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Discrimination of seismic sources in an underground mine using full waveform inversion

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ABSTRACT

To discriminate the type of the induced seismicity in the underground mine, full waveform inversion and statistical methods were used to investigate the different microseismic source mechanisms in a more quantitative way. To eliminate possible effects caused by specific configuration of monitoring network, potential error in source location and wave propagation mismodelling, Jackknife resampling was used to obtain the probability density functions of inversion results and the moment tensor uncertainties. Firstly, the expected prior probability functions for mining blast, cavity collapse, fault slip, and tensional failure were defined, which are related to the percentage of the double couple, the compensated linear vector dipole, and the isotropic components. Secondly, the likelihood of a given candidate event to a certain source model was calculated, and the source type was determined according to the moment tensor decomposition of the case with the highest probability density. Tests with synthetic datasets were performed to evaluate the stability of the inversion in case of poor data quality and inaccurate source location. The calculated results with noise levels from 0% to 20% are all clustered closely around the initial source in the source type diagram, which indicates the reliability of the derived focal mechanism. The discrimination method of seismic sources in underground mine using full waveform inversion was verified by 8 events of field investigations in the Yongshaba Phosphate Mine, China. Results show that events 1, 5, 6 and 8 are tagged as fault slip events. Their probability of fault slip events are 0.53, 0.57, 0.37 and 0.60 respectively. The events 2, 3 and 7 are recognized as the cavity collapse events corresponding the probability 0.46, 0.51 and 0.50, respectively. The mechanism of the event 4 is recognized as a tensional failure with the probability 0.57.

1. Introduction

The discrimination of seismic source mechanisms is a crucial and fundamental issue to analyze and control seismic hazard in mining environments. Different types of mechanisms have been observed and modelled in the past, including cavity collapses, rock falls, pillar bursts, explosions, tensional ruptures, and fault-slips.[1–3] The current practices to identify those possible failure mechanisms are mainly based on manual experiences, generally distinguishing the temporal and spatial trends of events using seismic source parameters, such as the ratio of S- to P-wave energy and the Gutenberg-Richter relationship.[4,5] However, when multiple mechanisms exist within the population of events, it is likely to give an ambiguous result.

The seismic moment tensor is a term that used to describe the geometry of the forces acting at the source. Therefore, moment tensor inversion is generally considered to be an effective approach to recognize natural earthquakes, seismicity associated with volcanic processes, and hydrocarbon extractions.[6–8] Recent years, moment tensor inversions were further developed and carried out on much smaller scale to identify the rock cracking mechanisms during laboratory acoustic emission experiments.[9,10]

According to Jost and Herrmann,[11] the moment tensor can be compared to various source models, such as a displacement on a fault, a volume decrease with implosive failure, and a sudden volume increase due to explosion. Therefore, the moment tensor inversion is deemed as the most practical tool to discriminate the failure models of mining induced seismic events.[12] Lots of moment tensor inversion approaches have been developed in the past, where the most suitable ones for weak seismic events are the amplitude inversion, the amplitude ratio inversion, and the full-waveform inversion.[13] Vavryčuk[14] proposed a new waveform moment tensor inversion method in 2017 that utilizes the principal component analysis of seismograms. It shows less sensitive to the noise, more accurate and more robust than the traditional approaches. Those inversion approaches have been carried out successfully in mining environment to recognize the tensile failure of crack,[15] the shearing or non-shear events,[16] and the explosive

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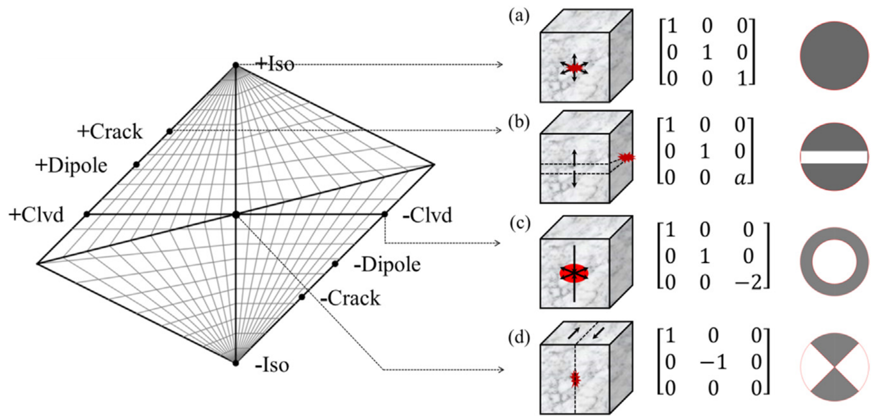

