

Research on Deep-Buried Roadway Surrounding Rock Stability and Control Technology

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Received: 4 February 2018 / Accepted: 22 May 2018 / Published online: 26 May 2018
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Abstract The research analyzed the deformation and fracture mechanism of roadway surrounding rock based on the geological conditions and fracture characteristics of deeply buried roadway in Binchang Mine, and explored the inefficiency of the original supporting scheme considering the testing results of plastic zones of roadway surrounding rock, as well as proposed control countermeasures for stability of roadway surrounding rock. The numerical simulation and theoretical analysis method were adopted to carry out optimized and design schemes. The new support of bolt and cable combine with inverted arch can realize common bearing with roadway surrounding rock and improve the integrity and bearing capacity of supporting structure. The engineering practice indicates that the new supporting scheme can efficiently control roadway deformation, showing significant technical and economic benefits and creating conditions for the safe and efficient production of mine, so it is also of great practical value for the roadway supporting in mine lot with similar geological conditions.

Keywords Numerical simulation · Deep roadway · Support scheme · Fracture characteristics · Inverted arch

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1 Introduction

With the large scale mining of coal resources and the increasingly deeper mining depth, more technical challenges occur. The stability of surrounding rock in deep roadway is one of the challenges to hinder the deep mining (Sun et al. 2017; Chen et al. 2016; Bai et al. 2016; He et al. 2005). The large crustal stress of deep mine and the complex geological conditions make roadway surrounding rock vulnerable to severe deformation, hinder roadway haulage and traffic, and block mine ventilation. What's worse, the whole roadway would be scrapped, having extremely significant influence on the safe production of mine. Therefore, it is necessary to carry out researches on supporting technology applied in deep roadway. Depending on the restoration work of haulage roadway in Binchang Coal Mine, this paper aims to solve the supporting difficulties on site and ensure the safe production in coal mine by studying the surrounding rock fracture mechanism and its supporting technology in the main haulage roadway.

For the deformation mechanism and support technology of roadway, experts and scholars have carried out numerous beneficial researches and practices, and the research on support theory is gradually deepened. Starting from the initial pressure arch hypothesis only considering the rock weight in caving arch and the Terzaghi K. formula considering limit equilibrium arch, the theory research now has developed into the

Kastner formula considering plastic zone support outside the surrounding rock of fracture zone at ultimate equilibrium (He et al. 2006). Multiple control methods including anchoring and grouting, floor beam with inverted arch, concrete pouring, etc. have been formed, and a certain effect has been achieved under the specific engineering conditions (Shen 2006; Liu and Ren 2015; Hu et al. 2015). These theories and practices have accelerated the roadway support technology but requiring further researches on how to determine the reasonable support parameters.

2 Engineering Overview

The coal seam depth is 704.5 ~ 824.4 m with an average depth exceeding 600 m and a coal seam pitch of $0^\circ \sim 5^\circ$. The coal mine is exploited in a vertical shaft. Five haulage roadways are designed in Panel 1, namely 1# and 2# auxiliary haulage roadways, 1# and 2# ventilation roadway as well as main haulage roadway. The roadway extends from east to west with an average length of 1700 m. The roadway is rock roadway. The cross section of the roadway is a semi-circular arch, with width and height 5640 and 2820 mm, respectively. The height of the vertical side walls is 1900 mm. As recorded in the geological survey data, the main haulage roadway of Panel 1 passes through a variety of rock stratum during driving, including mudstone, siltstone, medium sandstone, coal seam, post stone, sandiness mudstone, kern stone and argillaceous sandstone. The main haulage roadway in Panel 1 adopts the bolting and shotcreting with wire mesh, and the parameters of support are shown as follows: roof bolt adopted $\phi 20 \times 2200$ mm with inter-row space 800×800 mm, roof anchor cable adopted $\phi 17.8 \times 7300$ mm steel strand with inter-row space 1600×2400 mm; sidewall bolt adopted $\phi 20 \times 2200$ mm with inter-row space 800×800 mm; reinforcing mesh is welded by Q235 rebar with a diameter of $\phi 6$ mm, and the mesh density is 150×150 mm and mesh width 1000×2000 mm. Less than half a year after the main haulage roadway in Panel 1 was formed, the roof settled, and the sidewall severely converged, which seriously affect the safety production of mine; thus, it is necessary to restore the mine.

