Study on the deformation and failure mechanisms of a coal wall in a deeply buried longwall working face with a weak roof

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Abstract. Coal wall spall causes serious mining difficulties, especially in deeply buried longwall working faces with a weak roof. To study the deformation and failure mechanisms of the coal wall, the physical model experiments that were conducted using a special loading device that can simulate the formation process of the bearing pressure on the roof rock seam. Combined with numerical simulation, the dominant factors were obtained by sensitivity and weight analyses. The results show that in the advancing process of a working face, the coal seam undergoes a complex fracturing process and the fracturing of the coal seam is closely related to the distance from the coal wall. Both experiment and numerical simulation show that the fracture surfaces near the front face of the coal wall are tensile, but the fracture surfaces away from the front face of the coal wall are shear and tensile or shear. The failure degree of coal wall spall is mainly affected by mining depth, mining height, cohesion, and internal friction angle. These results are useful for understanding the deformation and failure of coal wall.

1. Introduction

Because of the increase of mining depth, the continuous improvement of mining methods and equipment, and the complexity of the coal seam occurrence environment, the deformation failure mechanism of coal rock mass in the working face under mining disturbance has become more complex. The mining influence and mine pressure tend to be serious due to the large mining height, long inclined length and large-scale fully mechanized caving[1]. These easily cause serious bearing pressure distributed in the form of deviatoric pressure on the coal seam in front of the coal wall, which results in serious coal wall spalling and asymmetric deformation failure of the roof. Then, coal wall spalling and asymmetric deformation failure of the roof further aggravate the stress concentration and deviatoric pressure degree that make support difficult and seriously threaten the safety of coal mine production[2-3]. Therefore, studying the deformation failure mechanism of coal wall spalling under the
deviatoric pressure from mining disturbance will help to reveal the failure mechanism and provide the basis for support design.

Nowadays, many studies have been undertaken to investigate the failure mechanisms and failure modes of coal walls and the bearing pressure in the working face through the use of various methods including theoretical analysis\(^4\text{-}^6\), in-situ tests\(^7\), laboratory experiments\(^8\text{-}^{10}\), and numerical simulations\(^1\text{-}^{13}\).

Yuan et al.\(^{14}\) used the principle of damage mechanics to study coal wall rib spalling, and a mechanical model was built to analyze the effect of factors that influencing spalling. Bai et al.\(^{15,16}\) analyzed the influence of supporting resistance, other influencing factors on coal stress and horizontal displacement in the working face based on the mechanical properties and microstructure of brittle coal. The results indicated that the coal wall spalling mechanism of brittle coal working face was tensile cracking and compression shear sliding, and the mechanism of coal wall spalling in a brittle coal face was verified by combining with field observation. Kong et al.\(^{17,18}\) established the “coal face support roof” mechanical model to illustrate the factors affecting the stability of the coal face, and sensitivity analysis of influencing factors, the dominant factors and the stress distribution around the coal face were obtained by combining with a numerical simulation.

The abovementioned studies enhanced our understanding of the mechanism of coal wall spalling from the theoretical analysis. In addition, the numerical simulation method also plays an important role in the comprehensive analysis of the relationship between working face stress and coal wall spalling. Shabanimashcool and Li\(^{19}\) proposed a new numerical method to simulate the longwall mining in detail to study the stability of gates and the loading process to rock bolts, and the results showed that the stability of the gates and the force of the rock bolts were closely related to the width of the chain pillars. Song et al.\(^{20}\) established two-dimensional finite element modeling of a typical longwall face to research the stress and displacement distribution in the face area, the results showed that the most face fall occurred in the upper part of the face. Yao et al.\(^{21}\) employed distinct Universal Distinct Element Code to investigate the distribution of abutment stress in front of the coal face at different mining dip angles from micro- and macro-perspectives, which revealed the main failure form and location of the coal rib.

An in-situ test and the physical model test can intuitively reflect the mode of coal wall spalling and track the failure process. Lu et al.\(^{22}\) utilized pure vibration signals in the coal wall during the operation of mining machinery to investigate the dynamic damage mechanism of coal wall, and the results showed that stress concentration zones tended to induce tensile stress generation and coal failure, and resulted in the coal undergoing zonal failure and spalling. In addition, Li et al.\(^{23}\) predicted fuzzy risk of the roof fall and rib spalling using the fuzzy fault tree analysis, dynamic fuzzy comprehensive evaluation (FFTA-DFCE) and risk matrix methods. The results indicated the validity and feasibility of the risk analysis and prediction model for roof fall and rib spall.

