Numerical studies on surrounding rock deformation controlled by pressure relief groove in deep roadway

Chaoke Liu*, Jianxi Ren, Kun Zhang, Shaojie Chen

School of Civil Engineering and Architecture, Xi’an University of Science and Technology, Xi’an 71005, China

*Corresponding author e-mail: liuchaoke8@163.com

Abstract. After entering deep mining, the roadway is in a high stress state, the deformation of surrounding rock becomes larger, and the roadway floor is particularly significant under unsupported state, which brings great difficulty to the safe production and support of the coal mine. Pressure relief method can change the stress field of surrounding rocks so that the surrounding rock can be in stress-reducing area. The present paper studied the deformation law of the roadway and the changes in the stress state and plastic zone of the surrounding rocks around the roadway before and after the excavation of pressure relief groove on the bottom floor of the high-stress roadway by using FLAC under the engineering background of one mine in Binchang, analyzed the influence of different groove depths and widths on the floor heave, convergence on both sides and roof subsidence. The simulation results show that: after the roadway floor was grooved in the high stress roadway, a larger stress-relaxed area will be formed near the roadway floor, the stress will be transferred to the deep roadway floor, and the pressure relief groove plays a better control effect on the deformation of the high-stress roadway. With the increase of the width and depth of the pressure relief groove, the convergence of the top and bottom of the roadway will be decreased accordingly, but the effect is not significant, while its influence on the convergence on both sides is relatively significant. After applying the simulation results to the engineering practice, the practice shows that: the combined support of anchor rod, anchor rope plus pressure relief groove can control the deformation of the roadway well and the conclusion obtained can provide some reference values for the study and design of the grooving pressure relief control technology.

1. Introduction

With the rapid economic development, the demand for energy is increasing, which results in that the shallow coal becomes depleted gradually and the burial depth of the roadway depth becomes increased year by year, according to statistics, the mining depth of coal is progressively increased at an annual rate of 10-20 meters and the average mining depth of coal has reached 600 meters and those of partial coal mines have reached more than 1000 meters [1]. After entering the deep part, the deformation of the surrounding rock around roadway becomes remarkable, and the roof fall, rib spalling, floor heave and other phenomena often occur on the roadway support so that it needs frequent maintenance and reinforcement, the maintenance workload is heavy and the support is expensive, which brings serious
influence on the normal safe mining of the mine, thus the stability control of the surrounding rocks in deep roadway is the most important problem to be solved at present [2-5].

After long-term study by experts and scholars, a number of effective support methods have been put forward currently, in general, according to the different mechanisms, it can be divided into two categories: reinforcement method and pressure relief method [6-9]. Pressure relief method is to make the original continuous rock body in a discontinuous state with some artificial measures, change the stress state of the surrounding rock around the roadway and transfer the concentrated stress around the roadway to the deep part of the surrounding rock around the roadway so as to make the roadway floor rock formation in the stress reducing area, hereby ensuring the reliable state of the roadway floor, it is especially suitable for high-stress roadway. At present, in the underground engineering, the applied pressure relief method has joint-cutting, drilling, blasting, roadway digging pressure relief and other forms. With the application and promotion of the grooving machine in the mine engineering, the pressure relief groove construction problem has been solved, which lays the foundation for the promotion of the pressure relief method. The present paper studied the grooving pressure relief and deformation mechanism on the roadway floor, the influence of the changes in the pressure relief groove width and depth on the roadway deformation and plastic zone by using FLAC under the engineering background of one mine in Binchang, which provides the basis for the scheme engineering design and a certain reference value for the study and design of the grooving pressure relief.

2. Engineering Overview

There are three main haulage roadway between the auxiliary shaft and the panel, they are no.1 auxiliary transport roadway, no.2 auxiliary transport roadway and the belt transport roadway. The roadway lies in the east-west direction, the average length is 2300 meters, the average burial depth is 760 meters and the slope is 3.5 degrees. The actual measurement distance from the nearby coal worked-out section to the belt transport roadway is 130 meters and the working face width is 100 meters. According to the geological survey data, the transport roadway passes through the complex rock, mainly including mudstone, siltstone, fine sandstone, coal seam and argillaceous sandstone.

The cross section of the belt transport roadway is a straight wall semicircle arch with a roadway width of 5640mm and a roadway height of 4720mm (straight wall:1900mm,arch height:2820mm),the thickness of concrete floor is 300mm and the spaying layer thickness is 120mm.The roadway support method is bolting and concreting with wire mesh, roof and side anchor bolt diameter is 20mm,its length is 2700mm,inter-row spacing is 800mm.Anchor cable diameter is 17.8mm,its length is 7300mm,spacing is 1600mm,row spacing is 2400mm;the weld reinforcing mesh is manufactured using 6mm diameter Q235 steel wire rod, grid size is 150mm.

