

Numerical Simulation Technique for Gateroad Stability Analysis under Fractured Ground Condition

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ABSTRACT

The ground stability of gateroads is a major concern in underground coal mines, especially where the surrounding strata are weak and fractured. This paper presents a novel numerical modelling technique for gateroad stability analysis based on a case study conducted in Zhaogu No.2 mine, China. Considering the occurrence of fractures and its weakening effect on the stiffness of rock mass, a tension-weakening model is implemented into FLAC3D, whereby the stiffness of rock mass is progressively decreased according to failure state. A relationship between the intensity of fractures and the residual properties is built. A parametric study of the tension-weakening model with respect to weakening parameter is carried out, and the results are compared to perfect elasto-plastic model and strain-softening model. The comparison shows that the tension-weakening model exhibits a noticeable effect on ground deformation and rock support loading, and can simulate more realistic behavior of a gateroad. The proposed model provides a rigorous approach for gateroad stability analysis and can be utilized for rock reinforcement design under similar geotechnical circumstances.

KEYWORDS: numerical simulation; ground stability; coal mine gateroad; tensile failure; fractures

1. INTRODUCTION

The stability of roadways is a long-standing issue in underground coal mines, especially for gateroads that serve and ensure the safety production for longwall panels. Ground stability and failure mechanisms of roadways vary depending on stress, geological and geotechnical conditions. However, as distinct from drifts and other roadways, the difficulties of maintaining gateroad stability are mainly due to weak surrounding rock mass and continuous geotechnical disturbance.

A large number of researchers analyzed gateroad stability with numerical modelling methods for the past few years. Among these studies, the most commonly used constitutive models are perfect elasto-plastic and strain-softening models using Mohr-Coulomb failure criterion (Shen, 2014; Zhang et al., 2015; Li et al., 2015).

Due to the sedimentary effect of coal-forming process, the surrounding rock mass of underground coal mines exhibit a geologically stratified structure. Under this geologic feature, tensile failure plays the dominate role when the surrounding rock is not subjected to high horizontal stress (Vaziri, 2001; Bakun-Mazor, 2009). This rock failure characteristic of underground coal mining activities is also demonstrated with field investigation (Hebblewhite and Lu, 2004) and numerical analysis (Shabanimashcool and Li, 2012). Since joints and

other fractures in rock can offer little or no resistance to tensile stresses, fractures will take place and develop in a brittle manner when rock mass is subjected to tensile stress. Previous studies (Cai et al., 2001; Mitri et al., 1995; Hoek et al., 2002) elaborate on the relation between the modulus of elasticity of rock mass and the occurrence of cracks and fractures, and corresponding formulas are proposed. In light of the previous studies examining the post-peak behavior of surrounding rock, it is therefore reasonable to take the variation of elastic modulus induced by tensile failure into consideration for stability analysis of openings in underground coal mines.

In the present study, tension-weakening model, which allows for the reduction in the stiffness of rock mass due to fracture generation, is developed with FISH (a programming language embedded within FLAC3D) and implemented into FLAC3D - a three dimensional explicit finite-difference program, in order to simulate the gateroad stability based on a case study in Zhaogu No.2 mine. In the numerical model, the failure state of rock mass is continuously monitored during analysis, and the properties are weakened according to different failure states to simulate the post-failure behavior. Numerical simulations with perfect elasto-plastic model, strain-softening model and tension-weakening model are conducted for comparison analysis to the field

measurement. In addition, a model parametrical study of the tension-weakening model is carried out to examine the effect of tension-weakening and provide basis for gateroad stability investigation and rock support design.

2. CASE STUDY

2.1 Geology and geotechnical overview of Zhaogu No.2 mine

Zhaogu No.2 mine is located in Xinxiang City, Henan Province, China. All panels in this mine are using retreat longwall method to extract coal seams. The coal seam is nearly horizontal with a mean thickness of 6.12m.

The target gateroad for this case study is the tailgate of panel 11050 at a depth of 600 m. The panel is approximately 180m wide along the dip and 2000 m long along the strike as illustrated in Fig. 1. The roof strata of this panel are mainly composed of mudstone, sandy mudstone and sandstone. The immediate roof is a layer of less than 2 m thick mudstone, which would cave and fall into the goaf, following the advance of coal extraction and shield support.

The tailgate of panel 11050 is 3.3 m high and 4.8 m wide. The gateroad is driven along the roof line of the thick coal seam, which leaves the ribs and immediate floor consisting of coal. Cable bolt support is employed as primary support, and wire mesh is utilized to prevent rock falling.

