Failure characteristics and control technology for large-section chamber in compound coal seams—A case study in Tashan Coal Mine

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Abstract
The coal production exploited from extra-thick coal seams accounts for 45% of China’s total coal production. With large coal output, the extra-thick coal seams require that the chamber section be more than 100 m². In case of parting (the noncoal rock, usually mudstone, sandwiched in the coal seam) in the extra-thick coal seams, the integrity of the coal seams will be damaged and the large-section chamber is extremely easy to occur rib spalling and roof leakage, which will increase the chamber’s supporting difficulty. To solve such problems, this paper took the electromechanical chamber in Tashan Coal Mine as the engineering background and analyzed the deformation and failure characteristics of this chamber surrounding rocks by the numerical simulation method during the excavation process. The results indicated that the failure areas of surrounding rocks were mainly in partings, chamber ribs, and chamber dome with the failure depths of 15 m, 10 m, and 5 m, respectively. Based on the obtained deformation and failure characteristics, the supporting method of grouting integrated with high-strength bolts and anchor cables was put forward. The grouting method was firstly used to improve the integrity of the chamber surrounding rocks, and the high-strength bolts and anchor cables were used for supporting. Then, the supporting parameters of the bolts and anchor cables and the grouting parameters were optimized by the numerical simulation method. The optimized parameters were applied in the electromechanical chamber in Tashan Coal Mine, and the on-site chamber ribs lateral displacement and roof separation amounts were only 0.018 m and 0.012 m, respectively, indicating that the surrounding rocks were controlled effectively.

Keywords
compound coal seam, control technology, failure characteristics, large-section chamber
1 | INTRODUCTION

Ultra-thick coal seams are main seams in Chinese high efficiency for coal production. The arrangement of main roadway in the ultra-thick coal seam could not only increase the excavating velocity significantly, but also could increase the coal production. Sometimes, in order to meet the requirements of the installation and maintenance of underground electromechanical equipment and, washing and crushing of gangues, large-section chamber is formed by the local extension of the main roadway. Due to large production of the ultra-thick coal seam mining, the area of the large-section chamber shall be generally more than 100 m$^2$. In general, coal seams are softer and easily broken than strata. On the other hand, with the large-section chamber, the damage range of surrounding rocks is large. The discontinuous area in ultra-thick coal seams with partings is likely to occur separation. Then under the influences of underground pressure, the chamber is extremely easy to occur rib spalling and roof falling, thus increasing the difficulty in chamber support.

Currently, many researches on large-section chamber or roadway support have been carried out. Fan et al. used the numerical method to study the blasting-induced plastic failure of large-section chamber surrounding rocks. Based on the theory of elasticity and structural mechanics, Dang et al. gave a reasonable cross section of the tunnel, and the computing formulas of the hoop and radial stress in the tunnel. Bai et al. described the deformation and failure process of the large-section roadway under rich aquifers by the discrete element method. Coggan et al. studied the effects of weak immediate roof lithology on coal mine roadway stability. Kang et al. studied the support parameters of large-section roadway in weak rock strata. Zheng et al. revealed the decoupling mechanism of large-section roadway at a resin-rock interface through theoretical calculation. Tonon et al. studied the full-face tunnel excavation of two 260 m$^2$ tubes in clays with sub-horizontal jet-grouting under minimal urban cover.

The aforementioned researches mainly focus on the excavation methods, supporting parameters, failure characteristics of large-section chambers, and roadways. However, there are no in-depth studies on the failure characteristics and support schemes during the excavation process of the large-section chamber in compound coal seams which refer to the coal seam with partings. This paper firstly analyzed the geological conditions of the electromechanical chamber in Tashan Coal Mine. Then, the failure characteristics of the chamber surrounding rocks during the excavation process were analyzed by numerical computation method. According to the obtained failure characteristics, the support parameters of the chamber surrounding rocks were optimized. Besides, the stress states, deformation, and failure characteristics of chamber surrounding rocks were predicted after the supporting. Finally, the industrial experiment was carried out in the electromechanical chamber in Tashan Coal Mine.

