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Numerical simulation study of the failure evolution process and failure mode of surrounding rock in deep soft rock roadways

Meng Qingbin [a,b,*], Han Lijun [a], Xiao Yu [a], Li Hao [a], Wen Shengyong [a], Zhang Jian [a]

[a] State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou 221116, China

[b] Shandong Provincial Key Laboratory of Depositional Mineralization & Sedimentary Minerals, Shangdong University of Science and Technology, Qingdao 266590, China

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ABSTRACT

Based on the safety coefficient method, which assigns rock failure criteria to calculate the rock mass unit, the safety coefficient contour of surrounding rock is plotted to judge the distribution form of the fractured zone in the roadway. This will provide the basis numerical simulation to calculate the surrounding rock fractured zone in a roadway. Using the single factor and multi-factor orthogonal test method, the evolution law of roadway surrounding rock displacements, plastic zone and stress distribution under different conditions is studied. It reveals the roadway surrounding rock burst evolution process, and obtains five kinds of failure modes in deep soft rock roadway. Using the fuzzy mathematics clustering analysis method, the deep soft surrounding rock failure model in Zhujixi mine can be classified and patterns recognized. Compared to the identification results and the results detected by geological radar of surrounding rock loose circle, the reliability of the results of the pattern recognition is verified and lays the foundations for the support design of deep soft rock roadways.

1. Introduction

With increasing mining depth, deep rock is in a complex mechanics environment of 'three high and one disturbance' [1–3], and the combination of factors determine the stability of the surrounding rock of deep soft rock roadways. The deep geological environment is complicated, so the destruction of the surrounding rock of a roadway shows a diversity of characteristics. The surrounding rock has different failure modes so support of the roadway should also be changed. Scientific and reasonable support design schemes and parameters would more effectively control the deformation of the surrounding rock and reduce support costs.

Engineering practice shows that the failure modes of the surrounding rock of tunnels or roadways in underground projects differ [4,5] under different engineering and geological conditions. Xiang et al. [6] set up a failure mode classification method for the surrounding rock in large-scale underground cavities. In this method, the large size, large aspect ratio and cavity interaction characteristics in large the cavern group are fully considered. Based on three levels: controlling factors, damage mechanism and occurrence conditions, 18 kinds of typical failure mode of the surrounding rock were summarized. Wu et al. [7] established the failure mode classification method for hard surrounding rock in deep tunnels. The failure phenomenon in deep hard rock tunnels can be divided into 3 categories and 9 kinds of typical failure mode. Using this system, the mechanism of various failure modes, forms, and control strategies were analyzed. Studying the stress field distribution which was formed by underground mining in Jinchuan, Gansu province, Zhao et al. [8] pointed out that the deformation and failure characteristics of the rock surrounding a roadway showed gradual changes at different stages and at different locations. It was shown that the deformation and failure mode characteristics of a roadway could be explained by the surrounding rock deformation characteristics. Based on a rock model which can describe multi-joint behavior, Cui et al. [9] used numerical simulation technology to study the effect of joint angle and lateral pressure coefficient on the failure mode of a tunnel in jointed rock. Using two kinds of typical geological materials, including sand, Fang et al. [10] carried out a model test, and systematically studied the failure mode of a tunnel in surrounding rock which is considered to be a continuum. Using the rock failure process analysis software RFPA^{2D}, Zhang et al. [11] analyzed the deformation and nonlinear gradual failure characteristics surrounding a round hole, as well as the stress variation in the key parts surrounding the roadway. Using RFPA^{2D}, Yuan et al. [12] studied the effect of unloading confining pressure on the failure mode of pillars. Based on the rock

* Corresponding author. Tel.: +86 13951468390.
E-mail address: mqb1985@126.com (Q. Meng).

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failure process analysis system, Zhao et al. [13] used numerical simulation to study the failure form in tunnels of different section. Citing test data from 30 cases, Zhu and Xu [14] analyzed the surrounding rock mass with clastic structure by the method of fuzzy clustering. Using the standard model, the failure mode of 8 test samples was predicted. Gao et al. [15] put forward a new kind of evolutionary neural network (ENN) model in which new structures and weights evolved at the same time. It was applied to the identification of the failure mode of surrounding rock.

In conclusion, experts and scholars at home and aboard have researched the failure mode of surrounding rock in underground engineering, with some useful conclusions being obtained. However, the related research into the rock burst evolution process and failure mode of the surrounding rock in deep soft rock roadways has not been studied. Based on the research of a deep soft rock roadway project in Zhujixi mine, Huainan, the failure modes of the surrounding rock of deep soft rock roadway are discussed, and the damage evolution process of deep soft rock roadway surrounding rock revealed. Finally, this paper provides a reference for the improvement in support technology in deep mines.

