Hindawi
Advances in Materials Science and Engineering
Volume 2021, Article ID 2833210, 9 pages
https://doi.org/10.1155/2021/2833210

Research Article

Research on Mechanism and Control Technology of Rib Spalling in Soft Coal Seam of Deep Coal Mine

Shaobo Li,[1] **Lei Wang**,[1] **Chuanqi Zhu**,[1] **and Qihan Ren**[2]

[1]*State Key Laboratory of Mining Induced Response and Disaster Prevention and Control in Deep Coal Mines, Anhui University of Science and Technology, Huainan Anhui 232001, China*
[2]*CCTEG Chongqing Research Institute, Chongqing, China*

Correspondence should be addressed to Lei Wang; leiwang723@126.com

Received 20 August 2021; Accepted 27 September 2021; Published 20 October 2021

Academic Editor: Zhengyang Song

In order to solve the difficult problem of coal wall spalling of soft seam in deep mining, the occurrence mechanism of coal wall spalling in deep mining is studied based on the limit equilibrium theory of D-P criterion. Through the analysis of the formula of plastic zone, it can be concluded that the coal wall spalling of soft coal seam is related to mining depth, mining height, stress concentration factor, internal friction angle of coal, cohesion, and the compressive strength of coal body. Also, the change of uniaxial compressive strength of soft coal with different moisture content is studied through laboratory experiments. The experimental results show that the uniaxial compressive strength of soft coal reaches the maximum value when the moisture content is about 3.3%. The comprehensive research shows that the cohesion and strength of coal mass can be improved by increasing the working resistance of support, water injection in advanced deep-hole coal seam of two roadways, and pre-grouting in shallow hole of coal wall. The control measures can effectively control the coal wall spalling of soft coal seam. The research results have important guiding significance for safe and efficient mining of soft coal seam.

1. Introduction

As economic development increases the demand for energy and shallow coal resources are gradually depleted, coal mining is forced into the deep underground [1–4]. In deep mining, coal wall spalling is a common failure phenomenon in longwall faces and usually induces roof falls. Soft coal seam is usually associated with faults, folds, occurrence changes, and changes of coal seam thickness. Due to the low strength and well-developed structure of the soft coal seam, the coal wall spalling and even more serious coal rock dynamic disasters are prone to occur under the action of mining stress [5].

The serious coal wall spalling not only affects the safety of normal production but also is the precursor of serious coal and rock dynamic disasters such as coal and gas outburst and rock burst, which will seriously threaten the personnel safety of the mine. Therefore, it is necessary to study the mechanism and control measures of coal wall spalling in soft coal seam. It is of great significance for the prevention and control of coal wall spalling in soft coal seam and ensuring the safe and efficient production of coal mines.

Many experts and scholars have carried out extensive research on the mechanism of coal wall spalling. Qi et al. [6] simplified the coal wall as a compression bar model. It is considered that the influencing factors of coal wall spalling include not only the size and mechanical properties of coal body but also the load size. Yin et al. [7] analyzed and studied the physical and mechanical characteristics including the coal wall deflection by establishing the compression bar model of coal wall. Yang and Kong [8] carried out the research on the stability of coal and rock at the end face of fully mechanized mining with large mining height according to the geological conditions of extremely soft thick coal seam and obtained the mechanism and control technology of rib spalling in soft coal seam with large mining height. Liu et al. [9] studied and analyzed the overburden fracture and movement after mining the lower protective layer and concluded that the coal wall failure is mainly related to roof load, coal cohesion, internal friction angle, coal seam inclination, and support strength. Bai et al. [10] concluded that in the early stage after coal wall exposure, tensile stress concentrated in a small area near the coal wall, leading to layered tensile splitting failure.

Aiming at the control technology of rib spalling of coal seam, Wang [11] concluded that the coal wall spalling in extremely soft coal seam is the main factor affecting the efficient production of the mine and studied the corresponding prevention measures. Chang et al. [12] studied the mechanism of rib spalling in fully mechanized working face with large mining height and proposed the technology of controlling rib spalling in fully mechanized working face with large mining height. Cui et al. [13] studied the characteristics of roof stress evolution under three-soft coal seam mining conditions. A numerical simulation experiment was used to study the change law of the grouting borehole stress field under different grouting pressures. The effect of grouting reinforcement was verified through different monitoring methods.

It can be seen from the above research that the influence range of plastic zone is the key to study the mechanism of coal wall spalling in soft coal seam, which is very important for analyzing the influencing factors of coal wall spalling [14–18]. However, the intermediate principal stress is not considered in the calculation of the plastic zone, and the intermediate principal stress should be considered in the calculation of the plastic zone in front of the coal wall. Compared with the traditional M-C criterion, the D-P yield criterion has the advantages of considering the intermediate principal stress, calculating the plastic zone width of coal wall accurately, which is suitable for soft coal seam [19].

In this paper, we derive the calculation formula of the plastic zone range of soft coal body and obtain the main factors influencing the rib spalling based on the limit equilibrium theory of D-P criterion. Through the analysis of the main factors influencing the rib spalling, we obtain the mechanism of coal wall spalling and the feasible technology of controlling coal wall spalling. Our research of technology of controlling coal wall spalling has important guiding significance for the safe and efficient production of coal mines.

