

Research Article

Study on the Failure Characteristics of Coal Wall Spalling in Thick Coal Seam with Gangue

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Coal wall spalling is one of the main factors restricting the safe and efficient mining of thick coal seam, and the gangue has an important impact on the coal wall spalling. To obtain the failure characteristics of coal wall spalling in thick coal seam containing gangue, numerical calculation and theoretical research were used to analyze the morphological differences of coal wall spalling with different gangue positions. Besides, the damage depth, width, and stress environment of coal wall panel caused by the position of gangue were mainly studied, and the failure mechanics model of coal seam containing gangue was established by using the stability theory of pressure bar. The results show that, compared with coal wall spalling in coal seam without gangue, coal seam with the lower and middle gangue has a significant weakening effect on the wall spalling, and coal seam with the upper gangue has little effect on the wall spalling. In the case of coal seam with gangue, the upper gangue has the highest risk area of coal wall spalling with the maximum depth and width of 2.0 m and 2.3 m. For coal seam with the upper gangue, the dangerous areas of coal wall spalling are mainly distributed in the vicinity of the gangue; for coal seam without the gangue, they are mainly distributed in the middle of the coal seam. The gangue cannot change the law of the external stress distribution of the coal seam, but it has an obvious impact on the internal stress distribution of the coal seam. With the different positions of the gangue, the stress distribution in the coal seam has a great difference, and the maximum difference is 1.8 MPa. This shows that the stress environment of the coal seam containing gangue has the following typical characteristics: “the external stress is controlled by the overburden fracture, and the internal stress environment is controlled by the gangue.” Through the mechanical analysis of the coal seam containing gangue, it is further verified that the coal seam containing gangue is more prone to spalling at the position of gangue.

1. Introduction

The mining of thick coal seam with large mining height has the advantages of high recovery rate, good safety, and large production capacity and has achieved good economic and social benefits in production. It is also considered as one of the main mining methods for safe and efficient mining of thick coal seam in China [1, 2]. The effective support working resistance and appropriate roof control technology are two critical factors for safe and productive mining in the thick coal seam fully mechanized face mining with hard roof conditions [3]. However, with the increase of one-time mining height, the exposed area of coal wall also increases, and the probability of spalling disaster will be greatly increased.

The coal wall spalling further induces the roof-fall accident in the mining face, which seriously restricts the safe and efficient production of the mine. Therefore, a lot of research on the mechanism of coal wall spalling in large mining-height mining has been performed. Wang et al. [4] analyzed the coal wall failure mechanism and stability influencing factors at fault structure in the working face of large mining-height mining. Wang et al. [5] considered that the roof pressure of coal wall is the most effective measure to prevent coal wall damage. Gao et al. [6] and Ju and Xu [7] analyzed the rules of abutment stress distribution affected by three influencing factors, namely, horizontal-vertical distances between overlying coal pillar and working face and buried depth of overlying, and proposed that the key to controlling the strata behavior is to understand the

structural characteristics of key strata and its movement law. Yang et al. [8, 9] pointed out that coal properties, multiple mining stress superposition, and support performance are the main factors affecting coal wall spalling and revealed the mechanism of coal wall spalling of multikey strata crossing coal formation and remote protected layer. Li et al. [10] used the fuzzy fault tree analysis method to distinguish the likelihood of roof fall and rib spalling. Guo et al. [11] concluded that there is a negative correlation between support strength and coal wall spalling depth [12]. Kong et al. [13] analyzed the sensitivity of various influencing factors to the stability degree of coal mining face through the orthogonal test design. Fu et al. [14] analyzed the instability mechanism of coal wall under the unloading stress field by using the theory of unloading rock mass mechanics and fracture mechanics. Based on the strength weakening theory of gangue, Yin et al. [15] obtained the instability criterion of coal wall containing gangue [16]. Wang et al. [17, 18] analyzed the influence of dip angle of the working face on coal wall spalling, and the influence mechanism of mining thickness on coal wall stability was also revealed. Likar et al. [19] established mutual connections between the geo-mechanical parameters of the occurring geological materials in connection with the intensity of coal mining. Zhang and Wu [20], Wu et al. [21], and Si et al. [22] studied the spalling characteristics of coal wall in the stope with a large dip angle and large mining height. Besides, the system structure diagram was constructed for the analysis of coal mass shedding characteristics, and the shear slip failure was verified as the main failure mode. Yuan et al. [23] focused on analysis of coal wall rib spoiling process and establishment of damage mechanical model of coal wall crack development evaluation system. Zhang et al. [24] presented an integrated approach for field test and numerical modeling to investigate the relationship between gateroad stability and yield pillar size. Yang et al. [25] concluded that the mining failure surface of hard coal in a jointed coal seam is the conjugate surface composed of shear failure surface and joint tensile failure surface. Peng et al. [26] pointed out that, according to the bearing structure, the deformation of surrounding rock was divided into plastic reshaping and flowing area, peeling layer area, and shearing and yielding area. Yang et al. [27] studied the mechanism of coal wall spalling in the working face of coal seam containing gangue [28] and concluded that hard gangue can effectively improve the overall stability of coal wall. Sinha et al. [29] predicted a steady damage accumulation in the rib for certain face locations. Li et al. [30] and Li et al. [31] established the Bishop mechanical model of coal wall sliding instability and deduced the general equation of safety factor of each sliding surface. Li et al. [32] analyzed the effects of the slope direction, height, and angle on the stability of voussoir beam structure formed by fractured blocks of the primary key stratum. Bai et al. [33] constructed 2D finite difference models, and the strain-softening constitutive model was used to reveal the brittle failure characteristics of the coal wall. Yao et al. [34] revealed the main failure mode and location of coal wall spalling from the micro- and macroperspectives by using numerical software.

