In view of the unsymmetrical large deformation and failure phenomenon that often occurs after the excavation and support of the roadway in steep seam with weak structural plane, the numerical simulation analysis and engineering application research on the deformation and failure characteristics of its surrounding rock are carried out. The results show that the key position of asymmetric deformation is near the weak structural plane and the intersection of the roadway section and the inclined direction of the rock. On this basis, the “unsymmetrical high prestress pressure relief coupling control technology” is put forward, and the industrial test is carried out. The practice shows that the unsymmetrical coupling support technology cannot only effectively solve the differential deformation of the surrounding rock but also ensure the coordinated deformation of the support structure and the surrounding rock, thus improving the overall stability of the roadway, greatly reducing the repair rate of the roadway, and saving the support cost.

1. Introduction

In recent decades, with the gradual depletion of China’s shallow coal resources, coal mining has completely transited to the deep mining stage. According to statistics, China’s steep seam accounts for 15%–20% of the total coal reserves, and its annual output accounts for about 10% of the total coal production in China. To meet the rapid development of China’s economy, the proportion of deep coal seam with large dip angle in coal mining will increase year by year [1]. However, the geological conditions of deep coal seam will be more complex than that of shallow coal seam, especially the stability control problem of roadway in deep and steep seam with weak structural plane influence which is increasingly prominent [2].

For this reason, many scholars have carried out a lot of in-depth research on the instability and failure law of this kind of roadway and have obtained a series of research results: some have carried on the research from the in situ stress field, such as W. J. Gale, and summarized and analyzed the relationship between the roadway stability and the direction of the maximum horizontal principal stress. When there is a certain angle between the roadway axial and the maximum horizontal principal stress, the deformation and failure of the roadway show obvious asymmetry. Some of them have studied the occurrence of rock strata; for example, Wu et al. [3] and others established and analyzed the mechanical model of steep seam by means of theoretical analysis, similar simulation, and numerical simulation and pointed out that the difference of rock stratum structure on two sides of roadway in large inclined coal seam is the fundamental reason for asymmetric failure of roadway. Some studies have been carried out in terms of weak structures; for example, Fan and Jiang [4] focused on the role of weak structural bodies such as weak rock strata or rock pillars in the process of roadway instability and failure and
found that the asymmetric failure of roadways is often caused by local weak structures in the surrounding rocks of these roadways, and the initial position of failure is often near these weak structures.

Based on the previous research results of this kind of roadway, it is found that the deformation and failure of deep and steep seam roadway have typical asymmetry. However, if there is a weak structural plane in the surrounding rock of roadway, how to effectively restrain the slip and dislocation of weak structural plane and what kind of reasonable support measures should be adopted according to the asymmetry of roadway deformation, so as to achieve the purpose of controlling the stability of roadway; it is urgent to have a set of support measures complete roadway support technology system. Therefore, based on the research of deep and large inclined seam roadway under the influence of weak structural plane, this paper deeply analyzes the mechanism of asymmetric large deformation and failure and puts forward the coupling control technology of asymmetric high prestress yielding pressure, which effectively solves the supporting technical problems of this kind of roadway.

2. Failure Characteristics of Asymmetric Large Deformation

The research results of many scholars on deep coal seam roadway with large dip angle show that the lithology of roof, two sides, and floor of such roadway are often different, and the strata are easy to slide and move along the weak structural plane. The main deformation characteristics are as follows [3–8]:

1. The influence of the difference of surrounding rock structure: due to the difference of surrounding rock structure on both sides of the roadway, the stress of the whole roadway is asymmetric. The side with weak rock structure is easy to lose stability before the surrounding rock on the other side under high stress, which makes the deformation and failure of the whole roadway have typical asymmetry.

2. The influence of large dip angle structure: due to the large dip angle, the force of gravity along the bedding direction of each rock stratum increases obviously. In addition, the instability of weak structural plane between strata and the influence of mining dynamic pressure on working face can easily cause rock mass sliding and staggering along the inclined plane.

3. Influence of stress concentration on contact surface: for this kind of inclined coal seam roadway, the boundary of roadway side and floor often intersects with inclined strata. In these intersection parts, the surrounding rock structure is generally poor, and it is easy to cause stress concentration phenomenon. Therefore, these weak parts of the roadway usually lose stability before other parts; as a result, the roadway has the asymmetric deformation characteristics: severe deformation at low top shoulder corner and relatively stable deformation on high side.

