Abstract: The overlying strata movement has an important influence on the stability of coal during fully mechanized top-coal caving mining. Based on the actual characteristics of the Liuxiang Coal Mine, a simulation experiment of the overlying strata movement is carried out in this study via the methods of digital image correlation (DIC) and stress electric measurement to study the influence of the overlying strata movement on the stability of coal during fully mechanized top-coal caving mining in thick coal seams. The characteristics of overlying strata movement, stress concentration, and deformation are analyzed. The following conclusions could be drawn. The movement of strata can be divided into two stages: the first stage, dominated by vertical displacement, and the second stage, dominated by horizontal displacement. The vertical movement of the overlying strata along the goaf in the first stage caused vertical stress concentration of the coal, and the horizontal movement in the second stage caused interlayer friction and sliding between the roof and the coal, which triggered a shearing effect on the coal. Under these two effects, the strength of the coal and rock masses along the goaf approaches the strength limit, deformation localization occurs, and micro-cracks are further concentrated and merged in the area to form macro-cracks. When the macro-cracks expand and an unstable expansion occurs, the sudden release of elastic energy will lead to dynamic disasters, such as rock burst.

Keywords: overlying strata movement; simulation experiment; stress concentration; DIC; interlayer sliding

1. Introduction

The movement of the overlying strata in thick coal seam mining causes the redistribution of stress and forms a stress reduction zone and a stress increase zone in coal along the goaf [1–3]. This greatly affects the stability of coal along the goaf and makes the working face more prone to coal burst when disturbance occurs. Therefore, carrying out research on the influence of the overlying strata movement on coal along the goaf in thick coal seams, to understand and master the law of overlying strata movement and its action mechanism on coal along the goaf and prevent the occurrence of coal burst, has important theoretical and practical value.

It has become important to observe the movement of overlying strata and the deformation rule of coal along the goaf by using similar simulation experiment methods [4–9]. In recent years, with the improvement of various experimental observation methods, the temporal and spatial non-uniformity characteristics, and the evolution processes of various physical and mechanical quantities in the overburden migration process, as well as the stress distribution and deformation of coal at the edge of the goaf, have aroused extensive research interest of scholars. In the model experiment of fully mechanized caving of thick coal...
seams, the techniques of optical fiber, resistance strain gauge, and the total station instrument are commonly used experimental observations [10–15]. Among them, optical fiber and resistance strain gauge were used to monitor the stress in the local area of the model experiment, and the total station instrument was used to quantitatively measure the displacement in the local area of the experimental model. In the study of overlying strata migration, Liu, Y. et al. [16] used a borehole television system to study the development height and evolution characteristics of the roof water-flowing fractured zone in fully mechanized caving mining. Li, S. et al. [17] used digital photography to study the movement, crack distribution, and evolution of the overburden during mining, and found that under the influence of repeated mining, the overburden cracks experienced five dynamic changes. Zhang, J. et al. [18] studied the distribution, development, and penetration of vertical and horizontal cracks in the mining overburden using the total station measurement method and proposed an effective method to determine the height of the “three zones”. Zhang, H. et al. [19] used the EH-4 magnet method and the numerical simulation method to determine the failure height of overburden, which was consistent with the theoretical calculation results. Zhang, P. et al. [20] studied the overburden structure and its evolution law during mining and proposed the hazard law of the overburden structure during mining. Ma, Z. et al. [21] studied the movement law of mining of the overburden structure, the evolution of mining fissures and stress changes in coal seams, and the expansion deformation of coal seams. Zhang, X. et al. [22] studied the deformation, failure, and stress distribution evolution characteristics of surrounding rocks in fully mechanized caving mining by using similar simulation and numerical simulation methods, and they proposed the instability modes of the overburden bulk arch structure, such as tensile-compression composite instability and shear instability. Most of the above studies are focused on the overburden movement, but the corresponding relationship between the overburden migration and the evolution of coal and rock deformation along the goaf needs further experimental research.

In this study, we take Liuxiang Coal Mine as the engineering background, adopt the DIC method and the stress electric measurement as the monitoring methods, and then we carry out a simulation experiment of the overlying strata movement. The characteristics of overlying strata movement, stress distribution along the goaf, deformation along the goaf, and friction and sliding between the coal and rock layers are analyzed.

