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Study on Surrounding Rock Deformation Failure Law and Soft Rock Roadway Support with Thick Composite Roof

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Abstract

With exploitation of coal resources, mining activities in China have gotten increasingly deeper. Risk coefficient increases continuously, and the supporting difficulty has become more prominent in deep soft rock roadway because of the increasing complexity of geological conditions. Although existing roadway support technique is applicable to shallow surrounding rocks, it is not well suited for deep complicated fractured soft rock roadways. In order to solve the problem that the conventional support technique cannot provide stable support to prevent serious surrounding rock deformation failure in deep soft rock roadway with thick composite roof, in this study, the mechanical parameters of soft rocks in the air return roadway of A3 coal seam in Xieyi Mine of Anhui China were tested through the rock mechanics experiment. The failure area of soft rock roadway with thick composite roof was analyzed by drilling site test. A 3D numerical model of the soft rock roadway was constructed to explore the roadway deformation and failure range under different support schemes. Results demonstrate that in a thick composite roof, the roof that surrounds the rocks are loose and weak, accompanied with crack development in the separation line. The loose failure range is approximately 2.4 m, and the maximum failure range is approximately 4.2 m, indicating that the conventional support technique cannot offer stable support for similar roadway. The support scheme that integrates super-long strong pre-stressed anchor cable + bolt + bolt-grouting was proposed on the basis of the characteristics of the surrounding rocks. Results indicate that this combined support scheme has acceptable application effects and can effectively control great deformation failures in deep soft rock roadway with thick composite roof. Related study conclusions can provide reference for soft rock roadway support under similar geological conditions.

Keywords: Composite roof, Soft rock roadway, Numerical simulation, Combined support, Stability control

1. Introduction

The depletion of shallow coal resources has resulted in increasingly deeper mine exploitation. These mines have soft rocks which pose increased support challenge. Severe deformation failure of deep soft rock roadway shortens its effective service life and prolongs the alternation time during normal exploitation, thereby causing considerable difficulties in safe and efficient mine production [1], [2], [3], [4], [5]. Therefore, stable control in deep soft rock roadway is a technical problem in deepening mining activities that should be solved. When a thick composite roof exists at the roadway, a deformation caused by plastic failure of roof converges and becomes more serious, resulting in a larger failure area. The problems of disclosing the failure mechanism and deformation law of soft rock roadway with thick composite roof and seeking reasonable and effective supporting technology for soft rock roadway should be solved urgently.

Compared with traditional roadway supporting practices, the supporting technology in deep roadway with thick composite roof is more difficult and complicated. Most existing studies focus mainly on failure process, causes, and supporting techniques of roadway. For example, Huang et al.[6] analyzed the steady-state process of roadway roof failure systematically. They proposed the self-stabilization arch concept and established the ellipse extremity equation of steady-state curve arch. Wang et al.[7] discussed the influences of geological conditions, equipment parameters, and surrounding rock properties on roadway deformation failure through field survey and Delphi method. Zhang et al.[8] analyzed the geological features and control difficulties of deep surrounding rocks from the perspective of supporting technology, determined three influencing factors of surrounding rock stability in roadway, and proposed the surrounding rock control techniques for deep roadway based on the new anchor control technology.

Although these studies provide certain references for soft rock roadway support, none of them explored the lithology of surrounding rocks on the roadway. Few studies discussed the deformation and failure mechanism of roof with separation line and fractures. However, these separation lines and fractures develop extensively in practical mining activities because of the complicated geological conditions

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and significant differences in physical and mechanical properties of surrounding rocks, especially the appearance of thick combined roof in deep mining. These issues increase difficulties of roadway support and create new problems for mining alternation and support.

Hence, to achieve stable support of surrounding rocks in deep soft rock roadway and when thick composite roof exists, a support scheme that integrates super-long strong prestressed anchor cable+bolt+bolt-grouting that fully considers the adverse impacts of separation line and fractures in composite roof on roadway support was proposed.

2. State of the art

Deformation failures of deep soft rock roadway have different morphologies and mechanisms, which are related to complex and changing geological conditions, thereby increasing difficulties of supporting techniques. Chinese and foreign scholars studied deformation mechanism and supporting techniques of soft rock roadway through experiment and simulation tests. However, they focused mainly on monolayer rock mass. Rafiqul Islam et al.[9] analyzed roadway deformation and coal seam failure behavior in Balapulia Mine in Bangladesh through numerical simulation analysis of 2D boundary element method (BEM). They emphasized that roadway deformation is caused initially by tensile fractures and then developed into large-scaled tension failure. Zhou and Li[10] established a prediction model to loosen the damage thickness of surrounding rocks in deep roadway based on nonlinear regression analysis and provided an idea to determine the loosening circle of deep roadway. Małkowski et al.[11] analyzed the area of influence of a reasonable numerical model on surrounding rock failure on roadway, and compared it with field test by considering the elastic and elasto-plastic models. Coggan et al. [12] analyzed the strengthening technique for roadway roof using different numerical simulation technologies and pointed out that weak mudstone plays a key role in the instability process of roadway roof. They suggested that roadway support must reinforce weak mudstone. Lieta[13] developed abundant geomechanical model tests in Zhaolou Coal, Juye Mine, China, and disclosed the variation laws of surrounding rock displacement and stress under cable anchor support. Ma et al. [14] established the shear slip instability model of roadway, analyzed the anchoring mechanical properties of soft surrounding rocks, and proposed the use of surface whitewashing and grouting to prevent adverse impacts of water on surrounding rock control. Mostafa Ghadimi et al.[15] analyzed the influences of anchor shape and interval in roadway on shear strength of surrounding rocks using ANSYS, disclosed the exponential decay of anchor bolt with rock displacement and shear stress, and proposed that grouted anchor can improve stability of surrounding rocks on the roadway. Iurii Khalymendyk et al.[16] created an anchor cable test for the mining roadway of Stepova Mine, Ukraine. They also analyzed the strengthening effect of anchor cable on soft surrounding rocks on the roadway and proposed the superiority of cable to end support and pillar. Navid Bahrani et al.[17] analyzed the strengthening effects of soft rock roadway under different grouting reinforcements using the UDEC numerical simulation software and disclosed the force-displacement curve under local and global strengthening conditions to obtain applications of discontinuous stress analysis model on roadway support.

