

Optimization of inclined coal seam tunnel section angle and anchor angle based on response surface method

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ABSTRACT

The mining of inclined coal seams is often accompanied by problems such as difficult to control deformation of the tunnel roof and failure of anchor bolts. Taking the transportation channel of Jinping Coal Industry 1071-1 in Shanxi Xiangkuang Mine as the background, FLAC3D numerical simulation software was used, and the method of response surface experimental design and data analysis was used to systematically study the effects of the anchor installation angle and the roof inclination angle of the tunnel section on different inclination angles. Influence of the surrounding rock stability of coal seam roadways. On this basis, a multi-index tunnel support design evaluation method based on the response surface method was proposed, and the actual support plan was optimized and industrial tests were carried out based on the actual on-site support plan. The research results show that: in terms of inclined coal seam support, the degree of influence on the tunnel stability is in the following order: anchor installation angle > tunnel section roof inclination angle > coal seam inclination angle; the optimized support design obtained through the proposed technology The method has good application effect and can improve the stability of the roadway during the mining of the working face. It also proves the effectiveness of this technology and provides new ideas for the design of anchor support of inclined coal seam roadways and the optimization of roadway sections.

KEYWORDS

Anchorage angle; Section angle; Inclined coal seam; Response surface method; Roadway deformation

1. INTRODUCTION

As an important energy source for my country's current industrial development, coal has always occupied a dominant position in my country's energy structure. my country's near-horizontal and gently sloping coal seam reserves account for 85.96%, of which the reserves and production of gently sloping coal seams account for approximately 40% of the national corresponding values, sloping coal seams account for 10.16%, and steeply sloping coal seams account for 3.88% [1-2]. Due to the influence of the rock layer inclination angle and rock layer structure of the inclined coal seam, coal mining, especially the stability control of the roadway, brings great difficulties.

In view of the problem that the stability control of surrounding rock after tunnel excavation is particularly difficult due to the influence of inclination angle of inclined coal seams, domestic and foreign researchers have conducted a large number of studies on this type of tunnel support technology, mainly focusing on large inclination angles and sudden emergencies. In inclined coal seams, the cross-sectional forms are mainly rectangular tunnels and arched tunnels, but the above-mentioned surrounding rock control problems also exist in gently inclined coal seams [3]. Gao Lin [4] proposed collaborative anchor protection control technology by analyzing the disturbance of

gently sloping coal seams caused by mining. Tu Hongsheng et al.[5] analyzed the deformation and fracture characteristics of coal pillars under different tilt angles and different coal pillar sizes, and concluded that coal pillars are mainly affected by shear damage along the inclination. ZHANG[6] studied the deformation of the surrounding rock of an asymmetric roadway in an inclined coal seam, analyzed the asymmetric deformation and damage characteristics of the roadway under the original support scheme, and optimized the support parameters. Wang Hongwei [7] et al., through research on the deformation and failure laws and support failure mechanisms of large-angle coal seam tunnels, proposed a combined support scheme of "anchor net spraying + rigid and flexible supports". Xin Yajun et al. [8-9] established the instability state equation of the surrounding rock of soft rock roadways in large-angle coal seams by analyzing the instability characteristics of the soft rock roadways in large-angle coal seams. Cao Xinqi et al. [10] proposed an optimization plan for advance support of mining tunnels under different roof inclination angles based on existing roof support technical measures. Regarding the anchoring angle of the anchor bolt, Yang Songlin et al. [11] analyzed whether the rock was damaged due to extrusion, and obtained the corresponding relationship between the shear stress and displacement of the anchor reinforcement joint during the shear process. Han Jianxin [12] set the anchoring angle as a variable variable and established a function model between the compressive strength of the supporting rock mass and the anchoring angle of the anchor rod. Kang Hongpu [13] concluded through simulation test analysis that in the prestressed support system of horizontal coal seams, the maximum angle of the inclined anchor should not exceed 10°. Liu Quansheng et al. [14-16] analyzed the influence of parameters such as different anchor inclination angles, surrounding rock compressive strength, and anchor diameter on the shear strength of anchored joint surfaces. Cao Juncai [17] proposed the concept of shear stress ellipse by analyzing the damage mechanism of shear stress ellipse to roof deformation.

As we all know, there are many factors that affect the stability of tunnels, and the standards for evaluating the effectiveness of tunnel support are also multifaceted. Although scholars have conducted in-depth research on the section selection and support scheme selection of inclined coal seam tunnels. However, most of these studies only analyzed a single influencing factor and rarely considered the interactive effects of multiple factors. Therefore, this paper takes the geological conditions of the 1071-1 working face of Jinping Coal Industry in Xiangkuan, Shanxi as the engineering background, and proposes a tunnel support optimization method based on response surface experimental design and data analysis. The influence of the stability of the surrounding rock of the roadway [18], and combined with on-site industrial tests to confirm the rationality of this method. The study not only obtained the best support optimization plan, but also derived the interaction relationship between various influencing factors, providing a new idea for the optimization design of inclined coal seam tunnel support.

2. PROJECT OVERVIEW

The design length of the 1071-1 working face of Jinping Coal Industry in Shanxi Xiangkuang Co., Ltd. is 2032.5m, with an average burial depth of 655.65m. It is tunneled along the 3# coal seam. It is a full coal tunnel construction. The coal seam thickness is 5.9~6.45m, with an average thickness of 6.41m. The lower part there is about 0.2~0.5m gangue inclusion, and the coal seam inclination angle is 10°~25°. The tunnel section is rectangular, with tunnel width × height = 5.24m × 4.5m. According to its excavation geological instructions and geological drilling detection results, its comprehensive geological column diagram is shown in Figure 1.

Name of roof and floor	Name of coal seam	Columnar	Thickness (m)	Petrographic characteristic
The Old Roof	Sandy mudstone and Fine grain quartz sandstone		$\frac{5.43 \sim 10.25}{7.51}$	Gray white, massive, quartz-based, Calcareous cementation, hard, horizontal bedding, f=4~8.
Immediate Roof	Mudstone and Sandy mudstone		$\frac{2.04 \sim 4.15}{2.96}$	Black, homogeneous, dense, massive, Containing plant fossils, f=2~4.
False Roof	Carbon mudstone		$\frac{0.20 \sim 0.30}{0.25}$	Black, coal line or coal chips, Joint development, easy to fall, f=2~3.
Coal	3# Coal Seam		6.41	Black, medium-thick layered, banded structure, Diamond luster, bright coal, dark coal, semi bright coal The coal quality is PSM.
Direct Bottom	Mudstone and Sandy mudstone		$\frac{2.75 \sim 5.04}{3.84}$	Black, blocky, homogeneous, Containing plant fossil debris, f=2~4.
Old Bottom	The fine feldspathic sandstone		$\frac{4.12 \sim 9.54}{6.52}$	Gray white, feldspar, quartz second, Thick block, black layer, oblique bedding. Calcium cementation, hard, f=4~8.

