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Inversion of stress field evolution consisting of static and dynamic stresses by microseismic velocity tomography

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ABSTRACT

In order to reveal the stress precursors of the "3.15" rockburst disaster that occurred in the No. 1 working face of Junde coal mine, the combined stress field inversion including static and dynamic stresses was conducted by using P-wave velocity tomography, and the static high-stress concentration regions were further designated. Simultaneously, the evolution of dynamic stress generated by seven periodical caving events of primary roof was analyzed, and the fracturing characteristics were described in detail. Ultimately, the stress precursors of the "3.15" rockburst for early warning were clearly revealed. The main conclusions are as follows: (1) the micro-fissures inside coal and rock mass produce the significant reflection and refraction on the propagation of microseismic (MS) waves, and thus P-wave overall characterizes with lower velocity and higher velocity gradient; (2) after the slightly fracturing of primary roof on March 9, 2013, the maximum stress concentration factor suddenly rises to 20. This sign can be viewed as an early warning precursor of rockburst; (3) until March 12, 2013, the large-scale micro-fractures begin to form inside primary roof, and thus the corresponding high velocity gradient regions are generated. This phenomenon can be regarded as an effective precursor of macroscopic fracturing of primary roof; and (4) before the "3.15″ rockburst, the scope of P-wave velocity gradient in the No. 1 working face does not change significantly. The above findings may put forward a certain reference for accurately warning the stress precursors of rockburst by P-wave velocity tomography.

1. Introduction

The compressional P-wave velocity of underground coal and rock materials and its effect on mining-induced vibration wave propagation are of fundamental interests in many engineering studies. Mining-induced vibration is also called microseismic (MS) event. MS events, i.e., fractures and slips in coal and rock that radiate detectable seismic waves, are the common phenomenon associated with coal and rock deformation and fracture in coal mines. The source of MS event may be far away from the mining area, however the damaging locations (such as the appearance regions of rockburst) triggered by dynamic load accompanied with MS wave propagation are commonly adjacent to the stress concentration or high stress gradient regions.[1] Generally, the triggering factors of rockburst mainly include the static high stress and strong dynamic load generated by MS activity. For example, Qi and Dou[2] proposed the "dynamic-static load superimposition" triggering mechanism of rockburst, and it has been widely verified by field investigations. Especially, according to the comprehensive analysis of the "3.15" hazardous rockburst accident in Junde coal mine (JCM),[3] the geological conditions of the rockburst occurrence location are very complex, and there exists a static high-stress concentration area with superimposition of dynamic loading disturbance generated by periodic caving of overlying key primary roof. In order to designate in advance the dangerous area and accurately warn the risk of rockburst, the distribution and evolution of the comprehensive stress field surrounding the No. 1 working face of JCM should be timely analyzed, and the fracturing characteristics and corresponding precursory signs of primary roof also need to be clearly revealed. Ultimately, the aim to warn and prevent this type of rockburst disaster may be accomplished.

How to designate the high stress concentration region in the mining coal and rock mass and warn the caving of roof strata is a key issue for rockburst prevention. Seismologically observed

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seismic wave velocity structures can provide important information on the stress state of rock, in conjunction with experimentally determined P- and S-wave velocities of rock samples. Reviewing related literature reveals that many fruitful studies have been conducted on investigations of the stress spatial structure of coal and rock through seismic wave velocity. For example, Adams and Williamson[4] established the wave velocity reconstruction method in the inversion region by seismic wave velocity tomography based on the relationship between elastic modulus of coal and rock and wave velocity. Mohorovicic[5] identified the boundaries of crust and mantle according to the sudden variation of seismic wave velocity when propagating through the interior of earth. The velocity of seismic wave is closely related to rock type, angle of rupture plane, anisotropy, porosity, stress, elastic modulus, and boundary conditions, etc. Therefore, the stress of coal and rock can be indirectly determined by measurements of seismic wave velocity. For example, Yale[6] found that the micro-cracks and holes will significantly reduce seismic wave velocity through diffraction effect in the direction of wave propagation. For most of rocks, the decrease of porosity will raise wave velocity with the increase of stress. Toksöz et al.[7] discovered that both saturation and pore fluid in rock have the influence on seismic wave velocity and the velocity increment of dry rock under the compressive stress was faster than that of wet rock. Jones and Wang[8] found that seismic wave velocity will decrease with the decrease of the effective stress of wet rock sample caused by pore pressure through resistance effect on confining pressure. Nur and Simmons[9] experimentally investigated the relationship between P- and S-wave velocities and imposed load direction by cylindrical granite samples, and found that P- and S-wave velocities rose with the increase of stress and the increment of velocity correlated to stress direction and P-wave propagation direction. Zappone et al.[10] presented new laboratory measurements of P-wave velocities conducted at high confining pressure on rocks from the Alpine metamorphic basement of the Betic Chain. Pinna et al.[11] revealed that the vertical P-wave velocity was the main indicator of overpressure, varying by almost 40% the value at normal pressure conditions for testing Kimmeridge shale. Sams et al.[12] conducted in situ P-wave velocity measurements at a borehole test site and on core samples in the laboratory to determine the elastic properties of a sequence of saturated sedimentary rocks. Mavko and Jizba[13] observed the velocity dispersion over a certain frequency range for both P- and S- waves. In summary, how to reveal the stress spatial distribution and evolution in a large-scale mining coal and rock mass is a conundrum still remains incompletely resolved in rock mechanics community, which may be attempted by stress inversion on basis of MS wave velocity tomography.

