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Research Article

Numerical Simulation of the Supporting Effect of Anchor Rods on Layered and Nonlayered Roof Rocks

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In order to clarify the influence of anchor bolts on the supporting effect of the layered weak roof and surrounding rock of nonlayered roof with good integrity, the mechanical model of the roadway with nonlayered homogeneous roof and layered weak roof was established using FLAC3D. The distribution characteristics of the stress field and the displacement field of the bolt support are analyzed, and the supporting effect of the bolt on the roof of two types of roadways is studied. The research results show that when the original rock stress is not considered, the bolt support shows obvious tensile, compressive stress areas and positive and negative displacement areas in the surrounding rock of the roof of the roadway; when the original rock stress is taken into account, the tensile and compressive stress zones and the positive and negative displacement zones of the anchor support in the surrounding rock of the roof plate disappear obviously. The effect of the bolt support on the stress field and plastic area of the surrounding rock of the two types of roadway roof is not obvious. However, it has a significant effect on suppressing discontinuous deformation such as delamination and sliding between layered roof rocks. The delamination phenomenon between rock layers disappeared obviously, and the range of each numerical curve of the displacement field of the surrounding rock in the anchoring area was significantly reduced. However, the effect of the anchor support on continuous deformation control such as elastoplastic deformation of roof rock of nonlayered roadway is very limited. There is almost no change in the displacement field curve in the depth of the roof-surrounding rock. Only the shallow surrounding rock displacement field curve range has decreased.

1. Introduction

With the exploitation of resources and continuing energy development, the roadways surrounding mechanical rock environments are becoming increasingly complex, typically exhibiting engineering response characteristics such as large nonconforming deformations and large-scale unstable failure. Tunnel collapse disasters remain a serious safety concern in China's coal industry. The 2017 Annual Work Report of the Association of Coal Mine Support Professional Committee (2018) stated that, from 2001 to 2017, a total of 19,996 coal mine roof accidents occurred in China (accounting for 36.5% of the total number of coal mine accidents), resulting in 54,729 deaths (51.8% of the total number of coal mine deaths) [1]. Thus, roadway roofing poses a great threat to the safe production of coal mines. There are still significant difficulties in controlling the instability of roadway roofs. To this end, in-depth research has investigated the mechanism of roadway roofing. Qin et al. proposed a new roofing calculation model for layered roadways and studied the geometry and area of the roof [2]. Yang et al. established a theoretical model for the roof rock of a layered roadway and proposed an analysis function for the roof stability. They also discussed the notional value of the upper line of the roof [3]. Ma et al. and Zhao et al. studied the mechanism of dome-shaped roofs from the perspective of the plastic zone. Analysis functions for the stability of the roof were proposed, and the theoretical value of the upper line of the roof was discussed [4, 5]. Kaya et al. established a numerical finite element method (FEM) model based on engineering geological surveys and based on the lithology and structural characteristics of the tunnel and studied the effect of bolt support on the total displacement and size of the plastic zone on the roof [6].

Based on a study of microseismic activity parameters, Zhang et al. predicted the stability of roadway roofs [7]. Coggan et al. considered the coal-bearing strata to be directly related to the stability of the tunnel roof and calculated the roof deformation behavior using numerical simulation techniques such as continuum, noncontinuum, and combined finite-discrete element coding. They found that the relatively weak mudstone thickness at the top of the roadway has a significant effect on damage and requires enhanced support [8].

As one of the most important supporting methods for coal mine roadways, bolts provide more than 70% of the total support of coal mine roadways in China [9]. Experts have conducted intensive research on the mechanism of bolt support. For instance, Li et al. established the calculation theory for the interfacial bond strength between the anchor agent and the roadway-surrounding rock and analyzed the influence of different interfacial bond strengths on the control of roadway-surrounding rock [10]. Based on the simplified anchor model, Shang et al. performed numerical simulations combined with laboratory tests to study the microscopic and macroscopic shear failure mechanisms of fully grouted steel anchors and analyzed the anchor-anchor shear strength and failure mode of the interface. The numerical simulations were found to be in good agreement with the laboratory results [11]. Yokota et al. used discontinuous deformation analysis to study the effects of anchoring angle, mortar thickness, anchor spacing, and bolt shape on the performance of the anchor-cement interface [12]. Liu et al. studied the effect of bolting on the deformation of the rock surrounding a roadway containing a large number of joint planes under different bolting conditions [13]. Mirzaghorbanali et al. studied the shear strength of the bolts and the control of roadway-surrounding rock under different prestressed loads [14]. Ding et al. found that the stress characteristics of the anchor section in the soft interlayer are significantly different from those in the hard rock. The bolt not only has a restraining effect on the free surface of the roadway-surrounding rock, but also prevents tensile and shear failure of this rock region [15]. Based on field simplified model tests and numerical simulations, Han et al. studied the effects of anchor length, anchoring direction, and bolt spacing on the bearing characteristics of soft-sand, soft rock tunnels [16]. Kang et al. believed that improving the initial support stiffness and strength of the bolt system could effectively control the swelling deformation and maintain the integrity of roadway-surrounding rock [17]. Low et al. proposed a reliability-based roadway support method, combined with specific targets for the reliability design of the bolt length and spacing and derived a failure probability for the bolt support [18]. Based on a large number of engineering surveys, Marinos et al. identified that the main reason for the failure of the main support methods of conventional tunnels was related to the ignorance of the geological and on-site characteristics that determine or affect the behavior of the tunnel-surrounding rock. The design of a tunnel-surrounding rock support method must consider the support structure itself, tunnel geometry, principal stress conditions, water conditions, and geological characteristics [19]. Yang et al. conducted theoretical calculations, numerical simulations, and field tests and determined that increasing the support strength and support density under the current support level was not an effective means of controlling the roadway-surrounding rock [20]. Overall, therefore, the problem of roadway roof fall accidents has not been adequately solved, the roadway maintenance remains challenging, the repair rate is high, and the maintenance and repair costs are considerable [21–24]. The control of the roadway-surrounding rock is still one of the main technical bottlenecks of deep mining.

The above-mentioned studies mainly focus on the control of the roadway-surrounding rock using bolts from the aspects of prestressing, the anchoring agent, anchor strength, stiffness, and support density and have not fully considered the influence of the structural features of the rock surrounding the roadway roof on the bolt support. Therefore, it is impossible to truly reflect the support mechanism provided by the anchor rod to the surrounding rock of the coal mine roadway roof. Based on the actual situation of the surrounding rock structure of coal mine roadways, this paper analyzes the distribution characteristics of the stress field and the positive displacement field of the bolt supports. The effects of the bolts on the stress field, displacement field, and plastic zone of the surrounding rock are studied for nonlayered homogeneous roofs with good surrounding rock and layered roadways with good integrity. The problem of the anchoring mechanism of the surrounding rock support in the two types of coal mine roadway roofs is discussed.

2. Analysis of Mechanical Action of Anchor-Surrounding Rock

Generally, the roof of a roadway can be classified as either layered or nonlayered according to the condition of the rock mass of the roof. The layered roof-surrounding rock is extruded from two or more layers of the rock mass. Differences in rock lithology and the bond strength of interlayer bonds mean that the deformation and damage degree of surrounding rock in layered roofs are very serious issues after roadway excavation. These problems are mainly manifested by the interlayer slip shear and separation phenomenon, as shown in Figure 1(a). Nonlayered roof-surrounding rock with good integrity is often composed of a single rock mass, containing few or no other rock mass components, and the rock layer does not contain faults or other structures. The surrounding rock of this roof type contains fewer joints and weak surfaces, and the surrounding rock remains intact and stable as a whole. After excavation through the roadway, the roof of the roadway mainly shows a tendency of bending and sinking, and there is a certain shearing effect inside the rock mass. However, due to the complete structure of the surrounding rock, it is difficult for separation and slippage of the roof to occur, as shown in Figure 1(b).