2. Geological Conditions

The design production capacity of Xiayukou coal mine of Hancheng Mining Company of Shaanxi coal group is 1.5 Mt/a, and the multi-level joint development mode of adit inclined shaft vertical shaft is adopted. The 23210 fully mechanized working face is located in the north wing of 2-3 mining area of the second level of the mine. The average thickness of the 2# coal seam is 1.5 m. The coal seam is granular and foamy, with general brightness, which belongs to soft coal seam. The coal seam is in structural unconformity contact with the upper and lower strata (Figures 1 and 2).

The 23210 fully mechanized working face of Xiayukou coal mine has many kinds of coal wall spalling in the process of preparing roadway and early mining. As shown in Figure 3, the occurrence of coal wall spalling seriously affects the mining process of the mine. Therefore, it is necessary to study the mechanism and control measures of coal wall spalling in soft coal seam in order to realize the safe and efficient mining of the working face.

3. Theoretical Analysis

3.1. Model Establishment and Stress Analysis. The coal body in front of the working face is subjected to advance bearing pressure when longwall fully mechanized coal mining face is working. Loose area, plastic area, elastic area, and original rock stress area are produced along the coal wall to the deep part of coal body (Figure 4).

In Figure 4, R_1 is the width of bulk area, R_2 is the width of plastic area, R_3 is the width of inelastic area, K is the stress concentration factor, γ is the weight of overlying strata of coal seam, and H is mining depth of coal seam.

First of all, the foundation of establishing the model is to assume that the coal body is an uniform, isotropic, and continuous ideal elastic-plastic body. Within a certain range in front of the coal wall, an unit body is taken as the research object, where dx is the unit body's length and M is the unit body's height.

In Figure 5, c is the cohesion between the coal seam and its roof and floor, f is the friction coefficient between the coal body and its roof and floor, σx is the horizontal stress, and σy is the vertical stress on the unit body.

According to Figures 4 and 5, the equilibrium differential equation along the x-axis can be obtained.

$$M\sigma_x + 2\left(c + f\sigma_y\right)\mathrm{d}x = \left(\sigma_x + \frac{\mathrm{d}\sigma_x}{dx}\mathrm{d}x\right)M. \quad (1)$$

Simplify the above formula to obtain

$$\frac{\mathrm{d}\sigma_x}{\mathrm{d}x} - \frac{2\left(c + f\sigma_y\right)}{M} = 0. \quad (2)$$

3.2. Theoretical Analysis of Limit Equilibrium. Considering the influence of intermediate principal stress on the calculation of plastic zone width, the limit equilibrium theory is used in the design based on D-P criterion.

3.2.1. Analysis of Stress in Fracture Zone Based on D-P Criterion. D-P criterion:

$$\alpha I_1 + \sqrt{J_2} = k. \quad (3)$$

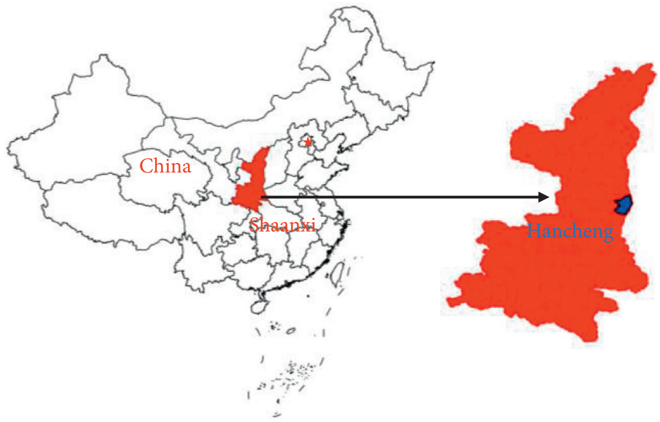
The first stress invariant:

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3. \quad (4)$$

The second stress bias invariant:

$$J_2 = \frac{1}{6}\left[\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2\right]. \quad (5)$$

D-P criterion coefficient:



Columnar	Thickness (m)	Lithology
	5.0	Medium grained sandstone
	4.0	Fine sandstone
	4.5	Siltstone
	1.5	2 Coal
	1.5	Sandy mudstone
	3.0	Siltstone
	7.5	Medium grained sandstone
	3.0	Siltstone
	5.5	3 Coal

Figure 1: Location of the coal mine and its general stratigraphic column.

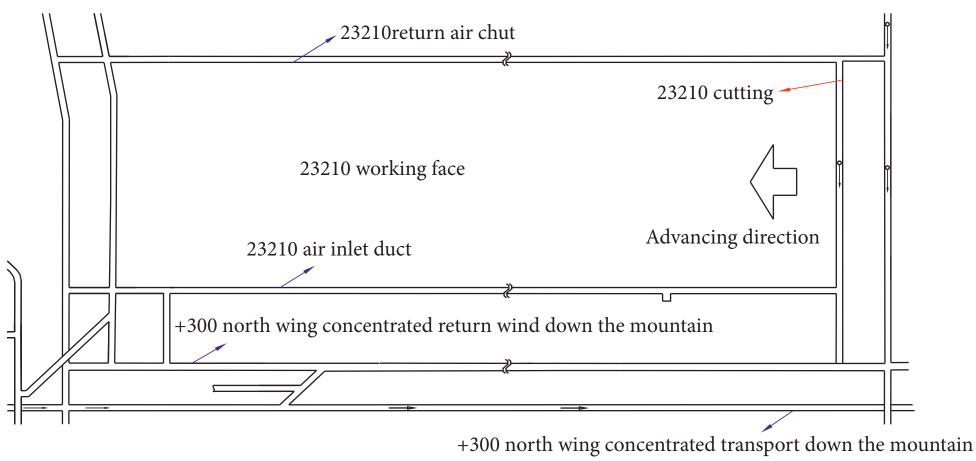


Figure 2: Schematic diagram of 23210 working face.

