Research Article

Study on Rules of Fault Stress Variation Based on Microseismic Monitoring and Numerical Simulation at the Working Face in the Dongjiahe Coal Mine

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Microseismic monitoring technology was used to study the real-time evolution of rock mass damage generated by a working face as it approached a fault in Dongjiahe Coal Mine. The influence of vertical zoning of overlying strata on damage at the fault was analyzed. Numerical simulation using finite element method based on meso-statistical damage theory was used to investigate the nonlinear and nonuniform failure behaviour of the rock mass near the fault. The response of the fault stress to excavation activity and the rule of fault activation were examined. The results show that the fault damage has segmental characteristics. Microcracks are first generated at the fractured zone that is divided into lower, middle, and upper sections, located 30~70 m, 120~180 m, and 230~280 m above the coal seam, respectively. There was also a segmentation phenomenon in the stress response of fault. The risk of fault activation was evaluated by using the ratio of shear stress to the maximum principal stress. When the working face was 260 m and 140 m away from the fault, the activation risk at the upper-middle and lower sections began to increase, respectively. When the fault was within 60 m, the risk of fault activation was highest.

1. Introduction

During the process of coal mining, mining in the vicinity of a fault can lead to abnormal movement of the overlying rocks and great intensification of mechanical pressure in the vicinity of the working face. This can produce a situation of increased hazard for workers at the face. However, certain mining layouts require that faults are penetrated by the mining face. Therefore, it is of great significance to study the effects of overlying rock movement and fault activation for mining safety. Jiang et al. [1] studied the regularity of normal and shear stress variation close to the fault by using three-dimensional numerical simulation. The spatial-temporal evolution of the fault stress field during the excavation process was simulated, and the activation risk at different locations along one wall of a fault was presented. Through

establishing a dynamic Colombian crack stress increment model, Ji et al. [2] quantitatively analyzed the excavation disturbance effect and compared the different risks of fault activation when the working face lies perpendicular versus parallel to the fault face. Sainoki and Mitri [3] analyzed the influence of friction angle, burial depth, advancing speed, and stiffness with regards to a fault slip by adopting three-dimensional numerical modelling. The limitation of Mohr-Coulomb criterion in the dynamic analysis of fault slippage was also discussed. Wang et al. [4] investigated fault activation under excavation disturbance by establishing a similar material model. The results showed that the stress first dramatically increased and then slowly grew, and the displacement moderately increased. This indicated that these features could possibly be used as precursor information for the fault activation. Taking large

thrust fault F16 in Yiwu orefield as background, Zhao [5] studied the effect of mining activity on the overlying rock movement when a working face passing through the fault zone, using similar model physical experiment. In his study, the difference between the movement laws, before and after the fault activation, was pointed out.

In the studies mentioned above, the numerical simulation and physical model experiment are usually applied to study the characteristics of overlying rock movement and the laws of fault activation when a working face is passing through the fault. Instructive conclusions have been obtained for engineering sites. However, it is reasonable that different vertical zones of the overburden rocks have different mechanical behaviours. The above studies pay little attention to the effects of the vertical zones on the segments of fault activity, especially for the fracture zone with its vertical height of generally several tens to hundreds of meters. There is a distinction in rock deformation behaviour of the fracture zone which is greatly different than those of other zones, and the fault behaviour should as well be further segmented.

Generally, the vertical zones of the overburden rock above the coal seam were divided into three zones from bottom to top: caving zone, fractured zone, and sagging zone. In order to study the variation of deformation and fractures in the rock strata of fractured zone, Palchik [6] further divided the fractured zone into three zones based on long-term field observation. Thus, a total five-belt model shown in Figure 1 was proposed for overlying strata movement under long-arm mining operation, which includes belts named as caving zone, rock blocks, through-going vertical fractures, separate horizontal fractures, and continuous zone according to their individual mechanical features. Based on the five-belt model, this paper studies the distinctiveness of fault activity within the fracture zone and investigates the spatial-temporal evolutions of damage at different segments along the fault.

