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Case study of seismic hazard assessment in underground coal mining using passive tomography

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ABSTRACT

The relation between applied stress and wave velocity is examined firstly at the laboratory-scale by using ultrasonic technique. Subsequently, an island longwall face under hard-thick strata, suffering from the threat of seismic hazards, e.g. rock burst, strong tremor, was chosen for a case study of passive velocity tomography. Based on continuous seismic monitoring during mining operation, passive tomographic imaging has been used to locate high seismic activity zones and assess seismic hazard around the face. The results show that the high velocity and velocity gradient regions correlated well with the high seismic activities occurred in future mining period. In addition, the high velocity or velocity gradient regions redistributed with the retreat of coalface and large-scale movement of key strata. Passive velocity tomography can be a promising tool to continuously monitor the relatively high stress zone or evaluate seismic hazard in underground coal mining.

1. Introduction

The safety and productivity of underground mining can be severely affected by seismic activity. Mining-induced seismic events, which are induced by sudden release of strain energy accumulated in the coal-rock mass, are associated with not only superficial structure movement triggered by stress manifestation, but also related to large geological discontinuity, affected by the extent and means of mining [1,2]. Rock bursts and strong tremors are particular cases of seismic events induced by mining activity that result in damage to underground workings or surface buildings, and in some cases, injury and loss of life [3]. In China, these dynamic hazards are encountered in many coal mines due to large-scale rupture or movement of hard strata, irregular layout of coalface, large mining depth, reaction of anomaly geological structures, etc., and become progressively more severe as the average mining depth and mining intensity increase continuously [4,5].

Anomalous information identification and mining stress analysis is the key issue to reduce and prevent the hazards. Several methods to estimate abutment pressure, detect structure defaults, and evaluate rock burst hazard around the coalface have been introduced, such as electromagnetic emission [6,7], drilling bits [8], acoustic emission [9], borehole exploration [10], and pressure sensor installation [11], etc. The conventional methods mentioned above are not sufficient to meet the needs of underground mining and engineering projects due to the shortcomings of time consuming, easy disturbance, localized monitoring range, or destructive effect in production, etc. Thus, it needs to develop a simple, rapid, and cost-effective tool for imaging locations of stress concentration zones, anomaly geological structures, or high seismic activity zones during mining operation. Microseismic monitoring has been proven as a powerful tool to quantify seismicity and can contribute valuable information for dynamic hazard evaluation [12]. In addition, as a new geophysical method, the velocity tomography has been gradually used for crack detection, geological structure exploration, stress redistribution imaging, etc. [13]. Therefore, combining the microseismic monitoring and tomography imaging, may be a better approach for seismic hazard assessment or pre-warning in coal mining.

Velocity tomography relies on the transmission of seismic waves, especially P-waves, through coal-rock mass. It can be classified as “active” and “passive” based on the type of source used [14]. Active tomography, which using explosives [15], hammer strikes [16,17], vibrations generated by shearer [18], etc., as the sources, can allow for consistent seismic ray path distribution. It is preferred to apply in the relatively accurate detection of stress distribution and hidden structure defaults in the pre-mining coalface, while the detection area usually does not exceed areas of 200 m × 200 m and is not

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always feasible for long time-lapse investigation [14,19]. Passive tomography, which using mining-induced seismic events as the sources [14,19–23], can continuously estimate the relatively high stress or rock burst hazard during the whole mining process, and its detection area can reach to about 2000 m × 2000 m [19] if the layout density of microseismic monitoring network is high and the ray path density meets the inversion requirement.

Stress distribution in various underground structures has been imaged by passive tomography, including longwall panels, coal pillars, entries, geologic structures and discontinuities, etc. [14,22–27], while there are few examples of rock burst hazard detection using passive velocity tomography [19,20,28]. Particularly, application of passive tomography starts fairly late in China, and is mostly used in geophysical exploration [13,25] and earthquake tomography [29,30], while the application in stress distribution imaging and seismic hazard evaluation in underground mining has been seldom involved [28].

The sites chosen for this study are an underground island longwall face in Baodian Coal Mine, Yanzhou Mining Group, Shandong Province, China, where strong mining-induced tremors and rock bursts are the main safety threats in underground coal mining. The face was monitored continuously by microseismic network for 8 months. Thus, the site has considerable microseismic activities, making it ideal for passive tomographic imaging of high seismic activities during mining process.