2 | ENGINEERING BACKGROUND

2.1 | The geological conditions

As shown in Figure 1, Tashan Coal Mine is located in Datong coalfield in Datong city of Shanxi province in China. The upper Jurassic coal seams have been basically mined out, and the Carboniferous coal seams are under mining. The Carboniferous system 3-5# coal seams have the thickness between 14 m and 30 million tons.

To meet the requirements of coal transportation, 1070 transportation roadway was arranged in the floor of 3-5# coal seam in Tashan Coal Mine. It used the vertical wall and semicircular arched section due to its sound stability and high supporting intensity. As shown in Figure 2, the roadway has the width of 2.6 m. The supporting parameters are as follows.

The dome supporting scheme is as follows. The thread steel bolt without left-hand longitudinal steel was adopted. It has the yield strength of 600 MPa, the tensile strength of 800 MPa, the diameter of 22 mm, and the length of 2.4 m. The spacing is 0.8 m × 0.8 m. The resin extended anchorage was used. The pre-tightening force of the bolt is 100 kN. The high-strength tray with the specification of was 130 mm × 130 mm × 10 mm adopted. The anchor cable has a diameter of 17.8 mm and a length of 7.8 m. The pre-tightening force of the anchor cable is 150 kN. A total of 5 anchor cables were used. The length of the anchorage was 2.5 m. One K2335 resin power stick and 3 Z2360 resin power sticks were used. The thickness of W steel strip is 4 mm, and the width is 250 mm. The metal mesh was used to protect the roof.

The supporting scheme of both ribs is as follows. The high-strength bolt was used for supporting. The material properties of the bolt are the same with those of the chamber dome. The spacing is 1 m × 0.8 m. The resin extended anchorage was used. The pre-tightening force of the bolt is 100 kN. The installation angle of the bolt near the roof is 10°. W steel strip has the thickness of 4 mm and the width of 250 mm. The metal mesh was used to protect the roof.

The boreholes around 1070 transportation roadway indicated that 3-5# coal seams had the thickness of 18.14 m and
FIGURE 1 The position of Tashan Coal Mine

FIGURE 2 The supporting scheme of 1070 roadway

5 layers of mudstone parting with different thickness. Figure 3 shows the occurrence of roof and floor, coal seams and parting.

2.2 | The excavation scheme of the chamber

To meet the installation of underground electromechanical equipment, the large-section full coal chamber was formed by local extension of the original 1070 transportation main roadway. According to the design requirements, the chamber’s length is 9.5 m and the height is 11.85 m. The concrete extension steps are shown in Figure 4.

During the extension process, the coal transportation should be ensured. Meanwhile, in order to protect personnel safety, U-shaped steel supports were arranged in 1070 transportation roadway. The round steel link chains were used between sheds, and the cement backboard and plastic woven bags with crushed gangue were used for filling behind the shed.
During the excavation process, the failure states of large-section full coal roadway surrounding rock could provide guidance for the prediction for chamber failure and supporting schemes. To reveal the failure characteristics of surrounding rocks, the deformation and failure numerical model of chamber surrounding rocks was established to analyze the evolution laws of failure characteristics.

3.1 | The numerical simulation

In the numerical simulation, the mechanical parameters of surrounding rocks and coal seams at the stope were firstly obtained. Then, the excavation of the model was carried out according to excavating technology. Finally, the failure characteristics of surrounding rocks were monitored.