3 Deformation and Fracture Characteristics of Roadway

Main haulage roadway in Panel 1 was relatively stable and minor deformation was found on surrounding rock within 2 months after the roadway is opened through. However, the roadway deformation grew increasingly severe after 2 month, especially in the subsequent 3 months, and the use requirement of main haulage roadway was seriously affected.

The roof of roadway on the side of the roadway driving which closes to primary working face was severely caved, with an average deflection of 0.5 m, even more than 0.8 m in some sections. Anchor cable tray in some roadways, thus, was severely deformed due to too much loading; top reinforcing mesh was broken, and putty on roadway roof cracked and peeled off. Crushing and dilatation occurred to the sidewall, and the roadway converged and deformed for up to 300 mm. In addition, affected by the sidewall deformation, the roadway base angle became an arc from the original right angle. The sidewall was repaired for twice by adding bolts to sidewall, but it was of no use, which not only increased supporting cost, but influenced the normal transportation of main haulage roadway. It is known from the feedback information of field investigation that some parts of roadway floor had fractures up to 30 mm, and bulged about 200 mm. The two times of floor treatment didn't work, but on the contrary, increased the rework cost, affected the installation of belt conveyor and coal production.

4 Reinforcement Scheme Design

4.1 Mechanism Analysis

The severe deformation of roadway surrounding rock is mainly caused by too much roadway depth and high stress. Mudstone passed by haulage roadway and the poor geological conditions on site, especially the non-supporting status of roadway floor, make the roadway floor bulge severely. Thus, support should be provided for the roadway floor. The broken-rock zones of roadway roof and sidewall are between 2.0 and 2.6 m, which exceeds the supporting range 2.2 m of bolt in the original supporting scheme and finally generates severe roadway deformation. To improve the roadway stability, the expansion of broken-rock zone should be

stooped, so it is required to increase the length of bolt from 2.2 to 2.8 m, and restoration scheme for roadway floor should be proposed to improve the integrated stability of surrounding rock. If the floor of deeply buried roadway is not supported, the floor shear stress is bound to be larger than its shear strength, cause the floor heave (Zhao et al. 2015; He et al. 2006). Based on the above analysis, It is proposed that enhance the roof and sidewall support, adopt reinforced concrete inverted arch support for the roadway floor support.

4.2 Roadway Floor Support Design

According to the theories of rock mechanics and elastic mechanics, a roadway mechanical model under the even-distributed loads from two directions was built, as shown in Fig. 1. Dead weight of the buried roadway roof and floor was much less than that of upper strata, so it can be neglected. For convenience of obtaining the analytical solution, the following assumption was made: The cross section of roadway was calculated by the roadway circumcircle; It was assumed that lateral pressure coefficient $\lambda = 1$; The support resistance to surrounding rock was assumed as p_i .

According to the equilibrium equation, geometric equation and physical equation, the redistribution elastic stress equation is obtained (Shen 2006):

$$\sigma_r = p_0 \left(1 - \frac{R_p^2}{r^2} \right) + \sigma_c \frac{R_p^2}{r^2} \tag{1}$$

$$\sigma_\theta = p_0 \left(1 + \frac{R_p^2}{r^2} \right) - \sigma_c \frac{R_p^2}{r^2} \tag{2}$$