Figure 1. Comprehensive column chart of the transportation channel of Jinping Coal Industry 1071-1 working face

3. THEORETICAL ANALYSIS

The response surface method is an optimization method that combines experimental design and statistical principles [19]. It includes multiple steps such as experimental design, establishing mathematical models, model testing, and optimization of combined conditions. By performing regression analysis on experimental data and drawing response surfaces and contour plots, the impact of each factor on the response value can be intuitively analyzed. When using the response surface method to construct an approximate function, you must first determine the form of the approximate function, then use statistical experimental design methods to select sufficient samples in space, and finally use the least squares method principle to fit the analysis results to the experimental design samples to obtain the response surface. function. Usually the response surface function is expressed in terms of a second-order function, that is

$$y = f(x_1, x_2, \dots, x_k) = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \dots + \sum_{i < j} \sum_{j=1}^k \beta_{ij} x_i x_j + \varepsilon \quad (1)$$

β represents the coefficient of each term of the model, where β_0 is the constant term of the model, and ε is the random error. It is usually assumed that it obeys the normal distribution $N(0, \sigma^2)$, and the homoscedasticity is independent of each other. When fitting the response of the test conditions to the selected basis function regression equation, the least squares method is the most commonly used method.

Let $p=(k+2)(k+1)/2$, the number of test runs is n, and formula (1) can be expressed in matrix form:

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon} \quad (2)$$

in:

$$\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}, \boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix}, \boldsymbol{\beta} = \begin{bmatrix} \beta_1 \\ \vdots \\ \beta_k \\ \beta_{11} \\ \vdots \\ \beta_{kk} \\ \beta_{12} \\ \vdots \\ \beta_{(k-1),k} \end{bmatrix} \quad (3)$$

$$\mathbf{X} = \begin{bmatrix} 1 & x_{1,1} & \cdots & x_{1,k} & x_{1,1}^2 & \cdots & x_{1,k}^2 & x_{1,1}x_{1,2} & \cdots & x_{1,k-1}x_{1,k} \\ 1 & x_{2,1} & \cdots & x_{2,k} & x_{2,1}^2 & \cdots & x_{2,k}^2 & x_{2,1}x_{2,2} & \cdots & x_{2,k-1}x_{2,k} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{n,1} & \cdots & x_{n,k} & x_{n,1}^2 & \cdots & x_{n,k}^2 & x_{n,1}x_{n,2} & \cdots & x_{n,k-1}x_{n,k} \end{bmatrix} \quad (4)$$

Experimental design point $\mathbf{x} = (x_1, \dots, x_k)^T$ the response value at any point in is:

$$y(\mathbf{x}) = \mathbf{x}_m^T \boldsymbol{\beta} + \varepsilon \quad (5)$$

in: $\mathbf{x}_m = [x_1, \dots, x_k, \dots, x_1^2, \dots, x_k^2, x_1x_2, \dots, x_{k-1}x_k]^T$.

4. MULTI-FACTOR ANALYSIS OF INCLINED COAL SEAM ROADWAY SECTION ANGLE AND ANCHOR ANGLE AND DETERMINATION OF REASONABLE OPTIMIZATION PLAN

4.1 Numerical Model Establishment

A numerical model was established through FLAC3D numerical simulation software based on the geological conditions of the 1071-1 working face of Jinping Coal Industry in Xiangkuan, Shanxi. The numerical model was simplified into a plane strain problem, and the actual calculation efficiency and the influence of boundary effects on the calculation results were taken into account. The model size was finally determined to be $X \times Y \times Z = 100 \text{ m} \times 80 \text{ m} \times 100 \text{ m}$, as shown in Figure 2. Anchor rods and anchor cables are simulated through the built-in Cable structural unit of FLAC3D. Normal constraints are used on the left and right sides, front and rear sides of the model, and its bottom is set as a fixed boundary. The top of the model is the stress boundary, and a vertical stress of 10.5 MPa is applied to simulate the self-weight of the overlying rock layer under real conditions. The model yield criterion is Moore-Coulomb. The mechanical parameters of the corresponding rock mass were obtained after reduction based on the geological report of the Jinping Coal Industry 1071-1 working face transportation channel and related rock mechanics experimental results, as shown in Table 1.

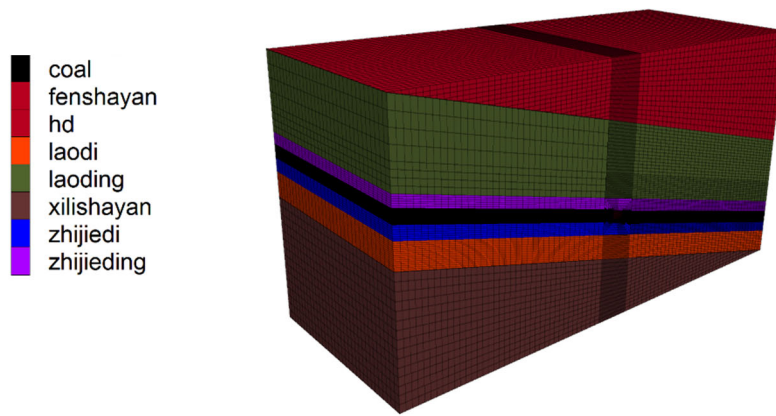


Figure 2. Numerical calculation model

Table 1. Physical and mechanical parameters of roof and floor rock formations

rock formation type	Bulk modulus/GPa	shear modulus/Gpa	tensile strength/MPa	cohesion/MPa	internal friction angle/°	density/kg/m ³
siltstone	1.5	1.46	9.07	18.38	35	2682
coal	1.23	0.72	0.11	1.1	30	1421
mudstone	3.11	3.22	2.9	3.18	27.2	2691
sandy mudstone	5.05	4.5	3.19	4.11	28.2	2710
fine grained sandstone	4.8	5.25	3.51	4.39	37.4	2772

4.2 Box-Behnken Response Surface Method Design And Results

Design Expert It is a software focused on experimental design that can conduct professional analysis of experimental data and generate comprehensive and visual models and optimization results. According to the Box-Behnken response surface method design in Design Expert 13, different anchor installation angles, tunnel section roof inclination angles, and coal seam inclination angles are selected as dependent variables, and the tunnel deformation is the response value, and a response surface design of 3 factors and 3 levels is carried out. There are a total of 19 groups in the program. The experimental design plan and response values are shown in Table 2.

