Research Article

Analysis of the Progressively Enhanced Mine Pressure in the Fully Mechanized Top Coal Caving Work Face of a 20 m Ultra-Thick Coal Seam

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Considering the large mined area, wide strata moving range, strong mine pressure occurrence, and difficult roof control for the fully mechanized top coal caving in 20 m ultra-thick coal seams, this study analyzes the strata structure evolution and mine pressure occurrence behavior through field test, numerical simulation, and theoretical analysis. Based on the mine condition of the Tashan Coal Mine in the Datong mining area, mechanical models are established for the compound overlying structures. The following can be demonstrated from this study: (1) The hard strata can form three different compound spatial structures at different positions in the overlying rock strata, including the lower combined cantilever structure I, the middle combined cantilever structure II, and the upper hinged structure. (2) Failure of the higher structure can induce compression on the lower structure, which changed the break span of the lower structure. (3) “Simultaneous and nonsimultaneous structural failures” of the compound spatial structure were caused by the variation of the break span of the multilayered structure. (4) Based on the weighting characteristics, there were three stages during work face weighting, including a gradual pressure increase stage (Stage I), an accelerated pressure increase stage (Stage II), and a fast pressure increase stage (Stage III). (5) The mine pressure occurrence demonstrated a “small to medium and to large” feature. (6) Prefracturing techniques should be additionally incorporated to prevent simultaneous failure of the multilayered structure. Findings of the work can demonstrate the emergence of strong mine pressure in the Datong mining area and have theoretical significance and reference value for maintaining safe mining in similar conditions.

1. Introduction

With the continuous development of theories, techniques, and equipment, 20 m ultra-thick coal seams can be entirely extracted using the fully mechanized top coal caving approach; however, it leaves a large mined area to cause severe overburden movement and strong mining disturbances [1–6]. This may also lead to high weighting strength at the work face, large dynamic load coefficient, frequent opening of safety valve, support crushing, column collapse, coal wall spalling, excessively crushed top coal, and other hazards [7–12]. Many researchers have analyzed the disturbance range, overlying rock movement, and structural characteristics of the mine pressure behavior during the fully mechanized top coal caving. Zhang et al. [13] studied the failure height of the overlying rock of a 15 m thick coal seam in the Tongxi Mine using the magnetotelluric analysis and similarity simulation, and they found that the failure height of the overlying rock is 10–11.5 times higher than the mining height. Kong et al. [14] found that the mine pressure occurrence of the work face was caused by the strata movement at 75–150 m away from the work faces, based on high-precision microseismic monitoring technology. Yan et al. [15–17] analyzed the relationship between the maximum
2. Shock and Vibration

**compression angle of the fracture surface and bending moment.** They concluded that an increase of the free space for the overlying rock can cause the hinged rock seam structure to move up vertically. The entire overlying rock can form a hinged structure at the top and a combined cantilever structure at the bottom, which leads to both stronger and weaker periodic weightings during periodic structural failure. Yang et al. [18] and Liu et al. [19] found that failure of single-layered and multilayer hard strata can cause different work load of the supports. Yu et al. [20] and Liu et al. [21] developed a structure evolution model for the Datong mining area with ultra-thick coal seams and hard roofs. They believed that an increase of the layers of the hinged beam structure formed in the near field can cause stronger mine pressure at the work face, and the radial compression of the control roadway can lead to deformation and damage to the roadway adjacent to the mined area. From the measured variation of the support resistance, they also observed both stronger and weaker periodic weightings and strong mine pressure concentration at the work face. From field tests and theoretical analysis, Li et al. [22] argued that the weighting behavior with high strength, short period, and strong dynamic load at the work face of Buliangou Coal Mine was due to the slip failure of the entire overlying structure at the top of the coal seam. Kang et al. [23] conducted a similarity simulation for fully mining a 20 m ultra-thick and medium-hard coal seam and observed roof cutting with a cutting height of 13 m. Xu [24] analyzed the support crushing incidents at the work face of Cuimu Coal Mine and suggested that the frequently occurred roof cutting when mining ultra-thick coal seam was a result of the cutting of the overlying rock layers along the coal walls.

