Research on Robotized Advance Support and Supporting Time for Deep Fully Mechanized Excavation Roadway

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Abstract: To keep coal workers away from the hazardous area with frequent accidents such as the roof fall and rib spalling in an underground coalmine, we put forward the solution with robotized self-moving anchor-supporting unit. The existing research shows that the surrounding rock of the roadway has self-stability, and the early or late support is not conducive to the safe and reliable support of the roadway, so there is a problem of support opportunity. In order to study the supporting effect and the optimal supporting time of the above solution, we established the mechanical coupling model of surrounding rock and advance support, and investigated the surrounding rock deformation and advance support pressure distribution under different reserved roof subsidence by using the numerical simulation software FLAC3D. The results show that the deformation of surrounding rock increases and finally tends to a stable level with the increase of pre settlement of roadway roof, and when the pre settlement of roof is between 8-15mm, the vertical pressure of the top beam of advance support reaches the minimum value, about 0.58MPa. Based on the above research, we put forward the optimum supporting time in roadway excavation, and summarized the evaluation method based on the mechanical coupling model of surrounding rock-advance support.

Keywords: Coalmine Safety, Robotized Advance Support, Optimum Supporting Time, Deep Fully Mechanized Excavation Roadway, Mechanical Coupling Model

1 Introduction

In an underground coalmine, the fully mechanized excavation face is an area with frequent accidents such as roof fall and rib spalling, which seriously threatens the personal safety of coal miners at the working face. With the increases of mining depth, the mining location gradually shifts to the deep underground, the coal production is undergoing a transition period from shallow mining to deep mining, and safety issues are becoming increasingly prominent. It will be safe with fewer people even no people at the working face. Therefore, solving the safe issue of coal production, it is an effective way to replace people with mechanization and to reduce people through automation, which liberates coal miners from the heavy labor and keep them away from the dangerous areas.

Guanghui X. [1-3] numerically simulated the deep surrounding rock pressure and its influence on advanced support, put forward a new type of advance support for fully mechanized excavation roadway, and analyzed its supporting performance and the determination method of the working resistance for the advance support. Yong H [4] studied the control problem of stepping hydraulic support column of advance support. Guanghui X. [5], LUAN L. J. [6], and LU J. N. [7] studied compound control strategy of the electro-hydraulic servo-position and pressure, and multi-cylinder control strategy of the stepping leading bracket for the fully mechanized excavation roadway.

Roadway surrounding rock control and support theory is a critical issue in roadway excavation, and always attracts the attention of researchers related to coalmine production. From the original Platt Pressure Arch Hypothesis (1907) which only considers the weight of rock in caving arch and the Karl Terzaghi Formula (1942), which considers the ultimate equilibrium arch, to the Castner Formula (1948), which considers the ultimate equilibrium surrounding rock support [8, 9]. With the proposal of the "support-surrounding rock" interaction concept, many scholars put forward the bolt support method with active support and full use of the self-supporting capacity of surrounding rock. The theory of bolt support has gradually developed from the initial suspension theory to the theory of composite beam [10], extrusion reinforcement, broken rock zone [11, 12], and the theory of "given deformation" and "limited deformation"[13]. Most soft rock roadways have a phenomenon of floor heave or rib spalling, which affects the stability of the roof. Researchers have proposed the theory of the ultimate self-stabilized equilibrium arch of roadways and the principle of bolt support design and construction [14, 15]. A large number of studies have shown that the surrounding rock is a natural bearing structure, which can act with strong self-bearing capacity under specific conditions. It is uneconomical to support too early because the supporting structure has to bear a lot of deformation pressure. Therefore, when supporting roadways, the surrounding rock should be allowed to produce as much deformation as possible under the premise of continuity, and the self-supporting capacity and self-stability of surrounding rock should be utilized to the maximum extent, that is yielding supporting, to reduce the support strength required by roadway support and the cost of manual support [16]. However, if the support is not timely, the surrounding rock will deform excessively, resulting in relaxation and instability. Therefore, the appropriate supporting time is very important for roadway excavation support. Researchers at home and abroad have done a lot of research on the "optimal support opportunity" by means of field monitoring, theoretical derivation and numerical simulation [17-19], and have made positive progress. However, the theoretical analysis and mechanism research of the problem is still very lacking. How to determine the optimal support time reasonably and accurately and achieve "timely support" is still lack of reliable theoretical guidance, and can only be determined based on on-site monitoring information or a large number of numerical simulation tests.

Numerical simulation has become an important methodology to solve various problems in tunneling and underground space engineering and to achieve optimal parameter selection for design and operation purposes [20, 21]. At present, researchers have developed many computational methods, such as the Discrete Element Model (DEM), the Discontinuous Deformation Analysis (DDA), the Scaled Boundary Finite Element Method (SBFEM), the Peridynamics (PD), and the 4-Dimensional Lattice Spring Model (4D-LSM), with many advantages in solving various problems including discontinuous deformation, large deformation, and dynamic fracturing.

