Stability and rockburst tendency analysis of fractured rock mass considering structural plane

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Abstract. The stability analysis of surrounding rock mass is an important prerequisite and basis for judging the technical factors of tunnel excavation. In this research, the geological disasters such as roof falling, and rockburst have occurred at the oredrive located in the north wing of -630m level an underground mine belonged to Shandong Gold Group. Combined with the joint fracture scanning, rock mechanics test and PFC2D numerical simulation, the prediction of rockburst tendency and rock mass classification were carried out in this area. Based on the rock mechanics parameters of the complete rock mass, the rock mass mechanics parameters and the original rock stress were estimated. Results show that: A. The surround rock in this area is grade III rock mass, and the quality of rock mass is poor while accompanied by wedge caving; B. There is a medium to strong potential to experience rockburst, however, due to the development of joints in the area, the rock mass cannot store a large amount of elastic strain energy, which reducing the possibility of rockbursts in this area; C. The failure of rockmass in this area is dominated by structural plane.

1. Introduction

The depth and intensity of mining activity in China are increasing annually resulted from the significant demand for mineral resources. The high in-situ stress, ground temperature and exceedingly excavation disturbance in deep mining have caused a series of engineering geological disasters such as large deformation of roadway, large range of surrounding rock instability and even rockburst, which not only leads to high roadway support cost, but also crucial affects the safety and efficiency of mining and operation [1-3]. Therefore, rapid stability analysis and evaluation of surrounding rock in deep roadways have shown their indispensable during the mining activity. Moreover, acquisition of structural plane information, strength calculation of rock mass, rock mass rating and prediction of rockburst tendency are paramount criteria for stability assessment, parameters selection of supporting system and stope geometry [4].

Scholars have done a multitude of research on stability analysis of fractured rock mass. Liu Jun et.al[5] determined the relationship between the dip of joint and the stability of deep-buried tunnel by numerical simulation. Literatures [6-7] utilize the structural plane information of rock mass as a correction parameter to evaluate the macroscopic rock mass quality of surrounding rock mass. While literatures [8-10] obtained the rockburst proneness index based on lithology through the geomechanical
test of intact rock. However, this index didn’t consider the influence of the structure in poor rock strata on the rockburst inoculation mechanism.

This research focuses on the surrounding rock failure of deep roadway in a mine affiliated to Shandong Gold Group. Though the field investigation of failure, joint fracture scanning, indoor rock mechanics experiment and PFC2D numerical simulation, the rock quality classification and rock burst tendency prediction are carried out. Combined with the actual experimental data, the Rocscience series software, which operating based on the actual experimental data, is used to estimate the mechanical parameters of rock mass to obtain the basic rock mechanical properties of the oredrive tunnel. On this basis, the Phase2D is used to analyze the failure characteristics of surround rock, determining the orientation and mechanical of failure rock mass. It provides theoretical parameters for the optimization of support system in deep roadway.

2. Project profile
The mining area locates in the southern section of Jiaojia fault zone. The total ore reserves is 9.19 million tons, while containing metal quantity of 29409kg, and the average grade is 3.20x10^{-6}. At present, the -630m level is the major production area in this underground mining site. The production capacity of primary design in this site is 2300t/d. Considering the thickness of orebody is 80m with 30° of dip angle, the upward horizontal layered tailings cemented filling mining method is mainly employed in this mining area. The in-situ investigation found out that relatively development joints in some deep roadways have resulted in the roof caving and sliding. On the contrary, rockburst has not occurred.

![Figure 1. Major failure modes happened at oredrive tunnel in mining area: (a) Spalling dominated by structural plane; (b) Roof caving; (c) Arching rupture resulted from stress release](image)

3. Scanning of rock mass structural plane

3.1. Principle of Sirovision Remote Sensing Photogrammetry System
In practical engineering, these small and large number of structural planes experience critical potential to result large-scale hazards. Therefore, it is indispensable to analyze the characteristics of joint development such as distribution law, surface characteristics and spatial combination form, and these will assist to explore the failure mechanism of fractured rock mass in roadway. The Sirovision Remote Sensing Photogrammetry system selected in this research consists of two parts: hardware and software. One is CAE stereo image acquisition instrument (Figure2 (a)), which consists of two 10 million pixels industrial cameras and a self-contained controllable intensity flash lamp, two replaceable rechargeable batteries, four laser emitters and a touchable screen. The Sirovision image processing system is able to synthesize the collected two-dimensional image into three-dimensional image (Figure2 (b)), and combine the positioning coordinates collected in the mine site to stitch the three-dimensional image, so as to realize the three-dimensional model reconstruction of the actual project in the mine site.
3.2. Structural plane information acquisition

