Experimental study on the overburden movement and stress evolution in multi-seam mining with residual pillars

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Abstract
When faced with multi-seam mining, some coal pillars are left to support the overlying strata when mining the lower seam, where stress concentration usually occurs. When the working face in the lower seam advances to the area influenced by these coal pillars, high ground pressure behavior occurs. Furthermore, the instability of coal pillars under the participation of the roof may induce rock burst, which threaten the safe production of coal mine. To study the roof strata movement and coal pillar instability in multi-seam mining, a coal mine in Datong was taken as an example. Firstly, the bursting liability of coal and rock stratum was tested. The test results show that the 7#, 8#, and 11# coal seams in the mining area all have strong bursting liability. And the roof was dominated by siltstone and firestone, which also have strong bursting liability. Then, based on the geological conditions of the coal mine, we investigated roof movement and instability of the coal pillar during multi-seam mining through physical simulation. The simulation results indicate that multi-seam mining aggravates the roof damage, which leads to the increase in the fracture range of overlying strata, and that the failure height increases from 46 to 121 m. In addition, the detailed distribution of stress on residual coal pillars and its influence on the lower working face were studied through numerical simulation. The results show that, when the working face 8707 of the 8# coal seam advances to a horizontal distance of 20 m from the coal pillar, it enters the influence zone. As the working face advances beneath the coal pillar, the stress reached to 24 MPa. Moreover, when the working face passes by the coal pillar, the coal pillar is cutoff, thus affecting the working face.

Keywords
bursting liability, coal pillar, fracture zone, hard roof, multi-seam mining
1 | INTRODUCTION

The underground mining method has been employed in more than 90% of coal mines in China. However, the casualties and accidents frequently occur because of the complicated geological conditions of coal seams, especially under multi-seam mining, such as Datong (Shanxi Province), Pingdingshan (Henan Province), Huainan (Anhui Province), Huaiabei (Anhui Province), and Shandong areas. At present, in the Datong mining area, there exist many close-space minable coal seams with protective coal pillars between working faces. Moreover, the roof strata are mainly characterized by hard and large, which are difficult to cave. For certain conditions, when mining an upper coal seam, many protective coal pillars are left to support overlying strata. And the strength of such coal pillars would decrease over time. Field tests show that the roadways in the strata under the residual coal pillars are hard to maintain, which is due to the highly concentrated stress in floor strata under coal pillars. In addition, due to the influences of mining disturbance caused by the lower seam extraction, and mining activities in overlying strata and lateral roof strata tend, the stopping roadways and coal pillars would seriously deform, resulting in a series of adverse consequences. This can lead to strong ground pressure behavior of working faces, rib-spalling of coal walls, and even rockbursts.

To investigate the overburden movement and the influencing factors induced by underground mining, domestic scholars and engineers have conducted a great number of research work. Huang et al. employed the theoretical analysis, numerical simulation, and engineering test to study the effect of filling ratio on the overburden movement in coal mining with compacted backfilling, and the results show that the fracture of the main roof is mainly controlled by the filling ratio and is noncorrelated to the shield supporting pressure. Yang et al. found that the height of free space in goaf increases exponentially with the increase in mining thickness. As the result of overburden movement, caved zone, fractured zone, and continuous deformation zone are formed in the overlying strata. Zhang et al. proposed that the development of the mining-induced overburden failure is affected by the key strata. It is observed that the deformation and breakage of key strata play important roles in overburden movement and even surface deformation in the shallow coal seams. In a word, a great number of experiments and field tests have been conducted to study the rule of overburden movement, but few studies were carried out to study the movement of overlying strata from multi-seam mining.

During the extraction of coal seam with hard roof, the instability of coal pillars may cause coal mine disasters. Thus, it is of significance for engineering practice to study the mechanical response characteristics to external mining stress. Wang et al. presented a numerical investigation on the dynamic mechanical state of a coal pillar and the assessment of the coal bump risk during extraction using the longwall mining method. The results predicted that the peak abutment stress occurs near the intersection between the mining face and the roadways at 7.5 m from the mining face. Kostecki and Spearing used the FLAC3D software to analyze the plastic flow characteristics of coal pillars and compared the shear strength, tensile strength, and the influence of mine space constraints on the strength of coal pillars. Field measurements conducted by Guo et al. show that the width of coal pillar in plastic zone becomes larger and the vertical stress of coal pillar presents a saddle-shaped distribution in deep mine, where wide strip pillar mining method was employed. Based on the field tests in Shendong coalfield, Zhu et al. found that the failure of the chamber coal pillars causes the sudden break and even rotation of the key strata, thereby leading to strong dynamic load that crushes the supports in the longwall face.