Table 2. Response surface test design and results

Simulation plan	Anchor installation angleA/(°)	Section roof inclination angleB/(°)	Coal seam dip angleC/(°)	Roadway deformation /mm
1	90	30	20	564
2	80	20	30	174
3	100	10	20	398
4	90	20	20	314
5	90	30	10	257
6	90	20	20	239
7	100	20	10	142
8	90	20	10	267
9	90	20	20	81
10	80	30	20	97
11	100	20	20	398
12	100	20	30	78
13	100	30	20	215
14	90	10	30	336
15	90	30	30	94
16	80	20	20	153
17	90	20	30	313
18	80	20	20	166
19	90	20	30	102

After analysis, the response surface function of the roadway deformation is:

$$Y=6970-168A-7.05B+16.57C-0.3AB-0.1AC-0.47BC+1.06A^2+1.12B^2+0.09C^2 \quad (6)$$

4.3 Model validation

The coefficient of determination R^2 represents the closeness between the calculated value of the response surface and the actual value, reflecting the consistency of the response surface and the experimental data:

$$R^2 = 1 - \frac{\sum_{i=1}^k (y_i - \hat{y}_i)^2}{\sum_{i=1}^k (y_i - \bar{y}_i)^2} \quad (7)$$

It can be seen from the formula $R^2 \in [0, 1]$, when $R^2 \rightarrow 1$ hour, indicating the higher the accuracy of response surface fitting. A scatter plot is drawn using the measured and predicted values of tunnel deformation in different schemes, as shown in Figure 3.

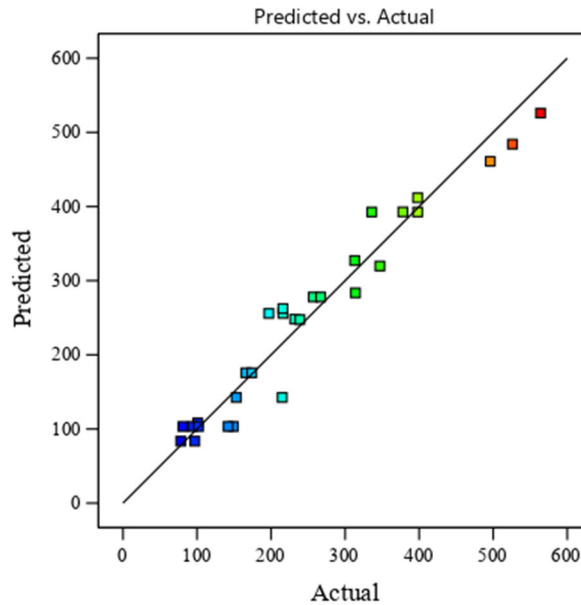


Figure 3. Comparison of calculated and predicted values of roadway deformation

It can be seen from Table 3 that the coefficient of determination of the surrounding rock deformation regression model fitting $R^2=0.9867$, indicating that the fitting effect is better [20]. In order to intuitively reflect the fitting effect diagram and prediction results, we can use the sample data of the numerical simulation test and the fitting prediction results as the horizontal and vertical coordinates to plot the deformation amount y of the surrounding rock respectively. By observing the plotted scatter plot, we can find that the scatter points are approximately evenly distributed near the diagonal. This shows that the prediction results of the model are consistent with the actual observed values, and the fitting effect is good.

Table 3. Response surface function fitting measurement values

response surface function	R2
y	0.9867

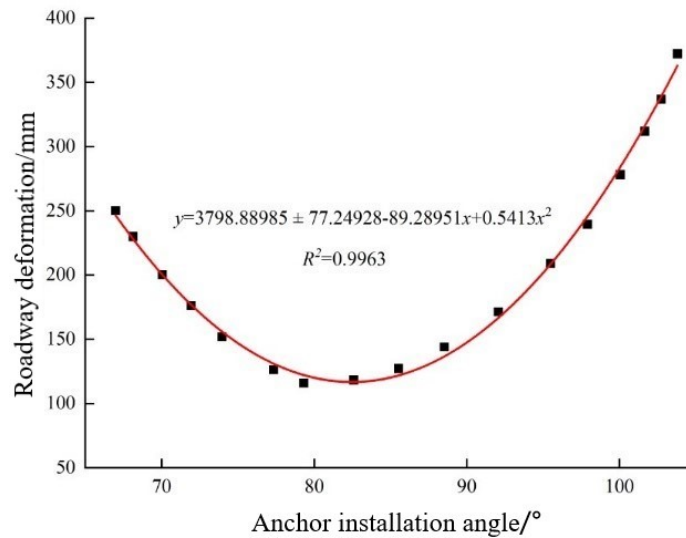
The results of variance analysis of the regression equation of roadway deformation obtained from the optimization test are shown in Table 4. Among them, the P value is used for hypothesis testing to reflect the significance level of the corresponding regression model, and the F value is used to test the significance of the regression equation. $P < 0.05$ Indicates that the equation has reached the significance level. It can be seen from Table 4 that the F test value of the regression equation is 20.55, $P < 0.0001$, It shows that this equation has extremely high significance. while the misfit term $P = 0.2245 > 0.05$, There is no significant difference, which shows that the model fits well and the regression equation has high credibility [20]. According to the F value in the table, the degree of influence of each factor is sorted. The result is anchor installation angle $>$ roadway section roof inclination angle $>$ coal seam inclination angle.

