Unloading Mechanism and Design Analysis of Surrounding Rock in Deep High Stress Roadway

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Abstract. The strong pressure on the roof, excessive concentration of stress, soft and broken surrounding rock, and difficulties in roadway support have always been important factors affecting the safety and stability of deep high stress soft rock roadway. Based on the special space unloading function of the pressure relief groove in the deep soft rock roadway, starting from the unloading pressure theory of deep surrounding rock, this paper has analyzed the effect of the pressure relief groove in relieving the pressure of the deep mine and controlling the deformation of surrounding rock. Three dimensional numerical simulation software FLAC3D was used to compare and analyze the surrounding rock failure and stress distribution characteristics before and after the excavation of the pressure relief groove in the deep high-stress soft rock roadway, and the optimum setting position of the pressure relief groove was also optimized. The results show that the deformation of surrounding rock can be effectively controlled after excavating and unloading pressure trough in deep high-stress soft rock roadway, and the displacement of top and bottom plate and roadway side can be reduced by nearly 30mm; the stress concentration is significantly reduced, the stress peak is transferred to the deep part of surrounding rock, and the pressure relief effect is obvious, which effectively maintains the safety and stability of the roadway, and indicates the direction for the pressure relief adjustment and stress control of the high-stress soft rock roadway at the deep part.

1. Introduction

With the increasing depth of mine mining, the stop support encounters many problems. The problem of ground pressure and support of high stress of soft rock roadway is particularly prominent. The greater the mining depth, the more severe the impact of rock burst. In addition, the complex roof conditions of coal and rock, different rules of initial and periodic pressures make it more difficult to manage and control the "roof -- bracket -- floor", and the supporting condition is not optimistic [1-5]. In view of the characteristics of high concentration of stress in surrounding rock of roadway, loose inside rock layer and weak strength, on the one hand, the surrounding rock should be strengthened to prevent the surrounding rock from breaking and keep the rock strata stable; on the other hand, necessary pressure relief measures should be taken to relieve the mine pressure, avoid stress concentration and control the deformation of surrounding rock [6-8].

According to the failure mechanism analysis of roadway surrounding rocks, the serious deformation and failure of roadway are mainly the result of comprehensive actions such as lithology, fracture development of surrounding rock, ground stress and dynamic pressure. Surrounding rock itself is both the forcing carrier and the stress carrier. Roadway supporting should give full play to the
self-supporting ability of surrounding rock, to unloading the rock mass at the same time, both to maintain the security and stability of roadway [9-12].

This design based on the practical field of Anhui mining group, a deep coal mine, using numerical simulation method of roadway excavation unloading tank before and after the failure characteristics of surrounding rock and stress distribution were analyzed, and it optimizes the best placement of the pressure relief groove. Through the popularization and application of pressure relief groove, the harmful influence of mine pressure on roadway is effectively alleviated, the distribution of surrounding rock stress is improved, and the organic unification of production management, roadway support and pressure relief is achieved, with remarkable results.

2. Unloading Principle of Pressure Relief Groove
Pressure relief groove refers to a certain width and depth in the roadway by using pneumatic pick or hand pick. Its role is that after the pressure relief trough is excavated, the stress of the surrounding rock of the roadway is transferred to the deep part of the coal. The unloading pressure range of the upper part is enlarged, a large amount of surrounding rock deformation is absorbed, the stress field distribution of surrounding rock in the roadway is changed, and the harmful influence of mine pressure on the roadway is slowed down, so as to effectively protect the roadway [13-14]. As a stress control method, the pressure relief groove plays an active role in the control of surrounding rocks of high stress soft rock roadway.

3. Engineering Background

3.1. Engineering Overview
In a deep coal mine of Anhui mining group, the impact pressure is large and the roof rock layer is soft and easily broken, the roof pressure appears severe and the roadway bottom dropsy is serious. Therefore, it is not easy to choose the form of active support such as bolt support, but the passive support of metal steel support. The metal steel support is mainly I-steel and U type steel support, metal stent is suitable for the mine roadway support, many are especially suitable for complex section of geological structure such as coal softness, collapse column, top plate hard to control. It can control the top plate effectively and timely, prevent the surrounding rock from falling off, and has strong support capacity, good stress effect and high safety performance.

