Supporting Reinforcement and Stability Analysis of the Roadway Crossing the Fault in Deep Mining

Limei Tian*
Institute of Architectural Civil Engineering, Langfang Teachers University, Langfang 065000, China
*Corresponding author (E-mail: 305663189@qq.com)

Bingqian Yan
School of Civil and Resource Engineering, University of Science and Technology Beijing, 100083, China

Jinghua Zhang
China Petroleum Pipeline Engineering Corporation, Langfang 065000, China

Abstract
There is a F3 large fault with inclination close to 90° in the Xiling mining area of Sanshandao gold mine, and the entire middle roadway driving through the F3 fault. The surrounding rock is broken, so the stability of the surrounding rock is very poor in the process of roadway crossing, and the problems of collapse and large deformation appear. In order to ensure the safety of mining and construction, it is very important to put forward the support design scheme of advanced support bolt, U-shaped steel frame and shotcrete in order to ensure the stability of the surrounding rock based on the joint fissure statistics, the quality of the surrounding rock and the stress environment test. Through the numerical modeling, the stress, displacement and the distribution of the plastic damage zone of the roadway surrounding are analyzed during the tunneling process. The results show that the support system can effectively control the deformation and damage of roadway surrounding rock during the roadway crossing fault, and has good support function to the roadway surrounding rock in the surrounding area. It can guarantee the safety of personnel and equipment in the process of roadway excavation and post-mining and transportation.

Key words: Surrounding Rock Stability, Numerical Simulation, Support Design

1. INTRODUCTION
With the increase in mining depth, the geomechanics environment of a mine is complex and is greatly different from the shallow one (Chen, et al., 2016), which makes the stability of roadway surrounding rock become a prominent issue for safe mining (Russo-Bello and Murphy, 2000; Yan, et al., 2012). The deep surrounding rock is affected by high gravity stress and residual tectonic stress, it is in high stress state as a result and even has reached the strength of surrounding rock (Hao, et al., 2016). The excavation and effective support of roadway are facing severe challenges under such a high stress state. In addition, a fault and its fracture zone are the common geological phenomena during the excavation of the roadway, and its distribution section is one of the unstable sections of the surrounding rock. In most cases, the fault zone is a weak zone with low strength, deformability, high water permeability and poor water resistance, and the physical and mechanical properties of the rock mass on both sides of the fault are significantly different (Liu, et al., 2010). A roadway crosses the fault zone where the geological conditions are complex and abrupt (Islam and Shinjo, 2009), the surrounding rock has asymmetric large deformation and failure under the influence of high stress, fault and fracture cutting, which makes the deep roadway support problem more serious (Wang, et al., 2000; He, et al., 2011).

There are many researches on deformation and failure of surrounding rock affected by fault. The results of physical simulation and numerical simulation show that the deformation of the surrounding rock is increased obviously and the shear deformation along the weak surface is obvious due to the weak surface (Jeon, et al., 2004). The normal stress on the free surface of the roadway should be restored to the maximum extent in the shortest possible time after the excavation of roadway that through the fault, the bolt and anchor cable also should be installed timely and apply proper prestress to improve the deteriorated stress state of near-surface surrounding rock caused by roadway excavation, and improve the non-intrinsic strength and deformation modulus of the surrounding rock (Liu, et al., 2010). Asymmetric damage occurred at the key parts of the roof and the bottom corner of the two sides of the roadway that through fault under symmetrical supporting conditions, a coupling support control strategy of grouting + asymmetric anchor net + bottom corner bolt was...
put forward to control the stability of the deep soft rock roadway (Hao, et al., 2016). The increase of fault rock mass is not significant with the increase of fault development degree when the degree of fault development reaches a certain threshold, which should be fully considered in support design (Liao, et al., 2005).

The numerical simulation method was used to analyze the engineering mechanics, and to study the effect of crossing across faults on the failure of surrounding rock and guide the reliable design and reasonable construction of the site. The roadway excavation project that through F3 fault in -690 levels in Sanshandao gold mine was selected to provide the guidance for the follow-up actual project in the paper.