Furthermore, most existing models are simply elastic. However, the damage and fracture of the geological material are essentially inelastic phenomena caused by strong nonlinear and irreversible deformation. The development extents of natural faults are obviously different, and the mechanical behaviours of the same fault can be different in different regions. Stress gets complex inside the shattered zone of the fault, along the two side walls of the fault and the surrounding influence range of the fault. There are limited studies on numerical simulation of fracture tectonic stress field due to its difficulty in the current rock mechanics. In the study by Sadeghi et al. [7], a mechanical model based on the ANSYS finite element method was designed by using MATLAB script to compile the stress field of the fault surrounding rock. The deformation mechanism of the fault structural plane under certain stress field was investigated, and the composite stress field was considered as an important factor affecting the mechanical behaviour of the fault plane. The main factor influencing fault development is the nonuniform deformation of the fault surrounding area caused by the stress at the rock strata within the fracture zone. Yan et al. [8] numerically simulated the tectonic stress

field of North China by 3D viscoelastic finite element model and studied the influence of recent stress field changes on fault activity. The maximum tensile stress and the maximum compressive stress distribution areas were shown, and the segmentation characteristics of Coulomb stress in the Tanlu fracture zone were revealed. However, due to the long-term natural fault movement, it is difficult to capture and detect damage and fracture information of the different segments of the fault completely by conventional monitoring methods during the space-time evolution process, especially for studying the mechanical behaviour of different segmental fault in deep rock formations. There is an urgent need for a monitoring technique and method that can detect information on damage and fracture of deep rock masses.

The damage and failure process of a rock mass can be regarded as the process of energy accumulation and release. When energy accumulates to a critical value, it will cause the appearance and expansion of microcracks, along with stress wave emitting and propagating rapidly in the rock mass. Microseismic monitoring is a three-dimensional monitoring technology to acquire and analyze elastic waves produced by the appearance of microcracks in rock mass. It can determine the information such as seismic event location, seismic event magnitude, and source parameters including seismic energy that is released by microcracks in the rock mass. In recent years, microseismic monitoring technology has been widely applied to analyze the large rock masses in coal mines [9–12], metal ore mines [13, 14], hydropower station diversion tunnels [15], underground plants [16, 17], slope excavation [18, 19], and oil reserve caverns [20]. It can provide good information about the rock mass deformation process caused by mining.

In this paper, microseismic monitoring technology is used to obtain the field data of the fault surrounding rock rupture, and the fault segmentation damage area is delineated to provide references for numerical simulation. A numerical simulation method based on statistical mesoscopic damage theory is used to simulate the progressive failure in macroscopic medium by the cumulative damage of mesoscopic units which represent microcracks. The numerical simulation of the inelastic and nonuniform damage of the fault surrounding rock is conducted. The fracture processes at different segmentations are reproduced. The variation law of equivalent fault stress at different segments is studied. This study provides useful references for roof control, anti-impact stress release, and reinforcement when an advancing working face passes through a fault zone.

2. Mining Conditions

The working face #22517 of Dongjiahe Coal Mine is located in the east of the haulage-dip of galley level 2, mining area #2. Its north and south are both unmined coal seams. Coal seam #5 with Shanxi formation is the primary mining area due to stable coal deposit there. The thickness of this strata is 2.5 m to 4.1 m with an average of 3.3 m. The seam is generally inclined 3 degrees to the northeast. The maximum differences in altitude are 50 m along the east-west direction and 20 m along the south-north direction. The gradient of the

FIGURE 1: Illustration of the five-zone theory on overlying rock vertical division.

whole working face is about 3 degree, which is an approximately flat seam. The working face is 1217 m long along the strike and 185 m wide along the dip. The excavation was implemented from east to west, corresponding to the margins from 1217 m to 0 m. The open-off cut is located at the point distance of 1217 m, while the stopping line is at the point distance of 100 m. The false roof for mining this coal seam is made of mudstone with 0.6 m thickness. The direct roof is 0.65~1.66 m thick coarse siltstone, with thin strata or strips of fine sandstone inclusions on its top. The basic roof is 5.7~11.77 m thick medium grain and fine grain sandstones. The direct bottom which is dense and hard with well-developed fissures is 0.8~1.72 m thick quartz sandstone. The basic bottom is 0.89~3.23 m thick fine siltstone.