2. Engineering Background

The Liuxiang Coal Mine is located in Yulin City, Shaanxi Province, and the main mining seam is the No. 3 coal seam. The location of Liuxiang Coal Mine is shown in Figure 1. The thickness of the No. 3 coal seam is 10.20~11.65 m, with an average of about 11.05 m, a standard deviation of 0.37, and a coefficient of variation of 3.33%. The thickness of the coal seam obviously increases from the southwest to the north and east. The buried depth of the coal seam is 209~321 m, generally 240~270 m, and the floor elevation changes between 1065 and 1088 m. The whole coal seam is slightly inclined to the northwest, with a dip of 320, with an average depth of 5.2 m/km and an average dip angle of 0.3, and some gentle undulations are formed locally. The structure of the coal seam is simple, with some containing a layer of gangue, with a thickness of 0.05~0.08 m and a lithology of mudstone. The direct roof of the coal seam is mainly mudstone and silty mudstone, and the floor is mainly argillaceous siltstone and siltstone. Through the identification of the coal and rock impact tendencies, the coal seam, direct roof, and floor strata all had a weak impact tendency.
3. Simulation Experiment of Overlying Strata Movement

3.1. Experimental Model

With the above real conditions as the engineering background, a two-dimensional plane model was established. Figure 2 presents a schematic diagram of the experimental model. The height of the model was 750 mm, and the coal seam was 70 mm. The materials were mainly composed of aggregate and cementing material, whereby fine sand was selected as the aggregate, and lime and gypsum were used as the cementing material. The basic parameters are shown in Table 1. To simulate the strata pressure, a counterweight was applied at the top of the model. Stress sensors were laid on the floor of the coal seam to monitor the stress distribution along the gob side of the coal seam. Points a–e at the top of the coal seam were set to calculate the interlayer friction sliding displacement. The orange dashed line represents the calculation area of the coal seam deformation field along the goaf.

According to mechanical similarity, the geometric similarity ratio, $\alpha_L$, time similarity ratio, and stress similarity ratio were obtained from the perspectives of geometric similarity, $\alpha_t$, motion similarity, and dynamic similarity, $\alpha_\sigma$. The similarity ratios were 150:1, 12:1, and 140:1, respectively, and the calculation process was as shown in Equations (1)–(3):

$$\alpha_L = \frac{L_H}{L_m}$$  \hspace{1cm} (1)

$$\alpha_L = \sqrt{\alpha_t}$$  \hspace{1cm} (2)

Table 1. Main physical parameters and material ratios of each rock formation.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Specific Gravity /g × cm³</th>
<th>Compressive Strength /MPa</th>
<th>Elastic Modulus /MPa</th>
<th>Poisson’s Ratio</th>
<th>Stratification × Layer Thickness/cm</th>
<th>Proportion</th>
<th>Sand /kg</th>
<th>Lime /kg</th>
<th>Gypsum /kg</th>
<th>Water Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy soil</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1 × 7</td>
<td>8:1:1</td>
<td>26.1</td>
<td>3.2</td>
<td>3.2</td>
<td>5%</td>
</tr>
<tr>
<td>Mudstone</td>
<td>2.75</td>
<td>71.8</td>
<td>1186</td>
<td>0.36</td>
<td>3 × 3</td>
<td>9:7:3</td>
<td>6.6</td>
<td>5.2</td>
<td>2.2</td>
<td>5%</td>
</tr>
<tr>
<td>Fine sandstone</td>
<td>2.71</td>
<td>72.8</td>
<td>4507</td>
<td>0.23</td>
<td>10 × 4</td>
<td>8:7:3</td>
<td>8.2</td>
<td>7.2</td>
<td>3.1</td>
<td>5%</td>
</tr>
<tr>
<td>Siltstone</td>
<td>2.73</td>
<td>81.2</td>
<td>3439</td>
<td>0.26</td>
<td>1 × 2</td>
<td>8:6:4</td>
<td>4.1</td>
<td>3.1</td>
<td>2.1</td>
<td>5%</td>
</tr>
<tr>
<td>Coal</td>
<td>1.43</td>
<td>20.5</td>
<td>1008</td>
<td>0.33</td>
<td>1 × 7</td>
<td>9:9:1</td>
<td>17.1</td>
<td>17.1</td>
<td>1.9</td>
<td>5%</td>
</tr>
</tbody>
</table>
\[ \alpha_v = \frac{\gamma_h \alpha L}{\gamma_m} \]  

where \( L_h \) is the actual size, \( L_m \) is the model size, \( \gamma_h \) is the actual material bulk density, and \( \gamma_m \) is the model material bulk density.