2. Velocity tomography for seismic hazard assessment

2.1. Experimental relation between stress and wave velocity

The origins of tomography can be traced back to the X-ray discovery in 1895 by Wilhelm Conrad Roentgen [31]. Modern technology allows doctors to use X-rays to map the internal human

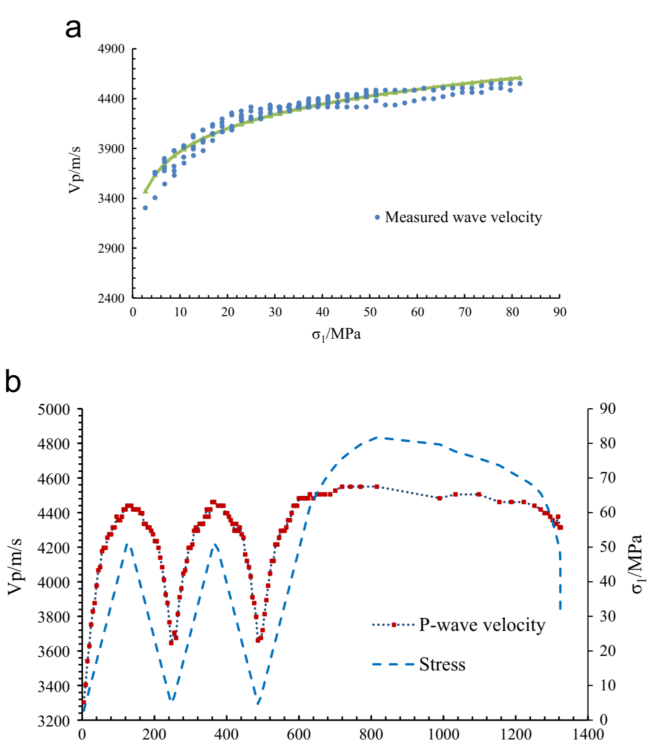

Fig. 1. Relation between stress and ultrasonic wave velocity in uniaxial loading test: (a) relation between wave velocity and stress in uniaxial compression loading and (b) relation between wave velocity and stress in uniaxial cyclic loading and unloading.

body. Based on the same key principles, scientists have extended tomography to the geophysical field by using seismic waves [32], which is known as seismic tomography. P-wave is the first part of the seismic wave to arrive and generally the easiest to measure. Thus, the key of the seismic tomography relies on the variation of seismic waves (especially P-wave) transmitted through rock mass under stress. According to the inversion parameters of seismic wave, seismic tomography can be classified as velocity tomography and attenuation tomography [27]. In velocity tomography, the inversion parameter is the wave velocity distribution with travel time, and attenuation tomography focuses on measuring the amplitude of seismic wave to detect the absorption property of geological media. Additionally, seismic velocity tomography is classified as "active" and "passive" based on the type of source used [14].

As early as in 1920s, Adams et al. found that passive tomographic imaging should be built on the close relation between elasticity modulus of rock mass and wave velocity [33]. Yale discovered that rock porosity may decrease with the increase of stress, which results in the increase of wave velocity transmitted in rock mass [34]. Meanwhile, it is found that obvious change of wave velocity always appears in the high stress stage [35], and velocity variation also correlates with the roughness of rock fracture plane [36].

To understand how velocity tomography can be applied in stress state imaging and seismic hazard assessment, and investigate the relation between seismic wave and stress, the ultrasonic wave velocities of rock samples were tested under the uniaxial compression and uniaxial cyclic loading and unloading conditions, respectively. The rock samples were collected from no. 10 Mining District of Baodian Coal Mine, and were processed to cylinders with the height of 100 mm and width of 50 mm. There are two inner-set ultrasonic sensors functioned as receiver and transmitter in the upper and lower plate of MTS815 loading system, respectively. Meanwhile, one circumferential and two axial extensometers were installed for acquiring the circumferential and axial strain data. In addition, a layer of lead foil with 0.3 mm in thickness was attached to the upper and lower surface of rock samples before the loadings, so as to obtain clearer ultrasonic signals [28]. At the loading intervals of three seconds, the transmission velocities of acoustic waves through the samples were acquired along with the stress loaded.

Fig. 1 shows the typical fitting curves of stress and ultrasonic wave (P-wave) velocity during loading process. It is found that there exists an exponential function relation between P-wave velocity and axial stress. In the uniaxial compression loading, P-wave velocity usually increases rapidly with the increase of stress at lower stress levels, and after the inelastic stage of rock samples, the increasing gradient of wave velocity slows down and gradually turns to be stable at higher stress level. In the uniaxial cyclic loading and unloading process, the stress variation correspondingly results in the change of P-wave velocity, while wave velocity changes quickly during the loading and unloading process of lower stress stages, and changes slowly in the higher stress stages.

In coal mines, the occurrence of seismic hazards, e.g. rock burst, strong tremor, is closely related to the underground in situ and mining stresses. Above results in the laboratory present that velocity tomography can be useful for inferring the stress state and redistribution in coal-rock mass. Thus, the high seismic activity zones and seismic hazards can be assessed by tomographic imaging.

2.2. Theory of velocity tomography

Tomography requires dividing the body into grid cells called pixels in two-dimensional situation, or cubes called voxels in three-dimensional situation to estimate the body characteristics in all pixels or voxels. Velocity tomography depends on the