Pre-evaluation of fault stability for underground mining based on geomechanical fault-slip analysis

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\textbf{ABSTRACT}

In underground near-fault mining, fault reactivation is related to many kinds of mine disasters such as mine water inrush, mine earthquakes, gas outburst, rock burst, roof collapse. Pre-evaluation of fault stability in the pre-mining phase is of great significance for predicting possible mine fault-related disasters. In this study, based on the geomechanical analysis of fault slip tendency, a technique to the pre-mining evaluation of fault stability under Andersonian stress system was introduced by extending the original Morris’s theory of fault slip tendency, effects of fault orientation, in-situ stress and pore fluid pressure on fault stability were analyzed. Taking Shilin coal mine as the research background, a pre-evaluation on the stability of all 15 faults distributed in the whole coalfield at the mining depths of 369 and 514 m was conducted, the analysis results demonstrated that all faults in the Shilin coalfield are quite stable at the two mining depths. The work presented in this study is practical and can provide a quantitative geomechanical way in the analysis of pre-mining fault stability and in the risk pre-assessment of fault-related mine disasters.

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1. Introduction

During the process of underground mining, sudden slipping between the hanging wall and footwall of a pre-existing fault caused by mining activities is usually related to a triggering of huge release of accumulate strain energy, which can lead to a large-scale instability of near-fault surrounding rocks and result in many kinds of geological dynamic solid-related mine disasters such as rockburst (Williams et al. 1992; Li et al. 2016; Wang et al. 2017; Keneti and Sainsbury 2018; Lu et al. 2019), coal burst (Jiang et al. 2017; Shen et al. 2020), mine seismic tremor (Hofmann and Scheepers 2011) and roof collapse (Das et al. 2018; Wang et al. 2019). Moreover, because of the pore structure developed in fault zone, underground fault also has the function of...
fluid transportation and fluid storage so fault slipping in underground mining may cause the sudden change of the permeability of fault zone and then further triggering fluid-related mine disasters such as gas outburst (Wang et al. 2019; Zhou et al. 2019), water inrush (Ma et al. 2017; Ma et al. 2020; Zhu et al. 2017; Zhou et al. 2017, 2018). All in all, fault is the root of many solid- and fluid-related disasters in underground mining, pre-evaluating the stability of faults pre-mining has an especially important value in assessing the risk of possible fault-related mine geological disasters in advance.

To date, a lot of efforts have been made by previous researchers for analyzing the contributing factors of fault slipping in underground mining. Numerical analyses (Ji et al. 2012; Sjöberg et al. 2012; Sainoki and Mitri 2014, 2018) revealed that fault-slipping induced by mining disturbances is mainly influenced by frictional angle, fault stiffness, mining depth and fault position, mining arrangement, mining sequences. Theoretical analysis (Zhao et al. 2018) performed in Zhaolou coal mine found that the distribution of Coulomb stress on fault plane is jointly affected by the fault orientation and the frictional coefficient and the mining stress redistribution (Wang et al. 2018). Experimental study (Deng et al. 2018) indicated that the threshold of fault slipping triggered by external disturbances is significantly affected by the initial stress state. A field investigation (Jiang et al. 2017) in Yima mine area in China found that fault slipping has a relation with the high tectonic stress, an field study (Kong et al. 2019) from Dongtan coal mine discovered that fault is more stable when the panel is mined through the fault from the footwall than mining the panel through the fault from the hanging wall, an investigation (Alber and Fritschen 2011) conducted in a deep underground longwall coal mine in the German Saar mining district revealed the role of pore fluid pressure on the fault stability.

Overall, while at present many studies have been performed in analyzing the contributing factors of fault slipping during mining, analysis of fault slip-tendency for pre-mining phase is still a problem that needs further research. In the present work, by extending the original Morris’s theory of fault slip-tendency (Morris et al. 1996; Lisle and Srivastava 2004), a geomechanical technique to the pre-mining evaluation of fault stability under Andersonian stress systems is provided.