In this study, five measuring points in the north wing of the -630m level in a mine affiliated to Shandong Gold Group are selected for structural plane scanning and ensure that each measuring point covers more than 8m roadway. The selection of points is shown in Figure 3. In order to authenticate the joint information on the generated 3D rock surface, it is necessary to coordinate the obtained 3D rock surface model. The development of joints and fissures in the region was obtained through the processing of the software, meanwhile the joint measurement results were grouped and counted. The joint Schmidt diagram and joint rose diagram were plotted, and the results are shown in Figure 4. According to its analysis result, the summarization of joint information as shown in Table 1.

As shown in Table 1, there are mainly three groups of dominant joints in this region, which are $302.7^\circ \angle 55.2^\circ$, $89.2^\circ \angle 80.3^\circ$, $32.2^\circ \angle 47.2^\circ$ respectively. Meanwhile the joint rose diagram shows that the arcs of the three groups of joints in the rock mass do not surround the center of the stereographic projection circle. At this time, there is a critical potential of wedge sliding in roof area of the roadway.

Figure 2. Sirovision remote sensing photogrammetric system: (a) CAE stereo image acquisition instrument; (b) 3D Photo Synthesis; (c) Field application.

Figure 3. Rock mass structural plane analysis of 1# measuring point in north wing of -630m level by Sirovision
Figure 4. Schmidt and rose diagram of oredrive in north wing of -630m level by Dips 6.0

Table 1. Structural plane information summary of oredrive in north wing of -630m level

| Location                      | No. | Major joint set | Dip direction of major joint set | Dip angle of major joint set | Jointing conditions                                                                 |
|-------------------------------|-----|-----------------|----------------------------------|------------------------------|--------------------------------------------------------------------------------------|
| Hanging wall of oredrive in   | 1   | 302.7           | 55.2                             | 16                           | The joints of rock mass are relatively developed, and the joints are mostly wavy or   |
| north wing of -630m level      | 2   | 89.2            | 80.3                             | 74                           | rough and irregular. There are fillings between some joints, and the structural plane is |
|                               | 3   | 32.2            | 47.2                             | 52                           | relatively wet                                                                       |

4. Obtaining mechanical parameters of rock mass

4.1. Rock quality classification

In engineering practice, in order to analyze and evaluate the stability of roadway surrounding rock in a wide range and provide strong technical assistant for subsequent production, the comprehensive evaluation is usually carried out based on the development of joint fissures in rock mass, the basic rock mechanics data of intact rock and the distribution of groundwater. The quality classification of rock mass is divided on this basis. However, when the roadway is located in the bad rock strata, a single evaluation standard cannot accurately reflect the stability of the roadway [11-12]. Therefore, it is necessary to conduct a multi-standard comprehensive evaluation of the roadway. At present, the rock mass classification system widely used in domestic and foreign projects is mainly divided into Q system, RMR classification and GSI respectively [13].

According to the Q system evaluation criteria proposed by Barton et al. [14] and the conversion criteria between RMR classification, GSI classification and Q system, based on the uniaxial compressive rock mechanics experiment of intact rock samples and the analysis results of Sirovision remote sensing photogrammetry system, the classification results of the survey area are summarized in Table 2.
Table 2. Rock mass quality classification of hanging wall

| Location | Compressive strength of intact rock (MPa) | Tensile strength of intact rock (MPa) | Q Grade | Description | RMR Grade | Description | GSI Value |
|----------|------------------------------------------|--------------------------------------|--------|-------------|--------|-------------|---------|
| Hanging wall of oredrive in north wing of -630m level | 132 | 29 | III | Poor | III | General | 63 |

Figure 5. Whole process curve of rock uniaxial compression at -630m level

4.2. Estimation of rock mass mechanical parameters
Through the in-situ test of the rock mass, its mechanical properties in the engineering environment can be obtained, and it can reflect the real failure characteristics of the rock mass, which leads to a more reliable stability evaluation of the roadway. However, the cycle of in-situ test is generally long and the cost is high, which brings the inconvenient for a large-scale promotion [15]. After years of engineering applications, scholars have summed up a large number of empirical formulas used to estimate the mechanical parameters of the intact rock mass. Rocklab software is based on the Hoek-Brown strength criterion and the rock mechanics data of the intact rock to calculate the mechanical properties of the rock mass in the region [16-17]. It is employed to analyze the uniaxial compressive data and GSI values of intact rock samples at five measuring points in the north wing roadway of the -630m level to generate the mechanical parameters of rock mass in the region, which follows the generalized Hoek-Brown empirical strength criterion.