2. Numerical simulation of the damage evolution process and failure mode of surrounding rock in deep soft rock roadway under the condition of single factor effect

A FLAC 3D simulation was established, having length, width and height of 60 m, 50 m and 50 m respectively. The displacement of the model base is 0. According to the buried depth of the roadway, gravity stress was applied on the upper surface. On the basis of the lateral pressure coefficient, different horizontal stresses were applied. According to the rock testing results, numerical simulation parameters were taken, as shown in Table 1. Using the Mohr–Coulomb failure criteria, the deformation characteristics of the rock surrounding the roadway and the evolutionary regularity of the plastic zone under different conditions were revealed.

2.1. Results of numerical simulation under the conditions of different buried depth

(1) Evolution law of surrounding rock displacement

Eight depths of burial were used: h = 500 m, 600 m, 700 m, 800 m, 900 m, 1000 m, 1100 m and 1200 m, and the lateral pressure coefficient was taken as $\lambda = 0.8$. In the model of the roadway, a monitoring line was set up along the vertical direction in the center of the roadway roof, floor and sides, in order to monitor the displacement of the roadway roof, floor and two sides [16–19]. The roadway surrounding rock displacement curves under different burial depths are shown in Fig. 1 and the numerical values are given in Table 2.

Fig. 1 and Table 2 show that the amount of roof sag, floor heave and side extrusion have a linear relationship: $V_{roof} = 0.4564h - 106.7$ and $R^2 = 0.997$, $V_{floor} = 0.5943h - 164.93$ and $R^2 = 0.993$, $V_{sides} = 0.5768h - 200.97$ and $R^2 = 0.993$. With increasing burial depth, the amount of roof sag, floor heave and side extrusion also increase, but the deformation amplitude of the surrounding rock decreases. This demonstrates the following rule: "the increase in

Table 1
Physical and mechanical properties test results of bed plate roadway of track crossheading and haulage gate.

Roadway	Lithology	γ (g/cm^3)	σ_t (MPa)	σ_c (MPa)	E (GPa)	μ	c (MPa)	φ (°)
Bed plate roadway of track crossheading	Fine standstone	2.53	7.60	97.386	70.5	0.212	9.52	49.51
	Siltstone	2.62	5.77	66.622	59.7	0.252	5.67	45.36
	Mudstone	2.34	3.56	45.165	55.1	0.315	2.51	51.44
Bed plate roadway of haulage gate	Fine standstone	2.48	7.67	94.233	70.3	0.218	9.33	48.13
	Siltstone	2.60	5.85	66.850	57.2	0.254	5.42	46.09
	Mudstone	2.31	3.67	43.476	52.8	0.310	2.39	51.89

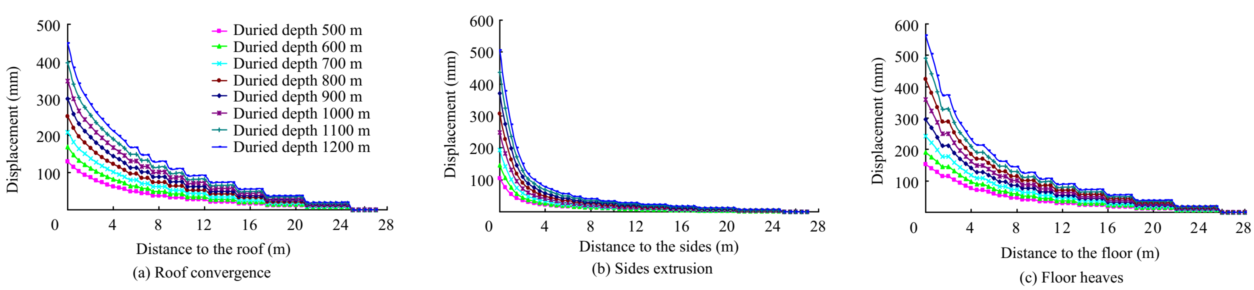

Fig. 1. Roadway surrounding rock displacement curves under different buried depths.

Table 2
Roadway surrounding rock displacement under different buried depths.

Buried depth (m)	Roof convergence and increment (mm)			Floor heaves and increment (mm)			Sides extrusion and increment (mm)		
	Convergence	Increment	Amplitude (%)	Floor heaves	Increment	Amplitude (%)	Extrusion	Increment	Amplitude (%)
500	130.3	0.0	0.00	152.1	0.0	0.00	105.6	0.0	0.00
600	168.6	38.3	22.72	192.0	39.9	20.78	146.1	40.5	27.72
700	208.3	39.7	19.06	242.0	50.0	20.66	193.9	47.8	24.65
800	251.5	43.2	17.18	297.1	55.1	18.55	247.7	53.8	21.72
900	298.7	47.2	15.80	358.6	61.5	17.15	307.8	60.1	19.53
1000	347.0	48.3	13.91	423.3	64.7	15.29	371.0	63.2	17.04
1100	395.6	48.6	12.29	491.9	68.6	13.95	436.7	65.7	15.05
1200	449.6	54.0	12.01	564.5	72.6	12.86	505.7	69.0	13.65