The geological structure of the working face is relatively simple. According to the results of microseismic monitoring and three seismic surveys, there is a small reverse fault 200~350 m away from the margin of the railway tunnel. Its dip angle is about 73 degrees and it heaves up to 3 m. There is an anticline fold at 480 m~720 m from the margin of the working face. Between the core and the flanks of this fold, the maximum difference in altitude is 4 m. There are thin coal zones at 530~840 m from the margin of rail tunnel and 500~810 m from the margin of transportation tunnel. The progress of working face advancing is shown in Table 1.

3. Microseismic Monitoring Covering Fault Influencing Area

3.1. Construction of Microseismic Monitoring System. An advanced high-accuracy microseismic monitoring system from ESG Corporation, Canada had been installed for working face #22517 to provide real-time monitoring, positioning, and analysis on coal-rock mass failures in the mining influencing area. The topology structure of the microseismic monitoring system is shown in Figure 2.

The system consisted of microseismic sensors, Paladin® downhole data loggers, Hyperion ground data loggers, and

TABLE 1: Some part of advancing progress of working face #22517.

Time	Point distance (m)
2015/10/09	578
2015/10/19	553
2015/10/30	530
2015/11/09	514
2015/11/18	499
2015/11/29	476
2015/12/09	457
2015/12/18	443
2015/12/30	426
2016/01/08	410
2016/01/18	397
2016/02/05	369
2016/02/18	357
2016/02/28	330
2016/09/09	310
2016/03/18	300

3D visualisation software based on the remote network transmission developed by Mechsoft Co. Ltd. in Dalian, China. The microseismic sensors have a usable frequency range of 15 Hz to 1,000 Hz and a sensitivity of 43.3 V/m/s. Referring to the geological conditions and excavation status of the working face, the seismometers were installed in the floors of rail gallery and transportation gallery. Each seismometer was set with an interval of 100 m along the strike of nonexcavation slope bank. The seismometers were both staggered vertically and along strike, as shown in Figure 2. Each sensor is connected to a Paladin® data logger with a copper cable. All signals are digitized at the Paladin® and are then transmitted to the surface via a fiber-optic cable.

The sensor cable in the excavated area was cased and sealed to ensure that signal transmission would be sustained even if there was a collapse in the area. Signals were transmitted through fibers from the data loggers in the rail gallery and transport gallery to the underground workstations. The collected data from every sensor were uploaded

FIGURE 2: Topology structure of the microseismic monitoring system.

through fibers to the data processing server, the storage server, and the transmit server via cross-cut gallery #7 and #5. Data were then made available to scientific research institutes and first-party units after being processed by site operators.

3.2. Analysis of Microseismic Activities in Fault-Affected Area.

The working face #22517 was excavated on Oct 5, 2014. The microseismic monitoring was conducted from Nov 25, 2014, to Oct 10, 2016. When the working face approached the fault, the microseismic events from Nov 12, 2015, to Dec 15, 2015 were chosen to analyze the distribution law of microseismic events. There were 42 valid microseismic events detected. In the microseismic event distribution diagram, a circular ball represents the microseismic event caused by the damage of rock mass, and the sphere colour represents the seismic event moment magnitude. Figure 3 is the vertical profile projection of microseismic events along the fault dip direction during this period.