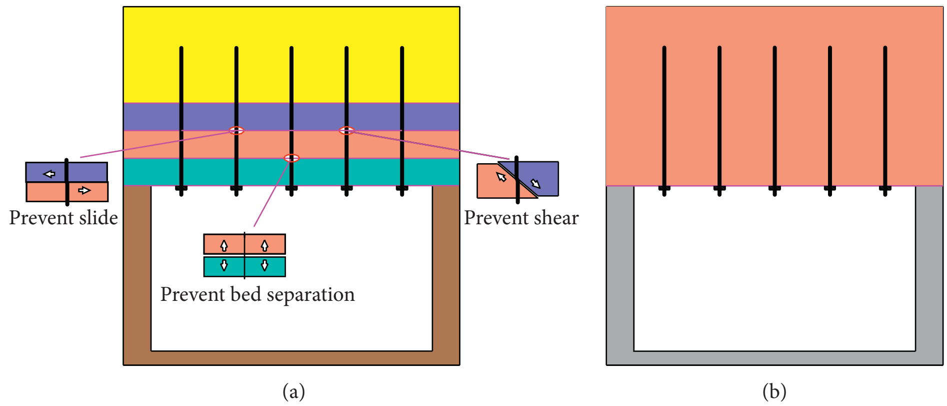


Figure 1: Schematic diagram of bolt support mechanics for different types of roadway roof. (a) Layered roof (b) Nonlayered roof.

The deformation characteristics of the surrounding rock of the roadway roof are closely related to the force and deformation law of the roof bolts. The difference in mechanical properties between layered and nonlayered roof-surrounding rock determines the difference in the bolt support for the different types of the roof support.

An anchor rod runs through the multilayer rock mass and suspends the layered weak roof on the hard rock layer. Prestressed anchor rods are subjected to stretching of the anchor rod body to compact the weak top plate, which is about to be separated or has been separated from the layer, and form a "combined beam" structure above the roadway. In addition, because the strength of the interfacial bond is generally lower than that of the rock mass, the weak top plate, which is prone to slippage between rock layers, causes the bolt body to be severely sheared. Actual engineering examples show that the shearing failure in layered roof roadways is the most important failure mode of the bolt [25]. Under the same stress environment, an anchor rod in the surrounding rock of a nonlayered roof is still subjected to the tensile effect caused by the subsidence of the roof. Unlike the layered top plate, the increase in the shear resistance of the nonlayered top plate results in a significant reduction in the shearing action of the anchor.

3. Numerical Simulation

3.1. Neglecting the Original Rock Stress

3.1.1. Model Establishment. In underground engineering, the interaction between the anchor and the roadway-surrounding rock forms stress and displacement fields. Current understanding suggests that the bolt support strength is about 1 MPa [26], a few tenths (or even less) of the original rock stress. The relationship between the strength of the existing bolt support and the magnitude of the original rock stress is very different. To clearly identify the stress field and displacement field of the bolt support, the $FLAC^{3D}$ software was used to analyze the distributions of these fields in the surrounding rock of a roadway roof without using the original rock stress.

The model domain measured $26\,m \times 26\,m \times 26\,m$ (width × height × thickness) and had a lane size of $3.6\,m \times 3.6\,m$ (width × height). The other physical and mechanical parameters were as follows: bulk modulus of 13.11 GPa, shear modulus of 9.14 GPa, cohesive force of 3.5 MPa, tensile strength of 1.28 MPa, internal friction angle of 25°, and Poisson's ratio of 0.26. The bolt was simulated with a cable unit and arranged perpendicular to the top plate. The bolt had a diameter of 22 mm and length of 2.1 m; the breaking load was 310 kN and the prestress was 120 kN. The end anchoring-grouting method was adopted, and the anchoring length was set to 0.5 m. The left and right boundaries, front and back boundaries, and upper and lower boundaries of the computational model were all constrained by displacement. The simulation proceeded as follows: establish model ⟶ roadway excavation ⟶ install anchor and apply pretightening force ⟶ anchor rod calculation. The stress field and displacement field distributions of the rock surrounding the bolt support without considering the original rock stress are shown in Figures 2 and 3.

3.1.2. Stress Field of Bolt Support. Figure 1 indicates that the stress field of the roadway-surrounding rock supported by a bolt exhibits the following primary characteristics:

(1) A single bolt forms an elliptical compressive stress zone and tensile stress zone in the roadway-surrounding rock: (i) A compressive stress concentration zone is generated in the vicinity of the tail of the bolt, and the maximum compressive stress value is 0.14 MPa (Figure 2(a)). The compressive stress value decreases gradually with distance from the tail of the bolt and from the tunnel roof, and the compressive stress value decreases to 0.0 MPa at one-fifth of the length of the bolt. (ii) The phenomenon of tensile stress concentration occurs in the anchorage section of the bolt, but the degree and range of this tensile stress are relatively small, with a maximum tensile stress value of 0.04 MPa (Figure 2(a)). (iii) In terms of the overall distribution of the stress field in the surrounding rock supported by the bolt, there is a relatively large compressive stress zone in the vicinity of the tail of

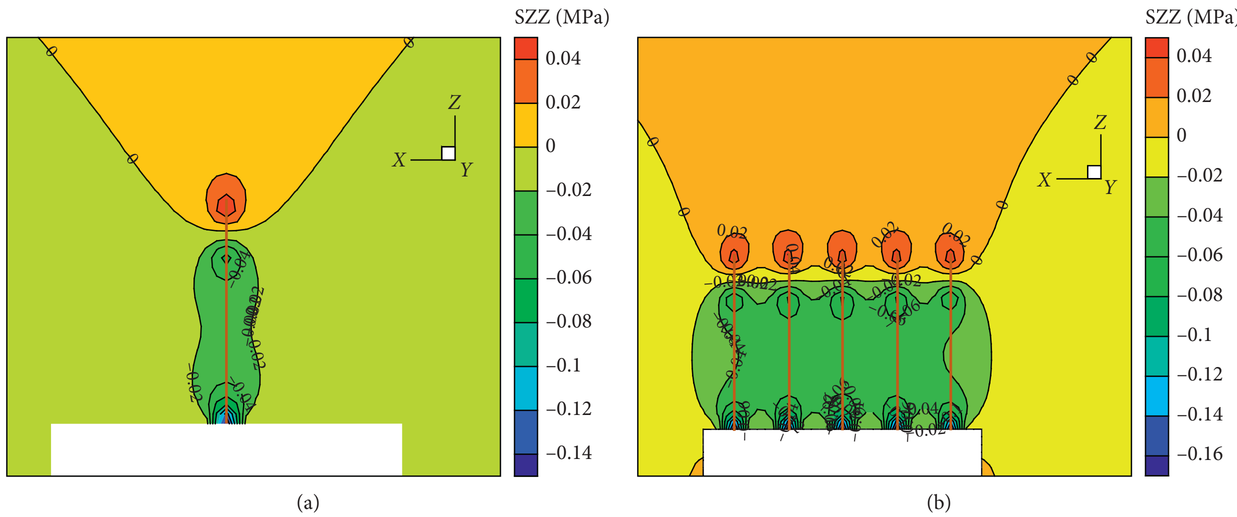


FIGURE 2: Stress field distribution of bolt support without considering the original rock stress. (a) Single bolt support and (b) multiple bolt support.