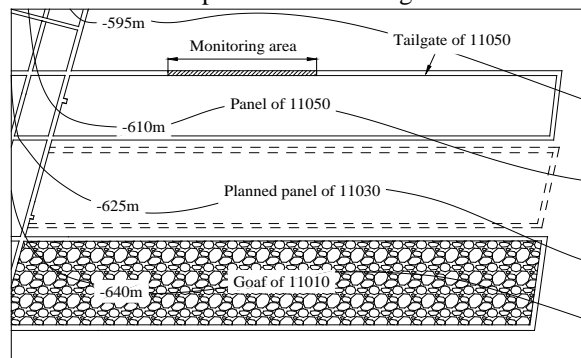


Figure 1: Plan view of local panel layout

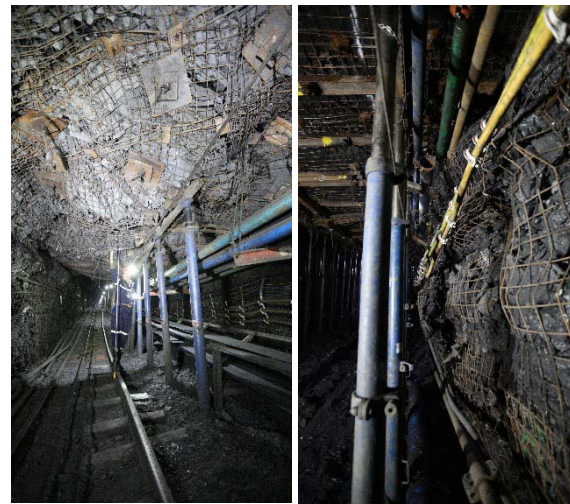
2.2 Field monitoring of ground stability

As can be seen from field, as shown in Figure 2, the surrounding rocks are severely fractured into small and loose fragments after the gateroad excavation has advanced, which also is accompanied by significant rib convergence.

3. NUMERICAL SIMULATION WITH TENSION-WEAKENING MODEL

3.1 Local model based on case study

The tailgate of panel 11050 is numerically modelled to investigate its ground stability using finite-difference software FLAC3D.



(a) (b)

Figure 2: Field observations of severely deformed and fractured area (a) Roof (b) Rib

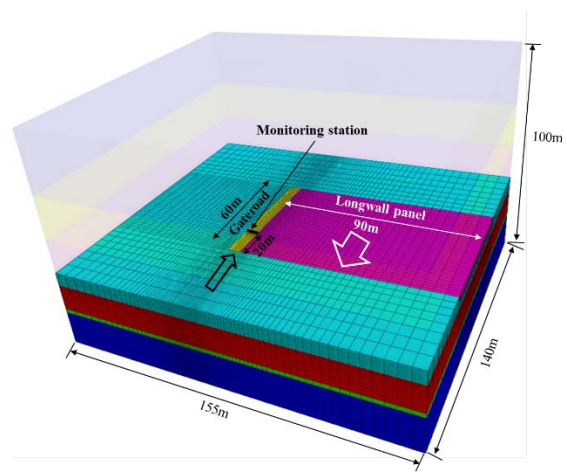


Figure 3: Isometric view of local model

Considering the symmetry of the panel with respect to its centerline, a 3D numerical model encompassing the tailgate of panel 11050 is generated, as shown in Figure 3. The dimensions of the model are 155 m wide, 140 m long and 100 m high, which are determined based on model sensitivity analysis with regard to size and mesh density. A vertical stress of 15 MPa is applied at the top model boundary to simulate overburden pressure. The horizontal-to-vertical stress ratio is set to 0.8 and 1.2 in the x- and y-directions, respectively (Yan et al.,

2013). No horizontal displacement is allowed at side boundaries, and no vertical displacement is allowed at the bottom boundary of the model. Rock mass properties for the numerical simulation, as listed in Table 1, are estimated from the intact rock properties and by using the generalized Hoek-Brown failure

criterion (Hoek et al., 2002). Values of softening parameters, ϵ_p and c_r are assumed according to the literature on strain-softening behavior in gateroad stability analysis using numerical simulation (Shen, 2014; Zhang et al., 2015; Li et al., 2015; Shabanimashcool and Li, 2012).