The microseismic events have obvious partitioning features along both vertical and horizontal directions. Microcracks were mainly distributed on the hanging-wall of the fault along a horizontal direction. This is due to fault blocking effect on overburden stress transfer, resulting in stress concentration to the fault as well as over its hanging-wall. Therefore, the hanging-wall covered by overburden rocks severely ruptured with a large number of generated microseismic events. Vertically, there are three concentration regions of microseismic events, known as A, B, and C, (which are located near at 30~70 m, 120~180 m, and 230~280 m above working face, respectively). According to

the “five-zone” theory, A, B, and C concentration regions are closely associated with the vertical zonality features of overburden rock structures.

The microseismic monitoring results on the working face #22517 were provided by Dalian Mechsoft Co. Ltd. and data collected from boring sampling from the “two zones” of Dongjiahe coal mine was further analyzed by Tiandi Technology Co. Ltd [21]. The boundaries of caving zone, rock blocks zone, through-going vertical fractures, separate horizontal fractures, and continuous zone are located at 20 m, 70 m, 220 m, and 340 m above the working face, respectively. Based on the vertical zoning and microseismic monitoring results in the vertical direction, region A is within the separate horizontal fractures and is adjacent to the primary key strata. There is a fine siltstone strata which is 58 m thick above region A, and the end region of the fault is also in this area, resulting in a high magnitude and energy level in microseismic events within this zone. Region B is primarily affected by the vertical crack penetration zone, and there is an inferior key strata above, which is a fine siltstone strata with 28.5 m thick obstructing the microcracks from expanding above. In this zone, the microseismic events are widely distributed vertically but relatively concentrated below the inferior key stratum. Region C is primarily affected by the zone rock blocks. Above region C, there is a fine siltstone strata with 14.9 m thickness. As shown in Figure 4(a), region A and B are influenced by the inter-strata separation and the through-going vertical fractures, resulting in significantly higher energy of microseismic events compared to region C. They are sensitive to disturbances from mining the excavation, and the fault surrounding rocks are relatively unstable.

FIGURE 3: Vertical section projection of the microseismic events around fault area between Nov 12, 2015, and Dec 15, 2015, (a) 2015.11.12~2015.11.30, (b) 2015.11.12~2015.12.10, and (c) 2015.11.12~2015.12.15.

According to the “O” ring theory of overlying rock breakage, the vertical zoning of overlying strata is distributed as an inverted trapezoid on the vertical cross section. The higher the zone lies, the larger the range of horizontal displacements. In Figure 4(b), it can be seen that the change in deformation by microseismic data along the dip direction

is larger in region A and B. The deformation and failure in different types of zones obviously have different features. This inevitably results in distinctly different patterns of stress redistribution within different sections along the fault. As the working face gradually approaches the fault, the microcracks occur inside the fault surrounding rocks. One

FIGURE 4: Spatial distribution of major parameters of microseismic events between Nov 12, 2015, and Dec 15, 2015. (a) Energy density and (b) seismic deformation.

numerical simulation method was used to study the influence of vertical zoning of overburden rocks on the stress changes of the fault. This method obeys the constitutive relations of quasi-brittle rock materials and is applied to conduct a numerical simulation study on the process of fault activation while the working face passing through the fault.

4. Influence of Mining on Stress inside the Fault Surrounding Rock

4.1. The Numerical Simulation Method. In this study, a finite element method based on meso-statistical damage theory is used to implement numerical simulation. Analysis of nonlinear problems for rock failure is realized by the simulation. The whole process of crack initiation, propagation, coalescence, and rupture instability in rock is, in a way, reproduced. [22–24] The main features of this method are as follows:

- (1) The integrated properties of a combination reaction with several simple meso-elements reflecting the basic properties of rock so as to simulate complex macroscopic rock mechanics behaviour. Macroscopic failure is the cumulative process of meso-element failure [25].
- (2) It is considered that the meso-element is linear, elastic, and brittle. The heterogeneity of rock strength results in progressive failure behaviour [26, 27]. The elastic parameters of each mesoscopic element are defined by Weber distribution, and the heterogeneity of the strength of the rock is fully reflected [25, 26, 28].
- (3) Failure occurs when the mesoscopic element strength reaches the criterion of failure. We deal with the degradation of stiffness after failure. Therefore, the problem of physical discontinuous media can be treated by continuous medium mechanics method [29].
- (4) It is considered that the damage amount and acoustic emission of rock are directly proportional to the number of failure elements [30].