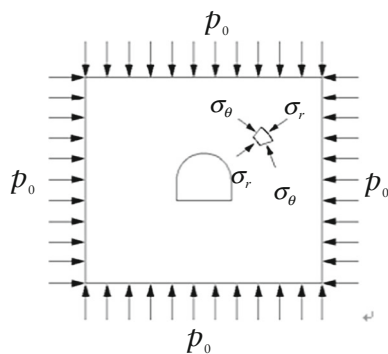


Fig. 1 Mechanics model

The plasticity and elastic interface stress:

$$\sigma_{rp} = (p_i + C_m \cot \theta) \left(\frac{R_p^2}{r_a} \right)^{\xi-1} - \frac{\sigma_c}{\xi-1} \tag{3}$$

$$\sigma_{\theta p} = \xi(p_i + C_m \cot \theta) \left(\frac{R_p^2}{r_a} \right)^{\xi-1} - \frac{\sigma_c}{\xi-1} \tag{4}$$

$$\xi = \frac{1 + \sin \theta}{1 - \sin \theta} \tag{5}$$

$$C_m = \frac{\sigma_c(1 - \sin \theta)}{2 \cos \theta} \tag{6}$$

$$\sigma_{\theta p} + \sigma_{rp} = 2P_0 \tag{7}$$

Combine formula (3), (4) and (7), the supporting force of plastic region are expressed in the following form when the supporting force exists.

$$P_i = (p_0 + C_m \cot \theta)(1 - \sin \theta) \left(\frac{r_a}{R_p} \right)^{\xi-1} - \frac{\sigma_c}{\xi-1} \tag{8}$$

where r_a is the radius of roadway circumcircle, σ_r is radial elastic stress, σ_θ is tangential elastic stress, σ_{rp} is radial plastic stress, $\sigma_{\theta p}$ is tangential plastic stress, p_0 is surrounding rock pressure, r is radius, p_i is supporting resistance, c is cohesion, R_p is radius of plastic zone. θ is internal friction angle.

4.3 Roadway Support Design

Remove the cracked and swelling putty on the surface of damaged surrounding rock at first. Add $\varnothing 20 \times 2800$ mm bolts on the roof and the both sidewalls with an inter-row space of 800×800 mm to form a hexagon shape with the original bolts. Set $\varnothing 18.9 \times 8000$ mm anchor cable on the roof and the left sidewall with an inter-row space of 1600×1600 mm. In the meantime, add anchor in floor at both sides base angle.

The floor is jointly supported by the bolts on base angle and the inverted arch on the reinforced concrete. With support force obtained by the formula 9 as the load on inverted arch, radius of plastic zones was gotten by actual measurement. The maximum axial force N_{max} on inverted arch can be obtained by the structural mechanics.

$$N_{\max} = \alpha_1 f_c b h_0 + f_y A_s \quad (9)$$

The reinforced concrete inverted arch span was the roadway width 6.2 m and the arch height to ground was 1.2 m; the concrete grade of inverted arch was C30, rebar grade was RRB400, inverted arch thickness was 400 mm. The area of main rebar in the inverted arch could be figured out by formula 9 (Liu and Ren 2015). Reinforcement diameter was 20 mm, and the layout space was 250 mm. Fill the inverted arch with coal slag and then compacted it, and finally pave concrete with a thickness of 200 mm on the coal slag to harden the surface.

5 Numerical Analysis

To verify the feasibility of the renovation scheme, a numerical simulation model was created based on the geological conditions of main haulage roadway in Binchang Mine, and FLAC3D software was used to simulate the original supporting scheme and the reinforcement scheme to analyze the stress state and deformation characteristics of roadway surrounding rock under the above two schemes and verify the feasibility of the renovation scheme.

5.1 Modeling

This simulation considers the roadway as a space problem. A section of roadway in parameters of length 80 m, width 40 m to the right and left, height 45 m to the up and down was selected to carry out the research. Considering the computer simulation speed and the accuracy of simulation results, the density of mesh surrounding the roadway was increased properly, but that far away from the roadway was decreased. The finite difference meshes formed on this basis, as shown in Fig. 2. The model was divided into 39,750 units with 42,532 nodes. To accurately simulate the roadway floor deformation under different supporting schemes, the roadway excavation and supporting was conducted strictly according to the actual construction process. Anchor cable and rock bolt were simulated by cable unit, while the inverted arch was simulated by solid element. Solve the initial stress field and initial displacement field at first, and reset the initial displacement field after the solution, and then carry out roadway excavation and supporting. Given

