and discriminant parameter are established, respectively.
- On-site test identified the distribution rules of the elastic wave velocity and velocity anomaly zones internal 16302C island workface, therefor three high danger zones of rockburst are determined: one is near the terminal line, the other at the crossheading and the last nearby the open-off cut. The results of mining tremor monitoring in LW16302C show that the consistency of the prediction hazard locations determined by elastic wave CT fluoroscopy technology and the results of microseismic monitoring is more than 80%.

Acknowledgments

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