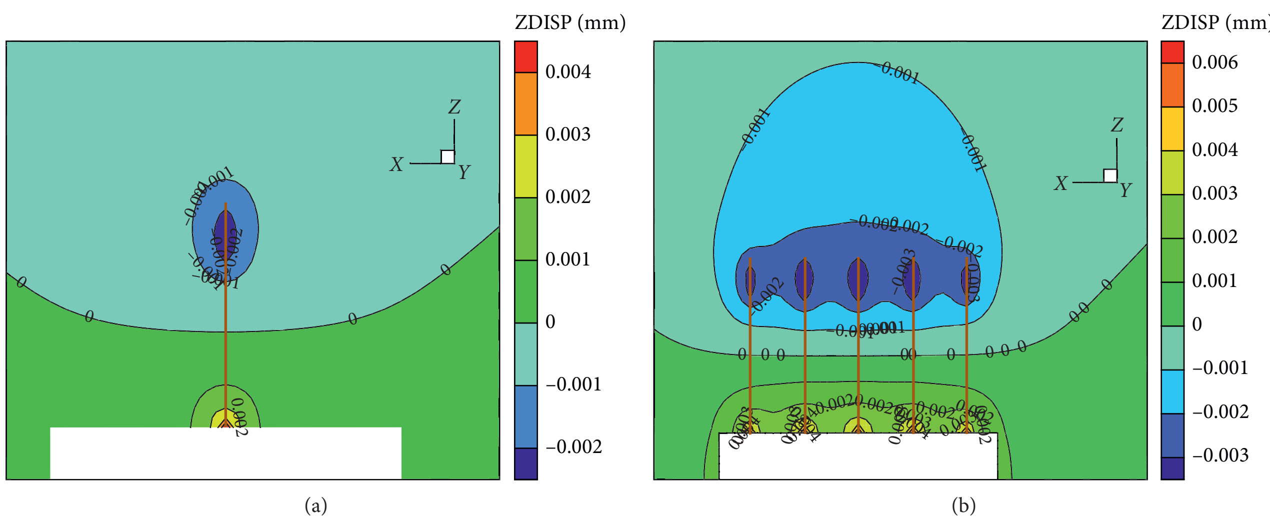


FIGURE 3: Displacement field distribution of bolt support without considering the original rock stress. (a) Single bolt support and (b) multiple bolt support.

the bolt and a relatively small range of tensile stress in the vicinity of the anchorage section of the bolt.

(2) The roof is supported by the bolt groups: (i) The supporting stress fields formed by a single bolt are superimposed on each other, and areas with higher stress values between the bolts are enlarged and connected, eventually covering the roof of the tunnel, as shown in Figure 2(b). (ii) When the tunnel roof is supported by the bolt groups, the maximum compressive stress zone still appears in the vicinity of the tail of the bolt, and the compressive stress value decreases gradually with distance from the tail of the bolt and from the tunnel roof. The maximum tensile stress zone still appears in the vicinity of the anchorage section of the bolt and the degree and range of tensile stress are relatively small. (iii) As the number of supporting bolts increases, the bolt support density increases, and the effect on the expansion of the stress field of the roadway-surrounding rock and the diffusion of prestress in the bolt gradually weakens.

(3) The stress field of the roadway-surrounding rock in the deep roof is not affected by the bolt support; that is, the range of influence of the bolt support is limited. Increasing the length of the bolt is conducive to the formation of a large compressive stress area, which is more helpful in terms of improving the stability of the roadway-surrounding rock.

3.1.3. Displacement Field of Bolt Support. It is clear from Figure 3 that the displacement field of the roadway-surrounding rock supported by the bolt exhibits the following main characteristics:

(1) A single bolt forms a semielliptical positive displacement zone and a negative stress zone in the

roadway-surrounding rock: (i) A significant positive displacement concentration zone appears near the tail of the bolt, and the maximum displacement value is 0.004 mm (Figure 3(a)). The displacement value gradually decreases with distance from the tail of the bolt and from the tunnel roof, and the displacement value at half the bolt length has decreased to 0 mm. (ii) A negative displacement concentration occurs in the anchorage section of the bolt, but the degree of displacement is relatively small, with a maximum value of 0.002 mm (Figure 3(a)). However, the range of influence is relatively large. (iii) Regarding the overall distribution of the displacement field of the roadway-surrounding rock of the bolt support, a relatively small positive displacement zone forms near the tail of the bolt and a relatively large negative displacement zone forms near the anchorage section of the bolt, as shown in Figure 3(a).

(2) The roof is supported by the bolt groups: (i) The displacement fields formed by a single bolt are superimposed on each other, and the areas with higher displacement values between the bolts are enlarged and connected. The effective positive displacement can cover the shallow rock of the tunnel roof, as shown in Figure 3(b). (ii) When the roof of the roadway is supported by the bolt cable groups, the maximum positive displacement zone still appears in the vicinity of the tail of the bolt, and the displacement value decreases gradually with distance from the tail of the bolt and from the tunnel roof. The maximum negative displacement zone appears near the anchorage section of the bolt. Although the degree of negative displacement is relatively small, the range of influence is relatively large. (iii) As the number of supporting bolts increases, the bolt support density increases, and the expansion of the displacement field of the roadway-surrounding rock gradually weakens.

3.2. Considering the Original Rock Stress. A large number of engineering investigations suggest that, in the coal-forming process, the influence of geological and environmental changes leads to various types of sedimentary lithology and lithofacies in the geological deposition process of coal seam roofs. The characteristics of the different combinations can vary substantially. In particular, the strength, thickness, and relative position of each rock formation in the vertical direction of the roadway roof are different. For example, the direct top rock strata of the Datangtashan Coal Mine and the Huangyanhui Coal Mine are largely single-layered, and the lithology is sandy mudstone with a thickness of 7.5 m or more [27–29]. The average thickness of the direct roof rock in Zhuxiangzhuang Coal Mine Roadway is 6.4 m, but the rock stratum contains a large number of bedding and weak surfaces, and considerable roof subsidence can occur [30]. To clarify the effect of the nonlayered roof-surrounding rock with a good anchor on the integrity of the roadway, the supporting effect of the surrounding layered roof with a large number of bedding or weak faces must be determined.

According to the actual situation of the roof of an underground roadway, the surrounding rock is divided into two cases for numerical analysis. The first case considers the thickness of the roof rock layer on the temporary surface to be large, so that the surrounding rock of the roof can be regarded as a nonlayered homogeneous rock mass for the numerical analysis. The second case considers several layers in the roof of the roadway, with the thickness of each layer assumed to be equal for the numerical analysis. Considering the original rock stress, the FLAC^{3D} finite difference program was used to simulate the influence of the bolt support on the stress field, displacement field, and plastic zone in the rock surrounding the roadway roof.

