Study on the influence of angle of bedding plane on stability of roadway surrounding rock in layered mass

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Abstract. In view of the large deformation in the roadway of layered surrounding rock, with W22602 return air roadway of Datong No.1 Mine as the engineering background, using the finite-difference software FLAC3D, we explored the influence of the angle of the bedding plane under the prestressed bolt support on the plastic zone and the stress and strain distribution law of the surrounding rock of the roadway, and analyzed the deformation and failure characteristics of the bedding plane under the action of the bolt. The results show that: with the increase of the inclination of the bedding plane, the horizontal and vertical deformation of the bedding plane first increase and then decrease, showing a "Λ"-shaped change characteristic; in horizontal layered surrounding rock, as the prestress of bolt support increases, the strength of the weak rock layer gradually increases, and the surface displacement of the bedding plane gradually decreases; the plastic zone of the surrounding rock with different dip angles has a significant “angle effect”, and the angle between the bolt and the bedding surface has a significant difference in the control effect of the bedding plane; based on the simulation results when the inclination angle is 15°, field practice is carried out. And it shows that the optimization scheme can improve the stability of the surrounding rock of the roadway more economically and effectively.

Key words: bedding surface inclination; Roadway stability; prestressed support; numerical simulation.

1. Introduction
In the process of underground mining in China, the surrounding rock of the roadway mostly exists in the form of layered rock mass, which produces structural surfaces such as faults, bedding planes, and micro-cracks during the long and complex geological evolution process. The weak surfaces not only control the mechanical properties of the surrounding rock mass of the roadway, but also restrict the deformation of the surrounding rock of the roadway, the range of the loosening circle of the surrounding rock, and the failure mechanism of the rock mass. Thus it has a significant impact on the stability of the surrounding rock of the roadway and the safety of mining work. Therefore, studying the stability of the structure facing in the layered surrounding rock roadway has very important engineering significance.
At present, the research on layered rock masses mainly through theoretical analysis, laboratory tests, physical simulations, numerical simulations, etc., to study its strength characteristics and deformation and failure laws under different conditions. In terms of theoretical analysis, Xian et al. [1-3] studied the physical and mechanical properties and strength characteristics of rocks with or without cohesive joint surfaces, single and multiple groups of joint surfaces in the layered rock mass and the impact factors of the strength of the layered rock mass. Many scholars have used uniaxial compression, tensile and shear resistance, triaxial compression and other laboratory mechanical experiments to study the strength characteristics of the rock with structural planes [4-9]. Due to the discontinuous nature of the surrounding rock with joints, numerical simulation software FLAC\textsuperscript{3D} and 3DEC are widely used to simulate the stability analysis of surrounding rock roadways or excavated caverns with structural surfaces [10-14]. However, few studies have considered the influence of the mechanical characteristics of the bedding plane on the overall stability of the surrounding rock [15-16]. This paper takes the W22602 return airway of the Datong No. 1 mine as the research object, through theoretical analysis and finite difference simulation software FLAC\textsuperscript{3D}, innovatively investigate the strengthening mechanism of prestressed bolt support to surrounding rock in layered surrounding rock roadway, and the influence law of different bedding plane inclination on the stability of surrounding rock in supported roadway. And field tests are carried out in this roadway according to the simulation results.

2. Project overview
Datong No.1 Coal Mine is located in Datong Town, Qijiang District, Chongqing, China, and belongs to Chongqing Energy Co., Ltd. W22602 air return roadway is a section of seam coal and rock roadway serving the mining of M6-3 coal seam. The inclination angle is 15°, the coal thickness is 0.20 ~ 1 m, and the average is 0.80 m. The tunnel is a semi-circular arch tunnel with a net cross-sectional area of 9.33 m\textsuperscript{2}. The basic mechanical parameters of the surrounding rock of the roadway are shown in Table 1.

| Rock material     | Density kg/m\textsuperscript{3} | Compressive strength/MPa | tensile strength /MPa | Cohesion /MPa | Internal friction angle (°) | Elastic modulus /GPa | Poisson's ratio |
|-------------------|----------------------------------|---------------------------|-----------------------|---------------|-----------------------------|----------------------|----------------|
| Mudstone          | 2545                             | 19.16                     | 3.25                  | 1.20          | 30                          | 2.99                 | 0.27           |
| Limestone         | 2800                             | 65.72                     | 6.70                  | 11.40         | 38                          | 10.69                | 0.18           |
| Argillaceous siltstone | 2699                         | 27.94                     | 2.48                  | 2.80          | 39                          | 3.66                 | 0.29           |