This paper proposed the advance supporting scheme of self-moving support and anchoring unit and the concept of optimum supporting time, and then studied the deformation of surrounding rock under different support time and its influence on support capacity through numerical calculation with Flac3D software, with the consequence of the law between the deformation of surrounding rock and support time. At last, we summarized the method to determine the optimum supporting time.

2 Robotized Self-moving Anchor-supporting Unit

The Robotized self-moving anchor-supporting unit consists of tunneling robot, supporting robot, anchoring robot, and subsidiary mechanism, with the characteristics of multi-station cooperative operation, fast coordination of support-anchor, and fast forward movement of support and flexible self-movement of drilling-anchor mechanism, as shown in Fig. 1. Tunneling Robot mainly completes roadway excavation. The function of supporting robot is temporary support of the roadway. It could adjust the height and width to meet the needs of the different cross-section size of the roadway and its movement forward. The anchoring robot realizes the permanent support of the roadway, and its multi position anchor-drill displacement manipulator can achieve the anchoring cooperative operation in the multi degree of freedom environment to complete the installation of the roof bolt and rib bolt. The supporting vehicle can carry the supporting robot forward and provide operation platform for supporting and anchoring.

Compared with the current machines, the unit shows such outstanding advantages: (1) to provide larger safety operation space for coal miners, (2) to provide the conditions of the multi-position operation of anchoring, (3) to make parallel operation of excavation possible, so improves the efficiency of the excavation to some degree, (4) to improve the automation level in roadway excavation. The combined unit can change the tunneling technology of the fully mechanized excavation working face and solve the problem that the tunneling, supporting, anchoring and other operations cannot be carried out simultaneously, resulting in improvement of the driving efficiency while ensuring the safety of the coal miners.

As shown in Fig. 2, the working principle of Robotized self-moving anchor-supporting unit is as follows:

Step 1: The whole unit is in the initial state, as Fig.2 (a).

Step 2: After the tunneling robot excavates forward a support step width, the advance support at the rear of the supporting robot shrinks to the minimum size state, clamped on the supporting vehicle, as Fig.2 (b).

Step 3: The supporting vehicle transports the rear advance support to the newly excavated roadway section position and releases it. Meanwhile, the anchoring robot moves forward and carries out permanent support

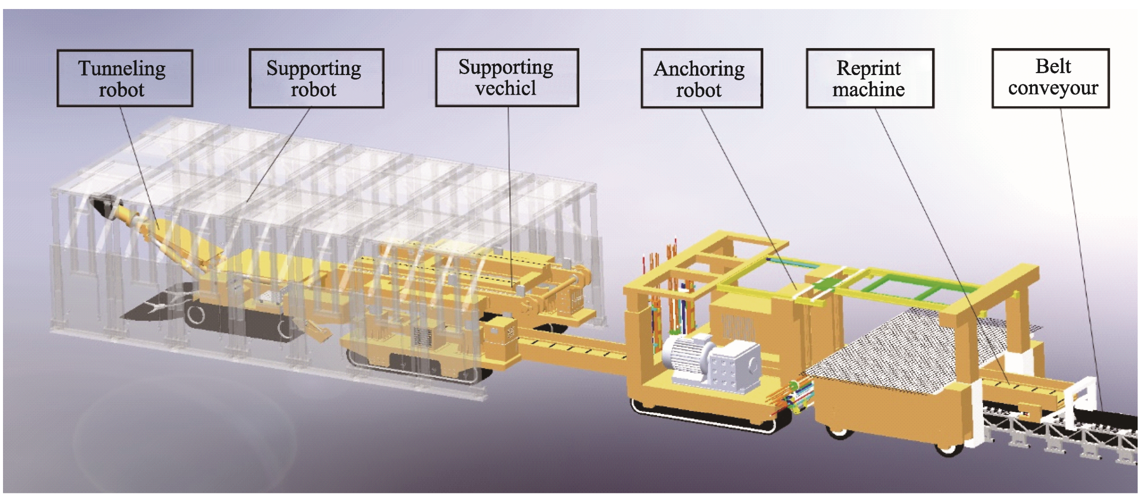
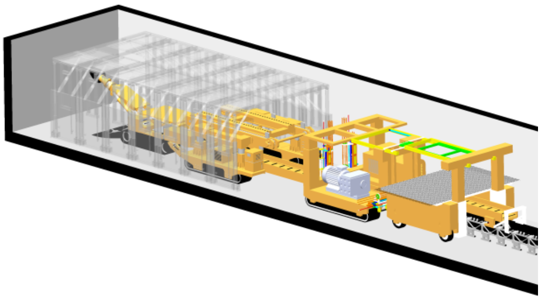
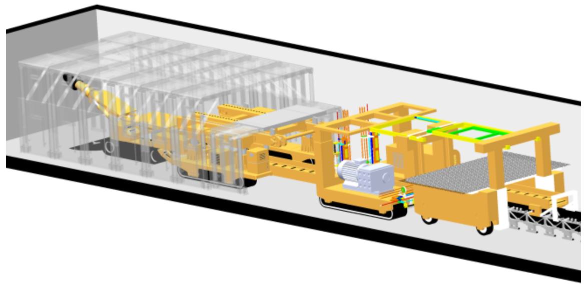