3.1.1 | Rock mass strength criterion at the stope

The complete mechanical parameters of rock mass near the chamber were obtained through experiment, as shown in Table 1. There are a large number of irregular joints and fissures in the chamber surrounding rocks, so the rock mass parameters measured in the experiment were higher than the strength of rock mass at the stope. To simulate the strength reduction, Hoek and Bra proposed the generalized Hoek-Brown criterion. The specific expression is as follows:

\[ \sigma_1 = \sigma_3 + \sigma_{ci} \left( \frac{m_b \sigma_3}{\sigma_{ci}} + s \right)^a \]  

where \( \sigma_1 \) is the maximum principal stress; \( \sigma_3 \) is the minimum principal stress; \( m_b \) is a reduced value (for the rock mass) of the material constant \( m_i \) (for the intact rock); \( s \) and \( a \) are constants which depend upon the characteristics of the rock mass; \( \sigma_{ci} \) is the uniaxial compressive strength (UCS) of the intact rock pieces. The expressions of \( m_b, s \) and \( a \) are as follows:

\[ m_b = m_i \exp \left( \frac{GSI - 100}{28 - 14D} \right) \]
where GSI is the geological strength index; D is a “disturbance factor mi” which depends upon the degree of disturbance to which the rock mass has been subjected by blast damage and stress relaxation. It varied from 0 for undisturbed rock masses to 1 for very disturbed rock masses. 0 was selected here; mi is a material constant for the intact rock. RocData software could provide empirical parameters of GSI and empirical values of mi from China and USA. The values of mb, s and a by RocData are shown in Table 1.

### Table 1  Mechanical parameters of rock and rock blocks

| Lithology        | Elasticity modulus E/GPa | σci/MPa | Poisson’s ratio/μ | GSI | m_i | m_b | s   | a   |
|------------------|--------------------------|---------|------------------|-----|-----|-----|-----|-----|
| Medium sand      | 45.5                     | 69.4    | 0.26             | 86  | 17  | 9.098 | 0.2111 | 0.500 |
| Sandstone        | 36.2                     | 23.6    | 0.32             | 89  | 21  | 14.178 | 0.2946 | 0.500 |
| Mudstone         | 15.8                     | 17.4    | 0.29             | 65  | 10  | 2.865  | 0.0205 | 0.500 |
| Coal-mudstone    |                          |         |                  |     |     |       |      |      |
| 3-5# Coal        | 6.8                      | 13.2    | 0.26             | 75  | 11  | 4.504  | 0.0622 | 0.501 |
| Mudstone         | 6.5                      | 10.0    | 0.25             | 56  | 10  | 2.007  | 0.0075 | 0.504 |
| Mudstone         | 15.2                     | 7.2     | 0.31             | 63  | 12  | 3.201  | 0.0164 | 0.502 |
| Coarse sandstone | 35.1                     | 75.6    | 0.25             | 89  | 20  | 13.503 | 0.2946 | 0.500 |

\[
s = \exp \left( \frac{GSI - 100}{9 - 3D} \right)
\]

\[
a = \frac{1}{2} + \frac{1}{6} \left( e^{-GSI/15} - e^{-20/3} \right)
\]

where GSI is the geological strength index; D is a “disturbance factor mi” which depends upon the degree of disturbance to which the rock mass has been subjected by blast damage and stress relaxation. It varied from 0 for undisturbed rock masses to 1 for very disturbed rock masses. 0 was selected here; mi is a material constant for the intact rock. RocData software could provide empirical parameters of GSI and empirical values of mi from China and USA. The values of mb, s and a by RocData are shown in Table 1.

3.1.2 | Strain softening model of the coal mass

The strain softening phenomenon will occur during the compression process of the coal mass. That is, after the coal mass reached the peak strength, the strength will rapidly decrease to a relatively low level with the increase of the deformation. Based on compaction experiment, scholars generally hold that the strain softening model of the coal mass could be divided into the elastic stage, softening stage, and residual stress stage, as shown in Figure 5A. It was necessary to obtain the residual elasticity modulus, cohesion, and internal friction angle to get the strain softening model in the experiment. As shown in Figure 5B, the reliability of the strain softening model was verified by comparing the uniaxial compression stress-strain curves of coal samples in axisymmetric numerical simulation and compaction experiment.