Fig. 1. Schematic diagram of possible failure models, their moment tensors, beachballs, and corresponding positions in the Hudson plot. The diagonalized moment tensor matrix examples are used to show the relationship between its eigenvalues. The variable a presents the third eigenvalue of tensile failure, $a = \frac{1}{\nu} - 1$, where ν is the Poisson's ratio of the medium.

mechanisms.[2,17–19]

Different from the above mentioned qualitative recognition studies, we aim to discriminate the type of the induced seismicity in a more quantitative way. A data set recorded in an underground phosphate mine with local magnitude ranges from -0.5 to 1.0 was selected. Pure seismological inversions by fitting the amplitude spectra in frequency domain and fitting the displacement waveforms in time domain were applied to derive the point source moment tensor. A probabilistic approach is followed to calculate the likelihood of a given candidate event to a certain source model.

2. Methodology

2.1. Moment tensor inversion

The displacement field (u_k) caused by a seismic source can be expressed as the convolution of the moment tensor and the Green's functions (which is used to account for wave propagation from source to receiver), mathematically presented as following[11]:

$$u_k = M_{ij}*\frac{\partial G_{ki}}{\partial x_j} = M_{ij}*G_{ki,j}i, \quad j, \quad k = 1, \quad 2, \quad 3 \tag{1}$$

where M_{ij} are the moment tensor elements of the force couples acting in the direction of x_i axis with arm in line with the x_j axis; G_{ki} is the Green's function; and the symbol '*' denotes convolution. In 3D space, displacements in the far field are a sum of the displacements caused by each of the force couples M_{ij}.

The moment tensor inversion concerns in the calculation of the nine seismic moment tensor elements, on the basis of the displacement field recorded by seismic network surrounding the source. Although several codes are available to perform the moment tensor inversion, only part of them can derive a full moment tensor. For the moment tensor inversion in mining environment, we adopt a two-step full waveform inversion scheme which implements a combined inversion in the frequency domain (fit of amplitude spectra) and the time domain (fit of displacement waveforms).[20]

In the first step, the scheme relies on the fit of the amplitude spectra, resolving both the double-couple (DC) model (parameterized by centroid location, centroid time, scalar moment, magnitude, strike, dip and rake) and the full moment tensor model (centroid location and time, full moment tensor configuration).[20,21] In the second step, the polarity ambiguity is resolved by fitting the displacement traces in the time domain through calculating the synthetic waveforms for the two possible solutions and cross correlating the synthetic seismogram with the observed seismogram.[20,21]

2.2. Green's functions calculation

For the moment tensor inversion in mining environment, the inversion requires a good knowledge of the velocity model. Spurious non-DC components may be retrieved if the model does not meet the target environment.[22–24] Based on velocity tomography result, the constructed Green's function database uses a homogeneous velocity model, following reflectivity method on Thomson–Haskell propagator algorithm.[25]

2.3. Moment tensor interpretation

The resolved full moment tensor matrix can be divided into an isotropic (ISO) component which corresponds to volume changes in the medium, a DC component which corresponds to shear displacements, and a compensated linear vector dipole (CLVD) component which corresponds to the source where one strain axis is shortening while the other two are lengthening.[26] The mathematical decomposition of the full moment tensor matrix in terms of the ISO, DC and CLVD components is followed the formula summarized by Vavryčuk.[27]

To discriminative representation the source mechanisms in terms of the ISO, DC and CLVD components, Hudson et al.[28] proposed a diagram by the quantities k and T. Both quantities vary between -1 and 1. A source with $k = 1$ corresponds to a pure explosive event (Fig. 1a), while one with $k = -1$ corresponds to a pure implosion. The $T = \pm 1$ correspond to $\pm$CLVD sources, which are equivalent to the compression/tensile failure (Fig. 1b) with the isotropic component removed. All pure DC sources are uniquely described by $k = T = 0$ (Fig. 1d). The variety of complex source mechanisms can be discriminated in the source type diagram, in which the horizontal scale describes the type of constant volume component in the source, while the parameter on the vertical scale describes the proportion of the volumetric change. The elemental failure models in mining environment, their diagonalized moment tensors, beachballs, and their corresponding positions in the source type diagram are shown in Fig. 1.

Theoretically, a mining blast (explosion) is associated with abrupt volume changes. In terms of the moment tensor, it can be represented by three orthogonal linear force dipoles which form a pure ISO source.[3] A cavity collapse would reproduce the effects of a rock fall, driven by gravity, or a more energetic rock burst. In both models, source patterns would produce a moment tensor combined by a negative ISO component and a CLVD with vertical symmetry.[3] For a tensile failure of the cap rock, horizontal dipoles could be used to describe the source radiation patterns. A fault slip can be represented by a pure DC. In mining environment, a combination of the proposed mechanisms can likely occur at the same time and result in a superposition of the ISO, DC and