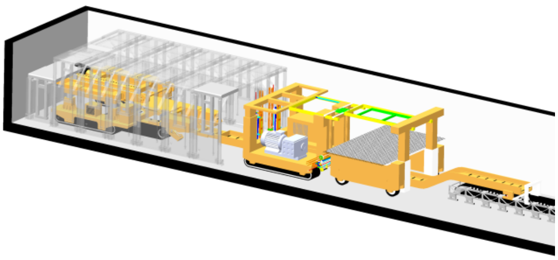
Fig.1 Overall Diagram of the Self-moving Support and Anchoring Unit



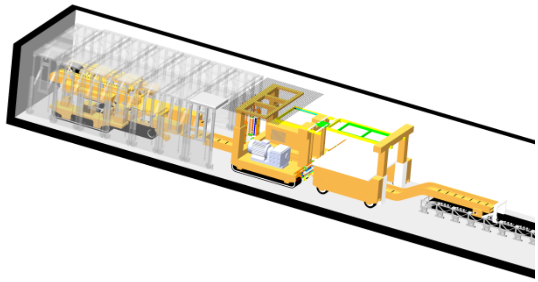
(a) Initial state of the whole unit



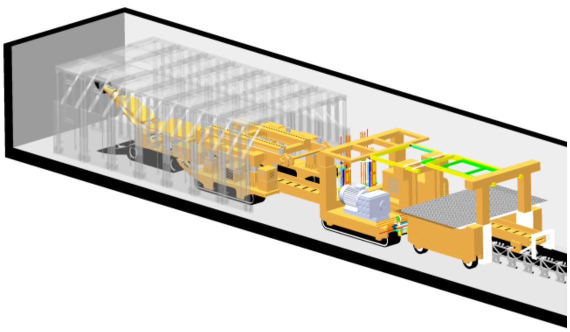
(b) Advance support shrinks and is clamped on the supporting vehicle



(c) Supporting vehicle transports advance support to the right location and release it. At the same time, anchoring robot carries out anchoring operation.



(d) The released advance support extends, lifts and supports the roadway roof to realize the temporary support of the roadway



(e) Tunneling robot starts a new round of excavation, and the anchoring robot continues the anchoring and other permanent support operations

Fig.2 The Operating Principle of Robotized Self-moving Anchor-supporting Unit

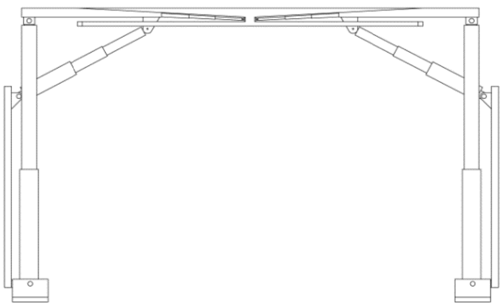
in the rear area of the supporting robot, as Fig. 2 (c).

Step 4: The released advance support extends, lifts, and supports the roadway roof to realize the temporary support of the roadway, as Fig.2 (d).

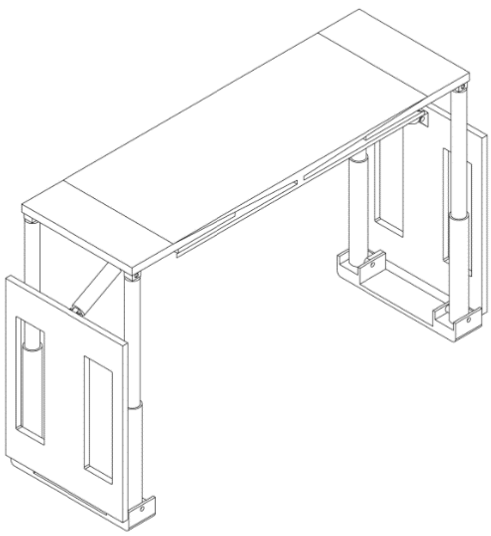
Step 5: The tunneling robot moves forward a cut depth and starts a new round of excavation. At the same time, the anchoring robot continues the anchoring and other permanent support operations in the rear area of the supporting robot, as Fig.2 (e).

Step 6: Repeats Step 2 to Step 5.