2. ENGINEERING SURVEY AND GEOLOGICAL CONDITIONS

The F3 fault is a difficult fault encountered in the process of mine shaft construction, which runs through the directly under mining area of Sanshandao gold mine. The average width of the fracture belt is about 10 to 25m, and the groundwater reserves are very rich. The long-term immersion of the groundwater into the fractured zone degrades the physical and mechanical properties of the rock and fault gouges in the belt, which further reduces the mechanical properties of the crushed rock and threatens the safe construction of the mine development project. Due to the F3 fault is large scale and still extends in the deep area of the mine, the future excavation works of the deep middle haulage way will inevitably be affected by the F3 fault. Therefore, the issue that chronic focused on is how to formulate the design, construction and support scheme scientifically and so that the roadway development process can safely pass the F3 fault area and can long-term stability for the mine production service. High in-stress condition in deep (Xie, et al., 2015; Cao, et al., 2016) will increase the difficulty of the design and construction. In this context, numerical simulation software was used to simulate the whole process of excavating the F3 fault area under the support scheme of -690 horizontal middle roadway and the displacement field and plastic failure zone around the roadway were studied to provide the scientific basis for the design and construction in the future.

In the field survey, the fractures of the surrounding rock of -690 horizontal section were investigated. The statistics mainly include the occurrence of joints, the number of joints, spacing, filling materials and groundwater, etc., the statistical results are presented in Table 1.

<table>
<thead>
<tr>
<th>Table 1. -690m Joint statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical length</td>
</tr>
<tr>
<td>115.5m</td>
</tr>
</tbody>
</table>

-690 mid-section of the main advantage of the joint plane was divided into three groups, the dip direction and dip are presented in Table 2.

<table>
<thead>
<tr>
<th>Table 2. -690m Joint formation of different tendencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>First</td>
</tr>
<tr>
<td>Second</td>
</tr>
<tr>
<td>Third</td>
</tr>
</tbody>
</table>

The three groups of joints account for 63.5% of the total number of the footwall joints. Dip is mostly distributed in 50°~70°, and the dominant orientation in accordance with the strike can be divided into 15°, 60°, 330°. Rose diagram of joint fracture occurrence was presented in Figure 1.

The strike of F3 fault is NW, with the dip approaching 90°. The broken rock in fault zone is mainly composed of gravel, debris, kaolin, sand and gravel and clay, the long-term immersion of groundwater makes it in water saturation state, resulting in reduced friction between particles of filler material. And debris flow disaster will be prone to occur when the roadway is excavated to F3 fault.

The lithology of F3 fault area in -690 level is dominated by monzonitic granites, sericite granites, and serpentinitic cataclasites. In the vicinity of F3 fault, the tectonic fissure is relatively developed due to the tectonic effect, the fracture frequency is generally lower than 4, and the RQD value is generally more than 75%. The roof rock away from the F3 fault is intact, the fracture is not developed, and the RQD is generally greater than 75%. The floor rock away from the main fracture is also intact, the fracture is not developed, the RQD value is generally greater than 90%, the hardness of the rock is large, and the rock quality is good or excellent. The rock mass is intact or complete, which belongs to the whole structure and the engineering geological conditions are good.
3. SUPPORT DESIGN AND CONSTRUCTION PROGRAM

Corresponding support measures must be taken when the roadway crosses the fault. According to the geological data, F3 fault extends to -690 level, the roadway in -690 level is going through the fault, so the roadway needs to be supported. Pipe roof ahead of the pre-support program was adopted to support the roadway based on the comparison of experience of the past and the actual project(Yang, et al., 2004; Hebblewhite and Lu , 2004; Cai, et al., 2007; Ren, et al., 2014; Wang, et al., 2016). The previous construction situation shows that geological hazards will occur during the construction process, such as gushing water and the roadway roof and two sidewalls instability. In view of the difficulty of the roadway’s construction, which only can be carried out under the conditions of security protection measures and advanced construction techniques. In addition, the construction works must be closely linked to ensure that roadway excavation, U-shaped steel support and shotcrete support and other operations are completed in the shortest time(Xu, et al., 2016). Specific process of the construction technology is divided into the following stages(Liu, et al., 2011).