A large number of meso-elements have three forms: matrix element, air element, and contact element [22, 29]. The matrix element is a substance medium, and its properties are described by the constitutive relation of rock. The air element is characteristic as virtual body. After the meso-element fails under tensile stress, the properties of the original substance element are replaced by those of the elementary element with very low elastic modulus. As the elastic modulus of the new element is very low, it can be assumed that the behaviour of the substance medium does not exist. After the failure of the elementary medium, the compressive stress will continue to appear and the elementary stiffness will be taken into account. This is the contact element. The process of elementary transformation is shown in Figure 5.

4.2. The Construction of a Model. Based on the geological condition of working face #22517 in Dongjiahe coal mine, the influence of mining disturbance on the fault stress was simulated to analyze the in situ fracture process using RFPA-2D which is a two-dimensional statistical mesoscopic damage finite element simulator. The model is 800 m long and 520 m high with a 4 m coal seam in it along the strike direction. As illustrated in Figure 6, the geometrical model is then numerically discretized into 104,000 elements with the aspect ratio of 400×260 . The boundary conditions are as follows: The horizontal displacements are fixed on both left and right sides with the vertical displacement fixed on the bottom and the top set as free. The initial condition of field stress is vertically formed by the volumetrical force of gravitation due to the rock density and gravitational acceleration, while horizontal stress is formed by laterally restricted elastic deformations representing infinite media extension in horizontal direction beyond the model. The Mohr–Coulomb criterion is adopted as the material damage criterion. The parameters of physical and mechanical properties of each rock strata and fault are shown in Table 2.

The continuous stepwise excavation was applied to simulate the advance of the working face. As shown by the red

FIGURE 5: The types of elements and their transformation process.

FIGURE 6: Schematic illustration of numerical model and excavation advance.

line in Figure 6, the upper end of the fault is approximately 150 m from the left side of the model with a dip angle of approximately 73 degrees. The excavation seam is the 18th seam in Table 2. Considering the boundary effect, the first excavation is carried out at 380 m away in the right from the fault and 200 m from the right side of the model. The working face is 185 m long. The masonry beam structure is formed in the goaf, and the simulation is based on the coal rock storage conditions in the middle part along the working face. Except for the end effect, the roof falling law should manifest similar behaviours on any X-Y cross-section cut along the most middle portion of the working face in Z direction. Microcracks are limited locally in size along the third Z direction. The effect of overburden movements on the fault damage mode was studied using the plane-strain model. This is helpful to roughly understand the patterns of stress change regularity. Although the planar model produces errors in the microcrack field quantitatively, it is still considered to provide a reference for analyzing the physical process mechanism qualitatively.

4.3. Deformation Analysis of Overburden Rocks. Figure 7 shows the distribution of acoustic emission events during advancing of the working face. Three microcrack regions a, b, and c inside the fault surrounding rock were located at the separated fracture zone, through-going vertical fracture zone, and rock block zone in the overlying strata which extends away along horizontal direction, respectively. In the figure, red, white, and black events indicate tensile damage, compressive damage, and cumulative acoustic emission damage, respectively. The fault areas affected by through-going vertical fractures, separate horizontal fractures (regions a and b), and rock block zone (region c) suffered failing in sequence during the simulation. Along the simulation running, the AE signals first occur over a and b regions, which are located at 250~300 m and 120~200 m upwards from the mining level, respectively. As the working face was further pushed forward for additional 30 m after 350 m, a red event occurred within the region c which is located at 50 m right above the floor. These simulated outcomes are consistent with the data processing results from microseismic monitoring.