To sum up, the mechanism of coal wall spalling has been studied from different perspectives, and the criterion for determining the instability of coal wall spalling under different conditions is given [35–37]. Besides, the stability of coal seam containing gangue has been explored in certain studies, and some meaningful conclusions have been obtained [38, 39]. However, the research is mainly carried out on the stability of the coal wall, without considering the influence of the position of gangue on the coal wall; through a large number of field observations, it is found that the distribution of gangue in the coal seam is unstable, and different positions of gangue in the coal seam also have an important impact on the coal wall spalling. In this paper, the fully mechanized caving face 42105 with the large mining height in Buertai Coal Mine was taken as the research object. Through the numerical calculation and theoretical analysis method, the distribution characteristics of stress field and displacement field of coal body in front of working face under different gangue positions were analyzed. Besides, the influence mechanism of gangue on coal wall spalling was revealed. This study provides a theoretical basis for further prediction and control of the spalling disasters in thick coal seams containing gangue.

2. Engineering Background

The working face 42105 of the Buertai Coal Mine was located in the first panel of coal seam 4-2. The dip angle of coal seam was $1\text{--}9^\circ$ with an average of 5° . The strike length was 5231 m and the dip length was 230 m. The mining was performed along the coal seam strike. The coal thickness of coal seam 4-2 was 5.9 m–7.3 m, with an average of 6.7 m. The coal mining was carried out by the comprehensive mechanized caving with strike longwall retreating. The coal cutting height of the shearer was 3.7 m and the thickness of the top coal was 3 m. The working face was protected by double column shield-type hydraulic support. There were 2-3 layers of gangue in the coal seam, and the position of the gangue was greatly changed, which had a controlling effect on the spalling of the working face. As shown in Figure 1, the spalling depth reaches the maximum at the gangue position. The different position of gangue has a significant influence on the spalling state of coal wall.

3. Numerical Calculations of Coal Wall Failure Characteristics

3.1. Establishment of the Numerical Model. To study the influence of different positions of gangue on coal wall spalling, the mining geological conditions of working face 4105 of Buertai Coal Mine were considered, and the abutment pressure in front of coal wall and the stress field and displacement field inside the coal seam (especially near the gangue) during thick coal seam mining under different conditions of gangue were studied by using numerical calculation method.

To intuitively illustrate the failure state of the coal wall in the mining of thick coal seam containing gangue, UDEC

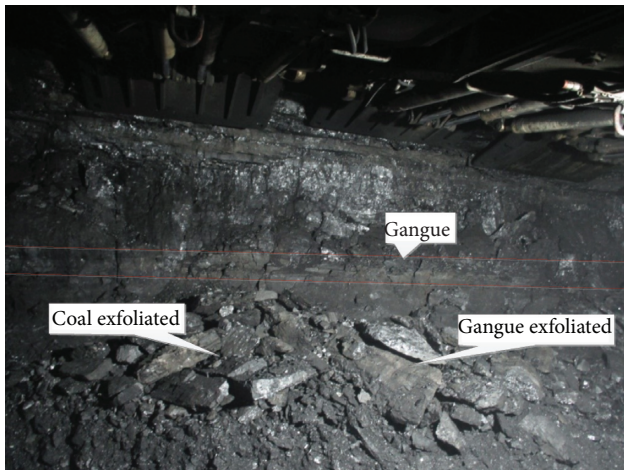


FIGURE 1: Site map of coal wall spalling in the working face.