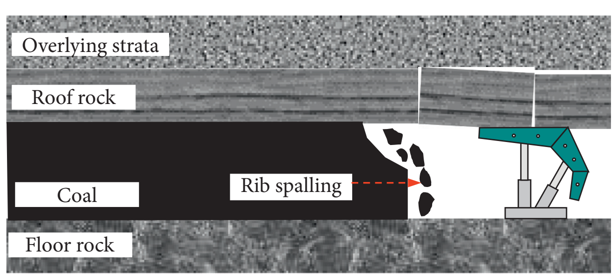


Figure 3: Schematic diagram of coal wall spalling.

$$\alpha = \frac{\sin\varphi}{\sqrt{3}\sqrt{3+\sin^2\varphi}},$$
$$k = \frac{\sqrt{3}c\cos\varphi}{\sqrt{3+\sin^2\varphi}}. \tag{6}$$

In formulas (5) and (6), φ is the internal friction angle, σ_1 is the maximum principal stress and σ_3 is the minimum principal stress. According to the D-P criterion derived from geotechnical plastic mechanics [20-21], the derivation formula is as follows:

$$\varepsilon_2 = \frac{[\sigma_2 - \mu(\sigma_1+\sigma_3)]}{E}, \tag{7}$$

$$\sigma_2 = \frac{1}{2}(\sigma_1+\sigma_3) = -\frac{1}{2}(\sigma_x+\sigma_y), \tag{8}$$

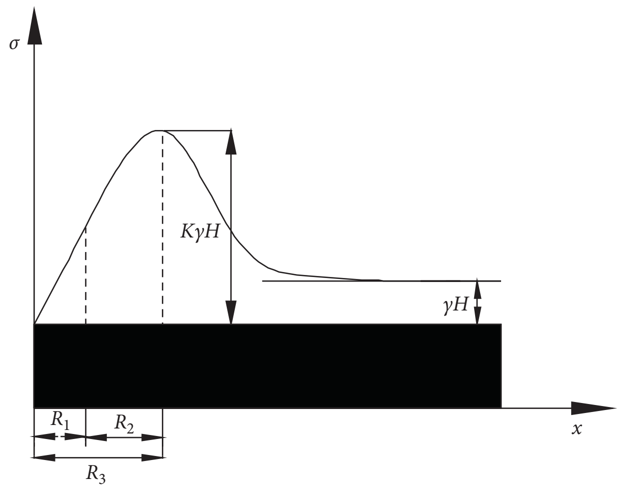


Figure 4: Coal body division and abutment pressure distribution.

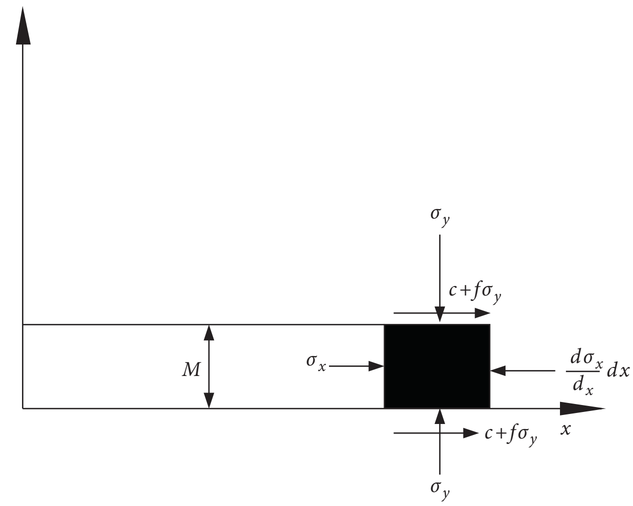


Figure 5: Force analysis of coal unit.

$$I_1 = -\frac{3}{2}\left(\sigma_x + \sigma_y\right),$$
$$J_2 = \frac{1}{8}\left(\sigma_y - \sigma_x\right)^2, \tag{9}$$

where ε_2 is the strain, μ is Poisson's ratio, and E is the elastic modulus. In order to simplify the formula, Poisson's ratio is 0.5.

Substitute the above formula in formula (3) to obtain

$$\sigma_y = \frac{1+3\alpha}{1-3\alpha}\sigma_x + \frac{2k}{1-3\alpha}. \tag{10}$$

Substitute the above formula in formula (2) to obtain

$$\frac{\mathrm{d}\sigma_x}{\mathrm{d}x} - \frac{2f(1+3\alpha)}{M(1-3\alpha)} = \frac{2c}{M} + \frac{4kf}{M(1-3\alpha)}. \tag{11}$$

Solve the first-order linear differential equation to obtain

$$\sigma_x = -\frac{c(1-3\alpha)+2fk}{f(1+3\alpha)} + De^{(2f(1+3\alpha)/M(1-3\alpha)x)},$$
$$D = p + \frac{c(1-3\alpha)+2fk}{f(1+3\alpha)}, \tag{12}$$

where $x=0$, $\sigma_x = p$. Then,

$$\sigma_x = -\frac{c(1-3\alpha)+2fk}{f(1+3\alpha)} + \left[p + \frac{c(1-3\alpha)+2fk}{f(1+3\alpha)}\right]e^{(2f(1+3\alpha)/M(1-3\alpha)x)},$$
$$\sigma_y = -\frac{c}{f} + \left[\frac{(1+3\alpha)}{(1-3\alpha)}p + \frac{c}{f} + \frac{2k}{1-3\alpha}\right]e^{(2f(1+3\alpha)/M(1-3\alpha)x)}. \tag{13}$$