Although many useful results on supporting soft rock roadway have been achieved, they concentrate mainly on single lithology of roadway, but neglect the effects of separation line and fracture development on thick composite roof on roadway deformation failure. For instance, Li et al.[18] analyzed the instability mechanism of high-stressed soft rock roadway from supporting strength, ground stress, and surrounding rock strength, and found that arch support with certain strength and rigidity is effective in controlling surrounding rocks. However, they overlooked creep softening and multi-fracture separation line characteristics of complicated roof in deep roadway under high stress. Liu et al.[19] analyzed the mechanical mechanism of deformation of soft rock roadway and proposed three applicable supporting techniques based on the roadway deformation monitoring in JianxinMine of Jiangxi Fengcheng Bureau of Mine. However, they did not explore extensively the lithologies of surrounding rocks on the roadway.

A roadway mechanics model of thick composite roof was proposed and the corresponding mechanical analysis was performed given the shortcomings of existing studies. Therefore, a support scheme that integrates super-long strong pre-stressed anchor cable + bolt + bolt-grouting was proposed, and a numerical simulation model was constructed to analyze convergence deformation of roadway roof under this support scheme. Calculated results provide a theoretical basis for the application of the proposed support scheme.

The remainder of this study is organized as follows. Section 3 introduces the geological conditions of soft rock roadway with thick composite roof and establishes the mechanical model. Numerical simulation and parameter selection were also carried out. Section 4 discusses the effect of the proposed support scheme that integrates super-long strong pre-stressed anchor cable + bolt + bolt-grouting and verifies its reasonability. Section 5 provides the conclusions.

3. Methodology

3.1 Introduction of the roadway engineering

Xieyi Mine of Huainan Bureau of Mine lies in the south beach of Huaihe River in Huainan City. It is located near the XinzhuangZi Mine and borders the Xieli Coal Mine. The designed production capacity is 3,000,000 *t/a*. The mine is exploited by mixing vertical and inclined shafts. The longwall slice downward coal mining method is applied. Mining, transportation, and support in fully mechanized coal face are completely equipped. The A3 coal seam with an average thickness of 3.2 *m* and a dip angle of 5° is the main mining face. Coal roof and floor are composed mainly of sandstone, medium fine sandstone, and fine sandstone with some coarse sandstone and sandstone. The air return way in the south wing of the A3 coal seam is a rectangular roadway. The designed net width and net height are 4.2 ×3.2 *m*. The roadway is arranged along the floor of A3 coal seam at a buried depth of approximately 600 *m*. The ground stress test result shows that the vertical stress in this roadway is approximately 14.5 *MPa* and the maximum horizontal stress is approximately 18.1 *MPa*. The direction is N8°E. The minimum horizontal stress is approximately 12.42 *MPa*. Generally, the horizontal tectonic stress takes a dominant role.

The air return way in A3 coal seam of Xieyi Mine originally adopted the anchor-mesh combined support scheme. However, an overall anchoring structure can be difficult to form, and the convergence deformation of soft rock roadway with composite roof cannot be controlled effectively because of the weak composite roof strata, poor integrity, and low strength of the surrounding rocks. The surrounding rocks still suffered severe deformation failure, breakage of anchor rob and cables, and dramatic shrinkage of roadway sections despite using the anchor-mesh combined support scheme (Fig. 1). Therefore, an effective technology to control soft rock roadway with thick composite roof should be explored, to realize the stability of the surrounding rocks and supporting structure in roadway and maintain the normal service of the roadway.

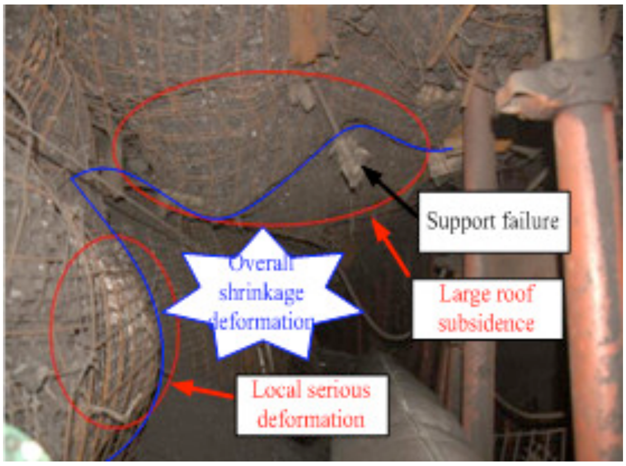


Fig. 1. Field observation of roadway deformation failure

The roof in the air return way of A3 coal seam is a typical thick composite roof (Fig. 2) composed mainly of sandy mudstone, medium fine sandstone, and a thin layer of sandstone. The composite roof strata are thin and interact mutually without stable main roof stratum. The stratum belongs to a lower-soften and upper-hard composite roof. The upper and lower rock strata in the roof of A3 coal seam have significantly different physical and mechanical properties. Joint fissures are developed in the roof, and the rock strata are weathered, which exhibits strong anisotropism. The uneven strength and rigidity of different rock strata can easily cause uncoordinated deformation failure and bottom-up layered collapses, which increase the difficulty providing roadway support.