Table 4. ANOVA table

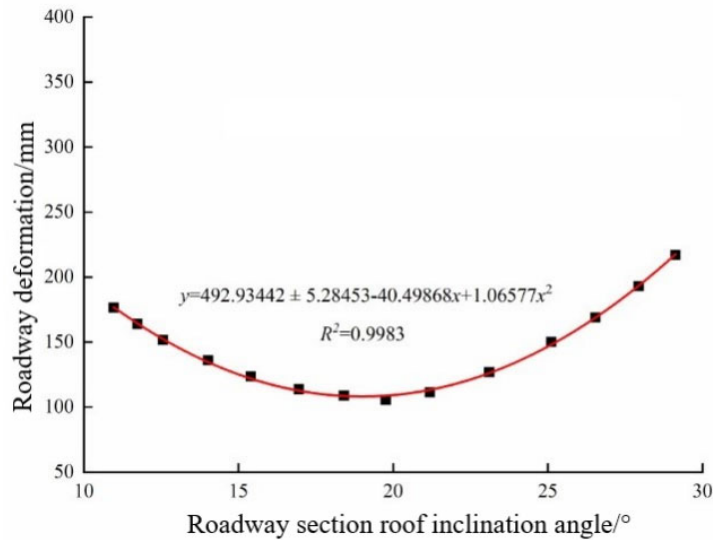
Source of variance	sum of square	degrees of freedom	sum of mean squares	<i>F</i> value	<i>P</i> value
Model	497400	14	35526.73	20.55	<0.0001
Anchor installation angle	39445.33	1	39445.33	22.81	0.0003
Section roof inclination angle	6500.31	1	6500.31	3.76	0.0029
Coal seam dip angle	6329.91	1	6329.91	3.66	0.0764
residual	24205.26	14	1728.95	-	-
Lack of fit term	20564.06	10	2056.41	2.26	0.06245
error	3641.20	4	910.30	-	-
sum	521600	19	-	-	-

4.4 Analysis Of The Influence Of A Single Factor On The Deformation Of The Surrounding Rock Of The Tunnel

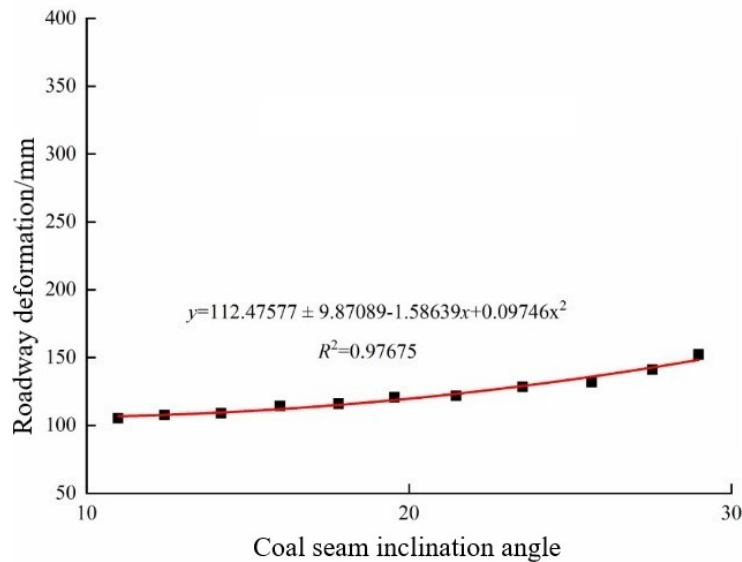
In order to intuitively analyze the influence of a single factor on the deformation of the roadway under the inclined coal seam, the horizontal axis is the horizontal value of the independent variable in the table, and the response value corresponding to each horizontal value, that is, the deformation of the roadway, is the vertical axis. In order to facilitate the description and analysis, the anchor angle is set to 80°, the coal seam inclination angle is 10°, and the roof inclination angle of the tunnel section is 20°. The single-factor influence curve of the maximum deformation of the tunnel in the excavation working face is shown in Figure 4.



(a) Effect of anchor installation angle on tunnel deformation



(b) Effect of the inclination angle of the roof of the tunnel section on the deformation of the tunnel



(c) Effect of coal seam inclination angle on roadway deformation

Figure 4. Effect of single factor on roadway deformation

It can be seen in Figure 4-a that the deformation of the tunnel (the amount of movement of the roof and bottom plates and the amount of movement of the two gangs) first decreases and then increases with the increase of the anchor installation angle. When the anchor installation angle increases from 70° to 80°, the peak deformation of the roadway decreases from 201mm to 129mm, a reduction of 35.8%; when the anchor installation angle increases from 80° to 90°, the peak deformation of the roadway increases from 129mm to 147mm, an increase of 14.0%. And the peak value of the tunnel deformation changes when the anchor installation angle is 80°.

It can be seen in Figure 4-b that the deformation amount of the tunnel (the amount of the roof and bottom plates moving closer and the amount of the two gangs moving closer) shows a trend of first decreasing and then increasing with the increase of the inclination angle of the roof of the tunnel section. When the inclination angle of the roof of the tunnel section increases from 10° to 20°, the peak deformation of the roadway decreases from 186mm to 117mm, with a reduction rate of 37.1%; when the inclination angle of the roof of the roadway section increases from 20° to 30°, the peak deformation of the roadway increases from 117mm to 223mm, with an increase of 91.1%, and the peak value of the tunnel deformation occurs when the inclination angle of the roof of the tunnel section is 20°.

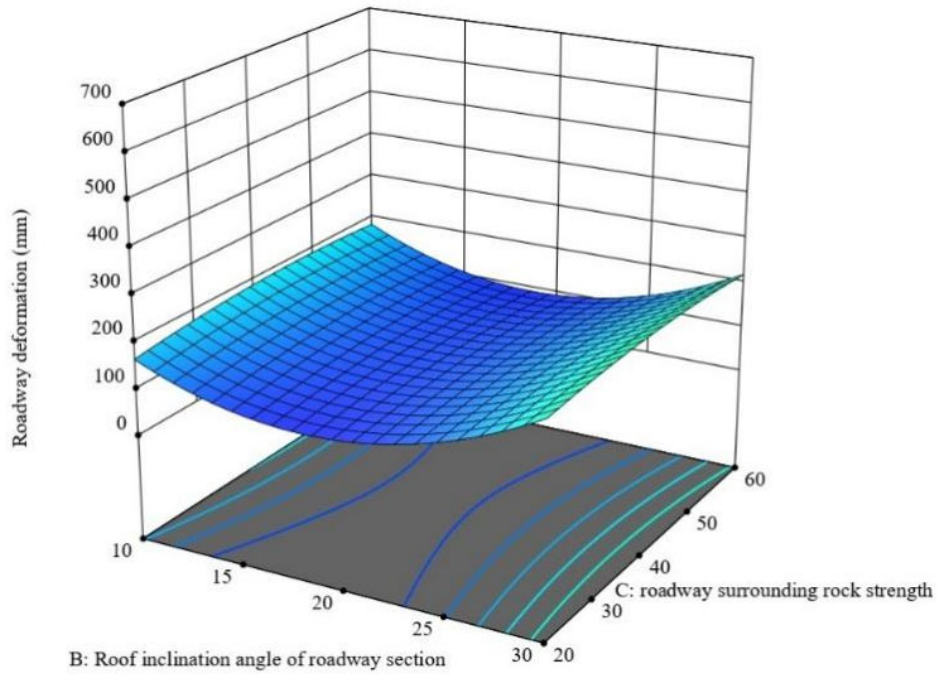
It can be seen in Figure 4-c that the deformation amount of the surrounding rock of the tunnel (the amount of roof and bottom plate movement and the amount of two gangs moving closer) shows an increasing trend with the increase of the coal seam inclination angle. When the coal seam inclination angle increases from 10° to 30° , the peak deformation amount of the roadway increased from 107mm to 169mm, with an increase of 57.9%. There was a positive correlation between the peak deformation amount of the roadway surrounding rock and the inclination angle of the coal seam.