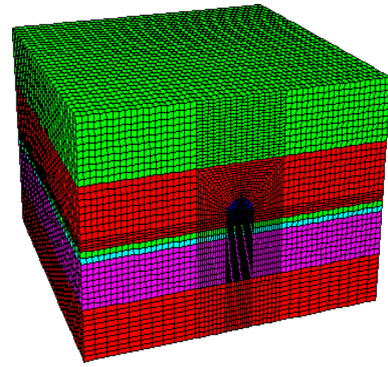


Fig. 2 Established model for the FLAC

that stress relief and displacement deformation may occur to the surrounding rock from the completion of roadway working face excavation to the completion of supporting, it is necessary to set certain calculation procedures to finish the stress relief after the completion of excavation, and the roadway supporting calculation can be started when about 30% stress is released (Hu et al. 2015; Zhou et al. 2009; Cai 2004). The calculation stopped automatically when the surrounding rock stress reached a balanced state, and the deformation and stress distribution status of roadway surrounding rock under different supporting forms was obtained. For the renovation scheme, sides and roof supporting was carried out at first, and the supporting for the inverted arch and the rock bolts on base angle was conducted after the calculation balance.

Main features of the calculation model are as follows:

1. The physical model adopts elastic–plastic model, and the failure criterion adopts Mohr–Coulomb model.
2. The classification of model sandstone is consistent with the actual layer position of roadway, and various rock stratum are deemed as homogeneous and isotropic body; the influence of surrounding rock and the structure surface, fractures and weak intercalated layer in rock stratum on the intensity is not considered (Liu and Kong 2007).
3. It is known from the Saint–Venant principle that the local excavation of rock only has significant influence on a limited area. Considering the boundary effect of the simulation and based on

the mining theory and practical simulation, the affected area is determined as 3 ~ 6 times of the excavated spatial span, and the roadway is located at the center of the model (Sun and Wang 2011; Han et al. 2015).

4. Model boundary conditions: the left and right boundaries restrict the horizontal displacement; the bottom boundary restricts vertical and horizontal displacement; and the upper boundary imposes stress which is equivalent to the self-weight of overlying rock. The average buried depth adopted in this simulation is 400 m (Li et al. 2010).
5. The physical and mechanics parameters of rock are subject to the laboratory test results, as shown in Table 1.

5.2 Calculating Monitoring Points Layout

To obtain the calculated values of roadway deformation under different working conditions, four monitoring points were set on roadway roof and sidewalls, and roof settlement, floor heave and horizontal displacements of spandrel and sides were figured out. In addition, the deformation value of roadway surrounding rock reflected the surrounding rock stability and it was used to evaluate the supporting effect. The floor rock stratum is the key point for this numerical calculation, so six monitoring points were laid at the depth of 0, 1, 1.6, 2, 2.5 and 3 m below the roadway floor. These monitoring points recorded the vertical displacements and horizontal stresses of floor rock stratum at different depths under different supporting forms, and provided a basis for evaluating the supporting effect.

5.3 Calculation and Analysis of Numerical Simulation

Analyzing and collecting monitoring data obtained from numerical simulation calculation can derive calculated values of vertical and horizontal roadway displacements as well as horizontal stress and vertical displacement of floor under different supporting schemes, as shown in Table 2.

It can be seen from Table 2 that if the roadway floor is not supported, the roof settlement (16.43 mm) is relatively lower than the sidewalls convergence and floor heave, which indicates a good stability of roof surrounding. However, the sidewalls convergence and floor heave reach 51.89 and 331.8 mm respectively, causing severe deformation and influencing the normal use of roadway. If the floor is supported by concreted inverted arch and anchor in floor and sides and roof are reinforced, the roof settlement, floor heave and sidewall convergence reduces to 6.21, 13.26 and 22.26 mm, respectively; the minor deformation of roadway surrounding rock is able to meet the requirements of roadway ventilation and haulage, and in particular, the floor heave is obviously restricted. These effects indicate that the reinforcement scheme is reasonable.