It can be seen that the mine pressure of this kind of roadway is more violent, and the stress of the supporting components is obviously asymmetric. If the traditional symmetrical supporting system of anchor mesh cable is adopted, it is easy to cause the local supporting components to be damaged due to the excessive stress, thus causing the failure and instability of the overall supporting system. As a result, the roadway often needs to be renovated many times, and the renovated roadway still cannot meet the safety production demand of the mine, and the support cost is greatly increased. Therefore, it is urgent to find a safe and efficient support technology to solve such problems.

3. Simulation Analysis on the Process of Surrounding Rock Failure of Asymmetric Large Deformation Roadway

To understand the mechanism of unsymmetrical large deformation and failure of deep and steep seam roadway under the influence of weak structural plane, taking Dayuan coal 1201 working face as an example, the numerical simulation software FLAC3D is used to simulate the deformation and failure of surrounding rock of roadway under the condition of no support and original support, respectively.

3.1. Engineering Background. Dayuan coal mining field is located in the southeast wing of Ningwu mine area syncline, with a Northwest tendency in stratigraphic form. Among them, working face 1201 is located in the deep part of the mine field, with a large dip angle (45° on average and 60° at maximum). It is greatly affected by structural forces and gravity, and the structure is relatively complex.

The average buried depth of the mining roadway of 1210 working face is 800 m, which is arranged along the coal seam floor. The roof strata of the roadway are claystone and sandstone, and the floor strata are sandy mudstone and mudstone, in which the immediate roof is claystone, which is easy for cross caving; there is weak structural plane between the immediate roof and the immediate roof, which is easy to separate and slip; the hardness of the roof, floor, and coal seam is small. According to the in situ stress test results, the maximum principal stress at—800 m level in Dayuan coal industry is horizontal stress, which is 32.5 MPa. The traditional symmetrical support form of “bolt net spray + anchor cable + steel belt” was used in the tunnel. At the beginning of the tunnel excavation, the local support components were damaged and failed, the floor heave of the tunnel was serious, and the two sides of the tunnel were deformed greatly. After many times of maintenance and repair, the tunnel still could not meet the needs of mine safety production.

3.2. Numerical Model. According to the engineering geological conditions of Dayuan coal 1201 working face, the numerical simulation software FLAC3D is used to establish the numerical calculation model. Considering all factors, the inclination of rock stratum is taken as 45 degrees, and the model is simplified: the model size is 150 m × 50 m × 80 m, the section of mining roadway is straight wall semicircle
arch, in which the straight wall height is 2.0 m, the bottom width is 4.3 m, and the net radius of semicircle arch is 2.15 m. A contact surface is set between the pseudo roof and the direct roof to simulate the weak structural surface. The whole numerical model is divided into 77606 units and 87120 nodes. Boundary conditions of the model: the boundary around the model defines horizontal displacement, the boundary at the bottom of the model defines vertical displacement, and the top boundary of the model imposes a uniform load of $2.5 \times 10^4 \times 800 = 20$ MPa equivalent to the gravity of the overlying strata (the burial depth is calculated as 800 m). Considering the measured in situ stress results, the lateral pressure coefficient is taken as 1.5. Cable element is used to simulate anchor rod and anchor cable, beam element is used to simulate reinforced joist, and shell element is used to simulate concrete spray layer. The numerical calculation model is shown in Figure 1, and the physical and mechanical parameters of each coal seam and rock layer are shown in Table 1.

3.3. Original Support Parameters. The section shape of the mining roadway in working face 1201 is straight wall and semicircle arch, the width of the roadway is 4300 mm, the height of the straight wall is 2000 mm, and the net radius of the semicircle arch is 2150 mm. The traditional symmetrical support method of “bolt mesh spraying + anchor cable + reinforced joist” is adopted. The specific support scheme is as follows:

(1) Bolt support

Top bolt: the model of the top bolt is BHR500, $\Phi 22 \text{mm} \times L2400 \text{mm}$ left-hand threaded steel bolt. The row spacing between the bolts is 1000 mm $\times$ 800 mm, each row of the top bolt is 6, and the anchorage length is 1200 mm. The bolt is installed vertically on the roadway roof.

