Hindawi
Advances in Materials Science and Engineering
Volume 2021, Article ID 5755055, 15 pages
https://doi.org/10.1155/2021/5755055

Research Article

Influence Factors' Analysis of the Face-End Roof Leaks Exposed to Repeated Mining Based on Multiple Linear Regression

Qiang Li ,[1] Dezhong Kong ,[1] Guiyi Wu ,[1] Zhijie Wen ,[2,3] and Yuqi Shang [1]

[1]*College of Mining, Guizhou University, Guiyang 550025, Guizhou, China*
[2]*Key Laboratory of Mining Disaster Prevention and Control, Qingdao 266590, China*
[3]*Shandong University of Science and Technology, Qingdao 266590, China*

Correspondence should be addressed to Guiyi Wu; 495881085@qq.com and Zhijie Wen; wenzhijie@sdust.edu.cn

Received 19 May 2021; Accepted 20 August 2021; Published 8 September 2021

Academic Editor: Zhengyang Song

In view of the fact that the face-end roof fall under repeated mining of close-distance coal seams seriously affects the normal production of the working face, this paper takes working face 17101 as the background, different influencing factors of face-end roof caving exposed to repeated mining are analyzed through field observation of mine pressure data, different calculation schemes are obtained by using the orthogonal experiment, the subsidence of the face-end roof is taken as the judgment index, UDEC simulation software is used to calculate the subsidence of the face-end roof when different influencing factors change, and the application of SPSS statistical software is used for various parameters of multivariate linear regression analysis. The research results show that the influence degree of different factors from large to small is, respectively, mining height > tip-to-face distance > advancing speed > distance of coal seams > surrounding rock strength > support setting load. It is necessary to strengthen the coordination of all influencing factors and comprehensively control the stability of the face-end roof exposed to repeated mining. Through the analysis of the regression model, it is found that there is no collinearity among the influencing factors, which has a significant influence on the regression equation and regression coefficient, and the multiple linear regression equation has a good fitting effect. The model can predict the stability of the face-end roof exposed to repeated mining, which provides a basis for controlling the face-end roof exposed to repeated mining.

1. Introduction

In the process of repeated mining of close-distance coal seams, the roof bearing capacity will be greatly reduced, and the roof area exposed in the mining process between the hydraulic support and the coal wall is easy to produce leakage, forming a large range of empty roof, known as face-end roof leaks, which pose a great threat to the safe mining of the working face. The stability of the face-end roof exposed to repeated mining has an important influence on the mining of the close-distance coal seams, which is one of the main factors restricting the safe and efficient mining of the close-distance coal seams. In view of different mining conditions, scholars have analyzed and studied the mechanism of roof caving and rib spalling exposed to repeated mining in close-distance coal seams from the aspects of overburden structure movement, supporting pressure distribution, and working face support parameters and obtained some research results [1, 2]. Therefore, it is necessary to study the influencing factors of the roof caving exposed to repeated mining and put forward effective control methods, which is an inevitable requirement to realize the safety of close-distance coal seams' mining [3].

Some scholars have studied the mechanism and control technology of the instability of the face-end roof, analyzed the mechanism of the collapse of the pressure frame under the influence of the special withdrawal technology on the working face of large mining height, and simulated the critical burial depth in that the coal can maintain stable when the technology is used [4]. The influence of moisture change on roof caving is studied, and the maximum water content prediction method for roof caving is proposed. The mechanical relation model and conditions for maintaining the stability of the rib and face-end roof are established, and the interaction among the support setting load, the forward inclination angle of the column, and the mining angle is discussed [5]. The mechanical model of coal deformation and failure under abutment pressure and the analysis of rib spalling are established. They show that the increase of abutment pressure concentration coefficient, the increase of mining height, and the decrease of support load will increase the degree of rib spalling [6]. The risk of ground caving during pillar mining increases under the condition of multicoal seam mining. The hazards related to pillar mining in multiseam mining include roof cutting, roof caving, rib rolls, coal outburst, and floor heave. For the recovery of total coal pillars in the case of close multiple coal seams, the superposition of goafs in the two coal seams is optimal, but the superposition of coal pillars is not required [7]. Some scholars use mathematical methods to analyze coal mine accidents, and the deformation characteristics of subsidence and movement induced by mining under thin bedrocks and thick unconsolidated layers are researched using field measurements and the prediction method of artificial neural networks (ANNs). The improved neural network was used for modeling and predicting the mining subsidence. The ANN output can reflect the change trend of ground movement and deformation [8]. In order to obtain the main factors controlling the deformation and instability of the composite roof, the effects of six controlling factors, namely, the lithologic characteristics of the roof, the size of the roadway section, the stress of the original rock, the thickness of the layers, the position of the weak sandwich, and the thickness of the weak sandwich, were studied and analyzed [9].

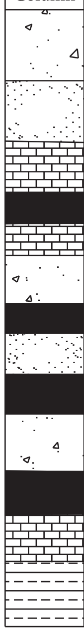
To sum up, most scholars have studied the induced mechanism of face-end roof leaks and proposed different control technologies of face-end roof leaks. However, there are many influencing factors, and the relationship is complicated for the face-end roof leaks under repeated mining. Based on the influencing factors of roof falling under repeated mining, the influence of different influencing factors on roof falling is analyzed, so as to predict the face-end roof leaks under repeated mining and put forward the corresponding prevention measures. Therefore, this paper determines the influencing factors of the face-end roof caving exposed to repeated mining, and the factors affecting the stability of the face-end roof exposed to repeated mining were analyzed by the orthogonal test. Taking the roof subsidence as the judgment index, the influence degree of each factor is obtained, and the concrete measures to prevent the face-end roof caving exposed to repeated mining are put forward. Then, statistical analysis software SPSS was used to carry out multiple linear regression analysis on each factor, and the regression equation of each factor was obtained. The regression model of the stability of the face-end roof exposed to repeated mining was established, which provided a basis for the stability control of the face-end roof exposed to repeated mining in the close-distance coal seams.

2. Basic Conditions of the Mine and General Situation of the Roof Falling Accident

2.1. Basic Conditions of the Mine. The mine is located in Guizhou Province, China. The geological structures in this coalfield are complex. The geological faults and folds are widely distributed. Four close-distance coal seams (15#, 16#, 17#, and 18#) are available to extract within this coalfield. The average thickness of 15#, 16#, 17#, and 18# coal seams is 2.5 m, 2.0 m, 4.0 m, and 5.0 m, respectively. The detailed stratigraphic section of selected coal mines is shown in Figure 1. At present, 15# and 16# coal seams have been completely mined out, and 17# coal seam is being extracted. Working face 17101 is the first mining face of 17# coal seam, with a mining depth of about 500 m. The length of the working face is 150 m, and the designed advance length is 1000 m. The spatial position relationship of coal seams is shown in Figure 2.

2.2. Overview of Roof Falling Accidents. There have been three large-scale roof falling accidents in working face 17101 of 17# coal seam since mining, in which the roof fall height reaches 0.8 m. The field statistics found that roof caving occurred at both ends and the middle parts of the working face, and roof caving occurred mostly in the unsupported space from the beam end of the hydraulic support to the coal wall. During the initial weighting of the working face, the phenomena of roof caving and rib spalling are serious, in which the rib spalling mostly occurs in the middle and lower part of the coal wall, and the coal wall breaking is more serious in the middle area of the working face. The depth of the rib spalling is 0.3~0.8 m, and the roof caving height is 0.3~0.5 m. There are 143 supports in the 17101 working face. The roof fall range of no. 35 support is $0.6\,\mathrm{m} \times 1.0\,\mathrm{m}$, and the rib spalling range of no. 65 support is $0.8\,\mathrm{m} \times 1.5\,\mathrm{m}$. Also, during the periodic weighting of the working face, the roof caving and rib spalling phenomena are still serious. The rib spalling depth of the whole working face is 0.4~1.0 m, and the roof caving height is 0.3~0.8 m. The roof fall range of no. 25 support is $1.5\,\mathrm{m} \times 1.2\,\mathrm{m}$, and the rib spalling range of no. 75 support is $2.5\,\mathrm{m} \times 1.2\,\mathrm{m}$. It can be seen that because the working face 17101 is arranged under the goaf of the upper coal seam, it is in repeated mining, the fully mechanized mining technology is adopted, and the phenomenon of roof caving is always more serious during the working face mining.