It can be derived from Table 3 that the vertical displacement of floor rock stratum decreases with the increasingly deeper buried depth; vertical displacement on floor with a range from 141.1 to 331.8 mm mainly occurs to rock stratum 3 m below the floor; on the other side, the floor horizontal stress increases with the increasingly deeper buried depth, and the maximum horizontal stress (8.86 MPa) occurs to the rock stratum 3 m below the floor, horizontal stress of the floor is shown in Figs. 3 and 4. The roadway floor

Table 1 Physical and mechanical properties of stratum

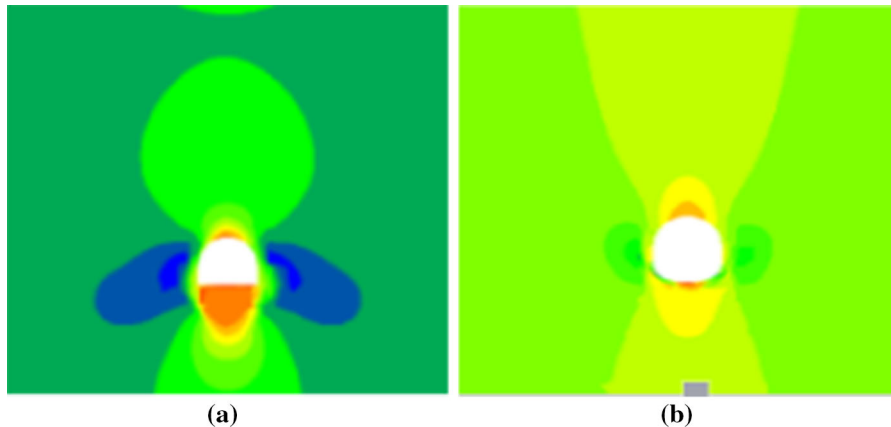
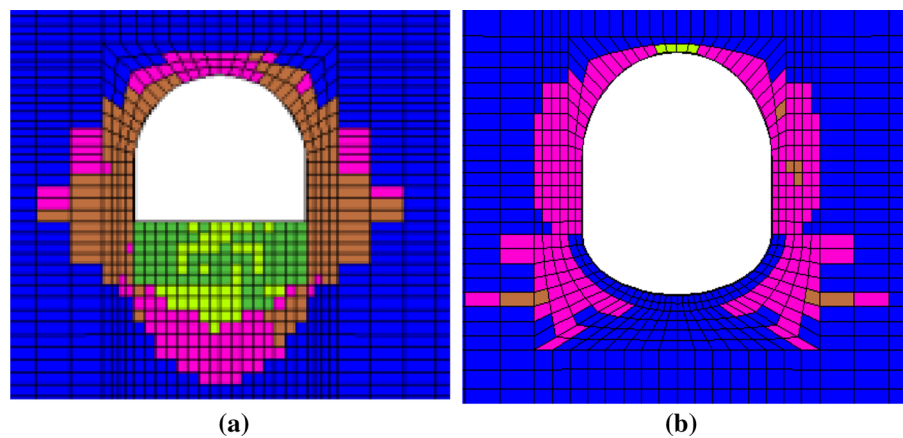
Rock type	Shear modulus (GPa)	Cohesion (MPa)	Tensile strength (MPa)	Internal friction angle (°)	Density (kg/m ³)
Fine grain sandstone	4.83	10.5	5.4	40.7	2600
Siltstone	4.62	7.2	2.1	39.7	2500
Mud stone	1.4	0.8	0.6	27	1970
# 4coal	0.82	3.64	0.5	30.23	1680
Mudstone	4.52	9.3	2.2	39.8	2450

Table 2 Simulation results of roadway deformation

Monitoring project	Floor heave (mm)	Sides converge (mm)	Roof sedimentation (mm)
Original scheme	351.8	70.89	16.43
Reinforcement scheme	13.26	22.26	6.21