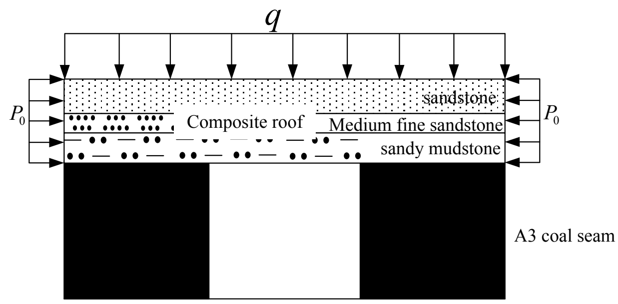


Fig. 2. Composite roof in the air return way of A3 coal seam

Samples were collected from the air return way in A3 coal seam for indoor rock mechanics test, which was conducted to obtain the mechanical parameters of surrounding rocks on the soft rock roadway with thick composite roof (Table 1).

Table 1. Mechanical parameters of surrounding rocks

Lithology	Elastic modulus /MPa	compressive strength /MPa	tensile strength /MPa	Poisson ratio	density /$(kg{\cdot}m^{-3})$
gritstone	15.2	116	1.18	0.13	2556
sandstone	13.5	102	1.13	0.12	2487
Medium fine sandstone	22.4	135	1.21	0.15	2565
sandy mudstone	8.75	72.9	0.86	0.25	2300
A3 coal seam	5.2	15.7	0.12	0.31	1600
fine sandstone	23.1	158	1.24	0.17	2702

Table 1 shows that the uniaxial compressive strength of the A3 coal seam is only 15.7 *MPa*, which is lower than the strata strengths of the roof and floor. The field observation reveals that joint fissures are developed extensively in A3 coal seam and the air return roadway advances along the floor. The roof and two sides are soft coal seams, which results in the low overall strength of surrounding rocks in the roadway and severe deformation failure of the roadway.

3.2 Field test of existing supporting scheme and deformation failure characteristics of surrounding rocks in the roadway

Anchor-mesh combined support scheme is used in the advancement of air return way in A3 coal seam. The roof anchor used φ20×2200 *mm* left longitudinal rib steel bolt. The interval between rows is 1000×800 *mm*. The rows are connected by W steel belts. The roof anchor cables of φ17.8×6000 *mm* are placed perpendicular to the roadway roof at a row interval of 2000×1600 *mm*. Anchor cables are connected by W steel belts. The anchor bolts at the sides use φ20×2000 *mm* glass steel anchor bolts at an interval of 1200×800 *mm*. The original roadway support section is shown in Fig. 3.

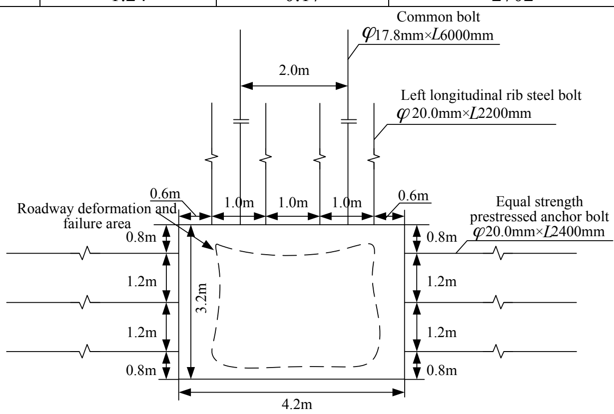


Fig. 3. Original roadway support scheme

When the supporting parameters in Fig. 3 are used, roadway advancement suffers serious roof separation and wall caving in less than one month, accompanied by serious roof deformation. The roadway deformation failure law is acquired through field observation.

Hence, to analyze deformation failure characteristics of surrounding rocks in the air return way of A3 coal seam, the plastic failure of surrounding rocks on the roadway is detected using drilling TV, which provided references for selection of roadway supporting techniques and parameters.

3.3 Mechanical analysis of surrounding rock failures

The mechanical model of the composite roof in Fig. 2 is simplified in Fig. 4. The surrounding rocks are assumed to be continuous and uniform, and the roadway advances infinitely long. This assumption is equivalent to the problem of plane strain. The stress states of the first layer of sandy mudstone close to the roadway in Fig. 2 are analyzed. With roadway advancement, the initial three-way stress state of the surrounding rocks is developed into the approximately two-way stress state, resulting in deformation failure of surrounding rocks and development of separation line and fractures in the composite roof. The sandy mudstone only bears gravity in the vertical direction. These strata are simplified into the supported beam in Fig. 4. Gravity stress is applied onto the beam as uniformly distributed load $q(\text{x})$ and horizontal stress P_0 is applied at two ends of the beam.