2. Basic theory of fault slip-tendency

In any a given stress field defined by three compressive principal stress \(\sigma_1 > \sigma_2 > \sigma_3\), the shear (\(\tau\)) and the effective normal (\(\sigma_{ef}\)) stresses acting on any a arbitrarily oriented plane within the stress field can be derived (Jaeger et al. 2007) as:

\[
\tau^2 = (\sigma'_1 - \sigma'_2)^2l^2m^2 + (\sigma'_2 - \sigma'_3)^2m^2n^2 + (\sigma'_3 - \sigma'_1)^2l^2n^2
\]

\[
\sigma_{ef} = l^2\sigma'_1 + m^2\sigma'_2 + n^2\sigma'_3,
\]

where \(l, m\) and \(n\) are the direction cosines of the plane’s normal with respect to the principal stress axes, \(\sigma'_1, \sigma'_2,\) and \(\sigma'_3\) are the effective principal stresses defined as
\( \sigma'_1 = (\sigma_1 - p_f) \), \( \sigma'_2 = (\sigma_2 - p_f) \), and \( \sigma'_3 = (\sigma_3 - p_f) \), in which \( p_f \) is the pore fluid pressure.

Without considering the effect of the cohesive strength, Morris et al. (1996) proposed to assess the plane’s potential of frictional reactivation by using the ratio of the shear stress to the corresponding effective normal stress, which is also commonly named as the fault slip-tendency \( (T_s) \) and can be expressed as:

\[
T_s = \frac{\tau}{\sigma_{ef}}
\]  

Substituting equation (1) and (2) in equation (3), slip-tendency of fault can be further given as:

\[
T_s = \frac{\left( (\sigma'_1 - \sigma'_2)^2 l^2 m^2 + (\sigma'_2 - \sigma'_3)^2 m^2 n^2 + (\sigma'_3 - \sigma'_1)^2 l^2 n^2 \right)^{1/2}}{l^2 \sigma'_1 + m^2 \sigma'_2 + n^2 \sigma'_3}
\]  

3. Computing fault slip-tendency under Andersonian stress systems

In underground mining, for engineering conveniences in-situ stress field is generally described with the Andersonian stress systems (Anderson 1951), in which one principal axis of crustal stress tensors is assumed in vertical and the other two principal axes are assumed in horizontal (Simpson 1997). In real mining practices the horizontal principal stresses (the maximum horizontal stress \( \sigma_H \) and the minimum horizontal stress \( \sigma_h \)) can be tested in various ways like hydraulic fracturing method, stress-relief method, strain recovery method and so on, and the vertical stress (\( \sigma_v \)) can be estimated by the self-weight of the overlying strata. Under the Andersonian stress systems, an in-situ stress field can be classified into three stress regimes including the normal-faulting stress regime \( (\sigma'_1 = \sigma_v, \sigma'_2 = \sigma_H \text{ and } \sigma'_3 = \sigma_h) \), the strike-slip faulting stress regime \( (\sigma'_1 = \sigma_H, \sigma'_2 = \sigma_v \text{ and } \sigma'_3 = \sigma_h) \) and the reverse faulting stress regime \( (\sigma'_1 = \sigma_H, \sigma'_2 = \sigma_h \text{ and } \sigma'_3 = \sigma_v) \).

Applying formulae (4) to the above three stress regimes, fault slip-tendency under the Andersonian stress systems can be further provided as:

1. Normal-faulting stress regime:

\[
T_s = \frac{\left( (\sigma_v - \sigma_h)^2 l^2 m^2 + (\sigma_H - \sigma_h)^2 m^2 n^2 + (\sigma_h - \sigma_v)^2 l^2 n^2 \right)^{1/2}}{l^2 \sigma_v + m^2 \sigma_H + n^2 \sigma_h}
\]