Therefore, the face-end roof caving under repeated mining has seriously affected the normal mining of working face 17101. It is necessary to study the stability of the face-end roof under different influencing factors from the influencing factors of face-end roof caving under repeated mining and put forward the corresponding prevention measures to solve the face-end roof leaks of working face 17101 so that the coal seam can be safely and efficiently mined under repeated mining of close-distance coal seams.



Column	Rock name	Thickness (m)	Lithologic character
	Fine sandstone	12.50	Light gray, horizontal bedding, loose structure, easy to break.
	Siltstone	10.00	Light gray to gray, with horizontal stratification, slightly oblique stratification.
	Mudstone	3.00	Dark gray, lumpy, soft rock, strong water absorption, easy to weathering.
	15# Coal seam	2.50	Black powder, good coal, contains plant fossils
	Mudstone	2.00	Dark gray, lumpy, soft rock, strong water absorption, easy to weathering.
	Fine sandstone	4.00	Light gray, horizontal bedding, loose structure, easy to break, strong water absorption.
	16# Coal seam	2.00	Black powder, good coal, contains plant fossils
	Siltstone	6.00	Dark gray, silty structure, dense and brittle.
	17# Coal seam	4.00	Black powder, good coal, contains plant fossils
	Fine sandstone	15.00	Light gray, horizontal bedding, loose structure, easy to break, strong water absorption.
	18# Coal seam	5.00	Black powder, good coal, contains plant fossils
	Mudstone	8.00	Dark gray, lumpy, soft rock, strong water absorption, easy to weathering.
	Medium sandstone	16.00	Hard, not easy to collapse, dark gray, block water absorption is strong, easy weathering.

Figure 1: Stratigraphic section of selected layers.

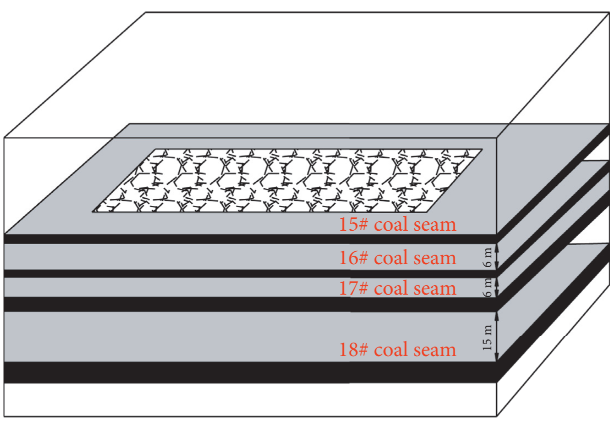


Figure 2: Schematic diagram of the spatial position relationship of coal seams.

2.3. On-Site Statistics of Bottom Face Roof Caving under Repeated Mining. In order to analyze the basic situation of face-end roof caving, 5 measuring stations were evenly arranged along the fully mechanized mining face 17101, respectively, located at the supports of no. 15, no. 45, no. 75, no. 105, and no. 125, as shown in Figure 3.

Steel plate rule and steel tape measure were used to observe the situation of the face-end roof caving in the working face, including the tip-to-face distance, the working resistance of the support, the height, the width, and the length of roof caving. The frequency of observation is once a day. The final distribution range of face-end roof caving at each station is shown in Table 1, and the working resistance statistics of supports at the working face are shown in Table 2.

It can be seen from Table 1 that the proportion of height less than 0.25 m at two stations (15# and 125#) at the end of the working face is 90%; the roof fall of the three stations in the middle is relatively serious. The proportion of the height less than 0.25 m is between 86% and 88%, and the height of some stations is more than 0.5 m. From this analysis, the face-end roof caving occurs in the middle support, and the roof caving height of the middle roof is serious.

Table 2 shows that the support resistance of no. 1~35 supports in the working face is mainly distributed in 40–60 MPa, and the resistance value of 40–60 MPa accounts for 44.5%, indicating that the resistance value of the support in the lower part of the working face is low. By comparison, no. 36~105 supports are the middle area of the working face, and the resistance value distributed in the 40~50 MPa interval is increased, indicating that the pressure in the middle area of the working face is relatively large. No. 105~143 supports in the working face are the middle and upper parts of the working face, and the support resistance above 45 MPa reaches 24.7%, indicating that the roof pressure is still large. Overall, the support resistance of the whole working face is mainly distributed in 30–50 MPa, reaching 76.45%, while the resistance above 60 MPa only accounts for 2.175%.

From the above statistical results, it can be seen that there is a certain inevitable connection between the face-end roof fall and the support resistance. Similarly, there is a certain relationship between the support technology and mining methods and the face-end roof leaks. In order to determine the key influencing factors and degree of face-end roof leaks at the working face, it is necessary to further analyze and find out the correlation between them.

3. Orthogonal Experimental Calculation Model

3.1. Determination of Influencing Factors. Scholars have conducted a lot of research studies and analyses on the stability of the face-end roof exposed to repeated mining, mainly from the following three aspects [10, 11, 12, 13]:

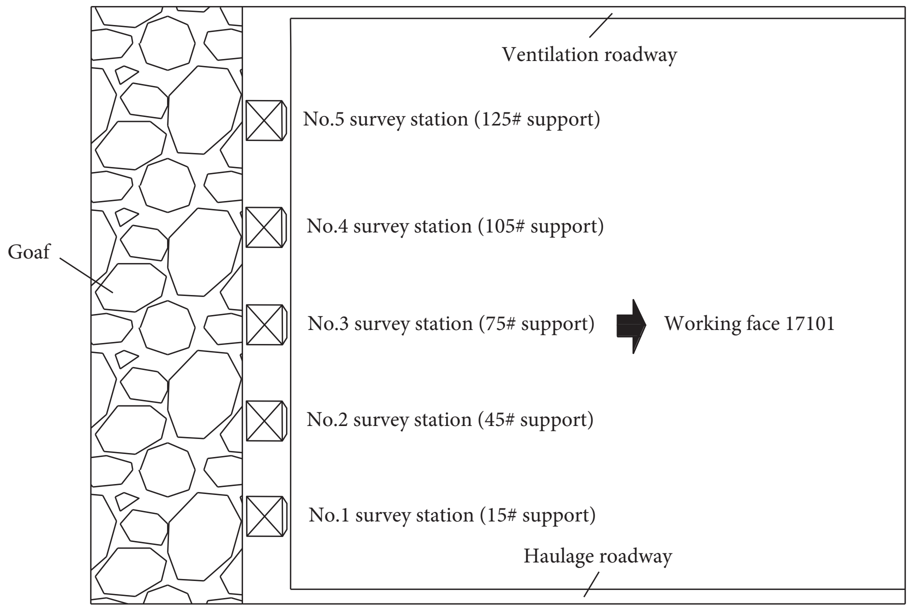


Figure 3: Layout of mine pressure observation stations at working face 17101 under repeated mining.

Table 1: Distribution range of face-end roof caving at each station.

Support number	Roof height (m) distribution ratio (%)				
	0–0.25	0.25–0.5	0.5–0.75	0.75–1	> 1
No. 15	92	5	3	0	0
No. 45	88	7	5	0	0
No. 75	86	10	4	0	0
No. 105	87	7	6	0	0
No. 125	90	4	6	0	0

Table 2: Support resistance distribution in each area of the working face.