Take all factors into account, it is reasonable to use I-beam and U-beam support in this mine. At the same time, timely and effective adjustment was made to the change of roof pressure and rock strata movement, which improved the supporting conditions of the roadway and ensured the safe construction of the roadway.

3.2. Design of Roadway Support Form
Machine alley, wind alley, cutting hole and inlet wind alley of the mine 4111 working face are supported by I-steel shed, and U-shaped shed is used for the assembly chamber. The detailed design rules are as follows:

(1) According to the design of roadway support condition
According to the comparative analysis of the supporting conditions and economy of roadway, it is determined that the main body of 4111 working face machine roadway, wind road, cut eyes and inlet wind alley is supported by the I-steel shed, and the U-shaped shed support is adopted in case of special geological conditions.

(2) Designed by engineering analogy method
The geological conditions of the 4111 working face are basically the same as that of the 4113 working face. The 4113 working face adopts 11# mining I-steel shed support, therefore, the 4111 working face also adopts 11# coal mine I-steel shed support.

(3) Design of the shape of the roadway
The machine roadway, wind roadway, cutting hole and inlet wind roadway of 4111 working face are determined by the conditions of surrounding rock on site. All adopt a trapezoidal section, and that assembly chambers adopt u-shaped steel support and inclined legs semicircular arch section.
3.3. Determination of Roadway Support Parameters

3.3.1. Determination of Supporting Parameters of Roadway Scaffolding

(1) 4111 machine alley, wind alley and inlet wind alley: the I-type steel shed support adopts the mining 11# I-beam, and the Tong bar matches the bar waist to pass the top, and the shed distance is 0.6m.

(2) Hole cutting and chamber assembly

(a) The guide tunnel side adopts the I-steel shed support, which is selected for mining 11# I-steel, the top beam is 3.2-m long, the leg is 2.6m long, the bolt holes are reserved for the backside top beams, the Tong bar matches the bar waist to pass the top and the shed distance is 0.6m.

(b) The large side of brush is supported by I-steel shed, which is made of mining 11# I-steel, the top beam is 3.1m, the leg is long 2.6m, the top beam of the brush side and the guide cavern beam are sutured with the diameter of 24mm bolt and 40mm thick steel plate, and each side of the suture line is arranged in a row of CIS tents along the sides of the suture line. The Tong bar matches the bar waist to pass the top, and the shed distance is 0.6m.

(c) Assemble cavern: The U type steel shed support choose the U29 steel which is commonly used in the mining area. It adopts five sections of semi-circular arch support with inclined legs. The length of the top beam is 2.6m, the length of leg is 3.6m, and the length of lap joint is 0.4m. The cable is equipped with the limit card matching with the U29 steel, the reinforcing steel mesh is matched with the iron back plate, the waist leg is over the top, the shed leg angle is 8°, the shed distance is 0.6m, and the bracket is connected by iron shed support.

(3) Pressure relief groove

In the two sides of roadway adopt the method of loose blasting in combination with artificial excavation to excavate unloading Pressure relief groove. The size is 50cm * 80cm, that is, the width of the pressure relief groove is 50cm and the depth is 80cm. The exposed coal and rock face shall be treated timely after the groove is opened, and the groove mouth shall be sealed with metal mesh. Both sides shall use boards to reinforce the groove wall, and the middle shall be fixed with wooden piles. A special person is set to observe the displacement changes of the pressure relief trough regularly, and the slot size is updated at the right time.

3.3.2. Determination of Roadway Strengthening Support Parameters

When roof crushing, water spraying and mine pressure appear in the machine roadway and wind roadway of 4111 working face, support is strengthened by reducing shed distance, and other supporting parameters remain unchanged.

