Research Article

Analysis of the Regularity and Mechanism of Fault Activation Caused by Deep Continuous Mining of Shizishan Copper Mine, China

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1. Introduction

In underground mining, with the deepening of mining depth and the expansion of goaf, there are many mine disasters [1, 2]. The fault is a geological structure [3] in which rock mass breaks under the action of tectonic stress and has evident displacement along the fracture surface. Its existence destroys the continuity and integrity of rock strata and changes the stress and displacement field of surrounding rock mass [4, 5]. The fault activation phenomenon caused by various influencing factors will cause many mine disasters such as rock burst, mine water inrush, surface subsidence, and others, resulting in many casualties, equipment damage, and loss of mineral resources. These disasters will also seriously threaten the life and property safety of workers in the mining area, which also have a negative social impact, and seriously restrict the development of the national economy and mining enterprises [6, 7]. The fault activation caused by mining has always been an important factor affecting underground mining safety [8].

In recent years, many scholars have researched the regularity and mechanism of fault activation induced by deep continuous mining. In terms of theoretical analysis, Zhang et al. [9] proposed a multi-slip-spring model of fault activation and considered fault activation as a local to global linkage instability. Yin et al. [10] considered fault activation as a displacement extreme point-type instability with a sudden jump in force. Pan [11] proposed a criterion for discriminating the disturbance response that the leading cause of fault activation is an increase in fault shear stress or a decrease in normal stress. Zhao et al. [12] and Wang et al. [13] analyzed the changing law of Coulomb stress at the fault face and concluded that the failure of the coal body at the working face was the main reason for fault activation. Li [14]
and Pan et al. [15] proposed a viscous slip-viscoelastic brittle body mutation theory and a folded mutation model to classify the fault activation mechanism into dynamic and steady-state cases. They described the stability mechanism of the system in the precursor stage and post-activation stage of fault activation. For experiments, Cai et al. [16] and Han et al. [17] combined numerical simulation and similar simulation experiments to propose the mechanical mechanisms of two types of fault activation, namely, mining stress dominated and mining vibration load dominated. Zhuo et al. [18], Wang et al. [13], and Wu [19] reproduced the physical process of fault activation based on similar simulation experiments, and the mechanism of fault activation caused by coal mining was analyzed and revealed the mode of induced fault activation under different mining sequences in the hanging wall and footwall working face. In terms of numerical simulation, Islam et al. [20] used the boundary element method to simulate coal mining to analyze the law of fault activation induced by mining. The results showed that the deformation and stress field of the fault and the surrounding rock in its vicinity under the effect of mining disturbance produced significant changes. The stress concentration at the fault end is high. Jiang et al. [21] used a 3D numerical calculation method to simulate and analyze the characteristics of coal seam roof movement and the law of fault activation. They compared the analysis with engineering examples for verification. Sainoki and Mitri [22] studied the influence of stress waves, fault plane roughness, and other factors on fault activation based on FLAC3D secondary development simulation.

In summary, the current research on mining-induced fault activation mainly focuses on coal mines, and there are few studies on fault activation caused by deep continuous mining in non-coal mines. Moreover, there are few reports on the domino law effect and induced mechanism of fault activation caused by continuous mining in deep mining. In this paper, based on field rock movement investigation and theoretical analysis of fault activation sliding criterion and the discrete element numerical simulation software 3DEC, the law and mechanism of fault activation induced by deep continuous mining in Shizishan Copper Mine are analyzed. The research results have great significance for the deep mining area development, mining alignment arrangement, and disaster prevention and control caused by fault activation.

2. Overview of Engineering Geology in Mining Area

Shizishan Copper Mine is located in Xiaojie township, Yimen County, Yunnan Province, China, which is located at the junction of Yimen, Shuangbai, and Lufeng counties. It is 51 km away from Yimen County, with convenient transportation. The geographical location and surrounding geological map of the Shizishan Copper Mine are shown in Figure 1. The mining area is located on the west side of the fault of the Yimen depression basin. Under the influence of the east-west extrusion force, a north-south structural system is formed, and the bending faults are very developing.

The main backbone structure in the mining area is mainly composed of the fault of Tanglang-Yimen and Yuanmou-Lvzhijiang, which is more than 100 km long and extends northward to Sichuan. It is one of the major faults in the north-south structural system of Sichuan and Yunnan. The strata of the Kunyang group exposed in the mining area can be divided into seven groups: Lvzhijiang formation, Etouchang formation, Luoxue formation, Yinmin formation, Meidang formation, Dalongkou formation, and Heishantou formation from top to bottom, respectively. It is a set of shallow marine clastic rock formations and carbonate formations, with a total thickness of more than 10,000 m. After the Jinning movement, the area was relatively calm, and there was activity after the Yanshan movement. The activity in this period was mainly manifested in superimposing on the NNW fault in Jinning period, staggering the Mesozoic red bed, which is characterized by counterclockwise horizontal torsion, destroying the orebody and was a post-mineralization fault [23].

The dip angle of the orebody is 70–80°, which is a steep orebody with a thickness of 20 m–160 m. The designed mining and selection scale is 1700 t/d, and the actual production scale is 1750 t/d–2200 t/d. The mine began production in October 1977. The highest surface elevation of the mine is 2143 m, and the design elevation of the project’s first phase is 1807 m–1587 m (sublevel 4 to 8). The design of the mine capacity is 1750 t/d, and stopping has been completed. The design elevation of the project’s second phase is 1587 m–337 m (sublevel 8 to 13). The designed ore capacity is 1000 t/d. The design elevation of the third phase project is 1337 m–1237 m (sublevel 14 to 15). The designed ore capacity is 1000 t/d. The basic stopping of the third phase project is completed. The design elevation of the project’s fourth phase is 1237 m–787 m (sublevel 16 to 24).

