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Study on the formation mechanism of intense rock pressure in fully mechanized top-coal caving mining under conditions of large burial depth and thick unconsolidated layer

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Targeting the “two hard and one soft” overlying strata (fine sandstone, siltstone, and coal seam) of the 5th coal seam in Yanbei Coal Mine, Huating Mining Area, this study investigates the influence of key strata on strata movement and rock pressure during deep fully mechanized top-coal caving (FMTC) mining. A physical model using similar materials was conducted under three mining conditions: single working face mining, simultaneous mining of two working faces, and extended mining. Results showed that during single face mining, the key strata only bent and subsided without fracturing, leading to stable and mild pressure on the face. When two faces were mined simultaneously, the key strata fractured, causing sudden stress increases and intensified impact loads. In subsequent stages, pressure mainly depended on the suspended length of the key strata and the size of fractured blocks. The stope displayed a coexistence of “small structures”—formed by immediate roof breakage and controlling local strata damage—and “large structures”—formed by key strata breakage, which dominated pressure transfer and served as the main load-bearing system. The control range of the key strata was influenced by the face width and coal pillar section, with the presence or absence of a core area in the coal pillar being a decisive factor at a fixed width. Field practice in Yanbei Coal Mine confirmed that removing the core area from the section coal pillars effectively reduces the dynamic and static loads released by key strata failure, decreases the risk of intense rock pressure, and maintains the stability and safety of working faces during deep mining.

KEYWORDS

deep-well mining, key strata, section coal pillar, intense rock pressure, fully mechanized top-coal caving

1 Introduction

The reserves of thick coal seams account for approximately 44% of China's total coal reserves, and their output accounts for around 45% of the raw coal output (Mou et al., 2025; Wu Z. G. et al., 2025). In China, Fully Mechanized Top-coal Caving (FMTC) is mostly adopted for thick coal seam mining. Due to the large mining thickness and high mining intensity of FMTC, the overlying strata suffer more severe damage, which increases the difficulty of rock pressure control in working faces (Zhang S. et al., 2025). In particular, when key strata exist, the impact of their fracture on the working face pressure urgently requires research.

Recent studies also indicate that the stability assessment of a mining excavation can be effectively supported through the monitoring of powered supports (Zhang et al., 2026). Parameters such as support working resistance, dynamic load response, and temporal variation in shield behavior can directly reflect changes in roof activity and overlying strata movement, thereby serving as an important basis for evaluating excavation stability (see, e.g., SGEM 2018 (Herezy et al., 2018)). Incorporating support monitoring improves the understanding of strata control mechanisms, especially under deep and complex geological conditions (Zhang L. et al., 2025).

Scholars at home and abroad have conducted extensive research on the pressure conditions of coal mining working faces (Wang, 2025; Zhang et al., 2024; Zhang S. et al., 2023; Zhang, 2023; Zhang Q. et al., 2023), and have also carried out a great deal of research on the development height of the "two zones" of overlying strata and the impact of key strata on the development of the "two zones" (Wang et al., 2021; Xu et al., 2021; Shu et al., 2020; Li et al., 2020; Peng et al., 2019; Cui et al., 2019). However, existing studies mostly focus on single or partial stratum conditions (e.g., only thick coal seams, only key strata) and lack exploration of extreme combined stratum conditions (Jia et al., 2024). Specifically, research on the coupling impact mechanism of key strata fracture on FMTC working face rock pressure under the combined conditions of "deep burial (burial depth usually >800 m, while the 5# coal seam in Yanbei Coal Mine is ~480 m), thick unconsolidated layer (unconsolidated overburden thickness >100 m), and two-hard-one-soft (two hard key strata, hard floor, and soft coal seam)" remains blank (Xu et al., 2022). Under such combined conditions, the high *in-situ* stress caused by deep burial, the uneven load transfer characteristics of thick unconsolidated layers, and the mechanical parameter differences of "two-hard-one-soft" strata overlap with each other, which significantly changes the fracture law of key strata and the characteristics of rock pressure manifestation—existing theories cannot directly explain or guide on-site practice (Wu X. et al., 2025). Moreover, research results on the impact of key strata on the rock pressure of FMTC working faces (even under non-combined conditions) are still relatively scarce (Cui et al., 2019; Xu, 2009).

2 Engineering geological conditions

In addition to the stratigraphic and structural characteristics described below, the Huating Mining Area is also affected by several natural mining-related hazards. Due to the relatively large burial depth (~480 m), the high *in-situ* stress environment increases the likelihood of dynamic disasters such as impact ground pressure and rock bursts. Locally enriched gas zones within the Jurassic coal-bearing strata present a potential risk of gas outbursts during mining disturbances. Furthermore, the 180 m-thick unconsolidated overburden layer makes the region sensitive to surface subsidence, and water-bearing rock layers in the overlying strata may pose roof water inrush hazards if large-scale fractures connect aquifers with the mined-out area. These natural hazard factors must be fully considered in mining parameter design and stability assessment (Dai et al., 2025).

The main strata in Yanbei Coal Mine include the Quaternary Holocene Series, Neogene Gansu Group, Middle Jurassic Zhiluo Formation, and Yan'an Formation. Among them, the coal-bearing strata of the mine are Jurassic strata, which contain 1# to 5# coal seams. The main minable seam is the 5# coal seam, which is an extra-thick coal seam with an average thickness of over 20 m and a maximum thickness of more than 40 m. The burial depth of the 5# coal seam is approximately 480 m, with a dip angle of about 8°.

Conditions of the coal seam roof: The immediate roof is silty mudstone with a thickness of 4.5 m, which has poor stability and collapses as the working face advances. The main roof is fine sandstone with a thickness of 37.66 m. At 120 m above the roof of the 5# coal seam, there are two hard rock layers (one layer of fine sandstone and one layer of siltstone) with a total thickness of approximately 36 m. These two layers have high mechanical strength (unconfined compressive strength >69 MPa) and good integrity, and play a controlling role in the movement and failure of the overlying strata, thus being identified as the key strata. There are no hard rock layers between the 5# coal seam and the key strata that can control the deformation and failure of the overlying strata, meaning no additional key strata exist in this interval. From the key strata up to the ground surface, the rock mass is relatively soft, and there are no thick rock layers with high strength—indicating that there are no composite key strata in the strata of Yanbei Coal Mine. Meanwhile, there is an unconsolidated layer with a thickness of approximately 180 m on the ground surface, which serves as the main loading layer for the key strata. Therefore, the overlying strata of the 5# coal seam in Yanbei Coal Mine exhibit the "two hard and one soft" characteristic (i.e., two hard key strata and one soft coal seam). The overview of the overlying strata structure is shown in Figure 1.