4. Optimum Design of Pressure Relief Groove

According to the geological and technical conditions of the mine, on the basis of field measurement, the nonlinear finite difference software FLAC was used to simulate the surrounding rock failure under different conditions of the roadway. In this simulation, the failure problem of roadway surrounding rock is studied in two cases of unexcavated pressure relief groove and excavated pressure relief groove, and the location of pressure relief groove is discussed accordingly.

4.1. Model Establishment

The range size of the model is 40m × 25m × 46m, which is divided into eight layers from top to bottom according to the physical and mechanical characteristics of the rock. Followed by sandstone, 4 coal, mudstone, 5 coal, sandy mudstone, 5 coal, siltstone and mudstone. In the middle part of the model, namely the sandy mudstone, the semi-circular arch roadway with straight wall was excavated. The cross-section size of the roadway was 5m × 5m, that is, the roadway height was 5m, the vertical wall height was 2.5m, and the semi-circular arch diameter was 5m. The left and right boundary of the model is 17.5m from the left and right sides of the roadway, the upper and lower boundary is 21.5m from the top and bottom of the roadway, and the width of the model is 25m. The grid division of the model is large, with a total of 20 × 25 × 72 grids divided. The middle area serves as the transition, and the number of grids around the roadway is small.
The top of the model considers the self-weight of the overlying strata on the stope while applying a uniform vertical compressive stress of 16 MPa; the right and left sides also apply a uniform compressive stress of 16 MPa; the bottom end is fixed. The model uses the Mohr-Coulomb yield criterion to judge the damage of surrounding rock, and the plastic flow and dilatancy damage are not considered in the calculation process [15-16].

For the roadway for excavation pressure relief groove, two sets of excavation pressure relief grooves in the semi-circular arched roadway of straight wall are required. The size of the pressure relief groove is 50cm × 80cm, that is, the groove width is 50cm and the depth is 80cm. The later calculation can be based on actual needs to make corresponding improvements and adjustments.

The different layout positions of the pressure relief groove have obvious influence on the pressure relief effect. In order to determine the optimal position of the pressure relief groove, it is arranged in the following three cases at the two sides of the roadway: First, the pressure relief groove is arranged in the upper part of straight wall alley, 2.5m away from the bottom plate, that is, arranged in the middle of the whole semi-circular arched roadway of the straight wall; the second is to arrange the pressure relief groove in the middle of straight wall alley, 1.5m away from the bottom plate, that is, placed in the lower part of the whole semi-circular arched roadway of the straight wall; The third is to arrange the pressure relief groove in the lower part of the straight wall alley, 0.5m away from the bottom plate, that is, placed at the bottom of the whole semi-circular arched roadway of straight wall.

4.2. Numerical Simulation

4.2.1. Roadway Simulation of Unexcavated Pressure Relief Groove

By simulating the surrounding rock failure in the unexcavated pressure relief groove of the roadway, the failure figure, vertical and horizontal stress distribution cloud map of the surrounding rock of the roadway are obtained, and the statistical results are shown in figure 1.

![Figure 1. Roadway Simulation Diagram of Unexcavated Pressure Relief Groove](image)

4.2.2. Roadway Simulation of Excavation Pressure Relief Groove

(1) The upper part of the straight wall roadway excavates pressure relief groove

The surrounding rock failure condition of the relief groove arranged in the upper part of the straight semi-circular archway is simulated. The failure pattern, vertical and horizontal stress distribution cloud diagram of the surrounding rock of the pressure relief roadway are obtained. As shown in the figure 2.
(2) The middle part of the straight wall roadway excavates pressure relief groove
The surrounding rock failure condition of the relief groove arranged in the middle part of the straight semi-circular archway is simulated. The failure pattern, vertical and horizontal stress distribution cloud diagram of the surrounding rock of the pressure relief roadway are obtained. As shown in the figure 3.

(3) The lower part of the straight wall roadway excavates pressure relief groove
The surrounding rock failure condition of the relief groove arranged in the lower part of the straight semi-circular archway is simulated. The failure pattern, vertical and horizontal stress distribution cloud diagram of the surrounding rock of the pressure relief roadway are obtained, as shown in figure 4.