![Figure 5](https://example.com/figure5.png)

**Figure 5** The strain and softening curves. (A) The strain softening constitutive model; (B) the comparison for the experiment and numerical simulation.
3.1.3 The establishment of the model

According to the geological conditions of the electromechanical chamber in Tashan Coal Mine, a two-dimensional model with the length of 150 m and the height of 54.43 m was established. The model’s grid size was between 0.1 m and 1.5 m. The generalized Hoek-Brown criterion was used by the rock mass. The Mohr-Coulomb strain softening model was used by the coal mass. The horizontal displacement was restrained by the right and left side of the model, and the vertical displacement was restrained by the bottom of the model. A 12.5 MPa uniform loading was applied on the top to replace the weight of the overlying 500 m rock strata. The excavation work was carried out according to the chamber excavation scheme. The model after excavation is shown in Figure 6.

3.2 Failure characteristics of chamber surrounding rocks

3.2.1 Failure characteristics of surrounding rocks during the excavation process

The failure characteristics of chamber surrounding rocks during the excavation process could provide the basis for the prediction of rib spalling and roof leakage, and ensure the safe transportation of coal in 1070 transportation main roadway. As shown in Figure 7, the tensile and shear failure areas of the chamber surrounding rocks were extracted during the excavation process.

As shown in Figure 7, after the excavation of 1070 transportation roadway, the surrounding rock failure areas were mainly in the positions of roadway dome and partings at the first stage. The surrounding rocks between the roadway chamber dome and partings were likely to occur collapses. At the time, the roof maintenance should be strengthened to prevent the dome leakage of 1070 main roadway. At the second stage, the failure areas of the surrounding rocks increased rapidly after the excavation of chamber dome. The partings in the coal seam, 1070 roadway floor and dome, and the chamber dome all experienced damages, so they also should be strengthened. At the third stage, the failure areas on the left side of the chamber increased markedly. The left side of the 1070 transportation roadway dome was basically damaged. At this time, the separation of the coal at the roadway dome should be prevented. At the fourth stage, both the right side of the chamber surrounding rock and the dome of the 1070 transportation roadway occurred failure. At this time, the dome of the 1070 transportation roadway should be reinforced, and meanwhile, the coal separation at the chamber dome should also be prevented. At the fifth stage, the right side of the 1070 transportation roadway was completely damaged, which should be reinforced to prevent coal separation. At the sixth stage, the failure areas on the right side of chamber increased. At this time, the surrounding rocks experienced the greatest damage, and the chamber should be supported in time.

3.2.2 Failure areas of surrounding rocks after excavation

The determination of failure areas of chamber surrounding rocks has important guiding significance for grouting reinforcement. Based on evolution laws of chamber surrounding rock failure characteristics during the excavation...
FIGURE 7  Failure laws of chamber surrounding rocks during the excavation process

FIGURE 8  Failure areas of chamber surrounding rock
process, the final chamber failure areas were fixed, as shown in Figure 8.

As shown in Figure 8, the failure areas were mainly in the partings in the coal seam, chamber floor, ribs, and dome. To further verify the accuracy of the failure areas in the numerical simulation, boreholes were arranged on the left side of the chamber to monitor the damage situations of surrounding rocks at positions of 2 m, 5 m, and 10 m. A large number of serious broken surrounding rock could be found at 2 m of the left side. The broken surrounding rocks were reduced obviously at 5 m, and there were still plentiful fractures. The surrounding rocks were basically intact at 10 m. The results of actual monitoring are well correspondent with the results in numerical simulation, thus verifying the accuracy of the numerical simulation results to a certain extent.