3 Physical similar material simulation

Similar simulation experiment is a model experimental technology based on similarity theory, which refers to a method for studying natural laws by utilizing the characteristics of similarity and analogy existing between things or phenomena. It is particularly suitable for research fields where results are difficult to obtain through theoretical analysis methods, and also serves as an effective means for analyzing and comparing the outcomes of theoretical research. As a laboratory research method, it is based on similarity theory and dimensional analysis. Currently, the similar simulation experimental research method has broad application prospects in numerous fields such as mining, geotechnical engineering, and water conservancy.

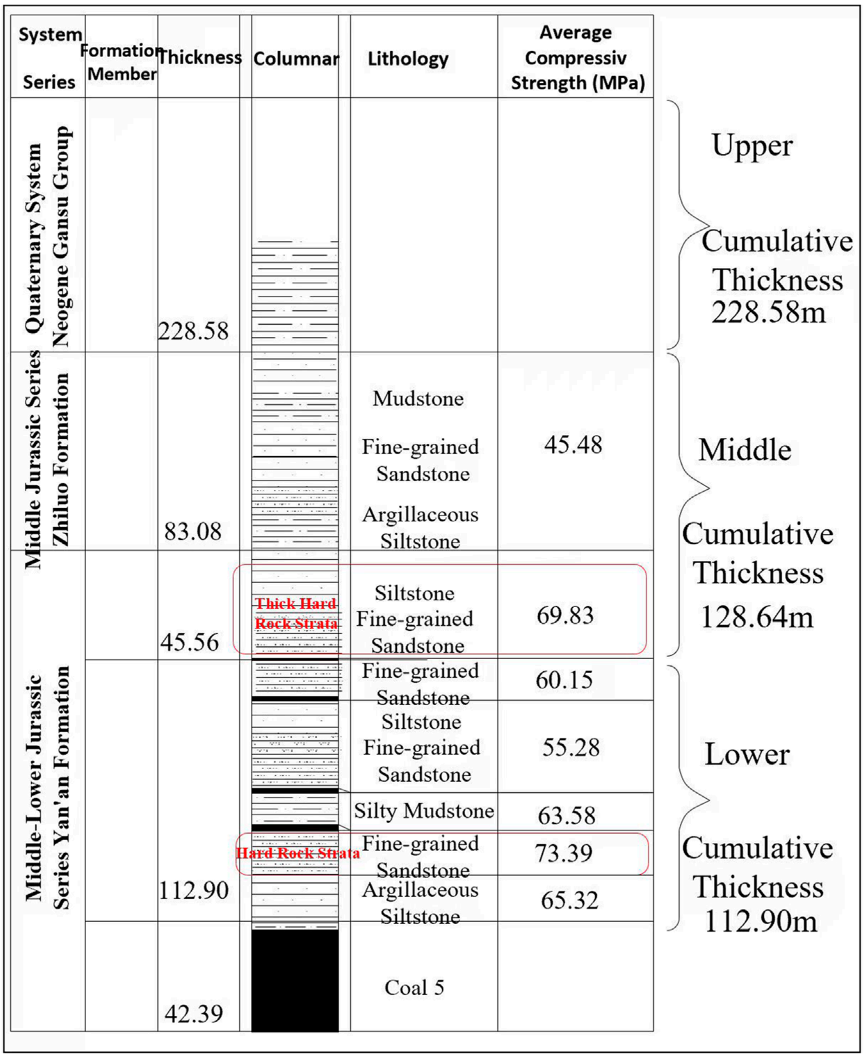

FIGURE 1
Distribution overview diagram of overlying strata in Yanbei coal mine.

3.1 Experimental model and similarity conditions

In this experiment, three working faces (250,204, 250,205, and 250,206) of Yanbei Coal Mine were taken as the simulation objects. The main mining coal seam of these working faces was the 5# coal seam, with an average mining slice thickness of 12 m. The mining method adopted was the slice fully mechanized top-coal caving with full caving method, featuring a working face width of 200 m and a section coal pillar of 10 m between adjacent working faces. Mining sequence: The three working faces (250,204, 250,205, 250,206) were mined in sequence.

In order to accurately reproduce the combined static and dynamic loading conditions acting on the working face—especially the transient impact loads generated by the breakage of key strata—a dynamic support (dynamic load) modeling scheme was introduced into the similar-material simulation. The modeling principles are as follows:

3.1.1 Static load modeling

Static loading was provided by the self-weight of the overlying model strata. A total of 96 pressure sensors were installed on the coal seam floor to record the initial stress field. According to the similarity ratio (1:333 for stress), the initial model stress of approximately 0.03 MPa corresponds to an *in-situ* stress of about 10 MPa in the prototype.

3.1.2 Dynamic load modeling (dynamic supports)

In fully mechanized top-coal caving (FMTC), the sudden breakage of key strata produces significant transient dynamic loads. To simulate this behavior, additional short-duration loads were applied to the pressure sensors at appropriate moments. Based on field measurements from multiple mining areas (see Table 2 in the main text) and considering the burial depth, mining height, and roof structure of Yanbei Coal Mine, the dynamic load coefficient was determined as $K_d = 1.60$.

3.1.3 Application method of dynamic loads

Dynamic loads were applied following the principles below:

Dynamic impacts were imposed instantaneously when the main or sub-key strata fractured; The additional load acted for a short duration, consistent with the transient nature of key-stratum breakage; Dynamic loads were applied only to supporting zones (coal wall, coal pillar), not to the goaf; After the dynamic disturbance, the load returned to its static state.

This loading approach reflects the real mechanical process whereby dynamic loads are transmitted to supporting structures when key strata lose stability.

3.1.4 Combined static–dynamic load expression

To quantitatively describe the bearing state under combined loading, the total stress acting on the support area is expressed as:

$$\sigma_{total} = K_d \sigma_{static}$$

where:

σ_{total} is the total stress under dynamic loading;

σ_{static} is the static stress induced by overburden self-weight;

K_d is the dynamic load coefficient (1.60 in this study).

During periodic weighting events, a lower value of K_d (1.2–1.4) may be used, while the maximum value K_d = 1.60 corresponds to the intense dynamic loading caused by key-stratum fracture.

