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A correlation radius estimate between in-panel faults and high-stress areas using Monte Carlo simulation and point process statistics

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ABSTRACT

Since quantitative correlation association between in-panel faults and high-stress areas have not been well understood, we propose a workflow to quantitatively estimate this spatial association through Monte Carlo simulations and point process statistics using measured fault traces and tomographic seismic velocities as inputs. According to different distribution scenarios of fault traces and high-stress areas based on in situ characteristics, we build three different spatial statistical models: a no spatial correlation model, an anti-correlation model and a correlation model to analyze and compare with the observed data. By estimating and cross plotting RHA (Ratio of High-stress Areas over total area) and RFL (Ratio of included Fault-trace Length over total fault-trace length) pairs for Monte Carlo realizations of those models, we generate a template to estimate the correlation association between in-panel faults and high-stress areas for the study panel. After comparing the observed cross plots of RHA vs. RFL pairs with the template, we find that the in-panel faults and high-stress areas have positive correlation association and yield an estimate of correlation radius for the study panel. This result is in accordance with previous geological analysis. However, the estimated correlation radius can be affected by velocity artifacts and inaccurate interpreted faults. Considering the influence of velocity artifacts, we achieve a calibrated template to better estimate the correlation radius between in-panel faults and high-stress areas. This estimate could be a practical parameter to optimize mining methods and to minimize stress related rock failures.

1. Introduction

With the massive mining of underground coal in China, dynamic failures such as gas outbursts and rock bursts have caused losses of several million dollars and several hundred lives. According to present researches, the presence of faults is a primary factor affecting gas outbursts and rock failures (Cao et al., 2001; Chen et al., 2015; Dou et al., 2012; Hanson et al., 2002; Wold et al., 2008; Zhai et al., 2016). As the results revealed in China and around the world, normal faults, strike slip faults as well as reverse faults can induce severe gas outbursts and rock failures (Cao et al., 2001; Shepherd et al., 1981; Wold et al., 2008; Zhai et al., 2016). Among all outbursts, most of the severe outbursts have been located in strongly deformed zones along the axes of faults. Because of the tectonic deformation and structural heterogeneity, stress and gas are concentrated in the narrow zone (Shepherd et al., 1981; Wold et al., 2008). Apart from natural factors, some human factors, such as CO2 injection and underground mining activity, can also affect the reactivation of pre-existing faults and cause local stress field perturbations (Cappa and Rutqvist, 2011; Faulkner et al., 2010, 2006; Jeanne et al., 2014; Rinaldi et al., 2014). Nevertheless, fault zones and fault systems control the mechanics and flow properties of the crust. If pre-existing stress in a mining zone is high, the perturbation related to underground mining activities may have more chance to reactivate pre-existing faults or generate new rock failures than the same perturbations in a less critically-stressed zone.

In general, geomechanics, pore pressure, constitutive laws, and stress/strain boundary conditions govern the association between faults and local stress (Brady and Brown, 2013; Faulkner et al., 2010, 2006; Heap et al., 2010). Traditionally, researchers use Boundary Element Method, Finite Element Method and other numerical methods to

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simulate the effect of faults on local stress field and to identify the correlation radius between faults and their associated high-stress zones. Those methods need some preconditions such as obtaining exact information of fault geometry, geomechanical properties, pore pressure and stress/strain boundary condition (Brady and Brown, 2013; Kattenhorn et al., 2000; Li et al., 2011). In many practical situations, those preconditions are incompletely accessible before coal extraction in underground coalmines. Instead of geomechanical modeling, active seismic survey and passive seismic monitoring are popular methods to delineate the fault distribution and estimate the velocity heterogeneity in underground coalmine panels (Chen et al., 2015; Dou et al., 2012; Ge, 2005; Hatherly, 2013; Mason, 1981; Maxwell and Young, 1995; Si et al., 2015; Zuo et al., 2009). The delineations of high-velocity areas and detected or measured in-panel faults are the most accessible data. Because stress and elastic wave velocity have positive correlation in the shallow crust, the monitored velocities can be used to locate high-stress areas and to estimate a relatively accurate stress level (Chen et al., 2015; Dou et al., 2012; Mason, 1981). If one can use those monitored velocities and detected/measured in-panel faults to better understand the spatial correlation and association between high-stress areas and in-panel faults, it could help coalmine operators to minimize stress related rock failures and gas outbursts.

Stochastic simulation as a popular modeling tool has been used in geosciences for many years. In the coal industry, researchers use it to estimate coal-bed methane resources, to map the heterogeneities of coal quality, and to quantify the geological uncertainties and risks (Olea and Luppens, 2015; Tercan and Sohrabian, 2013; Zhou et al., 2012). Geologists use it to simulate 2D and 3D fracture and fault distributions, to analyze the association between faults and fractures, and to model the association between stress field and fractures (Kattenhorn et al., 2000; Noroozi et al., 2015; Viruete et al., 2001, 2003). Point process statistics (also called Boolean spatial process) have been widely used in mining, geology, forestry, and environmental sciences to analyze the geometrical patterns formed by objects that are distributed randomly in one-, two- or three-dimensional space (Connor and Hill, 1995; Illian et al., 2008; Moller and Waagepetersen, 2004; Russell et al., 2016). In order to estimate the association between in-panel faults and high-stress areas under incomplete information of underground coalmine panel, stochastic simulation and point process statistics are useful options.