Table 3 Vertical displacement and horizontal stress of floor

Monitoring points	1	2	3	4	5	6
Distance from the floor (m)	0	1.0	1.6	2.0	2.5	3.0
Displacement of original scheme (mm)	331.8	255.2	141.1	46.17	38.12	22.83
Displacement of reinforcement scheme (mm)	13.26	12.62	11.33	9.35	7.66	6.09
Horizontal stress of original scheme (MPa)	0.365	0.381	0.492	0.397	8.39	8.86
Horizontal stress of reinforcement scheme (MPa)	0	5.918	6.38	6.873	7.476	7.426

**Fig. 3** Horizontal stress of the surrounding rock. **a** Horizontal stress of original support, **b** horizontal stress of reinforcement scheme**Fig. 4** Distribution of surrounding rock plastic zones. **a** Original scheme, **b** reinforcement scheme

tends to move to the roadway center, but the reinforcement scheme allows the inverted arch to restrict its displacement, and the acting force applied by rock stratum on the inverted arch can be evenly dispersed. The reinforcement scheme significantly reduces the plastic zones of roadway surrounding rock, especially that of the roadway floor, plastic zones of surrounding rock is shown in Fig. 4. The results indicate that the reinforcement scheme can effectively restrict the expansion of plastic area. To sum up, the reinforcement scheme can improve the roadway stress state, effectively control the deformation of roadway surrounding rock and ensure the stability of roadway surrounding rock.

6 Evaluation of Roadway Renovation Effect

To verify the effectiveness of reinforcement scheme, 3 convergence measurement cross-sections were laid out in the haulage roadway after it is reinforced, and nearly 4 months of monitoring on surrounding rock deformation were carried out from March to July, 2016 to understand the deformation rules of rock and roadway. Monitoring profile is shown in Fig. 5.

The displacements of monitoring points is showed in Fig. 6, The monitoring results indicated that the deformation of roadway roof, floor and two sidewalls was obviously mitigated than that before reinforcement; the maximum roof convergence was 18.5 mm; the maximum displacement of two sides was 51.2 mm; the floor heaved 12.2 mm and the deformation tended to be stable after 2 months. Thus, it can be seen that the coupling support scheme combining

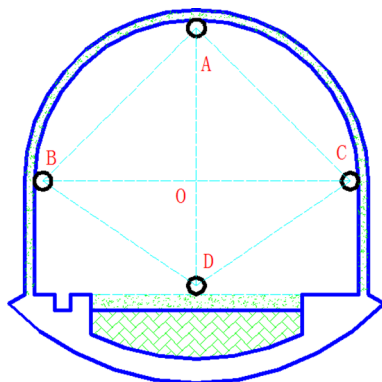


Fig. 5 Monitoring profile

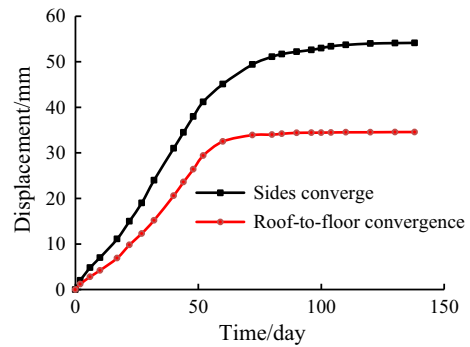


Fig. 6 Roadway displacement monitoring curve

reinforced sides, roof and concrete inverted arch successfully solved the difficulty of roadway support in deeply buried weak rocks under high ground stress and ensured a long-term stability of roadway surrounding rock and supporting structure, which made it a technology deserving promotion in the deeply buried weak rock roadway.

7 Conclusion

1. By analyzing the failure mechanism of main haulage roadway, The main reason for the deep roadway instability is that the roadway support strength is too small, and the other roadway is high stress state.
2. Combining with the test results of plastic zones and supporting theory, the coupling support scheme composed of reinforced sides, roof and concrete inverted arch was proposed against problems of the original supporting scheme, and numerical simulation calculation was employed to verify the reasonability of this reinforcement scheme.
3. The field monitoring results indicated that the roadway reinforcement scheme was reasonable and effective enough to suppress roadway deformation and meet the safety production requirements of coal mine. It is also of great engineering practice value for the roadway support in the mines with the similar geological conditions.

Acknowledgements 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).

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