3.1.5 Physical significance of dynamic support modeling

The dynamic support model captures two categories of load behavior observed in deep top-coal caving:

Weak dynamic effects associated with periodic weighting trong impact loads generated by sudden breakage of high-position key strata or the collapse of large overlying structures.

Therefore, this modeling method ensures that the simulation accurately reflects the alternating "static–dynamic–static" loading environment encountered during actual mining.

In the experimental simulation area, the average burial depth of the coal seam was 480 m, the thickness of the unconsolidated layer was approximately 180 m, and the thickness of the bedrock was about 300 m. Within the bedrock, some rock layers with small thickness or those having similar lithology to adjacent rock layers were treated as a single rock layer. Finally, from the ground surface to the coal seam floor, the strata were simplified into 19 rock layers, 2 unconsolidated layers, and 2 coal seams. The detailed parameters and proportions are presented in Table 1. In accordance with the requirements of the similar simulation experiment, a model frame with dimensions of 500 cm (length) × 200 cm (height) × 20 cm (width) was used. The model scale was 1:200, and the installation height of the model in the frame was 120 cm. The weight corresponding to the unmodeled strata was compensated with counterweights, and the simulation model is shown in Figure 2. Based on the similarity principle and dimensional analysis, the similarity ratios were determined as follows: 1:1.67 for unit weight, 1:333 for strength, elastic modulus, and cohesion, 1:14 for time and velocity, and 1:333 for load.

During the simulation, along the advancing direction of the working face, a set of pressure sensors was arranged on the coal seam floor, including 96 sensors with dimensions of 20 cm × 5 cm × 5 cm; the upper and lower surface areas of each sensor were 100 cm^2. The pressure data curve of the pressure sensors before model excavation is shown in Figure 3. It can be seen from the pressure data curve that the initial *in-situ* stress in the simulation experiment was approximately 300 N/100 cm^2 (equivalent to 0.03 MPa). With a similarity ratio of 333 for *in-situ* stress, the actual *in-situ* stress was about 10 MPa.

The similar materials adopted in the experiment were as follows: main material - sand; auxiliary materials - whiting powder, calcined gypsum, mica, and water. Among them, fly ash was added when preparing the mixture for the coal seam. Mica powder with a particle size of 8–20 mesh was used as the layered material. Since sand served as the main material of the model and the proportion of auxiliary materials was relatively small (exerting little impact on the bulk density of the model material), the bulk density of all layers except the coal seam was calculated as 1,600 kg/m^3.

According to a large number of domestic mining practices, the rock pressure of working faces in large mining height and top-coal caving working faces is significantly affected by dynamic loads. Particularly, when there are key strata in the overlying strata, the manifestation of dynamic loads becomes more obvious. Combined with the actual mining conditions of multiple working faces in domestic mining areas (e.g., the 2,306 working face of Sihe Coal Mine and the 6,203 large mining height fully mechanized top-coal caving working face of Lu'an Wangzhuang Coal Mine), the specific dynamic load parameters of each working face after mining are presented in Table 2. Considering the actual mining conditions of Yanbei Coal Mine (burial depth ~480 m, mining thickness 12 m, inclination angle 8°), the dynamic load coefficient of Yanbei Coal Mine was finally determined as 1.60.

3.2 Experimental phenomena

3.2.1 Experimental phenomena during the mining of working face 250,204

When the working face advanced to 76 m, the caving height of the overlying strata reached 30 m, and first weighting occurred at this point. The pressure sensors on the floor showed a significant pressure increase in the area ahead of the working face: the pressure on the coal wall ahead of the working face was 21.104 MPa, and the pressure behind the working face was 17.584 MPa.

When the working face advanced to 112 m, the caving height of the overlying strata increased to 64 m, triggering periodic weighting with a periodic weighting step of 36 m; the caved rock layers were arranged in the goaf in a regular pattern. When the working face advanced to 160 m, the caving height reached 120 m—equivalent to the position of the key strata. A separation space appeared between the caved rock layers and the key strata, with a separation length of 64 m and a separation height of 3.6 m. Meanwhile, the pressure ahead of the coal wall gradually increased to 24.832 MPa, and the pressure behind the working face was 21.904 MPa. As mining progressed, the pressure borne by the goaf (from the caved zone and fractured zone rock layers) increased gradually, reaching 4.16 MPa.

When the working face advanced 200 m (i.e., at the end of mining), the caving height of the coal seam roof remained 120 m. The separation length between the caved rock layers and the key

TABLE 1 Mechanical parameters and mix proportions of rock in overlying strata of mined coal seam.

No.	Rock stratum	Thickness/m	Bulk density kg/m^3	Compressive Strength/MPa	Tensile strength/MPa	Elastic Modulus/MPa	Poisson's ratio	Mix proportion	Remarks
1	Sandy soil	9.50	1,600	0.01	0.002	10	0.30		
2	Loess	169.30	1,600	0.01	0.002	10	0.30		
3	Silty mudstone	46.25	2,220	43.76	3.52	27,900	0.16		
4	Conglomerate	8.47	2,220	43.76	3.52	27,900	0.16		
5	Silty mudstone	14.77	2,530	45.32	3.12	17,400	0.14	828	
6	Mudstone	14.52	2,420	35.53	4.32	14,000	0.22	928	
7	Mudstone & fine sandstone	16.45	2,540	43.39	4.15	36,300	0.13	837	
8	Argillaceous siltstone	7.68	2,530	45.32	4.12	17,400	0.14	828	
9	Silty mudstone	19.68	2,530	45.32	4.12	17,400	0.14	828	
10	Argillaceous siltstone	14.35	2,530	45.32	4.12	17,400	0.14	828	
11	Siltstone	15.79	2,660	69.83	9.03	48,600	0.12	837	Key strata
12	Fine sandstone	20.19	2,610	70.76	9.54	43,200	0.13	837	
13	M1 (coal seam)	0.88	1,300	13.27	1.86	800	0.46	928	
14	Silty mudstone	10.43	2,530	60.32	7.12	17,400	0.14	828	
15	Mudstone	2.76	2,420	35.53	4.32	14,000	0.22	928	
16	Coarse sandstone	12.14	2,410	49.83	6.03	28,600	0.17	828	
17	Silty mudstone	13.85	2,510	63.39	8.15	29,300	0.13	828	
18	Silty mudstone	18.75	2,530	65.32	7.12	17,400	0.14	828	
19	Fine sandstone	37.66	2,540	73.39	8.15	41,300	0.13	837	Main roof
20	Medium sandstone	18.28	2,530	68.32	7.12	17,400	0.14	828	
21	Silty mudstone	4.50	2,530	65.32	7.12	17,400	0.14	828	
22	M5 (coal seam)	30.00	1,300	24.97	3.01	600	0.29	928	
23	Medium-grained sandstone	23.00	2,360	34.76	4.03	8,200	0.19	928	

strata became longer (72 m), and the caving angle was approximately 68°. At this stage, the key strata exhibited bending and subsidence, indicating that the key strata restrained the development of the height of the water-conducting fractured zone. Under the condition of mining a single working face, the maximum height of the water-conducting fractured zone was 120 m. The morphology of Working Face 250,204 at the end of mining is shown in Figure 4, and the sketch map of the working face's caving morphology is shown in Figure 5.

