Control Mechanism and Support Technology of Soft Coal Roadway in the Fully Mechanized Mining Work Face

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Abstract: Aiming at characteristics of the soft coal roadway engineering geology and deformation, the exposure research of the soft coal seam, theoretical analysis, numerical calculation and program design were carried out. First of all, according to the disclosure, soft coal seam engineering characteristics and geological conditions in Xinxing coal mine were expounded. Meanwhile, the soft coal roadway bolt supporting axial effect, the bolt supporting transverse effect, the anchorage body mechanics strengthening mechanism and problems such as supporting strength have been analyzed. The paper pointed out that the soft coal with very small cohesive force can form a composite anchorage body under the combined action of the anchor cable group, the W-type steel band and the metal net. The soft coal body in the plastic damage area formed anchorage balance arch with a certain bearing capacity and adapted to the rock deformation, and which played an effective support role in the roof outside the balance arch of the roadway. Therefore, the full-cable support technology was proposed. And then, numerical calculation and comparative analysis were conducted on three schemes of the roadway with non-support, with combined support of “anchor bolt and cable” and the full-cable support. The results show that when the roof is supported by anchor cable, it not only controls the continued increase of the subsidence value of the roof, but also effectively suppresses the convergence amount of the floor heave value and the amount on the sidewalls of the roadway. Whether it is from the stress distribution situation, or the viewpoint of plastic zone scope, the combined support of full-cable is more reasonable than that with non-support and that with the combined support of “anchor bolt and cable”. Finally, based on the features of soft coal seam in No.2265 work face of Xinxing coal mine, the relevant support schemes were put forward, and its specific support parameters and cross-section designs were drawn as well.

Keywords: soft coal seam, mining roadway, surrounding rock control, numerical simulation, support design

1. Introduction

The soft broken coal lies in the sidewalls of soft coal seam roadway, and which is very easy to generate large deformation. Meanwhile, the soft coal roadway generally means mining roadway which is affected by one or more times of the different degrees and types mining influence. The mining influence will even more easily cause the stress concentration on the surrounding rock of soft coal seam roadway, result in high stress. Under the action of the mining high stress, the surrounding rock of roadway will occur a large range of broken zone and plastic zone. And then will be more broken, because of this, its supporting will be more difficult (Yu and Du 2014, Yu et al 2015a and 2015b, Zhang et al 2012). The problem of mining roadway support in soft coal seam has been more serious in the production for a long time (Xu and Kang 2013). At present, the support technology in the soft coal seam mainly uses the anchor bolt, anchor cable or shed supporting (Cheng and Zhao 2015, An et al 2007, Zhang and Huo 2015, Li et al 2015).

Based on the above soft coal seam control theories, this paper aims at the characteristics of the soft coal roadway engineering geology and deformation, the exposure research of the soft coal seam, theoretical analysis, numerical calculation and program design were carried out. Through the study of deformation mechanism and control principle in this kind of soft coal seam roadway, related support schemes were put forward. At the same time, its specific support parameters and cross-section design were drawn as well. Consequently, it is of great significance to the safety production and economic benefits of the coal mine.

2. Project Overview

The No.6 coal seam of Xinxing coal mine fully mechanized mining work face roadway project was exposed a soft and fragile monoclinal structure, with the average coal thickness 3.4 m including majority pulverized coal. Coal seam with complex structure including 2 to 3 rather thin layers of gangue. The immediate roof is the black carbonaceous mudstone, and main roof is the dark grey fine sandstone,
while immediate floor is the ash dark grey siltstone and the old floor is deep gray-gray white medium fine sandstone.

From the field geological conditions in the No.2265 work face roadway (as shown in Figure 1a), the roadway coal mass body is soft, easy to crush, with small cohesive force. After the excavation of the roadway, the stress of surrounding rock becomes concentrated and coal and rock mass stress state is transformed from the original three dimensional stress state to two dimensional stress state. Therefore, the strength of surrounding rock decreases, especially on the sidewalls of the work face roadway which occur different degrees rib spalling. In addition, increases the span of roadways and then increases the difficulty of the roof support.