Previous studies showed that the damage range can grow exponentially with the increase of the mining height when mining the ultra-thick coal seams using the fully mechanized top coal caving. The structure of the overlying rock layers can change dramatically with diverse dynamic behaviors to cause varying mine pressure behaviors at the work face, especially when extracting a 20 m thick coal seam using the fully mining approach. However, to our knowledge, there are very few existing works that have studied the mechanism of the strong mine pressure behavior in terms of structural integrity and dynamics. Therefore, focusing on the strong mine pressure of the fully mechanized top coal caving work face of the Datong mining area with 20 m ultra-thick coal seams, this study focuses on assessing the cause of the strong mine pressure jump at the work face using field tests, numerical simulation, and theoretical analysis, which may provide fundamental knowledge to effectively control the damage caused by strong mine pressure at the work face of coal mines with ultra-thick coal seams.

**2. Mine Condition and Mine Pressure Behavior**

**2.1. Mine Condition.** The No. 8222 work face of the Tashan Coal Mine is buried 520 m deep with a length of 230 m along the strike, an advancing length of 2464 m along the dip, and an average inclination angle of 2°. The coal seam has an average thickness of 20 m. The mining-caving ratio is 1/3 with a mining height of 5 m and a caving height of 15 m. The annual production of the work face is 10 Mt. The four-pillar chock-shield hydraulic support with a working load of 15000 kN is used in the mine. The core analysis suggests that there are three layers of high-integrity and compact hard rock in the mining area, including 6.83 m of fine-grained sandstone, 9.13 m of coarse-grained sandstone, and another 12.76 m of coarse-grained sandstone. The details of the rock types of the strata are summarized in Figure 1.

**2.2. Mine Pressure Behavior in the Target Work Face.** According to the field test results, the fully mechanized top caving work face of the 20 m ultra-thick coal seam showed the following mine pressure behaviors during the advancing of the work face: (1) mine pressure demonstrated a progressive enhancement, where 1–2 rounds of enhancement can be observed before the strong weighting occurred. A stable period can be reached during each enhancement. (2) Support settlement can be observed between 53 and 72 mm during the stable period. However, the roof dropped quickly during weighting and the cumulated support settlement reached 860 mm. The safety valve of the support was opened frequently during this period. (3) High dynamic load coefficient was found to reach 2.68. (4) Strong weighting occurred with a maximum true workload (16880 kN) higher than the default workload by 13%. Support overload can cause support failure and leg failure as shown in Figure 2.

**3. Dynamic Behavior of the Multilayered Overburden in the Mining Face**

The strata structure and its failure features are the key factors to affect the behavior of mine pressure occurrence.

**3.1. Model Development.** Based on the geological conditions of the No. 8222 work face, the work face model was built with certain simplification and the measured mechanical properties of the rock strata are listed in Table 1.

In this study, the work face model has a dimension of 300 m × 100 m, with a floor thickness of 10 m. To reduce the boundary effect, 30 m of the coal pillars were assigned to both sides with a total excavation length of 240 m. Five line probes were set at different positions in the model, as shown in Figure 3.

Field observation showed that the first weighting of the No. 8222 occurred when the work face advanced to its first 50 m during mining. Then, strong mine pressure appeared when the work face advanced to around 200 m with severe support crushing. In general, simulation results were in good agreement with the observation. Based on these results, the strata movement and mine pressure occurrence are analyzed for the fully mechanized top coal caving in ultra-thick coal seams.

**3.2. Failure Behavior of the Overburden at Different Advancing Distances.** The evolution of the overlying rock strata at different advancing distance is shown in Figure 4. The hard
Figure 1: Rock type of the strata.

Figure 2: Incidents due to mine pressure. (a) Hydraulic support failure. (b) Support leg failure.

Table 1: Physicomechanical properties of overlying rock strata in the No. 8222 working face.