Each layer of material was laid in turn, according to the preset parameters. After the model was dry, a 400 kg weight was uniformly placed on the top of the model. Marking points were laid on the working face, and artificial speckle spraying was carried out in the coal seam area and the overlying strata. In order to prevent the weight from falling and prevent off-plane displacement during excavation, a transparent plexiglass plate was fixed in front of the model for restraint.

![Figure 2](image_url)

**Figure 2.** Schematic diagram of the model size and the analysis area. (a) presents the model’s schematic diagram, while (b) illustrates the analysis area diagram of the sliding displacement between layers.
3.2. Experimental System

The observation system utilized charge-coupled devices with a frequency of 5 fps. The image resolution was 1600 pixels × 1200 pixels, and the object surface resolution was 0.50 mm/pixel. The layout of the observation system is shown in Figure 3. The cameras on both sides were used to collect the speckle field images of the coal seam area, and the middle camera was used to collect the entire field of the marking points.

![Experimental site layout.](image)

The principle of the digital speckle correlation method is to measure the displacement and strain of a region by matching the position information of the corresponding points before and after deformation, on the basis of the assumption of the principle of the grayscale invariant (Song et al. 2011 [23]). The digital marking point method is mainly used to study the measurement accuracy of image displacement. The principle is to extract the center position of circular marking points through an image processing algorithm, match the position information of corresponding points before and after deformation, and calculate the physical quantities, such as the overburden subsidence and the interlayer displacement. Compared to traditional displacement measurement methods, DIC method offers advantages such as whole-course measurement, no contact, simple operation, and high calculation accuracy. These methods provide a measurement accuracy of up to 0.01 pixel.

3.3. Experimental Process

Prior to the experiment, the image acquisition system and the stress sensor acquisition equipment were matched to ensure the time synchronization of the two systems. To ensure the integrity and clarity of the images, the cameras were adjusted to the optimal position and definition settings, and two lighting lamps were placed on the front side of the coal seam along the goaf, respectively. Considering the reflection problem of the glass plate, the glass panel in the coal seam area along the goaf was cut off, and the position and angle of the lighting lamp were adjusted so that it only illuminated the coal seam area along the goaf, without affecting the upper glass panel.

The experimental process was divided into two stages: working face mining and roof free subsidence. The first stage was the mining stage of the working face. The simulated mining work was carried out on the back of the model, and the coal seam of the working face was quickly mined. The second stage was the free subsidence stage of the roof. The fractured rock mass in the goaf was slowly compressed by the pressure of the overlying...
strata until the overlying strata sunk to the stable stage. During the experiment, a strain acquisition instrument and a CCD camera were used to continuously collect data until the end of the experiment. After the experiment, the loading and observation system was closed, and the experimental data were classified and analyzed by the DIC method.

3.4. Experimental Results

Figure 4 shows the stress curves of sensors 1–6 on the right side of the coal along the goaf. The two vertical dotted lines in the figure are two marking points of time, where marking point 1 corresponds to the time of 1000 s and marking point 2 to 1700 s. The period from the beginning to the time of marking point 1 is the time period for the mining stage, and the time period from the time of marking point 1 to the last moment is the stage of the free sinking of the overlying rock in the goaf.

Figure 4. Stress curves of coal along the goaf.

In order to analyze the influence of the overlying strata movement on the stability of the coal, the following section analyzes the characteristics of overlying strata movement, stress distribution along the goaf, deformation along the goaf, and friction and sliding between the coal and rock layers.

4.1. Overlying Strata Movement Characteristics

By calculating the subsidence curve of overlying strata in the goaf and the displacement vector of overlying strata along the goaf, the temporal and spatial evolution characteristics of the overlying strata movement were analyzed in-depth.

Figure 5 shows the experimental model diagram of the working face after mining. Due to the movement of overlying strata caused by excavation, a caving zone and a fracture zone appeared in the overlying strata in the goaf, and the height of the two zones was 87 m, forming a “hinged rock beam” structure as a whole. With the subsidence of the overlying strata, the deformed strata in the upper part of goaf the were gradually compacted, forming a trapezoidal distribution compaction area. In the fracture zone, cracks were distributed vertically or obliquely in the rock, and there was a crack at the left end of the fracture zone that ran through the whole overlying rock, and the crack opening was obvious. There were unexploited coal seams on both sides of the goaf, and the overlying strata were divided into two areas, namely, the overlying strata in the goaf and the overlying strata in the coal seam area along the goaf.