The authors have measured the distribution of in situ stress field in the mining area. According to the three-dimensional in situ stress measurement results, in the regional tectonic gravitational field, the maximum principal stress direction is NNW-SSE, and the trend of the maximum principal stress is consistent with the direction of the maximum principal stress. It shows that the dominant direction of the maximum principal stress in the mining area is consistent with the direction of the maximum principal stress and perpendicular to the orebody’s strike. The maximum and minimum principal stress difference is significant, and the average ratio is 2.54. This indicates that the dominant direction of the principal stress in the mining area is evident. The three principal stresses in the field investigation show an increasing linear trend with the increase of mining depth. The increasing rate of vertical principal stress and minimum principal stress is less than that of maximum principal stress. It can also be seen that the dominant stress in the mining area is the maximum principal stress. The linear regression equation of in situ stress value (MPa) in three directions with depth \( H \) (m) is, respectively, shown in formulas (1)–(3) [23].

\[
\sigma_{h,\text{max}} = -0.0163 + 0.0511H, \tag{1}
\]
\[
\sigma_{h,\text{min}} = -0.3883 + 0.021H, \tag{2}
\]
\[ \sigma_v = -0.6018 + 0.0307H, \]  

(3)

where \( \sigma_{h,\text{max}} \) is the maximum principal stress, \( \sigma_{h,\text{min}} \) is the minimum principal stress, \( \sigma_v \) is the vertical principal stress, and \( H \) is the mining depth.

According to the results of in situ stress measurement in mining area, the indoor rock mechanics test results, and the quantitative standard of high in situ stress [24–26], the mining area should belong to the category of high in situ stress area. The deposit structure of the mining area is the same as the regional geological structure. The dominant fault group that has a significant impact on the deep mining of the mine is the NE trending longitudinal fault group. They are fault F2 (strike 222°, dip direction 132°, dip angle 69°), fault F3 (strike 221°, dip direction 131°, dip angle 71°), fault F4 (strike 219°, dip direction 129°, dip angle 78°), fault FC2 (strike 272°, dip direction 182°, dip angle 35°), and fault FC3 (strike 311°, dip direction 221°, dip angle 33°) located in the footwall of the main orebody. Among them, faults F2 and F3 extend from sublevel 10 to 15, extending more than 200 m, and there are many engineering revelations in sublevels 11 and 12. Fault F4 extends from sublevel 6 to 18, which are weak intercalation of carbonaceous slate. Faults FC2 and FC3 are a pair of parallel ore-controlling faults located below sublevel 18, dislocating the deep orebody to the right. The distribution of each fault is shown in Figure 2.

4. Slip Criterion Analysis of Mining-Induced Fault Activation

Under the redistribution of stress field of surrounding rock caused by mining, fault dislocation between hanging wall and footwall is called “fault activation.” Under the action of ground pressure, the fault activation is a process in which the mining disk of the fault undergoes shear deformation along the fault plane and then generates new fractures at one or both ends of the fault so that the fault can expand. The cracks located in the mining disk will also change accordingly.

4.1. Coulomb–Mohr Criterion. For non-water-conducting faults, activation plays two important roles. Firstly, through activation, the cement on the fault plane is “cut off,” which makes the “bonding” state between the hanging wall and footwall of the fault transform into a “breaking” state, which makes it easier to introduce groundwater. Secondly, the fault tip and fault-derived joints expand through activation, which significantly enhances the permeability of the fault zone and its adjacent rock mass. When the fault zone has groundwater or imports groundwater, the softening effect of groundwater can reduce the shear strength of the fault zone and fault material modulus of deformation. The potential energy of the excavated rock mass will be transformed into plasticity work to a high extent. In contrast, the magnitude of

3. The Field Situation of Fault Activation Slip in Mining Area

The authors have carried out several investigations on the rock mass movement status of the footwall from sublevel 7 to 15 of the main orebody in the Shizishan mining area. These investigations focus on identifying the dominant faults in the footwall that have an important impact on the stability of the project, and selecting appropriate monitoring points for the layout of the rock movement monitoring network. The investigation in April 2010 showed that the footwall of fault F2 had a significant influence on rock mass movement. The maximum slip of fault F2 was 0.50 m in the area exposed by the project, and severe deformation and failure of roadway and chamber were controlled by fault. The entire hanging wall of the fault sinks, which leads to the abandonment of many works. In contrast, faults F3 and F4 are not activated, and faults FC2 and FC3 in the lower part of sublevel 18 have not been exposed. The field investigation in April 2015 showed that during the past few years, affected by deep mining, the slip amount of fault F2 continued to increase and reached about 1.6 m, while fault F3 was activated due to the influence of deep mining, and the fault dislocation was obvious. The slip amount reached about 0.30 m. Tectonic development, such as faults in the footwall of the main orebody of the mine, and the objective presence of soft surfaces create conditions for roadway deformation, span fall, collapse, and rock movement. Figure 3 shows photos of a partial slip of fault F2.

Figure 1: Geographical location and surrounding geological map of Shizishan Copper Mine.
rock movement is bound to be greater, the process is more rapid, and the activation of faults is more pronounced.

Assuming that the hanging wall and footwall of the fault are elastic rock bodies, the fault plane is the contact surface of the hanging wall and footwall, and the initial activation of the fault is marked by the shear motion of the hanging wall and footwall. Modeling the fault activation force state [3, 27] is shown in Figure 4.