(1) It is necessary to check the quality of the U-shaped steels and whether the parts of U-shaped steels are neat and so on before the excavation, and then apply it to the steel structure support.

(2) The underground chamber is assembled by construction bracket during the excavation process, and the U-shaped steels are installed in the vehicle on the surface at the same time, and they are ready to be transported underground.

(3) The supporting work will be carried out after the completion of the underground chamber is assembled by construction bracket. Specific steps are that the connected brackets are transported to the support area by the scraper (the number of steel stents is determined by site), and then the steel support is secured immediately. Next, the roadway’s sides and vault are densely filled with pitwo and waste rock after the installation of steel mesh and straw mat, and the support operation is completed.

(4) Concrete masonry support is carried out rapidly after the steel support is completed, and then the vault gap filled with cement mortar by shotcrete machine, and the roadway’s sides are supported by sprayed concrete. Spraying concrete can be divided into two times in the arch section, spraying 3 to 5cm thickness to close the rock first, and then laying bolt, the second shot of concrete is carried out after the support of the arch until the design thickness is reached. If there is rock face leaking water, concrete spraying operation is carried out after the water diversion, the construction process is from no water area to water area.

(5) The construction of pre-support bolt should begin to be done after the completion of the excavation and support operation of the chamber, Φ32 bolt is selected for pre-support, its circumferential spacing is 0.2m and length is 5m.

(6) the excavation work of the broken belt is carried out after the completion of the pre-supporting bolt. The construction sequence is that the small section crosses the broken belt first, then moving forward 2 to 5m according to the roadway design section after the technical analysis of the site. Finally, rib spalling, coping as well as supporting operations of the broken belt are carried out, the roadway section is 5.2×4.5m.

(7) The steps (1)-(6) are cycled until the roadway through the F3 fault area. In the construction process, the following key points need to be paid attention to: less disturbance, which is to reduce the frequency and intensity of the surrounding rock disturbance, and taking full-section blasting to control the dose. Fast
excavation that is to improve the efficiency of tunneling, completed within 24 hours. Fast support, that is, U-shaped steel support is completed immediately after the completion of the tunneling work and complete the support within 8 hours. Tightly closed, that is, concrete injection and grouting operations are completed immediately after the completion of the support work, reducing the exposure of the surrounding rock in the air time. The support design of the construction process was presented in Figure 2.

![Figure 2. -690m Support design in fault area](image)

**4. ANALYSIS OF STABILITY SIMULATION**

**4.1. Numerical Simulation Model**

The numerical model of the area near F3 fault in -690 level is established by using MIDAS and FLAC3D. The horizontal direction of the model is X axis, which is perpendicular to the strike of the roadway, the strike of the roadway is Y axis and the vertical direction is Z axis. The dimensions of the model on each axis are 50m, 50m and 60m respectively, which are divided into 21534 units, 39203 nodes(Fig.3).

![Figure 3. Numerical model](image)

The bottom of the model is fixed constraint boundary, the top of it is stress boundary, and the remaining boundary is one-way boundary. The maximum horizontal principal stress, the minimum horizontal principal stress and the vertical principal stress variation with depth as follows.

\[
\sigma_{h,\text{max}} = 1.433 + 0.043H \\
\sigma_{h,\text{min}} = 0.536 + 0.024H \\
\sigma_v = 0.838 + 0.027H
\]

Where \(\sigma_{h,\text{max}}, \sigma_{h,\text{min}}, \sigma_v\) are the maximum horizontal principal stress, minimum horizontal principal stress and vertical principal stress respectively, in MPa; \(H\) is the depth, in m.