Figure 5. Collapse diagram of the overlying strata on the working surface.

Figure 6 shows the subsidence curves of the overlying strata in the goaf. It can be seen that the overlying strata in the goaf formed a “hinged rock beam” structure after mining, and the fracture occurred at the end of the fracture zone. The subsidence of the overlying strata in the middle of the goaf was the largest, and the largest displacement was about 12 m. Under the combined action of the overburden and weight of the strata, the overburden strata in the goaf bent and sunk, leading to a large number of inclined fissures between the strata as well as the fracture of some strata.

Figure 7 shows the vector displacement of the overlying strata along goaf. The red dotted areas in Figure 2a are the specific analysis areas. It can be seen from Figure 7 that at the time of marking point 1, the displacement of the strata above the coal along the goaf was mainly vertical, while at the time of marking point 2, the proportion of horizontal displacement obviously increased. Therefore, the movement of strata above the coal along the goaf can be divided into two stages. In the first stage, due to the stress transfer of the overlying strata in the goaf, the strata along the goaf compressed the coal seam under the guidance of vertical stress, and the displacement in this stage was mainly vertical displacement. In the second stage, due to the collapse of the overlying strata in the goaf, the strata along the goaf had the freedom to move horizontally, and under the action of horizontal stress, the displacement in this stage was mainly horizontal displacement. This is an important reason for the vertical stress concentration and horizontal shear action in the coal along the goaf.
Figure 6. Subsidence curves of overlying strata in the goaf.

Figure 7 shows the vector displacement of the overlying strata along the goaf. The red dotted areas in Figure 2a are the specific analysis areas. It can be seen from Figure 7 that at the time of marking point 1, the displacement of the strata above the coal along the goaf was mainly vertical, while at the time of marking point 2, the proportion of horizontal displacement obviously increased. Therefore, the movement of strata above the coal along the goaf can be divided into two stages. In the first stage, due to the stress transfer of the overlying strata in the goaf, the strata along the goaf compressed the coal seam under the guidance of vertical stress, and the displacement in this stage was mainly vertical displacement. In the second stage, due to the collapse of the overlying strata in the goaf, the strata along the goaf had the freedom to move horizontally, and under the action of horizontal stress, the displacement in this stage was mainly horizontal displacement. This is an important reason for the vertical stress concentration and horizontal shear action in the coal along the goaf.

Table 2 shows a comparative analysis of the u field (displacement in x-direction) and the v field (displacement in y-direction) of the overlying strata along the goaf at different times. Among them, the data in rows 1–5 represent the displacement calculation results of 5 characteristic points along the horizontal axis at different times, with the y-coordinate unchanged. From the data of rows 1–5, it can be found that in terms of horizontal displacement, the rock layer as a whole moved towards the goaf, and the farther away from the goaf, the greater the horizontal displacement. The horizontal displacement at marking point 2 was much greater than that at marking point 1. In terms of vertical displacement, the closer to the goaf, the greater the vertical displacement. The data in rows 6–12 represent the displacement calculation results of 7 characteristic points along the vertical axis at different times, with the x-coordinate unchanged. From the data of rows 6–12, it can be obtained that in terms of horizontal displacement, the overall direction...
was towards the goaf, the value increased with the increase of height, and the horizontal displacement at the time of marking point 2 was also much larger than that at the time of marking point 1. As for the vertical displacement, with the increase of the height, the vertical displacement value at $y = 10–30\,\text{m}$ was close at two moments. At $y = 30–70\,\text{m}$, the value of vertical displacement at point 2 was larger than that at point 1.

Table 2. The calculation results of the deformation field at different times.