Assume that the fault plane dip is $\alpha$, the fault is subjected to the maximum compressive stress, and the minimum compressive stress is $\sigma_1$ and $\sigma_3$. The bond coefficient of the fault plane is $c$, and the internal friction angle is $\varphi$. The shear and normal stresses acting on the fault plane are given in the following formula:

$$
\begin{align*}
\tau &= \sigma_1 \sin \alpha + \sigma_3 \cos \alpha, \\
\sigma_n &= \sigma_1 \cos \alpha - \sigma_3 \sin \alpha, \\
\tau_n &= c + (\sigma_n - P_0) \tan \varphi,
\end{align*}
$$

where $P_0$ is the pore water pressure and $\tau_n$ is the shear strength of the fault plane, and when the pore water pressure...
should satisfy formulas (8) and (9).

\[ \tau = \begin{cases} \tau - \tau_n = \sigma_1 (\sin \alpha - \cos \alpha \tan \varphi) \\ - \sigma_3 (\cos \alpha - \sin \alpha \tan \varphi) - c. \end{cases} \] (6)

The criterion for fault activation is shown in the following formula:

\[ \Delta \tau \geq 0. \] (7)

4.2. The Sliding Criterion of Byerlee. The main problem in determining the stability of faults in rock masses is the correct selection of the sliding criterion (frictional strength). At present, it is difficult to determine the slip characteristics and criteria of the fault by accurately determining the shear strength parameters of the fault. Byerlee supplemented the Coulomb–Mohr criterion by using the spring-slider experiment in the laboratory and obtained the practical value of the sliding friction coefficient. According to Byerlee’s sliding criterion formula [3], \( \tau = \mu (\sigma_n - P_0) \), where \( P_0 \) is the pore water pressure. When the fault is dry and closed, the sliding criterion formula is \( \tau = \mu \sigma_n \). According to many rock friction experiments, Byerlee proposed that the conditions for the frictional sliding of rocks along the sliding plane should satisfy formulas (8) and (9).

\[ \tau = 0.85 \sigma_n, \quad 3MPa < \sigma_n < 200MPa, \] (8)

\[ \tau = 50 + 0.6 \sigma_n, \quad 200MPa \leq \sigma_n < 1700MPa, \] (9)

where \( \tau \) is the shear stress and \( \sigma_n \) is the normal stress.

5. Regularity and Mechanism Analysis of Fault Activation Induced by Continuous Mining in Deep Mining Area

5.1. Establishment of Numerical Calculation Model. Based on the schematic diagram of the distribution of faults and orebodies in Section 40 of the mining area, the 3D discrete unit method software 3DEC was used to build the calculation model. The top boundary of the numerical calculation model is taken to the surface, and the bottom boundary of the model is taken to 1400 m below the surface. In order to eliminate the influence of too close boundary, the left and right boundary are extended outward for a certain distance. The length of the model along the X direction is 3000 m, and 100 m is taken along the direction of the orebody strike, simplifying the surface at the top of the model into a horizontal plane. Figure 5 shows the schematic diagram of the final calculation model. The model dimensions are 3000 m, 1400 m, and 100 m in x, y, and z directions, respectively. In order to ensure the calculation accuracy and ensure that the unit has no distortion, the entire model is divided into 634,500 units and 126,850 nodes.

5.2. Parameter Selection and Calculation Scheme. The Mohr–Coulomb elastoplastic constitutive model is adopted for calculation. Except for setting free boundary conditions on the ground of the calculation model, the bottom of the model restricts the vertical displacement, and other boundaries restrict the horizontal displacement. In situ stress is applied inside the model according to the actual measurement in the mining area. Based on the rock physical and mechanical parameters obtained from the laboratory test and the RMR value of the rock mass quality evaluation, the Hoek–Brown strength criterion is used to reduce and correct the rock mass mechanical parameters to estimate the rock mass mechanical parameters. The macroscopic rock mass physical and mechanical parameters of the Shizishan Copper Mine finally determined are shown in Table 1. The shear stiffness is 0.6 GPa, the normal stiffness is 0.285 GPa, the tensile strength is 0.43 MPa, the cohesion is 0.25 MPa, and the internal friction angle is 25° which are the parameters used in the fault calculation. Fault mechanics parameters were determined from the inversion of slip on fault F2 after mining the orebody in deep sublevel 14, sublevel 15, and above.

The calculation scheme is one-time mining in a single sublevel, each mining height above sublevel 18 is 50 m, and from sublevel 19 to 24, each mining height is 30 m. It has been continuously mined from the level of 1787 m in sublevel 4 to the level of 787 m in sublevel 24. In order to analyze the stress field and slip variation of each fault during calculation, monitoring points are set up on each fault, namely, points A, B, C, D, and E, as shown in Figure 6.

5.3. Analysis of Calculation Results

5.3.1. Activation Law and Mechanism Analysis of Fault F2 (1) Effect of Continuous Mining at Depth on the Stress Field of the Fault Plane. Figure 6 shows the positive and shear stress curves on fault F2 plane with the mining depth. When the mining depth is above fault F2 in sublevel 10, the positive stress on fault F2 plane is 3.49 MPa. When mining to sublevel 13, fault F2 plane is affected by mining. Additional tensile stress is generated on the fault plane, the positive stress on the fault plane decreases sharply to 0.15 MPa, and the positive
stress decreases more. The positive stress on the fault plane decreased sharply to 0.15 MPa, with a large reduction in positive stress. Then, the positive stress on the fault plane showed a slightly decreasing trend with the increase of mining depth, and the change of positive stress was relatively stable. When mining to sublevel 10, the shear stress on the fault plane is 1.0 MPa. When mining to sublevels 11 and 12, the shear stress on the fault plane decreases to 0.45 MPa. When mining to sublevel 13, the shear stress on the fault plane increases sharply to the peak, the shear stress is 0.80 MPa, and then the shear stress decreases gradually. When mining reaches sublevel 16, the shear stress decreases to 0.05 MPa, and the shear stress on the fault plane changes steadily from 0 MPa to 0.25 MPa during mining from sublevel 16 to 24.