From the viewpoint of the roadway excavation, the coal mass has been broken with larger fracture water in roadway which can be affected by small coal mining (as shown in Figure 1b). Besides, it is prone to occur large areas of rib spalling and roof fall when the roadway is under excavation, thus, which is extremely unfavorable to supports. The roadway excavation safety is difficult to get a powerful guarantee. Therefore, the design of the roadway support is a stability control problem for unstable extremely soft coal seam large section thick-layer compound roof seam roadway surrounding rock, with big control difficulty on sidewalls and poor safety condition on the roof.

Figure 1. Characteristics of coal seam in Xinxing coal mine. (a) Exposed soft coal seam; (b) The water leaching situation on sidewalls support structure.

3. Roadway Control Mechanism and Technology in Soft Coal Seam

3.1 The relationship between bolt and surrounding rock

The soft coal seam roadway in interactions region of bolt and soft coal mass within the anchorage zone composition of anchorage body which can form a unified bearing structure. The bearing structure can not only carry its own weight and the deformation force caused by deformation, but also can play the supporting role on the external surrounding rock. Furthermore, due to the bearing structure limiting the external deformation of surrounding rock, which can maintain the roadway stability.

(1) The axial action mechanism of bolt support: Coal and rock mass is in the state of the original rock stress before excavation. When the roadway is excavated, the stress of a certain aspect in coal and rock mass is released to destroy the original mechanical equilibrium state. In this case, a new deformation and even rupture occurred in coal body. In the condition of low confining pressure, the residual strength of the original rock is very sensitive to the confining pressure. When the confining pressure is increased slightly, the residual strength of the surrounding rock can be greatly increased. Therefore, the improvement of the bolt support strength can be achieved by improving the broken off load of a single bolt or narrowing the distance of row and line distance. On top of this, it is more favorable to improve the broken off load of a single bolt from the consideration of reducing support costs and improving the driving speed.

(2) The transverse action mechanism of bolt support: The surrounding rock deformation quantity will increase rapidly due to the influence of work face advance support stress in roadway during mining period. Therefore, the roadway deformation mainly appears in the form of weak plane dislocation of the ruptured coal and rock mass along the crack and expansion. At this point, the bolt plays an important role in the transverse effect to improve the weak plane shear capacity within the anchorage range. Meanwhile, this support can also halt or delay ruptured coal and rock mass weak plane dislocation. The support of the anchor bolt to improve the shear capacity of the weak plane can be represented in the following formula:

$$\Delta \tau = \tau_1 + \tau_2 + \tau_3$$

where $\Delta \tau$ is the improved value of bolt supporting weak plane shear capacity, MPa; $\tau_1$ is the equivalent shear strength caused by the normal component of the anchor bolt axial force along the weak plane, MPa, $\tau_1 = \sigma_b \cdot \eta \cdot \sin \alpha \cdot \tan \varphi_j$; $\tau_2$ is the equivalent shear strength caused by the tangential component of the anchor bolt axial force, MPa, $\tau_2 = \sigma_b \cdot \eta \cdot \cos \alpha$; $\tau_3$ is the equivalent shear strength caused by the anti-shear capacity of anchor bolt body, MPa $\tau_3 = \tau_{b_r} \cdot \eta \cdot (\sin \alpha - \cos \alpha \cdot \tan \varphi_j)$; $\sigma_b$ is the axial stress of anchor bolt, MPa; $\eta$ is the section area ratio of bolt cross section with the joint surface area of single bolt action; $\alpha$ is angle of bolts and joints, °; $\varphi_j$ joint friction angle, °; $\tau_{b_r}$ is the bolt shear stress of the cross section, MPa.