<table>
<thead>
<tr>
<th>Coordinates (m)</th>
<th>$u$ Field of Point 1 (cm)</th>
<th>$u$ Field of Point 2 (cm)</th>
<th>$v$ Field of Point 1 (cm)</th>
<th>$v$ Field of Point 2 (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10,30)</td>
<td>0</td>
<td>–13.1</td>
<td>16.8</td>
<td>19.1</td>
</tr>
<tr>
<td>(20,30)</td>
<td>0.2</td>
<td>–16.4</td>
<td>11.1</td>
<td>11.8</td>
</tr>
<tr>
<td>(30,30)</td>
<td>–1.6</td>
<td>–18.0</td>
<td>8.5</td>
<td>8.7</td>
</tr>
<tr>
<td>(40,30)</td>
<td>–2.2</td>
<td>–19.7</td>
<td>6.1</td>
<td>6.4</td>
</tr>
<tr>
<td>(50,30)</td>
<td>–2.8</td>
<td>–22.2</td>
<td>4.1</td>
<td>4.9</td>
</tr>
<tr>
<td>(30,10)</td>
<td>0.8</td>
<td>–17.3</td>
<td>5.2</td>
<td>4.5</td>
</tr>
<tr>
<td>(30,20)</td>
<td>–1.0</td>
<td>–16.9</td>
<td>8.2</td>
<td>7.2</td>
</tr>
<tr>
<td>(30,30)</td>
<td>–1.6</td>
<td>–18.0</td>
<td>8.5</td>
<td>8.7</td>
</tr>
<tr>
<td>(30,40)</td>
<td>–2.9</td>
<td>–19.6</td>
<td>9.3</td>
<td>11.0</td>
</tr>
<tr>
<td>(30,50)</td>
<td>–3.7</td>
<td>–20.8</td>
<td>9.8</td>
<td>11.9</td>
</tr>
<tr>
<td>(30,60)</td>
<td>–8.2</td>
<td>–25.5</td>
<td>10.7</td>
<td>13.2</td>
</tr>
<tr>
<td>(30,70)</td>
<td>–11.2</td>
<td>–26.6</td>
<td>10.1</td>
<td>14.1</td>
</tr>
</tbody>
</table>

4.2. Stress Concentration of Coal along the Goaf

It can be seen from the stress curves (Figure 4) that the stress below the coal seam increased with the mining of the working face, and the closer to the goaf, the faster the stress value increased. Among them, the stress fluctuation phenomenon at the 400 s position was caused by the breakage and rotation of the roof during the advancing process of the working face. After the mining was completed, the stress value at the No. 1 position tended to decrease, and the stress values at other positions tended to stabilize.

Figure 8 shows the distribution law of lateral support pressure at marking points 1 and 2 after the mining of the coal seam in the working face. It can be seen that after the mining, the vertical stress at the position 0–4 m away from the goaf sharply increased, from 6.9 MPa to about 14.1 MPa, and vertical stress in this position reached the peak value. The vertical stress of the section from 28 m to 44 m tended to be stable, which is the original rock stress region. The analysis showed that the stress balance of the original strata was destroyed by the mining of the working face, resulting in the single-hump shape of the vertical stress, which increased at first and then decreased. The stress concentration phenomenon was formed near the edge of the goaf.

Figure 8. Distribution curve of lateral abutment pressure in the coal seam.
After mining, the equilibrium state of the original stress field of the rock stratum was broken, and the stress of the overlying strata in the goaf was transferred to the coal seam along the goaf side, which made the stress concentration phenomenon appear in the edge coal of the goaf. At the edge, the coal reached the peak strength, a plastic zone appeared, the bearing capacity gradually decreased, and the vertical stress presented a single-hump shape that first increased and then decreased.

4.3. Deformation Evolution of Coal

Figure 9 shows the displacement contour map of coal along goaf in the x-direction at the time of marking points 1 and 2. The analysis area is shown in the orange area in Figure 2b, with the x-axis to the right and the y-axis to the bottom, as positive. In the horizontal direction, coal moved away from the direction of the goaf, and the isolines on the left side were dense and small in magnitude, while the displacement on the right side was uniform but large in magnitude. The isolines in the upper left corner were dense and had a certain torsion angle, which was due to the bending moment effect on the lower coal seam caused by the rotation of the overlying strata. The horizontal distribution of the isolines at the upper boundary position of the coal seam indicated that there was an interlayer slip between the coal seam and the direct roof.

Figure 10 shows the displacement contour map of coal along goaf in the y-direction at the time of marking points 1 and 2. In the vertical direction, coal moved downward as a whole due to compression. In the area near the goaf, the vertical displacement isoline of the coal was densely distributed, and the magnitude difference was obvious, while in the
area far from the goaf, the vertical displacement of the coal was close. This showed that the coal next to the goaf entered a plastic state, which made the displacement occur more easily. With the subsidence of the overlying strata, the displacement isoline extended to an area far away from the goaf, which indicated that the plastic area of the coal was expanding.