3.2.2. Calculation of Plastic Zone Width. The vertical stress in plastic zone is σ_{yp}:

$$\sigma_{yp} = -\frac{c}{f} + Ee^{(2f(1+3\alpha)/M(1-3\alpha)x)}. \tag{14}$$

Therefore,

$$\sigma_{yp}\big|_{x=R_1} = \sigma_c, \tag{15}$$

where σ_c is the compressive strength of coal in the fracture zone.

Among them:

$$E = \left(\sigma_c + \frac{c}{f}\right)e^{-\left(2f(1+3\alpha)/M(1-3\alpha)R_1\right)}. \tag{16}$$

Substitute the above formula in formula (14) to obtain

$$\sigma_{yp} = \left(\sigma_c + \frac{c}{f}\right)e^{\left(2f(1+3\alpha)/M(1-3\alpha)\left(x-R_1\right)\right)} - \frac{c}{f}. \tag{17}$$

According to the model establishment and stress analysis, R_2 is the width of plastic zone. It is necessary to calculate the width of plastic zone and obtain the factors affecting coal wall caving of soft coal seam.

According to the continuous condition of stress boundary in material mechanics, at the critical point of elastic zone and plastic zone of coal, the bearing pressure in elastic zone is equal to that in plastic zone.

$$\sigma_{yp}\big|_{x=R_3} = \sigma_{ye}\big|_{x=R_3} = K\gamma H. \tag{18}$$

Substitute the above formula in formula (17) to obtain

$$\left(\sigma_c + \frac{c}{f}\right)e^{\left(2f(1+3\alpha)/M(1-3\alpha)\left(R_3-R_1\right)\right)} - \frac{c}{f} = K\gamma H. \tag{19}$$

Solution:

$$R_3 = \frac{M(1-3\alpha)}{2f(1+3\alpha)}\ln\frac{c/f + K\gamma H}{\sigma_c + c/f} + R_1. \tag{20}$$

Therefore, the width of plastic zone R_2:

$$R_2 = \frac{M(1-3\alpha)}{2f(1+3\alpha)}\ln\frac{c/f + K\gamma H}{\sigma_c + c/f}. \tag{21}$$

According to formula (21), by determining four parameters, study the change of plastic zone width caused by the change of one parameter and obtain the relationship

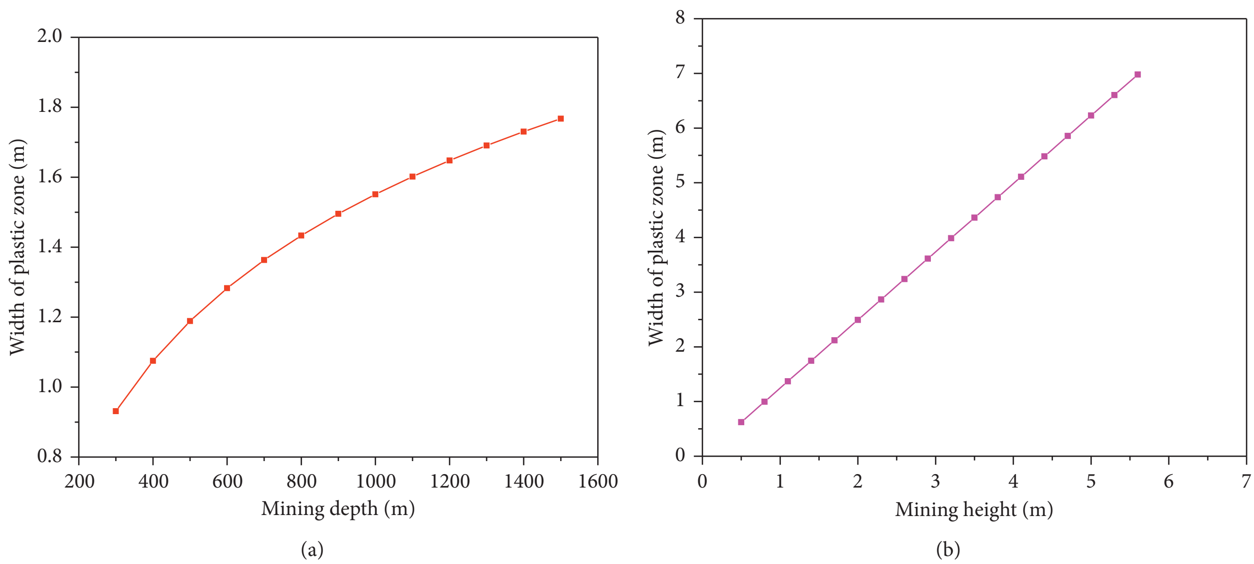


Figure 6: Relationship between width of plastic zone and mining depth and mining height.