<table>
<thead>
<tr>
<th>Rock strata</th>
<th>Compressive strength $\sigma$ (MPa)</th>
<th>Elastic modulus $E$ (GPa)</th>
<th>Tensile strength $\sigma_t$ (MPa)</th>
<th>Density $\rho$ (kg/m$^3$)</th>
<th>Cohesion $c$ (MPa)</th>
<th>Friction $f$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mudstone</td>
<td>54.5</td>
<td>26.6</td>
<td>7.3</td>
<td>2400</td>
<td>8.3</td>
<td>32</td>
</tr>
<tr>
<td>Siltstone</td>
<td>60.2</td>
<td>32.4</td>
<td>8.5</td>
<td>2500</td>
<td>10.9</td>
<td>36</td>
</tr>
<tr>
<td>Coarse-grained sandstone</td>
<td>72.3</td>
<td>38.6</td>
<td>12.6</td>
<td>2600</td>
<td>23.8</td>
<td>47</td>
</tr>
<tr>
<td>Fine-grained sandstone</td>
<td>59.8</td>
<td>35.5</td>
<td>10.8</td>
<td>2500</td>
<td>15.2</td>
<td>39</td>
</tr>
<tr>
<td>Siltstone mudstone</td>
<td>62.4</td>
<td>25.3</td>
<td>7.8</td>
<td>2600</td>
<td>8.3</td>
<td>33</td>
</tr>
<tr>
<td>Coal</td>
<td>24.8</td>
<td>4.2</td>
<td>3.9</td>
<td>1400</td>
<td>12.3</td>
<td>30</td>
</tr>
</tbody>
</table>
Strata I first broke when the work face advanced to 50 m, with a breaking angle of 67°. Due to the breaking angle, the hang distance was 23.8 m for the medium-hard Strata II and formed a simple beam structure.

The periodic breaking of the hard Strata I appeared when the work face advanced to 64 m with a break span of 14 m and a breaking angle of 64°. The remaining hard Strata I and the weak strata I formed a combined cantilever structure I. The caved rocks failed to fill the entire mined area and the hanging hard strata II started to bend from the center. Simultaneously, the weak Strata II dropped until separation occurred at the bottom of the hard strata III, as shown in Figure 4(a).

When the work face advanced to 80 m, the middle hard Strata II first broke with a break span of 65 m. During the work face advancing, the combined cantilever structure I experienced two periodic breakings with the same break span. As the work face advanced to 105 m, the combined cantilever structure II experienced the first periodic breaking with a break span of 25 m and a break angle of 61°. The remaining hard strata II and weak strata II formed the combined cantilever structure II. The failed combined cantilever structure II can act as an extra burden to the lower strata to cause early failure of the combined cantilever structure I to the mined area. The hanging hard strata III started to bend from the center but can still form a simple beam structure with its bearing capacity, as shown in Figure 4(a).

The upper hard strata III first broke when the work face advanced to 140 m. During work face advancing, two periodic breakings with the same break span occurred for the combined cantilever structure II, whereas four appeared for the combined cantilever structure I. The broken and caved rocks of the hard strata III formed a hinged structure with the unbroken strata. Turning of the hinged structure can compress the lower strata to generate developed fractures near the edges of the combined cantilever structure I and II until failure as shown in Figure 4(d).

As the work face advanced to 202 m, the upper hinged structure broke periodically with a break span of 62 m and a break angle of 56°. In this period, the combined cantilever structure II experienced two periodic breakings with the same break span and the combined cantilever structure I experienced four. The broken rock and remaining strata of the hard strata III formed a hinged structure, which pressed the lower strata as it turned, resulting in fracture development near the edges of the combined cantilever structure I and II until failure as shown in Figure 4(d).

During work face advancing, the overlying strata evolved into three compound structures at different positions with varying break spans, including the combined cantilever structure I, II, and the hinged structure. The field measurement of the overlying movement results at the adjacent roadway also confirmed the evident strata movement behavior at different positions, as shown in Figure 5 [20, 21].

3.3. Stress Evolution of the Overburden. To explore the peak stress evolution of the coal seam and the fully mechanized top coal caving work face, the peak stress measured ahead of the work face and from the floor, as shown in Figure 6.

From Figures 5 and 6, the upper overlying strata broke progressively to enable a periodic structure to form and break during mining operations. There were three stages during work face weighting, including a gradual pressure increase stage (Stage I), an accelerated pressure increase stage (Stage II), and a fast pressure increase stage (Stage III):

Stage I: as the work face advanced from 153 to 166 m, the overhang length increased for the lower combined cantilever structure I with the increase of work face stress. At 166 m, the combined cantilever structure I failed periodically, with the peak stress increased to 9.22 MPa at a rate of 0.19. Meanwhile, the overhang length and subsidence of the middle combined cantilever structure II were observed to increase.

Stage II: the hard strata II broke when the work face advanced to 171 m, which created compression and led to early failure for the lower combined cantilever structure I. Both failure loads combined to act at the work face to quickly increase the peak stress to 14.37 MPa at a rate of 0.54.