This paper, following the qualitative analysis of Chen et al. (2015), proposes a quantitative analysis workflow to estimate the spatial correlation association between in-panel faults and high-stress areas in an underground coalmine panel using monitored tomographic velocities from active seismic data, in situ measured faults, Monte Carlo simulation and point process statistics. The focus is on statistical spatial modeling of observed data, with the purpose of getting some practical estimates of spatial correlation association.

2. General geology

The panel used in this study is a longwall island panel of 163L02C from Jining3 coalmine. This mine is a key production colliery in Southwest Shandong coalfield that is located in Shandong province, eastern China as shown in Fig. 1. The target of this panel is No.3 coal (about 675 m in depth). Its lithology is anthracite with glass luster, and its thickness is 3.0–6.0 m. Except for the faulted areas, the coal-bed thickness is relatively uniform. Both the coal bed and its roof and floor belong to Lower Permian formation as shown in Fig. 2. The direct roof is thin and non-uniform silt sandstone; while the direct floor is thin and non-uniform mudstone. In contrast with the thin and non-uniform direct roof and floor, the main roof and floor are thick and uniform sandstone as shown in Fig. 2. Since they are more stiff, uniform and thick than the coal bed, generated seismic waves will likely refract from them for a source deployed in the coal bed. Therefore, this panel is suitable for the imaging using refraction tomography (Chen et al., 2015).

In the Yanshanian Orogeny (208 Ma) and the Himalayan Orogeny (65 Ma), the coal field of this panel experienced a series of tectonic movements. During roadway excavation and in-panel coal extraction, the operators of this mine identified in-panel faults and measured their characteristics daily. As a result, the 163L02C panel shows fifteen mapped faults (Fig. 3). Their strikes are shown in Fig. 4. In general, those faults belong to two main fault sets. One set consists of normal faults with NNW-SSE trend, and the other consists of normal faults with NNE-SSW trend. Because most faults are along NNW-SSE trend, this trend dominates the faulting characteristics of this panel. Considering the fault trends, most of them are near north direction with up to $\pm$ 30° deviation. This characteristic is a key input factor during fault simulation. The fault throws are small (0.7–1.6 m). We ignore the influence of fault throw during fault simulation. The fault lengths differ largely from fault to fault (Chen et al., 2015). The longest one is F3 (209 m), and the shortest one is F14 (17 m). We consider the influence of fault length during fault simulation.

Chen et al. (2015) carried out active seismic tomography in this underground panel to measure the velocity distribution before coal extraction. Lithologically the formations are quite homogeneous and lithological variations are not a source of P-velocity heterogeneity in this case, as analyzed in Chen et al. (2015). Since P-velocity has a positive correlation with stress in the shallow crust, imaged P-velocities will indirectly depict the stress distribution of the panel (Chen et al., 2015; Dou et al., 2012; Mason, 1981; Maxwell and Young, 1995; Young and Maxwell, 1992). In order to achieve a categorical assessment, Chen et al. (2015) classified the imaged P-velocities into three stress levels (High, Medium and Low) using a threshold method as shown in Fig. 5.

Almost all of the high-stress area are near faults except for area B. The spatial distribution of high-stress areas shows qualitative correlation with local stress field, previous mining activity and local fault distributions (Chen et al., 2015). After previous mining activities, the west and east sides of 163L02C panel have formed two mined out voids. Because of the existence of those voids, the coal bed and its main roof in this island panel have been detached from its adjacent strata. Therefore, the maximum horizontal principal stress (with near *E*-W direction) has been relieved from this panel (Chen et al., 2015). This may cause perturbations of the local stress field and the concentration of high stress around faults. Instead of a qualitative analysis as in Chen et al. (2015), we focus on the fault zone to analyze quantitatively the correlation association between measured faults and categorized high-stress areas as shown in Fig. 5. The fault zone is defined as the rectangle with dashed lines as most of the in-panel fault traces and high-stress areas are within this rectangle.

3. Estimates of correlation association

Geologically, the existence of faults will be accompanied with the heterogeneity distribution of stress as shown in Fig. 5. A deterministic estimate between in-panel faults and their related high-stress areas will be convenient and practical for coalmine operators to optimize mining methods and minimize stress related rock failures. In this section, we propose a feasible workflow to quantitatively analyze the correlation association with Monte Carlo simulation and point process statistics. The input data are simulated fault traces and high-stress areas referenced from the measured in situ characteristics. Because the coalbed is relatively flat and all faults found in the study panel are normal faults with limited dip angle and throw variations (Chen et al., 2015), we ignore the influences of fluctuations in the coalbed floor and small variations in fault's dip angle and throw. We use a 2D-panel model to approximate the true 3D panel. In addition, we ignore the damage zones around faults during simulation because the true damage zones in the 163L02C panel are nearly invisible. The concerned variables are fault strikes, fault lengths, and tomographic seismic velocities.