Since the geological conditions of Sanshandao gold mine are abundant groundwater and the surrounding rock is in the high salinity and weakly acidic groundwater for a long time, the damage effect should be taken
into account. The parameters (Table 3) of the rock are selected from the existing geologic data and relevant literature.

### Table 3. Mechanical parameters of the rock mass

<table>
<thead>
<tr>
<th>Position</th>
<th>Density (kg/m³)</th>
<th>Bulk modulus (GPa)</th>
<th>Shear modulus (GPa)</th>
<th>Poisson ratio</th>
<th>Cohesion (MPa)</th>
<th>Friction angle (°)</th>
<th>Compression strength (MPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hanging side</td>
<td>2665</td>
<td>3.28</td>
<td>2.58</td>
<td>0.22</td>
<td>8.9</td>
<td>28.0</td>
<td>36.9</td>
<td>3.77</td>
</tr>
<tr>
<td>Footwall side</td>
<td>2595</td>
<td>5.33</td>
<td>3.18</td>
<td>0.26</td>
<td>33.6</td>
<td>33.0</td>
<td>46.0</td>
<td>5.16</td>
</tr>
<tr>
<td>F3 Fault</td>
<td>1707</td>
<td>0.521</td>
<td>0.313</td>
<td>0.31</td>
<td>0.0903</td>
<td>14.8</td>
<td>14.2</td>
<td>0.0154</td>
</tr>
</tbody>
</table>

### 4.2. Numerical Simulation Process

According to the geological data, the thickness of the fault is 15m, and the distance from the roof is 10m. Three times excavation of the model is selected, and the numerical simulation is carried out, at a distance of 5m from the fault, and over the fault 5m. The analysis process is as follows.

1. According to the actual geological report and the convenience of the study. The horizontal direction of the model is X axis. The Y axis is parallel to the roadway direction, and the Z axis is the vertical direction. The thickness of the fault is 15m, and the distance from roadway roof is 10m. The simulated roadway section is basket-handle arch, net width and height of the roadway is 4.5m, 3.2m respectively.

2. The depth of roadway is 780m, X axis is the horizontal direction of the model and is perpendicular to the strike of the roadway, Y axis is parallel to the strike of the roadway and the vertical direction is Z axis, and the dimension of model is 50m, 50m and 60m on each axis.

3. The model was established in MIDAS and meshed.

4. The elastic-plastic model and the Mohr-Coulomb strength criterion were selected.

5. The stability of the surrounding rock reaction in the development law of its displacement and stress.

Four monitoring points were set around the roadway, namely the midpoint of the roadway, the midpoint of the floor and the midpoint of the two sides.

### 4.2. Numerical Simulation Process

The excavation of roadway is simulated by the method of step excavation, the excavation was carried out once every 5m, and the excavation was 10 times.

1. Analysis of displacement fields in X and Z directions of different times of roadway excavations

The displacement of the roof and floor and the two sides of the excavated roadway are shown in Table 4. The displacement of the midpoint of roadway roof is not in the fault area is about 6.7mm, the displacement of the midpoint of two sides is largest but not exceed 8.7mm. The displacement increases after entering the fault area, however, due to the effect of advance cable support, log cushion, U-shaped steel and shotcrete, the roof and two sides of the roadway are effectively controlled. The maximum displacement in the fault area is at the time of the second excavation, but it does not exceed 2.3cm. In the same section of the fault area, the area with the largest displacement is the floor, and the maximum displacement of the floor in the F3 fault area is 7.3cm. The reason is that the release of stress can only be in the supporting relatively weak floor in the process of excavation, so it caused a large displacement of the floor. Therefore, the displacement of the floor should be paid more attention in the excavation of roadway, some appropriate supporting measures can be taken in the area which is easy to be destroyed and deformed, for example, and the closed loop can be added to enhance the integrity of the support system of the roadway.