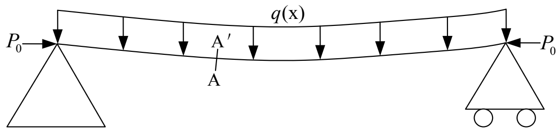


Fig. 4. Mechanical model of the composite roof

For A-A′ in the mechanical model in Fig. 4, the stress state at the left end is analyzed and differential equation for deflection is obtained as follows:

$$EI\frac{d^2\omega_1}{dx^2}=M(\text{x}) \tag{1}$$

$$M(\text{x})=\int_0^x q(\text{x})\,\text{xdx}+\frac{ql}{2}x-P\omega_1 \tag{2}$$

where EI is the flexural rigidity, $M(\text{x})$ is the bending moment, and ω_1 is the deflection.

Integrating Equation (2) into Equation (1) yields the following:

$$EI\frac{d^2\omega_1}{dx^2}+P\omega_1=\int_0^x q(\text{x})\,\text{xdx}+\frac{ql}{2}x \tag{3}$$

$q(\text{x})$ is a uniform load and is constant. If $q(\text{x})=\text{q}$, then the following is obtained:

$$EI\frac{d^2\omega_1}{dx^2}+P\omega_1=\frac{1}{2}qx^2+\frac{ql}{2}x \tag{4}$$

If $EI\neq 0$, then the two sides of Equation (4) is divided by EI as follows:

$$\frac{d^2\omega_1}{dx^2}+\frac{P\omega_1}{EI}=\frac{1}{2EI}qx^2+\frac{ql}{2EI}x \tag{5}$$

If $\frac{P}{EI}=k^2$, then the homogeneous differential equation of Equation (5) is as follows:

$$\frac{d^2\omega_1}{dx^2}+k^2\omega_1=0 \tag{6}$$

The general solution of Equation (6) is as follows:

$$\omega_1=C_1\cos kx+C_2\sin kx.$$

If $\omega^*=a_1x^2+a_2x+a_3$ is the particular solution of Equation (4), then integrating ω^* into the equation will yield the following:

$$2EIa_1+P(a_1x^2+a_2x+a_3)=\frac{q}{2}x^2+\frac{ql}{2}x \tag{7}$$

When the coefficients of the same power at two sides of Equation (7) are same, the following can be obtained:

$$Pa_1=\frac{q}{2}$$

$$Pa_2=\frac{ql}{2}$$

$$2EIa_1+Pa_3=0$$

$$P\neq 0,$$

$$a_1=\frac{q}{2P}$$

$$a_2=\frac{ql}{2P}$$

$$a_3=-\frac{q}{Pk^2}.$$

Then, $y*=\frac{q}{2P}x^2+\frac{ql}{2P}x-\frac{q}{Pk^2}$.

The general solution to Equation (4) is as follows:

$$\omega_1=C_1\cos kx+C_2\sin kx+\frac{q}{2P}x^2+\frac{ql}{2P}x-\frac{q}{Pk^2} \tag{8}$$

The boundary conditions of the two beam ends indicate that the bending deformation is 0. Then,

(1) When $x=0$, $\omega_1=0$. That is,

$$C_1=\frac{q}{Pk^2} \tag{9}$$

(2) When $x=l$, $\omega_1=0$. That is,

$$C_1\cos kl+C_2\sin kl+\frac{ql^2}{P}=\frac{q}{Pk^2} \tag{10}$$

Combining Equations (9) and (10) yields the following:

$$C_1=\frac{q}{Pk^2}$$

$$C_2 = \frac{1-k^2l^2-\cos kl}{pk^2\sin kl}q$$

C_1 and C_2 are integrated into Equation (8), as follows:

$$\omega_1 = \frac{q}{Pk^2}\cos kx + \frac{1-k^2l^2-\cos kl}{pk^2\sin kl}q\sin kx + \frac{q}{2P}x^2 + \frac{ql}{2P}x - \frac{q}{Pk^2} \quad (11)$$

When $x = l/2$, the deflection in Equation (11) reaches the maximum, as follows:

$$\omega_1 = \frac{(2-k^2l^2)q}{2Pk^2\cos\frac{kl}{2}} + \frac{3ql^2}{8P} - \frac{q}{Pk^2}$$

$$\omega_2 = \frac{(2-k_2^2l^2)q}{2Pk_2^2\cos\frac{kl}{2}} + \frac{3ql^2}{8P} - \frac{q}{Pk_2^2}$$

$$\omega_3 = \frac{(2-k_3^2l^2)q}{2Pk_3^2\cos\frac{kl}{2}} + \frac{3ql^2}{8P} - \frac{q}{Pk_3^2}$$

The analysis of ω_1 reveals that the deflection of beam (bending degree) is closely related to the gravity stress on the beam (q), horizontal axial stress (P), suspended length of the beam (l),polar moment of inertia of the beam section (I), and elasticity modulus of beam (E). Given the same axial stress, the bending degree increases when the gravity stress of the strata is high.

The comparative results of the maximum values of ω_1, ω_2, and ω_3 show that bending deformation of different strata varies because of the different physical parameters and suspending conditions of the roof, thereby resulting in the separation of different rock strata.

The analysis reveals that the key to an effective support to roadway with thick composite roof is to reduce the separation line and fracture development caused by excavation disturbance and to increase the bearing capacities of surrounding rocks, especially the roof. Therefore, selecting a reasonable support scheme is significant in obtaining stable support for the thick composite roof of deep soft rock roadway.