The floor heave occurred in the belt transport roadway two months after the completion of the roadway support, the maximum floor heave amount reached 300mm, the phenomena of rib spalling and partial roof fall occur, which severely impact on the coal mine safety and roadway stability.

3. Numerical Simulations

3.1. Computational modelling

In accordance with the Saint-Venant’s principle, influence range is generally from 3 to 5 times of the hole scope after excavation.in order to ensure the calculation accuracy, the model selection range is larger than 5 times of the hole size. The working surface width of the nearby coal mine is 200m and the overlying rock formation within a range of 100m only on one side near the coal pillar in the nearby coal mined-out area influences the deformation of the roadway, thus, only 100 meters is taken from the nearby coal mine working surface. The calculating principle of unit division is to take the unit number as small as possible without affecting the accuracy of the calculation result, which is convenient to improve the efficiency of numerical simulation calculation. In the modeling process, in order to simplify the calculation, the secondary rock formation in minor thickness is ignored and the
fine sandstone, siltstone, mudstone, coal and argillaceous sandstone in the model are in different colors respectively, as shown in Figure 1.

3.2. Boundary condition

![Established model for the FLAC](image)

**Figure 1.** Established model for the FLAC

Fix the left and right displacement and the front and back displacement of the model in horizontal direct and fix the model bottom horizontal and vertical displacement, the upper boundary is the free boundary, in order to reduce the number of units and save the calculation time, the external load of 17MPa is applied on the upper part of the model to simulate the self-weight of the overlying rock formation.

3.3. Constitutive model selection

The Mohr-Coulomb yield criterion is used to determine the failure mode of the rock mass in the numerical simulation of rock mechanics elastic-plastic problem, as shown in formula1, after the load reaches the ultimate strength limit, the rock mass is destroyed, and the residual strength of the rock mass is decreased gradually with the development of deformation in the process of plastic flow after peak [10-14].

\[
f_s = \sigma_1 - \sigma_3 \left( \frac{1 + \sin \phi}{1 - \sin \phi} \right) - 2c \left( \frac{1 + \sin \phi}{1 - \sin \phi} \right)^{1/2}
\]

Where \( \sigma_1, \sigma_3 \) is the maximum and minimum principal stress, \( c, \phi \) is the adhesive force and friction angle respectively, when \( f_s \) is greater than zero, the material will be sheared failure, under normal stress state, the tensile strength of the rock mass is very low, thus, whether the tension failure is produced can be judged according to the tensile strength criterion.

3.4. Determination of calculation parameters

The values are taken for the physical and mechanical parameters of each rock formation in accordance with indoor rock test results, and the specific values are shown in Table 1.

| Rock type     | Shear modulus (GPa) | Cohesion (MPa) | Tensile strength (MPa) | Internal friction angle (degree) | Density (kg/m³) |
|---------------|---------------------|----------------|------------------------|----------------------------------|-----------------|
| Fine grain Sandstone   | 5.08               | 10.1           | 9.6                    | 40.7                             | 2700            |
| Siltstone      | 5.82               | 7.9            | 2.4                    | 39.7                             | 2500            |
| Mudstone       | 1.3                | 0.5            | 0.6                    | 28                               | 1900            |
| # 4 coal       | 0.76               | 3.64           | 0.11                   | 31.55                            | 1700            |
| Mudstone       | 5.91               | 10.7           | 2.2                    | 40.6                             | 2480            |
3.5. Working condition simulation and monitoring scheme

In order to study the grooving pressure relief mechanism and the influence of the pressure relief groove shape on the roadway deformation, a total of nine working conditions are designed, the first group simulates two kinds of working conditions respectively: not excavating pressure relief groove and excavating pressure relief groove; the second group designs four kinds of working conditions to study the influence of the depth of the pressure relief groove on the deformation of the roadway, pressure relief groove size is 600×800mm, 600×1200mm, 600×1600mm and 600×2000mm; The third group designs three kinds of working conditions to study the influence of the width of the pressure relief groove on the deformation of the roadway, pressure relief groove size is 400×1200mm, 600×1200mm and 800×200mm.

In order to monitor the deformation of the roadway, thirty-five monitoring points are set on the roadway surface, among which seven monitoring points are set on the roof to monitor the roof convergence. Eight monitoring points are set on the floor to monitor the floor heave quantity. Seven monitoring points are set on sides to monitor rib sides convergence. Six monitoring points are set along the depth of the pressure relief groove on the floor at the depth of 0.2, 0.4, 0.6, 0.9, 1.4 and 2.0 meters to monitor the stress and displacement of the rock formation on the floor.