Previous studies focused on the failure mechanisms and influencing factors of coal wall spall through theoretical analysis, numerical simulation and experiments. Most experiments used the uniform load or the point load to simulate the bearing pressure of the working face, which cannot truly reflect the deviatoric stress state of coal rock mass in the working face. In this paper, to study the stress distribution of the working face, physical model experiments were conducted using a special loading device that can simulate the formation process of the bearing pressure on the roof rock seam. Then, the deformation and failure process of the coal wall was replicated using numerical simulation, and the coal spall coefficient was introduced to obtain the dominant factors by sensitivity and weight analysis. This study can serve as a reference for the mechanism and failure mode analysis of coal wall spall in a deep-buried working face.

2. Engineering background

The coal wall of the No. 1307 working face of the Zhaozhuang Coal Mine in Shanxi Province, China is seriously damaged. The overlying strata of this face are broken rock strata with low strength. In situ investigation on the No. 1307 working face showed that coal wall spall often occurred and the roof strata were fractured and broken so that the roofs were unstable in the mining process. Hence, the
geological and mining conditions of this working face are used to investigate the deformation and failure mechanisms of the coal wall in a deeply buried longwall working face with a weak roof. The No. 1307 working face is located at a depth of 482-490 m. The coal seam has an average thickness of about 5.36 m and a dip angle of 3°. The roof above the coal seam is mudstone and fine sandstone and the rock seam above the mudstone and fine sandstone is broken siltstone, as shown in Fig. 1. The mechanical parameters of coal and rock strata are listed in Table 1.

### Table 1 Mechanical parameters of surrounding rock

| Strata            | Density (kg·m⁻³) | Compressive strength (MPa) | Elastic modulus (GPa) | Poisson’s ratio | Cohesion (MPa) | Internal friction angle (°) |
|-------------------|------------------|---------------------------|-----------------------|----------------|----------------|----------------------------|
| Siltstone         | 2706             | 46.47                     | 13.75                 | 0.24           | 12.64          | 31.51                      |
| Medium grained sandstone | 2716         | 61.30                     | 29.47                 | 0.21           | 30.76          | 24.00                      |
| Fine sandstone    | 2739             | 52.52                     | 27.96                 | 0.25           | 39.66          | 21.10                      |
| Mudstone          | 2782             | 25.56                     | 9.56                  | 0.29           | 7.49           | 33.54                      |
| Coal              | 1438             | 10.69                     | 3.15                  | 0.28           | 3.68           | 27.82                      |

3. Model test of coal wall deformation and failure

3.1. Experimental design and the model experimental device

In the mining process, a point of the coal seam in front of the working face wall is in a triaxial stress state. With continuous mining, the point in the coal seam gradually approaches the coal wall, and finally is in the position of the coal wall. At this moment, the stress state of the point becomes a uniaxial stress state. Thus, the real nature of the mining is the continuous unloading process of the coal seam in front of the working face. In addition, a deviatoric pressure load is formed in front of the coal wall affected by the bearing pressure. The distribution range of the deviatoric pressure load is evolving with the mining of the working face. The coal seam in front of the coal wall gradually becomes the coal wall, and the unloading effect on the coal seam appears repeatedly. Therefore, the idea of this test is to select the coal rock composite unit composed of the roof and the coal wall of the working face and use the gradient load to simulate the nonuniform bearing pressure. The deformation and failure characteristics of the coal rock mass and the coal wall can be studied by adjusting the thickness of the coal seam, the strength of the coal rock mass and the loading mode. The test design is shown in Fig. 2.
3.2. Experimental procedure

To measure accurately the failures of the coal wall in front of a working face, the following experimental procedure was performed:

(1) Sample construction. In this case, we designed similar 0.5 m × 0.5 m × 0.5 m cubic samples. Each sample is composed of an upper layer and a lower layer. Similar materials with higher strength are used to simulate the roof rock mass in the upper layer and the similar materials with lower strength are used to simulate the coal seam in the lower layer. Similar materials were made of aggregate and cementing agents. Aggregate was river sand, and cementing agents were cement, gypsum and water. With respect to the similarity ratio used, the reader is referred to Tian et al. [24] Nine experimental schemes were carried out to study the coal wall spall. In the following analysis, we describe the displacements and failures of No. 1, 4, and 7 samples in detail. Table 2 presents the parameters of these three samples.
Table 2 Model experimental schemes

| Samples | Coal seam thickness (mm) | Coal seam strength (MPa) | Roof strength (MPa) | Loading types |
|---------|--------------------------|--------------------------|--------------------|---------------|
| 1       | 200                      | 8                        | 25                 | A             |
| 4       | 250                      | 8                        | 35                 | C             |
| 7       | 300                      | 8                        | 45                 | B             |

(2) Loading of samples. The loading types were divided into three types A, B, and C. At stage L1, elastic cushions with high rigidity close to the side of plexiglass baffles were used. At stage L2, elastic cushions with low rigidity close to the side of plexiglass baffles were used. At stage L3, the horizontal constraint on the coal wall needed to be removed by dismantling the detachable plexiglass baffles. In the operation process, the unloading was not needed after satisfying the holding time of stage L2.