3.4 Establishment of numerical simulation model

The 3D numerical simulation model is constructed according to geological conditions in the air return way of A3 coal seam in the Xieyi Mine (Fig.5). The X-axis is the inclination of A3 coal seam (40 *m*), the Y-axis is the bearing (40 *m*) and the Z-axis is roadway advancement (40 *m*). The roadway section is rectangular, and the excavation size is 5×3 *m* (width × height). The boundary conditions of the model are as follows: displacement constraint is applied at the floor of the model, and the overlying load $\gamma h = 25kN/m^3 \times 600m = 15MPa$ is applied at the top of the model. At the two sides of the model, the corresponding horizontal stresses $\sigma_x = \sigma_y = \lambda\sigma_z = 19.5MPa$ are applied according to the field tested coefficient of the horizontal pressure (λ =1.3). The elastic-plastic Mohr-Coulomb constitutive model is used during the calculation. Numerical simulation parameters of different strata are shown in Table 2.

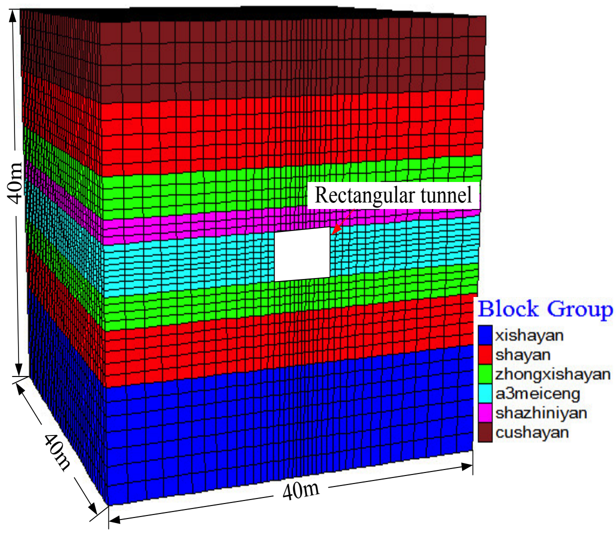


Fig. 5. FLAC3D numerical simulation model

Table 2. Mechanical parameters of surrounding rocks

lithology	bulk modulus /GPa	shear modulus /GPa	cohesive force /MPa	internal friction angle /°	tensile strength /MPa
gritstone	7.92	3.96	1.8	26	1.18
sandstone	7.55	3.85	1.7	25	1.13
Medium fine sandstone	8.05	4.18	2.1	28	1.21
sandy mudstone	3.46	1.98	1.7	23	0.86
A3 coal seam	2.22	1.41	1.1	20	0.12
fine sandstone	8.46	4.35	2.2	30	1.6

4 Result Analysis and Discussion

4.1 Analysis on field monitoring results of failure

4.1.1 Displacement

Results of the field observation reveal that the deformation failure of roof in the air return way of A3 coal seam is manifested by the separation line, falloff, collapse, and settlement.

(1) Large convergence deformation and evident separation line

The convergence deformation is serious and evident collapse and settlement occur during early roadway advancement (dotted line in Fig.3) because of the highly developed fractures in A3 coal seam and long-term disturbances from the movement of unstable overlying strata. The settlement of roadway roof reaches 525 *mm*, accompanied with severe damage, evident tuck net, and a leaking roof at some positions. The height of the caving zone is as high as 0.4 m.

(2) Serious convergence deformations at the two sides and at the base angle of the roadway

Serious damage can be observed in the coal mass at the two roadway sides. Large-scale internal displacements of wall caving occurred, and the maximum convergence reached 400 *mm* because of excavation disturbances. Without floor reinforcement in the original support scheme, serious deformation could be observed at the base angle of the roadway, accompanied by a considerably heaving floor and breakage of anchor bolts on the sides, which are close to the floor.

(3) Short self-stabilization of roadway

The air return roadway in A3 coal seam suffered significant deformation failure within three to five days after the excavation, indicating short self-stabilization of the roadway. Continuous deformation failures are detected in the field in the first two months of the excavation, accompanied by serious deformation at some positions. Satisfying the normal use of roadway section is difficult. Moreover, abnormal sound could be occasionally heard from the roof, indicating that deformation failure of the overlying strata on the roof develops continuously. This finding reflects that the roadway witnesses deformation of surrounding rocks for a long time. Roadway deformation lasts for approximately three months.

4.1.2 Plastic failure of surrounding rocks

The detection of air return way in A3 coal seam is shown in Fig. 6.

