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Moment tensor analysis of transversely isotropic shale based on the discrete element method

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ABSTRACT

In this study, the moment tensor of transversely isotropic shale was analyzed using a discrete element method-acoustic emission model (DEM-AE model). Firstly, the failure modes of the shale obtained from the acoustic emission (AE) events and physical experiments were compared. Secondly, the relationships between AE events and seismic magnitudes, and AE events and the resulting cracks were analyzed. Finally, a moment tensor *T-k* chart describing the seismic source was introduced to demonstrate the differences in the transversely isotropic shale. The results showed that, for different anisotropy angles, a linear logarithmic relationship existed between the cumulative AE events and the seismic magnitude in the concentration area of the AE events. A normal distribution was observed for the number of AE events as the seismic magnitude changed from small to large. The moment tensor *T-k* chart indicated that the number and proportion of linear tension cracks in the shale were highest. When $\theta = 30°$, the peak seismic magnitude was at a minimum. The average seismic magnitude in the concentration area of the AE events was also relatively small. Points close to the $U = -1/3\ V$ line and the number of cracks included in a single AE event were at a minimum, and the corresponding peak stress also reached its lowest level. In contrast, when $\theta = 90°$, all related parameters were contrary to the above $\theta = 30°$ case. The DEM-AE model and the moment tensor *T-k* chart are suitable for analyzing the distribution of shale cracks appearing during the loading process. This study can provide constructive references for future research on the fracturing treatment of shale.

1. Introduction

The bedding plane of rock has a significant effect on shale gas exploration, hydraulic fracture, fracturing treatment, crack propagation, and stability of gas wells, as well as other constructions [1–5]. The tensile strength of shale can be influenced easily and significantly by the bedding plane, which often results in anisotropy [6]. Therefore, more insights and reference data can be provided for construction projects by researching transversely isotropic shale.

At the laboratory scale, acoustic emission (AE) technology is often used to study the initiation, propagation, and coalescence of cracks in a rock mass [7]. Goodman first pointed out that the Kaiser effect exists in rock materials and proposed the concept of the moment tensor to research the seismic source [8]. Gilbert used the moment tensor to detect seismicity for the first time [9]. Subsequently, fracture mechanisms in a seismic source have been analyzed using the moment tensor theory. The moment tensor is divided into three main parts, namely the isotropy part M^{ISO}, the pure shear crack part M^{PSC}, and the compensated linear vector dipole part M^{CLVD} [10]. Liu et al. concluded that the processes of deformation or fracture in a rock mass, as well as seismicity, were caused by the quick release of elastic strain energy [11]. Therefore, a similar approach was used to investigate both processes. The characteristics of an AE source of granite were back-analyzed with an AE moment tensor. Similarly, back analysis was also conducted on the formation of mine water inrush using an AE moment tensor [12].

For the most part, researchers have used two methods to determine the mechanical properties of shale using a Brazilian test. First, physical experiments were conducted to investigate the bedding plane effect and the AE properties [13,14]. In addition, the mechanical behavior of the hydraulic fracture was analyzed further. Second, numerical simulation analysis was used to investigate the

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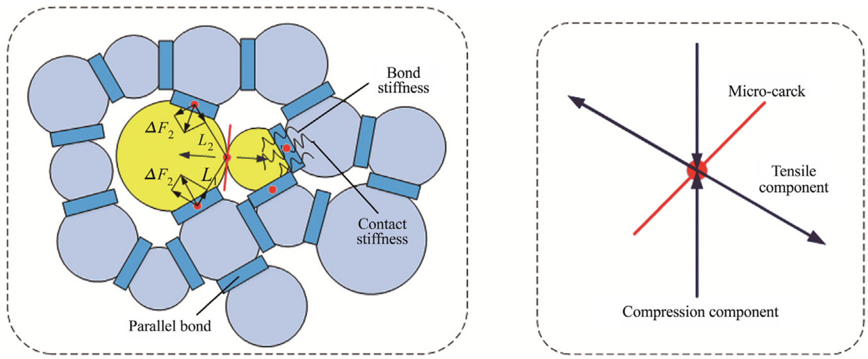


(a) Stress of particle after crack appearing (b) Calculation diagram of seismic moment tensor

Fig. 1. Single AE event containing only a crack; parameters of moment tensor.