Side bolt: the specification of side bolt is the same as that of top bolt. The row spacing between the bolts is 800 mm $\times$ 800 mm, with 3 bolts in each row. The distance between the bolts and the bottom plate is 300 mm, 1100 mm, and 1900 mm, respectively. The anchoring method and length of the anchor bolt are the same as those of the top anchor bolt. The anchor bolt near the floor of the roadway side is installed obliquely with an angle of 15° and the direction is downward. The rest of the anchor bolts are installed vertically on the roadway surface.

(2) Anchor cable support

Top anchor cable: the roadway anchor cable is made of $1 \times 19$ high-strength and low relaxation prestressed steel strand with a diameter of 22 mm. The length is 7300 mm, the anchoring length is 3967 mm, and the anchoring method is lengthening anchoring. The row spacing between anchor cables is 1100 mm $\times$ 1600 mm, with 5 cables in each row, all installed vertically on the roadway surface.

(3) Matching accessory support

The anchor bolt tray shall be 150 mm $\times$ 150 mm $\times$ 8 mm high-strength adjustable center support plate and matching nuts. The anchor cable tray shall be 300 mm $\times$ 300 mm $\times$ 16 mm high-strength adjustable center support plate and matched lock. The horizontal connection component of anchor bolt adopts double reinforced joist with model of $\Phi 16 \times 2200 \text{mm} \times 120 \text{mm}$, and the surrounding rock surface of roadway adopts diamond mesh with mesh size of 150 mm $\times$ 75 mm and diameter of 4 mm.

(4) Primary shotcreting support

The surface of the surrounding rock of the roadway shall be sprayed with a concrete spraying layer with a thickness of 30–50 mm. The concrete strength grade is C20.

The original support model is shown in Figure 2.

3.4. Analysis of Simulation Results. Figures 3 and 4, respectively, show the horizontal displacement cloud chart and vertical displacement cloud chart of the surrounding rock of the roadway under the condition of no support and original support. Figures 5 and 6 are, respectively, the distribution diagram of the plastic zone of the surrounding rock and the shear displacement nephogram of the weak structural plane of the roof slate under the conditions of no support and original support.

From the displacement point of view, it can be seen from Figures 3 and 4 that the deformation of the surrounding rock of the roadway shows obvious asymmetry under the condition of no support. The maximum displacement of the left side is concentrated near the left shoulder of the roadway, that is, the intersection of the roadway section and the inclined direction of the rock stratum, with the value of 1100 mm; the maximum displacement of the right side is concentrated near the lower right side of the roadway, with the value of 1413 mm; the subsidence of the roof is on the right side, obviously larger than the left side, and the maximum subsidence reached 1537 mm; floor heave was serious. Due to different lithology of floor strata (argillaceous siltstone on the left side and coal seam on the right side), floor heave was obviously shifted to the right side, with the maximum value of 1253 mm.

Under the condition of original symmetrical support, although the deformation of surrounding rock of the roadway has been controlled to some extent, the deformation is still large and shows obvious asymmetry. Among them, the maximum displacement of the left side is still concentrated near the left shoulder of the roadway, with a value of 206 mm; the maximum displacement of the right side is obviously further shifted to the lower right side of the roadway, with a value of 865 mm; the maximum subsidence of the roof is mainly concentrated in the roadway at the right shoulder of the roadway and the top of the roadway, and the value is 363 mm; the floor still has a serious floor heave phenomenon, the distribution rule is the same as that without support, and the maximum value is 1104 mm.
Table 1: Mechanical parameters of coal and rock.

| Lithology           | Thickness (m) | Elastic modulus (GPa) | Poisson ratio | Cohesion (MPa) | Internal friction angle (°) | Density (kg/m³) |
|---------------------|---------------|-----------------------|---------------|----------------|-----------------------------|-----------------|
| Underlying strata   | 60.0          | 3.0                   | 0.21          | 2.3            | 34                          | 2500            |
| Medium sandstone    | 12.0          | 3.9                   | 0.18          | 3.3            | 35                          | 2680            |
| Coal seam           | 1.0           | 0.8                   | 0.3           | 0.5            | 25                          | 1400            |
| Siltstone           | 2.6           | 2.2                   | 0.22          | 1.26           | 33                          | 2690            |
| Pelitic siltstone   | 2.8           | 1.0                   | 0.27          | 0.8            | 28                          | 2090            |
| No. 2 coal seam     | 5.0           | 0.8                   | 0.3           | 0.5            | 25                          | 1400            |
| Claystone           | 0.8           | 0.9                   | 0.29          | 0.6            | 26                          | 1800            |
| K3 sandstone        | 2.0           | 1.4                   | 0.22          | 2.1            | 32                          | 2200            |
| Coarse sandstone    | 8.0           | 1.8                   | 0.23          | 1.2            | 31                          | 2400            |
| K3 sandstone        | 5.0           | 1.4                   | 0.22          | 2.1            | 32                          | 2200            |
| Siltstone           | 4.2           | 2.2                   | 0.22          | 1.26           | 33                          | 2690            |
| Medium sandstone    | 5.3           | 3.9                   | 0.18          | 3.3            | 35                          | 2680            |
| Medium fine sandstone| 13.2       | 2.1                   | 0.31          | 2.2            | 33                          | 2560            |
| Overlying strata    | 42.0          | 3.0                   | 0.21          | 2.3            | 34                          | 2500            |