Table 1: Rock mass mechanical properties^a

Strata	Lithology	K (GPa)	G (GPa)	c (MPa)	ϕ (deg.)	c_r (MPa)	ϵ_p (%)
Roof	Sandstone	9.1	5.9	3.9	45	0.39	0.01
	Sandy mudstone	5.2	3.1	3.2	40	0.32	0.01
	Mudstone	2.4	1.1	2.1	35	0.21	0.01
Coal seam	Coal	1.3	0.6	1.4	31	0.14	0.01
Floor	Sandy mudstone	7.2	4.0	3.4	37	0.34	0.01
	Siltstone	9.6	6.5	4.2	47	0.42	0.01

^a K is bulk modulus, G is shear modulus, c is cohesion, ϕ is friction angle, c_r is residual cohesion, ϵ_p is plastic strain parameter at the residual strength

3.2 Model description of tension-weakening model

As indicated in Section 1, perfect elasto-plastic and strain-softening models are most widely utilized in numerical studies of ground stability of underground coal mines.

When perfect elasto-plastic behavior is assumed, the mechanical properties remain constant after the material yields and fails, which obviously is not in accordance with the true characteristic of most geological material (Cui et al., 2006). While, for the strain-softening model, the strength parameters are decreased with the increase in ϵ_p until reaching their residual values ultimately. However, for both of the constitutive models, elastic modulus remains constant, irrespective of the occurrence of failure.

The difficulty and feature of gateroad support lie with the ground stability that must be maintained not only during a gateroad driven period, but also when the panel is mined in retreat. According to the case study and numerical simulation, it is evident that the surrounding rocks are heavily fractured after the gateroad is driven. As the modulus of elasticity of rock mass is directly related to the occurrence of cracks and fractures (Cai et al., 2001; Mitri et al., 1995; Hoek et al., 2002), the variation of elastic modulus of the fractured area induced by tensile failure should be taken into consideration in order to simulate and analyze the gateroad stability properly, especially under mining influence. Otherwise, the stability analysis assuming constant elastic modulus may underestimate the ground deformation and fail to predict the stability condition.

For the purpose of simulating the variation of elastic modulus due to the tension-induced fractures, a novel numerical simulation technique, herein

referred to as tension-weakening model, is developed with FISH language and implemented into FLAC3D. The tension-weakening model is developed on the basis of the strain-softening model, whereby it overcomes the limitation of the conventional simulation techniques (Shen, 2014; Zhang et al., 2015; Li et al., 2015; Shabanimashcool and Li, 2012), that is, elastic modulus is kept constant regardless of rock mass failure and fracture propagation. Considering the observed brittle failure manner of the rock sample in laboratory experiments, both tension-weakening and strain-softening model employ an instantaneous decrease in strength parameters to the residual values and express the same post-peak behavior of rock. After the strength reduction, the parameters are kept at the residual values.

In order to take into account the variation of elastic modulus, a brittle tension-weakening parameter A is given as

$$E_r = A \cdot E_m \quad (1)$$

where E_r is the residual elastic modulus of rock mass after tensile failure takes place and E_m is the elastic modulus of rock mass estimated from experiment data. When tensile failure occurs, the elastic modulus decreases to the residual elastic modulus E_r in a brittle manner.

In order to characterize the post-peak behavior of fractured rock mass and estimate the residual elastic modulus, the Geological Strength Index (GSI) system is utilized to study the effect of different E_r on ground stability.

Although the GSI system developed by Hoek et al is generally used to determine the rock mass

deformability and strength on the basis of intact rock properties and geological structures, it is reasonable to assume that this index can be applicable to evaluating the intensity of fractures induced by tensile failure, such as blocky rock mass with tension-induced fractures shown in Fig. 4. In this study, GSI for rock mass with tension-induced fractures is defined as GSI_t . The implication is that GSI varies with the occurrence of tensile failure caused by the gateroad excavation.

For rock with $\sigma_c < 100$ MPa, the elastic modulus of rock mass E_m is estimated with GSI system from the following equation (Hoek et al., 2002):

$$E_r = \sqrt{\frac{\sigma_m}{100}} \cdot 10^{\left(\frac{GSI_t - 10}{40}\right)} \quad (2)$$

where σ_m is the uniaxial compressive strength of rock mass. Assuming $GSI_t = 90$ implies that no tensile failure occurs or no fractures and joints are induced by tensile failure, namely

$$E_m = \sqrt{\frac{\sigma_m}{100}} \cdot 10^{\left(\frac{90 - 10}{40}\right)} \quad (3)$$

By dividing Equation (2) by Equation (3), the weakening parameter A can be expressed as

$$A = \frac{E_r}{E_m} = 10^{\left(\frac{GSI_t - 90}{40}\right)} \quad (4)$$

In order to comprehensively investigate the weakening behavior after tensile failure, a parametrical study of the tension-weakening model is carried out with 4 different values of GSI_t (10, 30, 50, 70), and the obtained results are compared with those simulated with the perfect elasto-plastic and strain-softening models

4. RESULTS OF PAREMETRIC STUDY

Roof sag deformation is a major issue in ground control of gateroads. Failure or instability of the roof may cause not only economic loss, but more importantly also fatalities and injuries.