According to the discussion of the fault activation slip criterion in Section 4 of this paper, the slip properties of fault F2 were analyzed using the Coulomb–Mohr criterion and Byerlee slip criterion, respectively. \( \Delta \tau (\tau - 0.85 \sigma_n) \) is the difference between shear stress and shear strength at tracking point A on the plane of fault F2. The variation curve of \( \Delta \tau \) with the mining depth is shown in Figure 7. It can be seen from the calculation result that when mining from sublevel 10 to 12, the shear stress on the fault plane is less than the shear strength, indicating that the fault is in the static equilibrium state. After mining to sublevel 13, \( \Delta \tau \) was positive and peaked at sublevel 13, with a maximum value of 0.20 MPa, indicating that the shear stress on the fault plane was greater than the shear strength fault slipped unstably. Then, \( \Delta \tau \) gradually decreases. After mining to sublevel 14, \( \Delta \tau \) is mainly negative because the cohesive force \( c \) disappeared after the fault’s activation slip. The cohesive force is still taken into account in the calculation. Therefore, the Mohr–Coulomb criterion is only applicable to static equilibrium but not when the fault is activated and slipped.

Based on the Byerlee sliding criterion, the criterion for the occurrence of sliding on the fault plane is \( \tau \geq 0.85 \sigma_n \). By calculation, the variation curve of \( \tau - 0.85 \sigma_n \) on fault F2 plane with the mining depth is shown in Figure 8, and the value of \( \tau - 0.85 \sigma_n \) increases linearly with the increase of mining depth from sublevel 10 to sublevel 13. The ratio of shear stress to normal stress also increases rapidly at this

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Density ( \rho ) (g/cm(^3))</th>
<th>Modulus of elasticity ( E ) (GPa)</th>
<th>Poisson’s ratio</th>
<th>Tensile strength ( \sigma_t ) (MPa)</th>
<th>Cohesive force ( C ) (MPa)</th>
<th>Angle of internal friction ( \phi ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluish grey dolomite</td>
<td>2.85</td>
<td>20.0149</td>
<td>0.269</td>
<td>2.1966</td>
<td>2.6110</td>
<td>41.99</td>
</tr>
<tr>
<td>Faded dolomite</td>
<td>2.84</td>
<td>13.0620</td>
<td>0.280</td>
<td>2.1796</td>
<td>2.5504</td>
<td>34.05</td>
</tr>
<tr>
<td>Orebody</td>
<td>2.84</td>
<td>17.8847</td>
<td>0.214</td>
<td>2.2577</td>
<td>2.9637</td>
<td>47.42</td>
</tr>
<tr>
<td>Purple slate</td>
<td>2.63</td>
<td>4.5676</td>
<td>0.284</td>
<td>1.0431</td>
<td>1.5710</td>
<td>31.68</td>
</tr>
<tr>
<td>Carbonaceous slate</td>
<td>2.70</td>
<td>2.2416</td>
<td>0.350</td>
<td>0.9298</td>
<td>1.3848</td>
<td>35.42</td>
</tr>
</tbody>
</table>
time, the value of $\tau - 0.85\sigma_n$ is positive at sublevel 13, and the peak value is 0.24 MPa, indicating that the fault had been activated and started to slip at this point. After that, the value of $\tau - 0.85\sigma_n$ showed a stable trend with the increase of mining depth, and the values were all greater than 0.

(2) Influence of deep Continuous Mining on Fault Slip. Figure 9 shows the spatial and temporal variation curve of fault F2 slip with the mining depth. The results show that when mining above sublevel 12, fault F2 did not slip, and the fault was not activated. In contrast, after mining to sublevel 13, fault F2 was activated by mining, and the slip amount was 0.129 m. When sublevels 14 and 15 were mined, the slip amount of the fault increased to 0.630 m. According to the field monitoring, after mining to sublevel 15, the slip amount of fault F2 increases greatly, and the slip amount of fault F2 is 0.56 m. The calculated results agree well with the measured ones. The calculated results show that the slip of fault F2 increased to 2.44 m after the mining of sublevel 18. As the deep mining continued, the slip of fault F2 gradually increased, and when sublevel 22 to sublevel 24 (~1150 m to ~1300 m) were mined, the slip of fault F2 finally increased to 4.491 m. According to the calculated results of the fault slip, after mining sublevel 13, the fault slipped, which is consistent with the prediction result of the Byerlee slip criterion, indicating that it is feasible to use Byerlee’s law to determine mining-induced fault activation slip.

(3) Analysis of Activation Mechanism of Fault F2 Induced by Deep Continuous Mining. According to the above analysis, the activation mechanism of fault F2 under the effects of mining is as follows. As the deep mining of the main orebody continues until sublevel 10, the stress around the excavation area is redistributed under the influence of mining, and the mining influence scope spreads to fault F2, resulting in the decrease of normal stress on fault F2 plane and the apparent additional tensile stress $\Delta\sigma_n$. At this time, the shear strength $\tau = (\sigma_n - \Delta\sigma_n)\tan \phi + c$ of the fault plane decreased. After mining to sublevel 13, the difference between the fault plane’s shear stress and shear strength was greater than 0, and the Byerlee fault slip criterion is satisfied. The fault was activated by mining and began to slip steadily towards the goaf which is consistent with the actual situation on site. The analysis of this paper shows that the activation of steep dip fault is mainly caused by the decrease of normal stress of fault plane caused by mining. It is caused by additional tensile stress generated by excavation unloading.