2. Strike-slip faulting stress regime:

\[
T_s = \frac{\left( (\sigma_H - \sigma_v)^2 l^2 m^2 + (\sigma_v - \sigma_h)^2 m^2 n^2 + (\sigma_h - \sigma_H)^2 l^2 n^2 \right)^{1/2}}{l^2 \sigma_H + m^2 \sigma_v + n^2 \sigma_h}
\]
3. Reverse-faulting stress regime:

\[
T_s = \frac{(\sigma_H - \sigma_h)^2 l^2 m^2 + (\sigma_h - \sigma_v)^2 m^2 n^2 + (\sigma_v - \sigma_H)^2 n^2)}{l^2 \sigma_H + m^2 \sigma_h + n^2 \sigma_v}^{1/2}
\]  

(7)

To facilitate the application of the above formulas in mining engineering, we can use the fault dip and fault striking to express the three direction cosines with the following trigonometric relationships:

\[
l = \cos \theta
\]

(8)

\[
m = \sin \varphi \sin \theta
\]

(9)

\[
n = \cos \varphi \sin \theta,
\]

(10)

where \( \theta \) is the dip angle of the fault plane and \( \varphi \) is the angle between the fault striking line and the direction of the maximum horizontal stress \( \sigma_H \).

4. Relations between fault orientation, in-situ stress, pore fluid pressure and fault stability

4.1. Fault orientation

Faults with different orientations distribute in strata in various spatial shapes, in a given stress field (represented by three principal stresses), as expressed in equation (3), slip
tendency of a fault within the stress field is constrained by the normal and shear stresses acting on the fault plane, while the normal and shear stresses are determined by what the fault plane’s orientation regarding to the principal stress axes, so from this point of view fault orientation has very direct correlation with fault stability.

According to Sibson’s work (1985) on 2-D fault reactivation analysis, fault orientations can be classified as “favorably oriented” and “unfavorably oriented” depending on the effective stress ratio. In light of Morris’s work (1996) on 3-D fault reactivation analysis, under a given stress field, a fault plane has a slip tendency >0.5 can be defined as well-oriented plane that is more prone to be reactivated, whereas <0.5 represents the plane is mis-oriented (Lecl`ere and Fabbri 2013) and has higher stability.

Under the condition of a given stress field, slip tendencies of all possible orientations of fault planes can be calculated using equation (4), contouring all the calculation results in a lower-hemisphere equal-area stereoplot we can get the slip tendency stereoplot. Figure 1 shows an particular case of slip tendency stereoplot corresponding to the stress field \( \sigma_v = 50 \text{ MPa}, \sigma_H = 25 \text{ MPa}, \sigma_h = 10 \text{ MPa} \) (\( \sigma_v, \sigma_H, \sigma_h \) as down, East, North). As can be seen from the figure, fault planes with high slip tendency (well-oriented planes) have bimodal distributions about \( \sigma_h \), two domains of high slip-tendency distribute within a range of 56° to \( \sigma_H \), which indicate that under this stress field if the angle between a fault’s strike direction and \( \sigma_H \) is greater than 56°, the fault can be considered as a mis-oriented fault (stable fault). Thus, more attentions should be paid to well-oriented faults in mining practices as well-oriented faults are less resistant to mining disturbances and more prone to be reactivated to cause mine disasters.

4.2. In-situ stress

In addition to fault orientation, in-situ stress field is another important factor in determining the stability of fault. In shallow underground, in-situ stress field is more likely to be influenced by surface topography so that lead to a large dispersion of its value, but this influence is limited, it is generally believed that after the depth is >300 m the influence of surface topography on in-situ stress can be ignored. In an investigation from Kang et al. (2019), through collecting and analyzing the in-situ stress fields of a total of 1357 coal mines, it founds that the in-situ stress fields of China’s coal mine have the following characteristics: (1) buried depth (mining depth) is a main controlling factor of in-situ stress field, with the increase of mining depth, both the magnitudes of the vertical stress, the maximum and minimum principal horizontal stresses are positively correlated with the depth; (2) stress fields often present as reverse-faulting stress regime (\( \sigma_H > \sigma_h > \sigma_v \)) in shallow underground mining (depth<300m) and present as normal faulting stress regime (\( \sigma_v > \sigma_H > \sigma_h \)) when mining depth is greater than 1000m, and between the shallow and deep mining, stress field generally presents as strike-slip faulting stress regime (\( \sigma_H > \sigma_v > \sigma_h \)).