discrete element numerical calculation software was used for the numerical simulation. The average buried depth of the simulated coal seam was 420 m, the thickness of the coal seam was 6.7 m, the mining height was 3.7 m, and the drawing height was 3 m. Because the main research object of this paper was the spalling of coal seam with gangue, only the basic roof was involved in the vertical direction in the numerical model, and the rest of the top rock layers were replaced by equal loads. In this simulation, the gangue in the paper is hard clamped relative to the coal seam. The size of the model was 80 m (height) \times 300 m (length). The staged excavation was performed in the coal seam, with each excavation being 10 m and the total being 100 m. 100 m coal pillars were reserved on both sides of the model.

The displacement boundary conditions of the calculation model were as follows: the left, right, and lower boundaries of the model were the displacement boundaries, the left and right boundaries limited the horizontal displacement, the lower boundary limited the vertical displacement, the upper boundary was the free boundary, and the overburden above the upper boundary was applied to the upper boundary of the model as a load. Figure 2 shows the calculation model.

The simulation parameters and research scheme are as follows: the Mohr–Coulomb model was used for rock block, and the Coulomb slip model was used for the joint model. Table 1 shows the property parameters of each rock layer.

To effectively study the influence of different positions of gangue on coal seam spalling, the case of one layer of gangue was only studied in this simulation. The interaction between multiple layers of gangue will be described in future research. The specific simulation schemes of coal walls are as follows: (1) without gangue; (2) with the lower gangue (1.2 m away from the bottom of coal seam); (3) with the middle gangue (1.8 m away from coal seam bottom); (4) with the upper gangue (2.4 m away from coal seam bottom). The position of coal gangue is marked with a red dotted line in the calculation result map, and measuring lines and measuring points are set at the upper boundary of the gangue and the coal seam top interface. The length of the measuring line is 50 m, and the distance between the measuring points is 1 m. The specific layout is shown in Figure 3.

The abutment pressure distribution in front of the coal seam was generally divided into three areas, namely, decompression area, pressurization area, and stable pressure area. The coal wall spalling occurred in the decompression area, and the coal body in the decompression area was destroyed and destabilized under the action of roof pressure, causing interference to the normal production of the working face. In this paper, the limit range of the decompression area is defined as the limit point of coal failure to compare and analyze the influence of different positions of gangue on the spalling shape of coal seam.

3.2. Distribution Characteristics of Vertical Stress in Coal Seam. The vertical stress of coal seam is the main factor affecting the spalling of coal wall. The vertical stress of coal seam is analyzed when the working face is advanced to 30 m. Figure 4 is the cloud chart of vertical stress distribution inside the coal wall. The following can be seen: (1) For coal seam with the upper gangue and without gangue, the horizontal distance of the failure limit point of the coal body is 2.0 m and 2.1 m. The range of the decompression area in the coal seam with upper gangue and without gangue is large, and there is a small difference between the two conditions. This indicates that the upper gangue has little effect on weakening the coal wall spalling. (2) For coal seam with lower and middle gangue, the horizontal distance of the failure limit point of coal body is 1.1 m and 1.0 m, respectively. Compared with the coal seam without gangue, the range of decompression zone of coal seam with lower and middle gangue is smaller, which indicates that the lower and middle gangue has a greater weakening effect on the coal wall spalling. (3) The peak value of vertical stress of coal seam without gangue is mostly distributed in the middle and lower part of the coal seam, while that of the coal seam with gangue is mostly distributed in the adjacent area above or below the gangue. This shows that the gangue affects the internal stress structure of coal seam, leading to the obvious difference in its spatial distribution.

3.3. Horizontal Displacement Distribution Characteristics of Coal Wall Spalling. The variation of horizontal displacement of coal wall spalling is the main index to judge the danger of coal wall spalling. When the working face is advanced to 30 m, the horizontal displacement distribution characteristics of coal wall spalling are analyzed. Here, the area where the horizontal displacement of coal body changes by more than 0.2 m is defined as the dangerous area of coal wall spalling. Figures 5 and 6 show the cloud chart of the horizontal displacement distribution inside the coal wall and the horizontal displacement curve diagram inside the coal wall, respectively. The following can be seen: (1) In the case of lower gangue, middle gangue, upper gangue, or no gangue, the maximum depth of the dangerous area in the coal wall spalling is 1.1 m, 2.6 m, 2.0 m, 2.1 m, and the maximum width is 1.8 m, 1.8 m, 2.3 m and 2.2 m, respectively; although the depth of the middle gangue is the largest, the previous analysis has shown that the coal body with a depth of more than 1 m still has the bearing capacity, and there is no wall