Figure 1: Numerical calculation model diagram. (a) Overall drawing of model; (b) partial enlarged drawing.
Figure 2: Original support model.

Figure 3: Continued.

(a)
Figure 3: Nephogram of horizontal displacement of surrounding rock of roadway: (a) without support; (b) original support.

Figure 4: Continued.
Figure 4: Nephogram of vertical displacement of surrounding rock of roadway: (a) without support; (b) original support.

Figure 5: Continued.
Figure 5: Distribution of plastic zone in surrounding rock of roadway: (a) without support; (b) original support.

Figure 6: Continued.
From the perspective of plastic area distribution, it can be seen from Figure 5 that, under the condition of no support, the overall distribution of plastic area is large, showing a typical asymmetry. Among them, the plastic area at the lower left and upper right of the roadway is relatively prominent, with the damage depth of about 6.8 m at the lower left and 7.3 m at the upper right. At the same time, the shear damage at the left shoulder of the roadway (i.e., the intersection of the roadway section and the inclined direction of the rock stratum) is relatively serious. Under the original support condition, the distribution range of the plastic area at the left side and the roof is significantly smaller than that without support, but the overall distribution is significantly smaller. The distribution still shows typical asymmetry. Among them, the plastic area of the upper left and right sides of the roadway roof is relatively prominent. The damage depth of the upper left side is about 4.1 m, and the damage depth of the right side is about 5.0 m. At the same time, part of the left side of the roadway is connected with the plastic area of the floor. No matter what kind of working condition, the roadway floor shows obvious tensile failure characteristics.

Based on the analysis of the slip and dislocation of the rock strata near the weak structural plane of the roadway roof, it can be seen from Figure 6 that the maximum value of the shear displacement on the weak structural plane of the roadway roof is located directly above the roadway roof, with a value of 0.87 m, and the slip and dislocation of the rock strata of the roadway roof are mainly concentrated above the roadway roof. The shear displacement value on the weak structural plane of the roof slate layer of the roadway is significantly reduced under the constraint of the original support structure. The maximum value is located at the right shoulder of the roadway, and its value is 0.27 m. Moreover, the staggered sliding interval of the roof strata of the roadway is mainly concentrated near the right shoulder of the roadway.

4. Analysis of the Mechanism of Asymmetric Large Deformation and Failure

Based on the data of numerical simulation, field investigation and field measurement of ground stress, and structure distribution, the failure mechanism of surrounding rock in deep coal seam roadway with large dip under the influence of such weak structural plane can be summarized as the following:

1. Failure mechanism of slip and dislocation of weak structural plane

Due to the long-term tectonic movement of natural rock mass, there are various directional and non-directional weak structural planes, and the strength, deformation, and failure of rock mass are mainly controlled by these weak structural planes. Under the secondary stress caused by the excavation of the roadway, the weak structural plane of the roof slate layer produces slip and dislocation, which changes the lateral pressure exerted on the surrounding rock of one side of the roadway, and then causes the destruction of the surrounding rock of the roadway. The larger the slip and dislocation deformation, the greater the impact on the deformation and failure of the surrounding rock of the side of the roadway close to the weak structural plane. At the same time, the location of the maximum shear slip of the weak structural plane is mainly concentrated near the right shoulder of the roadway.
Structural plane directly determines the distribution of the overall deformation of the roadway. Therefore, due to the influence of the weak structural plane on one side of the roadway, the deformation and damage of the upper right and lower right side of the roadway roof are significantly greater than other parts.