The supporting robot consists of several groups of advance support. Every advance support is composed of a retractable top beam, a retaining plate, a supporting pillar, and a base, as shown in Fig. 3. The roof beam of the advance support is composed of the main body and the telescopic parts. A hydraulic cylinder connects the main body of the top beam and the auxiliary top beam; the retaining structure is composed of the retaining plate and the retaining jack, hinged with each other. The supporting column hinges with the retractable top beam and the base respectively. The working flow of each advance support can be summarized as "pressure relief-pole lowering-shrink (transverse) – moving forward - stretching-lifting- pressure stabilization ". Permanent support is conducted in the rear area of supporting robots. Thus, it can keep workers away from dangerous areas such as roadway cross-section to ensure their safety; on the other hand, excavating and supporting operations can be carried out concurrently to alleviate the contradiction between excavation and support and improve excavation efficiency.



(a) Front View



(b) Side View

Fig.3 Structure Sketch of the Supporting Robot

3 Optimum Supporting Time

Support strength refers to the support force given to the roof by the support in the unit area. From the safety point of view, the greater the support strength, the better it is. However, from the economic point of view, the support strength should be reduced as much as possible on the premise of ensuring safety. This is because the increase of support strength is at the expense of increasing the amount of support material and reducing workspace.

Based on the actual working condition of stope support and a large number of measured data, Zhenqi S. [22] put forward the concept of effective support capacity of stope support, analyzed the relevant influencing factors, studied the relationship between support strength at weighting time and roof position (which can be expressed by roof subsidence at anywhere of the controlled roof), and proposed that the support can work at "given deformation" and "limited deformation" with the relative to the position of the old roof. The "rock beam position equation" of support working under the "limited deformation" condition is established, and the specific method of establishing the position equation in the production site is given. In addition, the design criteria of roof control and the corresponding mechanical guarantee conditions are put forward based on the statistical analysis of major roof accidents and the practical experience of effective control, which provides a basis for rational selection of stope support forms and determination of support density [23-26].

The strength of support under the condition of "given deformation" is:

$$q_z = m_{z1}\gamma_{z1} + \frac{m_{z2}\gamma_{z2}}{2} \tag{1}$$

where, m_{z1}、m_{z1} is the height of the first layer and the second layer of the direct top, respectively, m; γ_{z1}、γ_{z2} is the bulk density of the first layer and the second layer of the direct top, respectively, kg/(m^2 · S^2).

The equation of position state of the support under the condition of "limited deformation" is:

$$P_{\mathrm{T}} = A + K\frac{\Delta h_{\mathrm{A}}}{\Delta h_{\mathrm{i}}} \tag{2}$$

Where, P_{T} is the support strength required in the normal propulsive stage of the working face, kN/m^2; A is the support strength of the direct roof, kN/m^2; $\triangle h_{\mathrm{A}}$ is the maximum roof subsidence at the rear of the controlled roof, m; $\triangle h_{\mathrm{i}}$ is the roof subsidence, m; K is the position constant, determined by the parameters of the rock beam and the roof control distance, and is:

$$K = \frac{M_E \gamma_E C}{K_T L_K} \tag{3}$$

Here, M_E is the thickness of the basic roof; m is the thickness of the basic roof, m; γ_E is the bulk density of the basic roof, kN/m^3; C is the periodic weighting step, m; K_T is the distribution coefficient of rock weight, the simple distribution coefficient between each mineral and melt in the rock is obtained by the weighted average of the content of each mineral in the rock; L_K is the controlled roof distance, m.

It can be seen from formula (1) ~ (3) that when the support works in the "limited deformation" state, the roof pressure is greater than that under the "given deformation" state, and it is directly related to the roof position that needs to be controlled, that is, the higher the roof position that needs to be controlled ($\triangle h_i$ is smaller), the greater the support strength needed; Whereas, the lower the roof position that needs to be controlled ($\triangle h_i$ is larger), the smaller the support strength is. When $\triangle h_i = \triangle h_A$, it is the "given deformation" state.

The equation of state shows that there is a mechanical equilibrium relationship between the working resistance of the support and the position of the basic roof rock beam to achieve equilibrium when the support works under the "limited deformation" state.

The research shows that with the roof subsidence, the gravity of overlying strata will be loaded on both sides of the coal body, and then a "stress arch" consisting of the peak abutment pressure of each stratum outside the "fracture arch" will be formed. The scope of the "stress arch" will continue to expand upward in a parabolic shape in the vertical plane of mining strike and inclination, and the strata within “stress arch” are the main supporting body [27], which will bear and transmit the overlying strata load. It can be inferred that the roof pressure applied on the support is not a constant value, but changes continuously with the roof sinking (before breaking), that is, there may be a minimum value.