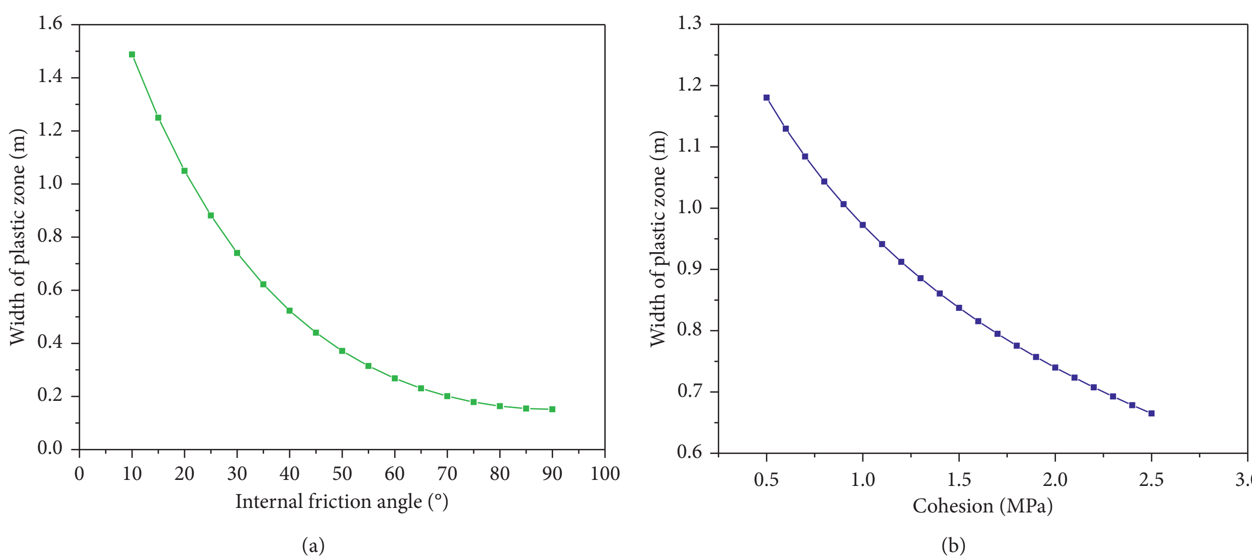


Figure 7: Relationship between width of plastic zone and internal friction angle and cohesion.

between the range of plastic zone and mining depth, mining height, cohesion, and internal friction angle (Figures 6–8).

The following conclusions are drawn from Figures 6–8:

(1) When other factors are constant and when the mining height is 2.0 m, the range of plastic zone is 2.5 m, and when the mining height is 4.1 m, the range of plastic zone is 5.1 m. The width of plastic zone increases linearly with the increase of mining height, indicating that coal wall slopes are more likely to occur with large mining height. So, it is necessary to control mining height reasonably.

(2) The width of plastic zone is affected by mining depth and increases nonlinearly with the increase of mining depth. It shows that the incidence of coal wall slope in deep mine is higher.

(3) The width of plastic zone is related to stress concentration factor and decreases nonlinearly with the decrease of stress concentration factor.

(4) The width of plastic zone is related to compressive strength of coal and decreases with the increase of the compressive strength of soft coal. When the strength of coal body is 1.10 MPa, the range of plastic zone is 0.75 m, and when the strength of coal body is 2.10 MPa, the range of plastic zone is 0.68 m, indicating that coal wall slopes are more likely to occur in soft coal body.

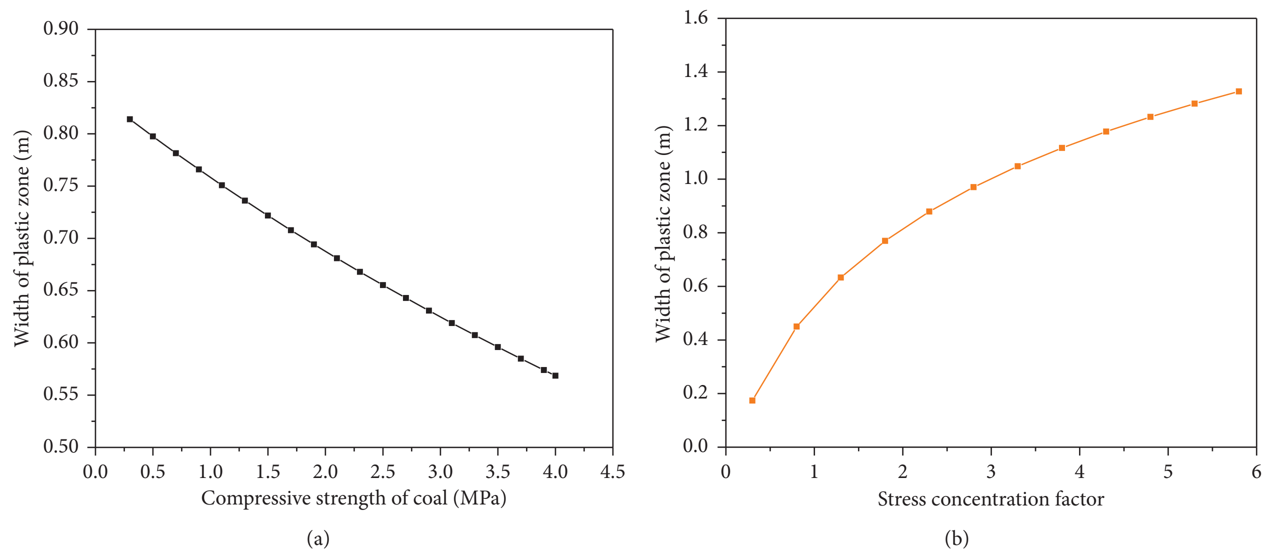


Figure 8: Relationship between width of plastic zone and compressive strength and stress concentration factor.