4.5 Response Surface Analysis Of Multi-Factor Interaction Of Tunnel Deformation In Excavation Working Face

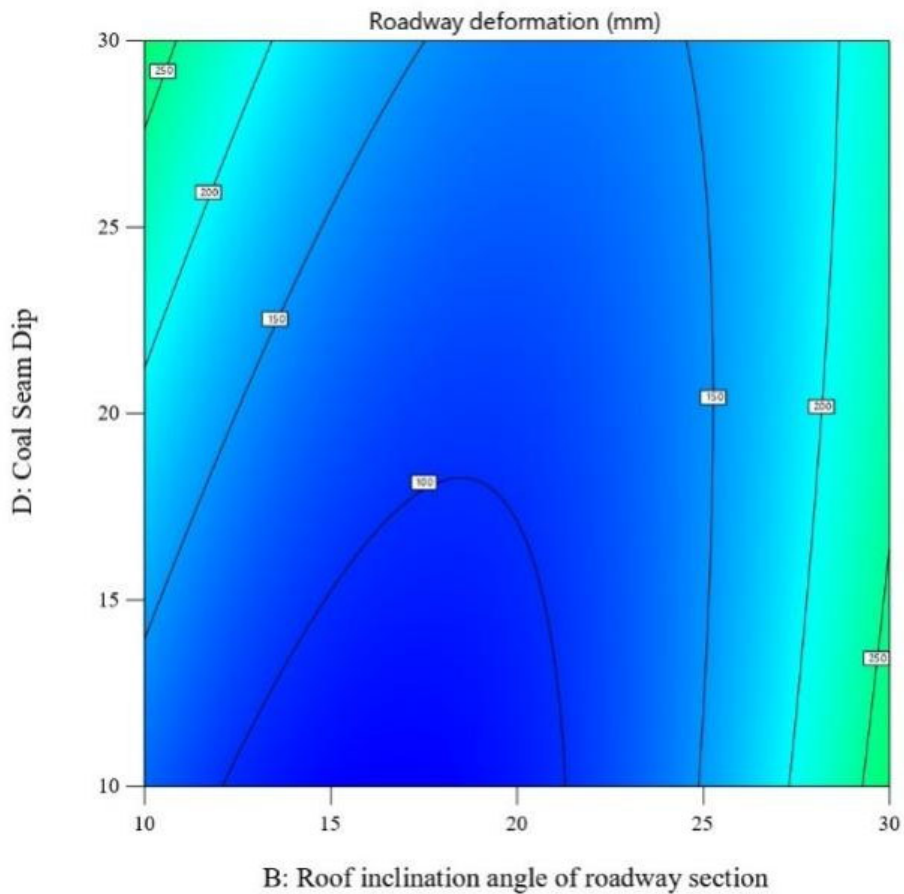
Divide the above influencing factors into controllable factors and uncontrollable factors. The inclination angle of the coal seam in the tunnel is uncontrollable and can be summarized as uncontrollable factors; the installation angle of the anchor rod and the inclination angle of the roof of the tunnel section can be controlled through the tunnel layout and support design, and can be summarized as controllable factors [21]. According to the simulation test results, a 3D response surface and contour map of the interaction between controllable factors and uncontrollable factors on the deformation of the tunnel under the inclined coal seam were established through response surface function regression. The contour lines are nearly linear, indicating that there is a certain interaction between influencing factors. The 3D response surface is relatively gentle, and the contour lines are close to linear, indicating that the interaction is weak; the 3D response surface is steep, and the contour lines are elliptical, indicating that the interaction effect is significant. The specific results are shown in Figures 5 to 7.

4.5.1 Coal seam inclination angle and roadway section roof inclination angle

The contour plot can reflect the significance of factor interaction. The closer the contour line is to an ellipse, the greater the significance of the factor interaction. On the contrary, the closer the contour line is to a straight line, the smaller the significance of the factor interaction. The shape of the mid-height line in Figure 5-b is close to an ellipse, indicating that there is a significant interaction between the inclination angle of the coal seam and the inclination angle of the roof of the tunnel section. Combined with Figure 5-a, the interaction between the coal seam inclination angle and the roadway section roof inclination angle is as follows: when the coal seam inclination angle is low, the roadway deformation first decreases and then slowly increases as the roadway section roof inclination angle increases. When the coal seam inclination angle is large, the deformation of the roadway shows a trend of first slowly decreasing and then increasing as the inclination angle of the roof of the roadway section increases. The interaction between the inclination angle of the roadway section roof and the coal seam inclination angle is as follows: when the inclination angle of the roadway section roof is small, the deformation of the roadway increases with the increase of the coal seam inclination angle; when the inclination angle of the roadway section roof is large, the deformation amount of the roadway increases with the inclination angle of the coal seam. The coal seam inclination angle decreases slowly with the increase.