3.2.2 Experimental phenomena during the mining of working face 250,205

Working Face 250,205 was mined after a 10 m section coal pillar was reserved following the mining of Working Face 250,204. The

TABLE 2 Mining dynamic load coefficients of top-coal caving working faces.

Mine & working face	Burial depth/m	Mining thickness/m	Inclination Angle/(°)	Strike length/m	Dip length/m	Dynamic load coefficient
Sihe coal mine working face 2,306	262~391.4	6.0	1~10	2,484.2	220.3	
Lu'an Wangzhuang coal mine working face 6,203	--	6.5	2~6			
Yangmei Kaiyuan coal mine working face 9,404	310~420	4.23		1,064	180	Upper: 1.3; lower: 1.63
Yangquan sijiazhuang coal mine 15# coal seam		5.5	7			
Pingdingshan No.13 coal mine working face 11,020		5.85	20~27			1.74
Bulian tower minefield 2–2 coal seam		7.1	1~3			
Nantun coal mine working face 93 shang 01	550~750	5.7	25			

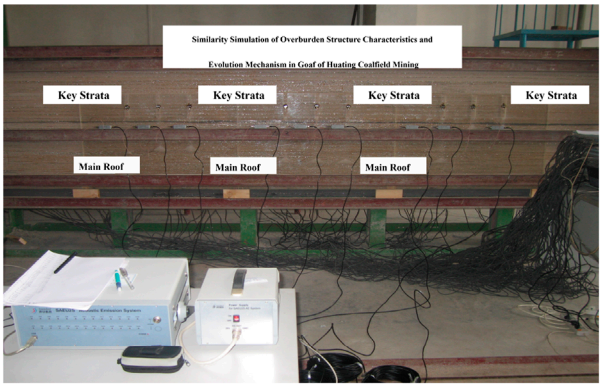

FIGURE 2
Panoramic view of similar material simulation experiment.

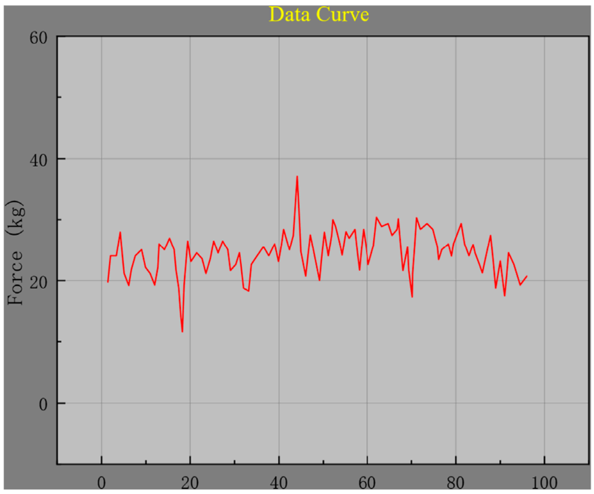

FIGURE 3
Pressure data curve before excavation.

experimental phenomena of surrounding rock failure during the mining of Working Face 250,205 are as follows:

When the working face advanced to 70 m, the caving height was 32 m, and slight bending occurred in the roof. At this point, the pressure sensor data curve showed that the section coal pillar bore relatively high pressure from the overlying strata; the pressure on the coal wall ahead of the working face was 22.112 MPa, and the pressure behind the working face was 40.544 MPa. In contrast, the goaf only bore the pressure from part of the caved rock layers in the caved zone, with a pressure of 0.64 MPa.

When the working face advanced to 94 m and 104 m, the caving heights were 54 m and 60 m, respectively. When the working face advanced to 117 m, the key strata above the previous working face (250,204) fractured; the entire key strata were almost fully penetrated by fractures, but the key strata did not lose stability. The failure height of the overlying strata was approximately 170 m, fractures occurred in the rock layers above the key strata,

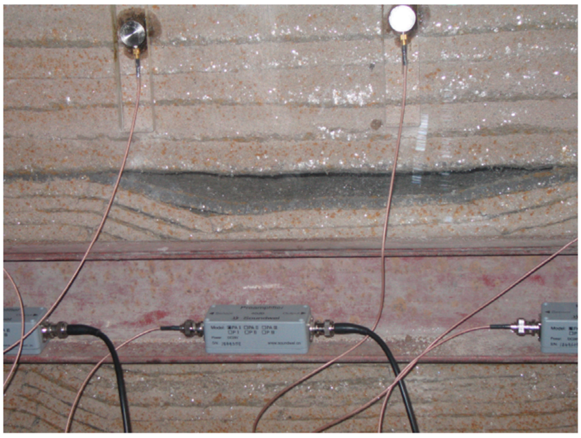

FIGURE 4
Roof caving morphology at the end of working face mining.

and multiple separations of varying sizes and heights appeared between these upper rock layers. Due to the fracture of the key strata, the abutment pressure ahead of the working face increased rapidly compared with that when the working face had advanced 70 m: the pressure on the coal wall ahead of the working face was 37.248 MPa, and the pressure behind was 41.664 MPa (see Figure 6).

When the working face advanced to 153 m, severe coal wall spalling occurred, and the key strata above the second working face (250,205) fractured with a fracturing thickness of 36 m; the rock layers in the goaf exhibited overall bending and subsidence (see Figure 7). Before the key strata fractured, relatively high pressure appeared both ahead of and behind the working face: the pressure on the coal wall ahead of the working face was 41.01 MPa, and the pressure behind was 45.40 MPa (see Figure 8). After the key strata fractured, they lost their controlling effect, and the overlying strata above the key strata were directly loaded onto the section coal pillar. Under the combined action of the dynamic load generated by the key strata fracturing and the static load it originally bore, the section coal pillar was instantly damaged. Subsequently, the pressure was gradually transferred to the upper part of the caved rock layers in the goaf, with the pressure on the coal wall ahead of the working face being 29.41 MPa and the pressure behind being 30.05 MPa (see Figure 9).