(5) The width of plastic zone is related to the internal friction angle and cohesion of coal body and decreases nonlinearly with the increase of cohesion and internal friction angle.

It shows that the width of plastic zone is related to the physical and mechanical properties of coal. Increasing cohesion and internal friction angle can reduce the width of plastic zone. Strengthening coal is conducive to the prevention of coal wall spalling of soft coal.

4. Control Measures of Coal Wall Caving

4.1. Strength Test of Coal with Different Moisture Contents. The change of uniaxial compressive strength of soft coal with different moisture content is studied through laboratory experiments. By analyzing the uniaxial compressive strength curve of coal with different moisture contents, we obtain that under the same moisture content, the compressive strength of coal increases to the maximum value first and then decreases to the final failure, which is the uniaxial compressive strength. The change trend of uniaxial compressive strength of soft coal with moisture content is shown in Figure 9.

It can be seen from Figure 9 that with the increase of moisture content, the uniaxial compressive strength of soft coal increases first and then decreases. First, it increases from 1.65 MPa to 2.50 MPa with the moisture content $w = 1.3\%$ to $w = 3.3\%$, with an increase of 51.5%. Then, it reaches the maximum value when the moisture content is about 3.3% and then slowly decreases to 1.50 MPa when $w = 5.7\%$, with a decrease of 40%.

Therefore, the uniaxial compressive strength of soft coal can be improved by water injection. The shear strength indexes of soft coal are different under different water contents. With the increase of water content, its cohesion increases first and then decreases. The water content at the extremely high point is about 3.072%. The cohesion of coal can also be improved by water injection [22, 23]. However, the water injection volume needs to be controlled within a reasonable range, so as to reduce the range of plastic zone and control the slope of coal wall in soft coal seam.

4.2. Analysis on Control Mechanism of Coal Wall Caving. Coal wall caving mainly includes shear failure caving and tensile failure caving. Based on the analysis of plastic zone theory based on D-P criterion, it is considered that the coal wall caving in soft coal seam is mainly related to mining depth, mining height of working face, internal friction angle of coal body, cohesion of coal body, support resistance, and other factors. The greater the mining height, the more prone the coal wall to caving. The smaller the cohesion of coal is, the longer the width of plastic zone is and the easier it is to slice.

Therefore, according to the analysis, the reasonable and feasible prevention and control measures of coal wall caving are determined.

(1) Water injection can improve the cohesion and compressive strength of coal in plastic zone. The cohesion and stability of soft coal body are improved by deep-hole water injection in coal seam. Therefore, the deep-hole advance coal seam water injection method is actually used to improve the cohesion of coal wall. The water injection volume needs to be controlled within a reasonable range.

(2) Properly reducing the mining height of the working face can reduce the width of the plastic zone, and reducing internal friction angle can reduce the width of the plastic zone, so as to ensure the stability of the coal wall.

(3) By increasing the working resistance of the hydraulic support in the working face and adopting a reasonable support mechanism, it is conducive to maintain the stability of the coal wall and effectively prevent the occurrence of coal wall spalling. It is conducive to maintain the stability of the coal wall

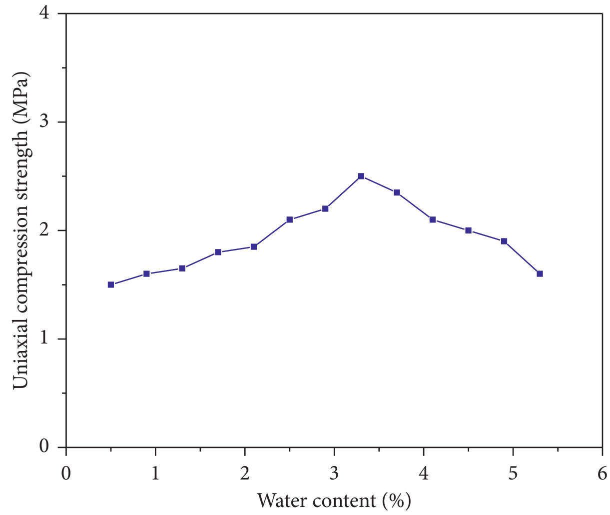


Figure 9: Variation trend chart of uniaxial compressive strength of soft coal with moisture content.

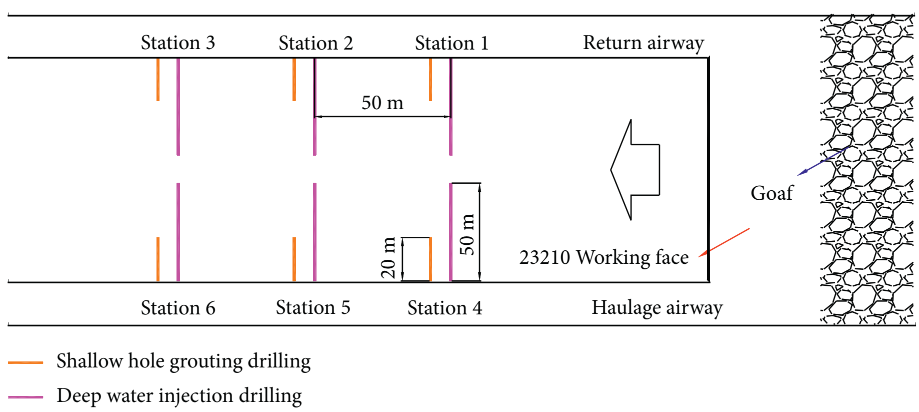


Figure 10: Schematic diagram of prevention and control measures of working face.

and effectively prevent the occurrence of coal wall spalling.