5. Control Technology of Unsymmetrical Large Deformation Failure

5.1. Unsymmetrical High Prestress Pressure Relief Coupling Control Technology

Because of the influence of rock occurrence in this area, the rock structure and lithology on both sides of the roadway show a high degree of asymmetry. Under the same stress condition, the internal stress of the surrounding rock on both sides of the roadway will show asymmetry, which will cause the asymmetric deformation and damage of the surrounding rock. Especially at the intersection of the roadway section and the inclined direction of the rock stratum, due to the different lithology and structure, the deformation and failure of the left side of the roadway and the floor show a typical asymmetry.

(2) Asymmetric failure mechanism of rock structure and lithology

Because of the influence of rock occurrence in this area, the rock structure and lithology on both sides of the roadway show a high degree of asymmetry. Under the same stress condition, the internal stress of the surrounding rock on both sides of the roadway will show asymmetry, which will cause the asymmetric deformation and damage of the surrounding rock. Especially at the intersection of the roadway section and the inclined direction of the rock stratum, due to the different lithology and structure, the deformation and failure of the left side of the roadway and the floor show a typical asymmetry.

(3) Deep high stress tensile shear failure mechanism

Because of the influence of rock occurrence in this area, the rock structure and lithology on both sides of the roadway show a high degree of asymmetry. Under the same stress condition, the internal stress of the surrounding rock on both sides of the roadway will show asymmetry, which will cause the asymmetric deformation and damage of the surrounding rock. Especially at the intersection of the roadway section and the inclined direction of the rock stratum, due to the different lithology and structure, the deformation and failure of the left side of the roadway and the floor show a typical asymmetry.

Therefore, to solve the problem of unsymmetrical large deformation support in deep coal seam with large dip under the influence of this kind of weak structural plane, the unsymmetrical high prestress pressure relief coupling control technology is proposed. The control idea of the technology is as follows. (1) Asymmetry: strengthen the support near the weak structural plane of the roof rock layer of the roadway and the intersection of the inclined direction of the rock layer and the roadway section. The support of other parts is normal, and the overall support is asymmetric. (2) High prestress: the main role of high prestress support is to control the expansion deformation of the separation, sliding, crack opening, and new crack generation of the surrounding rock in the anchorage area, which can make the surrounding rock in compression state, restrain the occurrence of bending deformation, tension, and shear failure of the surrounding rock, and make the surrounding rock become the main bearing body. At the same time, the prestressed bearing structure with high rigidity is formed in the anchorage zone, which can prevent the separation of strata outside the anchorage zone, especially near the weak structural plane, and improve the stress distribution in the deep part of the surrounding rock. (3) Pressure relief: the pressure letting support refers to the support measures that can closely stick to the surrounding rock or penetrate into the rock mass, effectively exert the self-supporting capacity of the surrounding rock, and allow the surrounding rock to deform and damage to a certain extent; even when the whole movement is made with the strengthened rock mass, it can still ensure a considerable support resistance. Generally, by adding pressure relief device (such as pressure relief ring or double bubble pressure relief pipe; see Figure 7 for details) to anchor rod and anchor cable, bird’s nest anchor cable with large elongation and good expansion performance (as shown in Figure 8) is adopted to relieve and release the high stress near the surrounding rock of roadway by allowing a small amount of common deformation of support components and surrounding rock, so as to improve the stress environment of surrounding rock of roadway.

The main principle of the technology is shown in Figure 9. After the excavation of the tunnel, firstly, the high prestressed anchor rod is used to form a mutually connected and overlapping pressure stress zone in the shallow part of the surrounding rock, in which the key parts are reinforced, i.e., the shallow stable pressure zone shown in the figure; secondly, the bird’s nest anchor cable with good pressure performance (good elongation) and guarantee of the anchoring effect is used to anchor the whole shallow bearing structure zone to the deep stability of the surrounding rock in the fixed rock stratum, and the deep stable zone shown in the figure is formed. At the same time, the bird’s nest in the free section of the bird’s nest anchor cable can be stretched along with the common deformation of the surrounding rock and the support body, so as to release the high stress in the surrounding rock and make the roadway in a low stress environment, so as to play a pressure relief buffer role, that is, the middle buffer zone in the figure. The purpose of this technology is to reasonably utilize the interaction of surrounding rock structure and supporting components, reduce the high stress around the roadway and increase the...
Figure 7: Structure diagram of yield bolts (cables).

Figure 8: Structural sketch of bird’s nest anchor cable.