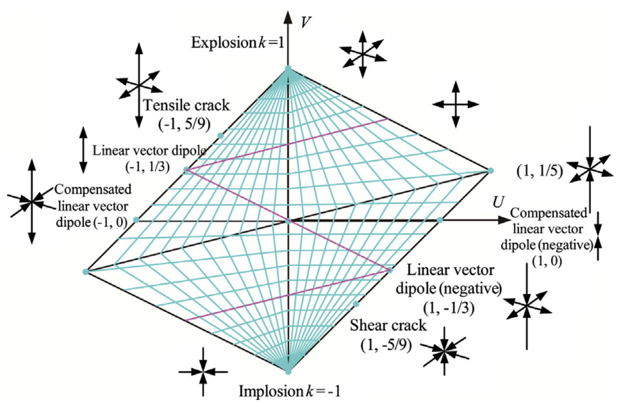
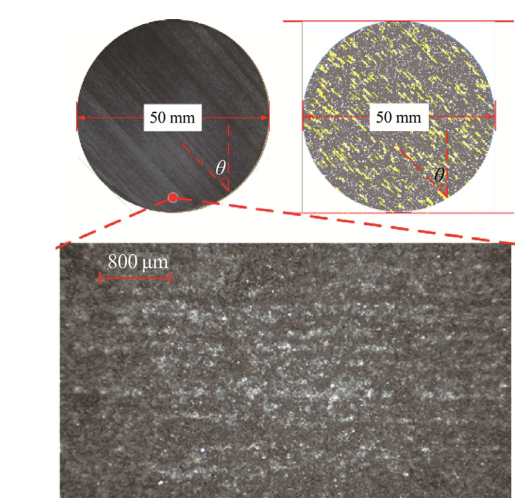


Fig. 2. Moment tensor *T-k* chart analysis method [23].



(a) Physical experiment specimen (b) Simulation specimen (c) Micro-structure of shale

Fig. 3. Specimen of Brazilian test.

failure modes and dynamic responses [15–17]. Using AE technology in numerical simulations to investigate the anisotropy of shale can facilitate the understanding of rock mechanics, but AE data cannot be derived from numerical simulations directly. Therefore, an independent sub-program was needed for the discrete element method (DEM). Additionally, some AE models have been developed in numerical simulations [18,19]. However, no studies have been conducted to date using the DEM-AE model to research transversely isotropic shale.

Table 1
Micro-properties used in SJ contact for simulated specimen after calibration.

Parameter	Non-brittle mineral	Brittle mineral	Bond
(a) Particle property			
Density (kg/m^3)	1750	2500	N/A
Particle radius R_{min} (mm)	0.25	0.25	N/A
R_{max}/R_{min}	1	1	N/A
Young's modulus (GPa)	36.2	68.2	N/A
Normal-to-shear stiffness ratio k_n/k_s	0.8	0.8	N/A
Friction coefficient μ	0.67	0.67	N/A
(b) Contact property			
Normal stiffness $\bar{k}_n$ (GPa/m)	72,400	136,400	78,000
Shear stiffness $\bar{k}_s$ (GPa/m)	90,500	130,500	97,500
Tensile strength $\bar{\sigma}$ (MPa)	25.6	32.8 ± 3	16.5 ± 5
Cohesion $\bar{c}$ (MPa)	30.3	37.6 ± 3	18.6 ± 5

This study is based on the results of our previous physical experiments and uses a DEM-AE model with an independent sub-program to analyze the moment tensor of transversely isotropic shale. The results of the failure modes of shale represented by the AE events in the DEM and in physical experiments were compared based on the moment tensor. The seismic magnitude of the AE events and their relationship with the numbers of cracks were analyzed. Finally, a moment tensor *T-k* chart describing the seismic source was introduced to represent the seismic magnitude of the transversely isotropic shale. This model can improve our understanding of the anisotropy of shale.

2. Method of moment tensor

The source related to the deformation and cracks of rocks is known as the AE source [20]. In order to detect and determine the signal magnitude of the AE source in rocks, AE instruments or micro-seismographs are often used for the inspection and quantitative analysis in the laboratory and the field. The basic method for measuring the seismic magnitude is the seismic moment. In addition, the seismic moment can also be analyzed using the discrete element method.

Since the stress exerted on shale particles and their movement can be obtained directly using this numerical simulation, it is feasible to calculate the scalar of the seismic moment based on the change of the contact force between occurring particles while new cracks are appearing. As shown in Fig. 1, the moment tensor in the DEM can be calculated by summing the moment values of the contact forces between the crack particles:

$$M_j = \sum_S (\Delta F_i L_j) \tag{1}$$

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