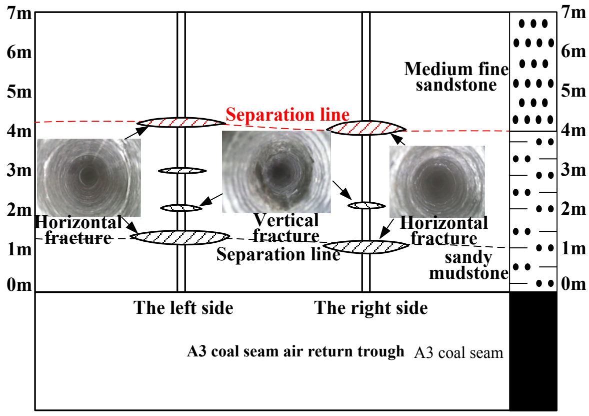


Fig. 6. Drilling TV view

Plastic failure test results of surrounding rocks on the roadway are shown in Fig. 6. The figure shows that the plastic failure area in the left side is 1.3–2.4 *m* and 3.5–4.2 *m* in some places, whereas the plastic failure area in the right side is 1.0–2.1 *m* and 4.0 *m* in some places. Most plastic failures on roof are concentrated in 1.0–2.4 *m* and 4.2 *m* in some places. Generally, the plastic failure area of the air return way in A3 coal seam is relatively large, thereby increasing the difficulties in ensuring support. Large-scale plastic failure occurs soon after the excavation of roadway because of the the A3 coal seam and surrounding rocks at the roof and floor are soft rock strata with low bearing capacity. A complete and effective anchoring structure around the roadway cannot be formed easily because of the mismatch between the original anchor-mesh support parameters and surrounding rock strength. Thus, strong deformation behavior of surrounding rocks on the roadway cannot be inhibited. As a result, large-scale roof deformation and serious heaving floor in the air return way of A3 coal seam could be observed.

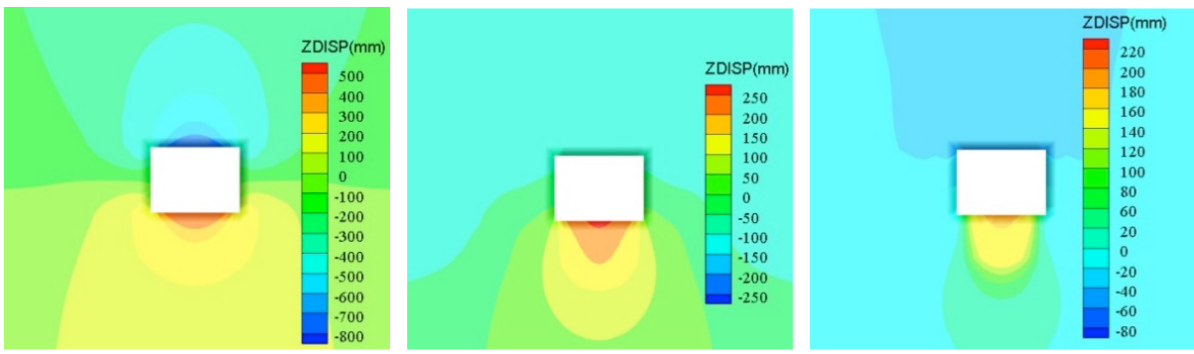
4.2 Analysis of numerical simulation results

Numerical simulation is performed after the model is established. Displacement monitoring lines are placed at the roadway roof, two sides, and floor to analyze the effects of the surrounding rock deformation on the support scheme. The variation laws of the surrounding rock deformation, plastic zone distribution, and stress environment in the deep soft rock roadway with and without support are disclosed.

Numerical simulations of the soft rock roadway without support, with support but no grouting, and with support that integrates super-long strong pre-stressed anchor cable + bolt + bolt-grouting were carried out under same geological conditions to verify the effects of different support schemes on the stability of soft rock roadways. The results are introduced in the following sections.

(1) Deformation characteristics

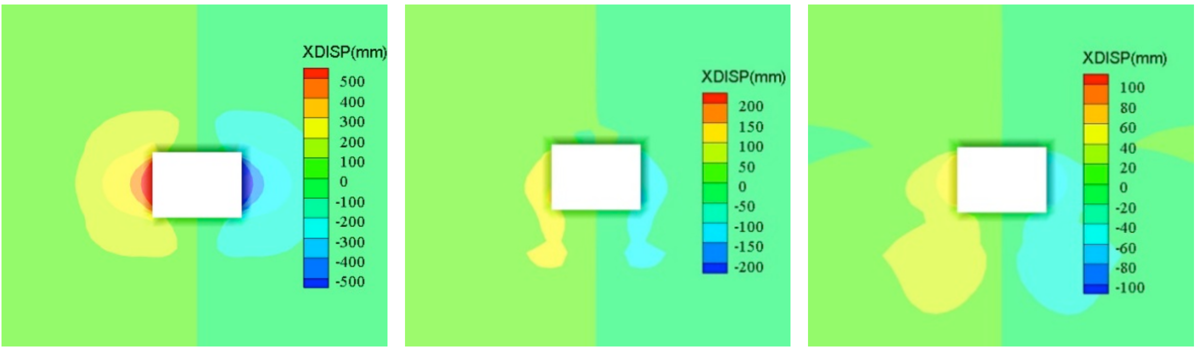
Cloud maps of surrounding rock deformations on the roadway without support, with only anchor-mesh support, and with support that integrates super-long strong pre-stressed anchor cable + bolt + bolt-grouting (hereinafter referred to as three-anchor combined support) are shown in Fig. 7.



(a) Without support, (b) With support but no grouting, and (c) Three-anchor combined support

Fig. 7. Cloud maps of vertical displacement distribution under different support schemes

Fig. 7 shows that the surrounding rocks on the roadway have serious convergence deformation in the absence of support. The deformation at the composite roof is relatively larger (approximately 800 *mm*), and the maximum heaving floor is 500 *mm*. When anchor-mesh support exists, the deformation of the surrounding rocks is relieved to some extent. The roof settlement is approximately 250 *mm*, and the floor heave is approximately 200 *mm*, which are lower than those with no support. The deformation of surrounding rocks decreases further when the three-anchor combined support is used. Roof settlement is 80 *mm*, which is 90% and 68% lower than the two previous supporting schemes. The floor heave is 160 *mm*, which is 68% and 20% lower. The results reflect that the convergence deformation of the roof and floor is highly sensitive to support schemes. The three-anchor combined support realizes stable control of surrounding rock roof and floors on the soft rock roadway.