5.3.2. Activation Law and Mechanism Analysis of Fault F3

(1) Influence of Deep Continuous Mining on Stress Field of the Fault Plane. Figure 10 shows the normal and shear stress curve of fault F3 plane with the mining depth. When mining from sublevel 10 to 13, the normal stress of fault F3 plane is 2.889 MPa, showing a steady trend. When mining from sublevel 14 to 16, the normal stress on the fault plane decreases greatly, and a large additional tensile stress is generated on the fault plane. After mining from sublevel 17 to 24, the normal stress on the fault plane shows a steady trend, ranging from 0 MPa to 0.1 MPa. When mining from sublevel 10 to 12, the shear stress on fault F3 plane is about 0.95 MPa, showing a steady trend. After mining from sublevel 13 to 15, the shear stress on the fault plane was reduced to 0.21 MPa. The shear stress on the fault plane was reduced, but the reduction was much less than the reduction in the positive stress on the fault plane. After mining to sublevel 16, the shear stress on the fault plane increased slightly to 0.43 MPa, indicating that additional shear stress was produced along the fault plane. After that, the shear stress on the fault plane varied steadily between 0.1 MPa and 0.2 MPa during mining from sublevel 17 to 24.
Figure 10: Relationship of stress state of fault F3 with mining depth.

Figure 11 shows the curve of $\tau - 0.85\sigma_n$ on fault F3 with mining depth. When mining from sublevel 10 to 13, the value of $\tau - 0.85\sigma_n$ slightly increased with the increase of mining depth. When mining from sublevel 14 to 16, the shear stress to normal stress ratio increases rapidly. The value of $\tau - 0.85\sigma_n$ is greater than 0 after mining to sublevel 16, and the peak value is 0.35 MPa, indicating that the fault has been activated and has started slipping. Later, with the increase of mining depth, when the value of $\tau - 0.85\sigma_n$ is slightly reduced, it shows a stable trend with little change, but all positive, indicating that fault F3 has been sliding after mining to sublevel 16.

(2) Influence of Deep Continuous Mining on Fault Slip

Figure 12 shows the spatial and temporal relationship curve of fault F2 slip with mining depth. The results show that when the orebody above sublevel 15 was mined, fault F3 did not slip, i.e., the fault was not activated. In contrast, after the end of mining sublevel 16, fault F3 was activated by mining, and the slip amount was 0.21 m. When sublevel 17 and sublevel 18 were mined, the slip amount of the fault increased sharply to 1.46 m; however, during the mining period from sublevel 18 to sublevel 22, the increase rate of slip on the fault plane decreases. The slip on the fault plane was 1.798 m at the end of mining sublevel 22, and the rate of increase in a slip on the fault plane increased again after mining from sublevel 23 to sublevel 24. Furthermore, the slip on the fault plane was 2.46 m after mining sublevel 24, showing a staged increase in the slip on the fault plane.

(3) Analysis of Activation Mechanism of Fault F3 Induced by Deep Continuous Mining

Through the above analysis, the mechanism of activation of fault F3 by mining is as follows. As the main orebody continues to be mined from sublevel 13 to 15, the stresses around the excavation area are redistributed by mining, and the mining influence spreads to fault F3, causing a corresponding decrease in the positive and shear stresses on fault F3, the decreasing range of normal stress is much smaller than that of shear stress and additional tensile stress, and the additional tensile stress on the fault $\Delta\sigma_n$ increases; the shear strength $\tau = (\sigma_n - \Delta\sigma_n)\tan\varphi + c$ of the fault plane decreases, but the shear stress on the fault plane is still less than the shear strength. When sublevel 16 is mined, according to the Byerlee fault sliding criterion, the value of $\tau - 0.85\sigma_n$ is greater than 0. The difference between the shear stress and shear strength on the fault plane is $\Delta\tau > 0$, indicating that the fault is activated by the mining influence and starts to slip steadily in the direction of the goaf, which is consistent with the actual situation on site.

5.3.3. Activation Law and Mechanism Analysis of Fault F4

(1) Influence of Deep Continuous Mining on Stress Field of Fault Plane

Figure 13 shows the normal and shear stress curve on fault F4 plane with the mining depth. When mining from sublevel 10 to 16, the normal stress on fault F4 plane is 2.635 MPa, showing a steady trend. After mining from sublevel 20 to 24, the normal stress on the fault plane began to change steadily, with the normal stress range varying in a steady trend around 0.1 MPa. When mining from sublevel 10 to 16, the shear stress on fault F4 plane shows a stable trend, varying from 1.148 MPa to 1.005 MPa, and after mining from sublevel 17 to 18, the shear stress on the fault plane decreased to 0.226 MPa. The shear stress on the fault plane decreases, but the decrease is much smaller than that of the normal stress on the fault plane. The shear stress on the fault plane increased slightly to 0.338 MPa after mining to sublevel 19, indicating that additional shear stress was generated along the fault plane. After that, the shear stress on the fault plane varied steadily around 0.15 MPa from sublevel 20 to 24.

Figure 14 shows the variation curve of $\tau - 0.85\sigma_n$ on fault F4 with mining depth. When mining from sublevel 10 to 18, the value of $\tau - 0.85\sigma_n$ is −1.2 MPa; as mining depth
increases, the curve shows a smooth change. When mining from sublevel 18 to 19, shear stress to normal stress increases steeply. The value of \( \tau - 0.85\sigma_n \) is greater than 0 after mining to sublevel 19, and the peak value is 0.196 MPa. It means that the fault has been activated and started to slide. After that, when mining depth increases, the value of \( \tau - 0.85\sigma_n \) decreases slightly and then stabilizes, but all of them are positive, indicating that after mining sublevel 19, fault F4 is activated by mining and is sliding.