(3) The improvement mechanical parameters of the anchorage body: The interaction of the anchor bolt and surrounding rock within the anchorage zone compositions of the anchorage body to form a unified bearing structure. When the mechanical parameters of the anchorage body have changed, it is the first that the bolt support has a great improvement on the elastic modulus of the anchorage body, namely, which increases with the increase of bolt support strength; The second is that bolt support has rather greater influences on the $\varphi$ value of the anchorage body, namely, which increases with the increase of the bolt support strength, but the increase amplitude is gradually decreasing; The third is when the anchorage body in the residual strength stage, c* and $\varphi^*$ both have improved in varying degree compared with that with non-bolt support. Besides, the greater bolt strength is, the larger $\varphi^*$ of the anchorage in the residual strength phase is, with the maximum increase of...
more than 90% under test conditions while $\varphi^*$ has changed little.

### 3.2 Study on the roadway support strength in soft coal seam

In the process of using the bolt to support the roadway, the bolt support strength is a key factor to determine whether the roadway by using bolt support can succeed. Generally speaking, the strength of bolts can provide mainly depends on the maximum load of the bolt, as well as the row and line distance of the anchor bolt. The confining pressure provided by the bolt support is:

$$\sigma = \frac{P}{sd} \quad (2)$$

where, $\sigma$ is the strength of bolt support, MPa; $P$ is axial load of the bolt, MN; $s$, $d$ are row distance and line distance of bolt support, m.

### 3.3 Soft coal seam roadway roof’s full-cable support technology

Due to the fissure development, when the soft structure of coal body adopts the “bolt, metal net, W-type steel band and anchor cable” to support roadway, as well as the small prestressed of the anchor bolt, the collapsing of the soft coal cannot be effectively controlled around the bolt. Together with the blasting in the excavation process or the vibration in the coal-cutting process of roadheader, then soft coal body falls from the plate on both sides of the bolt, there formed cracks between the support plate and top coal. Therefore, the prestressed of the anchor bolt gets reduced, until the complete loss of the prestressed, and finally the bolt failure. Through the field observation, it is found that there is no failure of the anchor cable, and the reason is that the prestressed of the anchor cable is large (above 120 KN), which can effectively control the caving of soft coal body. When the anchor cable is in the small support density, the main effect is suspension function. When the anchor cable reaches a certain density (that is, the intensive of anchor cable support), which has the same effect as the anchor and play the role of strengthening the coal body. The soft coal with very small cohesive force can form a composite anchorage body under the combined action of the anchor cable group, the W-type steel band and the metal net. In particular, the coal body which is easy to loose in the plastic damage area can formed anchorage balance arch with a certain bearing capacity and adapted to the rock deformation. The anchorage balance arch plays an effective support role in the roof outside the balance arch of the roadway. Because of length, prestressed and carrying capacity of the anchor cable is much larger than the bolt, therefore, the bearing capacity of anchorage balance arch formed by anchor cable support are much larger than anchorage balance arch formed by bolt support.

### 4. Numerical Calculation and Comparative Analysis of Roadway Support Design

According to the analysis of data and reference to the project with similar conditions, three kinds of support schemes and support parameters for numerical calculation are proposed, as follows:

1. Coal roadway without support: For the needs of the problem comparativeness and analysis, numerical analysis on the condition of non-support in the roadway has been carry out.
2. Coal roadway with combined support of “anchor bolt + cable” on the roof: The paper analyses the control effect of bolts and anchor cables on soft coal roadway. Where the row and line distance of the roof bolt is 800×800mm; The row and line distance of the anchor bolts on sidewalls is 700×800 mm; The row and line distance on the roof cables is 1200×800 mm.
3. Coal roadway with the full-cable support on the roof: The paper analyses the control effect of short anchor cables and long anchor cables on soft coal roadway. Where the row and line distance of the roof short cable (5000 mm) is 800×1600 mm; The row and line distance of the roof long cable (8000 mm) is 1200×1600 mm; The row and line of the anchor bolts on sidewalls is 700×800 mm.