FIGURE 1 The arrangement of the working faces
To sum up, scholars have conducted much research into overburden movement characteristics and the instability of coal pillars. However, few studies were reported to investigate the overburden movement from multi-seam mining with coal pillars.

In this paper, we obtained the bursting liability of coal (BLC) seam and roof strata by mechanical test. Based on this, we conducted physical simulation and numerical simulation based on a coal mine in the Datong mining area. Then, we observed roof strata movement during multi-seam mining and monitored the influence of overlying residual coal pillar on lower coal seam.

The main work of this study is as follows:

1. The BLC seam and roof strata was determined by mechanical test.
2. The roof strata movement and coal pillar stress were observed by similar simulation, and the fracture height of overlying strata was determined.
3. The stress distribution and evolution law of overlying residual coal pillar were studied by numerical simulation, and its influence on lower coal seam mining was analyzed.

## 2 | RESEARCH BACKGROUND

### 2.1 | Geological settings in mining area

The research object is a coal mine located in the northeast of the Datong mining area. The geological structure of the coalfield is simple. The current mining seams are 7#, 8#, 10#, 11-1#, and 12-2#, respectively. The 7# coal seam is located in the middle of the coal layers. The immediate roof is mainly composed of sandy mudstone, and the main roof mainly includes silt, fine sandstone, and some medium-coarse sandstone. The interval between the 8# and 7# coal seams is about 15 m, and the main roof is mainly composed of siltstone and medium-coarse sandstone. The 11# coal seam is located in the lower coal layers, and the distance from the 8# coal seam is about 35 m. The coal layer is stable, and the structure is simple. The buried depth of 11# is about 320 m, and the ground stress of working face is about 8 MPa. Besides, the roof strata are mainly fine sandstone with compact structure, good cementation, and high compressive strength. The fully mechanized longwall strike-retreat mining has been employed in this coal mine. Figure 1 shows the arrangement of the working faces, including working faces 8705 and 8707 in the 7# coal seam, working faces 8705, 8707, and 8709 in the 8# coal seam, and working faces 8705, 8707, and 8709 in the 11# coal seam. The length of the working faces ranges from 160 to 190 m, and coal pillars with widths of 20-24 m are left between the working faces.

### 2.2 | BLC and rock stratum

Bursting liability of coal is an inherent property of coal. Researchers have proposed various BLC indexes based on energy, stiffness, strength, and failure duration. The standard of BLC indexes widely used in China includes the uniaxial compressive strength ($R_C$), elastic strain energy index ($W_{ET}$), bursting energy index ($K_E$), and dynamic failure duration ($D_T$). $R_C$ and $D_T$ could directly reflect the ability to store energy and the rate of energy release. $W_{ET}$ represents the capacity of the rock to absorb the external inputs of energy before it achieves peaks strength. $K_E$ represents the ratio of deformation energy accumulated before peak to deformation energy consumed after peak.

| Classification | I | II | III |
|----------------|---|----|-----|
| $U_{WQ}$       | ≤15 | (15,120] | >120 |

| Indexes       | None burst | Weak burst | Strong burst |
|---------------|------------|------------|--------------|

## TABLE 1  Index values of BLC classification

| Burst liability | None burst | Weak burst | Strong burst |
|-----------------|------------|------------|--------------|
| Indexes         |            |            |              |
| $D_T$ (ms)      | > 500      | (50,500]   | ≤50          |
| $K_E$           | < 2        | (2.5)      | ≥5           |
| $W_{ET}$        | < 1.5      | (1.5,5)    | ≥5           |
| $R_C$ (MPa)     | < 7        | (7,14)     | ≥14          |
| Classification  | I           | II         | III          |