3.3. Deformation and failure of the coal wall

Three samples were taken as typical cases to analyze the failure mode to reflect the influence of different mining heights on the deformation and failure mode, as shown in Fig. 4.

(a) No. 1 sample (b) No. 4 sample (c) No. 7 sample

Figure 4. Failure modes of coal wall spall on the front face.

(1) The spall of the No. 1 sample was mainly concentrated in the upper part of the coal wall, and extended from the top to the bottom in the vertical direction. The spall height of the top part was about half of the mining height. In addition, flaky spall occurred at the bottom of the coal wall and the middle of the left side, and the range of flaky spall at the bottom was relatively large, while that at the left side was small. Fractures extended from the top of the coal wall. At the same time, fractures extended from the bottom and connected with the upper and middle parts of the coal wall. The upper and middle parts of the coal wall had serious spall and the spall depth was the largest, which increased the free face area of the coal wall, the formation of stress concentration, and the large roof subsidence in the middle.

(2) The spall of the No. 4 sample was mainly concentrated in the upper part of the coal wall, and the spall range was parallel to the coal-rock interface and extended to both sides. The spall maximum height was 1.18 m and the maximum depth was 0.80 m. In addition, a flaky spall occurred in the left bottom corner of the coal wall. There were fractures in the middle and left side of the coal wall, which extended downward from the upper rib area. The upper right part of the coal wall had serious spall and the spall depth was the largest, which increased the free face area of the coal wall, the formation of stress concentration, and the large roof subsidence.

(3) Because the simulated mining height of the No. 7 sample was the largest, the spall range of the coal wall is smaller than for the former two models, but the whole coal wall visibly bulged. The whole coal wall spall instability trend was obvious. There were obvious spall areas in the middle and upper part of the left side of the coal wall, and fractures appeared at the bottom of the coal wall and
continued to extend upward. Affected by the overall bulge of the coal wall, the coal-rock interface dislocated and the roof slightly subsided.

4. Numerical simulation of the mining face

4.1. Numerical model
Based on the geological condition of the No. 1307 working face of the Zhaozhuang Coal Mine, a three-dimensional numerical model was built using FLAC3D software, as shown in Fig. 5. The dimensions of the numerical model are 170 m (width) × 100 m (height) × 20 m (thickness). The geostatic stress of the overlying strata was replaced by a uniform load on the top, a fixed boundary was adopted at the bottom of the model to limit the vertical and horizontal displacement, and sliding hinge bearings were adopted around the model to limit the horizontal displacement. The mining distance was 60 m, a single mining step was set to 10 m, and a total of six steps were taken. Different advancing speeds were simulated by setting different calculation steps. The force of the support and the support plate were both applied with a uniform load. The influencing factors and levels of coal wall spall are shown in Table 3.

![Figure 5, Numerical model.](image)

| Number | Factors                        | Factor levels |
|--------|--------------------------------|---------------|
|        |                                | 1  | 2  | 3  | 4  | 5  |
| 1      | Mining depth (m)               | 400| 500| 600| 700| 800|
| 2      | Mining height (m)              | 2  | 3  | 4  | 5  | 6  |
| 3      | Advance speed (m/d)            | 1  | 2  | 3  | 4  | 5  |
| 4      | Coal elastic modulus (GPa)     | 1  | 2  | 3  | 4  | 5  |
| 5      | Coal cohesion (MPa)            | 1  | 2  | 3  | 4  | 5  |
| 6      | Coal internal friction angle (°) | 10 | 15 | 20 | 25 | 30 |
| 7      | Coal tensile strength (MPa)    | 0.1| 0.5| 1.0| 1.5| 2.0|
| 8      | GSI                            | 30 | 40 | 50 | 60 | 70 |
| 9      | Thickness of weak roof (m)     | 2  | 3  | 4  | 5  | 6  |
| 10     | Support resistance (MPa)       | 0  | 0.5| 1.0| 1.5| 2.0|
| 11     | Horizontal force of retaining plate (MPa) | 0  | 0.1| 0.2| 0.3| 0.4|

4.2. Horizontal displacement analysis of the coal wall
In general, the coal wall spall is characterized by the deformation of the coal wall to the goaf. The horizontal displacement of the coal wall to the goaf is an important performance and warning
precursor of the coal wall spall, and it is easier to collect the data using a numerical simulation. Therefore, the horizontal displacement $u_0$ of the coal wall is selected as one of the evaluation indexes of the coal wall. The numerical simulation results are shown in Table 4. A range analysis of horizontal displacement of the coal wall is shown in Table 5.