The calculation support parameters of anchor bolt and anchor cable are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Length (m)</th>
<th>Diameter (mm)</th>
<th>Anchorage length (m)</th>
<th>Prestress (kN)</th>
<th>Anchorage force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchor bolt</td>
<td>2.4</td>
<td>20</td>
<td>1.0</td>
<td>360</td>
<td>25</td>
</tr>
<tr>
<td>Anchor cable</td>
<td>6.3</td>
<td>15.24</td>
<td>2.0</td>
<td>360</td>
<td>144</td>
</tr>
</tbody>
</table>

### 4.1 Roadway model and calculation parameters

In order to ensure the smooth entry of fully mechanized mining equipment, as well as roadway after the final deformation can meet the ventilation, pedestrian and other safety production requirements, the roadway section was designed as a rectangular with the specific size with 3.6×2.8 m to establish the corresponding analytical model. Then, the model was established based on FLAC (Fast Lagrangian Analysis of Continua), with the size of 100×80×80 m, and with the width 3.6×2.8 m of roadway. The left, right and bottom boundaries of the model are displaced and fixed constraint boundaries, with the upper boundary is the stress boundary. Meanwhile, imposing uniform loads according to thickness of the overlying strata, upper boundary of the model from the surface of the earth is 787 m high. Therefore, 20.856 MPa force should be applied.

The general rock strata in the material model is selected as the Mohr-Coulomb model. Based on this, the mechanical parameters of the rock strata, coal seam and mechanics of jointed rock masses in the numerical model are determined according to the test report and the field condition, as shown in Table 2.
Table 2. Mechanical parameters of the main rock stratum.

<table>
<thead>
<tr>
<th>Rock-stratum name</th>
<th>Bulk modulus (GPa)</th>
<th>Shear modulus (GPa)</th>
<th>Density (kg·m⁻³)</th>
<th>Internal friction angle (°)</th>
<th>Adhesive force (MPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overlying strata</td>
<td>2.4</td>
<td>9.0</td>
<td>2500</td>
<td>36.0</td>
<td>2.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2.5</td>
<td>7.0</td>
<td>2400</td>
<td>31.5</td>
<td>3.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Siltstone</td>
<td>3.0</td>
<td>9.0</td>
<td>2500</td>
<td>48.0</td>
<td>2.5</td>
<td>/</td>
</tr>
<tr>
<td>Coal seam</td>
<td>1.4</td>
<td>3.18</td>
<td>1400</td>
<td>32.0</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Siltstone</td>
<td>3.0</td>
<td>9.0</td>
<td>2500</td>
<td>48.0</td>
<td>2.5</td>
<td>/</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2.5</td>
<td>7.0</td>
<td>2400</td>
<td>31.5</td>
<td>3.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>2.4</td>
<td>6.4</td>
<td>2300</td>
<td>32.5</td>
<td>1.8</td>
<td>3.5</td>
</tr>
</tbody>
</table>

4.2 Analysis of results

The calculation results of the three kinds of support schemes are shown in Figure 2, Figure 3 and Figure 4, respectively. Firstly, for the roadway surrounding rock in the condition without non-support, regardless of the roof and floor or the sidewalls of the roadway, the displacement degrees are all larger from the viewpoint of the roadway deformation. Furthermore, from the change trend of the curve, the deformation of the roadway surrounding rock is not stable, so the roadway has lost its stability and collapsed. Secondly, for the coal roadway with combined support of “anchor bolt + cable” on the roof, the deformation value of the roadway is significantly smaller than that with non-support. In this case, the maximum roof subsidence value is 81.35 mm, as well as the floor heave value is 120.23 mm, and sidewalls are respectively 60.20 mm and 68.28 mm. Then the deformation tends to be stable. From the displacement field contour map it can be seen, whether it is the roof and floor or the sidewalls, the loose range is significantly small, equivalent to 0.5 times of the roadway size. Finally, for the coal roadway with the full-cable support on the roof, the deformation value of the roadway is smaller than that with the non-support and that with the combined support of “anchor bolt + cable”. In this case, both the maximum roof subsidence value and the floor heave value are 38.16 mm and 48.15 mm, respectively. Besides, sidewalls of the roadway are respectively 28.65 mm and 44.03 mm, it means that the deformation tends to be gradually stable. From the displacement field contour map, it can be seen, whether it is the roof and floor or the sidewalls of the roadway, the loose range is significantly smaller, and its range is less than 0.5 times of the roadway size.