## TABLE 2  Test results of BLC

| BLC index | $D_T$ (ms) | $K_E$ | $W_{ET}$ | $R_C$ (MPa) | BLC | Classification |
|-----------|------------|-------|----------|-------------|-----|----------------|
| 7# coal   | 23-29      | 5.12-5.37 | 2.92-3.84 | 11.7-17.5 | Strong burst | III |
| Average value | 26 | 5.25 | 3.38 | 14.6 |
| 8# coal   | 19-25      | 6.67-7.63 | 3.65-4.87 | 15.7-19.7 | Strong burst | III |
| Average value | 22 | 7.19 | 4.26 | 17.7 |
| 11# coal  | 14-18      | 9.80-18.6 | 6.85-8.45 | 25.5-29.7 | Strong burst | III |
| Average value | 16 | 14.2 | 7.65 | 21.3 |

| Classification | I | II | III |
|----------------|---|----|-----|
| $U_{WQ}$       | ≤15 | (15,120] | >120 |

| Indexes       | None burst | Weak burst | Strong burst |
|---------------|------------|------------|--------------|

## TABLE 3  Index values of BLRS classification
Meanwhile, the bursting liability of rock stratum (BLRS) is an inherent property of rock. The standard of BLRS widely used in China is the bending energy index $U_{WQ}$, which reflects the deformation energy accumulated when the limit span of a unit width rock beam is reached under uniformly distributed load. Table 1 lists the BLC classifications according to the Chinese standard.37 Table 2 shows the test results of BLC. And Table 3 lists the BLRS classifications according to the Chinese standard.38 Table 4 shows the test results of BLRS. Based on the above test results, we could know that the strength of 7#, 8#, and 11# coal in this mining area is 25–28 MPa, and all of them have strong burst liability. The roof is mainly siltstone and fine sandstone, which also have strong burst liability, and the roof is locally shale with weak burst liability.

In order to analyze roof strata movement and coal pillar instability in multi-seam mining, the next study was conducted through similarity simulation and numerical simulation based on the obtaining BLC and roof strata.

3 | PHYSICAL SIMULATION OF THE OVERBURDEN MOVEMENT IN MULTI-SEAM MINING

3.1 | Similarity criteria and observation scheme

To investigate the overburden movement in multi-seam mining, a two-dimensional model framework of 3000 mm in length, 400 mm in width, and 1800 mm in height was selected to build a physical model based on similarity theory. The model should meet the basic similarity conditions, such as similarity of geometry, time, weight, elastic modulus, and strength. In accordance with similarity criteria, similar simulation coefficients are obtained as follows:

4. Geometric similarity ratio

Supposing the geometric dimensions of each rock stratum in the prototype and corresponding stratum in the model separately are $L_p$ and $L_m$, the geometric similarity ratio is:

$$C_L = L_m / L_p = 1/200$$

5. Similarity ratio of Poisson's ratio

It is assumed that Poisson's ratios of each rock stratum in the prototype and corresponding stratum in the model are $\mu_p$ and $\mu_m$, thus:

$$C_\mu = \mu_m / \mu_p = 1$$

6. Similarity ratio of weight

When the densities of each rock stratum in the prototype and corresponding stratum in the model are separately assumed to be $\rho_p$ and $\rho_m$, the density similarity coefficient is:

$$C_p = \rho_m / \rho_p = 1/1.5$$

7. Similarity ratio of elastic modulus

It is supposed that elastic moduli of each rock stratum in the prototype and corresponding stratum in the model are $E_p$ and $E_m$, so the elastic modulus similarity coefficient is:

$$C_E = E_m / E_p = C_L \cdot C_\mu = 1/300$$

8. Similarity ratio of time

If the mining time for coal seams in the prototype and the coal seam in the model are $CL$ and $C_t$, the time similarity coefficient is:

$$C_t = \sqrt{C_L} \approx 1/12$$

9. Similarity ratio of strength

If the compressive strengths of each rock stratum in the prototype and the corresponding stratum in the model are $\sigma_p$ and $\sigma_m$, the strength similarity coefficient is:

$$C_\sigma = \sigma_m / \sigma_p = C_L \cdot C_\mu = 1/300$$

### Table 1

| No. | Roof strata   | $U_{WQ}$ (kJ/m) | $R_c$ (MPa) | Classification | BLRS |
|-----|--------------|-----------------|-------------|----------------|------|
| 7#  | Fine sandstone | 342.69          | 93          | III            | Strong burst |
|     | Silt sandstone | 287.46          | 72          | III            | Strong burst |
|     | Shale        | 86.35           | 46          | II             | Weak burst   |
| 8#  | Silt sandstone | 496.45          | 75          | III            | Strong burst |
|     | Fine sandstone | 568.62          | 109         | II             | Weak burst   |
| 11# | Silt sandstone | 317.34          | 79          | III            | Strong burst |
|     | Fine sandstone | 376.38          | 111         | III            | Strong burst |
|     | Shale        | 104.63          | 57          | II             | Weak burst   |
To establish the physical model, river sand, calcium carbonate, gypsum, and water were selected as basic materials. Through multiple uniaxial compression tests on the samples mixed in different ratios, the optimum mix of the materials was determined. In addition, mica powder was sprinkled between the layers. The key physic-mechanical parameters of coal rocks and relevant ratios of similar materials are listed in Table 5.

The establishment of the physical model was carried out using similar materials, and the process can be divided into five steps: weighing materials, mixing materials, adding water and uniformly mixing, placing and tamping, and removing excess material. Finally, the total

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**Table 5** The main physical and mechanical parameters of the coal rock and the related ratios of similar materials

| Strata type          | Strata thickness (m) | Tensile strength (MPa) | Cohesion (MPa) | Internal friction angle (°) | Compression strength | Elastic modulus | Density |
|----------------------|----------------------|------------------------|----------------|-----------------------------|----------------------|----------------|---------|
| Fine sandstone       | 70                   | 5.82                   | 2.63           | 36                          | 70                   | 233            | 10.58   |
| Sandy mudstone       | 10                   | 3.25                   | 2.12           | 34                          | 36                   | 120            | 2.47    |
| Fine sandstone       | 3                    | 5.78                   | 2.55           | 35                          | 68                   | 227            | 9.86    |
| Siltstone            | 6                    | 5.74                   | 2.47           | 36                          | 72                   | 240            | 8.75    |
| Sandy mudstone       | 2.5                  | 3.23                   | 2.13           | 35                          | 37                   | 123            | 2.45    |
| Fine sandstone       | 1.5                  | 5.85                   | 2.60           | 36                          | 68                   | 227            | 9.94    |
| Siltstone            | 3.5                  | 7.62                   | 4.78           | 42                          | 95                   | 317            | 11.68   |
| Fine sandstone       | 2.4                  | 5.72                   | 2.58           | 35                          | 65                   | 217            | 9.72    |
| Sandy mudstone       | 1.6                  | 3.36                   | 2.16           | 34                          | 35                   | 117            | 2.28    |
| 7# Coal              | 1                    | 1.95                   | 1.80           | 32                          | 22                   | 73             | 1.96    |
| Carbonaceous mudstone| 2.5                  | 2.56                   | 2.35           | 33                          | 29                   | 97             | 3.25    |

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**Figure 2** Physical model
height was 1675 mm. After air-drying for 7 days, as shown in Figure 2, five monitoring lines were established in the model to observe changes in spatial movement of overlying strata. Three measuring lines (1#, 2#, and 3#) were arranged at intervals of 20 m from the top to the bottom above the roof of the 7# coal seam to observe roof subsidence after the extraction of 7# coal seam. A measuring line (4#) (10 m from the roof of the 8# coal seam) was arranged between the 7# and 8# coal seams for observing roof subsidence after the extraction of 11# and 8# coal seams. Furthermore, a measuring line (5#) (20 m from the roof of the 11# coal seam) was arranged to observe overlying strata movement during the extraction of 11# coal seam. Besides, two pressure sensors, numbered p1# and p2#, were installed at the coal pillar in working faces 8705 and 8707 in 7# coal seam, which were used to observe the stress change of coal pillar during the mining process of 7# and 8# coal seams.
FIGURE 4  The overburden movement with the advancement of working face 8707 in 8# coal seam. A, Preliminary excavation (20 m). B, The immediate roof caved (74 m). C, The immediate roof breaks periodically (92 m). D, The basic roof bend and sank (103 m). E, The whole basic roof bend and sank (123 m). F, Separation occurred in the basic roof (160 m).
3.2 | The movement characteristics of overlying strata in multi-seam mining with residual coal pillars

3.2.1 | The overburden movement in multi-seam mining

According to the predesigned mining sequence, the working face 8705 in 7# coal seam was firstly mined. And the overburden movement with the advancement of working face was shown in Figure 3.