(2) Influence of Deep Continuous Mining on Fault Slip. Figure 15 shows the relationship of the slip amount of fault F4 with mining depth. The results show that fault F4 does not slip after mining the orebody above sublevel 18, which means that the fault was not activated. After sublevel 19 was mined, fault F3 affected by mining was activated, and the slip amount was 0.18 m. When the orebody in sublevel 21 was mined, the slip amount of fault F4 rapidly increased to 0.767 m. Finally, after mining the orebody from sublevel 22 to 24, the slip amount on the fault plane increased to 1.008 m, and the slip amount on the fault plane showed an increasing trend in stages.

(3) Analysis of Activation Mechanism of Fault F4 Induced by Deep Continuous Mining. In summary, the mechanism of activation of fault F4 by mining is as follows. As the deep part of the main orebody continues to be mined until sublevel 18, the stress around the excavation area is redistributed by mining, and the impact of mining spreads to fault F4, causing the normal stress and shear stress on fault F4 plane to decrease accordingly, the reduction of normal stress is much larger than that of shear stress, and the normal stress on the fault plane \( \Delta\sigma_n \) increases and obvious additional tensile stress is produced. The shear strength of the fault plane \( \tau = (\sigma_n - \Delta\sigma_n)\tan \phi + c \) decreases, but the shear stress on the fault plane is still less than the shear strength. When sublevel 19 was mined, according to the Byerlee fault sliding criterion, the value of \( \tau - 0.85\sigma_n \) was greater than 0. It shows that the fault is activated by mining and began to slide towards the goaf.

5.3.4. Activation Law and Mechanism Analysis of Fault FC2

(1) Influence of Deep Continuous Mining on the Stress Field of Fault Plane. Figure 16 shows the curve of the positive and shear stress on fault FC2 plane with the mining depth. When mining from sublevel 10 to 20, the positive stress on fault FC2 plane is 16.23 MPa, showing a steady trend. When mining from sublevel 21 to 22, the positive stress on the fault plane decreases significantly. After mining to sublevel 22, the positive stress on the fault plane is 2.01 MPa. The fault plane has a large additional tensile stress generated. After mining from sublevel 23 to 24, the positive stress on the fault plane showed a stable trend, with a range of positive stresses around 1.70 MPa. The shear stress on fault FC2 plane was from 6.11 MPa to 5.43 MPa when mining from sublevel 10 to 21, showing a steady trend. The shear stress on the fault plane increased slightly to 2.670 MPa after mining to sublevel 22, indicating that additional shear stresses along the fault plane were generated at this time. The shear stress on the fault plane changes steadily at about 2.30 MPa during the mining of the sublevel 23 to sublevel 24.

Figure 17 shows the curve of the value of \( \tau - 0.85\sigma_n \) on fault FC2 plane changing with the mining depth. When mining from sublevel 10 to 21, with the increase of the mining depth, the value of \( \tau - 0.85\sigma_n \) is -7.50 MPa, showing a continuous change. When sublevels 21 and 22 were mined, the shear stress to normal stress ratio increased rapidly. The value of \( \tau - 0.85\sigma_n \) is greater than 0 after mining to sublevel 22, and the peak value is 0.97 MPa. It shows that the fault has been activated and began to slide. As mining depth increases, the value of \( \tau - 0.85\sigma_n \) decreased slightly, showing a stable
trend with little change. However, all were positive, indicating that after mining to sublevel 22, fault FC2 was activated, and sliding after the mining was affected.

(2) Influence of Deep Continuous Mining on Fault Slip. Figure 18 shows the spatial and temporal relationship between the slip amount of fault FC2 and the mining depth. The results show that when the orebody above sublevel 21 was mined, fault FC2 did not slip, i.e., the fault was not activated, while at the end of the mining of sublevel 22, fault FC2 was activated by mining and the slip amount was 0.15 m. When the orebody from sublevel 22 to sublevel 24 was mined, the slip amount on the fault plane finally increased to 0.68 m.

(3) Activation Mechanism Analysis of Fault FC2 Induced by Deep Continuous Mining. In summary, the mechanism of activation of fault FC2 by mining is as follows. As the main orebody continues to be mined until sublevel 21, the stresses around the excavation area are redistributed by mining, and the mining influence spreads to fault FC2, resulting in the corresponding decrease of normal stress and shear stress on fault FC2 plane. The amplitude of normal stress is much smaller than the amplitude of shear stress. Moreover, the reduction in the normal stress on the fault plane $\Delta \sigma_n$ increased, resulting in an obvious additional tensile stress. At this time, the shear strength of the fault plane $\tau = (\sigma_n - \Delta \sigma_n) \tan \varphi + c$ declines, but the shear stress on the fault plane is still less than the shear strength. When sublevel 22 was mined, according to the Byerlee fault sliding guidelines, the value of $\tau - 0.85\sigma_n$ greater than 0 indicates that the fault is activated by mining and begins to slide towards goaf. The change of fault slip amount with mining depth also proves this conclusion.

5.3.5. Activation Law and Mechanism Analysis of Fault FC3

Figure 18: Relationship of the slip amount of fault FC2 with mining depth.

(1) Influence of Deep Continuous Mining on Stress Field of Fault Plane. Figure 19 shows the normal and shear stress curve on fault FC3 plane with the mining depth. When sublevel 10 to sublevel 21 were mined, the normal stress on fault FC3 plane was 17.03 MPa, showing a steady trend. When sublevel 22 to sublevel 23 were mined, the normal stress on the fault plane was greatly reduced. After sublevel 23 was mined, the normal stress on the fault plane was 2.05 MPa, and a large additional tensile stress was generated on the fault plane. After mining from sublevel 23 to 24, the normal stress on the fault plane began to show a stable trend again, with the range of normal stress varying in a stable trend around 1.40 MPa. The shear stress on fault FC3 plane ranged from 5.28 MPa to 5.77 MPa when mining from sublevel 10 to 21, showing a steady trend. After sublevels 21 and 22 were mined, the shear stress on the fault plane decreased to 2.15 MPa, and the shear stress on the fault plane decreased, but the decrease was much smaller than the normal stress on the fault plane. After mining to sublevel 23, the shear stress on the fault plane increased slightly to 2.650 MPa. This means that additional shear stresses were generated along the fault plane, and the shear stress on the fault plane was 0.91 MPa after the orebody was mined in sublevel 24.