![Displacement contour map of coal](image)

**Figure 10.** y-Direction displacement contour map of coal at different times (unit: cm). (a,b) show the displacement contour map of coal along goaf in the y-direction at the time of marking points 1 and 2.

In order to analyze the evolution process of the deformation field of the coal along goaf in detail, a shear strain nephogram of the coal at different times was extracted and analyzed. As shown in Figure 11, at the time of marking point 1, a shear strain concentration zone appeared at the upper boundary of the coal, and the shear strain reached the maximum at \( x = 5 \) m. At the time of marking point 2, the shear strain variable value of the upper boundary further increased, and the x-range continuously extended, indicating that there was an obvious shear force between the coal and the direct roof. In addition, a new shear strain concentration area appeared at \( x = 10 \) m inside the coal. Combined with the y-direction displacement contour map of coal in Figure 10, it was found that this area was just at the boundary of whether the vertical deformation of coal was obvious or not. It can be seen that under the action of shear force, the micro-cracks in the coal at the boundary of the plastic zone were constantly expanding, and macro-cracks were gradually formed.

The research showed that the vertical movement of the overlying strata along the goaf in the first stage caused the vertical stress concentration of the coal, while the horizontal movement in the second stage exerted an obvious shearing effect on the coal. Under these two effects, the strength of the coal and rock masses along goaf approaches the strength limit, deformation localization occurred, and the micro-cracks were further concentrated and merged in the area to form macro-cracks. When the macro-cracks expand and an
unstable expansion occurs, the sudden release of elastic energy will lead to dynamic disasters, such as rock burst.

**Figure 11.** Shear strain cloud map of the coal seam at different times. (a,b) show shear strain cloud map of the coal seam at the time of marking points 1 and 2.

### 4.4. Interlayer Sliding of Coal and Rock

In order to better explain the shear force between the coal and the direct roof, and in consideration of the influence of section shear action on the deformation evolution of the coal seam, the interlayer sliding displacement of the monitoring points a–e was analyzed by a virtual extensometer [24]. Figure 12 presents the evolution curve of sliding displacement at the five monitoring points during the whole process of the overlying strata movement. It can be seen that during the excavation of the working face, there was no obvious slip between the coal and the direct roof. At the end of mining, friction and sliding occurred between the rock strata, and the direct roof moved to the right, relative to the coal. Points a and b were located at the boundary of the goaf, with large sliding amounts and an obvious interlayer friction effect, while the sliding amounts at the other positions were similar.

**Figure 12.** Evolution of layer sliding displacement during overlying strata movement.
According to the above analysis of sliding displacement evolution, it was indicated that an obvious interlayer slip will occur between the coal and the direct roof during the process of overlying strata movement, which is the reason for the interlayer shear force.

5. Conclusions

Taking the Liuxiang Coal Mine as the engineering background and using the DIC method and the stress electric measurement as the monitoring methods, a simulation experiment of overlying strata movement was carried out. The characteristics of overlying strata movement, stress distribution along the goaf, deformation along the goaf, and friction and sliding between the coal and rock layers were analyzed. The following conclusions were drawn.

The movement of the strata above the coal along the goaf could be divided into two stages. In the first stage, due to the stress transfer of the overlying strata in the goaf, the strata along the goaf compressed the coal seam under the guidance of vertical stress, and the displacement in this stage was mainly vertical displacement. In the second stage, due to the collapse of the overlying strata in the goaf, the strata along the goaf had the freedom to move horizontally, and under the action of horizontal stress, the displacement in this stage was mainly horizontal displacement. These were important reasons for the vertical stress concentration and the horizontal shear action in the coal along the goaf.

The vertical movement of the overlying strata along the goaf in the first stage caused the vertical stress concentration of the coal, and the horizontal movement in the second stage caused the interlayer friction and sliding between the roof and the coal, which triggered the shearing effect on the coal. Under these two effects, the strength of the coal and the rock masses along the goaf was close to the upper limit, deformation localization occurred, and the micro-cracks were further concentrated and merged in the area to form macro-cracks. When the macro-cracks expand and an unstable expansion occurs, the sudden release of elastic energy will lead to dynamic disasters, such as rock burst.

Author Contributions: Validation, C.Z.; Resources, Y.S.; Writing—original draft, H.R.; Visualization, L.D. and J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (grant numbers: 51974150 and U1908222).

Informed Consent Statement: Written informed consent has been obtained from the patient(s) to publish this paper.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author.

Conflicts of Interest: No potential conflict of interest was reported by the authors.

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