On the premise of ensuring safety, the support strength should be reduced as much as possible. With the increase of mining depth, crustal stress will increase continuously, so that the support strength of support will be difficult to meet the requirement of "limited deformation". The support of fully mechanized excavation roadway will evolve into the working state of coexistence of "given deformation" (yielding support) and "limited support". Before the roof subsidence reaches $\triangle h_A$, the roadway surrounding rock has entered a stable equilibrium state because of its self-supporting ability, that is, there may be an optimum supporting time, which not only ensures the continuity of the roof surrounding rock and roadway space, but also minimizes the support intensity required by the roadway support, to reduce the support cost.

4 Numerical Simulation and Analysis

Based on the geological conditions of QISHAN Mine, the corresponding mechanical coupled numerical model of surrounding rock and support is established, and the advanced support scheme is studied by numerical simulation.

According to the results of geological drilling [28], Table 1 gives the occurrence of coal seam and its physical and mechanical parameters in QISHAN Coal Mine. Based on the Mohr-Coulomb yield criterion with tension cut-off, a coalfield geological model is established, which is 36 m long, 25 m wide and 46.6 m high. The roadway cross section is a rectangle with 5.0 m wide and 3.6 m high. It is meshed into 264584 grid units. According to the research in the reference[29], the calculation error of the model is less than 10%, which meets the engineering requirements. The load applied on the upper boundary is calculated with the mining depth of 1030m, and the vertical movement of the lower boundary is restricted vertically. According to the measured results, the vertical crustal stress is 27.1 MPa and the two horizontal crustal stress is 40.5 MPa, and the lateral coefficients is 1.49.

The supporting robot consists of seven groups of advance support, each of which is 5 m of long, 1.6 m wide, and 3.6 m high. The top beam and the lateral plate of the support is 0.5m thick. The material of

Table 1 Geological Conditions and Mechanical Parameters in QISHAN Coal Mine

No.	Layer name	Density /(kg/m^3)	Thickness /m	Deep Tired /m	Bulk Modulus /GPa	Shear Modulus /GPa	Cohesion /MPa	Internal Friction angle /°	Strength of Extension /MPa
1	Sandstone	2650	24.0	1078.6	6	3.6	3.00	35	2.47
2	Sand Mudstone	2000	4.0	1036	5	3.0	2.00	33	1.78
3	Coal	1650	3.6	1054.6	3	2.0	0.08	18	0.5
4	Mudstone	2550	15.0	1051	5	2.3	1.20	28	0.8

advance support is Q235 steel. According to the structure shown in Fig. 3, we establish the supporting robot's Flac3D model, as shown in Fig.4.

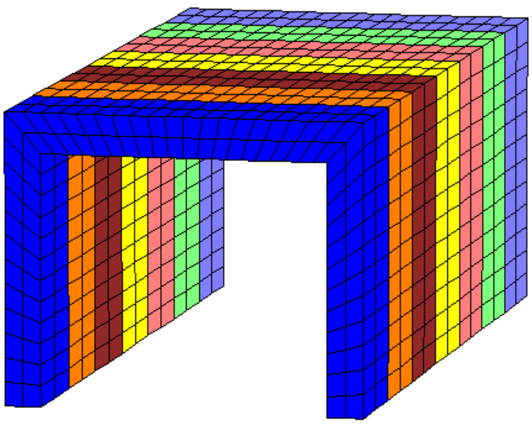


Fig.4 Flac3D Model of the Supporting Robot

Based on the above description, the numerical simulation model and the extent of surrounding rock-advance support in QISHAN Mine is established, as shown in Fig.5.

Assumptions: 1) the roof, floor and two sides of the roadway are loaded uniformly; 2) the roof of the support is in good contact with the roof of the roadway; 3) the support base is in face contact with the floor of the roadway, and the contact is good.

Fig.6 shows the force model of the advance support, where H is the height of support, L is the width of support, F_1 is the pressure of roadway roof to support, F_2 is the support pressure of roadway floor to support, F_3 is the pressure of two sides of the roadway to support, F_4 is the pressure of support cylinder, F_5 is the pressure of support pillar, mg is the weight of support. Then the vertical force of advance support in balance status is:

$$F_1 + mg = 2F_2 \tag{4}$$

The vertical force on the top beam of the support is:

$$\sum F_1 = 2F_4\cos\alpha + 2F_5 \tag{5}$$

Where, α is the angle between the lateral plate and the top beam. According to the structure of advance support, α=30°. The strong coupling between support and surrounding rock is the foundation of the stability of the support-surrounding rock system. The force of the leading support on the top of the support and the load of the overlying strata on the top of the support is a pair of interaction forces. The pressure F_1 of the roadway roof to support can be calculated by the following formula.