TABLE 2: The mechanics and physical parameter statistics of rocks in model.

	Rock stratum	Elasticity modulus (MPa)	Compressive strength (MPa)	Thickness (m)	Friction angle (°)	Poisson's ratio (—)	Class density (kg/m ³)
1	Medium grain sandstone	8500	29	13	28	0.26	2450
2	Fine siltstone	8200	35	41	28	0.26	2450
3	Medium grain sandstone	8500	29	12	28	0.26	2450
4	Fine siltstone	8200	35	15	28	0.26	2450
5	Medium grain sandstone	8500	29	10	28	0.26	2450
6	Fine siltstone	8200	35	13	28	0.26	2450
7	Medium grain sandstone	8500	29	14	28	0.26	2450
8	Fine siltstone	8200	35	33	28	0.26	2450
9	Medium grain sandstone	8500	29	8	28	0.26	2450
10	Coarse siltstone	8800	45	13	26	0.24	2450
11	Fine siltstone	8200	35	21	28	0.26	2450
12	Fine grain sandstone	7800	24	4	29	0.28	2450
13	Coal	1650	8	2	36	0.32	1500
14	Coarse siltstone	8800	45	8	26	0.24	2450
15	Fine grain sandstone	7800	24	6	29	0.28	2450
16	Medium grain sandstone	8500	29	4	28	0.26	2450
17	Fine grain sandstone	7800	24	3	29	0.28	2450
18	Coal	1650	8	2	36	0.32	1500
19	Quartz sandstone	8850	48	38	25	0.24	2650
20	Fault	1000	7	—	28	0.26	2000

FIGURE 7: Diagram of acoustic emission events representing microcracks around the fault zone. (a) The state when the working face advances 350 m. (b) The state when the working face advances 380 m.

4.4. Stress Analysis on Fault Zone. According to the results from both microseismic monitoring and numerical simulation, the deformation and failure of surrounding rocks have close association with the vertical zoning of overburden rocks. The different features of the movement in different zones resulted in significant variations of the stress distribution as well as their evolution inside the overlying rocks. To study the influence of different vertical zones on the stress of overlying rocks, as shown in the Figure 6, three displacement and stress measuring points marked as 1, 2, and 3 were selected in the microcrack regions named as a, b, and c, respectively. The selection of stress measuring points follows

the first failure element in each region. Furthermore, the rule of the fault activation was investigated.

As shown in the Figure 8, shearing stress τ_{xy} of measuring point 1, 2, and 3 has a general increasing tendency before the substantial occurrence of cracks. It can be seen that the shearing stress of measuring point 1, 2, and 3 started to rise at the distances of 300 m, 260 m, and 160 m away from the working face to the fault direction, respectively. The shearing stress within these three spots responded similarly in sequence from top to bottom. Measuring points 1 and 2 responded nearly the same, while point 3 started to increase later at the distance of 160 m. Until the distance reduces to

60 m, the fault area of measuring point 3 falls into the influence range of the stress peak zone due to the support effect of advancing working face, leading to a rapid increase in shearing stress. This is caused by the continuous or discontinuous overall deformation or concrete failure of the vertical section or zone in overlying rocks, which is roughly formed as an inverted trapezoid as a whole. The range with distinct overlying rock deformation became larger as the altitude grew higher, especially in the horizontal deformation including the separation as well as the intercalated dislocation between zone-to-zone interfaces. The deflection of a higher zone causes its horizontal stress to change which is transmitted toward the fault, resulting in stress redistribution inside the fault surrounding rocks. The working face advanced from the hanging-wall to the fault. Due to the fact that the fault is not absolutely vertical, but abruptly dips down toward the excavated space, the deflection magnitude of the bending upper zones had been partially impaired by this particular structure. Therefore, the response time of point 1 is almost simultaneous to that of point 2, but the shearing stress nearby point 3 which is the nearest to the coal seam responded the latest among the three points.