Figure 2. Roadway Simulation Diagram of Pressure Relief Groove Excavated in Upper Part of Straight Wall Roadway

Figure 3. Roadway Simulation Diagram of Pressure Relief Groove Excavated in Middle of Straight Wall Roadway

Figure 4. Roadway Simulation Diagram of Pressure Relief Groove Excavated at the Lower Part of Straight Wall Roadway
4.3. Simulation Result Analysis

4.3.1. The Change Curve of Roof and Floor of Roadway and two Sides

According to the statistical analysis of the displacement change before and after excavating the unloading pressure groove of the roadway, the change curves of the top, bottom and two sides of the roadway under different conditions are obtained, as shown in fig.5-7.

Figure 5. Comparison Diagram of Roof Deformation Curve before and after excavating pressure Relief groove

![Figure 5](image)

Figure 6. Comparison Diagram of Deformation Curves of Roadway before and after Excavating Pressure Relief Groove

![Figure 6](image)

Figure 7. Comparison Diagram of Bottom Plate Deformation Curve before and after Excavating Pressure Relief Groove

![Figure 7](image)

It can be found from Fig. 5~7 that after the excavation pressure relief groove can effectively control the variation of surrounding rock, the displacement of the top and bottom plates and the roadway is reduced by 20~30mm, and the pressure relief effect is obvious. By comparing the pressure relief grooves at different positions of the roadway, it can be seen that the closer the pressure relief groove is to the top, the smaller the sinking amount of the roof plate is reduced and the change is
moderate; the closer the pressure relief groove is to the bottom, the smaller the amount of floor heave decreases and the more moderate the change, that is, the closer to the pressure relief groove, the better the pressure relief effect. Comprehensive analysis revealed: The pressure relief effect is most obvious when the pressure relief groove is excavated in the upper part of the lane upper, that is, in the middle of the semi-circular archway of the straight wall. The change in the amount of displacement of the top and bottom plates and the lanes is the most moderate.

(2) Vertical stress and horizontal stress distribution curve of surrounding rock in roadway

The stress changes before and after excavating the unloading pressure groove of the two sides of the roadway were analyzed, and the vertical stress and horizontal stress distribution characteristic curves of the surrounding rock in different conditions are obtained, as shown in Figures 8 and 9.

![Figure 8. Vertical Stress Distribution Characteristics of two Sides of Roadway before and after Excavating Pressure Relief Groove](image)

![Figure 9. Horizontal Stress Distribution Characteristics of two Sides of Roadway before and after Excavating Pressure Relief Groove](image)

From the curve analysis of the above figure, we can get the following results: The vertical stress and horizontal stress decrease in different degrees after the excavation of the roadway pressure relieve groove, and the stress peak shifts to the right, indicating that the pressure relief groove acts as a pressure relief, which not only reduces the surrounding rock pressure but also causes the stress rise zone to transfer to the deep part of the surrounding rock, so as to avoid the excessive concentration of stress at the roadway tip and effectively protect the roadway. By comparing the pressure relief grooves at different positions in the lane, it is found that the pressure relief effect is best when the pressure relief groove is excavated in the upper part of the roadway, that is, in the middle of the semi-circular archway of the straight wall, the stress changes are relatively gentle, and the roadway is easier to maintain.
5. Conclusion

Through numerical simulation and comprehensive analysis of engineering applications, the following conclusions can be drawn:

(1) The pressure relief groove can effectively reduce the amount of surrounding rock migration and reduce the harmful effects of mine pressure on the roadway. After the roadway excavation pressure relief groove, the coal rock mass around the pressure relief groove is prone to plastic displacement and damage, and the unloading pressure failure zone is formed in the two sides of the roadway, so that the stress rise zone is transferred to the deep part of the surrounding rock, and the plastic zone range is continuously expanded. The stress distribution range increases, the stress changes tend to be gentle, the stress concentration phenomenon decreases, and the stability of the roadway is easy to guarantee.