(a) Without support, (b) With support but no grouting, and (c) Three-anchor combined support

Fig. 8. Cloud maps of horizontal displacement distributions under different support schemes

In Fig. 8, convergence deformations at the two sides differ significantly under the three support schemes. Convergence deformations at the two sides in (a), (b), and (c) are 500, 100, and 40 *mm*, respectively. The convergence deformation at the two sides under the three-anchor combined support is respectively 92% and 60% lower than those under the two previous support schemes, indicating significant support effect.

The surrounding rock deformation curves on the roadway under different support schemes are shown in Fig. 9.

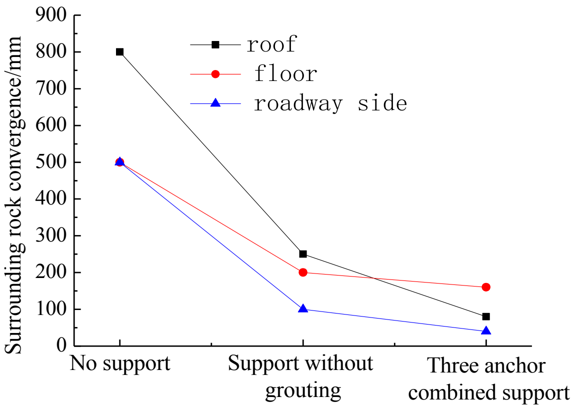


Fig. 9. Variations of surrounding rock convergence under different support schemes

Fig. 9 shows that after the excavation of the roadway, the surrounding rocks suffer different ranges of convergence deformation when the three-way stress changes into two-way stress. The separation line and fractures at the composite roof are highly developed, and the deformation reaches 800 *mm*, which affects the normal service of the roadway significantly. The surrounding rock convergence is relieved significantly after support without grouting is used, and is controlled effectively when the three-anchor combined support is applied. The effects of deliquescence and weathering on falloff failure of the surrounding rocks are controlled effectively because the surface whitewashing isolates air, water, and surrounding rocks. The original strength and stability of the surrounding rocks are also maintained effectively. The tight combination between anchor plate and surrounding rocks is strengthened, which can distribute stress on the anchor bolt uniformly and strengthen the support of anchor bolts and cables to the surrounding rocks. Grouted bolt can reduce separation lines and fracture in the composite roof to complete the bearing structure of the surrounding rocks. The anchor cable can fully utilize the bearing capacities of the surrounding rocks in deep roadway and relieve stress concentration on roadway surface to ensure stable control of soft rock roadway.

4.3 Supporting parameters in field application

The results of the ground stress test in the air return way of A3 coal seam of the Xieyi Mine, surrounding rock loose circle test, and laboratory rock mechanics test show that serious surrounding rock deformation can be observed in this deep soft rock roadway and that the original support scheme cannot easily achieve stable support. Hence, a support scheme that integrates super-long strong pre-stressed anchor cable + bolt + bolt-grouting was proposed (Fig.10).

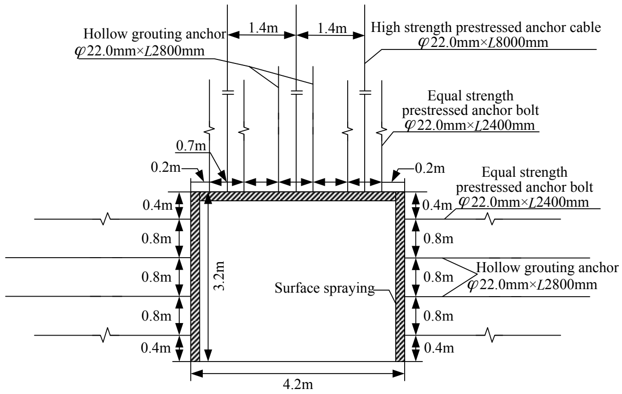


Fig. 10. Roadway support scheme

The roof uses high strength pre-stressed anchor cable (φ22.0 *mm* × L8000 *mm*) at a row interval of 1400 *mm* ×1600 *mm*. Three-anchor cables are placed uniformly on the roof at an equal interval of anchor bolts. Each cable is fixed by three volumes of Z2350 resin anchoring agent. The anchoring length is larger than 1200 *mm*, and the pre-tightening force reaches 180 *kN*. Equal strength pre-stressed anchor bolts (φ22.0 *mm* × L2400 *mm*) are deployed at an interval of 700×700 *mm* on the roof and 800×800 *mm* on the sides. The bolts fixed by two volumes of Z2350 anchoring agents. The anchoring length is larger than 1200 *mm*, and the pre-tightening force reaches 50 *kN*. The 1000×2000 *mm* metal mesh is composed of φ6 *mm* steel bars obtained through rolling.

After the anchor-mesh support is applied, a 100 *mm* thick layer of C20 concrete was grouted onto the surrounding rock surface. The water cement ratio of the concrete is 0.5. It is prepared by R32.5 Portland cement, medium-coarse sand, and stones at the proportion of 1:2:2.