Support working resistance (MPa)	Working face area support resistance distribution ratio (%)				
	1–35	36–70	71–105	105–143	Average
20–30	1.7	1.5	2.3	1.8	1.825
30–40	34.1	25.8	33.5	32.4	31.45
40–50	44.5	48.6	47.3	39.6	45.00
50–60	17.2	22.3	14.0	24.7	19.55
60–70	2.5	1.8	2.9	1.5	2.175

(1) Natural factors: coal seam burial depth, distance of coal seams, thickness of coal seams, coal seam dip angle, coal strength, primary joints and fractures, and geological structure

(2) Controllable factors: working face length, mining height, tip-to-face distance, advancing speed, pitch angle of the support, support setting load, and support force of the support beam end

(3) Uncontrollable factors: roof pressure, rib spalling, support load deviation, support working resistance, and support stiffness

For the stability of the face-end roof of the close-distance coal seams, it is undoubtedly a tedious process to analyze numerous influencing factors one by one, and each factor is inextricably related to each other, which makes the analysis situation become fuzzy. Therefore, appropriate influencing factors are selected as indicators in this paper. From the perspective of direct contact of the face-end roof, coal wall and hydraulic support are the key control objects on both sides of the face-end roof. By analyzing the relationship between the coal wall, hydraulic support, and face-end roof, the coal wall and hydraulic support of the working face are the key control objects on both sides of the face roof, and the coal strength and support condition should be considered. The influencing factors of face-end roof leaks of close-distance coal seams can be clearly studied, and the reasonable control measures can be put forward. In this paper, by establishing the model of "face-end roof-coal wall-support" under repeated mining of close coal seams, as shown in

Figure 4, combined with field observation data, the stability of the face-end roof is considered from many aspects. The main influencing factors selected include mining height, tip-to-face distance, distance of coal seams, surrounding rock strength, support setting load, and advancing speed.

3.2. Orthogonal Experimental Design Scheme. When all kinds of influencing factors are taken into full consideration to design the simulation scheme, the number of design schemes will be huge, and the workload of calculation and analysis will be heavy. In view of this, the orthogonal experiment method is proposed to study the influence of controllable factors in the simulation scheme on face-end roof caving. In this scheme, 6 controllable factors are considered, with 5 levels for each factor. The experimental index is the subsidence of the face-end roof. The horizontal values of each factor are shown in Table 3, $L_{25}(5^6)$ orthogonal experimental table is used for the test, and the calculation scheme is shown in Table 4 [14].

3.3. Establishment of the Numerical Simulation Model. The field observation sample selection has certain limitations, and the field production conditions are generally determined, so it is difficult to cover various influencing factors. In order to obtain a more general conclusion, the numerical simulation method in this paper can take into account the changes of various factors, so as to draw a more reliable conclusion.

In view of the fact that the integrity of the face-end roof in the lower coal seam of the close-distance coal seams has been damaged under repeated mining, the fracture is relatively developed, and the strength of the rock is reduced. Based on the study of working face 17101 in geological conditions and mining technology as the background, the numerical model is established by using the Mohr–Coulomb model in UDEC software. In the Mohr–Coulomb model, the failure of materials is defined by shear yield, which is applicable to the underground excavation of mining engineering. Therefore, the material constitutive relation selected in the simulation scheme is the Mohr–Coulomb model. Discrete element numerical software UDEC is used for simulation analysis, the rock mass constitutive model is the Mohr–Coulomb plastic model, and the model of calculation parameters includes bulk (K), shear (G), cohesion (C), friction (Φ), and density (ρ) [15, 16].

$$K = \frac{E}{3(1-2\nu)},$$
$$G = \frac{E}{2(1+\nu)}. \tag{1}$$

In the formula, E is the elastic modulus of rock mass, GPa; ν is Poisson's ratio of rock mass.

In order to obtain effective numerical calculation parameters, the representative rock samples were selected from the site and systematically tested in the laboratory. Considering the difference of physical and mechanical parameters between rock and rock mass, the rock mass mechanical parameters are obtained by multiplying the mechanical parameters of rock mass by the corresponding coefficients, and the final effective physical and mechanical parameters of rock mass are determined as the input parameters of this numerical simulation. Physical and mechanical parameters of rock mass are shown in Table 5. The physical and mechanical parameters of joints are shown in Table 6.

4. Analysis of Results of Different Programs

4.1. Stability Analysis of the Face-End Roof under Different Schemes. UDEC simulation software was used to study the stability of the face-end roof under different schemes. Figure 5 shows the stability of the face-end roof under different schemes.

According to the orthogonal experimental scheme designed above, UDEC simulation software was used to simulate each scheme, and orthogonal analysis was conducted between the roof subsidence of different schemes and each influencing factor, as shown in Table 7.

It can be seen from Table 7 that, with the continuous increase of mining height, the subsidence of the face-end roof is gradually increasing. Therefore, the mining height affects the subsidence of the face-end roof. When the tip-to-face distance changes from 0.5 m to 1.0 m, the subsidence of the face-end roof increases. When the tip-to-face distance changes from 2.5 m to 1.5 m, the subsidence decreases again. According to the observation of simulation, the smaller the tip-to-face distance, the more stable the face-end roof is. With the increase of distance of coal seams, the influence of repeated mining decreases, the damage of the roof decreases, and the subsidence of the face-end roof decreases. As the strength of the surrounding rock increases, the subsidence of the face-end roof decreases. It can be seen that the subsidence of the face-end roof is inversely proportional to the strength of the surrounding rock. Therefore, it is necessary to strengthen the roof. The greater the support setting load, the smaller the subsidence of the face-end roof. Therefore, when other conditions cannot be changed, the support setting load can be appropriately increased. Meanwhile, the pitching angle of the support should be controlled well to ensure a good working condition of the support. Rule of the influence of working face advancing speed on the stability of the face-end roof is the faster the advancing speed is, the smaller the subsidence of the face-end roof is. Therefore, if conditions permit, the higher the working face advancing speed is, the more stable the face-end roof is.

In general, without considering the interaction between factors, the greater the variation of the value of each influencing factor level, the greater the influence degree of the factor. The influence degree of each factor can be obtained through range analysis. R_j represents the range of test indices for each scheme in column j. k_{ij} represents the roof subsidence of the scheme in row i and column j [17].

$$R_j = \max\left(k_{1j}, k_{2j}, k_{3j}, k_{4j}, k_{5j}\right) - \min\left(k_{1j}, k_{2j}, k_{3j}, k_{4j}, k_{5j}\right). \tag{2}$$

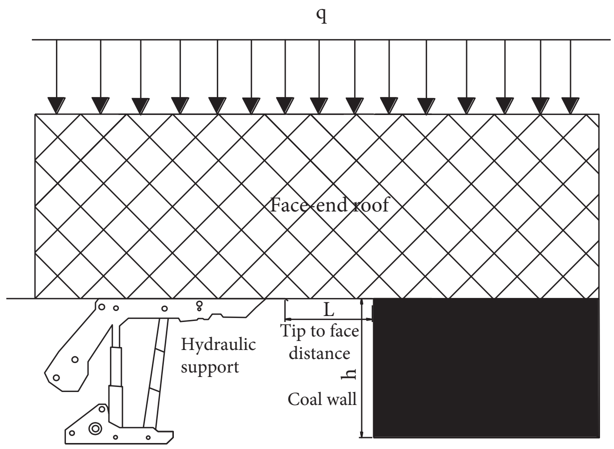


Figure 4: "Face-end roof-coal wall-support" model.

Table 3: Level values of each factor.

Test number	Mining height (m)	Tip-to-face distance (m)	Distance of coal seams (m)	Surrounding rock strength (MPa)	Support setting load ($\times 10^3$ kN)	Advancing speed (m/d)
1	2	0.5	3	1.0	4	2
2	2.5	1.0	6	1.5	5	3
3	3.0	1.5	9	2.0	6	4
4	3.5	2	12	2.5	7	5
5	4.0	2.5	15	3.0	8	6

Table 4: Numerical simulation scheme.