As shown in Figure 3, as the working face advanced, the immediate roof (sandy mudstone) above the 7# coal seam first separated, then bended, subsided, and caved. Besides, bending and subsidence were found in the first (fine sandstone) and second main roofs successively, followed by the combination of the main roofs. Thereafter, the overlying strata tended to move in a stable manner and the extent of the influence zones moved upwards to the second layer of sandy mudstone (12 m). When the working face advanced to about 40 m, bed separation was first generated in the rock strata (sandy mudstone and fine sandstone), 4 m above the roof, and bed separation increased with gradual advancement of the working face. When the working face advanced to 70 m, the immediate roof first fractured and a large bed separation was generated on the upper siltstone (7.5 m above the roof). With the constant advancement of the working face, bending and subsidence occurred in the immediate roof (sandy mudstone), while no caving was observed. At a location 10 m above the immediate roof, a combination of fine sandstone, siltstone, and fine sandstone moved, and then gradually bended and subsided. As the working face advanced to about 120 m, the main roof (fine sandstone, siltstone, and fine sandstone) came into contact with the caved gangue in goaf. Meanwhile, a large bed separation was generated at 30 m (in the middle of the sandy mudstone) above the roof of the working face. With the constant advancement of the working face, main roof strata slowly sank until the working face was mined out. Therefore, under the condition of primary extraction of the coal seam with a hard roof, the main roof presented slow subsidence movement and the failure height of overlying strata was about 30 m.

When mining the working face 8707 in 7# coal seam, the overlying strata movement was consistent with that caused by the extraction of working face 8705. Due to that the working face 8707 is longer than working face 8705, affected by the extraction of the adjacent working faces, the mining influence zone of working face 8707 was larger, about 46 m above the roof. Besides, influenced by the extraction adjacent working faces, the failure height of overlying strata above working face 8705 developed from 30 to 41 m.

The mining effect of adjacent working faces has significant influences on the spatial movement and development of fractured zone of overlying strata. The longer the working face, the greater the spatial movement, as well as the fracturing zone of the overlying strata. Figure 4 demonstrates overlying strata movement when mining the working face 8707 in 8# coal seam. Figure 5 shows the overall failure morphology of overlying strata after the extraction of the 8# coal seam.

When mining the 8# coal seam after the completion of 7# coal seam, the working face 8707 in 8# coal seam would pass through a protective coal pillar (Figure 6A) between working faces 8705 and 8707 in 7# coal seam. The upper part of the 7# coal seam has been mined out, so the weight of overlying strata was transferred to working face 8707 through the coal pillar. When the working face 8707 advanced to beneath the upper coal pillar, a crack was generated along the coal wall of the working face and propagated obliquely upwards at 60° (Figure 6B,C). This crack penetrated the interlayer and connected to the upper coal pillar. As the working face continuously advanced, the crack propagated and formed a fissure. When the working face advanced to 70 m (passed by the upper coal pillar), shear failure occurred in the interlayer along the fissure, so that the interlayer was fractured and sank (Figure 6D). After the extraction of working face 8707 in 8# coal seam, the failure height of overlying strata reached 40 m. The movement of the interlayer after the extraction of the working face 8709 in 8# coal seam can be seen in Figure 7. When mining the 11# coal seam, the fracture movement of overlying strata is similar to that in the 8# coal seam and the interlayer remained incompletely fractured after mining the working face due to its greater thickness (Figure 8).

Figure 9 shows the spatial distribution pattern of roof strata after the extraction of the 11# coal seam. As the 7# coal seam has been mined out, the coal pillar bore a greater pressure. Thus, due to the mining influence of the 8# coal seam, the interval strata were fractured. Moreover, the strata above working face 8707 in 7# coal seam underwent significant movement and the spatial extent of the failure zone increased accordingly.
After the extraction of working face 8707 in 7# coal seam, the failure height of overlying strata developed to 46 m. After the extraction of 8# coal seam, the failure height of overlying strata increased to 86 m. And after the extraction of 11# coal seam, the final failure height of overlying strata increased to 121 m. On the other hand, the fracture angle of the overlying strata above the 7# coal seam increased from 50 to 60°.