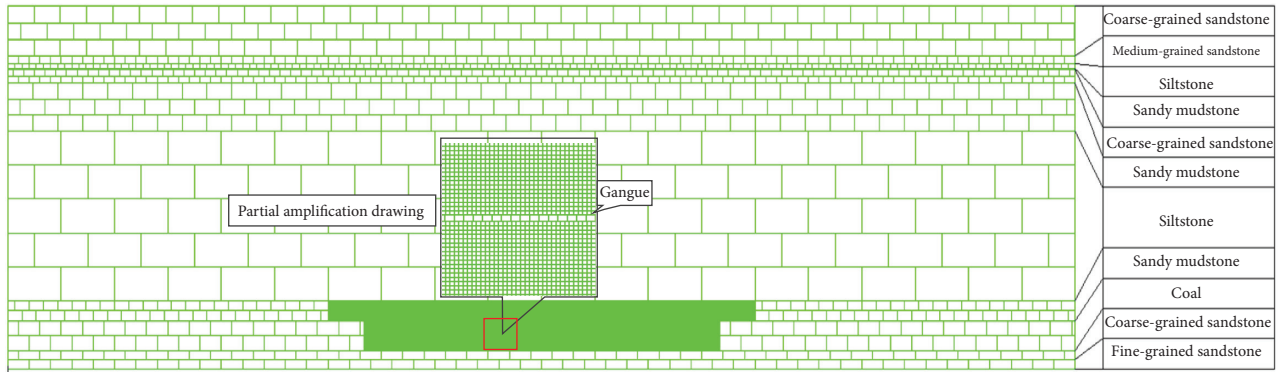


FIGURE 2: The numerical calculation model.

TABLE 1: Physical and mechanical parameters of the block.

Lithology	h (m)	Density (g/cm^3)	Tensile strength (MPa)	C (MPa)	F ($^\circ$)
Coarse-grained sandstone	11.5	2526	1.45	14.186	32.6
Medium-grained sandstone	1.39	2369	2.10	5.247	37.5
Siltstone	1.15	2343	7.90	13.973	29.7
Sandy mudstone	0.26	2111	2.10	15.1168	24.16
Coarse-grained sandstone	2.91	2377	1.45	8.652	28.5
Sandy mudstone	11.5	2321	2.10	18.89	26.6
Siltstone	37.1	2325	7.90	22.43	27.4
Sandy mudstone	4.31	2403	6.60	27.79	26.6
Coal	6.56	1274	1.68	2.51	30
Gangue	0.2	2021	2.70	2.50	32
Coarse-grained sandstone	1.98	2232	2.00	8.61	28.5
Fine-grained sandstone	1.99	2301	5.61	30.91	20.0

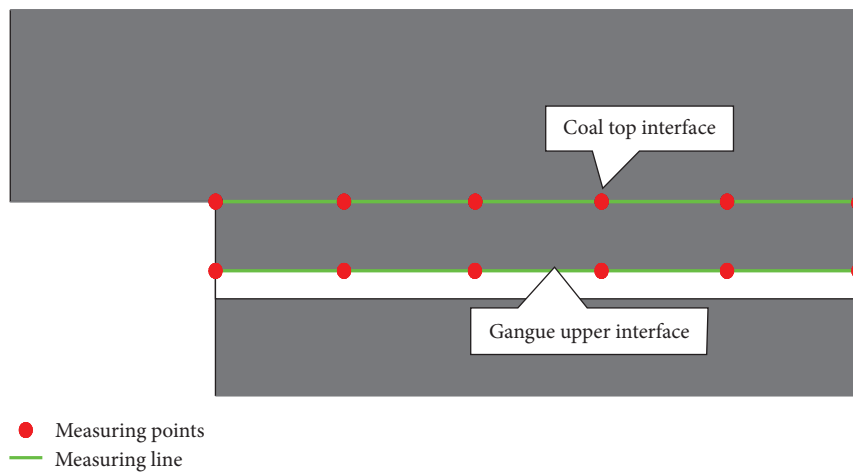


FIGURE 3: Layout of measuring lines and measuring points.