When the working face advanced 200 m (i.e., at the end of mining for Working Face 250,205), the fractures expanded further, and the overlying strata showed a typical bending and subsidence phenomenon. The pressure on the coal walls both ahead of and behind the working face was gradually transferred toward the goaf, resulting in an increase in the pressure above the goaf while a decrease in the pressure above the coal walls. At this point, the pressure on the coal wall ahead of the working face was 22.32 MPa, and the pressure behind was 27.07 MPa; the average pressure at the goaf was approximately 12.83 MPa. This indicates that the overlying strata were severely damaged, and the goaf bore about 80% of the pressure from the upper load.

3.2.3 Experimental phenomena during the mining of working face 250,206

After the completion of mining for Working Face 250,205, Working Face 250,206 was advanced from the opposite direction (i.e., toward Working Face 250,205). Through the simulation experiment, the failure phenomenon of the section coal pillar and the relationship between the section coal pillar failure and intense rock pressure were further analyzed. The specific experimental phenomena are as follows:

When the working face advanced to 106 m, the caving height was 60 m, and the characteristics of the fractured zone were obvious; when the working face advanced to 121 m, the caving height reached 80 m. With the gradual excavation of the third working face, the pressure borne by the section coal pillar increased significantly: the pressure on the section coal pillar ahead of the working face was 27.97 MPa, and the pressure behind was 22.85 MPa.

When the working face advanced to 146 m, the caving height was 104 m; when it advanced to 156 m, the caving height reached 108 m (approximately 6 m below the lower part of the key strata), and the caving angle was about 68°. At this stage, the pressure on the section coal pillar increased remarkably: the pressure on the section coal pillar ahead of the working face was 37.09 MPa, and the pressure behind was 24.99 MPa.

When the working face continued to advance to the 180 m position, the excessive pressure from the overlying strata caused the key strata to fracture. The section coal pillar reached the ultimate pressure, was crushed and failed, and the pressure above the section coal pillar dropped rapidly, resulting in intense rock pressure and a rock burst phenomenon. On the coal mass behind the goaf, the pressure generated when the key strata fractured was 41.34 MPa, which was more than 4 times the *in-situ* stress (see Figure 10). The pressure generated ahead of the working face was 51.68 MPa, leading to the instantaneous failure of the 30 m-wide section coal pillar. After the failure, the pressure above the section coal pillar was only 7.99 MPa (see Figure 11). The sketch map of the overlying strata caving morphology when Working Face 250,206 had advanced 180 m is shown in Figure 12. Although the coal pillar in Figure 12 maintains its geometric width of 30 m under industrial conditions, its effective bearing width remains nearly unchanged under static load but decreases sharply under dynamic load induced by key-stratum breakage.

4 Analysis of experimental results

A simulation study on the fully mechanized top-coal caving (FMTC) mining of three working faces (250,204, 250,205, and 250,206) in Yanbei Coal Mine of Huating Mining Area was conducted via physical similar material simulation, and the experimental phenomena were analyzed as follows:

1. During the mining of Working Face 250,204, both first weighting and periodic weighting occurred. The first weighting step was 76 m, and the periodic weighting steps were 36 m, 28 m, 21 m, and 40 m, respectively. During the first weighting, the pressure ahead of the working face increased by 11.104 MPa compared with the *in-situ* stress, the pressure behind the working face was 17.584 MPa, and the pressure

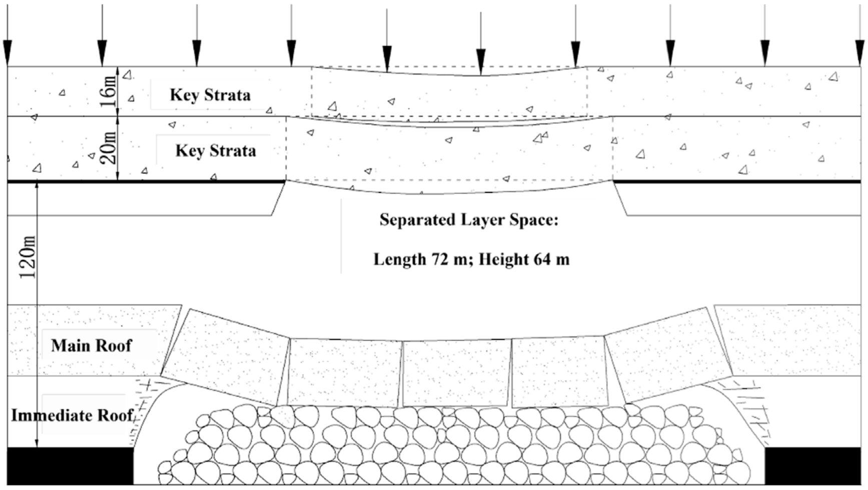

FIGURE 5
Sketch map of roof caving morphology at the end of working face mining.

FIGURE 6
Corresponding pressure data curve when advancing 117 m during mining.

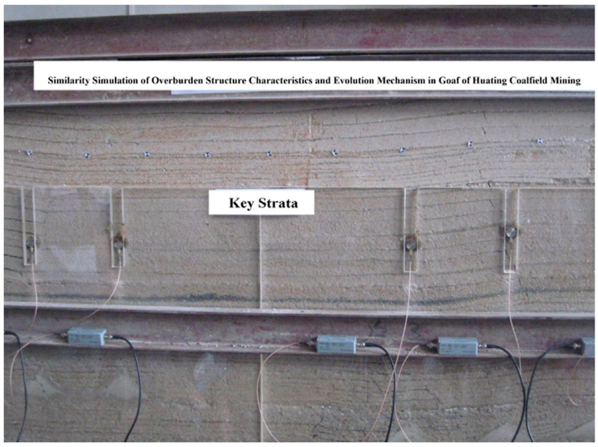

FIGURE 7
Roof caving morphology when the working face advances 153 m during mining.

in the goaf was only 0.964 MPa. In the subsequent periodic weighting processes, the pressure ahead of and behind the working face both increased, but the magnitude was small. When the working face advanced to 160 m (i.e., during the third periodic weighting), the height of the fractured zone developed to the position of the key strata, and separation occurred with a length of 64 m and a height of 6 m. By the end of mining for Working Face 250,204, the key strata showed bending and subsidence but remained intact without fracturing; the separation space increased to a length of 72 m and a height of 6 m, and there was no significant change in the working face pressure. Throughout the mining process of Working Face 250,204, the working face pressure did not change significantly, indicating that the key strata exerted a controlling effect on the working face pressure.