3.2.1. Model Establishment

(1) Mechanical Model of Nonlayered Homogeneous Roof Roadway. The model domain measured 51 m × 37 m × 10 m (width × height × thickness), the roadway size was 5.4 m × 3.9 m (width × height), and hexahedral elements were used to form the mesh. Each cell measured 0.3 m × 0.3 m × 0.3 m, and the boundary constraints are shown in Figure 4. The calculation model used the Mohr–Coulomb strength criterion and the rock mechanics parameters listed in Table 1. The original rock stress was set to $P_1 = 15$ MPa, $P_2 = P_3 = 25$ MPa. The bolts were simulated as cable units were arranged perpendicular to the direction of the top plate. Each bolt had a diameter of 22 mm and a length of 3.6 m; the bolting length was 0.5 m, the breaking load was 310 kN, and the prestress was 120 kN. The simulation proceeded as follows: model establishment ⟶ original rock stress balance ⟶ roadway excavation and preliminary pressure relief ⟶ installation of anchor bolts and preloading force ⟶ calculation of interaction between the anchor and surrounding rock.

(2) Mechanical Model of the Layered Roof Tunnel. The surrounding rock of caves in underground engineering projects often contains many discontinuous structural planes such as joints and bedding/weak planes. The interface unit in FLAC^{3D} can simulate the mechanical properties of discontinuous structural planes such as joints, bedding planes, and faults in the roadway-surrounding rock mass medium. Using the mechanical calculation model of the homogeneous roof roadway, four weak faces (numbered 1–4 from bottom to top) were arranged in the direction along the free face of the roadway to the roof. The weak faces of each layer were separated from the free face of the tunnel roof by 0.6 m, 1.2 m, 1.8 m, and 2.4 m, respectively, and the interface units in FLAC^{3D} were connected between weak planes. The parameters of the interface unit are presented in Table 2, and the rock mechanics parameters in the calculation model are listed in Table 3. The other conditions and the setting of the anchor were the same as for the nonlayered homogeneous roof roadway. The calculation model is shown in Figure 5.

3.2.2. Layout of Surrounding Rock Monitoring Points. To demonstrate the control effect of the anchor rod on the surrounding rock deformation of the roadway roof, nine

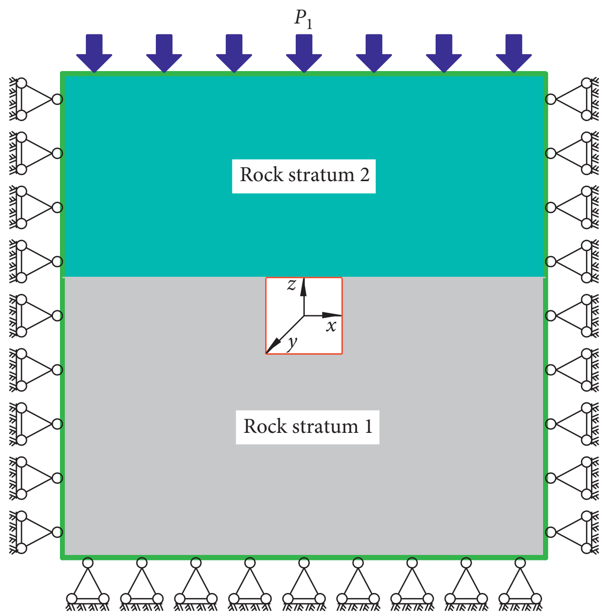


Figure 4: Numerical calculation model of surrounding rock of nonlayered homogeneous roof roadway.

Table 1: Rock mechanics parameters.

	Bulk modulus (GPa)	Shear modulus (GPa)	Friction angle (°)	Cohesion (MPa)	Tensile strength (MPa)	Density (kg·m^{-3})
Stratum 1	0.55	0.15	22	0.5	0.7	1500
Stratum 2	5.0	3.1	29	2.5	1.9	2500

Table 2: Interface unit parameters.

Weak plane	Normal stiffness (GPa·m^{-1})	Tangential stiffness (GPa·m^{-1})	Tensile strength (kPa)	Friction angle (°)	Dilatancy angle (°)
1#	13	12	50	30	2
2#	12	11	120	28	2
3#	11	10	150	28	2
4#	10	9	100	25	2

Table 3: Rock mechanics parameters.

	Bulk modulus (GPa)	Shear modulus (GPa)	Friction angle (°)	Cohesion (MPa)	Tensile strength (MPa)	Density (kg·m^{-3})
Stratum 1	5.0	3.1	29	2.5	1.9	2500
Stratum 2	0.55	0.15	22	0.5	0.7	1500
Stratum 3	0.60	0.20	22	0.5	0.7	1500
Stratum 4	0.60	0.20	22	0.5	0.7	1500
Stratum 5	0.63	0.23	22	0.5	0.7	1500

monitoring points were positioned along the support direction of the roof bolt in the vertical direction. The arrangement of the monitoring points is shown in Figure 6; monitoring point 1 is 0.3 m above the tunnel roof and the other points are located at intervals of 0.6 m.

3.2.3. Numerical Simulation Results

(1) Stress Field, Displacement Field, and Plastic Zone of Surrounding Rock of Nonlayered Homogeneous Roadway Roof. The results for the nonlayered homogeneous roadway roof are shown in Figures 7 and 8. From a comparative analysis of Figures 2, 3, and 8, it appears that, in the surrounding rock mass of the nonlayered homogeneous roadway under the condition of the original rock stress, the bolt support fails to form obvious tensile stress, compressive stress, positive displacement, and negative displacement zones. As the support force provided by the bolt is not of the same order of magnitude as the original rock stress, the stress field and displacement field formed by the bolt support are covered by the original rock stress field and displacement field.

A comparative analysis of Figures 7(a) and 8(a) indicates that the bolt support does not significantly improve the roadway-surrounding rock stress field in terms of the

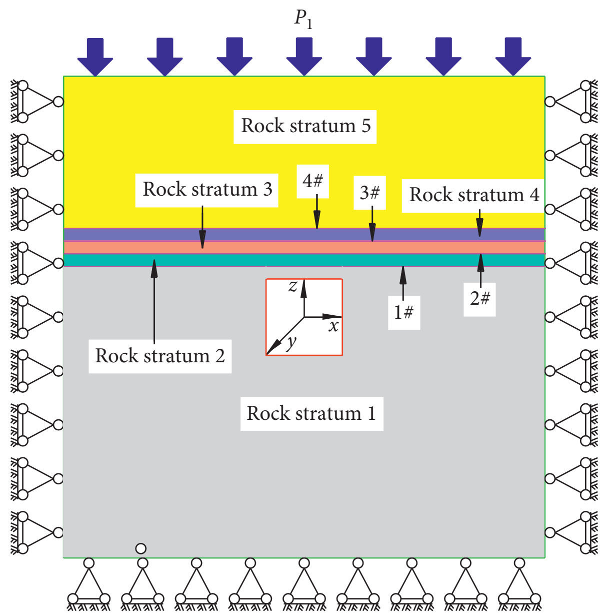


Figure 5: Numerical calculation model of surrounding rock of layered roof roadway.

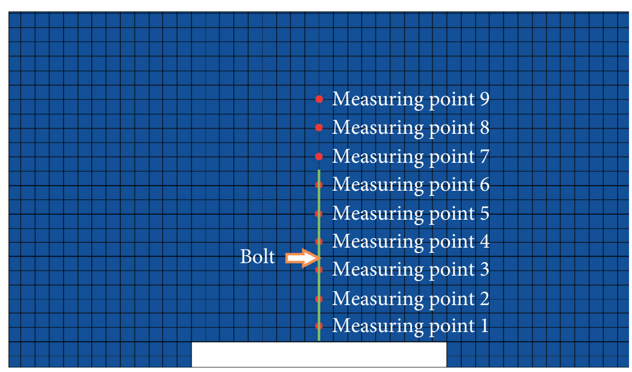


Figure 6: Monitoring point layout.