spalling. Therefore, when there is upper gangue or no gangue, the spalling area of coal wall is larger; when there is middle or lower gangue, the spalling area is smaller. (2) When there is gangue, the dangerous area of coal wall spalling is mainly distributed in the adjacent range of the gangue; when there is no gangue, it is distributed in the middle of the coal seam. This indicates that the gangue

changes the internal stress-bearing structure of the coal seam, and stress concentration is easy to occur near the gangue, leading to the high spalling risk near the gangue. (3) For the depth of the coal wall spalling, in case of middle gangue, the depth is 3.1 m, but the coal body with depth of more than 1.0 m still has bearing capacity. The depth of the coal wall spalling with the lower and middle gangue is

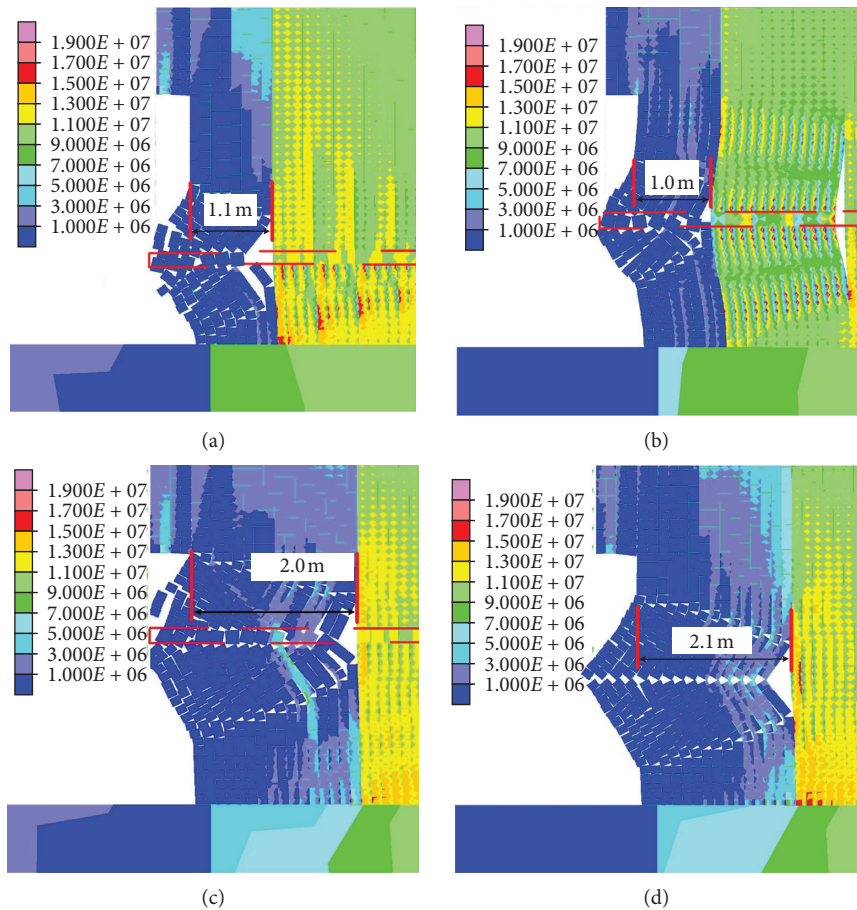


FIGURE 4: Cloud chart of vertical stress distribution in coal seam (Pa): (a) lower gangue; (b) middle gangue; (c) upper gangue; (d) without gangue.

smaller, which is 1.1 m and 1.0 m, respectively. In the case of upper gangue and no gangue, the fracture limit distance of coal body reaches 2.0 m and 2.1 m, respectively. It is concluded that the lower gangue and the middle gangue have obvious weakening effect on the coal wall spalling, while the upper gangue has little effect on weakening the coal wall spalling.

3.4. Comparative Analysis of Coal Gangue Stress Environment.

The stress environment of coal gangue determines the possibility and severity of coal wall spalling. Figure 7 shows the change curves of vertical stress outside the top interface of coal seam, and Figure 8 shows the change curves of vertical stress inside the upper boundary of gangue. When the working face is advanced to 30 m, the change curves of vertical stress of coal wall spalling are illustrated. The following can be seen: (1) The vertical stress at the top of the coal seam shows a trend of “first increasing, then decreasing, and then gradually stabilizing.” The peak value of vertical stress of the upper, middle, and lower gangue is 11.35 MPa, 12.03 MPa, and 12.38 MPa, respectively. The small difference indicates that the gangue has little influence on the external stress of the coal seam. (2) As the position of the gangue in the coal seam is different, the stress peak value in the coal seam is greatly different. The peak stress values of the upper,