Stage III: the work face advanced from 196 m to 205 m; the hard strata III broke and rotated to compress the lower combined cantilever structures I and II and led to a simultaneous movement of both structures. The peak stress increased to 42.2 MPa at a rate of 9.28. Meanwhile, the fracture width expanded quickly in the rock strata ahead of the work face, which generated a tensile zone.
In total, four small and two medium periodical variations occurred during two peaks. Based on the overlying structure analysis, the break lines coincide for all the upper, middle, and lower strata structures with associated structure failures and the peak stress increased rapidly to 43.4 MPa with a dynamic load coefficient of 2.23. As the work face advanced, the structures of different strata failed and broke. The intensity of the mine pressure occurrence changed with the strata structural failures, and the work face demonstrated the feature of “small-large-strong”.

**Figure 4:** Evolution of the overlying rock strata during work face advancing. (a) 64 m. (b) 105 m. (c) 140 m. (d) 202 m.
4. Theoretical Analysis of the Overlying Strata Structure

4.1. Determining the Multilayered Structure of the Overlying Strata. The overlying strata structure is the main supporting body of the mining-induced strata movement and is decided by the hard strata physicomechanical properties and the available lower space for movement. The weak strata often act as additional load on the bottom hard strata and moves along with the hard strata to form the combined structure. The combined structure may fail if the peak load-bearing capacity is reached for the hard strata.

The expressions of the maximum hard strata settlement $\Delta_j$ and the theoretical strata settlement $\Delta_m$ can be given as follows:

$$\Delta_j = h - \frac{q l^2}{2khR_c},$$

$$\Delta_m = M -(k_p-1)h_m,$$

where $h$ is the strata thickness; $k$ is a dimensionless parameter given by $k = 0.1$; $R_c$ is the compressive strength; $q$ is the line load; $l$ is the strata break span; $M$ is the mining height; $k_p$ is the swelling factor of rock; $h_m$ is the cumulative thickness of the rock strata from strata 1 to $m$.

Substituting the results from Figure 1 and Table 1 into equations (1) and (2):

- Hard strata I: $\Delta_{m1} = 15.50 \text{m}, \Delta_j = 4.83 \text{m}, \Delta_{m1} - \Delta_j > 0$
- Hard strata II: $\Delta_{m2} = 9.32 \text{m}, \Delta_j = 6.77 \text{m}, \Delta_{m2} - \Delta_j > 0$
- Hard strata III: $\Delta_{m3} = 5.65 \text{m}, \Delta_j = 8.21 \text{m}, \Delta_{m3} - \Delta_j < 0$

According to the criteria proposed in [1] for the strata structure in the fully mechanized top coal caving work face with ultra-thick coal seams, the broken and unbroken strata cannot form effective spatial contact when $\Delta_j - \Delta_m \leq 0$. The unbroken strata can only form a hinged-cantilever structure. When $\Delta_j - \Delta_m > 0$, the broken rocks of the hard strata can possess spatial hinged contact and form a hinged structure for the entire strata. The strata that can demonstrate cantilever structure are defined as the immediate roof, whereas the strata with the hinged structure are defined as the basic roof [1].

From the roof structure criteria, the 6.83 m fine-grained sandstone and 9.13 m coarse-grained sandstone of the immediate roof demonstrated the bearing capacity in the No.8222 work face. After failure, the overlying section of the work face can form the combined cantilever structure I and II. The 12.76 m coarse-grained sandstone possessed bearing capacity in the basic roof and formed a hinged beam after failure (i.e., the critical strata as defined in [25]). The weak strata under the hard strata I may cave undermining operation. Therefore, a three-layered “double combined hinged-cantilever structure” can be formed over the No.8222 work face. Based on the geological condition and structural analysis of the roof, a multilayered spatial structure model was established for the fully mechanized top coal caving work face with 20 m ultra-thick coal seams, as shown in Figure 7.

4.2. Dynamic Behavior of the Multilayered Overburden Structures. The fully mechanized top coal caving work face with ultra-thick coal seams demonstrated three layers of compound spatial structure for the overlying strata, which possessed different movement and load-bearing behaviors.