The tomography analysis can intuitively reflect the relationship between seismic wave velocity and stress by describing variation characteristics of seismic parameters in the spatial structure of coal and rock.[14,15] Seismic parameters mainly include amplitude and velocity, and P-wave velocity imaging is more widely used. For example, Worthington[16] firstly applied the tomography technology of seismic wave in the geophysical field. Mason[17] reconstructed the two-dimensional image of stress distribution in coal seam by using tomography technology. Cosma[18] applied the cross-hole tomography technology in Otonaki coal mine for evaluating the stress distribution. Bodoky et al.[19] attempted to detect faults and veins deposited in coal seam by using cross-hole tomography technology. Jackson and Tweeton[20] innovatively conducted the research on migration-geophysical tomography. Zhou[21] realized the travel-time tomography of seismic wave on basis of the spatial coherence filter geophysics technology. Westman et al. [22] investigated the stress distribution and variation of a longwall working face along with advancing by seismic wave velocity tomography, and found the high-velocity zones were in good agreement with the lateral abutment pressure zone. Young et al.[23] identified the integrity of rock mass overlying coal pillar by monitoring the abnormal velocities of P- and S- waves generated by small shallow-hole blasting in coal seam. Dubinski and Dworak[24] detected abnormal velocity distribution and designated rockburst dangerous regions by application of active seismic wave tomography. Maxwell and Young[25] discovered that the scope of high-energy seismic events induced by mining was strictly consistent with the distribution zone of high wave velocity, and there scarcely were events in the low-velocity region. Zimmerman and King[26] believed that seismic velocity changes commonly occurred in the high stress period during the actual fracturing of rock mass. Hopkins et al.[27] investigated the relationship between seismic wave velocity and interface roughness among rocks. Glazers and Lurka[28] found a good coupling effect between inversion results of seismic wave velocity and stress distribution. Young and Maxwell[29] deemed that the current research direction of MS induced by mining should focus on the passive tomography imaging of MS wave velocity. Moreover, Maxwell and Young[30] discovered that the high-energy MS events significantly concentrated in the high velocity-gradient regions and the stress concentration was accompanied with the increase of wave velocity. Friedel et al.[31] investigated the three-dimensional tomography of anomalous conditions in a deep silver mine by in-situ seismic measurements.

In summary, many researchers have carried out the research on passive seismic wave tomography for evaluating the stress concentration level of coal and rock in coal mines. However, the achievements on passive tomography of MS wave velocity in strong rockburst dangerous working face characterized with static high-stress concentration and hard roof are still scarcely reported. In addition, the evolution of stress field during roof caving, and the precursors of rockburst triggered by roof caving also lack field investigations by passive tomography of MS wave velocity.

The aim of our work is to establish possible relationship between P-wave velocity/velocity gradient and level of rockburst danger. Based on the relational model between MS wave velocity and stress obtained from theoretical analysis and laboratory experiments, the static high-stress concentration and high velocity gradient regions indicating rockburst danger surrounding the No. 1 working face of JCM were clearly designated by analysis of passive MS velocity tomography. Aiming at the factor of dynamic load, the MS velocity variation and dynamic stress evolution during primary roof caving were revealed, which provided the reference for accurately warning and evaluating the intensity of roof caving. Eventually, the “dynamic-static load superimposition” triggering mechanism of the “3.15” rockburst was verified based on the comprehensive stress field inversion, and the stress precursor of the rockburst was summarized.

2. Theoretical and experimental bases of MS velocity tomography

Passive travel-time tomography utilizes MS events as sources in a simultaneous inversion for event location and velocity structure, which has been used extensively in studies of earth structure and is being increasingly applied to mining problems. The passive tomography problem can be solved in many different ways.

2.1. Determination of P-wave velocity

The equations of seismic wave propagation in rock medium indicate that rock will generate two kinds of deformation under force, which manifest two different types of waves, namely