Test number	Mining height (m)	Tip-to-face distance (m)	Distance of coal seams (m)	Surrounding rock strength (MPa)	Support setting load ($\times 10^3$ kN)	Advancing speed (m/d)
1	2.0	0.5	3	1.0	4	2
2	2.0	1.0	6	1.5	5	3
3	2.0	1.5	9	2.0	6	4
4	2.0	2.0	12	2.5	7	5
5	2.0	2.5	15	3.0	8	6
6	2.5	0.5	6	2.0	7	6
7	2.5	1.0	9	2.5	8	2
8	2.5	1.5	12	3.0	4	3
9	2.5	2.0	15	1.0	5	4
10	2.5	2.5	3	1.5	6	5
11	3.0	0.5	9	3.0	5	5
12	3.0	1.0	12	1.0	6	6
13	3.0	1.5	15	1.5	7	2
14	3.0	2.0	3	2.0	8	3
15	3.0	2.5	6	2.5	4	4
16	3.5	0.5	12	1.5	8	4
17	3.5	1.0	15	2.0	4	5
18	3.5	1.5	3	2.5	5	6
19	3.5	2.0	6	3.0	6	2
20	3.5	2.5	9	1.0	7	3
21	4.0	0.5	15	2.5	6	3
22	4.0	1.0	3	3.0	7	4
23	4.0	1.5	6	1.0	8	5
24	4.0	2.0	9	1.5	4	6
25	4.0	2.5	12	2.0	5	2

Table 5: Parameters for different rock masses tested.

Category	Density (kg/m^3)	Cohesion (MPa)	Friction (°)	Bulk (GPa)	Shear (GPa)	Tension (MPa)
Sandstone	2368	5.84	43	10.12	9.65	5.08
Medium sandstone	2500	5.90	42	7.38	6.96	4.56
Siltstone	2540	5.20	40	6.85	5.47	3.86
Fine sandstone	2600	4.38	39	5.27	4.69	3.35
Mudstone	2550	1.24	37	4.16	2.83	3.02
Coal	1350	0.50	30	3.95	2.20	1.04

Table 6: The mechanical parameters of joints.

Category	Jkn (MPa)	Jks (MPa)	Jfri (°)	Jcoh (MPa)	Jten (MPa)
Sandstone	6368	5840	25	3.12	2.08
Medium sandstone	5500	5960	22	2.38	1.56
Siltstone	4540	4800	19	1.85	0.86
Fine sandstone	3600	4380	18	1.27	0.75
Mudstone	2550	2240	17	0.86	0.22
Coal	2350	2320	15	0.45	0.04

The influencing factors of the subsidence of the face-end roof are calculated, the influence degree of each influencing factor is the same, and the most important influencing factor is the mining height. However, there may be nonnegligible interaction between the factors of the orthogonal test, or other factors that have important influence on the test results may be ignored. Therefore, in order to obtain a more accurate and reasonable conclusion, the method of multiple linear regression analysis is proposed, and the regression coefficient of each influencing factor is analyzed.

4.2. Multiple Linear Regression Analysis Using SPSS Software. Regression analysis is a statistical method for exploring statistical relationships between phenomena. Phenomena involve explained variables and explanatory variables, the dependent variables are also called explained variables, the independent variables are also called explanatory variables, and some correlation is usually expressed by explained variable and explanatory variable equations. The regression equation can be divided into linear regression and nonlinear regression, and the nonlinearity can be reduced to linear. In this study, multiple linear regression analysis method was adopted to analyze the orthogonal experimental data and establish the regression model. The significance test of the multiple linear regression equation, regression coefficient, and goodness of fit was carried out to determine the significance of each parameter, as well as regression diagnosis of the premise assumptions of the regression model, including residual analysis and autocorrelation analysis. Finally, within the range of sample data, the fitted mathematical expression is predicted, another variable is controlled according to one or several variables, and the accuracy of prediction and control is tested [18–20].

4.2.1. Establishment of the Regression Model. According to the numerical simulation results of UDEC software, assuming that multiple influencing factors of the face-end roof caving under repeated mining meet the linear relationship, the multiple linear regression equation can be established as follows:

$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + \cdots + b_jx_j + \varepsilon. \quad (3)$$

In the formula, Y is the dependent variable representing the subsidence of the face-end roof; $X_1, X_2X_3, X_4 \ldots X_j$ are j controllable and measurable independent variables; b_0 is the regression constant; $b_1, b_2, \ldots b_j$ are the regression coefficients; and ε is a random variable.

4.2.2. Regression Model Analysis. Statistical Package for the Social Sciences was adopted to substitute the simulation test data and results into SPSS to process and study the stability data of the face-end roof and establish a multiple linear regression model. The test of the regression model includes three aspects: significance test of the multiple linear regression equation, regression coefficient, and goodness of fit. Table 8 shows the model summary, which indicates the general situation of model fitting .

(1) Goodness of fit (R^2): it refers to the fitting effect of the regression equation on sample observation points, which is usually tested by the sample determination coefficient. In the closed interval of 0 and 1, the closer R^2 is to 1, the better the fitting effect will be. The closer R^2 is to 0, the worse the fitting effect will be. It can be seen from Table 8 that $R^2 = 0.822$, and the adjusted value $R^2 = 0.762$, indicating that the regression equation has a good fitting effect on the sample observation points.

(2) Autocorrelation analysis: when constructing the regression equation, the autocorrelation phenomenon of random error term sometimes occurs, which will lead to the inaccurate prediction estimation of the regression equation and the reduced prediction accuracy. According to the sample size N and the

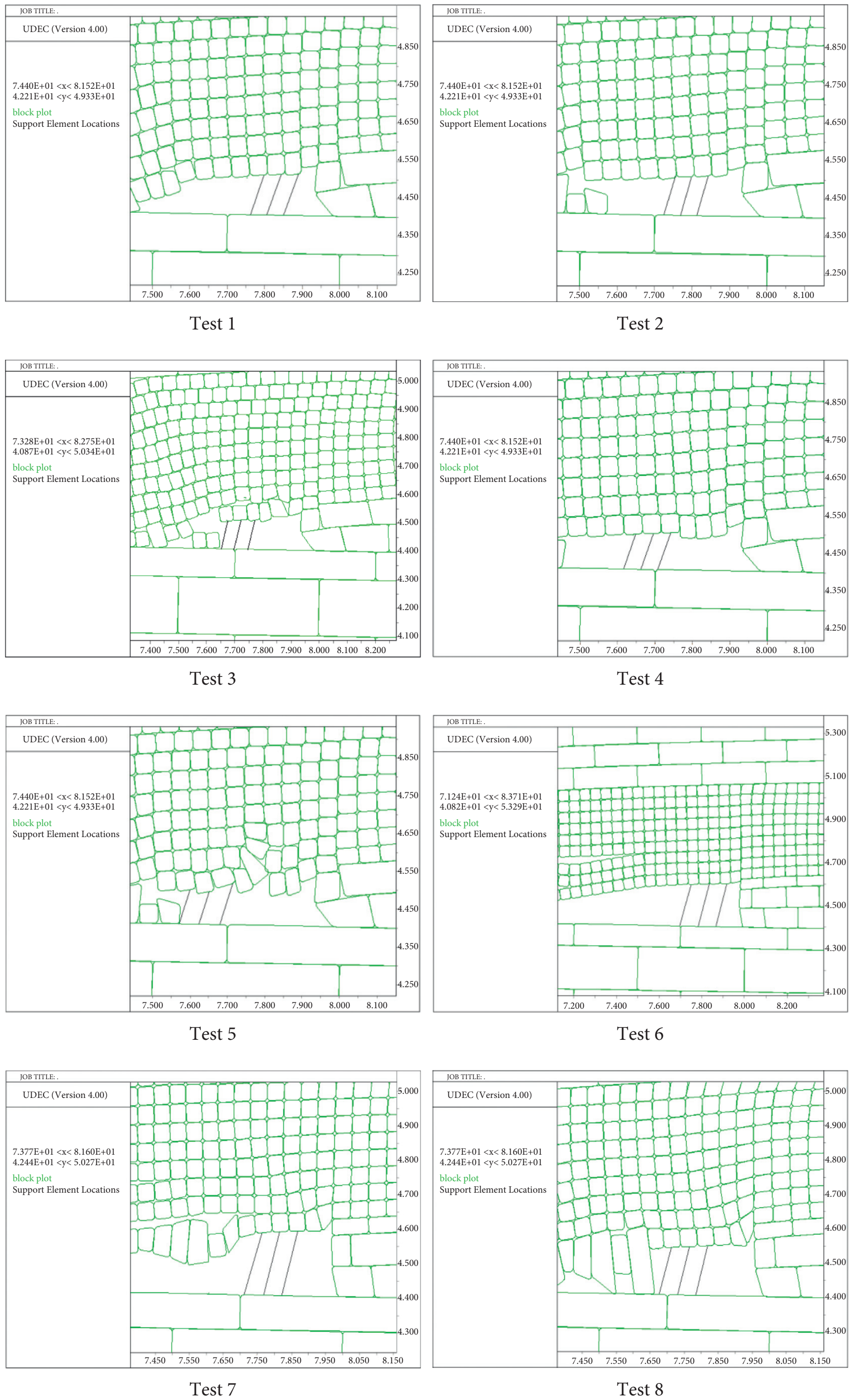
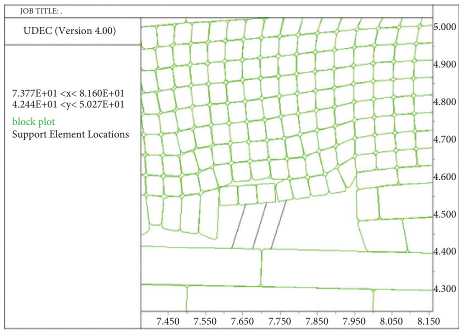
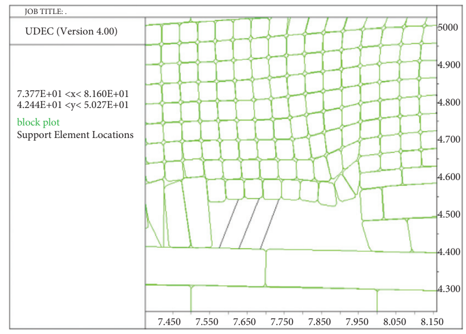