4.3 Scheme comparison

According to the above numerical analysis, the displacement value and safety factor of the roadway surrounding rock can be obtained when carried out with non-support, the combined support of “anchor bolt + cable” and full-cable support, results as shown in Table 3. It can be seen from the table, control effect of roadway surrounding rock deformation with combined technology of “anchor bolt and cable” is significant than that with non-support; In addition, the stability of the roadway is greatly improved with the safety coefficient calculated as 1.21. Owing to the poor ability of anchor bolt and many shear failures also occurred in the roof, it is unfavorable for the stability of roadway in the long run; When applying the full-cable support, the anchor cable will not only play the role of tension, but also cables will crush with each other to form the compression arch action to reinforce the coal body and improving the integrity and stability of the coal body. Therefore, the results of numerical calculation show that under this scheme, the roadway surrounding rock displacement values and the plastic zones become.
significantly reduced. In this case, with the stress distribution rather reasonable, and the safety coefficient increases to 1.37. Therefore, the temporary stability of the roadway gets effectively protected, which is favorable for the stability of roadway in the long run.

As it can also be seen from the Table 3, when the roof is supported by anchor cable, it not only controls the continued increase of the subsidence value of the roof, but also effectively suppresses the convergence amount of the floor heave value and the amount of the sidewalls in roadway. Available from the previous analysis, whether it is from the stress distribution situation, or the viewpoint of plastic zone scope, the combined support of full-cable support is more reasonable than that with non-support and that with combined support of “anchor bolt + cable”.

Table 3. The maximum amount of displacement and safety factor of the roadway surrounding rock support scheme.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Maximum displacement of the arch crown (mm)</th>
<th>Maximum displacement of the floor heave (mm)</th>
<th>Maximum displacement of low sidewall (mm)</th>
<th>Maximum displacement of high sidewall (mm)</th>
<th>Safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-support</td>
<td>2131</td>
<td>1761</td>
<td>1651</td>
<td>1619</td>
<td>0.74</td>
</tr>
<tr>
<td>“Bolt+ cable” combined support</td>
<td>81.35</td>
<td>120.23</td>
<td>60.20</td>
<td>68.28</td>
<td>1.21</td>
</tr>
<tr>
<td>Full-cable support</td>
<td>38.16</td>
<td>48.15</td>
<td>28.65</td>
<td>44.03</td>
<td>1.37</td>
</tr>
</tbody>
</table>

5. Determination of Support Schemes
5.1 Roadway excavation and design principles

The return airway and conveyance roadway of No.2265 work face are both excavated along the roof of coal seam. The roof is fine sandstone with high-strength which stability is higher, but the coal at the floor under the action of pressures will show a certain floor heave. Based on this, the bottom coal should be promptly cleaned up.

Since Xinxing coal seam occurrence extremely unstable and large deformation of seam thickness, when large seam thickness is (namely, top coal thickness greater than 2 m). After excavating, because of the roadway to meet the requirements, then the roadway roof coal impossible all down. Therefore, it will result in No.2265 work face double roadways maintenance difficulties. In addition, since the entire coal roadway appear loose structure, when using bolt support on the roof rock, due to the small bolt prestressing cannot effectively control soft coal body caving around the bolt. Then, which is easy to form gap between the plate and the top coal. Finally, bolt prestressed reduced until failure.