$$F_1(x,y) = \iint_A q(x,y)dxdy \tag{6}$$

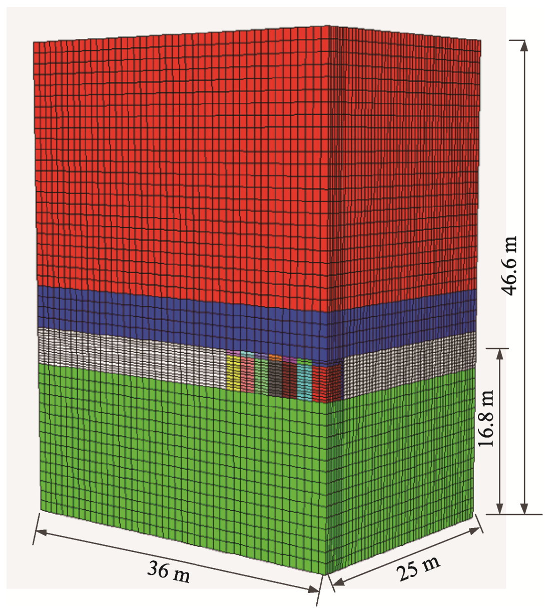


Fig.5 Mechanical Coupling Model of Roadway Surrounding Rock-advance Support

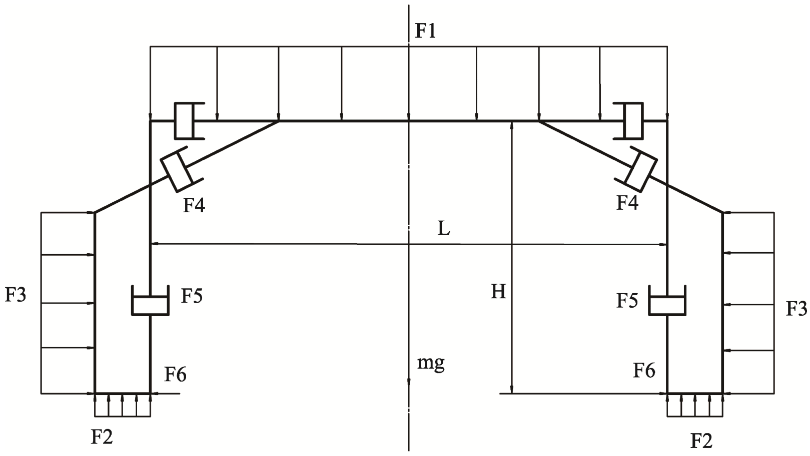


Fig.6 Mechanical Model Diagram of the Advance Support in Roadway

Where, $q\ (x, y)$ is the distribution function of the load of overlying strata to the support, N/m^2.

Using FLAC3D, the deformation of surrounding rock and the pressure on the top and bilateral of advance support are analyzed and calculated every 2 mm in the range of 0-20 mm of the roof free subsidence amount before supporting (namely reserved roof subsidence amount, when the roof subsides to the reserved amount, the advance support will support the roadway roof to prevent the roof from the further subsiding). The roof pressure, the horizontal and vertical pressure on advance support, the roof subsidence, and floor heave are obtained when it balances. The computational results are shown in Table 2. Fig. 7 shows the roadway surrounding rock deformation and the roof pressure at different reserved roof subsidence when being stable. Fig. 8 presents the pressure curves of every part of the advance support at different reserved roof subsidence when being stable. It can be seen that the surrounding rock of the roadway will reach a stable level under the support of the advance support, and the roof pressure will decrease first and then increase with the increase of the reserved roof subsidence. This shows that due to the self-supporting force of roadway surrounding rock, with the subsidence of roadway roof, the roadway roof pressure has been released to a certain extent. However, with the further subsidence, the self-supporting stability of roadway roof is destroyed, and the roof pressure does not drop but rises. At this time, if the support is not timely, the roof will collapse, that is, roof fall accident. From Fig. 8, we can see that with the increase of the reserved roof subsidence, the vertical pressure onto the support top beam decreases from 3MPa to 0.58MPa, which decreases by 2.42MPa or 80.67%, and the horizontal pressure decreases from 40MPa to 20MPa, which decreases 20MPa or 50%; the vertical pressure of the support column pillar sharply decreases from 90MPa to 20MPa, reducing 70MPa or 77.78%, and the horizontal pressure decreases from 60MPa to 20MPa, decreasing by 40% MPa or 66.67%. This is beneficial to reduce the support strength and increase the stability of the support.

To sum up, with the increase of reserved roof subsidence (active yielding pressure of advance support), the roof subsidence and floor heave of Roadway when balance after supporting show an increasing trend, and eventually tend to be stable, the roof pressure of the roadway shows a trend of decreasing first and then increasing. When the reserved roof subsidence is about 8-15 mm, the roof pressure on the advance support is smaller (only 0.58 MPa at 10 mm), and the change of roof subsidence and floor heave is not obvious compared with other subsidence, which is the best support window interval, that is, the optimum supporting time (The range between the two vertical dashed lines in Fig.7).