Figure 9: Continued.
5.2. Analysis on the Control Effect of Unsymmetrical High Prestress Relief Coupling Technology

To verify the rationality of unsymmetrical high prestress relief coupling control technology, taking Dayuan coal 1201 working face as an example, the numerical simulation software FLAC3D is used to simulate and analyze the surrounding rock support effect under the condition of unsymmetrical high prestress relief coupling control technology.

The numerical calculation model and the mechanical parameters of surrounding rock are the same as before. The supporting parameters of "unsymmetrical high prestress and pressure release coupling" of roadway are as follows:

(1) Bolt support

Top bolt: the model of the top bolt is BHR500 left-hand threaded steel bolt with specification of $\Phi 22 \text{ mm} \times L2800 \text{ mm}$. The top bolt is arranged asymmetrically. The spacing between the top bolts on the nonmining side is $800 \text{ mm} \times 800 \text{ mm}$. The spacing between the top bolts on the mining side is $1000 \text{ mm} \times 800 \text{ mm}$. There are 7 bolts in each row. The anchorage length is 1200 mm. The bolts are installed vertically on the roadway roof.

Side bolt: the parameters of side bolt are the same as the original support, but the length of anchor rod changes from 2400 mm to 2800 mm.

Bottom bolt: the bottom bolt is arranged in an asymmetric way. The row spacing between the bottom anchor bolts on the nonmining side is $500 \text{ mm} \times 800 \text{ mm}$, three in each row (one on the mining side and two on the nonmining side). The horizontal distance between the anchor bolts on both sides near the roadway side and the roadway side is 300 mm, and the inclination is 15°. The anchor rod on the nonmining side is 45°. The anchoring method and length of anchor bolt are consistent with those of top anchor bolt.

Pressure relief device shall be added for all anchor bolts.

(2) Anchor cable support

All cables are made of $1 \times 19$ strands of high-strength and low relaxation prestressed steel strand with a diameter of 22 mm. The whole cable body is equipped with a new type of bird’s nest cable which can be stretched freely.

Top anchor cable: the top anchor cable is arranged in an asymmetric way. The row spacing between the top anchor cables on the nonmining side is $900 \text{ mm} \times 1600 \text{ mm}$, with a length of 9300 mm. The row spacing between the top anchor cables on the mining side is $800 \text{ mm} \times 1600 \text{ mm}$, with a length of 6300 mm and 9300 mm, with 7 cables in each row, with a length of 3967 mm. The anchoring method is lengthening anchoring, which is installed vertically on the roadway surface.

Side anchor cable: the anchor cable is only arranged on the nonmining side of the roadway,
with a spacing of 1000 mm × 1600 mm and a length of 6300 mm. There are two cables in each row. The anchor length and anchor method are the same as the top anchor cable. The anchor cable near the bottom plate is installed at an angle of 15°, and the rest are installed vertically on the roadway surface.

Pressure relief device shall be added to all anchor cables.

(3) Matching accessory support
Channel steel is used as the longitudinal connection component of anchor cable, and other parameters are the same as the original support.

(4) Primary shotcreting support
It is the same as the original support.

(5) Floor reinforcement support  [15–20].

The bottom of the roadway floor shall be undercover first, then the stone cushion shall be laid for leveling, and finally the concrete floor construction shall be carried out. The thickness of the concrete floor is 300 mm, and the concrete floor construction shall reach the design height of the roadway after completion. During the construction, the concrete with different strength grades (C20 and C30) is used for pouring the roadway floor with different lithology.

The optimized support model is shown in Figure 10. The parameter table  [21] of support components in the optimization scheme is shown in Table 2.

Figures 11 and 12 are the displacement nephogram of surrounding rock and the distribution diagram of plastic zone under the optimized support condition, respectively. Figure 13 shows the nephogram of shear displacement on the weak structural plane of roadway roof under the optimized support condition. Table 2 shows the statistical table of surrounding rock deformation and other indicators under the original and optimized support conditions (both are maximum values).