Therefore, the roof should be adopted large prestressed bolt support. Furthermore, in order to achieve fast lane excavating in loose seam and provide workers with a safe space environment, the temporary support should be completed as soon as possible. Based on this, the paper put forward the roof support scheme is firstly arranged with short anchor cable, and then the long cable is arranged (long and short cable alternate arrangement). Namely: Short cable plays the role of interim support (equivalent to supporting the role of bolt), while long cable plays secondary support role. In addition, to conduct advanced horizontal bolt support when necessary.

To sum up, the design of the sidewalls takes the combined support technology with the high-strength bolt as the foundation, with the roof adopts the high prestressed long anchor cable and short anchor cable as the core. According to the results of above numerical analysis, the specific support scheme determined as sidewalls of high-strength bolt and the roof of full-cable support. The specific parameters are shown in Table 4, and the specific scheme is shown in Figure 5.

Table 4. Main support parameters of coal roadway support scheme.

<table>
<thead>
<tr>
<th>Position</th>
<th>Support structure</th>
<th>Row and line space (mm×mm)</th>
<th>Specifications (mm×mm)</th>
<th>Minimum prestressed (kN)</th>
<th>Minimum anchorage force (kN)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>Short cable</td>
<td>800×800</td>
<td>Φ15.24×5000</td>
<td>120</td>
<td>230</td>
<td>Steel strand</td>
</tr>
<tr>
<td></td>
<td>Long cable</td>
<td>1200×800</td>
<td>Φ15.24×8000</td>
<td>120</td>
<td>230</td>
<td>Steel strand</td>
</tr>
<tr>
<td>High sidewall</td>
<td>Bolt</td>
<td>700×800</td>
<td>Φ20×2400</td>
<td>100</td>
<td>80</td>
<td>Thread steel</td>
</tr>
<tr>
<td>Low sidewall</td>
<td>Bolt</td>
<td>700×800</td>
<td>Φ20×2400</td>
<td>100</td>
<td>80</td>
<td>Thread steel</td>
</tr>
</tbody>
</table>

5.2 Field monitoring and application effect

Figure 6 illustrates the variation curve of displacement of surrounding rock. When monitoring in time is about 80d, the deformation of roof to floor and sidewalls trend to small. Roof to floor convergence value is 120.7 mm, sidewalls average convergence value is 99.8 mm, respectively. In this case, both of them have reached a stable deformation curve.
The supporting method has played an inhibitory role on the deformation of the sidewalls and the roof to floor of the roadway, meanwhile, the deformation of the surrounding rock is within the control range, which can meet the production needs and safety of the roadway.

Figure 5. The whole section bolt support design of roadway in Xinxing coal mine.

Figure 6. Deformation monitoring curve.

6. Conclusions

(1) From the viewpoint of the roadway excavation, the structure of coal seam in Xinxing coal mine is rather complicated, which is soft and fragile with small bond force. In addition, the sidewalls may also affect by small coal mining, meanwhile, there also with rather large amount of fissure water. Besides, it is easy to occur a large area rib spalling and roof fall at the time of excavation which is extremely unfavorable to the support. Therefore, the design of the roadway support belongs unstable soft coal seam roadway surrounding rock stability control.

(2) The roadway control mechanism in soft coal seam is mainly manifested as the bolt axial action, the lateral action and the strengthening mechanism of anchorage body mechanics parameters and other mechanisms. In this case, the key technology with “bolt, metal net, W-type steel band and anchor cable” and full-cable support in the soft coal seam roadway roof are proposed.

(3) Numerical calculation shows that: The full-cable support can form the compression arch action to reinforce the coal body and improve the integrity and stability of the coal body, since it will not only play the role of tension but also crush with each other. Therefore, the temporary stability of the roadway gets effectively protected, and it is favorable for the stability of roadway in a long run.

(4) For the coal seam characteristics in Xinxing coal mine No.2265 work face, the design of sidewalls takes the combined support technology with high-strength bolt as the foundation, with the roof adopts the high prestressed long anchor cable and short anchor cable as the core, meanwhile, its specific support parameters and cross-section designs were drawn as well.

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