2. During the mining of Working Face 250,205, severe coal wall spalling occurred. The first weighting step was 70 m; at this point, the pressure ahead of the working face was higher than that during the first weighting of Working Face 250,204, the pressure on the coal pillar behind increased by 22.96 MPa compared with that behind Working Face 250,204 during its first weighting, and the goaf pressure was 0.64 MPa. When the working face advanced to 117 m, the key strata above Working Face 250,204 fractured, leading to a rapid increase in the pressure of Working Face 250,205. A comparison of the pressure at the corresponding position with that of Working Face 250,204 is shown in Figure 13; it can be seen from the comparison that the pressure of Working Face 250,205

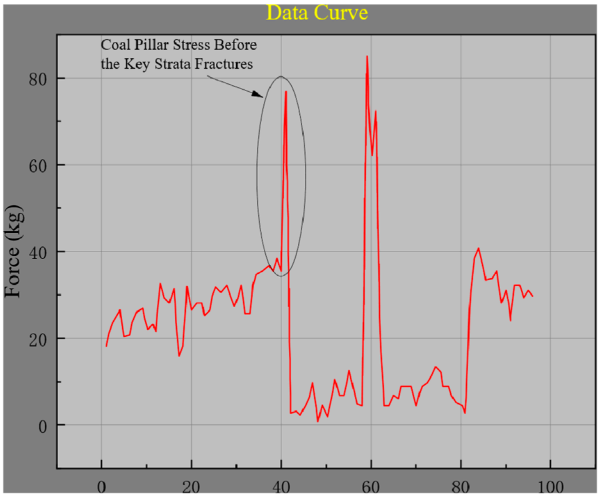

FIGURE 8
Corresponding pressure data curve before the key strata fractures.

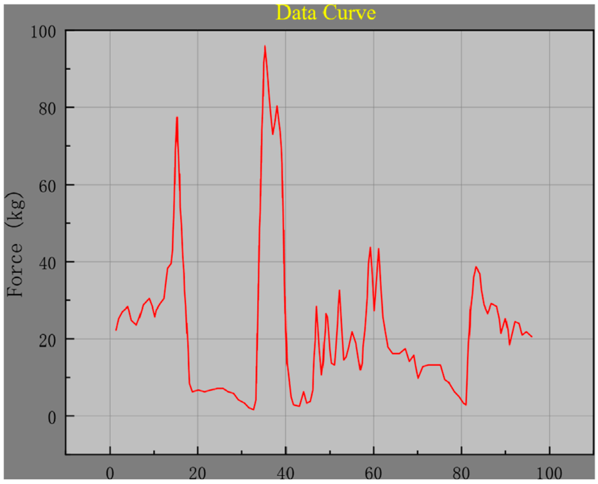

FIGURE 10
Corresponding pressure data curve when advancing 180 m during mining.

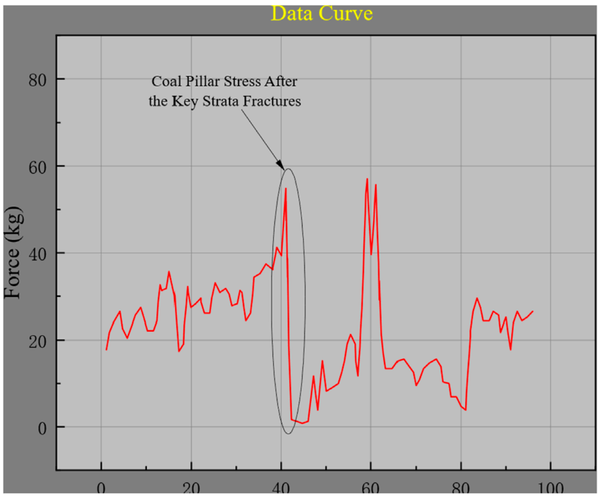

FIGURE 9
Corresponding pressure data curve after the key strata fractures.

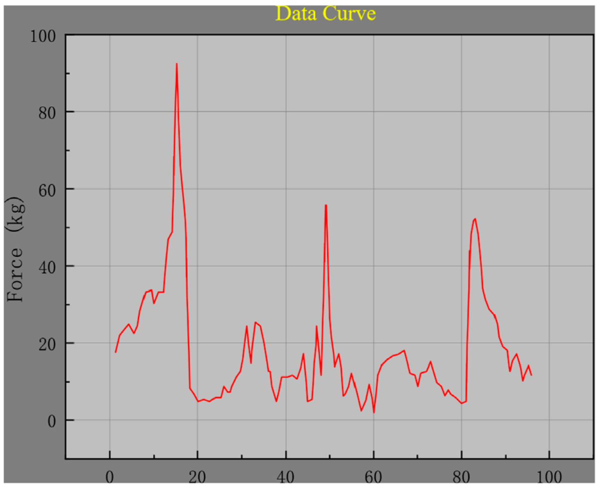

FIGURE 11
Corresponding pressure data curve when the coal pillar fails.

was much higher than that of Working Face 250,204 at the corresponding position. The analysis shows that during the mining of Working Face 250,204, the key strata bore the gravity of the overlying strata and transferred it to the deep parts at both ends of the working face, forming a "plate"-like structure, thus resulting in relatively low pressure. After the key strata above Working Face 250,204 fractured, the key strata formed a structure similar to a "cantilever beam", while the coal pillar between the two working faces acted as a support point in the middle of the beam. The pressure borne by the key strata was transferred to both ends of the working face, leading to a significant increase in the pressure ahead of and behind Working Face 250,205. As the working face advanced, the pressure at both ends continued to increase. When Working Face 250,205 advanced to 153 m, the pressure at both ends reached the maximum value; subsequently, the key strata above this working face fractured, the 10 m-wide coal pillar between the working faces was crushed, and the working face pressure was transferred to the goaf. At this stage, the key strata structure was similar to an "articulated rock beam". By the end of mining for Working Face 250,205, the pressure at both ends of the working face further decreased, and the goaf pressure increased to 12.83 MPa (accounting for approximately 80% of the upper load), indicating that the support effect at both ends of the working face gradually diminished.

3. Working Face 250,206 was mined in a direction opposite to that of Working Face 250,205 (i.e., advancing from the boundary toward Working Face 250,205). The first weighting step was 72 m; at this point, the pressure ahead of the working face was 21.95 MPa, and the pressure behind was 20.14 MPa.