middle, and lower gangue are 12.67 MPa, 10.86 MPa, and 10.83 MPa, respectively; the maximum difference is 1.8 MPa, which indicates that the position of the gangue has a great influence on the internal stress of the coal seam. (3) Through comparative analysis, it can be seen that gangue in the coal seam is in different position, and the variation curves of vertical stress outside coal seam top interface are almost consistent, indicating that it had little effect on vertical stress outside coal seam top interface, but the variation curves of vertical stress inside the upper boundary of gangue appeared stress value difference suggest a greater influence on the vertical stress inside the upper boundary of gangue. This shows that vertical stress at the top of the coal seam is controlled by the overlying rock breaking above the coal seam, and the vertical stress on the gangue boundary is controlled by the gangue. That is to say, the stress environment of the coal seam containing gangue has the following typical characteristics: “the external stress is controlled by the overburden fracture [40, 41], and the internal stress environment is controlled by the gangue.”

4. Mechanical Analysis of Coal Wall Spalling

Affected by the gangue in the coal seam, the mechanical characteristics of the coal wall are different from those of the

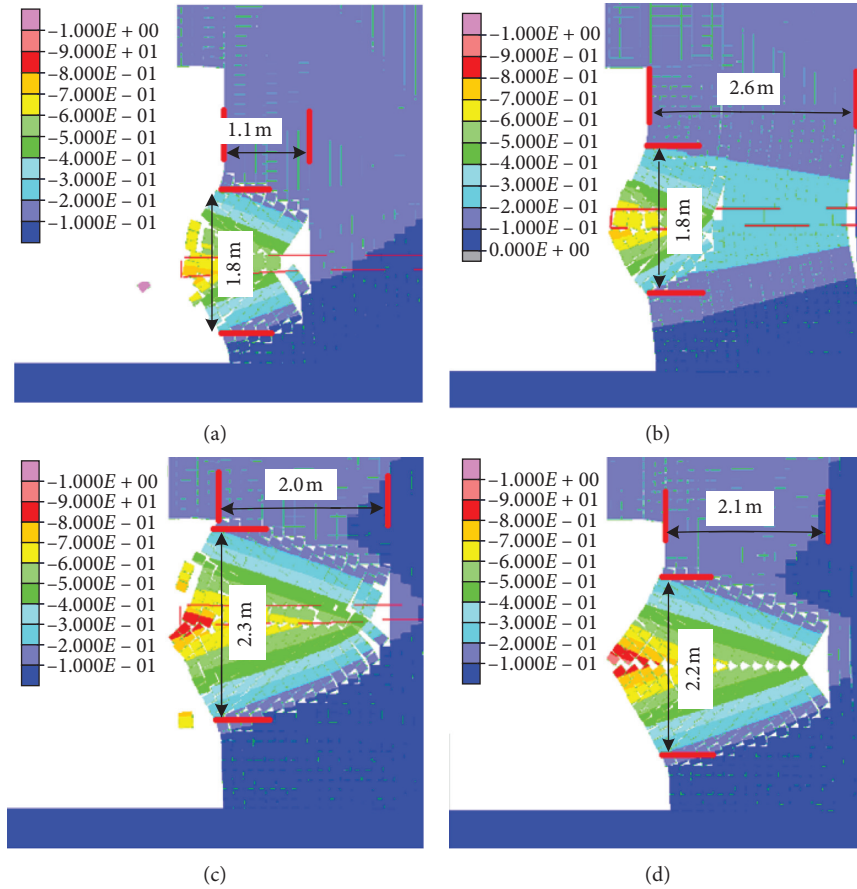


FIGURE 5: Cloud chart of horizontal displacement distribution in coal seam (m): (a) lower gangue; (b) middle gangue; (c) upper gangue; (d) without gangue.

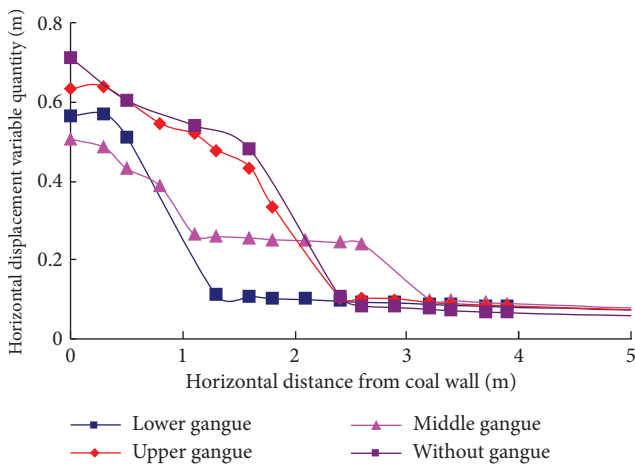


FIGURE 6: Horizontal displacement curve of coal seam.