3.6. Numerical simulation result analysis

Table 2. The deformation of roadway

| Working condition          | Bottom heave quantity (mm) | Subsidence of arch roof (mm) | Convergence on both sides (mm) |
|----------------------------|----------------------------|-----------------------------|-------------------------------|
| Before grooving            | 306.9                      | 333.7                       | 564.6                         |
| After grooving             | 162.1                      | 85.02                       | 214.3                         |
| Deformation reduction      |                            |                             |                               |
| quantity after grooving    | 144.8                      | 248.68                      | 350.3                         |

Figure 2. Displacement of the floor at different depths

Table 2 shows that the roadway vault subsidence quantity is 333.7mm, the floor heave quantity is 260.9mm, and the rib sides convergence is 564.6mm, and the deformation of the surrounding rock around the roadway is larger before grooving. The numerical simulation results show that the maximum vertical stress of the surrounding rock around the roadway is more than 40MPa, which makes the roadway in a high stress state. After the roadway floor is grooved, the floor heave quantity of the roadway is 162.1mm, reduced by 47.18%. The vault subsidence is 85.02mm, reduced by
74.52%. The convergence on two sides is 214.3mm, reduced by 62.04%. The above data show that the pressure relief groove has a good effect on the control of roadway deformation, and its effect on the vault subsidience and the rib sides convergence is especially remarkable [15].

According to Figure 2, when the floor is not grooved, the floor heave quantity is drastically decreased with the increase of the depth of the surrounding rock of the floor, and the deformation of the floor heave is mainly concentrated in the range of 1 meter above the roadway floor, the roadway floor is basically in a stable state at 2 meter, and the displacement is close to zero; The floor heave quantity of the roadway after grooving is obviously reduced, and the floor heave quantity is decreased accordingly with the increase of the depth of the floor, but the disease is more gentle and nearly close to the linear decrease, which indicates that the deformation of the rock formation along the floor depth tends to be uniform after grooving.

![Figure 3. Stress before grooving](image)
![Figure 4. Stress after grooving](image)

From Figure 3 and Figure 4, after the roadway floor is grooved for pressure relief, the monitoring point on the left side of the floor is reduced from 1.66MPa (when not grooved) to 0.98MPa, reduced by 40.96%. The monitoring point on the right side of the roadway floor is reduced from 1.69MPa originally to 0.92MPa, reduced by 45.56%. The above analysis shows that the roadway floor stress is obviously reduced after the roadway floor is grooved for pressure relief. It can be seen from the stress diagram that the range of the stress reducing area near the roadway floor after grooving is obviously increased and the stress is transferred to the deep part.

In summary, the pressure relief groove plays a significant role in controlling the deformation of the roadway, improving the stress state of the surrounding rock and treating the bottom heave.

![Figure 5. Displacement of different depths of the floor](image)
It can be seen from Figure 5 and Figure 6 that floor heave and vault subsidence quantity are decreased with the increase of the depth of the pressure relief groove, but the change of the floor heave quantity and the vault subsidence quantity are not significant. With the increase of the depth of the pressure relief groove, the convergence of the two sides is decreased relatively. It shows that the increase of the depth of the pressure relief groove has a relatively good effect on the convergence on two sides of the roadways and does not influence and is not insensitive to the floor heave and vault subsidence.

**Figure 6.** Displacement of vault subsidence and the convergence

**Figure 7.** Displacement of different width pressure relief
It can be seen from Figure 7 and Figure 8, with the increase of the pressure relief groove width, the roadway floor heave quantity is decreased accordingly, but not significant, when the pressure relief groove width is greater than 600mm, with the increase of the width, the floor heave quantity basically remains unchanged, thus, the width of the pressure relief groove has little effect on the floor heave quantity. With the increase of the roadway width, the convergence on two sides is decreased significantly, and the convergence slope on two sides is increased accordingly, indicating that the width of the roadway has a significant effect on the convergence of the two sides. The arch crown subsidence curve is gentle and close to the horizontal line, indicating that the width of the pressure relief groove has little effect on the arch crown subsidence.

4. Engineering Practices

The average burial depth of the transport roadway for one coal mine in Binchang is 760m, belonging to the deeply buried, the deformation of the surrounding rock around the roadway is larger under high stress, in order to control the deformation of the roadway, 60 meters test section is chosen in the auxiliary transport roadway and the test section uses anchor rod, anchor rope and pressure relief groove combined support scheme. The numerical study results show that the pressure relief groove width has a significant effect on the deformation of the rib sides, roof and floor. Therefore, 1000mm width is taken, 1200mm depth is taken considering the construction factor.