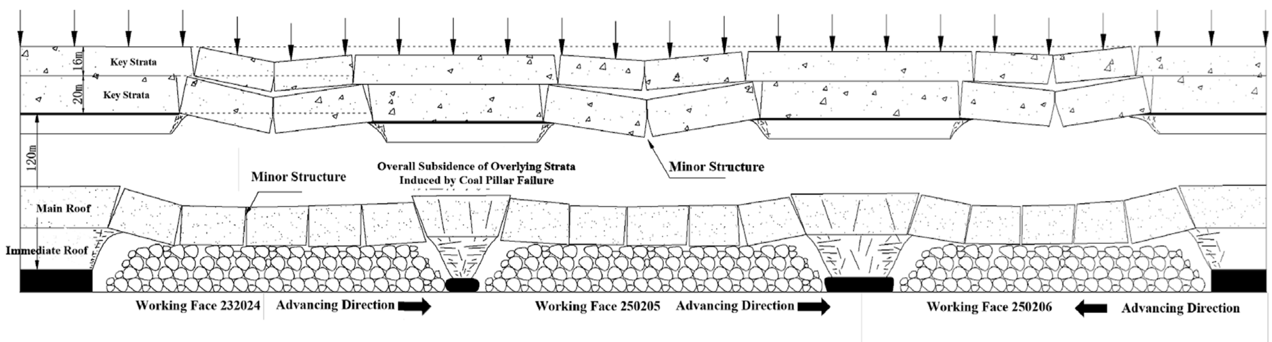

FIGURE 12
Sketch map of overlying strata caving morphology when working face 250,206 advances 180 m during mining.

When the working face advanced to 156 m, the pressure ahead was 37.07 MPa and the pressure behind was 24.99 MPa. As shown in Figure 13, the pressure ahead increased rapidly while the pressure behind increased relatively slowly. A higher mining rate generally accelerates the development of roof deformation, causing faster propagation of fractures and earlier activation of key-stratum bending or breakage, while a slower mining rate allows the overlying strata to deform more gradually and reduces the likelihood of sudden instability. This was mainly due to the expansion of the mining range and the redistribution of the upper overburden load, which led to a rapid increase in the pressure on the coal pillar between the working faces. When the working face advanced to 180 m, the key strata fractured due to excessive load bearing, resulting in abnormal pressure on the coal pillar (reaching 51.67 MPa). This caused the overall failure of the 30 m-wide coal pillar and the occurrence of intense rock pressure.

A comparison of the mining processes of the three working faces shows that the pressure curves of each working face when advancing to the same position are presented in Figure 13, and the histograms of the pressure ahead of and behind each working face are shown in Figure 14. As can be seen from the figures: during the mining of Working Face 250,204, the overall pressure was relatively small with little variation; the pressure of Working Face 250,205 was very high before advancing to 153 m, and afterward, it was basically consistent with that of Working Face 250,204; due to the different mining direction, the pressure of Working Face 250,206 was consistent with that of Working Face 250,204 before the first weighting, then increased rapidly, and finally intense rock pressure occurred.

In the overlying strata of Yanbei Coal Mine in Huating Mining Area, except for the two thick and hard layers (fine sandstone and siltstone) located 120 m from the coal seam roof (which can be regarded as key strata), there are no other rock layers that can serve as key strata. The rock layers above the key strata are relatively soft and do not have the conditions to form a controlling structure. A 180 m-thick unconsolidated layer exists on the ground surface, which acts as the main loading layer for the key strata.

During the mining of the three simulated working faces, both first weighting and periodic weighting occurred, which were caused by the periodic fracture of the immediate roof of the coal seam. After the immediate roof fractured, "small structures" were formed near the roof, and these structures exerted a certain controlling effect on the rock layers above the immediate roof. After the key strata in the overlying strata fractured, "large structures" in the form of articulation were formed in the high-position rock layers.

The fracture of the key strata will release the load they bear, generating dynamic pressure on the working face and causing the working face pressure to rise rapidly. The broken rock blocks of the key strata are articulated with each other to form "large structures", which will continue to bear the load transferred by the rock layers above and control the working face pressure. If the "large structures" lose stability, the working face will bear enormous ground stress, making safe production impossible. The stability of the "large structures" and the mining parameters of the working face will be studied in future research.

The reasons for the different stress conditions during the mining of the three working faces are analyzed as follows: the structure formed after the fracture of the key strata (serving as "large structures") controls the large-scale weighting and impact disasters of the working faces. During the mining of the working face, the overlying strata are damaged and the damage develops to the key strata. The key strata usually fracture when their ultimate span is exceeded or the overlying load exceeds their bearing capacity. In Yanbei Coal Mine, due to the loading effect of the overlying unconsolidated layer, the key strata fracture under a certain mining scale. When a single working face is mined, the key strata above the working face deflect, and the force on them is transferred to both ends of the working face, forming a "plate structure" that results in relatively low working face pressure (as in Working Face 250,204). With the expansion of the mining range, the force borne by the key strata above the second working face is transferred to both sides, causing the key strata above Working Face 250,204 to bear a load exceeding its bearing limit and thus fracture, which leads to a rapid increase in the pressure of this working face. Further advancement causes the section coal pillar between the working faces to exceed its bearing limit and fail, resulting in the fracture of the key strata above Working Face 250,205. The stress is then transferred to the goaf, the working face pressure decreases rapidly, and the key strata form an "articulated structure". Working Face 250,206 was mined in the reverse direction; as the

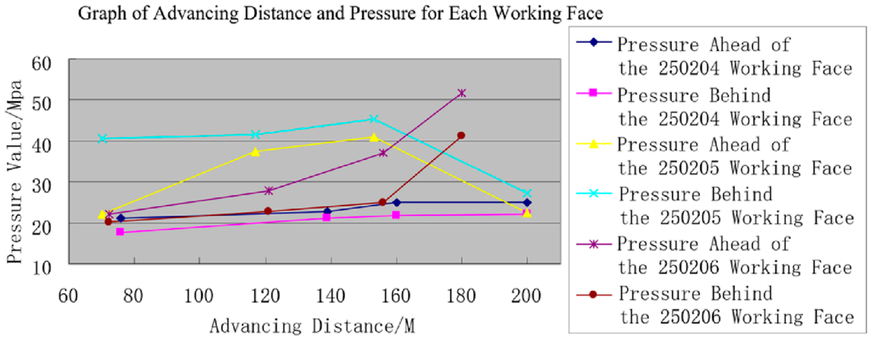

FIGURE 13
Comparison diagram of pressure curves ahead of and behind at the same position of the working face.