According to the previous investigation of rock mechanics, the average uniaxial compressive strength of intact rock mass in this region is 132 MPa, GSI is 63, disturbance strength D is 0, and empirical parameter m_i is 16. The following parameters are obtained by software simulation.

Table 3. Geomechanics parameters of rock mass at oredrive located in north wing of -630m level in mining area

| Density (t/m$^3$) | Compressive strength of rock mass (MPa) | Tensile strength of rock mass (MPa) | Poisson ratio | Elastic modulus (GPa) | Cohesive (MPa) | Friction angle ($^\circ$) |
|-------------------|----------------------------------------|-----------------------------------|---------------|----------------------|--------------|----------------------|
| 2.73              | 19.157                                 | 0.580                             | 0.261         | 12.80                | 10.515       | 38.45                |
5. Rockburst tendency analysis

5.1. Evaluation standard of single index rockburst tendency

In order to evaluate the potential risk of rock burst in roadway surrounding rock, a series of indoor rock mechanics experiments such as uniaxial compression, uniaxial loading and unloading, and Brazilian splitting are generally carried out on the intact rock in practical engineering to obtain the basic rock mechanics parameters, so as to further estimate the potential risk of rock burst based on the impact energy index WCF, deformation brittleness index Ku, elastic strain energy index Wet and linear elastic energy criterion We [6]. The impact energy evaluation criterion is to evaluate the rockburst tendency by comparing the elastic strain energy \( E_1 \) stored before the peak load and the energy \( E_2 \) consumed after the peak load until the complete failure process. The deformation brittleness index is determined by the ratio of the total deformation \( u \) of rock to the permanent deformation \( u_1 \) in the stress-strain curve before the peak load of rock. Elastic strain energy refers to the ratio of retained elastic strain energy \( \Phi_{sp} \) to plastic deformation energy consumption \( \Phi_{st} \). The linear elastic energy criterion takes the rock axial compressive strength \( \sigma_c \) and unloading tangent elastic modulus \( E_s \) as the evaluation criteria. The calculation formula and evaluation index of each index are shown in Table 4.

| Criterion                     | Formula                                      | Rank of rock burst |
|-------------------------------|----------------------------------------------|--------------------|
| Impact energy index \( W_{CF} \) | \( W_{CF} = \frac{E_1}{E_2} \)              | No rockburst       |
| Deformation brittleness index \( K_u \) | \( K_u = \frac{u}{u_1} \)                        | Minor rockburst    |
| Elastic strain energy index \( W_{et} \) | \( W_{et} = \frac{\Phi_{sp}}{\Phi_{st}} \)                  | Moderate rockburst |
| Linear elastic energy criterion \( W_e \) | \( W_e = \frac{\sigma_c^2}{2E_s} \)                  | Strong rockburst   |

5.2. Evaluation results of intact rock burst tendency

Referring to the above single index rock burst tendency evaluation standard, it is necessary to carry out a series of laboratory rock mechanics experiments, such as uniaxial compression, uniaxial loading and unloading, Brazilian splitting, so as to obtain the potential rock burst risk index of rock samples. In this study, several representative rock samples were taken from four roadways at the north wing in-630m level of a mine affiliated to Shandong Gold Group, and processed into cylindrical samples according to ISRM recommendation standard. The loading and unloading test was carried out by ZTR-276 rock triaxial testing machine. Through longitudinal strain control, the loading rate was 2x10^-6, and the axial compression reached 80% of the uniaxial compressive strength of the rock sample. According to the four single index rock burst risk evaluation indexes mentioned in the above section, the rock burst tendency of surrounding rock in this area is obtained as follows:

| Criteria                      | Impact energy index \( W_{CF} \) | Deformation brittleness index \( K_u \) | Elastic strain energy index \( W_{et} \) | Linear elastic energy criterion \( W_e \) |
|-------------------------------|----------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| Results                       | 4.87                             | 7.69                                   | 6.34                                   | 138.53                                 |
| Rockburst rank                | Moderate                         | Moderate                               | Strong                                 | Moderate                               |