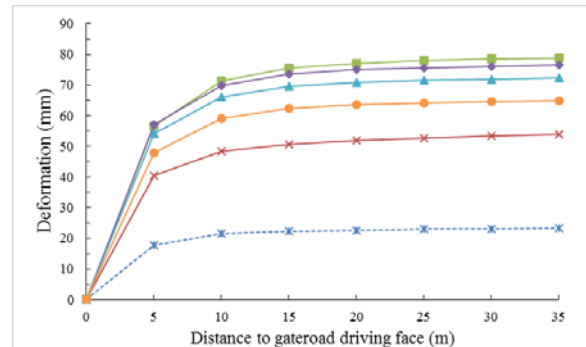
Figure 4 shows the evolution of roof sag for the different models during both the gateroad driven and retreat mining periods. As can be seen, for all the cases, large ground deformation takes place immediately after the gateroad is driven, and the increase rate of ground deformation becomes moderate or quite small after the distance between the monitoring station and the advancing driven face becomes greater than 15m. The surrounding rock begins to deform when the mining operation starts, however this increasing deformation is not noticeable until the mining face reaches a distance of 20 m from the monitoring station, and this effect is generally referred to as mining influence. As a result of the intensive mining influence ahead of mining face, the

gateroad undergoes significant ground destabilization and deformation.

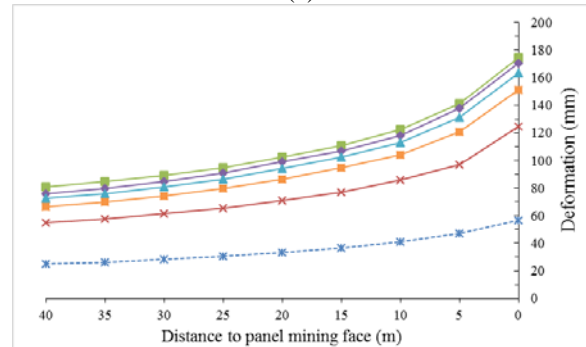
As shown in Figure 4, the ground deformation simulated with the strain-softening and tension-weakening models is remarkably larger than that simulated with the elastic-perfectly plastic model. This large difference is ascribed to the strength reduction and corresponding stress re-distribution during the post-peak behavior.

Also, the magnitude of deformation simulated with the tension-weakening model shows a negative correlation with GSI_t . This is due to the fact that high fracture intensity leads to low modulus of elasticity, ultimately resulting in severe deformation and instability. The maximum difference in deformation between the strain-softening and tension-weakening models during the gateroad driven period and the mining period is 25.1 mm and 49.7 mm for roof sag, 31.0 mm and 74.3 mm for floor heave, 51.9 mm and 99.8 mm for rib convergence. The large deformation induced by tension weakening is reasonable because, although the surrounding rocks almost stop deforming under the effect of ground self-stability and rock support, rocks that undergo tensile failure are weakened as a result of fractures development during the process of mining-induced stress readjustment, causing large deformation and instability.

---*--- Mohr-Coulomb ---x--- Strain-softening ---■--- GSIIt=10
 ---●--- GSIIt=30 ---▲--- GSIIt=50 ---○--- GSIIt=70



(a)



(b)

Figure 4: Evolution of roof sag (a) gateroad driven period;
(b) retreat mining period

5. CONCLUSION

A case study on gateroad stability at the Zhaogu No.2 coal mine in China is carried out. According to field observations and monitoring results, severe fractures and significant deformation severely destabilize the surrounding rock, which leads to potentially high risk to personnel safety.

Based on the geotechnical characteristics of the gateroad, a tension-weakening model allowing for the stiffening of rock mass due to tensile fracture generation is proposed and implemented into FLA3D to analyze the gateroad stability under severely fractured ground conditions. Taking into account the weakening effect of tensile fractures, a brittle tension-weakening parameter A is introduced to establish the relationship between the intensity of fractures induced by tensile failure and the residual property.

A model parametric study with respect to the weakening parameter is conducted, and the obtained results are compared to those simulated with the conventional elastic-perfectly plastic and strain-softening models. It is demonstrated that the effect of tension-weakening on the deformational behavior of the gateroad is significant during not only the gate road driven period but also the retreat mining period.

Considering the intensity of fractures induced by tensile failure and its weakening effect on rock mass, the tension-weakening model provides a rigorous simulation approach to studying the gateroad stability under fractured ground conditions. This model can be utilized for ground stability investigation, pillar design and rock reinforcement design (both primary and secondary support) under similar geotechnical circumstances.

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