### Table 4. Displacement during the roadway excavation

<table>
<thead>
<tr>
<th>Key points</th>
<th>Location</th>
<th>5m from the fault (mm)</th>
<th>The first excavation (mm)</th>
<th>The second excavation (mm)</th>
<th>The third excavation (mm)</th>
<th>Pass the fault 5m (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The midpoint of the roof (Z direction)</td>
<td>Z direction</td>
<td>6.666</td>
<td>10.04</td>
<td>11.12</td>
<td>10.49</td>
<td>6.653</td>
</tr>
<tr>
<td>The midpoint of the floor (Z direction)</td>
<td>Z direction</td>
<td>8.213</td>
<td>67.08</td>
<td>72.74</td>
<td>70.35</td>
<td>8.169</td>
</tr>
<tr>
<td>The midpoint of the left side (X direction)</td>
<td>X direction</td>
<td>8.678</td>
<td>19.65</td>
<td>23.32</td>
<td>19.08</td>
<td>8.561</td>
</tr>
<tr>
<td>The midpoint of the right side (X direction)</td>
<td>X direction</td>
<td>8.709</td>
<td>19.92</td>
<td>22.74</td>
<td>20.43</td>
<td>8.679</td>
</tr>
</tbody>
</table>

2. Analysis of plastic damage zone

The Z-displacement field of the surrounding rock of the roadway is shown in Fig.4. As can be seen, the
plastic failure zone of the roadway 5m away from the fault is obviously larger than that of the roadway over fault 5m, and the stability of the former is weaker. the former mainly occurs shear failure while the latter mainly occurs tensile failure. However, U-shaped steel and advanced cable are the main parts of supporting system, which can provide more reliable supporting effect when the rock mass around the roadway is damaged, and control the plastic damage zone of the roof and the two sides of the roadway in a reasonable range. In contrast to Fig.4 (c), (d), (e), the plastic deformation zone is mainly concentrated on the weak supporting floor. Due to the existence of fault at the top of the roadway, the redistribution of stress makes the deformation of the rock mass on both sides of the fault uneven in the excavation of the roadway, so that the rock mass between the fault and the contour line at the top of the roadway will be damaged. The roof and two sides of the roadway are mainly shear failure, but the tensile-shear failure is very pronounced in the weak supporting floor. Therefore, it is necessary to strengthen the monitoring of surrounding rock at the site, and attach importance to improving the influence of the shear failure of the floor.

(a) The plastic damage zone of the roadway from the fault 5m  
(b) The plastic failure zone of the roadway crossing the fault 5m

(c) The plastic deformation zone of the first excavation  
(d) Plastic deformation zone of the second excavation  
(e) The plastic deformation zone of the third excavation

Figure 4. Plastic damage zone around excavation roadway

5. CONCLUSIONS

According to the analysis of numerical simulation results of roadway development process, it can be concluded that the roadway adopts the support system composed of pre-support bolt, U-shaped steel and shotcrete, the advanced bolts embedded in the surrounding rock mass, with the surrounding rock together to form an approximate shell structure, bearing the force and deformation. The anchor will bear most of the load and play an important role in the surrounding rock support during the excavation of the roadway. The concrete will be sprayed immediately to enclose the exposed surface of the surrounding rock after the U-shaped steel frame is fixed, and the solidified concrete and the surrounding rock can form the whole arch supporting resistance. In addition, the cement mortar into the open rock cracks or joints to improve the strength of the surrounding rock, and make the U-shaped steel and the surrounding rock together, which has a relatively good support effect on the roadway near F3 fault area in -690 level, and can meet the safety of roadway construction in the pioneering project, as well as the basic requirements for roadway for the mine production and services. However, because the roadway in the high in-situ stress condition of the deep mine area and the hydrogeological condition is relatively more complex, and the simulation results show that the floor displacement of roadway is large, so it is necessary to pay attention to the possible floor heave of roadway and to strengthen the monitoring of surrounding rock deformation in the process of construction.

ACKNOWLEDGEMENTS

This work was supported by the State Key Research Development Program of China (Grant No. 2016YFC0600801 & No.2016YFC0600703), and the Fundamental Research Funds for the Central Universities (Grant No. FRF-BR-15-001C).
REFERENCES