3. Strengthening mechanism of surrounding rock of roadway supported by bolts
The stability of the surrounding rock of the roadway mainly depends on the strength and stress redistribution of the surrounding rock mass, but the support measures for the surrounding rock are also an effective way to improve the overall stability of the surrounding rock of the roadway. Bolt support, as one of the most common support methods, can improve the shear strength of the surrounding rock in the anchoring area and the cohesion of the rock mass c within the anchoring range [17], which is:

\[ c = c_0 + nc_m \]  \hspace{1cm} (1)

\[ c_m = \frac{F_{\text{max}}}{S \cos(45° - \phi)} \]  \hspace{1cm} (2)

Where: \( c_0 \) is the cohesion of the rock mass under the original rock stress state, MPa; \( \phi \) is the internal friction angle; \( n \) is the number of bolts; \( c_m \) is the cohesion of the bolt, MPa; \( F_{\text{max}} \) is the ultimate shear strength of the bolt body, kN. According to the Mises criterion:
\[
F_{\text{max}} = \frac{\sigma_s \pi d^2}{4\sqrt{3}} \\
\alpha = c_0 + \frac{n \sigma_s d^2}{4\sqrt{3} s \cos(45^\circ - \phi/2)}
\]

Where: \(\sigma_s\) is the yield strength of the bolt material, MPa; \(d\) is the diameter of the bolt, m; \(S\) is the area of the free surface of the tested bolt, m².

The uniaxial compressive strength of the anchor solid after bolt support is:

\[
\sigma_c = \frac{2c \cos \phi}{1 - \sin \phi}
\]

Simultaneously, the value before the failure of the anchor can be obtained.

The failure of the rock is mainly due to the change of cohesive force. Therefore, the strength of the rock mass after deformation in the anchoring zone in engineering application can adopt the Mohr-Coulomb criterion, and the residual strength of the anchor solid is:

\[
\sigma_c^* = \frac{2c^* \cos \phi^*}{1 - \sin \phi^*}
\]

In the formula; \(\phi^*, c^*\) are the internal friction angle and cohesive force after rock failure.

4. Simulation model building of the roadway

4.1. Constitutive model

Layered rock mass is a rock mass with many structural planes and has complex mechanical properties. Under the action of load, elastic-plastic deformation will occur, which has obvious transversely isotropic characteristics. In this paper, the most classic Mohr-Coulomb elastoplastic model of rock mechanics is used for calculation. The yield criterion is:

\[
f = \sigma_1 - \sigma_3 N_\phi + 2C \sqrt{N_\phi} = 0
\]

Where: \(N_\phi = \frac{1 + \sin \phi}{1 - \sin \phi}\).

4.2. Establishing model

This simulation uses the geometric characteristics of the W22602 return airway of the No. 1 mine as a prototype to establish a model. Using differential simulation software FLAC3D, two sets of models are established and calculated. The first set is established under the condition of horizontal layered surrounding rock roadway, and the prestress is 10 kN, 30 kN, 50 kN, 70 kN, 90 kN, respectively. The second group is established under the same bolt support condition, and the surrounding rock inclination angles is 0°, 15°, 30°, 45°, 60°, 75°, and 90°, respectively.

The surrounding rock of the roadway adopts solid elements, and the anchor bolt adopts the implanted element model. The simulation of the bedding plane generally adopts the contact element or the interlayer element. In order to improve the calculation accuracy, this paper adopts the contact element model. Solve the plane stress problem according to the theory of elasticity. The boundary conditions are: both sides of the model are horizontal fixed constraints, the bottom is fixed constraints in all directions, and the stress is applied on the top. Calculated by composite beam theory and suspension theory, the roadway bolt support parameters are: the bolt strength is 500 MPa, the length is 2.20 m, the diameter of the bolt is 22 mm, and the spacing between rows is 1 m. The size of the model is 60 × 30 × 60 m (length × width × height), and the model is shown in Figure 1.
5. Analysis of simulation results