### 4 | THE SUPPORTING PARAMETERS OPTIMIZATION OF LARGE-SECTION FULL COAL CHAMBER

#### 4.1 | Mechanical parameters of resin power stick

To simulate the bolt and anchor cable support, RS2 could provide a wide range of beam and bar elements, including end anchored, fully bonded and tieback elements. Among them, tieback elements could not only conveniently define the anchorage lengths of bolt and anchor cable, cohesive strength, and stiffness of resin power stick, but also could bear the tension, compression, and shear action of surrounding rocks, so they are selected for simulation. The cohesive strength \( K_{bond} \) and stiffness \( S_{bond} \) were important parameters to determine the anchor cable and bolt. RS2 has given the empirical formula of \( K_{bond} \), as follows: \(^{11,31}\):

\[
K_{bond} \cong \frac{2\pi G}{10 \ln (1 + 2t/d)}
\]

where \( G \) is the shear elasticity of the resin; \( d \) is the diameter of the bolt and cable; and \( t \) is the thickness of the resin.

Farmer et al.\(^{26}\) have given the shear elasticity \( G \) of resin power stick as 2.25 GPa. According to formula (5), when the diameter of the bolt was 22 mm and the diameter of the borehole was 29 mm, \( K_{bond} \) was \( 2.0 \times 10^9 \) N/m/m. When the diameter of the anchor cable was 17.8 mm and the diameter of the borehole was 28 mm, \( K_{bond} \) was \( 2.6 \times 10^9 \) N/m/m. For \( S_{bond} \), Zipf et al.\(^{26}\) have provided the empirical values for numerical calculation, and the specific parameter was 400 kN/m.

| Properties | Values |
|------------|--------|
| Bolt/anchor cable | 210 |
| Elastic modulus/GPa | 250/470 |
| Tensile strength/kN | 100/150 |
| Pre-tightening force/kN | 400 |

**TABLE 2** Mechanical properties of supporting materials

![Figure 9](image)

**Figure 9** The optimization of bolt pre-tightening force. (A) Spacing; (B) pre-tightening force
4.2 Parameters optimization of the bolt and anchor cable

The prestress theory is often used for the design of support schemes of ultra-large-section chamber surrounding rocks. To optimize the spacing, the spacing of selected bolts was 0.6 m, 0.9 m, 1.2 m, and 1.6 m. The mechanical properties of supporting materials are shown in Table 2. The compressive stress of the chamber surrounding rocks was monitored through numerical simulation. The proper spacing of the bolts was selected. When the bolt spacing was 0.9 m, the bolt pre-tightening force of 40 kN, 60 kN, 80 kN, and 120 kN was selected. Figure 9 shows stress states of the chamber surrounding rocks with different bolt spacing and pre-tightening forces.

As shown in Figure 9A, when the bolt spacing was 0.6 m, 0.9 m, 1.2 m, and 1.6 m, the compressive stresses on the surface of the chamber were 0.1 MPa, 0.21 MPa, 0.45 MPa, and 0.51 MPa, respectively. When the bolt spacing was 1.6 m and 1.2 m, the intact compressive stress did not occur in the chamber surrounding rocks. The intact compressive stress occurred when the bolt spacing was 0.9 m and 0.6 m. Based on the above laws, the bolt spacing was 0.9 m.

As shown in Figure 9B, when the bolt pre-tightening forces were 40 kN, 60 kN, 80 kN, 100 kN, and 120 kN, the compressive stresses on the surface of the chamber were 0.11 MPa, 0.21 MPa, 0.31 MPa, 0.45 MPa, and 0.51 MPa, respectively. When the pre-tightening forces were 40 kN, 60 kN, and 80 kN, the intact compressive stress did not occur in the chamber surrounding rocks. The intact compressive stress occurred when the pre-tightening forces were 100 kN and 120 kN. Therefore, the 100 kN was chosen as the proper bolt spacing (Figure 10).

The final supporting parameters of bolts and anchor cables were obtained through parameter optimization, as follows. The bolt spacing was 0.9 m × 0.9 m. The pre-tightening force was 100 kN. The length of the bolt in chamber was 2.5 m, and the bolt length both ribs was 1.8 m. The anchor cable spacing was 2.7 × 1.8 m. The pre-tightening force was 150 kN, and the length was 8.3 m.