4.2.1. Dynamic Behavior of the Combined Cantilever Structure. The combined cantilever structure I, as located at the bottom of the entire structure, consisted of the cantilever
I and the upper weak strata. The entire structural failure and its dynamic behavior were determined by the cantilever I. As the top coal and the cantilever structure I broke under the mining-induced stress, it lost its bearing capacity. For simplicity, a dynamic model was presented considering the stress acted on the cantilever from the support, q1(x), where 

\[ \sigma = \frac{Pc}{h} \]

\[ l_1 = \frac{h^2 \sigma}{6} \]

where \( q_1(x) \) is the load intensity of the cantilever, \( P \) is the stress acted on the cantilever from the support, \( c \) is the distance between the lower supporting stress and cutting line, \( G \) is the weight of the rock strata, \( M_1 \) is the maximum bending moment, \( \sigma_1 \) is the tensile strength, \( Q_1 \) is the shear stress, \( l_1 \) is the break span of the cantilever, \( h_i \) is the thickness of the loading layer of the cantilever I, and \( \gamma_i \) is the specific weight of the cantilever I.

Combining equations (3) to (5), one can obtain

\[ l_1 = \frac{[\sigma_1] h_1^2 + 2Pc}{3 \sum h_i \gamma_i} \] (6)

Considering force balance, the shear stress is the highest at the combined force of the support and the overhang length of the cantilever structure I is given by

\[ \Delta l_1 = \frac{(l_1 \sigma_1 h_1 + P) \times [\sigma_1] h_1^2 + 6Pc}{3(\sum h_i \gamma_i)^2} \] (7)

From equations (6) and (7), the break span of the combined cantilever structure I is reverse proportional to the loaded rock thickness and overhang length, as shown in Figure 9.

The cantilever structure broke with the same break span when the upper structure is stable. However, when the upper structure failed, the lower structure was forced to move, which reduced the break span. Substituting the mechanical parameters of the rock strata of the No.8222 work face into equations (6) and (7), the break span and overhang length of the cantilever structure I under no extra loading was \( l_1 = 14.1 \text{m} \) and \( \Delta l_1 = 5.3 \text{m} \).

The combined cantilever structure II (located in the middle of the entire structure) consisted of the cantilever II and its upper weak strata II. Failure and movement behaviors of the structure was determined by the bottom cantilever II. By considering that the upper weak strata II generated a downward load and the lower weak strata created an upward load, the mechanical model of the cantilever II can be established as shown in Figure 10.

By calculating the moment from point \( O_i \), the break span of the cantilever structure II can be obtained from

\[ l_2 = \frac{[\sigma_2] h_2^2 + [\sigma_1] h_1^2 + 6Pc}{3 \sum h_j \gamma_j} \] (8)

The overhang length of the cantilever structure II can be given by

\[ \Delta l_2 = \frac{[\sigma_2] h_2^2 + [\sigma_1] h_1^2 + 6Pc}{3 \sum h_j \gamma_j} - \Delta l_1 = \frac{[\sigma_1] h_1^2 + 6Pc}{3 \sum h_j \gamma_j} \] (9)

From equations (8) and (9), the break span of the cantilever structure II is reverse proportional to the loaded rock thickness and overhang length, as shown in Figure 11.

It can be found that the combined cantilever structure II broke with the same break span when the upper structure was stable. When the upper structure failed, the combined cantilever structure II was forced to move with a decreased break span. Substituting the mechanical parameters of the rock strata of the No.8222 work face into equations (8) and (9), the break span of the combined cantilever structure was 25 m with an overhang length of 10.9 m.

4.2.2. Failure Behavior of the Hinged Structure. As the hard strata III only endured the stable load from the upper weak strata III, it can form a hinged structure between broken rocks, where the break span is only related to the rock properties. The mechanical model is presented in Figure 12.
It was found in previous studies [1, 26] that the movement behavior of the fully mechanized top coal caving workface with ultra-thick coal seams is consistent with that of the traditional work face. The break span of the hinged structure can be obtained from

\[ l_3 = \frac{4h_3^2}{\sum h_k} \sum \sigma_k \] (10)

Substituting the mechanical parameters of the rock strata of the No.8222 work face into equation (10), the break span of the hinged structure was found to be 69 m.

It can be depicted from above that the upper hinged structure was at the top of the entire overlying structure of the work face without any extra load, which led to failure at the same break span. The upper structure can compress the lower strata when it failed, causing increased load to the lower structure, which changed the break span of the combined cantilever structure I and II, along with an increased load at the work face.