According to the Byerlee sliding criterion, the criterion for the occurrence of sliding on the fault plane is $\tau \geq 0.85\sigma_n$. Figure 20 shows the variation curve of $\tau - 0.85\sigma_n$ on fault FC3 plane with mining depth. When mining from sublevel 10 to 21, the value of $\tau - 0.85\sigma_n$ is $\sim 8.90$ MPa, which is a smooth change. When mining from sublevel 22 to 23, the shear stress to normal stress ratio increases rapidly during this time. The value is greater than 0 after mining sublevel 23, and the peak value is 0.95 MPa, which means that the fault has been activated and began to slide. After that, as the mining depth increases, the value of $\tau - 0.85\sigma_n$ slightly decreases. It is a stable trend, not much change, but all
positive, indicating that after mining to sublevel 23, fault FC3 was activated and slipped after being affected by the mining.

(2) Influence of Deep Continuous Mining on Fault Slip. Figure 21 shows the spatial and temporal relationship of the slip amount of fault FC3 with mining depth. The results show that when the orebody above sublevel 22 was mined, fault FC3 did not slip, i.e., the fault was not activated. In contrast, at the end of the mining of sublevel 23, fault FC3 may have been activated by mining, and the slip amount was 0.143 m, and when the orebody of sublevel 24 was mined, the slip amount of fault FC3 increased to 0.223 m.

(3) Analysis of Activation Mechanism of Fault FC3 Induced by Deep Continuous Mining. As a result of mining, the mechanism of activation of fault FC3 is as follows. As the deep part of the main orebody continues to be mined until sublevel 22, the stresses around the mining area are redistributed by mining, and the mining influence spreads to fault FC3, causing the normal stress and shear stress on fault FC3 to decrease accordingly; compared to the reduction in shear stress, the reduction in normal stress is much greater, and the reduction in the normal stress on the fault plane \( \Delta \sigma_n \) increased, resulting in an obvious additional tensile stress. At this time, the shear strength of the fault plane \( \tau = (\sigma_n - \Delta \sigma_n) \tan \varphi + c \) has declined, but the shear stress on the fault plane is still less than the shear strength. When mining to sublevel 23, according to the Byerlee fault sliding criterion, the value of \( \tau - 0.85\sigma_n \) is greater than 0, indicating that the fault is activated by the mining effect and starts to slip towards the goaf. The change of the slip amount of the fault with mining depth also proves this conclusion.

5.3.6. Domino Effect and Mechanism Analysis of Fault Activation under the Influence of Deep Continuous Mining. Figure 22 shows the spatial and temporal relationship of the slip of the faults in the footwall of the main orebody with mining depth. The analysis shows that the activation law of the footwall fault of the main orebody is that the movement law of the footwall rock mass of the main orebody in the mining area is mainly controlled by the dominant fault. There is a barrier effect of the fault on the distribution of stress and displacement fields in the footwall rock of the main orebody. With the end of stoping of the orebody in sublevel 13 (buried depth 700 m), the influence of mining spreads to fault F2, and fault F2 was activated by mining, and the rock body on the hanging wall of the fault near the mining area began sliding along the fault towards the mining area; when stoping of the orebody in sublevels 14 and 15 was completed, the slip of fault F2 gradually increased to 0.63 m. With the development, preliminary mining and stoping of the orebody in the sublevel 16. Mining also caused fault F3 to be activated, and the rock on the hanging wall of fault F3 began to slip along the fault in the direction of the goaf, and the slip of faults F2 and F3 was 1.476 m and 0.210 m, respectively, after the end of stoping in sublevel 16. When the deep mining continued to sublevel 19 (buried depth 1000 m), fault F4 was also activated under the influence of mining, and the rock mass from the hanging wall of the fault to the side of the goaf produces slip towards the goaf. After the end of stoping of sublevel 19, the slip of faults F2, F3, and F4 was 2.553 m, 1.506 m, and 0.18 m, respectively. After the end of stoping of the orebody in sublevel 22, fault FC2 was also activated by mining and started to slide. The slip of faults F2, F3, F4, and FC2 was 3.078 m, 1.798 m, 0.791 m, and 0.144 m, respectively. When the orebody in deep sublevel 23 (burial depth 1350 m) finished stoping, fault FC3 was also activated by mining and started to slip, and the slip of fault FC3 was 0.143 m. The slip amount on faults F2, F3, F4, FC2, and FC3 was 4.491 m, 2.460 m, 1.008 m, 0.675 m, and 0.223 m, respectively, after stoping of the orebody in deep sublevel 24. Based on the spatial and temporal correlation...
between the activation and slip of the fault group under the main orebody, the activation of the faults induced by the continuous mining conditions at depth has a “domino effect.” In an interconnected system, small initial energy may produce a series of successive activation of faults and slip of the hanging wall towards the extraction area during deep and continuous mining, i.e., the “domino effect.” Therefore, similar to the Shizishan Copper Mine, the steeply dipping geese column fault group in the footwall of the mining area induces fault activation under mining, which results in the hanging wall of the fault moving towards the mining area and slipping along the fault plane.