(a)3D response curve



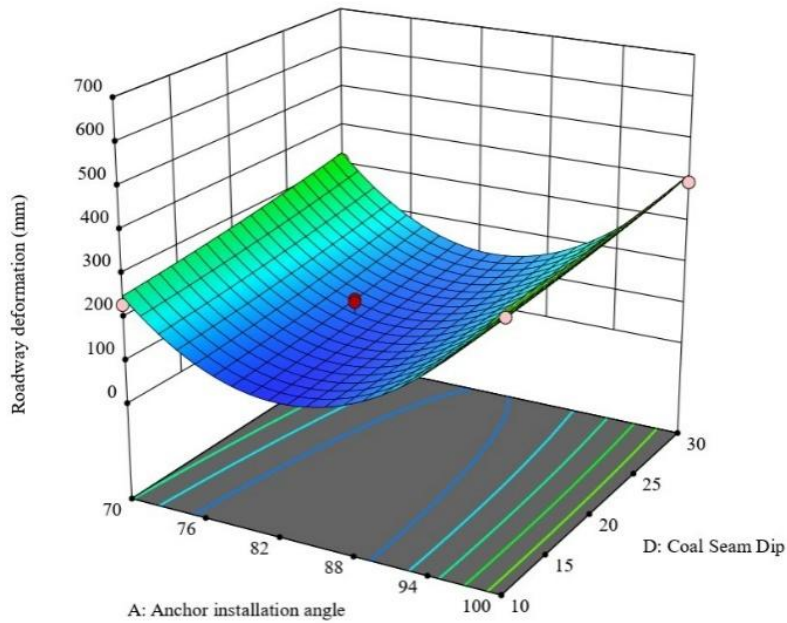
(b)contour line

Figure 5. The Interaction of Coal Seam Dip Angle and Roof Dip Angle of Roadway Section

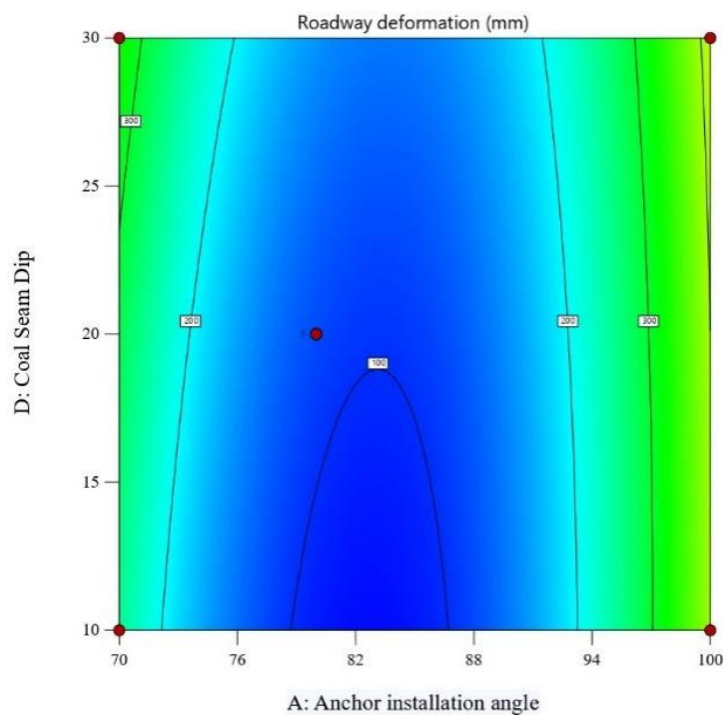
4.5.2 Anchor installation angle and coal seam inclination angle

The shape of the mid-height line in Figure 6-b is closer to an ellipse, indicating that there is a significant interaction between the anchor installation angle and the coal seam inclination angle.

Combined with Figure 6-a, the interaction between the anchor installation angle and the coal seam inclination angle is as follows: when the anchor installation angle is low, the deformation of the roadway increases with the increase of the coal seam inclination angle. When the anchor installation angle is relatively high, When the coal seam is large, the deformation of the roadway shows a slowly increasing trend with the increase of the coal seam inclination angle. The interaction between the coal seam inclination angle and the anchor installation angle is as follows: when the coal seam inclination angle is small, the tunnel deformation first decreases and then increases as the anchor installation angle increases. When the coal seam inclination angle is large, the tunnel deformation As the anchor installation angle increases, the deformation shows a trend of first slowly decreasing and then increasing.



(a)3D response curve

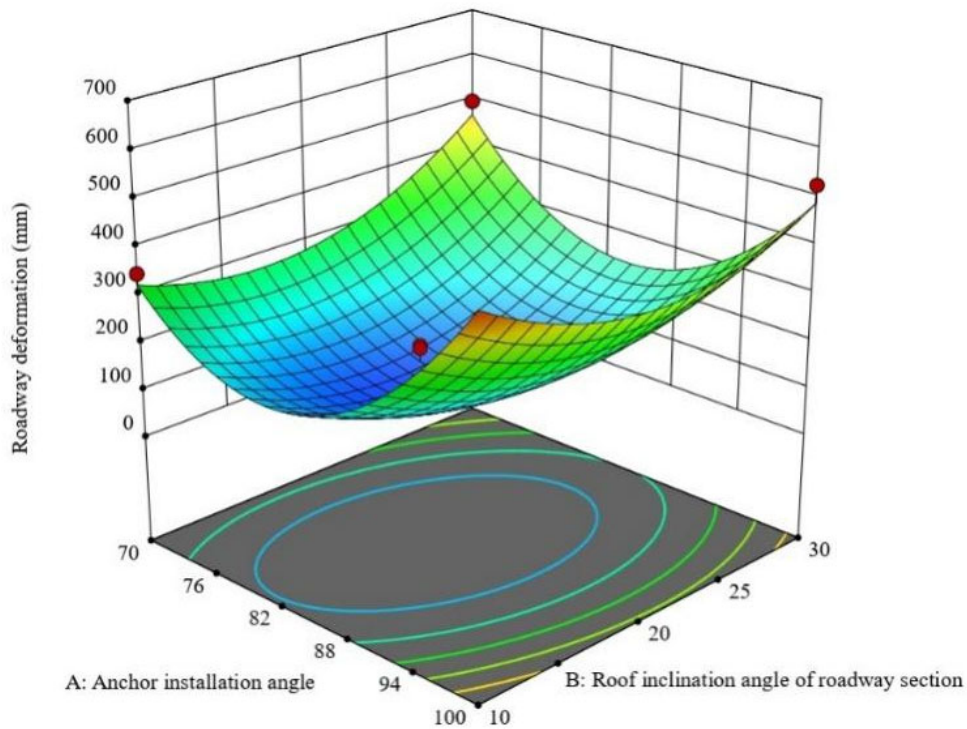


(b)contour line

Figure 6. Interaction between bolt installation angle and coal seam inclination angle

4.5.3 The inclination angle of the roof of the tunnel section and the installation angle of the anchor rod

The shape of the mid-height line in Figure 7-b is close to an ellipse, indicating that there is a significant interaction between the inclination angle of the roof of the tunnel section and the installation angle of the anchor rod. Combined with Figure 7-a, the interaction between the inclination angle of the tunnel section roof and the anchor installation angle is as follows: when the inclination angle of the tunnel section roof is small, the deformation of the tunnel first decreases slowly and then rapidly as the anchor installation angle increases. There is an upward trend. When the inclination angle of the roof of the tunnel section is large, the deformation of the tunnel will first decrease rapidly and then increase rapidly as the anchor installation angle increases. The interactive effect of the anchor installation angle on the inclination angle of the tunnel section roof is as follows: when the anchor installation angle is small, the deformation of the tunnel first decreases slowly and then rises rapidly as the inclination angle of the tunnel section roof increases. When the installation angle is large, the deformation of the tunnel first decreases rapidly and then increases slowly as the inclination angle of the roof of the tunnel section increases.