(2) The two sides of the roadway without unloading the pressure groove have severe pressure, and the roadway is prone to stress concentration, and the deformation is serious. The impact effect of the mine pressure on the two gangs is obvious, and the difficulty of roadway support is increased. After the pressure relief groove is excavated, the pressure relief groove can effectively control the movement of the surrounding rock, change the distribution law of the surrounding rock stress field of the roadway, and slow down the pressure of the two gangs. It is conducive to the maintenance of roadway safety.

(3) The pressure relief groove has a good application effect on the roadway with the impact of the mine pressure. The optimized design of the pressure relief groove is the key factor of the pressure relief effect. Only the reasonable slot size and accurate layout position can ensure the maximum degree of the pressure relief groove to exert the functions of pressure relief, decompression, and cushioning and deformation resistance.

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7. References

[1] Xu Y Q. Coal mining science. Xuzhou: China University of Mining and Technology Press, 1999.
[2] Wang X F, Gao M Z, Li L Q. Spatiotemporal coupling law of mining pressure, strata movement and fracture field distribution in deep stope. Journal of Mining and Safety Engineering, Vol. 33, Issue 4, 2016, p.604-610.
[3] Wang W J, Guo G Y, Zhu Y J. Malignant development process of plastic zone and control technology of high stress and soft rock roadway. Journal of China Coal Society, Vol. 40, Issue 12, 2015, p.2747-2754.
[4] Qian M G, Shi P W. Mine pressure and formation control. Xuzhou: China University of Mining and Technology Press, 2003.
[5] Zhang L, Zhao W. Exploration and suggestion of deep roadway support technology. Coal Mine Support, Issue 3, 2007.
[6] Wang X F, Li Y J, Tan X G. Mechanical Evolutionary Mechanism and Numerical Simulation Analysis of Roof Breaking for Stope With Variable Length. Electronic Journal of Geotechnical Engineering, Vol. 23, Issue 2, 2018, p.429-446.
[7] KYUNG H P, YONG J K. Analytical solution for a circular opening in an elastic-brittle-plastic rock [J]. Int. J. Rock Mech. Min. Sci, Vol.43, Issue 4, 2006, p.616-622.
[8] Lai X P, Li Y P, Wang N B. Roof deformation characteristics with full-mechanized caving face based on beam structure in extremely inclined coal seam. Journal of Mining and Safety Engineering, Vol. 32, Issue 6, 2015, p.871-876.
[9] Guo X L. Experimental study on pressure relief trough in soft rock roadway surrounding rock in high stress structural belt. China Mine Engineering, Vol. 40, Issue 6, 2011, p.47-48.
[10] Wang X F, Gao M Z. Mechanical model of fracture mechanism of stop roof for working face with variable length. Journal of China University of Mining and Technology, Vol. 44, Issue 1, 2015, p.36-45.
[11] Yang Q S, Gao M S, Liu B T. Study and Practices on Floor Heave Prevention and Control Mechanism with Pressure Releasing Slot in Floor of Mine High Stressed Roadway. Coal engineering, Issue 8, 2011, p.69-71.
[12] Junker Martin, Witthaus Holger. Progress in the research and application of coal mining with stowing. International Journal of Mining Science and Technology, Vol. 23, Issue 1, 2013, p.7-12.
[13] Wang B F, Liang B, Li G. Simulated testing exploration of the rock-burst preventive measures in the pressure-re-lief slots in No.5931 roadway of Xinzhou-pit coal mine. Journal of Safety and Environment, Vol. 15, Issue 5, 2015, p.48-53.
[14] Lin B Q, Zhou S N. Outburst Preventive Mechanism of Stress Relaxation Groove in Coal Tunnel. Chinese Journal of Geotechnical Engineering, Vol.17, Issue 3, 1995, p.32-38.
[15] Peng W B. FLAC3D Practical tutoria. Beijing: Machinery Industry Press, 2007.
[16] Gao M Z. The numerical analysis on the stress distribution and the displacement of the top coal in sublevel caving mining. Journal of Xiangtan Mining Institute, Vol.18, Issue 2, 2003, p.9-12.