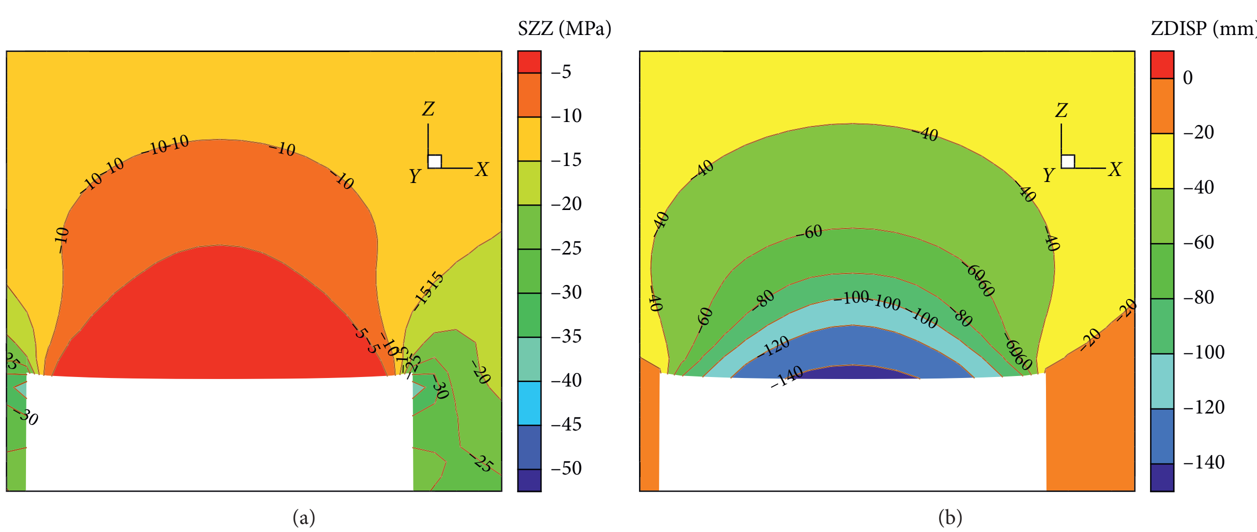
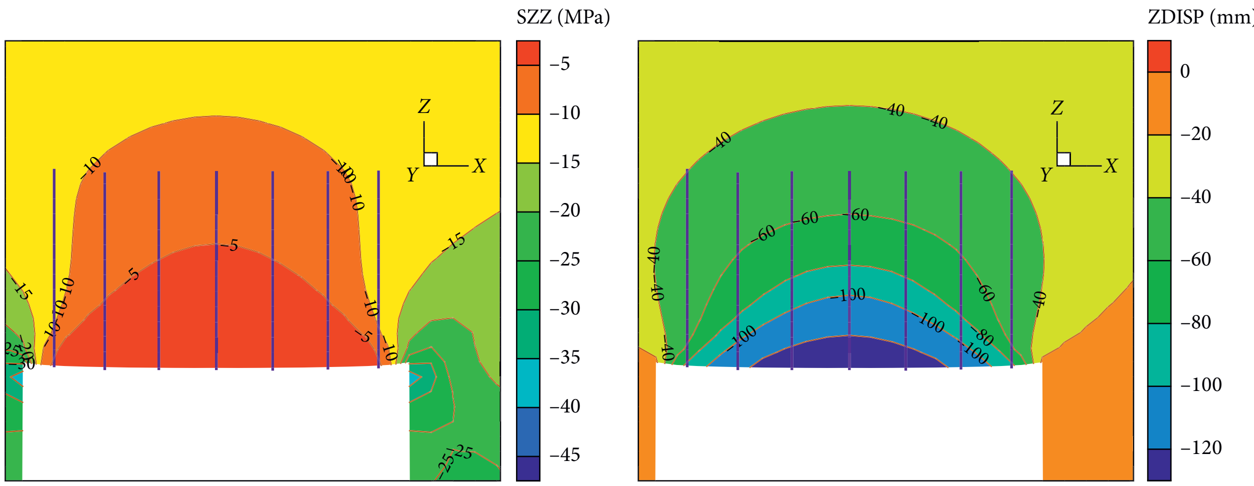


Figure 7: Distribution of stress field and displacement field of surrounding rock in nonlayered homogeneous roof. (a) Stress field and (b) displacement field.



(a)

(b)

Figure 8: Stress field and displacement field distribution of rock surrounding bolt support in nonlayered homogeneous roof. (a) Stress field and (b) displacement field.

geometric distribution and numerical value of the original rock stress field. From a comparison of Figures 7(b) and 8(b), it is clear that the range of the displacement field curve of the surrounding rock in the shallow roof of the roadway decreases after the bolt support is applied, and the maximum displacement field (140 mm curve) disappears. The range of the 120 mm curve is significantly reduced but has little effect on the extent of the various displacement field curves deep inside the rock of the roadway-surrounding rock. Therefore, it is considered that the effect of the bolt support on improving the displacement field of the surrounding rock deep within the roadway roof is limited, but the effect of improving the displacement field of the surrounding rock in shallow roadways is significant.

Comparing Figures 9 and 10, the geometrical distribution and range of the plastic zone of the rock surrounding the tunnel roof decrease after the bolt support is applied, but this effect is not obvious. Therefore, relying on the bolt support cannot achieve the purpose of effectively reducing the plastic zone of the rock surrounding the tunnel roof.

From Figure 11, it can be seen that the bolt support has a considerable influence on the deformation of the surrounding rock in the shallow part of the tunnel roof but has little effect in deeper regions. For example, under the unsupported condition, the subsidence of the rock surrounding the tunnel roof at monitoring point 1 is as high as 0.1394 m, and that at monitoring points 2, 3, and 4 is 0.1249 m, 0.1037 m, and 0.0783 m, respectively. With a bolt applied, the subsidence is slightly smaller (0.1264 m, 0.1147 m, 0.09769 m, and 0.07696 m at monitoring points 1–4, resp.). Thus, the deformation amount decreases from the free face to the deepest part of the surrounding rock of the tunnel roof. This is in contrast to the unsupported condition of the bare roadway. The reduction in deformation at the four monitoring points after bolt support is 0.013 m, 0.0102 m, 0.00601 m, and 0.00134 m, respectively. That is, bolt support has a significant control effect on the deformation of the surrounding rock in the shallow part of the tunnel roof, but this deformation control effect is progressively weakened away from the tail region of the bolt.

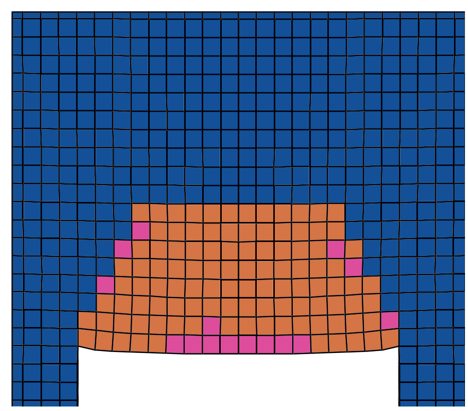


Figure 9: Distribution of plastic zone of surrounding rock in nonlayered homogeneous roof.