3.2.2 | The overburden movement when the working face passing by a coal pillar

Figure 10 shows variation in spatial movement of overlying strata observed through five monitoring lines. After the extraction of 7# coal seam, the subsidence curves of overlying strata showed double-V shape, as shown in Figure 10A. The two
The subsidence peak values of 1#, 2#, and 3# lines were 0.21 and 0.25, 0.32 and 0.36, and 0.41 m and 0.45 m, respectively. The closer to the mining seam, the greater the subsidence of overlying strata.

Figure 10B shows the subsidence curves of overlying strata after the extraction of 8# coal seam. The spatial shape of 1#, 2#, and 3# lines changed from double-V to single-V. And the maximum subsidence was 0.45, 0.89, and 1.35 m, respectively. The maximum subsidence occurred in 4# line, which was in conical shape accompanied with a large vertical displacement of 1.65 m. This is due to the breakage of coal pillars between 8705 and 8707 working faces in 7# coal seam caused by the stress concentration originating from the extraction 8707 working face in 8# coal seam.

Figure 10C shows the subsidence curves of overlying strata after the extraction of 11# coal seam. The variation characteristics of 1#, 2#, and 3# lines were similar to that after the extraction of 8# coal seam, which were still in single-V shape with maximum subsidence of 0.47, 0.91, and 1.38 m, respectively. Due to that the coal pillar where the no. 4 survey line was located has been fractured, during the extraction of 11# coal seam, the 4# line continued to subside and the maximum subsidence was 1.67 m. 5# line was located in the interlayers with a thickness of 35 m between the 8# and 11# coal seam. During the extraction of 11# coal seam, due to that the interlayers were not fully fractured, together with the existence of coal pillars, the 5# line was still in double-V shape, and the two subsidence peak values were 0.42 and 0.44 m, respectively.

Overall, the subsidence curves of measuring lines can reflect the overburden movement caused by mining effect in multi-seam mining.
3.3 | Pillar Stress evolution when mining 7# and 8# coal seam

Figure 11 shows the stress evolution of coal pillar in 7# coal seam during the 7# and 8# seam extraction. Obviously, the pillar stress increased with the advancement of the working faces. Influenced by the mining effect of working faces 8705 and 8707 in 7# coal seam, after the extraction of working faces 8705 and 8707 in 7# coal seam, the pillar stress reached 16 and 22 MPa, respectively. During the extraction of working face 8707 in 8# coal seam, the pillar stress reached maximum, about 24 MPa. When the working face 8707 in 8# coal seam passed by the coal pillar, the interval layer was broken and the coal pillar was cutoff. Thus, the pillar stress decreases abruptly. With the advancement of the working face, the collapsed pillars and strata were gradually compacted, leading to that the stress began to increase slowly.

4 | NUMERICAL SIMULATION OF STRESS EVOLUTION OF COAL PILLAR IN MULTI-SEAM MINING

4.1 | Simulation scheme

To study the stress distribution and transfer in multi-seam mining, a simplified model was established based on field conditions. First, the stress distributions after the extraction of working faces 8705 and 8707 in 7# coal seam were monitored. Then, the stress evolution during the extraction of lower seam (8# coal seam) was also monitored. During the advancement of working face 8707 in 8# coal seam, it would pass by the coal pillar left in 7# coal seam. Thus, the evolution of abutment pressure with the advancement of the working face would be monitored.
4.2 | Model establishment

According to actual field conditions, a model representing 560 m × 320 m × 222 m was built. Directions y and x separately represent the advancing direction and the longitudinal direction of the working face, m. To facilitate the calculation, the upper section of the model does not reach the ground surface but was subjected to a load with the same weight as the overlying strata with a thickness of 120 m. According to the field investigation, the horizontal stress is about 0.7 times the vertical stress. Therefore, the lateral pressure coefficient is 0.7. The simulation was based on the Mohr–Coulomb criterion, and the parameters were shown in Table 5. For the research purposes, the excavated coal seam was divided into dense grids, while the other parts were divided into sparse grids. The model contained 112 000 elements and 127 638 nodes.

4.3 | Numerical simulation results and analysis

As shown in Figure 12, after the extraction of working face 8705 in 7# coal seam, the stress concentration occurred at both ends of the working face and reached a maximum (16 MPa). After the extraction of working face 8707 in 7# coal seam, influenced by the mining effects, the stress concentration appeared at the coal pillar, causing that the pillar stress increased from 16 to 22 MPa. The specific stress distribution was shown in Figure 13. Obviously, the pillar stress shows bimodal characteristics. The left and right peak values of pillar stresses were 19 and 22 MPa, respectively. This indicated that the pillar has a high bearing capacity.