Assuming \( R_1 = \sigma'_1/\sigma'_2, R_2 = \sigma'_2/\sigma'_3 \) are the stress ratios between the three principal stresses, equation (4) can be reorganized as follows:

\[
T_s = \frac{((R_1R_2-R_2)^2L^2m^2+(R_2-1)^2m^2n^2+(1-R_1R_2)^2L^2n^2)^{1/2}}{L^2R_1R_2+m^2R_2+n^2} \quad (11)
\]
As can be seen from the above equation, fault slip-tendency is related to the ratios rather than the magnitude of the three principal stresses, this indicates the reason for the change of fault slip tendency at different mining depths is because the change of stress ratios rather than the change of stress magnitude.

Figure 2. Representation of the slip-tendency stereoplots under three different stress regimes. A. Slip-tendency stereoplots of the normal faulting stress regime; B. Slip-tendency stereoplots of the strike-slip faulting stress regime; C. Slip-tendency stereoplots of the reverse faulting stress regime.

As can be seen from the above equation, fault slip-tendency is related to the ratios rather than the magnitude of the three principal stresses, this indicates the reason for the change of fault slip tendency at different mining depths is because the change of stress ratios rather than the change of stress magnitude.
To explain how stress regime’s role in affecting fault stability, particular slip-tendency stereplots of three different stress regimes are provided in Figure 2. As can be seen from the figure, slip-tendency stereplot has two symmetrical peak domains about $r_h$ under normal faulting stress regime and has two symmetrical peak domains about $\sigma_H$ under reverse faulting regime, under strike-slip faulting stress regime, slip-tendency stereplot has four centro-symmetric peak domains about $r_h$ and $\sigma_H$.

On the basis of the above analysis, what can be summarized here is that if there is a change in the stress ratio or stress regime at different mining depths, then even for a same fault, its stabilities are different at these mining depths.

### 4.3. Pore fluid pressure

Under natural conditions, pore fluid pressure of fault is controlled by factors such as buried depth, fault type, fault sealing capability, so in general pore fluid pressure shows various distribution characteristics at different mining depths, mining areas and geological settings. During mining, mining-induced stress redistribution is another way in affecting pore fluid pressure as it changes the permeability of fault and thus resulting in the release or accumulation of fluids in the fault zone. Lots of previous studies have proved that raising pore fluid pressure in faults decreases their strength and then cause brittle failure (Handin et al. 1963; Blanpied et al. 1992).

According to the Mohr–Coulomb failure criterion (Jaeger and Cook 2007):

$$\tau_f = \mu \sigma_{ef} + c$$

Without considering fault cohesion ($c$), the friction resistance ($\tau_f$) of fault plane is positively related to the effective normal stress ($\sigma_{ef}$) acting on the plane, a plane with a higher effective normal stress has greater friction resistance to sliding induced by
the shear stress, this explains why increasing pore fluid pressure may reduce fault stability, because it decreases the $\sigma_{ef}$ and then leads to the reduce of fault plane’s resistance to the shear stress. Figure 3 shows the influences of raising pore fluid pressure on fault stability by using the 3-D Mohr diagram, as can be seen from the figure, raising fluid pressure causes the decrease of effective normal stress and makes the Mohr circle approach to the fault failure envelope. Figure 4 provides a specific example of slip tendency stereoplots corresponding to the given stress field $\sigma_v = 25\text{MPa}, \sigma_H = 50\text{MPa}, \sigma_h = 10\text{MPa}$ ($\sigma_v, \sigma_H, \sigma_h$ as down, East, North) with the raising of pore fluid pressure (A. $p_f = 0\text{MPa}$; B. $p_f = 3\text{MPa}$ C. $p_f = 5\text{MPa}$).