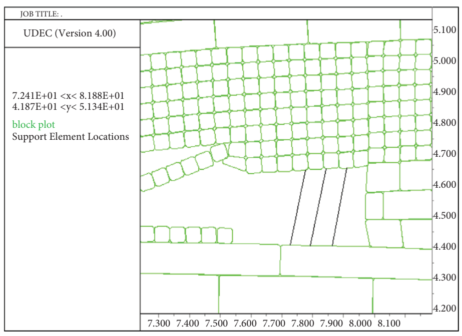
Figure 5: Continued.



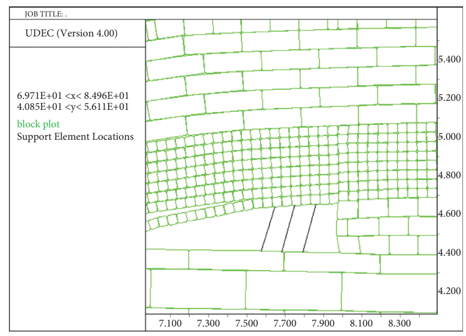
Test 9



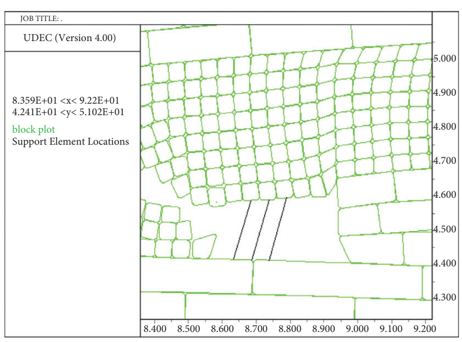
Test 10



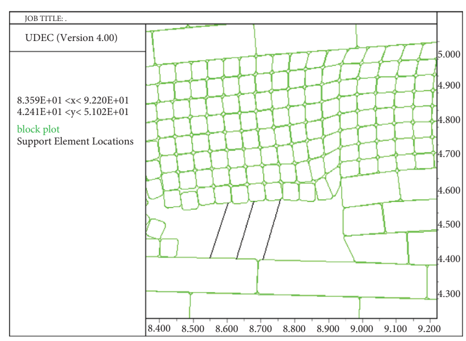
Test 11



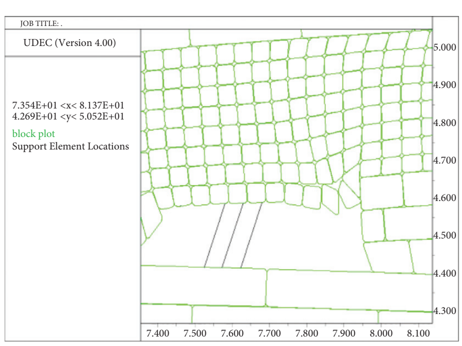
Test 12



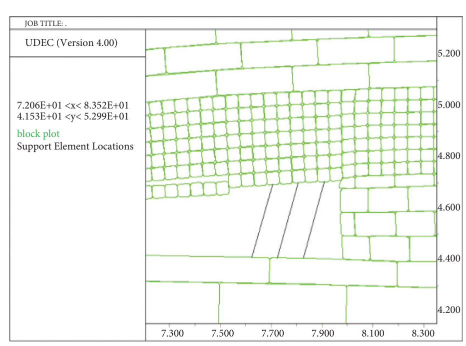
Test 13



Test 14



Test 15



Test 16

Figure 5: Continued.

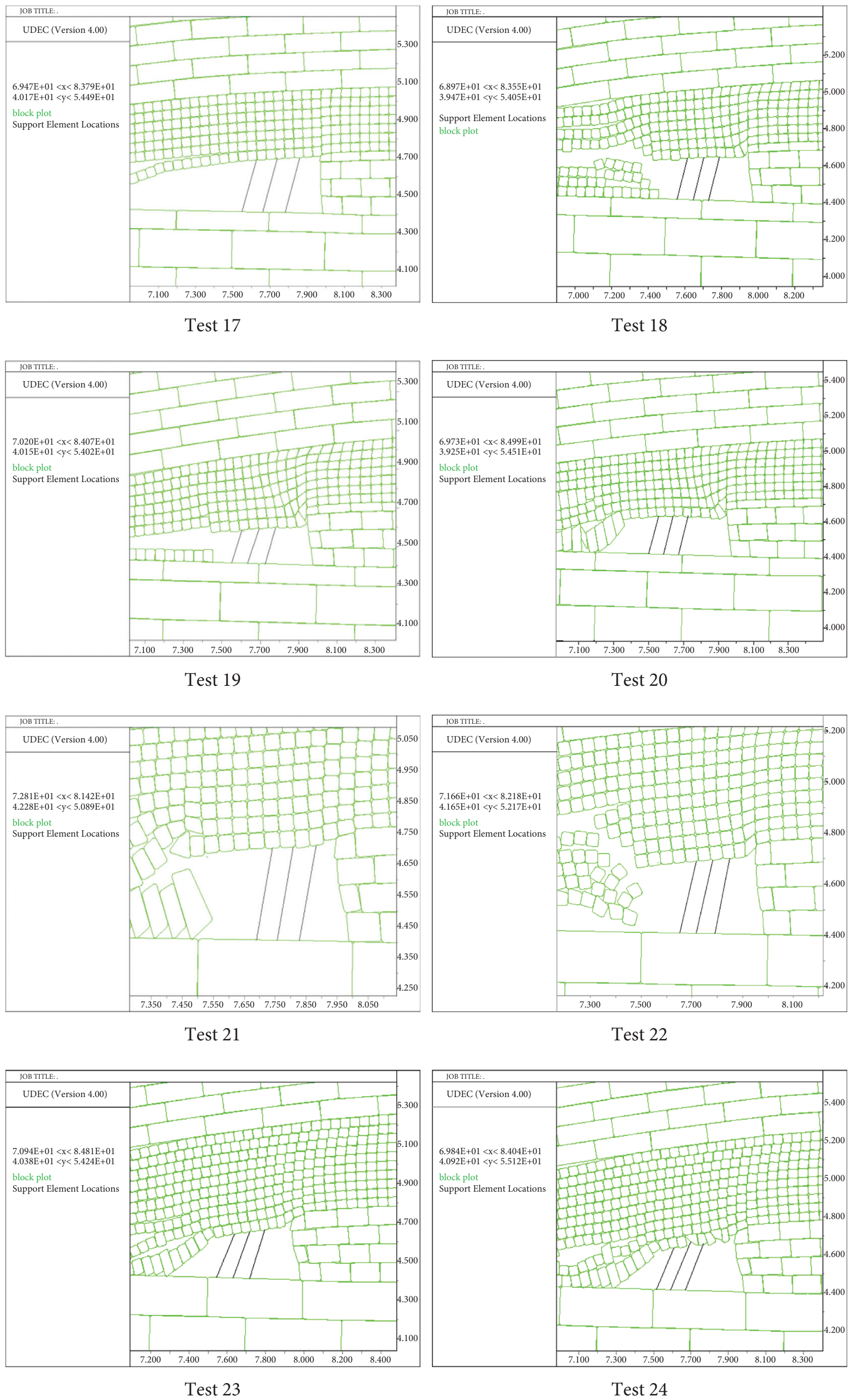
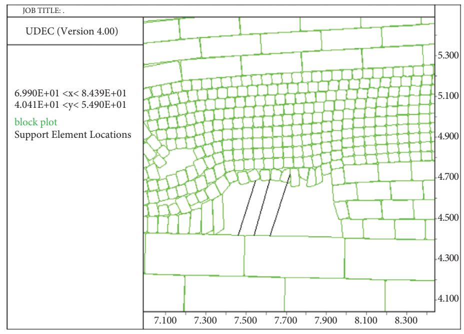