The value of shearing stress at point 1 maintained its increasing trend in the process of the working face advancing till it arrives to the fault where it reached its maximum value. The shearing stress at point 2 reached its maximum value when the working face is about 20 m away from the fault and then dropped instantly to its minimum value. The reason is that the cracks inferior to the key strata extended and coalesced, resulting in fractures and their propagation in surrounding rocks. Point 3 is located at the stress concentration region of coal pillars and falls into the influenced zone of advanced supporting stress induced by the working face. The fault obstructed the horizontal stress from continuously transmitting along the overlying rocks. Therefore, the overlying rock block zone above and the underlying rocks below referring to excavated coal cannot form an effective load-holding structure, i.e., the voussoir beam. All pressures of the above overlying rocks were applied to the region of coal pillars between the fault and the working face, resulting in the stress concentration and enhancement of the influence of advanced support stress. As the working face advanced to the fault, point 3 suffered the influences of advanced supporting stress and stress concentration of coal pillars. The value of shear stress increased rapidly.

As shown in Figure 9, the trend of the maximum principal stresses σ_1 in points 1, 2, and 3 was similar to that of the shear stress τ_{xy} . They both generally increased before the failure formed. When the working face advanced to the fault, the value of principal stress at point 1 reached its maximum. The surrounding rocks of the fault did not suffer a major failure or instability. The overlying rocks above the coal seam were stable. When the working face was located at a distance of 10 m from the fault, the fault at the inferior key strata failed, and the principal stress at point 2 decreased. As the working face was close to the fault, the influence from stress concentration and advanced supporting stress were intensified, and the aggression of principal stress at point 3

FIGURE 8: The states of shearing at the fault during the working face advancing.

FIGURE 9: The states of the principal stress at the fault during the working face advancing.

had increased rapidly when the distance between the working face and the fault got smaller than 60 m. However, the principal stresses at points 1, 2, and 3 responded quite different from that of shearing stress. Their response time is nearly the same, and the value and the gradient of the principal stress are similar to those of the shear stress when the distance approached up to 60 m. Furthermore, compared to the shear stress, the maximum principal stress is more sensitive to the excavation disturbance.

4.5. Process of Fault Activation. According to the friction law, the friction property of the contact surface depends on the ratio of the shear stress to the normal stress. In order to study the possibility of sliding along the fault, the ratio of shear stress to the maximum principal stress is chosen as an

inspection index. The variation of the index at points 1, 2, and 3 ahead of the advancing working face is shown in Figure 10.

The ratio of shear stress to the principal stress at points 1 and 2 generally increased with the advancing of the working face, and the risk of activation increased. However, the ratio decreased at point 3 when the working face is more than 140 m away from the fault, and then it turned to increase with the approaching of the work face. The analysis was carried out by calibration referring to the stress value of each point and the movement status of the overlying rocks. Shear stress at point 1 increased slightly when the working face advanced to 320 m, while the principal stress almost remained constant during this stage. Therefore, the ratio started to increase. With the working face advancing, the ratio remained increasing. During the advancing process of the working face to 120 m away from the fault, the ratio increased faster, gradually from 0.38 to 0.52, which indicates that shear stress got to play a more important role. During a further advance to 60 m away from the fault, the ratio increased slowly to 0.54, resulting in a virtually flat ratio. Under this condition, the activation of the fault became the most possible when slipping. The ratio of shearing stress to the principal stress at point 2 showed a slow increase when the working face was 280 m away. The rapid increase started at 200 m away from the fault. At 10 m ahead of the fault, the ratio was 0.70 which was about 2.5 times of its initial value. A further advance of the working face results in fault failure due to the deformation of the inferior key strata and a reduced ratio. Since point 3 is close to the coal seam, the principal stress increases while the shear stress remains virtually constant when the working face is far. When the working face is 140 m away from the fault, the ratio decreases to the minimum value of 0.28 from the initial value of 0.30, which indicates that the increasing trend of the principal stress was playing a dominant role in this process. As the working face is advancing, point 3 enters into the advanced supporting stress influencing zone, and the shear stress increases rapidly, resulting in a gradually increasing ratio. When the working face reaches 60 m ahead of the fault, the effects of the stress concentration of coal pillars became obvious, resulting in a further rapid increase in the ratio. The ratio becomes 0.39 when the working face is 10 m away from the fault, where the sliding is most likely to occur.