(a)3D response curve

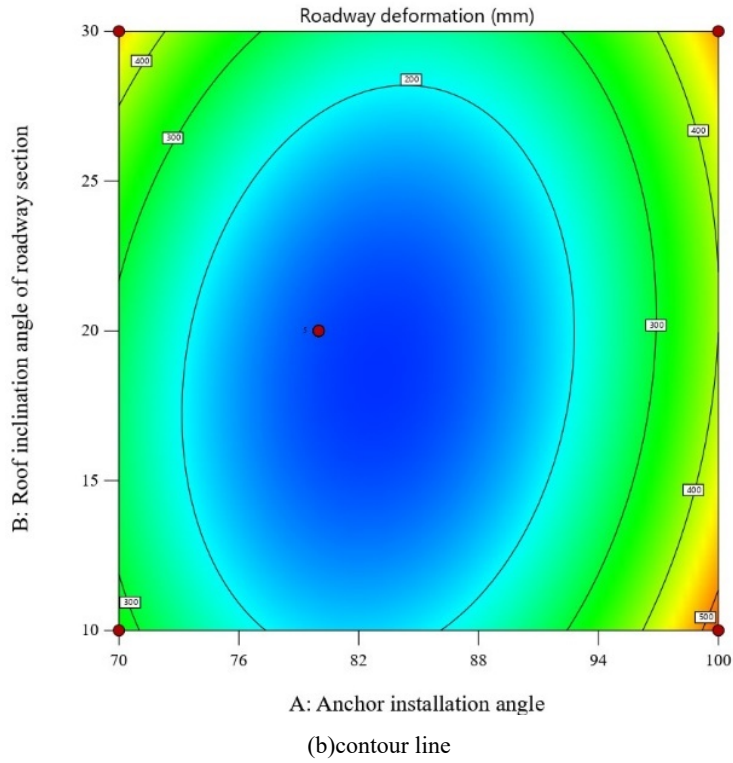
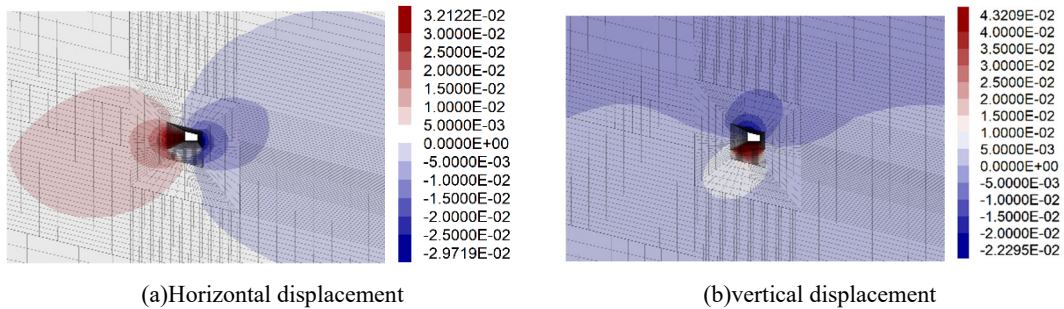
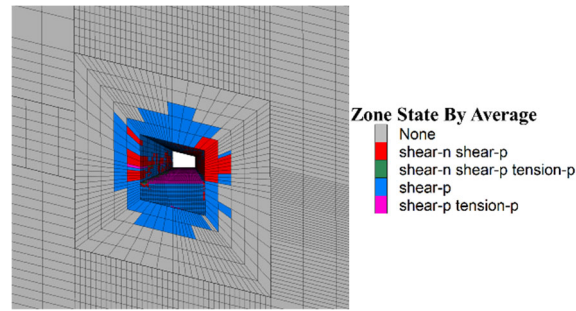


Figure 7. The Interaction of Roof Inclination Angle and Bolt Installation Angle of Roadway Section

4.6 Optimization Plan Determined

Using Design Expert 13 software analysis, the optimal test conditions for the deformation of the Jinping Coal Industry 1071-1 working face during transportation can be obtained: the installation angle of the roof anchor is 81.221° , the roof inclination angle of the tunnel section is 18.937° , and the coal seam inclination angle is 11.433° . Considering the convenience of on-site construction, the roof anchor installation angle is set to 80° , the roof inclination angle of the tunnel section is 20° , and a tunnel with a coal seam inclination angle of 10° is selected. Calculate using the optimized parameters in the numerical model to obtain the displacement cloud diagrams shown in Figure 8(a) and (b), and take the model section with $Y=0$ to obtain the plastic zone cloud diagram in Figure 8(c). The analysis results show that the deformation of the tunnel is basically controlled at 127~129 mm, and there is basically no bulging deformation of the floor, which is consistent with the theoretical value. In addition, it can be seen from the plastic zone cloud diagram that only the shallow surrounding rocks around the tunnel have tensile and shear damage, and the overall stability of the tunnel is well controlled.





(c)plastic zone

Figure 8. Optimal scheme support cloud diagram

The original support design plan has been calculated through numerical simulation. The subsidence of the tunnel roof is 56.473 mm, the distance of the two gangs is 118.521 mm, the bottom drum is 65.832 mm, and the plastic zone volume is 518.472 m³. Compare the original support plan with the optimal plan analyzed by response surface method, as shown in Figure 9. It can be seen from the figure that: the plastic zone volume of the optimal scheme is 479.264 m³, which is 7.56% smaller than the original support scheme; the roof and bottom plate movement distance is 65.504mm, which is 46.44% smaller than the original scheme; the two sides of the movement The advance amount is 61.841 mm, which is 47.82% less than the original support plan. It can be seen that the optimal support scheme obtained by response surface method analysis is relatively reliable.