Figure 5: Continued.



Test 25

Figure 5: Face-end roof stability under different schemes.

Table 7: Roof subsidence of the face end under different schemes.

Test number	Mining height (m)	Tip-to-face distance (m)	Distance of coal seams (m)	Surrounding rock strength (MPa)	Support setting load ($\times 10^3$ kN)	Advancing speed (m/d)	Roof subsidence (m)
1	2.0	0.5	3	1.0	8	2	0.5
2	2.0	1.0	6	1.5	9	3	0.4
3	2.0	1.5	9	2.0	10	4	0.4
4	2.0	2.0	12	2.5	11	5	0.6
5	2.0	2.5	15	3.0	12	6	0.7
6	2.5	0.5	6	2.0	11	6	0.4
7	2.5	1.0	9	2.5	12	2	0.4
8	2.5	1.5	12	3.0	8	3	0.6
9	2.5	2.0	15	1.0	9	4	0.6
10	2.5	2.5	3	1.5	10	5	0.8
11	3.0	0.5	9	3.0	9	5	0.3
12	3.0	1.0	12	1.0	10	6	0.5
13	3.0	1.5	15	1.5	11	2	0.7
14	3.0	2.0	3	2.0	12	3	0.7
15	3.0	2.5	6	2.5	8	4	1.0
16	3.5	0.5	12	1.5	12	4	0.5
17	3.5	1.0	15	2.0	8	5	0.6
18	3.5	1.5	3	2.5	9	6	0.7
19	3.5	2.0	6	3.0	10	2	0.8
20	3.5	2.5	9	1.0	11	3	1.1
21	4.0	0.5	15	2.5	10	3	0.8
22	4.0	1.0	3	3.0	11	4	1.1
23	4.0	1.5	6	1.0	12	5	1.1
24	4.0	2.0	9	1.5	8	6	0.9
25	4.0	2.5	12	2.0	9	2	1.3

Table 8: Model summary[b].

Model	R	R^2	Adjusted R^2	Error of the standard estimate	Durbin–Watson
1	0.906[a]	0.822	0.762	0.12906	1.570

[a]Significance of different differences. When there is a same labeled letter, it is insignificant difference; when there is a different labeled letter, it is significant difference. In this paper, a model is established, and "a" and "b" are not the research focus, using the calculation results of SPSS software.

number of explanatory variables K, Durbin and Watson established the lower critical value and upper critical value of D. W test statistics at a given significance level and determined the specific range used for judgment. In this paper, the D. W test method is used to test the autocorrelation of random error terms. According to the experimental data, the value range of statistics (d) is [0, 5]. From the critical value d_L, d_U was finally compared with the D. W criterion table to obtain the relationship between the random error terms. It can be seen from Table 8 that the Durbin–Watson value is 1.570, and then the

Durbin–Watson statistic critical value table is queried by $n=5$ and $P=25$, and the fitting effect of $d_L=0.756$ and $d_U=1.675$ measurement points is obtained, which is usually tested by the sample determination coefficient. $d=1.570$, and $d_L<d\leq d_U$. According to the D.W. criterion, it is impossible to determine whether there is autocorrelation between random error terms.

(3) Analysis of variance: the results of variance analysis in the regression fitting process are shown in Table 9. The F-test is the significance test of the regression equation, indicating the comprehensive influence degree of multiple factors. Significance value is less than 0.05, which is meaningful. SPSS software performs the F-test on the model, and the significant value of 0.000^b is less than 0.05, showing that mining height, tip-to-face distance, distance of coal seams, surrounding rock strength, support setting load, and advancing speed as a whole have a significant influence on the dependent variable, the subsidence of the face-end roof, the regression equation is significant, and there is a linear relationship, which is statistically significant, but it cannot reflect the effects of each independent variable on the overall strength. The statistical significance of the model does not mean that all the variables in the model are statistically significant, and the respective variables need to be further tested.

(4) Estimation of regression coefficient: the evaluation of the regression coefficient of the model is shown in Table 10. Therefore, the multiple linear regression equation is

$$
\begin{aligned}
Y = & -0.208 + 0.244x_1 + 0.216x_2 - 0.007x_3 \\
& - 0.016x_4 + 0.004x_5 - 0.024x_6.
\end{aligned} \tag{4}
$$

Y is the dependent variable representing the subsidence of the face-end roof; x_1 represents the influence of mining height on roof deformation; x_2 represents the influence of tip-to-face distance on roof deformation; x_3 represents the influence of distance of coal seams on roof deformation; x_4 represents the influence of surrounding rock strength on roof deformation; x_5 represents the influence of the support setting load on the roof deformation; x_6 represents the influence of advancing speed on roof deformation.

(5) Regression coefficient and significance test: the t-test is the significance test for a single independent variable. After t-test, the significant p values of mining height, tip-to-face distance, distance of coal seams, surrounding rock strength, support setting load, and advancing speed were all not more than 1, indicating that they had a significant impact on the regression equation, which was statistically significant and could not be excluded from the regression equation.

(6) Variance inflation factor (VIF), which is the reciprocal of tolerance: the greater the value of VIF, the more serious the collinearity problem. When "VIF >10," there will be a strong collinearity problem. Since the VIF values of mining height, tip-to-face distance, distance of coal seams, surrounding rock strength, support setting load, and advancing speed are all 1.000, there is no collinearity between model independent variables.

Table 9: Analysis of variance.

Model		Quadratic	DOF	Mean square	F	Significance
1	Regression	1.380	6	0.230	13.811	0.000^b
	Residual	0.300	18	0.017		
	Aggregate	1.680	24			

(7) Residual analysis: the purpose of residual analysis is to verify and ensure the quality of test data and to diagnose regression effect. In regression analysis, there will be a class of experimental values that are outliers, which are far away from other values and show a large residual error, affecting the fitting effect of the regression equation. It can be seen from Table 11 that the standard residual is <3, and the standard predicted value is <3, indicating that the observed data are not outliers and will not affect the fitting effect of the regression equation.

(8) Scatter diagram of the regression residual: the scatter diagram of the regression normalized residual is shown in Figure 6. It can be seen from Figure 6 that the residuals basically conform to the normal distribution, and the multiple linear regression equation has a good fitting effect.