By calculating normal stress and shear stress on each fault with mining depth, according to Byerlee’s law, the criterion of fault plane sliding is \( \tau \geq 0.85\sigma_n \). Figure 23 shows the temporal and spatial relationship curve of additional tensile stress on each fault plane with mining depth. Figures 24 and 25 show the temporal and spatial relationship curve of fault values of \( \tau - 0.85\sigma_n \) on the footwall of the main orebody with mining depth. Through analysis, the domino effect mechanism of fault activation in the footwall of the main orebody is as follows. As mining enters sublevel 10, as a result of mining, the additional tensile stress is first generated on fault F2 plane. With the downward mining, the additional tensile stress on fault F2 plane increases gradually, and the shear strength \( \tau = (\sigma_n - \Delta\sigma_n)\tan \phi + c \) of the fault plane decreases gradually. After mining the orebody to sublevel 13, additional tensile stress reaches a maximum value of 3.05 MPa. Currently, the shear stress on the fault plane exceeds the shear strength and satisfies Byerlee’s law. The value of \( \tau - 0.85\sigma_n \) is greater than 0. Under the influence of mining, the fault F2 starts to active and began to slip. The rock body on the hanging wall of the fault near the mining area starts to slide along the fault plane in the direction of the goaf, and then the additional tensile stress on the fault plane tends to stabilize. When the orebody is mined from the sublevel 14 to the sublevel 16, Fault F3 plane starts to generate additional tensile stress and reaches a maximum value of 2.799 MPa after mining the orebody to sublevel 16, and fault F3 also satisfies Byerlee’s law. Fault F3 was activated under the influence of mining, and the rock body on the hanging wall of fault F3 began to slip along the fault plane in the direction of the goaf. When the deep mining continued to sublevel 19 (buried depth 1000 m), the additional tensile stress on fault F4 plane also reached a peak of...
2.409 MPa, and fault F4 shows greater shear stress than its strength, and mining affected the fault's activation as well. The additional tensile stress on the fault plane also increases to the peak value of 11.23 MPa. It is also activated and begins to slip under the influence of mining.

From the analysis of the additional tensile stress and the spatial and temporal relationship of the fault activation slip with mining depth on each fault plane in the footwall of the main orebody, the positive and shear stresses on the fault plane decrease simultaneously after mining of the orebody, i.e., additional tensile stress and additional shear stress are generated. At this time, the additional tensile stress acts to reduce the shear strength of the fault plane and promotes fault activation. In contrast, the shear stress on the fault plane is reduced by the additional shear stress, preventing the activation of the fault. Through analysis, shear stress to positive stress ratios increase after mining on each fault plane, indicating that the nature of fault activation in the mine area is caused by the additional tensile stress generated on the fault plane due to excavation and unloading. In contrast, the increase of additional tensile stress on fault F2 leads to the reduction of the positive stress acting on the footwall by the rock body on fault F2. The footwall of fault F2 is the hanging wall of fault F3, which, according to the principle of force transfer, is the essence of the domino effect of fault activation under the influence of mining on the steep dip fault group.

6. Conclusion

(1) Within the area affected by underground excavation, the existence of fault plane and fault zones will change the normal distribution pattern of the displacement field and secondary stress field of the surrounding rock and become a barrier affecting the deformation and stress propagation of the surrounding rock, resulting in different characteristics of rock movement and deformation on both sides of the fault plane or fault fracture zone. With the change of potential energy of the rock in the excavation influence area, the work done by the self-weight volume force is mainly consumed in the slip action of the fault plane and the plastic deformation and slip deformation of the fault fracture zone, which makes it difficult to completely cross the fault fracture zone to the deeper part of the surrounding rock. The extrusion displacement and rebound deformation pointing to the mining space are mostly restricted within the fault fracture zone. This is the essence of displacement and stress barrier effect of faults and is also the main reason for the large deformation and high-stress concentration in the surrounding rock between the fault and the mining area.

(2) The normal stress and shear stress on each fault plane decrease simultaneously after mining the orebody, and additional tension stress and shear stress are generated. At this time, the additional tensile stress reduces the shear strength of the fault plane and promotes the fault's activation. The effect of the additional shear stress on the fault plane is to prevent the activation of the fault, but the decrease of normal stress on the fault plane is much greater than that of shear stress, and the shear stress on the fault plane is greater than the shear strength, resulting in fault activation. It also shows that the essence of fault activation in the mining area is caused by additional tensile stress on the fault plane caused by excavation unloading.

(3) The fault effect of rock movement in the footwall of the main orebody of the mine is obvious. The en echelon steep dipping fault group in the footwall of the mining area will move each fault block in the direction of the mining area and slip along the fault plane when the balance between mining and gravity is broken. The activation of the fault has a domino effect in time and space. After mining, the increase of additional tensile stress of fault F2 leads to the decrease of the normal stress exerted by the hanging wall rock mass of fault F2 on the footwall. The footwall of fault F2 is the hanging wall of fault F3. According to the principle of force transfer, the normal stress exerted by the hanging wall rock mass of fault F3 on the footwall rock mass will decrease, resulting in a decrease in the shear strength of fault F3. Similarly, the normal stress exerted by the hanging wall of fault F4 on the footwall decreases, and the shear strength of fault F4 also decreases, which is the essence of the domino effect of fault activation of en echelon steep dipping fault group under the influence of mining.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was supported and funded by the Scientific Research Fund Project of Yunnan Provincial Department of Education, China (no. 2022J0065), Key Projects of Analysis and Testing Fund of Kunming University of Science and Technology, China (no. 2021T20200145), China Postdoctoral Science Foundation Project (no. 2017M620433), and General Projects of Yunnan Basic Research Program (no. 2018FB075).

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