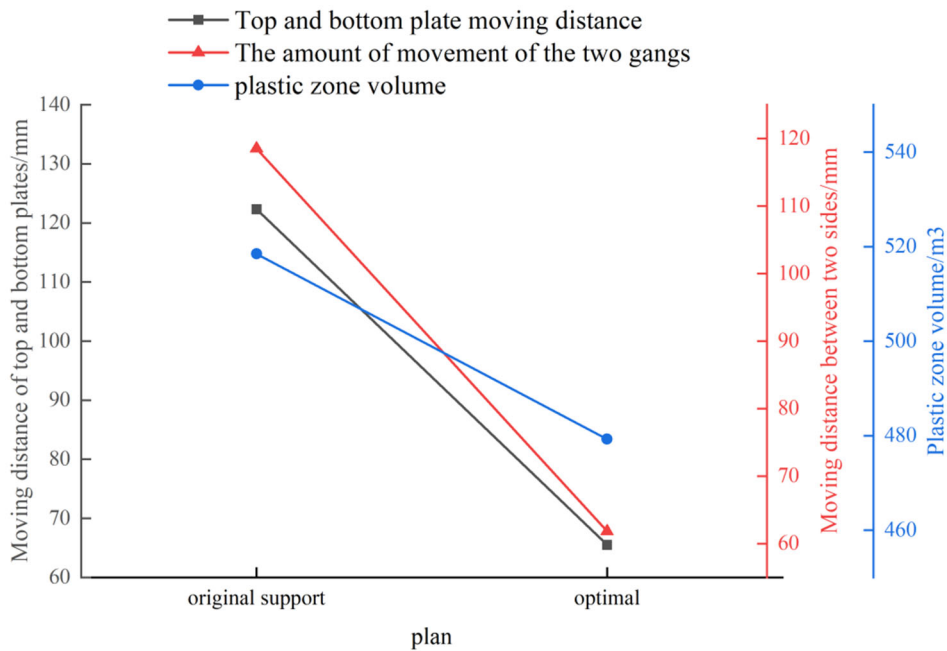


Figure 9. Comparison of support schemes

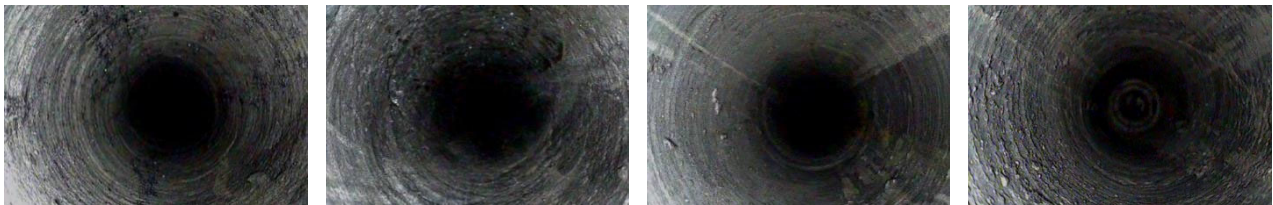
5. ON-SITE INDUSTRIAL TESTING

In order to verify the rationality of the optimized support plan analyzed using the response surface method, an on-site industrial test was conducted on the transportation channel of the 1071-1 working face of Jinping Coal Industry. Using the optimized support plan, no cracks or roof collapse occurred in the test tunnel, and the support effect was significantly improved. In order to further verify the support effect of the optimal support scheme, borehole peeping instruments (Figure 10) were used at 20m and 50m away from the excavation head of the test tunnel to peek into the tunnel section and observe the development of cracks inside the surrounding rock of the test tunnel.



Figure 10. Mine electronic borehole peeping instrument

The peek results at a distance of 20 m from the excavation head of the test tunnel are shown in Figure 11, and the peek results at a distance of 50 m are shown in Figure 12. It can be seen that: obvious cracks appear at 0.43 m and 1.46 m 20 m away from the excavation head; obvious cracks appear at 0.58 m and 2.15 m 50 m away, and no cracks inside the surrounding rock are found in the deeper drilling range. Obvious cracks. This shows that the optimal support scheme obtained by using the response surface method has a good support effect and has a good control effect on the development of the plastic zone of the surrounding rock of the tunnel.



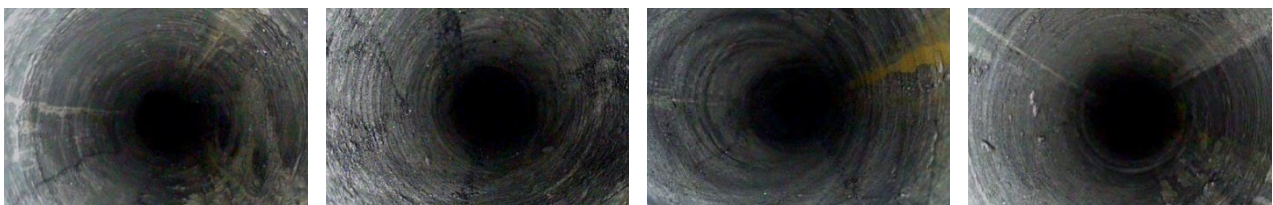
Zk20-0.43

Zk20-1.46

Zk20-8.4

Zk20-10.4

Figure 11. Peep view of the borehole 20 m away from the tunneling head



Zk50-0.58

Zk50-2.15

Zk50-8.38

Zk50-9.58

Figure 12. Peep view of the borehole 50 m away from the tunneling head

6. CONCLUSION

- (1) A roadway support optimization method based on response surface analysis is proposed, which can realize multi-factor analysis and multi-index evaluation of the roadway support effect under inclined coal seams, and significantly reduce the workload in actual engineering optimization.
- (2) Within a certain depth range, the inclination angle of the coal seam, the installation angle of the anchor rod, and the inclination angle of the roof of the roadway section all have a significant impact on the deformation of the roadway under the inclined coal seam. The influence level of each factor on the deformation of the roadway under the inclined coal seam is in order: Anchor installation angle > tunnel roof inclination angle > coal seam inclination angle.
- (3) According to the results of the response surface method, the interaction relationship between various influencing factors was analyzed, and it was concluded that the impact of uncontrollable factors (coal seam angle) on controllable factors (anchor installation angle, tunnel roof inclination angle) can be effectively reduced. Influence of deformation of surrounding rock in roadway.
- (4) Field tests have shown that the optimized support scheme obtained through response surface analysis can effectively control the deformation of the surrounding rock of the tunnel under the inclined coal seam, and better inhibit the development of the plastic zone of the tunnel, proving the effectiveness of the response surface analysis method in support optimization effectiveness.

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