Therefore, through the analysis of the multiple linear regression model, the conclusion is drawn that there are six main factors affecting the stability of the face-end roof, namely, mining height, tip-to-face distance, distance of coal seams, surrounding rock strength, advancing speed, and support setting load. Because the absolute value of the standard regression coefficient reflects the degree of impact collapse, the greater the absolute value, the greater the control. It can be seen from the table that the degree of influence is, in the descending order, mining height, tip-to-face distance, advancing speed, distance of coal seams, surrounding rock strength, and support setting load. It can be considered that the main influencing factors of roof subsidence in repeated mining are tip-to-face distance and mining height, while the secondary influencing factors are advancing speed, distance of coal seams, surrounding rock strength, and support setting load. To strengthen the coordination, various influencing factors should be considered from the controlled main influencing factors. For example, comprehensive measures such as controlling reasonable mining height, reducing the tip-to-face distance, speeding up the advancing speed, and improving the support setting load should be adopted. Technologies such as grouting to strengthen the face-end roof and shotcrete to strengthen the strength of surrounding rocks should be considered. The stability of the face-end roof exposed to repeated mining is

Table 10: Regression coefficient of subsidence of the face-end roof under repeated mining.

Model	Unstandardized coefficient		Standardized coefficient Beta	t	Significance	Tolerance	VIF
	B	Standard error					
Constant	−0.208	0.250		−0.831	0.417	1.000	1.000
Mining height	0.244	0.037	0.666	6.684	0.000	1.000	1.000
Tip-to-face distance	0.216	0.037	0.589	5.917	0.000	1.000	1.000
Distance of coal seams	−0.007	0.006	−0.109	−1.096	0.288	1.000	1.000
Surrounding rock strength	−0.016	0.037	−0.044	−0.438	0.666	1.000	1.000
Support setting load	0.004	0.018	0.022	0.219	0.829	1.000	1.000
Advancing speed	−0.024	0.018	−0.131	−1.315	0.205	1.000	1.000

Table 11: Residual statistics.

	Min	Max	Average	Standard deviation	Quantity
Predicted	0.3360	1.1840	0.700	0.2398	25
Residual error	−0.1820	0.2360	0.000	0.1117	25
Standard predictive value	−1.5180	2.0180	0.000	1.0000	25
Standard residual error	−1.4100	1.8290	0.000	0.8666	25

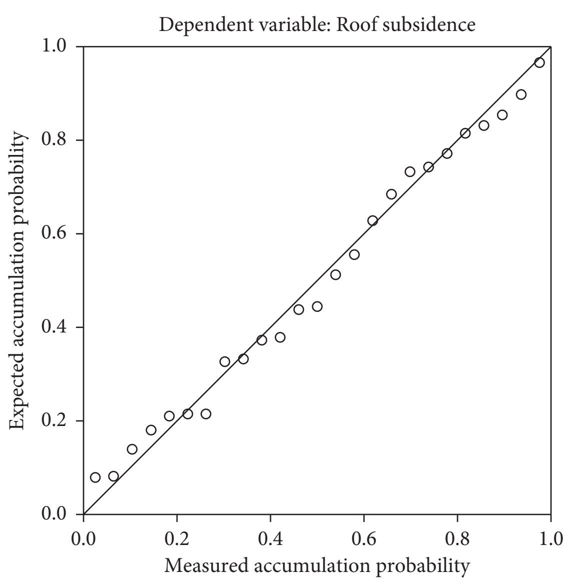


Figure 6: Scatter diagram of the regression normalized residual.

controlled comprehensively to prevent the face-end roof leaks exposed to repeated mining.

4.2.3. Model Error Analysis and Application. Combined with the actual value of subsidence of the face-end roof under repeated mining, the predicted value after the regression equation is adopted to obtain the relative error between the two, as shown in Table 12.

By comparing the relative error between the actual value and the predicted value of the face-end roof under repeated mining, the maximum error of the regression model is 9.2%, the minimum error is 1.2%, and the average error is 4.96%. Therefore, the SPSS linear regression model has a high accuracy and can be used to predict the subsidence of the face-end roof after repeated mining.

Table 12: Random error test of repeated mining under roof subsidence volume.

Scheme	Actual value	Predicted value	Relative error (%)
5	0.7	0.671	4.1
10	0.8	0.817	2.1
15	1.0	0.918	8.2
20	1.1	1.079	1.2
25	1.3	1.180	9.2

By searching the field data and substituting it into the regression equation above, the roof subsidence result is obtained. Through comparison, it can be found that the difference between this result and the actual face-end roof subsidence is very small, within the acceptable error range. This shows that the regression equation obtained by the multiple linear regression model is the practical significance of predicting the face-end roof leaks under repeated mining.

4.3. Prevention Measures of Face-End Roof Fall under Repeated Mining

4.3.1. Increasing Initial Supporting Force and Supporting Resistance of the Hydraulic Support. In the field observation, it is found that the support setting load of the hydraulic support is generally low, which is an important reason for the rib spalling and face-end roof leaks of working face 17101. Therefore, in order to effectively control the instability of the face-end roof, it is necessary to improve the support setting load and the working resistance of the support, which needs to be improved from the following aspects: (1) in the design of the hydraulic support, the working resistance of the front column is designed to be larger than that of the rear column. In the case of constant working resistance, the support capacity of the front column of the support is improved to improve the support efficiency and further improve the support effect. (2) The monitoring of support quality should be strengthened to ensure that the hydraulic support of the working face reaches sufficient support setting load and reasonable support resistance, improve the overall stability of the support-roof, and reduce the pressure of the coal wall, so as to improve the overall stiffness of the support-roof-coal wall system, ensure good support position, and prevent disasters caused by face-end roof fall [21, 22].

4.3.2. Increasing the Strength of the Roof and Surrounding Rock. The roof and coal seam are damaged, and the strength of the roof and coal wall is reduced in the process of repeated mining. It is prone to roof caving in the front of the support, which leads to roof caving and rib spalling and other disasters, resulting in the normal production of the stope. Therefore, it is necessary to increase the strength of the roof and coal. In view of the local face-end roof fall accident in a small range, grouting is used to control the roof fall, and the volume rapid expansion material is used to fill the fractured roof, which can greatly enhance the integrity and strength of the roof and control the broken roof of the working face under repeated mining.

4.3.3. Reduction of Tip-to-Face Distance. The simulation results show that reducing the empty roof area of the front end of the hydraulic support is beneficial to enhance the stability of the face-end roof of the stope, so as to prevent the occurrence of rib spalling and roof caving in the stope. According to the actual observation, the range of tip-to-face distance should be controlled from the following aspects to ensure the stability of the face-end roof and coal wall: (1) to control the cutting depth of the shearer; (2) timely supporting the newly exposed face-end roof; (3) to ensure that the roof mined by the shearer is flat, and the hydraulic support should be in a microelevation state, so as to reduce the empty roof area.

4.3.4. Control of Advancing Speed. The simulation results show that the advancing speed of the working face has a significant effect on the stability of the face-end roof. The slower the advancing speed of the working face is, the more serious the roof subsidence of the stope is. Therefore, the control of working face advancing speed can effectively reduce the probability of the face-end roof fall accident. The stope production should be carried out in strict accordance with the regular cycle operation and take reasonable and effective prevention measures to ensure the rapid and smooth mining of the working face and ensure the stability and reliability of the face-end roof. In the actual mining of the working face, the control of the advancing speed of the working face should be strengthened, and the advancing situation of the working face should be reasonably arranged, so as to prevent the face-end caving and the coal wall spalling, reduce the stope production caused by various stope accidents, and choose the stope production in the area with good roof conditions.

The strength of the roof and coal wall is reduced in the mining process of the upper coal seam, which is prone to roof caving at the front end of the support, leading to roof caving and rib spalling and other disasters, resulting in the failure of the normal production of stope, and seriously affecting the mining of close-distance coal seams. From the above analysis, it can be seen that the major influencing factors of face-end roof caving are found, and the corresponding control measures are put forward. Considering various influencing factors and combining various methods, the principle of coordinated control is used to control the instability of the face-end roof under repeated mining, so as to ensure the normal mining of the working face under repeated mining.