The test section monitoring data show that the maximal convergence value of the roof and floor is 120mm, and the maximum convergence value of rib sides is 113mm during the observation period, and convergence value of the roadway is basically stable after two months observation. The maximum convergence speed rate of the roof and floor is 2.8mm/d, and the average deformation speed rate is 0-0.5mm/d after deformation becomes stabilized. The maximum deformation speed rate of the rib sides is 2.5mm/d, and the average deformation speed is 0-0.5mm/d after deformation becomes stabilized. The deformation of the roadway is effectively controlled after adopting this scheme. Figure 9 is the deformation diagram for the pressure relief groove after 60 days.
5. Conclusion

Based on the previous papers of this study the following conclusions were pointed out.

(1) After the floor is grooved in the high stress roadway, a larger stress reducing area will be formed near the floor, the stress will be transferred to the deeper floor, and the deformation scope will increase towards the deep floor, the deformation becomes even and pressure relief groove plays a better control effect on the deformation of the high-stress roadway.

(2) With increasing width and depth of the pressure relief groove, the convergence of the roof and floor will be decreased accordingly, but the effect is not significant, while its influence on the rib sides convergence is relatively significant.

(3) The engineering practice shows that the combined support of anchor rod, anchor rope and pressure relief groove can effectively control the stability of the surrounding rock in deep roadway.

Acknowledgments

This work was financially supported by the National Nature Science foundation of China (No.11402195), the collaborative innovation in shaanxi province (No.2015XT-15), and Scientific research project in Shaanxi province department of education (No.16JK1512).

References

[1] Zhou Hongwei, Xie Heping, Zuo Jianpin. Developments in researches on mechanical behaviors of rocks under the condition of high ground pressure in the depths, Advances in Mechanics, 2005, 35(1), 91-99.

[2] Cao Rihong, Cao Ping, Lin Hang. Support technology of deep roadway under high stress and its application, International Journal of Mining Science and Technology, 2016, 26(5), 787-793.

[3] Bai Qingsheng, Tu Shihao, Zhang Cun, Zhu Defu. Discrete element modeling of progressive failure in a wide coal roadway from water-rich roofs, International Journal of Coal Geology, 2016, 167(10) 215-229.

[4] He Manchao, Xie Heping, Peng Suping, et al. Study on rock mechanics in deep mining engineering, Chinese Journal of Rock Mechanics and Engineering, 2005, 24(16), 2803-2813.

[5] Xiao Tongqiang, Wang Xiangyu, Zhang Zhigao. Stability control of surrounding rocks for a coal roadway in a deep tectonic region, International Journal of Mining Science and Technology, 2014, 24(2), 171-176.

[6] He Yongnian, Han Lijun, Shao Peng, et al. Some problems of rock mechanics for roadways stability in depth, Journal of China University of Mining & Technology, 2006, 35(3), 288-295.

[7] Yuan Liang, Xue Junhua, Liu Quansheng, et al. Surrounding rock stability control theory and support technique in deep rock roadway for coal mine, Journal of China Coal Society, 2011, 36(4), 535-543.
[8] Liu Quansheng, Lu Xingli. Research on nonlinear large deformation and support measures for broken surrounding rocks of deep coal mine roadway, Rock and Soil Mechanics, 2010, 31(10), 3273-3279.

[9] Cai Chengong. Simulation and testing study on outburst prevention measure of pressure-relief slots, Chinese Journal of Rock Mechanics and Engineering, 2004, 23(22), 3790-3793.

[10] Liu Jun, Kong Xianjing. Numerical simulation of behavior of jointed rock masses during tunneling and lining of tunnels, Rock and Soil Mechanics, 2007, 28(2), 321-325.

[11] Han Xu, Wang Ningwei, Su Jingyu, and Wang Wei. Numerical Analysis on Deep Foundation with Spatial Effect, Electronic Journal of Geotechnical Engineering, 2015, 20(18), 11017-11030.

[12] Qijun Hu, Yahui Xu, Zhiwei Long, and Pengcuo Zaxi. Impact Analysis of Deep Foundation Pit Excavation on Adjacent Pipeline in the Sand Gravel Area, Electronic Journal of Geotechnical Engineering, 2015, 20(2), 681-694.

[13] Zhou Chuanbo, Guo Liaowu, Yao Yingkang. Numerical simulation of wall rock deformation mechanism of mining tunnel, Rock and Soil Mechanics, 2009, 30(3), 654-658.

[14] Kang Hongpu, Study application of strata destressing method in coal roadway, Coal Science and Technology, 1994, 22(5), 14-16.

[15] Sun Jin, Wang Lianguo. Numerical simulation of grooving method for floor heave control in soft rock roadway, Mining Science and Technology (China), 2011, 21(1), 49-56.