5. Mechanism of the Progressively Enhanced Mine Pressure

The compound spatial structure broke at different positions to cause a varying break span. The break span increased with the height of the structure, that is, \( l_1 < l_2 < l_3 \). Therefore, during work face advancing, the break span of the multilayered structure demonstrated both nonsimultaneous and simultaneous failure. The simultaneous failure was caused by the overlap of break lines of different layered structures, whereas the nonsimultaneous failure occurred when the break lines did not overlap. The two failure modes can have different effects on the mine pressure occurrence due to different compression modes created during their associated failures. The nonsimultaneous failure is a common failure mode for the multilayered compound spatial structure, where the lower structure experienced early failure as the break line of the upper structure exceeds that of the lower structure. In comparison, simultaneous failure occurred for the multilayered compound spatial structure when the extended break lines of both upper and lower structures cross each other. This can cause simultaneous movement for the failed rock strata and is the major reason for causing the strong mine pressure occurrence in the work face.

5.1. Effect of the Nonsimultaneous Failure of the Overlying Strata on Mine Pressure. The lower strata structure suffered early failure due to the compression from the upper strata.
structure during the movement of the multilayered overlying strata structure. Therefore, the supports in the work face should bear both loadings from the completely broken upper structure and the partially broken lower structure. The loading on the work face from the lower structure failure can be obtained following [25] as given by

$$P_{III} = \left[ 2 - \frac{l \tan(\phi_i - \theta_i)}{2(h_i - \zeta_i)} \right] Q_i B,$$  \quad (11)

where $B$ is the support width; $Q_i$ is the loading of the broken rock and its upper strata; $\zeta_i$ is the settlement of the broken rocks; $l$ is the break span of the rock; $\phi_i$ and $\theta_i$ are the friction angle and break angle of the broken rocks.

When the overlying rock strata started to experience periodic failure, small periodic weighting occurred at the work face as the lower combined cantilever structure I failed when reaching the break span during the work face advancing, whereas the break span was not reached for the middle combined cantilever structure II (Stage I with gradually increased pressure). The supports at the work face needed to endure the loading from both the broken combined cantilever structure I and the lower broken strata. From force balance analysis, the support load can be obtained using equation (1), (2) and (6), as given by

$$P_1 = Q_0 + Q_1 = 8067 \text{ KN},$$  \quad (12)

where $Q_0$ is the load of hard strata I to the coal seam; $Q_1$ is the load of the broken combined cantilever structure I.

When the combined cantilever structure I suffered multiple periodic failures with the same break span, the overhang length reached the break span of the middle combined cantilever structure II as the work face advanced, whereas the periodic break span was not reached yet for the lower combined cantilever structure I. Turning off the combined cantilever structure II can cause compression on the combined cantilever structure I, where the load on the combined cantilever structure I increased from $q_j(x)$ to $q_j(x) + q_3(x)$. As shown in Figure 11, the break span of the combined cantilever structure I decreased and broke simultaneously with the combined cantilever structure II, resulting in strong mine pressure occurrence and severe periodic weighting at the work face (Stage II with accelerated pressure increase). The supports at the work face should endure the loading from both the broken hard strata I, the early broken combined cantilever structure I, and the fully broken combined cantilever structure II. From force balance analysis, the support load can be obtained using equations (1), (2), (9), and (11), as given by

$$P_{II} = Q_0 + Q_2 + P_{II1} = 12573 \text{ KN},$$  \quad (13)

where $Q_2$ is the load of the broken combined cantilever structure II and $P_{II1}$ is the load at the work face from the broken combined cantilever structure I.

After the combined cantilever structure II experienced multiple periodic failures with the same break span, the critical block B of the top-hinged structure approached the break span progressively as the work face advanced, whereas the periodic break span was not reached for the lower combined cantilever structure II. Turning failure of the critical block B can generate compression on both the combined cantilever structure I and II, with the load of the combined cantilever structure II increased from $q_j(x)$ to $q_j(x) + q_3(x)$. The break span decreased for the combined cantilever structure II as the critical block B broke. The overburden on the lower combined cantilever structure I increased to $q_j(x) + q_3(x)$ with further decreased break span and enhanced mine pressure occurrence (Stage III with fast pressure increase). The supports at the work face should endure the loading from both the broken strata below the hard strata I, the early broken combined cantilever structures I and II, and the failed hinged structure. According to force balance, the support load can be obtained using equations (1), (2), (10), and (11), as given by

$$P_{III} = Q_0 + Q_3 + P_{III1} + P_{III2} = 23202 \text{ KN},$$  \quad (14)

where $Q_3$ is the load of the failed hinged rock and the critical strata; $P_{III2}$ is the load at the work face from the broken combined cantilever structure II.