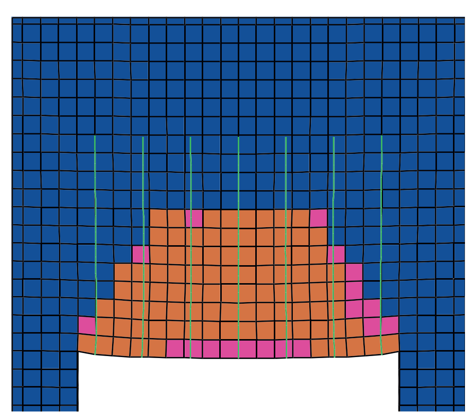


Figure 10: Distribution of plastic zone of rock surrounding anchor support in nonlayered homogeneous roof.

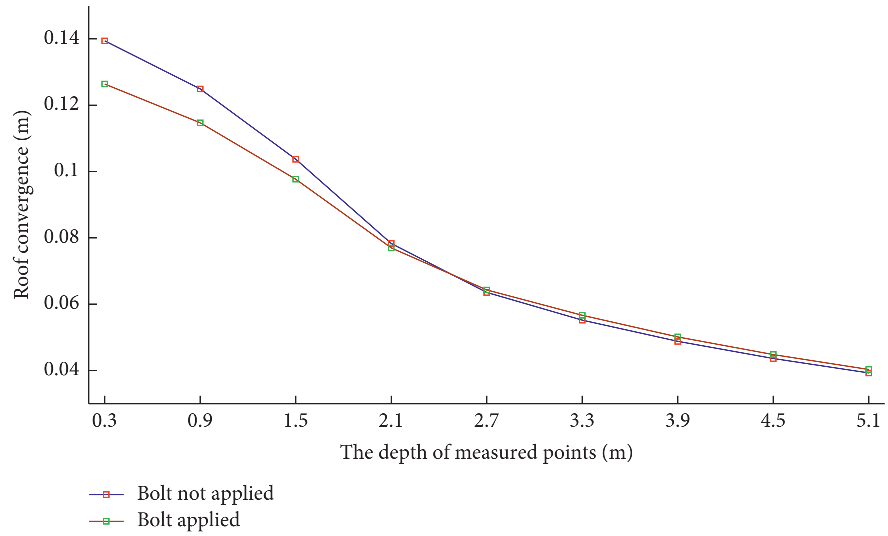


FIGURE 11: Deformation of each monitoring point of surrounding rock in nonlayered homogeneous roof.

At the same time, it can be seen from Figure 12 that within 3.3 m of the roadway facing the depths of the surrounding rock, the effect of bolt support is obvious, and the reduction rate of the roof rock deformation is rapidly weakened. However, outside the surrounding rock of the roadway, the deformation reduction rate is very small and there is almost no change. When the anchor length is 3.6 m and the anchor anchor length is 0.5 m, the deformation reduction rate of the surrounding rock within the free length of the anchor (3.1 m) changes rapidly, while the deformation of the surrounding rock outside the anchor anchor range decreases slower. This shows that the anchoring effect of the anchor rod has not failed, the anchor body and the surrounding rock are deformed synchronously, and no sliding occurs between them.

(2) Stress Field, Displacement Field, and Plastic Zone of Surrounding Rock in Layered Roadway Roof. The numerical results for the layered roof are presented in Figures 13 and 14. A comparative analysis of Figures 2, 3, and 14 indicates that, in the surrounding rock mass of the layered tunnel roof, the bolt support does not produce tensile stress, compressive stress, positive displacement, and negative displacement zones. From a comparison of Figures 13(a) and 14(a), it can be seen that the bolt support does not significantly improve the stress field of the roadway-surrounding rock in terms of the geometrical distribution and numerical value of the original rock stress field. Comparing Figures 13(b) and 14(b), it is clear that the numerical range of the displacement field of the surrounding rock decreases in the shallow part of the tunnel roof after the bolt support is applied, and the separation phenomenon within the soft rock disappears. The maximum displacement field (150–350 mm curve) has disappeared and the displacement field of the surrounding rock in the anchorage section is effectively improved. In addition, further into the surrounding rock of the tunnel roof, the effect of the bolt on the displacement field of the surrounding rock gradually weakens.

A comparison between Figures 15 and 16 indicates that the geometrical distribution and range of the plastic zone of the rock surrounding the tunnel roof decrease after the bolt support is applied, but this effect is not obvious. Thus, the bolt support cannot effectively control the plastic failure of the roadway-surrounding rock, but it is very effective in reducing the bed separation and slip within the soft rock of the tunnel roof.

Analysis of Figures 17 and 18 suggests that the control effect of the bolt on the soft rock deformation within 2.4 m of the tunnel roof is very significant, whereas the control effect in the deep surrounding rock is relatively small. For example, in the unsupported condition, the subsidence of the soft rock at monitoring points 1–4 is 0.3551 m, 0.2621 m, 0.1856 m, and 0.1212 m, respectively. After bolting, the subsidence is 0.1375 m, 0.1241 m, 0.1036 m, and 0.07911 m, respectively. The reduction in deformation at the four monitoring points is 0.2176 m, 0.138 m, 0.082 m, and 0.04209 m, respectively. From the free face of the roof to the depth of the roadway-surrounding rock, the deformation decreases; compared with the shallow soft rock of the tunnel roof, the control effect of the bolt on the deformation of rock stratum 5 is small. For example, when the tunnel roof is unsupported, the subsidence at monitoring points 7–9 is 0.0584 m, 0.0512 m, and 0.04528 m, respectively, and the amount of sinking after bolting is 0.04956 m, 0.04372 m, and 0.03889 m, respectively. The deformation has been reduced by 0.00884 m, 0.00748 m, and 0.00639 m, respectively. The bolt control effect in this area is very small.

It can be seen from Figure 18 that, within the range of 2.7 m deep in the tunnel facing the surrounding rock, the bolt support effect is more obvious. The rate of the deformation reduction of roof rock quickly weakened. The roadway-surrounding rock is 2.7 m away, and its deformation reduction rate is very small with little change. Through the comparative analysis of the weak surface position of each rock layer of the roof-surrounding rock and the reduction rate of the deformation of the roof-surrounding rock, it is found that the deformation reduction

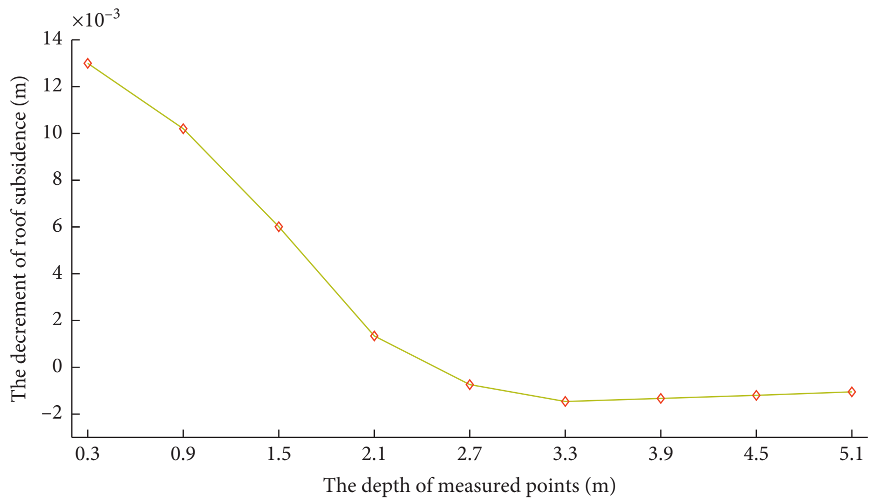


Figure 12: Deformation reduction at each monitoring point of surrounding rock in nonlayered homogeneous roof.