5. Discussion and Conclusions

(1) The orthogonality analysis of six factors of the stability of the face-end roof exposed to repeated mining is carried out by means of mathematical statistics, the subsidence of the face-end roof is taken as the test index, UDEC numerical simulation software is used to simulate 25 groups of orthogonal experiments, and the subsidence of the face-end roof is obtained when there are 6 influencing factors and 5 horizontal interactions, which overcomes the defect of neglecting the interaction of control factors in previous experiments.

(2) According to the analysis, there are many factors affecting the stability of the face-end roof, and the influence degree of each factor is, respectively, mining height > tip-to-face distance > advancing speed > distance of coal seams > surrounding rock strength > support setting load. To prevent the occurrence of face-end roof caving, it is necessary to strengthen the coordination of various influencing factors, which should first be controlled from the main influencing factors. For example, comprehensive measures such as controlling reasonable mining height, reducing the tip-to-face distance, speeding up the advancing speed, and improving the support setting load should be adopted. Second, technologies such as grouting to strengthen the face-end roof and shotcrete to strengthen the strength of surrounding rocks should be considered. The stability of the face-end roof exposed to repeated mining is controlled comprehensively to prevent the face-end roof leaks exposed to repeated mining.

(3) By using SPSS statistical software, the multivariate linear regression analysis of each influencing factor was carried out, the multivariate linear regression equation of the subsidence of the face-end roof was obtained, and the regression model of the stability of the face-end roof was established. Through the F-test, t-test, and regression diagnosis of the regression model, it is found that there is no collinearity among mining height, tip-to-face distance, distance of coal seams, surrounding rock strength, advancing speed, and support setting load, which has a significant influence on the regression equation and regression

coefficient on the whole. The multiple linear regression equation has a good fitting effect. The multiple linear regression analysis model can be used to predict the deformation of the face-end roof.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors acknowledge the financial support from the National Natural Science Foundation of China Youth Fund (no. 51904082), the National Natural Science Foundation of China Regional Fund (nos. 52064005 and 52164002), Guizhou Science and Technology Plan Project (Qianke Science Foundation (2020) 1Y214), Guizhou Science and Technology Plan Project (Qianke Science Support (2021) General 399), and Opening Project Fund of Key Laboratory of Mining Disaster Prevention and Control (MDPC202019).

References

[1] D. Kong, S. Pu, S. Zheng, C. Wang, and Y. Lou, "Roof broken characteristics and overburden migration law of upper seam in upward mining of close seam group," *Geotechnical & Geological Engineering*, vol. 37, pp. 3193–3203, 2019.

[2] S. Zheng, Y. Lou, D. Kong, G. Wu, and Y. Liu, "The roof breaking characteristics and overlying strata migration law in close seams group under repeated mining," *Geotechnical & Geological Engineering*, vol. 37, pp. 3891–3902, 2019.

[3] D. Kong, Q. Li, N. Wang, and G. Wu, "Analysis on the breaking law of soft and thick roof of fully mechanized top-coal caving face," *Geotechnical & Geological Engineering*, vol. 38, pp. 5941–5953, 2020.

[4] A. Osouli and B. Moradi Bajestani, "The interplay between moisture sensitive roof rocks and roof falls in an Illinois underground coal mine," *Computers and Geotechnics*, vol. 80, pp. 152–166, 2016.

[5] W.-B. Guo, Y. Lu, F.-C. Huang, C.-Y. Liu, M.-S. Pei, and Y.-S. Du, "Stability of surrounding rock in head face of upward fully mechanized caving face and its control technology," *Journal of Mining & Safety Engineering*, vol. 31, no. 3, pp. 406–412, 2014.

[6] J.-C. Chang, G.-X. Xie, and X.-H. Zhang, "Analysis on the wall mechanism of full-mechanized caving face with large mining height in extra-thick Coal seam," *Rock and Soil Mechanics*, vol. 36, no. 3, pp. 803–808, 2015.

[7] P. Zhang, B. Tulu, M. Sears, and J. Trackemas, "Geotechnical considerations for concurrent pillar recovery in close-distance multiple seams," *International Journal of Mining Science and Technology*, vol. 28, pp. 21–27, 2018.

[8] W. Yang and X. Xia, "Prediction of mining subsidence under thin bedrocks and thick unconsolidated layers based on field measurement and artificial neural networks," *Computers & Geosciences*, vol. 52, pp. 199–203, 2013.

[9] S. Liu, S. Cao, H. Wang, R. Pan, and B. Zhang, "Analysis of controlling factors of deformation and instability of roadway composite roof," *Chinese Journal of Geological Hazards and Prevention*, vol. 30, no. 2, pp. 83–88, 2019.

[10] M. Young, G. Walton, and E. Holley, "Investigation of factors influencing roof stability at a Western U.S. longwall coal mine," *International Journal of Mining Science and Technology*, vol. 29, pp. 139–143, 2019.

[11] A. Yuan, P. Wang, and Y. Li, "Movement laws of overlying strata and prevention measures of dynamic disasters under deep adjacent coal seam group with high gas," *Geomatics, Natural Hazards and Risk*, vol. 11, pp. 2339–2359, 2020.

[12] Y. Wu, H. Wang, Jielanshi, and Y. Zeng, "Numerical analysis of factors affecting the height of overburden fault zone in high-dip coal seam," *Coal Engineering*, no. 3, pp. 63–66, 2011.

[13] G. Cheng, T. Yang, H. Liu et al., "Characteristics of stratum movement induced by downward longwall mining activities in middle-distance multi-seam," *International Journal of Rock Mechanics and Mining Sciences*, vol. 136, Article ID 104517, 2020.

[14] W. Yin, G. Zhou, D. Liu, Q. Meng, Q. Zhang, and T. Jiang, "Numerical simulation and application of entrainment dust collector for fully mechanized mining support based on orthogonal test method," *Powder Technology*, vol. 380, pp. 553–566, 2020.

[15] Q. Yao, X. Li, B. Sun et al., "Numerical investigation of the effects of coal seam dip angle on coal wall stability," *International Journal of Rock Mechanics and Mining Sciences*, vol. 100, pp. 298–309, 2017.

[16] S. Rajwa, T. Janoszek, and S. Prusek, "Influence of canopy ratio of powered roof support on longwall working stability–a case study," *International Journal of Mining Science and Technology*, vol. 29, pp. 591–598, 2019.

[17] Y. Zhu, H. Shi, P. Wang, and E. Zhu, "Multiple linear regression analysis of influencing factors of roof caving height," *Journal of Hunan University of Science & Technology (Natural Science Edition)*, vol. 30, no. 3, pp. 1–6, 2015.

[18] J. Zhou and X. B. Li, "Evaluating the thickness of broken rock zone for deep roadways using nonlinear SVMs and multiple linear regression model," *Procedia Engineering*, vol. 26, pp. 972–981, 2011.

[19] H. S. Hussein and R. A. Abdula, "Multiple linear regression approach for the vitrinite reflectance estimation from well logs: a case study in Sargelu and Naokelekan formations-Shaikhan-2 Well, Shaikhan oil field," *Egyptian Journal of Petroleum*, vol. 27, pp. 1095–1102, 2018.

[20] T. Shepel, B. Grafe, P. Hartlieb, C. Drebenstedt, and A. Malovyk, "Evaluation of cutting forces in granite treated with microwaves on the basis of multiple linear regression analysis," *International Journal of Rock Mechanics and Mining Sciences*, vol. 107, pp. 69–74, 2018.

[21] Y. Xue, J. Liu, P.-G. Ranjith, X. Liang, and S. Wang, "Investigation of the influence of gas fracturing on fracturing characteristics of coal mass and gas extraction efficiency based on a multi-physical field model," *Journal of Petroleum Science and Engineering*, vol. 206, Article ID 109018, 2021.

[22] L. Zhu, F. Dang, Y. Xue, K. Jiao, and W. Ding, "Multivariate analysis of effects of microencapsulated phase change materials on mechanical behaviors in light-weight aggregate concrete," *Journal of Building Engineering*, vol. 42, Article ID 1027831, 2021.