During the progress of the working face advancing to the fault, the far end of the fault is firstly influenced by the excavation disturbance and therefore tends to slip there. Because the total deformation volume of overlying rocks looks as an inverted trapezoid, the top strata has the widest deformation extension along the horizontal strata, there the intersecting fault is influenced the earliest. The activation risk of the close-to-coal-seam zone starts rising at the distance of 140 m from the fault. Within the range of 60 m distance from the fault, the ratio of shear stress to the principal stress keeps a trend of rapidly increasing and reaches the maximum slope of the curve. Therefore, the risk of slipping as well as the fault activation there is the most possible.

The slippage of the fault during the process is demonstrated in Figure 11. The curves reflect the similar

FIGURE 10: The ratio of shear stress to principal stress during advance of the working face.

FIGURE 11: Fault slippery displacement with advance of the working face.

conclusions as that shown in Figure 10. The advancing of the working face up to 260 m from the fault is the stable stage to fault activation when there is virtually no slippage along the fault. The process of the working face advancing from distance 260 m to 60 m distance to the fault belongs to the stage of the activation risk increasing during when small amount of slippage occurs and does its increment along the fault. The process from 60 m away till the fault is during the high activation risk stage where the amount of slip and its increment are both relatively great. Furthermore, the far end of the fault is influenced by separate horizontal fractures and through-going vertical fractures. Slippage starts earlier within the far end than near-coal-zone area. The latter is influenced by its structure of rock blocks.

5. Conclusion

- (1) The feature of this study focuses on the segmentation of fault mechanical response, which is associated with structural zoning of overlaying rocks to mining excavation approaching. According to the microseismic monitoring results, the area of fault damage is obviously segmented. The upper section of the fault intersecting with region A was affected by the separate horizontal fracture zone, approximately 230~280 m above the working face. The middle section of the fault intersecting with region B was affected by the through-going vertical fracture zone, approximately 120~180 m above the working face. The lower section of the fault intersecting with region C was affected by the rock block zone, approximately 30~70 m above the working face. Numerical simulation was conducted and the findings are consistently supported by monitoring analyses.
- (2) The shear stress response of fault zones was from the top to bottom. The shear stress at the upper and middle sections of the fault responded earlier than the lower sections close to the coal seam. Shear stress starts increasing when the working face advanced to 260 m from the fault. The fault zone close to the coal seam is affected by the rock block zone and its shearing stress started to increase when the working face advanced to 160 m from the fault.
- (3) Affected by the characteristics of overlying rock zones, during the process of working face pushing forward, the increasing trend of shearing stress plays a dominant role within the upper and middle section of the fault. Meanwhile, the maximum principal stress takes the lead in early stages until the working face advances to 140 m from the fault. Shear stress increases gradually due to the influence of advanced support stress within the lower section of the fault.
- (4) The upper and middle section of the fault both have more slipping trends compared to the lower section of the fault. Activation risk begins rising when the working face is located in front of the fault with a distance of 140 m and 260 m away, respectively. When the working face advances to a distance of 60 m away from the fault, all activation risks over the three sections reach their maximums.

Data Availability

The microseismic monitoring data of this paper come from Dongjiahe Monitoring Group of Dalian University of Technology and Dalian Mechsoft Co. Ltd. So, it cannot be made freely available.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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