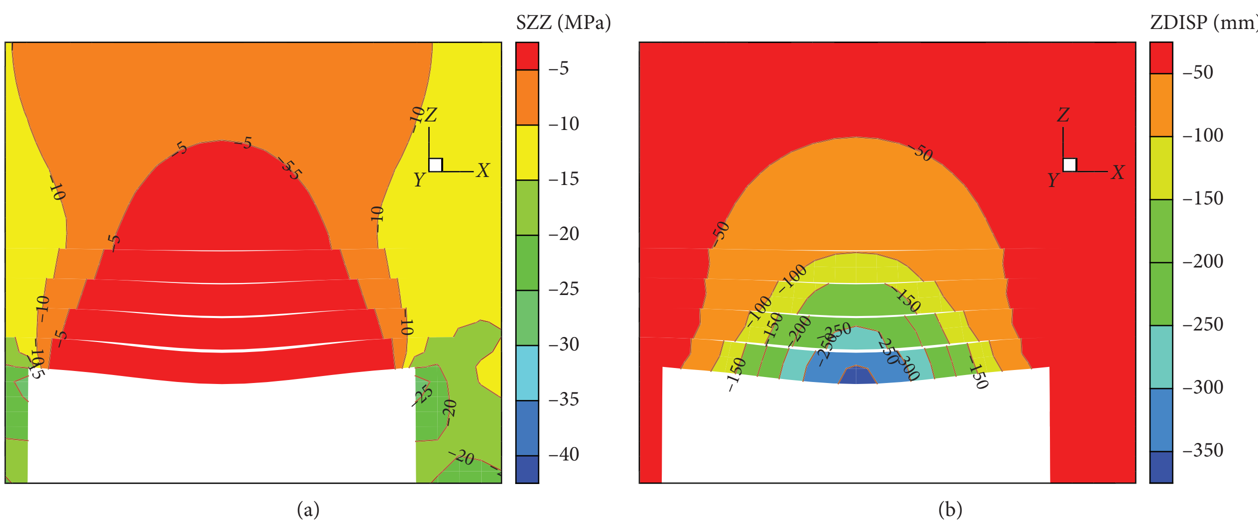


Figure 13: Distribution of stress field and displacement field of surrounding rock in the layered roof. (a) Stress field and (b) displacement field.

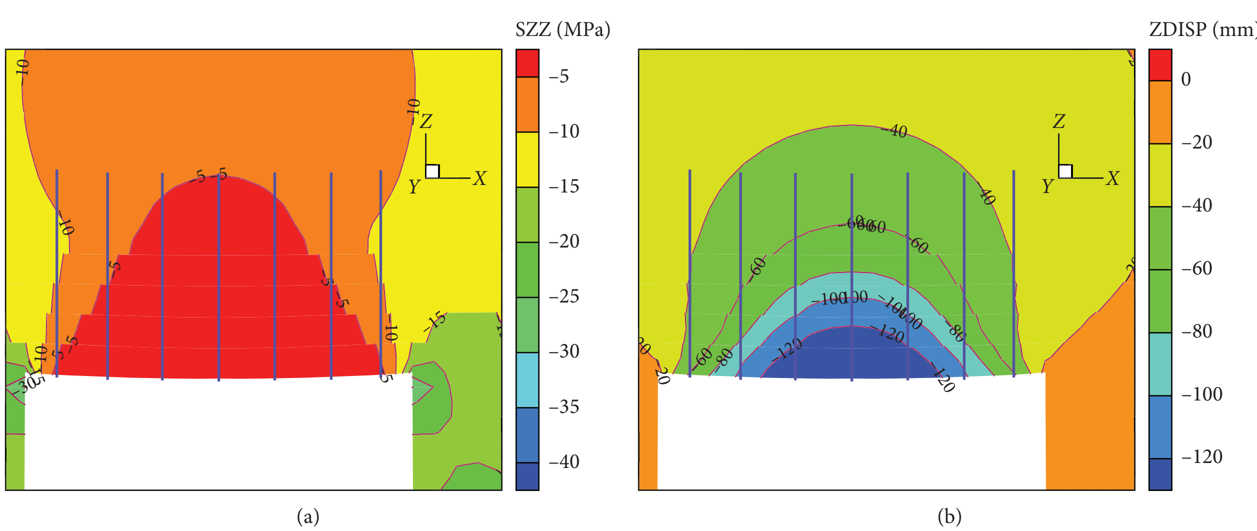


Figure 14: Distribution of stress field and displacement field of surrounding rock bolt support in the layered roof. (a) Stress field and (b) displacement field.

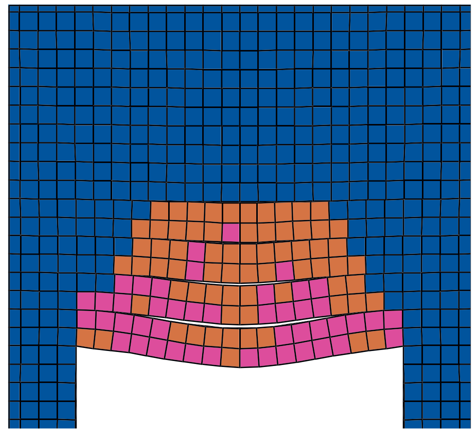


Figure 15: Distribution of plastic zone of surrounding rock in the layered roof.

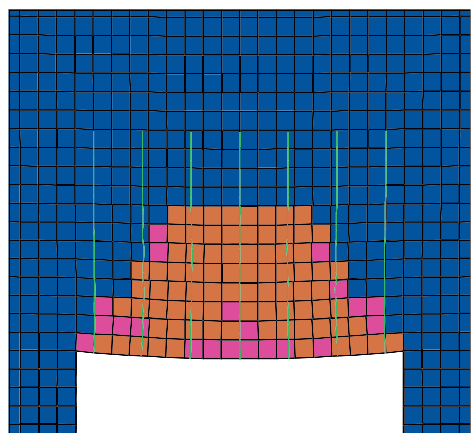


Figure 16: Distribution of plastic zone of bolt support of surrounding rock in the layered roof.