Table 5. Prediction of rockburst tendency at north wing of -630m level
5.3. Prediction of rockburst tendency considering structural plane

Thermodynamics points out that the conversion of rock energy is the direct result from its destruction. According to the first law of thermodynamics, when the rock is assumed to be in a completely confined space, the internal energy conversion caused by the external force on the rock input energy can be defined as the following formula:

\[ U = U^e + U^d \]  

Where \( U \) is the total strain energy input by the external force, \( U^e \) is the elastic strain energy, and \( U^d \) is the dissipation energy generated by the micro-crack activity or friction in the rock.

The single index rock burst tendency prediction of intact rock samples only represents that the rock has the rock burst property. However, in practical engineering, due to the roadway locates in the poor stratum structure, the joints in surrounding rock are developed, and the rock mass has poor elastic strain energy storage capacity. Compared with the evaluation index, it is more difficult to cause rockburst damage. To verify this assumption, PFC2D discrete element analysis simulation software was used to carry out uniaxial loading tests on intact rock samples and fractured rock samples, whereas the stress, energy, and strain curves were tracked. The rock parameters measured and estimated by previous experiments are utilized for calibration. Determining three joints and their dip angles are based on the previous data investigated in the field. The rock is processing into 50x100 standard sample, and the modeling is shown in Figure 8.

Uniaxial compression tests were carried out on two rock samples respectively. The evolution trend of stress and energy of rock samples is shown in Figure 8. When the rock sample at the initial compaction stage, the primary cracks in the rock sample will be gradually compacted with the increasement of stress and boundary energy. Therefore, the dissipation energy at this stage is generally greater than the elastic strain energy accumulated in the rock sample. When it at the elastic deformation stage, the original crack
inside the rock sample has been compacted and no new crack has been formed. The rock sample is at the elastic deformation stage, so the input energy at this stage is gradually converted to the elastic strain energy stored inside the rock sample. Under continuous loading, the fractured rock samples gradually turn into plastic weakening stage, and the internal cracks begin to expand and further produce dissipation energy, resulting in plastic failure. With the increase of deformation, when the loading force reaches the peak value, the accumulated elastic strain energy of the rock sample is suddenly released, resulting in a large number of plastic failure. The complete rock sample converts most of the input energy into elastic strain energy during the loading process, which will cause severe plastic failure and even rock burst. The dissipation energy of fractured rock mass due to the expansion of primary cracks during plastic failure consumes part of the strain energy stored in the rock sample, so the risk of rock burst caused by sudden energy release is lower than that of intact rock mass.

According to the analysis of the above energy evolution path, the fractured rock mass has poor storage capacity of elastic strain energy compared with the intact rock mass. There are two essential conditions to form a rockburst hazard: the ability to store high strain energy, and a stress environment forming high stress concentration and high strain energy aggregation at the same time. For the prediction of rockburst tendency of rock mass in the field, it is necessary to combine the single index rockburst tendency evaluation of complete rock samples with the development of joints in the field, so as to obtain the rockburst risk prediction in line with the actual situation of the field.

![Figure 8. Model of intact and fractured samples](image)

![Figure 9. Energy curve of intact and fractured samples](image)
6. Conclusion

Through the joint fracture investigation, indoor rock mechanics experiment and energy simulation, rock quality classification and rock burst single index prediction at the −630m level in a mine of Shandong Gold Group, the following conclusions are demonstrated:

(1) According to the rock mass structural plane scanning and Q system, RMR classification and GSI rock mass evaluation system, it is concluded that the surrounding rock of the investigated area is grade III rock mass, the rock mass quality is poor to general, and the rock mass in the area is prone to wedge caving.

(2) The single-index rockburst tendency prediction of $W_{CF}$, $K_u$, $W_{et}$ and $W_e$ is carried out on the rock mass in this region. The results show that the rock mass in this region has moderate to strong rockburst risks. However, considering that the surrounding rock joints are relatively developed and have poor storage capacity of elastic strain energy, there is a low rockburst risk, which is consistent with the field situation.

(3) The failure mode of roadway surrounding rock mainly occurs in the form of wedge falling and surrounding rock cracking, and is dominated by rock mass structural plane, which provides a theoretical basis for the failure phenomenon of deep roadway surrounding rock in mines.

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