### Table 4 Orthogonal design schemes and numerical simulation results

| Schemes | $u_0$ (mm) | Schemes | $u_0$ (mm) | Schemes | $u_0$ (mm) |
|---------|------------|---------|------------|---------|------------|
| 1       | 252.53     | 18      | 133.92     | 35      | 157.32     |
| 2       | 84.54      | 19      | 297.71     | 36      | 288.38     |
| 3       | 44.59      | 20      | 312.53     | 37      | 180.11     |
| 4       | 29.11      | 21      | 206.56     | 38      | 84.84      |
| 5       | 23.98      | 22      | 157.47     | 39      | 159.69     |
| 6       | 48.21      | 23      | 222.06     | 40      | 136.34     |
| 7       | 61.46      | 24      | 450.45     | 41      | 169.81     |
| 8       | 205.44     | 25      | 585.83     | 42      | 205.31     |
| 9       | 143.39     | 26      | 27.66      | 43      | 434.13     |
| 10      | 107.55     | 27      | 52.72      | 44      | 203.71     |
| 11      | 115.25     | 28      | 160.05     | 45      | 126.00     |
| 12      | 138.85     | 29      | 70.65      | 46      | 161.36     |
| 13      | 159.59     | 30      | 45.51      | 47      | 235.86     |
| 14      | 95.88      | 31      | 84.63      | 48      | 158.91     |
| 15      | 257.51     | 32      | 49.18      | 49      | 118.73     |
| 16      | 109.65     | 33      | 55.35      | 50      | 445.02     |
| 17      | 222.36     | 34      | 379.10     |         |            |

### Table 5 Range analysis of the horizontal displacement of the coal wall

| Factors | $K_{ij}$ | $K_{i2}$ | $K_{i3}$ | $K_{i4}$ | $K_{i5}$ | Range $R_i$ | Sensitivity ranking |
|---------|----------|----------|----------|----------|----------|-------------|---------------------|
| 1       | 79.13    | 129.16   | 161.64   | 221.51   | 274.23   | 195.09      | 1                   |
| 2       | 146.40   | 138.79   | 165.89   | 194.84   | 219.76   | 80.97       | 5                   |
| 3       | 176.20   | 154.63   | 172.66   | 198.98   | 163.2    | 44.35       | 7                   |
| 4       | 212.41   | 176.34   | 182.57   | 156.03   | 138.33   | 74.08       | 6                   |
| 5       | 298.76   | 192.55   | 139.72   | 129.00   | 105.64   | 193.12      | 2                   |
| 6       | 243.83   | 178.55   | 157.57   | 150.67   | 135.05   | 108.78      | 3                   |
| 7       | 155.76   | 165.61   | 199.43   | 172.12   | 172.77   | 43.67       | 8                   |
| 8       | 186.87   | 221.44   | 160.03   | 137.86   | 159.47   | 83.58       | 4                   |
| 9       | 165.89   | 154.22   | 173.59   | 183.59   | 188.40   | 34.18       | 10                  |
| 10      | 149.08   | 178.51   | 172.57   | 173.83   | 191.69   | 42.61       | 9                   |
| 11      | 161.74   | 168.31   | 164.97   | 176.58   | 194.08   | 32.34       | 11                  |

Fig. 6 shows the evolution trend of horizontal displacement with factor levels. After the comparative analysis in Table 5 and Fig. 6, the conclusions of the analysis are:

1. Mining depth, coal cohesion, and coal internal friction angle were more sensitive than other factors.
2. With the increase in mining depth, the horizontal displacement of the coal wall increased approximately linearly. The horizontal displacement of the coal wall had an obvious positive linear correlation with mining height.
(3) The horizontal displacement decreased with the increase in coal cohesion, which indicated that the increase in coal cohesion was conducive to improving the stability of the coal wall. The horizontal displacement decreased with the increase in coal internal friction angle and kept a steady decreasing trend.

(4) The influences of advance speed, coal tensile strength, support resistance, thickness of weak roof and horizontal force of the retaining plate on horizontal displacement were relatively small.

5. Conclusions
This paper studied the deformation and failure mechanisms of the coal wall in a deeply buried longwall working face with a weak roof using a model test and a numerical simulation. Through a comparative analysis of the results, the conclusions can be summarized as follows:

1) The coal wall spall mainly occurred in the upper part of the coal wall. Under the action of nonuniform loadings, an obvious shear sliding failure zone near the coal wall appeared.

2) Mining depth, coal cohesion and coal internal friction angle were more sensitive than other factors. The sensitivities to advance speed, coal tensile strength, support resistance, thickness of the weak roof and horizontal force of the retaining plate to horizontal displacement were relatively small.

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