4.3 Grouting reinforcement

A large area of failure regions exists in the chamber surrounding rocks. The anchoring effects of bolts and anchor cables were poor in these failure areas. To improve the integrity of surrounding rocks, the grouting reinforcement was carried out. Under the action of pump pressure, the grouts could penetrate, backfill, and close fractures of surrounding rocks, as well as reduce the porosity and improve integrity of surrounding rocks. Thus, the strength of the surrounding rocks could be enhanced. A large number of engineering practices indicate that grouting technology could improve the stress states of roadway surrounding rocks and increase the self-supporting and stability of broken surrounding rocks, so it is an effective way to solve the supporting problems of broken surrounding rocks.

The slurry diffusion radius is an important basis for the arrangement of the grouting holes. It has many influencing factors which mainly depend on grouting pressure, surrounding rock mechanical properties, fracture development, fluid mechanics parameters, and initial setting time of slurry, and etc. To optimize grouting parameters, the numerical calculation method was used to simulate the diffusion ranges of slurry under different grouting pressure. According to Table 3, when the grouting pressure was between 5 MPa and 6 MPa, the diffusion radius was basically stable at around 1.82 m. Therefore, the grouting pressure of 5 MPa was selected and the corresponding diffusion radius was 1.80 m. With 0.9 m of bolt spacing, a grouting pipe was set every two

| Grouting pressure/MPa | Slurry diffusion radius/m |
|-----------------------|--------------------------|
| 1.0                   | 1.21                     |
| 2.0                   | 1.45                     |
| 3.0                   | 1.63                     |
| 4.0                   | 1.73                     |
| 5.0                   | 1.80                     |
| 6.0                   | 1.81                     |
bolts. Then, the drilling and grouting was conducted in the broken partings area.

Through numerical simulation, the expansion radius of grouting slurry is 1.82 m. According to the expansion radius of slurry, the expansion range of slurry is delineated by numerical calculation software, as shown in Figure 10. On the basis of experiments, Kang et al. obtained that the strength of the surrounding rock after grouting is 20% higher than that of the initial surrounding rock. Therefore, in the numerical simulation, the strength of the surrounding rock within the diffusion range is directly increased by 20%.

5 | EFFECT PREDICTION OF DEFORMATION AND FAILURE FOR LARGE-SECTION CHAMBER IN COMPOUND SEAM

5.1 | The numerical model

Many scholars’ studies indicated that the grouting reinforcement for broken coal and rock mass could effectively improve the strength and overall performance. The cohesion of coal and rock mass could increase significantly. Table 4 lists the related research results, where $\Delta c$ refers to the increment of cohesion.33,34

As shown in Table 2, 1:1 cement grout and marithan could remarkably improve the strength of coal seam and mudstone, so they are used for the chamber surrounding rocks. In the numerical simulation, the cohesion of the coal and mudstone could increase by 100% after the implementation of grouting reinforcement.

The establishment process of the numerical model was similar the previous modeling process. 600 mm layer of concrete was increased in the model. Besides, the constraints of bolts and anchor cables were applied. The bolt spacing was 0.9 m × 0.9 m. The pre-tightening force was 100 kN. The length of the vault bolt was 2.5 m, and the length of the bolts on ribs was 1.8 m. The anchor cable spacing was 2.7 × 1.8 m. The pre-tightening force was 150 kN and the length was 8.3 m.

5.2 | The deformation and failure states of chamber surrounding rocks

5.2.1 | Failure areas

Figure 11 shows the failure areas of roadway surrounding rocks after reinforcement. It could be found that there was basically no failure in the partings of the coal seams, indicating that the broken partings could be integrated by grouting reinforcement and the strength was increased obviously. In addition, the tensile and shear failure areas were reduced remarkably on both ribs of the roadway. It could be found that the surrounding rocks were intact and experienced no failure on roadway ribs under the influences of grouting reinforcement, bolts and anchor cables, and concrete layers. It also found that the failure area in the chamber dome was basically unchanged, showing that the dome suffered relatively large vertical stress and the dome surrounding rocks still experienced failure.