5.1. The influence of different prestress on the stability of surrounding rock in horizontal layered rock mass

Through the analysis of the first set of numerical simulation results, we can see: in horizontal layered rock mass, the surface displacement and plastic zone area of the roadway show a decreasing trend with the increase of the prestress in the bolt support system. The larger the angle between the anchor rod and the bedding surface (between 0 and 90°), the smaller the bedding surface deformation. It shows that high prestress can significantly improve the cohesion of the rock mass in the anchoring zone and increase the overall strength of the surrounding rock of the roadway.

5.2. Stability analysis of surrounding rock roadways with different inclination angles under prestressed bolt support

5.2.1. Variation law of plastic zone in roadways with different inclination angles of bedding planes.

The cloud map of the plastic zone of the rock formations with different dip angles is shown in Figure 2. It is found through simulation: when φ = 0 ~ 45°, the range of the plastic zone shows an overall increasing trend with the increase of φ; when φ > 45°, the range of the plastic zone keeps shrinking, and the range of the plastic zone along the direction perpendicular to the bedding plane also keeps shrinking with the increase of φ. It can be clearly seen from the figure that the plastic zone has a strong angle effect, that is, the extent of the plastic zone changes with the angle of the surrounding rock bedding. When φ = 45°, the extent of the plastic zone is the largest.
5.2.2. Displacement characteristics of layered surrounding rock. The simulation results found: When the surrounding rock of the roadway is stable, the roof subsidence is the largest when \( \phi = 0^\circ \). With the increase of the inclination angle, the roof subsidence first decreases and then increases, showing a "U"-shaped change. The sinking amount of the roof is just the opposite, showing a "Λ"-shaped change. At the same time, the volume of the floor heave of the roadway increases with the increase of \( \phi \).

On the bedding surface 1 m above the roof of each model roadway, select the coordinates that are located close to each other as the monitoring point to monitor the displacement change characteristics of the bedding surface in the surrounding rock. The monitoring results are shown in Figure 3. When the inclination angle is 0\(^\circ\), the deformation in the x-direction is almost 0. At this time, the x-direction stress on the bedding surface is not enough to cause interlayer dislocation, and the bolt support state is the best. With the increase of \( \phi \), the x-direction displacement and z-direction displacement of the bedding plane both increase first and then decrease in a "Λ" type change law. When \( \phi = 45^\circ \), the horizontal and vertical displacements both reach the maximum. This is because with the increase of the inclination of the bedding plane, the compressive strength and deformation modulus of the rock show a tendency to first decrease and then increase.

5.2.3. The stress variation law of layered surrounding rocks with different dip angles. The stress cloud map in the x-direction of the surrounding rock of the roadway is shown in Figure 4. Plotting the horizontal and axial stress monitoring results at the monitoring points under different angles adopts the monitoring method in (2), as shown in Figure 5.
Figure 4. Stress cloud diagram in the horizontal direction.

Figure 5(a) shows the horizontal stress of the surrounding rock roadway with different dip angles. When $\phi = 0 \sim 30^\circ$, the shear stress on the bedding surface is small and increases with the increase of the dip angle. When $\phi = 45^\circ \sim 75^\circ$, the shear stress on the bedding surface also increases with the increase of the dip angle, but the stress in this interval is much greater than the stress at $\phi = 0 \sim 15^\circ$. The maximum shear stress is 29 MPa when $\phi = 75^\circ$. Figure 5(b) shows the compressive stress of the monitoring points under different dip angles. It can be seen from the figure that after the surrounding rock is stabilized, the stress in the vertical direction increases with the dip angle when $\phi = 0 \sim 30^\circ$ and $\phi = 60^\circ \sim 90^\circ$. But when $\phi = 45^\circ$, the vertical compressive stress is 15.5 MPa, which is between $60^\circ$ and $75^\circ$. This indicates that with the increase of the inclination angle, the greater the shear stress on the bedding surface, the easier it is to produce interlaminar sliding. When $\phi = 60^\circ \sim 90^\circ$, the bedding surface is subject to the greatest tensile stress, which may cause serious top and bottom drum phenomenon, should be taken seriously.
5.2.4. Variation characteristics of stress and strain of bolts in layered rock masses with different inclination angles. The strain cloud diagrams of the anchor rods in the horizontal direction in different inclination angle models are shown in Figure 6 (limited to space, only cloud diagrams with \( \phi = 15^\circ \), \( \phi = 30^\circ \), \( \phi = 45^\circ \), and \( \phi = 60^\circ \) are placed). In the figure, the maximum force and deformation of the anchor rod basically occurs in the anchor rod along the direction of the bedding plane, and with the increase of the angle, the failure form of the bolt at this position changes from shear failure to tension failure. The main reason is that this area is in a stress concentration area, and the bolt consumes elastic energy in the stress concentration area through its own deformation. Therefore, in engineering practice, the stress concentration area of the surrounding rock of the roadway and the position of the roadway corner need to be strengthened support. At the same time, it shows that in the complex and weak layered surrounding rock roadway, the deformation and instability of the roadway can be resisted by the appropriate bolt length, diameter, prestress, material, etc.