Figure 4. Representation of slip tendency stereoplots under the given stress field $\sigma_v = 25\text{MPa}, \sigma_H = 50\text{MPa}, \sigma_h = 10\text{MPa}$ ($\sigma_v, \sigma_H, \sigma_h$ as down, East, North) with the raising of pore fluid pressure (A. $p_f = 0\text{MPa}$; B. $p_f = 3\text{MPa}$ C. $p_f = 5\text{MPa}$).
25 MPa, $\sigma_H = 50$ MPa, $\sigma_h = 10$ MPa ($\sigma_v$, $\sigma_H$, $\sigma_h$ as down, East, North) under the condition of raising pore fluid pressures ($p_f = 0$ MPa, $p_f = 3$ MPa, $p_f = 5$ MPa). As shown in the figure, with the increase of pore fluid pressure, domains of high slip tendency ($T_s > 0.5$) in the slip-tendency stereoplot gradually increase, which indicates that the increase in pore fluid pressure can transform faults that were originally low-slip tendency into high-slip tendency faults.

From the above analysis, it can be concluded that during mining, the increase in fault gas pressure or water pressure caused by the mining-induced fault permeability change may further reduce the fault stability and increase the possibility of fault-related mine disasters.

5. A case study at Shilin coal mine

5.1. Engineering background

Shilin coal mine is located at the southeast of Fenxi synclinore basin in southwest Shanxi Province of north China, it is a coalfield belonging to the Huozhou mine area and about 5 km to Huozhou city, the geographical location of the coalfield is $111^\circ41'–111^\circ44'E$ and $36^\circ37'–36^\circ39'N$. The designed production capacity of the mine is 21,0000 tons per year, the No. 2 coal seam (seam thickness range is 0.65–3.56 m and buried depth range is 154–450 m) and No. 10 coal seam (seam thickness range is 1.33–2.95 m and buried depth range is 261–523 m) are two of the main coal seams to be mined.

In the coalfield, there are mainly 15 faults that have great influences on the mining of the No. 2 and No. 10 coal seams, most of them are N–E striking and striking directions are in the range of NE $20^\circ–67^\circ$, the largest fault is the Shilin fault oriented in E–W striking. Throws of the 15 faults range from 5 to 50 m, more detailed information of each fault in the coalfield is shown in Table 1.

A water-bearing Ordovician-limestone aquifer (depth in the range of 485–534 m), which is the main source of possible fault-reactivation-related mine water inrush in the process of coal mining, is located under the No. 2 and No. 10 coal seams. Water yield property of the aquifer was tested with a borehole pumping test, the testing results showed that the specific yield of the aquifer is 2.25–8.53 L/s and the aquifer pressure is 0–2.52 MPa. Through multiple hydrological boreholes distributed in the

| Fault name | Fault type | Strike direction | Dip angle | $T_s$ at depth of 369 m | $T_s$ at depth of 514 m |
|------------|------------|------------------|-----------|------------------------|------------------------|
| Shilin fault | Normal | Close EW | $75^\circ$ | 0.25 | 0.28 |
| F45 | Normal | NE30$^\circ$ | $70^\circ$ | 0.13 | 0.32 |
| F55 | Normal | NE45$^\circ$ | $64^\circ$ | 0.13 | 0.37 |
| F62 | Normal | NE55$^\circ$ | $79^\circ$ | 0.11 | 0.27 |
| F66 | Normal | NE67$^\circ$ | $62^\circ$ | 0.19 | 0.38 |
| F74 | Normal | NE45$^\circ$ | $70^\circ$ | 0.10 | 0.32 |
| F71 | Normal | NE20$^\circ$ | $70^\circ$ | 0.17 | 0.33 |
| F72 | Normal | NE35$^\circ$ | $67^\circ–75^\circ$ | 0.09 | 0.26 |
| F76 | Normal | NE35$^\circ$ | $65^\circ$ | 0.13 | 0.36 |
| F73 | Normal | NE25 | $65^\circ$ | 0.16 | 0.37 |
| F70 | Normal | NE20$^\circ$ | $75^\circ$ | 0.16 | 0.27 |
| F74 | Normal | NE20$^\circ$ | $72^\circ$ | 0.16 | 0.31 |
| F72 | Normal | NE20$^\circ$ | $55^\circ–80^\circ$ | 0.15 | 0.19 |
whole mining area, pumping tests were conducted on a number of major faults, the testing results showed that the water yield of these major faults are <0.1 L/(s.m).