5.2.2 | Surrounding rock stress

The stress state of the chamber surrounding rocks is an important indicator to assess the support effects. Figure 12 shows the extracted stress states of the chamber surrounding rocks. The vertical stress and horizontal stress on ribs were analyzed.

Figure 12 indicated that the vertical stress peaks on left rib were 16.7 MPa and 27.1 MPa before and after the support, respectively. The bearing capacity of the chamber surrounding rocks was enhanced significantly. Significant increase in the vertical stresses on both ribs could also be observed. It was indicated that the implementation of grouting, bolts and anchor cables is an effective way to reinforce the surrounding rocks.

\[
\begin{array}{|c|c|c|}
\hline
\text{No.} & \text{Characteristics of rocks} & \text{Slurry} & \text{Rate of increase} \\
\hline
1 & Mudstone and sand-shale interbed & Ordinary cement slurry & $\Delta c = 15.2\%-22.5\%$ \\
\hline
2 & Coal and sandstone & 1:1 Cement grout and Marithan & $\Delta c = 70\%-200\%$ \\
\hline
3 & Mudstone, siltstone and coal & Cement & Coal: $\Delta c = 50\%$
Siltstone: $\Delta c = 40\%$
Mudstone: $\Delta c = 47\%$
\hline
4 & Siltstone, sandstone, parting, and limestone & Cement grout + water glass & $\Delta c = 59\%$
\hline
5 & Rock structure surface & Cement sandstone & $\Delta c = 291\%$
\hline
6 & Sandstone and mudstone & Cement slurry & $\Delta c = 210\%$
\hline
\end{array}
\]

TABLE 4 Change laws of surrounding rocks mechanical parameters after grouting
FIGURE 11 Failure states of chamber surrounding rocks

FIGURE 12 Stress states of the chamber surrounding rocks. (A) The vertical stress; (B) the horizontal stress
anchor cables could increase the integrity and strength of surrounding rocks. It could also be observed that failure depths of ribs were 9.1 m and 4.1 m before and after the supporting work, respectively. It was illustrated that the failure areas of surrounding rocks did not move to the depth. As shown in Figure 12B, the horizontal stress on chamber ribs gradually increased toward the depth and tended to the original rock stress at the depth of over 20 m. The excavation of the chamber had disturbing effect on the horizontal stress of surrounding rocks at about depth of 20 m. The horizontal stresses on chamber ribs after supporting were smaller than those before the supporting, so the support was helpful to reduce the displacement of chamber ribs.

Therefore, the vertical stresses on ribs increased while the horizontal stresses reduced after the implementation of grouting and bolts and anchor cables. The strength of the chamber surrounding rocks increased obviously and the bearing capacity also increased.

5.2.3 | The chamber surrounding rocks deformation

The deformation of the chamber is the most direct performance of supporting effects under the action of surrounding rock stress. Figure 13 shows the chamber dome separation...
amounts and ribs displacement amounts before and after the implementation of supporting.

Figure 13A indicated that (1) the maximum separation amount reached 0.63 m before supporting. Lots of cracks could be observed in the dome. The fractures went through each other on the surface of the dome, and roof leakage occurred. The range of the roof leakage was between 0 m and 4.5 m before supporting, verifying that the separation was relatively large in the range of 0-5 m to a certain degree. Figure 13B indicated that the roof separation mainly occurred in the middle of the dome before and after the supporting. Before supporting, the roof separation showed a rapid increase in the range of 0-5 m, and the maximum amount was 0.63 m. In the range of 5-10 m, the separation
was basically 0.07 m. After the supporting, the roof separation almost did not occur. Only a small amount of separation could be observed in the range of 0-3 m, and the maximum amount was 0.025 m.