Figure 14 shows the pillar stress evolution during the lower seam extraction. From Figure 14A, due to the stress relief caused by the upper seam (7#) mining, the working face 8707 in lower seam (8#) was always subjected to a...
FIGURE 14  The variation of vertical stress distribution at coal pillars with different distances of working face 8707 in 8# coal seam. (A) −20 m, (B) −4 m, (C) below the middle of the coal pillar, (D) below the right edge of coal pillar, and (E) 4 m. (Left is negative and right is positive.)
lower-stress environment before passing the coal pillar. When the working face advanced to a location 20 m from the upper coal pillar, the working face entered the influence zone resulted from the pillar stress concentration in the upper seam. Due to the interaction of the mining effect and pillar stress, the abutment stress and the pillar stress increased significantly. When the working face advanced to the left edge of the upper coal pillar (Figure 14B), the pillar stress began to transfer to the working face 8707 in the lower (8#) coal seam, so a significant stress concentration was generated in the working face (about 24 MPa). From Figure 14C, when the working face 8707 in 8# coal seam advanced to the location directly below the upper pillar, due to the transfer of pillar stress, the pillars stress decreased, while the abutment stress in working faces increased. This can be verified by the simulation test. When the working face 8707 in lower seam advanced to the right edge of the upper coal pillar, the pillar stress concentration decreased significantly, as well as the abutment stress in the working face (Figure 14D). When the 8707 working face is mined from one side of the coal pillar to the other, the stress of the coal pillar suddenly decreases from 24 MPa to 8 MPa. This is due to the stress release of the coal pillar after the shear failure of the coal (Figures 14E and 15).

Figure 16 shows the variation of vertical stress of overlying strata during the advancement of working face 8707 in 8# coal seam. When the working face advances to a location 20 m from the left edge of the coal pillar, it was affected by the pillar stress concentration and the abutment stress in working face increased. When the working face advanced to the left edge of the upper coal pillar, the abutment stress in the working face increased rapidly. When the working face constantly advanced to a location directly below the coal pillar, the vertical stress reached a maximum (about 24 MPa). In addition, as the working face advanced to the other end of the coal pillar, the stress decreases rapidly to 8 MPa from the maximum value (24 MPa), indicating that the coal pillar has been damaged, which was consistent with the similar simulation results.

5 | CONCLUSION

Compared with single seam extraction, the overburden movement caused by multi-seam mining is more complicated. The overlying strata were seriously damaged by the multi-seam mining disturbances, leading to the interpenetration of the fractures in the overlying strata with close distances. And the failure height of overlying strata correspondingly increased. On the other hand, influenced by the pillar stress concentration in upper seam, the working face in lower seam would be subjected to complicated stress evolution when passing by the upper coal pillars. In this paper, by taking a coal mine with multi-seam mining in Datong as an example, the BLC and rock was firstly obtained. Then, based on the geological conditions, the physical simulation was conducted to investigate the characteristics of overburden movement in multi-seam mining. Moreover, to illustrate the variation of the stress evolution during multi-seam mining, the numerical simulation was conducted. The main conclusions of this study are as follows:
1. The 7#, 8#, and 11# coal seams in the mining area all have strong bursting liability. And the roof is dominated by siltstone and fine sandstone, which also have strong bursting liability.

2. Multi-seam mining aggravates the damage of the overlying strata, which leads to the increase in the failure height of overlying strata (from 46 to 121 m). Besides, the closer to the mining seam, the greater the subsidence of overlying strata. Due to the development of fractures in overlying strata from multi-seam mining, the residual pillar would be posed a great load, which further increases the abutment stress in the working face in the lower seam.

3. During multi-seam mining, the working face in the lower seam would experience complicated stress evolution when passing by a residual coal pillar in upper seam. When the working face 8707 in the 8# coal seam advanced to a horizontal distance of 20 m from the coal pillar, it entered the zone of influence of the coal pillar. As the working face advanced to a location directly below the coal pillar, the abutment stress reached its maximum (about 24 MPa), where the rock burst may occur. After the working face passed by the coal pillar, the shear failure occurred at the coal pillar and the pillar stress was released, leading to the decrease of the abutment stress in the working face.

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