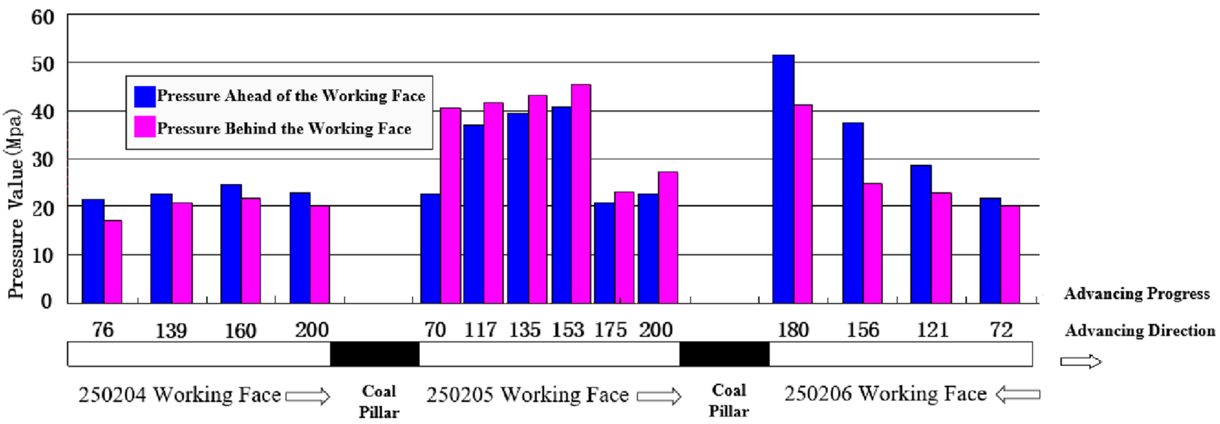

FIGURE 14
Schematic diagram of the relationship between pressure ahead of and behind the working face and advancement distance.

advancing distance increased, the load borne by the key strata was continuously transferred to both sides, and the pressure on the coal pillar between the two working faces increased steadily. Eventually, the 30 m-wide coal pillar was instantly damaged, and intense rock pressure occurred.

The "small structures" formed by the immediate roof only affect the pressure condition of the current working face; the "large structures" formed by the key strata affect the pressure distribution of multiple working faces and even control the pressure of the entire mining area. The "small structures" are controlled by the "large structures", and the instability of the "large structures" will directly lead to the instability of the "small structures".

5 Engineering practice

According to the results of the physical similar material simulation, when the section coal pillar between working faces was 10 m, a core area existed in the coal pillar during the working face mining process, maintaining the integrity of the coal pillar interior. When the overlying key strata fractured, the coal pillar lost stability instantly under the combined action of the energy released by the key strata fracture and the load borne by the coal pillar itself, leading to the manifestation of intense rock pressure.

In addition to optimizing the width of sectional coal pillars, both active and passive measures are essential to mitigate dynamic loading hazards. Active measures—such as pre-fracturing of hard roofs, deep-hole blasting for pressure relief, and advanced drilling for key-stratum weakening—aim to reduce the stored elastic energy before large structures lose stability. Passive measures, including high-capacity supports, reinforced roadway structures, and yielding support components, focus on enhancing the system's ability to withstand sudden impact loads. The combination of these approaches enables the working face to better resist dynamic threats and significantly improves overall operational safety.

To ensure safe mining and avoid the formation of intense rock pressure during production, the mine adopted the method of reducing the size of the coal pillar for mining. When the coal pillar size was 8 m, although the manifestation of intense rock pressure was somewhat alleviated, it still existed. The mine further reduced the coal pillar size; when the coal pillar size was reduced to 6 m, the coal pillar could be crushed as the working face advanced. This reduced the coal pillar's supporting effect on the overlying strata, significantly narrowing the control range of the key strata. When the key strata fractured, the harm of the dynamic load and energy released to the working face was greatly mitigated. Although this method could not completely eliminate the impact of the key strata on the working face rock pressure, it avoided the occurrence of intense rock pressure and prevented injuries to working face personnel and damage to equipment caused by the instantaneous failure of the coal pillar, ultimately achieving good production results.

6 Conclusion

A study on the fully mechanized top-coal caving (FMTC) mining in Yanbei Coal Mine of Huating Mining Area was conducted using physical similar material simulation. It was found that "large structures" and "small structures" exist in the overlying strata during the working face mining process, among which the stability of the large structures is of great significance to the safe mining of the working face. The main conclusions are as follows:

1. Similar to general longwall working faces, first weighting and periodic weighting also occur during the FMTC mining process in Yanbei Coal Mine. The first weighting step ranges from 70 m to 76 m, and the periodic weighting step is approximately 30 m.
2. "Large structures" and "small structures" exist in the stope during mining. The "small structures" are formed by the fracture of the immediate roof of the working face and exert a certain controlling effect on the failure of the overlying strata above. The "large structures" are formed by the fracture of the key strata, which control the pressure conditions of multiple working faces and serve as the main load-bearing structures in the strata after the key strata fractures. Their stability plays a crucial role in the control of working face pressure.
3. The key strata in Yanbei Coal Mine control the failure and deformation of the overlying strata. During the mining of a single working face, the key strata remain intact; as the mining range expands, the key strata are damaged. The entire process is a transition from a "plate structure" to a "cantilever beam structure" and then to a "masonry beam structure". Finally, the fractured rock blocks of the key strata form the "large structures" of the mining area, which in turn control the pressure changes of the working face.
4. Based on production practice, in view of the geological conditions of Yanbei Coal Mine, when the reserved size of section coal pillars between working faces is 6 m, the occurrence of intense rock pressure can be avoided, providing a guarantee for the safe mining of the mine.
5. The conclusions of this study are mainly applicable to the geological-construction method combination characterized by deep burial, thick unconsolidated layers, significant key strata, and fully mechanized top-coal caving (FMTC). When key strata are absent, the structure is extremely fragmented, or strong water-gas coupling exists, the evolution of the "plate-cantilever-masonry beam" dominated by key strata and its dynamic load amplification effect may be weakened or altered. In such cases, corrections and verifications must be conducted by integrating on-site monitoring and parametric analysis.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

WJ: Conceptualization, Data curation, Funding acquisition, Resources, Writing – original draft, Writing – review and editing. FJ: Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing. GS: Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

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