Figure 14A indicated that a large number of fractures occurred in the surrounding rocks in the range of 0-10 m. The horizontal lateral displacement of the surrounding rocks was relatively large in this area. The rib spalling could be found in the chamber.

Figure 14B indicated that the horizontal displacement of the chamber surrounding rocks mainly occurred in ribs and chamber dome. Before supporting, the lateral displacements...
of ribs decreased rapidly with the increase of the depth in the range of 0-10 m, and the maximum amount was 0.44 m. It changed slightly in the range of 10 m and 20 m. It was significantly reduced after supporting, and the maximum amount was only 0.022 much less than that before supporting.

Based on the displacement change laws of chamber surrounding rocks before and after supporting, the implementation of grouting, bolt, and anchor cable could play a good restraining role and the surrounding rock deformation was significantly reduced.

6 | ENGINEERING APPLICATION

6.1 | The chamber supporting scheme

According to the above analyses, the grouting pipe was used for grouting works, and the grouting pressure was 5 MPa. The bolt and anchor cable supporting was conducted after grouting. Figure 15 shows the specific supporting parameters.

The parameters of the dome supporting are as follows. The thread steel bolt without left-hand longitudinal steel was used with the diameter of 22 mm and the length of 2.5 m. The yield strength was 600 MPa. The tensile strength was 800 MPa. The spacing was 900 mm × 900 mm. The resin extended anchorage was applied. The pre-tightening force was 100 kN. The high-strength tray with the specification of 200 mm × 200 mm × 10 mm was selected. The anchor cable had a diameter of 17.8 mm and a length of 8.3 m. The spacing was 2700 × 1600 mm. The pre-tightening force was 150 kN. A total of 5 anchor cables were used. The length of the anchorage was 1.5 m. One K2335 resin and two Z2360 resins were used. The thickness of W steel strip was 4 mm, and the width was 250 mm.

The parameters of the chamber ribs supporting are as follows. The length of the bolt was 1.8 m. One K2335 resin and one Z2360 resin was used. Other parameters are same with those of vault supporting. The supporting parameters of anchor cable are also same with those of vault supporting.

In the process of excavation, 2.5-m-long bolt is used to reinforce the surrounding rock of the chamber dome, and grouting is carried out. Secondly, the both ribs of the chamber are reinforced with 1.8-m-long anchor bolts and grouted. The application time of anchor bolts and grouting is shown in Figure 16. Finally, the 8.3-m-long anchor cable is used to connect the broken area, plastic area, and elastic area to form two bearing rings and ensure the stability of surrounding rock.

6.2 | The actual measurement of chamber deformation

To monitor the deformation at different depths in the surrounding rocks, the monitoring points of multipoint displacement meter were arranged at the depths of 2 m, 4 m, 6 m, 8 m, and 10 m, as shown in Figure 17.

Figure 17A indicated that the lateral displacement variation of chamber ribs was relatively large within the range of 0-6 m, and the maximum lateral displacement was 0.018 m. The amount remained at 0.009 m beyond 4 m. The above laws presented that the chamber surrounding rocks deformation was controlled effectively.

7 | CONCLUSIONS

This paper took the electromechanical chamber in Tashan Coal Mine as the engineering background. The numerical
simulation method was used to analyze the deformation and failure characteristics of the compound coal seam large-section chamber surrounding rocks. The corresponding control methods were proposed as follows.

1. After the excavation of the chamber, the failure areas of the surrounding rocks were mainly in the partings, chamber ribs, and dome. The failure depths were 15 m, 10 m, and 5 m, respectively.

2. Based on the deformation and failure characteristics of the chamber surrounding rocks, the numerical simulation method was used to optimize the supporting parameters of the bolts and anchor cables as well as the grouting parameters.

3. After using the optimized bolts and anchor cable supporting parameters and grouting parameters, the chamber ribs lateral displacement and the roof separation amount was only 0.018 m and 0.018 m, respectively.

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