(4) As the width of plastic zone is also affected by the physical and mechanical properties of coal body, the compressive strength of coal body in soft coal seam is poor. It is necessary to improve the strength of coal body in soft coal seam. The stability of coal body is enhanced through the advance grouting of coal wall shallow hole.

4.3. Control Measures of Coal Wall Caving. According to the coal wall caving mechanism and control research conclusion, the coal wall caving control measures are formulated as follows. Comprehensive prevention and control measures such as deep-hole water injection to increase the strength of soft coal body, shallow-hole advanced grouting to strengthen coal body, and improving working resistance of support are adopted in 23210 working face. The depth of water injection is 50.0 m, and the depth of grouting is 20.0 m. The spacing between two water injection holes is 50.0 m (Figure 10). It ensures the safe and efficient mining of the working face and further proves that the comprehensive control measures have effectively prevented the coal wall caving of the working face.

5. Field Measurement

During the mining period of 23210 fully mechanized mining face in Xiayukou coal mine, the field technicians tracked and observed the coal wall caving every 20 m of excavation. By drawing the geological prediction map in time, they determined the scope of coal crushing area through

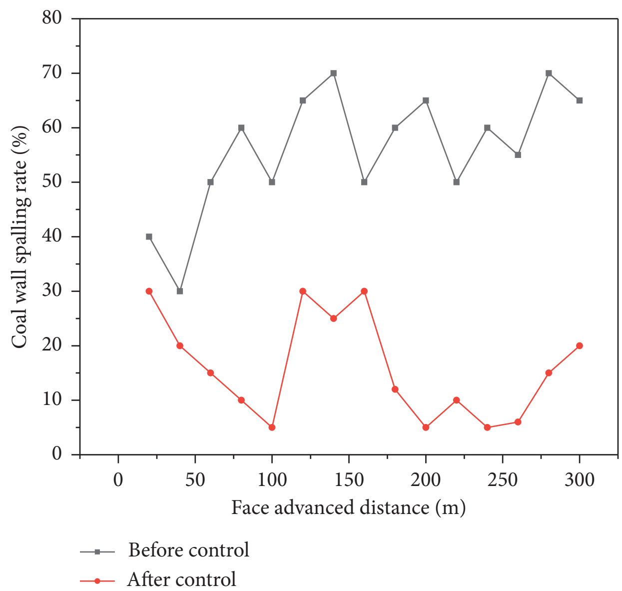


FIGURE 11: Comparison diagram of coal wall caving rate before and after treatment.

observation and geological prediction map and formulated corresponding measures to prevent coal wall caving according to the prediction. By comparing the rate of coal wall spalling before and after the treatment measures of coal wall spalling, the rate of coal wall caving significantly reduced (Figure 11). It is verified that the control measures of coal wall slope are effective.

6. Conclusions

The occurrence mechanism of coal wall spalling in deep mining was studied. The coal wall caving control measures were formulated based on the coal wall caving mechanism. The main conclusions are as follows:

(1) By analyzing the calculation formula of plastic zone of soft coal seam, it is concluded that the coal wall slope of deep mining soft coal seam is related to mining depth, mining height of working face, internal friction angle of coal body, cohesion of coal body, and the compressive strength of coal body.

(2) The width of plastic zone decreases nonlinearly with the increase of cohesion and internal friction angle. The width of plastic zone increases linearly with the increase of mining height and increases nonlinearly with the increase of mining depth.

(3) The change of uniaxial compressive strength of soft coal with different moisture contents is studied through laboratory experiments. The experimental results show that the uniaxial compressive strength of soft coal reaches the maximum value when the moisture content is about 3.3%.

(4) The uniaxial compressive strength of soft coal can be improved by water injection, and the water injection volume needs to be controlled within a reasonable range.

(5) Through the combination of improving the working resistance of the support in the working face, deep-hole water injection, and shallow-hole grouting reinforcement of coal seam, the coal wall caving of the soft coal seam can be effectively controlled.

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

This study was supported by the Foundation of University-Level General Projects of Anhui University of Science and Technology (grant no. xjyb2020-01), the Collaborative Innovation Funding Project of Colleges and Universities in Anhui Province (grant no. GXXT-2020-055), the National Natural Science Foundation of China (no. 52004007), and the Independent Research Foundation of the State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mines (grant no. SKLMRDPC19ZZ09).

References

[1] H. Xie, M. Gao, R. Zhang, G. Peng, W. Wang, and A. Li, "Study on the mechanical properties and mechanical response of coal mining at 1000 m or deeper," *Rock Mechanics and Rock Engineering*, vol. 52, no. 5, pp. 1475–1490, 2019.

[2] E. Unal, I. Ozkan, and G. Cakmakci, "Modeling the behavior of longwall coal mine gate roadways subjected to dynamic loading," *International Journal of Rock Mechanics and Mining Sciences*, vol. 38, no. 2, pp. 181–197, 2001.