5.2. Pre-evaluation of fault stability

Considering the threat of the Ordovician-limestone aquifer to the mining of No. 2 and No. 10 coal seams, pre-mining evaluation of the stability of each related fault is very necessary, which can help us to assess the potential of fault-related water inrush caused by mining-induced fault reactivation during mining.

Before mining the No. 2 coal seam, an in-situ stress test was carried out in a roadway at the depth of 369 m, the tested results of the in-situ stress field were \( \sigma_v = 9.8 \text{ MPa} \), \( \sigma_H = 12.9 \text{ MPa} \), \( \sigma_h = 8.7 \text{ MPa} \), belonging to the strike-slip faulting stress regime and the direction of \( \sigma_H \) was SE136°. Similarly, an in-situ stress test was conducted in a roadway at the depth of 514 m before mining the No. 10 coal seam, the three principal stresses were \( \sigma_v = 26.2 \text{ MPa} \), \( \sigma_H = 13.6 \text{ MPa} \), \( \sigma_h = 12.9 \text{ MPa} \), belonging to the normal faulting stress regime and the direction of \( \sigma_H \) was SE132°.
Assuming all faults in the coalfield as water-bearing faults and considering the maximum pressure of the aquifer as the possible fluid pressure for all faults, then we can quantitatively assess the stability of each fault by substituting the in-situ stresses and the possible fault fluid pressure into the formulae that we derived in section 3, equation (6) is applied for the mining depths of 369 m and equation (5) is applied for the mining depth of 514 m separately based on their stress regimes. The final assessing results are graphically presented in Figures 5 and 6. as can be seen from Figure 5, at the mining depth of 369 m (corresponding to the mining of No. 2 coal seam) slip-tendencies of all faults in the whole coalfield are less than 0.3, almost all faults have their slip-tendencies within the range of 0.1–0.2 except that the Shilin fault has the maximum slip-tendency of 0.25, therefore under this mining depth faults have very low slip-tendencies and their stability can be evaluated as super-stable. As shown in Figure 6, at the mining depth of 514 m, although faults have higher slip tendencies compared with the mining depth of 369 m, the maximum slip-tendency does not exceed 0.5, all faults distributed in the whole coalfield have their slip-
tendencies range from 0.1 to 0.4, belonging to low slip-tendency, therefore at this mining depth the stability of faults also can be evaluated as stable.

In light of the above pre-evaluation results of the two mining depths, faults distributed in the Shilin coalfield all have a relatively high stability, we can preliminarily predict that the possibility of fault-related water inrush caused by the Ordovician-limestone aquifer during the mining of No. 2 and No. 10 coal seams is relatively low.

6. Conclusion

In this work, we introduced a geomechanical technique to the assessment of pre-mining fault stability by extending the original Morris’s slip tendency theory, relationships between the fault orientation, in-situ stress, pore fluid pressure and fault stability were analyzed in detail with the proposed technique, according to our research in this work, the following conclusions can be drawn:

1. Under a given in-situ stress field, fault stability has a direct relation with fault orientation, a well-oriented fault has a higher slip tendency and is less resistant to mining disturbances and more likely to be reactivated to cause mine disasters,
2. Under different mining depths, the differences in stress regimes produce an effect on fault stability, slip-tendency stereoplots of different stress regimes have distinct characteristics, a same fault may have different stabilities with the variation of stress regimes.
3. Changing in pore fluid pressure also pose an effect on fault stability, increasing pore fluid pressure may transform a low slip-tendency fault into a high-slip tendency fault.

In addition, to show how to apply the proposed framework to real mining engineering practice, we conducted a case study based on the engineering background of the Shilin coal mine, our pre-evaluation results indicated that faults within the Shilin coalfield are quite stable at the two main mining depths.

Here we need to emphasize that the framework proposed in this study is mainly suitable for pre-evaluating the stability of faults in the pre-mining phase. If we want to evaluate the stability of faults during mining, influences of mining-induced stress redistribution need to be considered.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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