The mine pressure occurrence was gradually enhanced as the layered structure broke at different positions. The weighting pressure was only 0.86 of the support workload during the lower structural failure in Stage I. However, the weighting pressure increased by a factor of 1.5 as it reached Stage III. The mine pressure of the entire work face progressively varied from low to high and then to strong occurrence as the work face advanced.

5.2. Effect of the Simultaneous Overburden Failure on Mine Pressure. In general, the advancing work face experienced $T$ rounds of entire periodic break span, where the upper, middle, and lower structures broke simultaneously along the break line, with $T = n_1 l_1 = n_2 l_2 = n_3 l_3$. The entire overlying structure failed along the break line, and the break span reached the maximum value for each overlying structure. The load of the simultaneously failed overlying structure can be passed downward to the work face. Here, the supports at the work face should endure the loading from both the broken strata below the hard strata I, the early broken combined cantilever structures I and II, and the failed hinged structure. The support load can be obtained using

$$P_{III}' = Q_0 + Q_1 + Q_2 + Q_3 = 33056 \text{ KN}. $$  \quad (15)

The broken overlying strata structure, along with the weak strata, generated load on the work face to cause significant mine pressure occurrence. The mine pressure occurrence reached its peak at this point (blue sections in Figure 13) with the weighting pressure 2.21 times higher than the support workload, causing strong mining pressure occurrence.

From the above analysis, the progressive enhancement of the mine pressure occurrence at the work face was due to the nonsimultaneous failure of the multilayered structure, which is also the main reason for the increase of the support resistance at the work face. The simultaneous failure of the multilayered structure is the root cause for the strong mine
pressure occurrence at the work face. The mined area and the disturbance range are especially large for the fully mechanized top coal caving work face with 20 m ultra-thick coal seams, and the mine pressure condition can be hardly met by only increasing the support workload. Therefore, in practice, prefracturing of the roof is also adopted to prevent simultaneous failure of the multilayered structure and avoid the damage caused by roof cutting at the work face.

6. Conclusions

The conclusions drawn from this study are summarized as follows:

(1) A lower combined cantilever structures I, a combined cantilever structures I in the middle, and an upper hinged compound spatial structure can be formed, respectively, by three hard strata in the fully mechanized top coal caving work face with the 20 m ultra-thick coal seam.

(2) The break span was different for strata structures at different positions. As the strata position became higher, the break span increased with \( l_1 < l_2 < l_3 \). Simultaneous and nonsimultaneous failures of the compound spatial structure can occur due to the difference in the break span of the multilayered structure. Nonsimultaneous structural failure at different layers is a common failure mode for the overlying strata in the work face, which causes progressively increased mine pressure, whereas the simultaneous failure can lead to strong mine pressure occurrence at the work face. The simultaneous failure can occur when the extended break lines of different layered structures were along the same line, which caused severe mine pressure occurrence at the work face.

(3) The progressive variation of the mine pressure was caused by the multilayered feature of the overlying strata structure of the fully mechanized top coal caving work face with the 20 m ultra-thick coal seam. As strata structures formed and failed at different positions, the mine pressure occurrence experienced three stages: gradual pressure increasing in Stage I with the weighting pressure at 54% of the support workload and a peak strength rate of 0.19; accelerated pressure increase in Stage II with the weighting pressure at 84% of the support workload and a peak strength rate of 0.54; fast pressure increase in Stage III with the weighting pressure at 154% of the support workload and a peak strength rate of 9.28. Strong mine pressure occurrence can be observed especially when the upper structures experienced simultaneous failures, where the weighting pressure was 2.21 times higher than the support workload.

(4) The upper structure can generate a compression load on the lower structure when it failed, which increased the support load at the work face. It is rather difficult to maintain the safety of the work face only by increasing the support workload when the multilayered structure fails. Therefore, prefracturing techniques should also be applied to prevent simultaneous failure of the multilayered structure.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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