[3] X. S. Liu, D. Y. Fan, Y. L. Tan et al., "Failure evolution and instability mechanism of surrounding rock for close-distance chambers with super-large section in deep coal mines," *International Journal of Geomechanics*, vol. 21, no. 5, Article ID 04021049, 2021.

[4] F. Du, K. Wang, G. Wang, Y. Huang, and L. Yi, "The mechanism of damage in gas-bearing coal-rock combination bodies and gas seepage in coals," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 43, no. 10, pp. 1181–1201, 2021.

[5] Y. Luo, F.-q. Gong, X.-b. Li, and S.-y. Wang, "Experimental simulation investigation of influence of depth on spalling characteristics in circular hard rock tunnel," *Journal of Central South University*, vol. 27, no. 3, pp. 891–910, 2020.

[6] J. H. Qi, X. R. Meng, and Z. N. Gao, "Cusp catastrophe model analysis of coal wall slope instability," *Mining Safety & Environmental Protection*, vol. 38, no. 5, pp. 77–79+89, 2011.

[7] X. W. Yin, S. H. Yin, and Y. An, "Characters of the rib spalling in fully mechanized caving face with great mining height," *Journal of Mining & Safety Engineering*, vol. 2, pp. 222–225, 2008.

[8] S. L. Yang and D. Z. Kong, "Flexible reinforcement mechanism and its application in the control of spalling at large mining height coal face," *Journal of China Coal Society*, vol. 40, no. 6, pp. 1361–1367, 2015.

[9] S. Liu, K. Yang, T. Zhang, and C. Tang, "Rib spalling 3D model for soft coal seam faces with large mining height in protective seam mining: theoretical and numerical analyses," *Geofluids*, vol. 2020, Article ID 8828844, 17 pages, 2020.

[10] Q.-S. Bai, S.-H. Tu, M. Chen, and C. Zhang, "Numerical modeling of coal wall spall in a longwall face," *International Journal of Rock Mechanics and Mining Sciences*, vol. 88, pp. 242–253, 2016.

[11] J. C. Wang, "Coal wall caving and the prevention mechanism in the very soft thick coal seam," *Journal of China Coal Society*, vol. 32, no. 8, pp. 785–788, 2007.

[12] J. C. Chang, G. X. Xie, and X. H. Zhang, "Analysis of rib spalling mechanism of fully-mechanized top-coal caving face with great mining height in extra-thick coal seam," *Rock and Soil Mechanics*, vol. 36, no. 3, pp. 803–808, 2015.

[13] F. Cui, T. Zhang, and X. Cheng, "Research on control of rib spalling disaster in the three-soft coal seam," *Shock and Vibration*, vol. 2021, Article ID 2404218, 15 pages, 2021.

[14] G. Li, Z. Li, F. Du, and Z. Cao, "Study on the failure characteristics of coal wall spalling in thick coal seam with gangue," *Advances in Civil Engineering*, vol. 2020, Article ID 6668458, 10 pages, 2020.

[15] Y. Yong, T. Shihao, W. Qi, M. Xiaotao, T. Hongsheng, and S. Lulu, "Mechanics of rib spalling of high coal walls under fully-mechanized mining," *Mining Science and Technology*, vol. 21, no. 1, pp. 129–133, 2011.

[16] Y. P. Wu, D. Lang, and P. S. Jie, "Mechanism of disaster due to rib spalling at fully-mechanized top coal caving face in soft steeply dipping seam," *Journal of China Coal Society*, vol. 41, no. 8, pp. 1878–1884, 2016.

[17] Y. X. Xu, G. F. Wang, M. Z. Li, Y. J. Xu, H. J. Han, and J. H. Zhang, "Investigation on coal face slabbed spalling features and reasonable control at the longwall face with super large cutting height and longwall top coal caving method," *Journal of China Coal Society*, vol. 46, no. 2, pp. 357–369, 2021.

[18] W. Guo, C. Liu, G. Dong, and W. Lv, "Analytical study to estimate rib spalling extent and support requirements in thick seam mining," *Arabian Journal of Geosciences*, vol. 12, no. 8, p. 276, 2019.

[19] C. F. Zhao, Y. Z. Yang, C. G. Zhang, and Y. Li, "Investigation on applicability of common failure criteria considering intermediate principal stress," *Chinese Journal of Rock Mechanics and Engineering*, vol. 30, no. 2, pp. 327–334, 2011.

[20] C. J. Deng, G. J. He, and Y. R. Zheng, "Studies on drucker-prager yield criterions based on M-C yield criterion and application in geotechnical engineering," *Chinese Journal of Geotechnical Engineering*, vol. 28, no. 6, pp. 735–739, 2006.

[21] S. Cao, Y. Yu, and W. Bo, "Viscoelasto-viscoplastic solutions for circular tunnel based on D-P yield criterion and Nishihara model," *Chinese Journal of Geotechnical Engineering*, vol. 42, no. 7, pp. 1925–1932, 2021.

[22] L. Wang, C. Q. Zhu, Z. Q. Yin, and J. Hou, "Research on soft coal mechanics characteristic test for moisture content effect," *Journal of Mining & Safety Engineering*, vol. 33, no. 6, pp. 1145–1151, 2016.

[23] C. Q. Zhu, C. M. Li, Z. Q. Yin, and J. Hou, "Experimental study of soft coal mechanics characteristics with different moistures and clay contents," *Chinese Journal of Rock Mechanics and Engineering*, vol. 36, pp. 3258–3265, 2017.