It can be seen from the simulation results that the deformation of surrounding rock and the range of plastic zone are not only effectively controlled, but also distributed symmetrically. Among them, the maximum value of horizontal displacement is transferred to the deep part of the floor, the maximum displacement of the left side is 25 mm, the maximum displacement of the right side is 55 mm, and the maximum displacement of both sides is located in the middle of the roadway side; the maximum value of roof subsidence is 31 mm, which occurs in the upper part of the roadway to the left, and the maximum value of floor heave is about 213 mm, which is located in the middle of the floor. The range of plastic zone has been improved obviously. There is almost no plastic zone in the roof, only a small amount of plastic zone in the two sides, only a certain range of plastic zone in the floor, and the failure depth is about 3.8 m. At the same time, the sliding and dislocation of the roof strata of the roadway are effectively controlled. The maximum shear displacement on the weak structural plane of the roof strata of the roadway is located at the upper right side of the roadway, which is about 5 mm.

It can be seen from Table 3 that the supporting effect of the optimized supporting scheme is far superior to that of the original one, which further explains the rationality of the asymmetric high prestress pressure coupling control technology. The optimized scheme not only effectively controls the key parts of the roadway that are easy to lose stability and damage (i.e., the parts near the weak structural surface of the roadway roof and the intersection of the roadway section and the inclined direction of the rock), but also makes the roadway. The whole displacement deformation and plastic area of surrounding rock are controlled within the allowable scope of the project, and the displacement deformation is distributed symmetrically, and the deformation of all parts of the tunnel almost reaches a stable state at the same time.

6. Engineering Application Effect

The above research results have been applied in the later construction project of 1201 working face. According to the real-time monitoring curve of the deformation and time change of the surrounding rock of the roadway (as shown in Figure 14), after the excavation of the roadway, it has successively gone through the initial stage of severe deformation (0–10 days), the middle stage of slow deformation (10–30 days), and the later stage of stable deformation (30–50 days), respectively, corresponding to the rapid adjustment period of the surrounding rock stress of the roadway, the period of coordinated deformation between the support and the surrounding rock, and the surrounding rock of the roadway stress stability period. Among them, the subsidence of roadway roof is 36 mm, the floor heave is 217 mm, and the two sides’ indentation is 78 mm, which is basically consistent with the numerical simulation results.

The application of the results further verifies the correctness of the unsymmetrical high prestress pressure relief
Table 2: Parameter table of support components.

| Properties                          | Bolt           | Short cable    | Long cable       | Structural beam |
|-------------------------------------|----------------|----------------|------------------|-----------------|
| Contour dimension                   | Φ22 × 2800 mm  | Φ22 × 6300 mm  | Φ22 × 9300 mm    | —               |
| Yield strength (MPa)                | 500            | 1500           | 1500             | 500             |
| Ultimate strength (MPa)             | 700            | 1860           | 1860             | —               |
| Elasticity modulus (GPa)            | 200            | 195            | 195              | 200             |
| Stiffness of the grout (N/m/m)      | 2e9            | 2e9            | 2e9              | —               |
| Cohesive capacity of the grout (N/m) | 4e5           | 4e5            | 4e5              | —               |
| Interface normal stiffness (GPa/m)  | —              | —              | 10               | —               |
| Interface shear stiffness (GPa/m)   | —              | —              | 10               | —               |

Figure 11: Nephogram of displacement of roadway surrounding rock: (a) horizontal displacement; (b) vertical displacement.
coupling support theory, which not only realizes the purpose of the coordinated deformation and support of the roadway support components and the surrounding rock of the roadway, but also solves the support problems of such roadway and meets the requirements of the mine safety production.
Through the study of the failure mechanism and control technology of the surrounding rock of the deep coal seam roadway with large dip under the influence of weak structural plane, the following conclusions can be drawn:

(1) The surrounding rock of this kind of roadway often has the characteristic of large deformation and failure under the action of typical high stress; that is, the key part (i.e., near the weak structural plane of the roadway roof and the intersection of the roadway section and the inclined direction of the rock stratum) first loses stability and the overall deformation presents asymmetry.

(2) The existence and effective control of weak structural surface of roadway roof are very important for the support of the whole roadway. This kind of roadway should give priority to strengthening the support of surrounding rock near the weak structural surface and, at the same time, make the support components meet the requirements of flexible yielding and anticoordination.

(3) It is necessary to strengthen the unsymmetrical coupling support control measures for the asymmetric distribution characteristics of the surrounding rock lithology structure of the roadway, especially for the intersection of the roadway section and the inclined direction of the rock stratum.

(4) The engineering application results show that the unsymmetrical differential deformation of surrounding rock and the instability of key parts can be effectively controlled by using the unsymmetrical high prestress pressure relief coupling control technology, and the overall stability of the roadway can also be greatly improved.

Data Availability

Data are included within the manuscript.
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