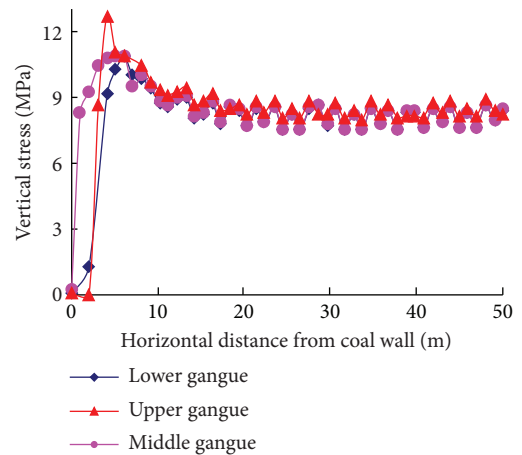


FIGURE 7: Variation curves of vertical stress outside coal seam top interface.

single coal seam. According to the stress characteristics of coal wall, the microunit with unit width along the vertical direction is taken as the research object; the coal wall is divided into coal seam, gangue, and coal seam from top to bottom. Assuming that the pressure bar is in the limit equilibrium state, the approximate deflection curve of coal wall is obtained, and the maximum deflection value of coal

wall is determined through the approximate differential equation of deflection and the end equilibrium condition. In other words, the most likely location of coal wall fracture is obtained. According to the actual stress situation of coal wall, the lower end of coal wall is set as a fixed end, and the upper end of coal wall is a free end. The mechanical model of

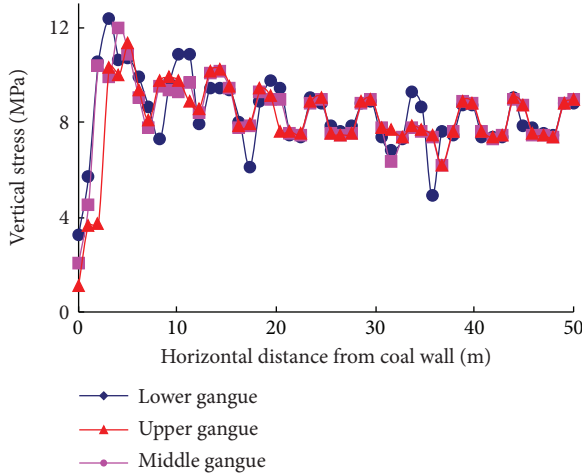


FIGURE 8: Variation curves of vertical stress inside the upper boundary of gangue.

coal seam containing gangue is shown in Figure 9. Due to the space limitation, the mechanical analysis of coal wall spalling is only discussed when the gangue is located in the middle of coal seam.

In the figure, h is the mining thickness of the working face, m; F_p is the abutment pressure of the coal wall, N; R is the gravity load of the coal wall, N; h_1 is the thickness of the gangue, m; h_2 is the vertical distance between the gangue and the top of the coal seam, m; h_3 is the vertical distance between the gangue and the bottom of the coal seam, m; and x is the vertical distance from the microunit to the bottom of the coal seam, m. However, the gravity load R of coal wall is far less than the abutment pressure F_p of coal wall, so the influence of gravity load R on coal wall failure is ignored in the following calculation. The fixed end moment is set as M_0 and the mining height is h . According to the overall balance condition of the bar, there is a horizontal reaction force M_0/h at both ends. According to the material mechanics stability theory, the moment balance equation is established with the centroid of x section as the center.

$$M = F_p \omega - \frac{M_0 x}{h}, \quad (1)$$

where M is the bending distance of x section centroid, N·m, and ω is coal wall deflection, m.

The differential equation of deflection curve is obtained from $M = -EI\omega''$ as follows:

$$EI\omega'' + F_p\omega = \frac{M_0 x}{h}, \quad (2)$$

where EI is the bending stiffness of the strut body, $K^2 = F_p/(EI)$.

The general solution of the differential equation (2) is as follows:

$$\omega = C_1 \sin Kx + C_2 \cos Kx + \frac{M_0}{F_p} \cdot \frac{x}{h}. \quad (3)$$

For the boundary conditions,

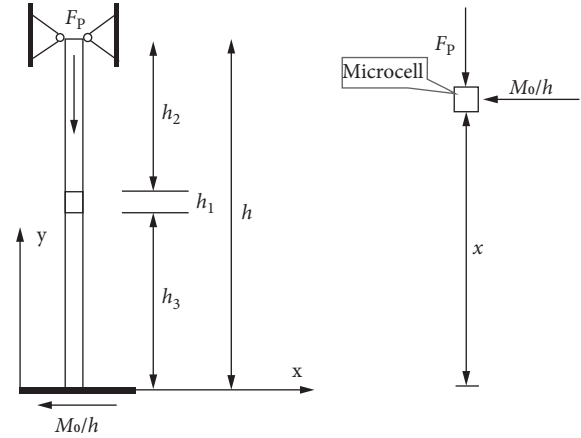


FIGURE 9: Mechanical model of coal seam with gangue.