Table 2 Deformation of Roadway and Pressure on Advance Support after Balance under Different Supporting Time

Yielding Roof Subsidence /mm	Roof Pressure /MPa	Pressure on the Advance Support /MPa				Roof Subsidence /mm	Floor Heave /mm
		top_z	pillar_z	top_x	pillar_x		
0	3.00	3.00	90.00	40	60	8.00	31.00
2.00	2.13	2.13	20	25	25	26.43	45.00
4.00	2.00	2.00	20	25	25	32.18	40.00
5.00	1.30	1.30	20	20	25	26.00	48.00
6.00	0.93	0.93	20	20	25	32.70	40.00
8.00	1.00	1.00	20	25	25	26.44	45.00
10.00	0.58	0.58	20	25	25	26.44	45.00
12.00	0.80	0.80	20	25	25	26.45	45.00
14.00	1.25	1.25	20	25	25	32.59	50.00
15.00	1.00	1.00	20	25	25	26.40	48.06
16.00	1.54	1.54	20	25	25	26.40	45.00
18.00	2.00	2.00	20	25	20	26.50	45.00
20.00	1.94	1.94	20	25	20	26.00	45.00

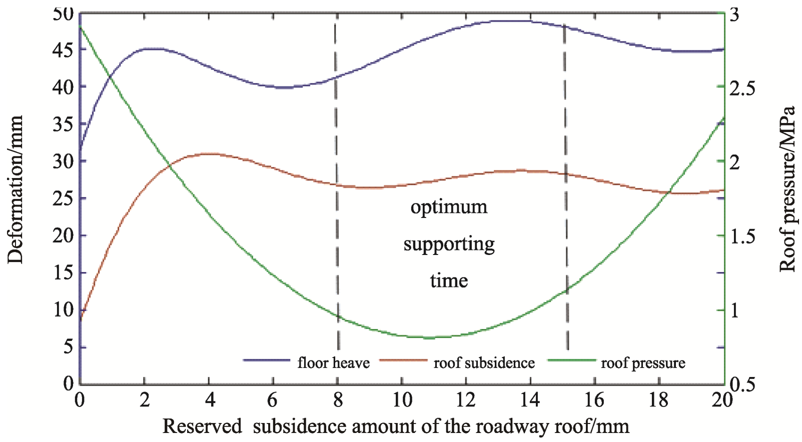


Fig.7 The Curve of Roadway Surrounding Rock Deformation and Roof Pressure with Different Reserved Roof Subsidence Amount

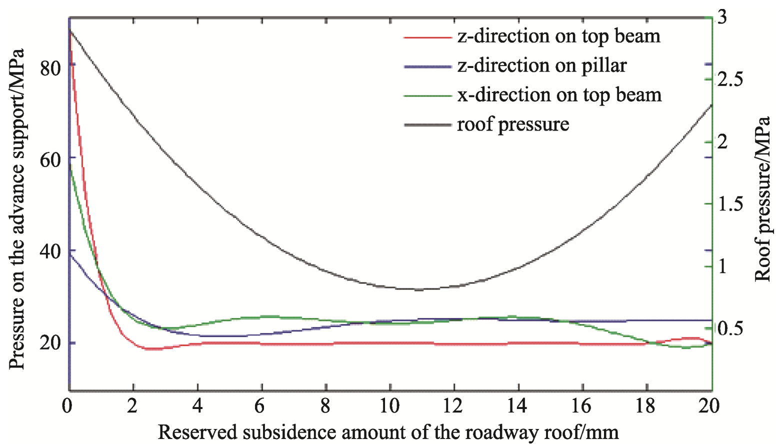
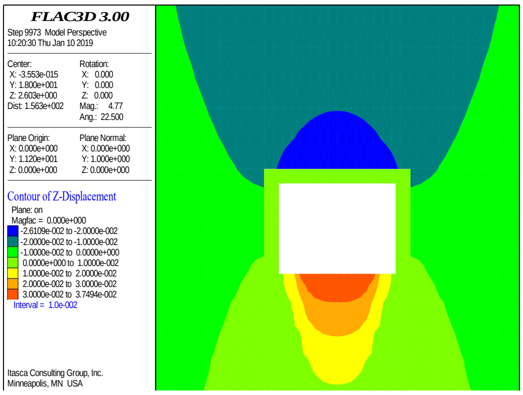
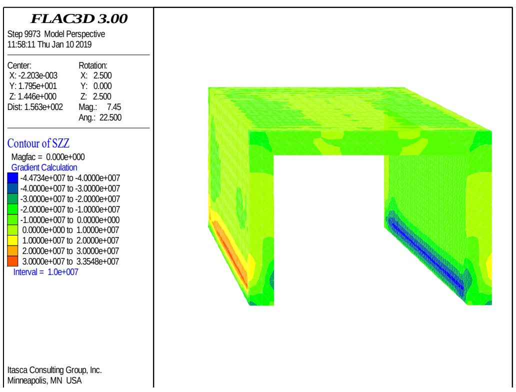


Fig.8 The Pressure Curve of Roadway Roof and Advance Support with Different Reserved Roof Subsidence Amount

Fig.9 shows the deformation and displacement nephogram of roadway surrounding rock and stress nephogram of advance support after being stable when the reserved roof subsidence is 10 mm. At this time, the maximum of roof subsidence, floor heave, and the pressure on the top of advance support are 26.1 mm, 30 mm, and 0.58 MPa, respectively. The deformation of roadway surrounding rock and the stress of support are both within the allowable and acceptable range, which can guarantee the safe supporting of the roadway.