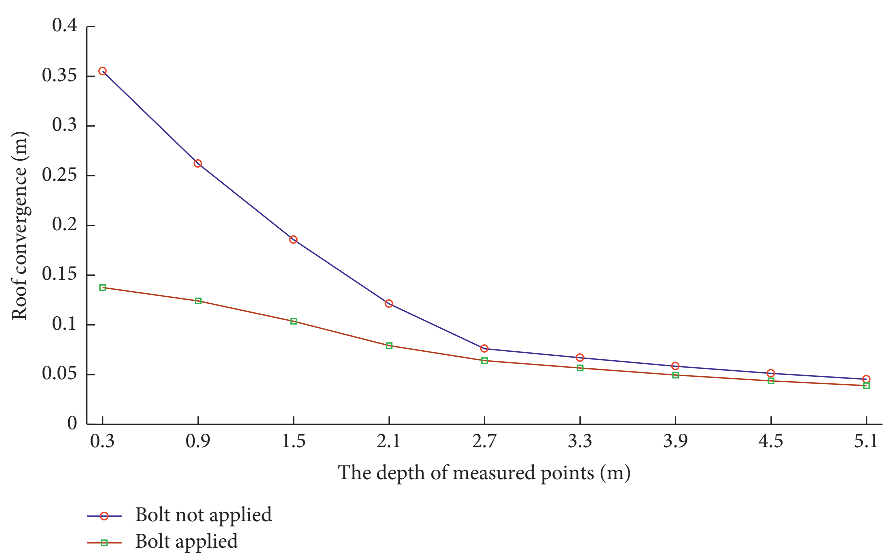


Figure 17: Deformation of each monitoring point of surrounding rock in the layered roof.

rate of the surrounding rock within the range of the weak surface (2.4 m) is faster. However, the reduction rate of the surrounding rock deformation outside the weak surface area is slower. These indicate that the deformation reduction of the surrounding rock of the roadway roof under the condition of bolt support mainly comes from the amount of open delamination on the weak surface, and this delamination deformation is a discontinuous deformation.

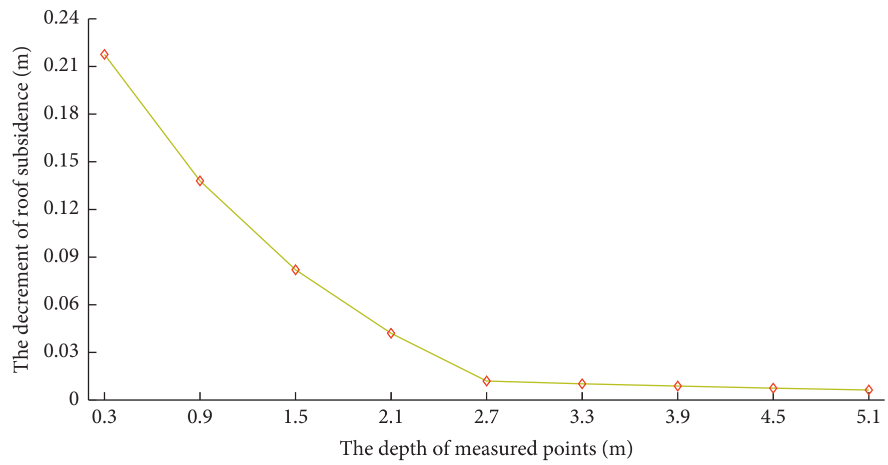


Figure 18: Deformation reduction of each monitoring point of surrounding rock in the layered roof.

According to the above numerical simulation analysis, it is found that the control effect of the bolt support on the surrounding rock of the layered roof and nonlayered roof is similar or different. (1) Similarities: the effect of bolt support on the stress field and plastic area of the surrounding rock of the two types of roadway roof is not obvious. The distribution and range of the stress field and plastic zone are relatively small. (2) Different points: the bolt support has a significant effect on the displacement field of the surrounding rock in the layered roof anchoring area, and the numerical curve range of the surrounding rock displacement field in the anchoring area is significantly reduced (Figures 13(b)–14(b)). The delamination phenomenon between the rock layers has disappeared obviously, and only the shallow surrounding rock displacement field curve range of the nonlayered roadway roof has decreased. There is almost no change in the displacement field curve in the surrounding rock depths (Figures 7(b)–8(b)).

4. Discussion

Generally speaking, roadways should be actively supported after excavation. However, in actual engineering applications, the roadway excavation and support are not synchronized in time. After excavation of the roadway, the deformation energy in the shallow surrounding rock can be released before the bolt support is applied, and the roadway-surrounding rock will inevitably move into the excavation space. This will result in a certain amount of internal displacement, which mainly includes continuous deformation due to elastic deformation and plastic deformation, discontinuous deformation such as bed separation, and sliding and crack opening of the surrounding rock structural plane in the soft rock and the fractured zone.

$FLAC^{3D}$ is a numerical simulation application based on continuum theory. Therefore, the deformation of surrounding rock in nonlayered homogeneous roofs (see Section 3.2) was considered in terms of elastic deformation and plastic deformation, that is, continuous deformation. The deformation of the roadway-surrounding rock of layered roofs includes not only elastic deformation and plastic deformation (continuous deformation), but also open sliding deformation between the weak faces of the roof, that is, discontinuous degeneration. From the control effect of the bolt on the continuous deformation and discontinuous deformation, the continuous deformation of the surrounding rock in nonlayered homogeneous roadways is only 0.013 m (Figures 12), and the continuous deformation and discontinuous deformation of the surrounding rock of the layered tunnel roof are 0.2176 m (Figures 18). Thus, the discontinuous deformation of the surrounding rock in layered tunnel roofs can reach 0.2046 m, which is an order of magnitude greater than the continuous deformation. In addition, from the perspective of the plastic zone, the plastic failure of the surrounding rock in the tunnel roof cannot be effectively controlled by the bolt, indicating that the bolt has a limited effect on the plastic deformation of the roadway-surrounding rock.

In summary, it can be seen that the main role of the bolt support is to control the discontinuous deformation of the roof soft rock and the structural plane of the surrounding rock of the anchorage section, that is, separation, sliding, and fracture opening. The bolt support ensures that the roadway-surrounding rock is under pressure and suppresses the appearance of tensile and shear failure in the surrounding rock.

The control effect of the anchor on the rock surrounding the roadway is affected by factors such as the bolt structure, support density, anchor material, anchoring agent, and rib spacing. At the same time, it will also be affected by the mechanics and structural features of the surrounding rock, such as the hardness coefficient, hydrological conditions, and rock structure. Only by scientifically and comprehensively considering various factors and optimizing the actual status of individual projects can we determine the true mechanism of the bolt support.

5. Conclusions

(1) Without considering the stress of the original rock, the anchor rod forms a more obvious stress field and displacement field in the surrounding rock near the roadway anchoring area. A compressive stress field and a positive displacement field appear near the tail

of the bolt. A tensile stress field and a negative displacement field appear in the anchored end region of the bolt. When the original rock stress is considered, the tensile and compressive stress zones and the positive and negative displacement zones of the anchor bolt in the surrounding rock of the roof of the roadway obviously disappear.

(2) The bolt support has no significant effect on the stress field and plastic zone of the surrounding rock of the layered roadway roof and nonlayered roadway roof. The plastic failure of the surrounding rock of the roadway roof cannot be effectively controlled.

(3) The range of each numerical curve of the displacement field of the surrounding rock in the anchorage area of the layered roadway is significantly reduced, while the range of the curve of the displacement field of the shallow wall of the nonlayered roadway is only reduced. However, the curve of the displacement field in the surrounding rock is almost unchanged. At the same time, the effect of the anchor rod on the displacement field of the roof rock of the two types of roadways gradually weakened as they penetrated into the roof rock of the roadway.

(4) The bolt support has a significant effect on inhibiting discontinuous deformation such as delamination and sliding between the layered weak roof rocks. The delamination phenomenon between the rock layers disappears obviously, and the continuous deformation control such as the elastoplastic deformation of the surrounding rock of the nonlayered roadway roof is limited.

Data Availability

This article contains all the data generated or published during the study; no other data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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