- (1) If $x = 0$, $\omega(0) = 0$
- (2) If $x = h$, $d\omega/dx = 0$

Combined with the above formula, the solution is obtained:

$$\omega = \frac{M_0}{F_p} \cdot \left(\frac{x}{h} - \frac{\sin Kx}{\cos Kx} \right). \quad (4)$$

Let $B = (x/h) - (\sin Kx/\cos Kx)$; then, the above formula can be simplified as

$$\omega = \frac{M_0}{F_p} \cdot B. \quad (5)$$

From the above formula, it can be seen that the deflection curve value is mainly determined by B and related to the elastic modulus and inertia moment of the material; it also has a nonlinear relationship with x . Besides, the larger the elastic modulus is, the less likely the material is to spall. Combined with the above formula, the curve diagram of coal body B_1 and gangue B_2 value is drawn, the curve chart of coal body B_3 containing gangue is drawn by fitting, and $B_3 = k(B_1 + B_2)$.

k is the correction coefficient, and $k = h_1/h$. The curve of coal body B_3 containing gangue is fitted. As shown in Figure 10, the spalling risk of coal wall near the gangue is higher than that at other positions of coal wall, and the results are consistent with the previous numerical simulation results.

5. Discussion

According to the above analysis, the influence of gangue on the regional structure movement of coal seam is mainly reflected in the following three aspects: (1) Gangue improves the bearing capacity of coal seam itself, improves the stability of the overall structure of coal seam, under the same external stress environment, and reduces the degree of spalling damage of coal wall. (2) When coal gangue is located at the lower part, the larger the coal gangue is constrained by roadway floor, the smaller the influence range of coal wall is. When the coal gangue is located in the upper part, the coal

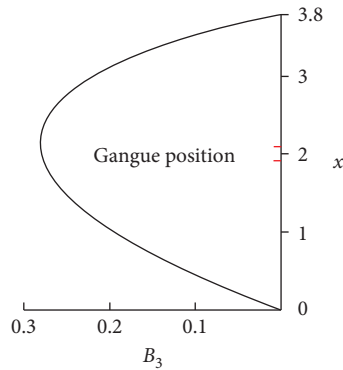


FIGURE 10: Relationship curve between $(B)_3$ and distance (x) from coal seam bottom.

gangue is strengthened by the restriction of roadway roof, which reduces the influence range of coal wall spalling. When the coal gangue is located in the middle, the coal gangue is restrained by the roadway floor or roof, and the influence range of coal wall spalling is obviously larger than the other two situations. (3) In the coal gangue stress environment, the vertical stress of the top coal seam is little affected by the gangue, and it is mainly affected by the overall movement of the rock strata above, while gangue mainly changes the internal stress structure of the coal seam and affects the movement of the regional structure of the coal seam. When the position of the gangue is different, the peak stress in the coal seam changes obviously, but the changing trend of the stress curve is consistent.

6. Conclusions

- (1) Compared with coal seam without gangue, the lower and middle gangue have an obvious weakening effect on the coal wall spalling, while the upper gangue has little effect on the coal wall spalling.
- (2) In the case of coal seam containing gangue, the highest danger area of coal wall spalling is found in the coal seam with the upper gangue, and its maximum depth and width reach 2.0 m and 2.3 m, respectively. Besides, the dangerous area of coal wall spalling is mainly distributed in the adjacent area of gangue, while it is distributed in the middle of coal seam when there is no gangue.
- (3) Gangue does not change the stress distribution law of the coal seam top interface but has a significant effect on the internal stress distribution of coal seam. As the position of gangue changes in the coal seam, there is a big difference in its boundary stress distribution, and the maximum difference is 1.8 MPa. This shows that the stress environment of the coal seam containing gangue has the following typical characteristics: “the external stress is controlled by the overburden fracture, and the internal stress environment is controlled by the gangue.”
- (4) Through the establishment of the mechanical model of coal seam containing gangue, further analysis and

verification are conducted. The results show that the coal seam containing gangue is more prone to spalling at the position of gangue.

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

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