(a) Roadway Surrounding Rock Displacement Nephogram



(b) Advance Support Top Stress Nephogram

Fig.9 Roadway Surrounding Rock Deformation and Load on Advance Support When the Yielding Roof Subsidence Amount Is 10 mm

5 Determination of Optimum Supporting Time

Therefore, with the subsidence of the roadway roof, there is an optimum supporting time during the support in a fully mechanized excavation roadway, because the surrounding rock of the roadway has a certain self-bearing capacity. When the supporting is completed at the optimum supporting time, after balance, the deformation of surrounding rock is smaller, the pressure load of surrounding rock to support is smaller, and the roof subsidence is smaller than those at other times [30]. Therefore, we should make full use of the self-bearing capacity and self-stability of surrounding rock during roadway excavation and support. The surrounding rock should be allowed to deform within the safe range on the premise of maintaining continuity, thus to reduce the support strength of the advance support and to reduce the cost of manual support. It is conducive to the safe and efficient support of deep fully mechanized roadway and lightweight, low-cost advance support design.

Based on the above research, the method to determine the optimum supporting time of advance supporting in a fully mechanized roadway is obtained, as shown in Fig.10.

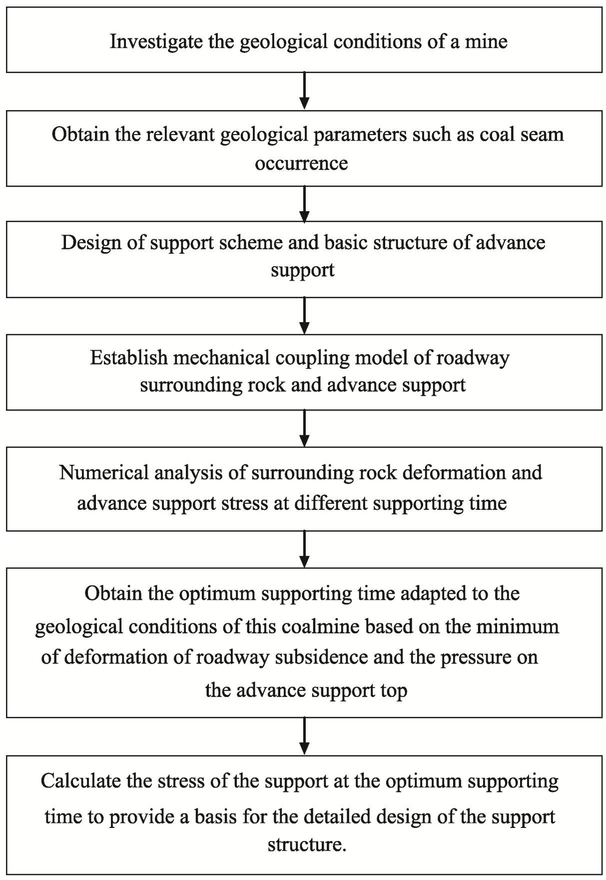


Fig.10 Determination Method and Process of Optimum Supporting Time

6 Conclusion

(1) Based on the designed Robotized self-moving anchor-supporting unit, the advance support scheme of fully mechanized excavation roadway is put forward, which has the advantages of multi-station cooperative operation, support-anchor coordination, and fast forward movement of supports and flexible self-movement of drilling anchor mechanism.

(2) The mechanical coupling model of surrounding rock and advance support is established. Taking the geological conditions of QISHAN coalmine as an example, the deformation and stress of surrounding rock in different supporting times were studied by using numerical simulation software FLAC3D. The results show that when the roadway roof subsidence is 8-15mm, the surrounding rock has a strong self-supporting capacity, and the roof pressure borne by the advance support is the smallest, about 0.58Mpa, which is conducive to the safe and effective support of deep fully mechanized roadway and the design of advance support. That is the optimum supporting time of the QISHAN coalmine roadway.

(3) This paper reveals the law between the deformation of surrounding rock and supporting time, and puts forward a method to determine the optimal supporting time by using the mechanical coupling model of surrounding rock and advance support. This provides a way to make full use of the self-supporting capacity of the surrounding rock, reduce the deformation of the surrounding rock, reduce the cost of roadway support, and improve the efficiency and safety of roadway support.

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