The grouting anchor bolt (φ 22.0× L 2800 *mm*) is prepared using seamless steel pipes. The pipes are placed at an interval of 700×700 *mm* on the roof and 800×800 *mm* on the sides. PO42.5 Portland cement is used, and water cement ratio is 0.6. Early strength water reducing agent (1.5% of cement mass) is added to prepare the grouting solution. The grouting pressure is 1.5–2.5 *MPa*.

4.4 Supporting effect

Some holes are drilled in the air return way of A3 coal seam in the Xieyi Mine to observe the internal separation line and fractures of the surrounding rocks (Fig.11) and reflect the supporting effect of the proposed three-anchor combined support. Displacement monitoring sites are also set on the roof and the two sides. The surrounding rock deformation is monitored for 45 days. The surrounding rock convergence curves at the roof and two sides are shown in Fig. 12.

(a) Hole on roof (b) Hole on sides

Fig. 11. Surrounding rock view in deep roadway

Fig. 11 shows that the separation line and fractures in the surrounding rocks are relieved significantly or disappeared after the three-anchor combined support is used, thereby indicating that the grouting anchor bolts offer strong anchoring effect and provide integral bearing structure for the deep surrounding rocks. It fully utilizes its strength, thereby simplify roadway support.

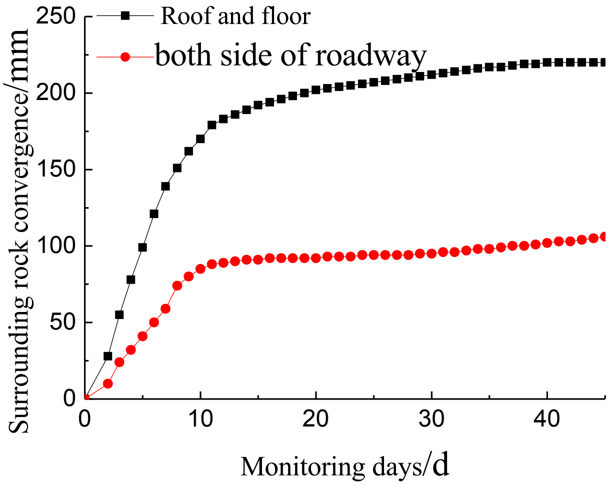


Fig. 12. Surrounding rock convergence in deep roadway

After the three-anchor combined support is used, as shown in Fig. 12, the surrounding rock convergence increases sharply in the first 10 days. This period is called the fast deformation period, and the deformation at the roof and floor reaches 180 *mm* or approximately 80% of the overall monitored deformation. The surrounding rock convergence becomes stable in 10 to 25 days. Although the surrounding rock convergence continues to increase, the growth rate declines significantly and consumes approximately 12% of the overall monitoring deformation. Grouting strength on the roadway surface reaches its peak during 25 to 45 days. The grouting anchor bolt strengthens the binding between the separation line and fracture at the roadway roof. The three-anchor combined support is used fully and can control the surrounding rock deformation stably.

5. Conclusion

In order to solve the problem that the conventional support technique cannot provide stable support to prevent serious surrounding rock deformation failure in deep soft rock roadway with thick composite roof and failure range under different support schemes. The deformation failure features of deep soft rock roadway are discussed by analyzing the corresponding deformation mechanism based on field observation and theoretical analysis. A numerical simulation model for soft rock roadway with thick composition roof is constructed using the laboratory-tested physical properties of the surrounding rocks to obtain roadway deformation characteristics under different support schemes. Therefore, a support scheme that integrates the super-long strong pre-stressed anchor cable+bolt+bolt-grouting is proposed. The following conclusions are obtained:

(1) Limited by the composite roof, surrounding rocks in the air return way of A3 coal seam in Xieyi Mine suffer from serious plastic damage after the excavation. Particularly, the plastic failure range of the roof is concentrated between 1.0–2.4 *m* and 4.2 *m* in some places. Under the original support scheme, serious deformation failure occurs on the roadway, causing difficulty in ensuring safety production.

(2) The separation line and fractures developed easily on the roof because of the differences in the physical and mechanical properties of the composite roof, thereby increasing support difficulties for the soft rock roadway.

(3) The support scheme that integrates super-long strong pre-stressed anchor cable + bolt + bolt-grouting is proposed based on the numerical simulation results by combining the mechanical analysis of composite roof and deformation failure features of deep soft rock roadway. The proposed scheme overcomes strong deformation failures in deep soft rock roadway with thick composite roof.

(4) The three-anchor combined support has surface grouting, which prevents the adverse effects of air and water on the surrounding rocks and effectively maintains the original strength and stability of the surrounding rocks. The use of grouting anchor decreases separation lines and fractures in the composite roof. Thus, the surrounding rocks become an integral bearing structure. The anchor cable makes full use of the bearing capacity of deep surrounding rocks and reduces stress concentration on the roadway surface to the maximum extent. Therefore, the overall supporting effect to the surrounding rocks is improved. Based on field practices, the proposed support scheme is reasonable and applicable to soft rock roadway in similar geological conditions.

In summary, the proposed three-anchor combined support is reasonable, economical, practical, and easy to construct in field engineering. It offers technological references to support deep soft rock roadway with thick composite roof. However, the effects of supporting density on supporting effect are not discussed in this study. Further studies on optimization of this support scheme are required in the future.

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