![Figure 6. The strain cloud diagram in the horizontal direction of the bolt.](image)

6. Field application

The W22602 return airway of Datong No. 1 Mine originally used intensive, low-strength, non-prestressed bolt support. The original support plan had a surface displacement of 100 mm and 120 mm for the roof and two sides within 30 days. According to the numerical simulation results, the original support plan is optimized. Combined with the simulation of \( \phi = 15^\circ \) in Section 3, it can be obtained that when \( \phi = 15^\circ \), the area where the rock strata is cut off by the roadway is the stress concentration area of the roadway, and support needs to be strengthened. And the angle between the anchor rod and the bedding surface should be as close as possible to 90°. The support model is shown in Figure 4(a). The surface displacement of the roadway obtained through actual monitoring on site is shown in Figure 7(The location of the monitoring point is the midpoint of the two banks and the midpoint of the roof at a distance of 200 m from the roadway).

The monitoring results in Figure 7 show that the moving amount of the two sides and the roof of the roadway at the measuring point 3 is the largest (the change of the two sides is 20 mm, and the change of the roof is 130 mm). The main reason is that the point is located in the fault and broken zone, and the two sides of the roadway are under pressure, and the roof is separated, and the anchor cable is not supported in time, which leads to the deformation of the surrounding rock. The maximum change of the roof is 50 mm, and the roofs of No. 3 and No. 4 are not more than 20 mm. The average deformation of the two sides of the measuring point is 29 mm, which is 63.7% lower than that of the two sides of the adjacent roadway. The mean value of the roof subsidence at the measuring point is 56 mm, which is 44% lower than that of the adjacent roadway. The initial convergence rate of bolt support in W22620 driving face is greater than the later convergence rate, and the convergence rate of the two sides and the roof of the roadway surrounding rock tends to be stable after about 18 days. It can be seen intuitively from Figure 8 that the optimized support effect is very good. The above results show that the optimized support scheme effectively restrains the deformation of the layered surrounding rock roadway, which has certain reference significance for engineering practice in similar situations.
Figure 7. The amount of two gangs move in (a) and roof sinking (b).

Optimize the deformation of the front roadway

Roadway deformation after optimization

Figure 8. Practice effect picture before and after optimization.

7. Conclusion
Through numerical simulation analysis, the influence of the distribution of different prestressed bolts and different bedding plane inclination angles on the stability of layered surrounding rock roadways was studied, and the following conclusions were obtained:

1) In the bolt support of horizontal layered surrounding rock roadway, the bolt prestress can increase the strength of the weak rock in the anchoring area, increase the cohesion of the anchored rock mass, and increase the bonding strength of the bedding surface.

2) For rock masses with different inclination angles, the plastic zone of the surrounding rock after support has an "angle effect". The strike of the bedding plane will affect the stress concentration range of the surrounding rock of the roadway. With the increase of dip angle, the bedding plane changes from interlaminar sliding to tensile action.

3) The inclination angle of the bedding plane has a significant effect on the stress and deformation of the surrounding rock of the roadway. When the prestressed bolt is used for support, in case of the bolt is perpendicular to the direction of the bedding surface, the bolt support effect is the best.

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