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Mining pressure law and strata movement of thick coal seam mining in isolated panel with multiple adjacent goafs

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ABSTRACT

The law of mining pressure and the characteristics of strata movement are the key factors affecting the safe and efficient mining of coal mines. Using numerical simulation via the Mohr–Coulomb model in FLAC3D and physical analog modeling, the mining pressure and strata movement of the mining area during the mining process of five adjacent goafs in the case study (Yangchangwan Coal Mine, China) was comprehensively evaluated. The stress distribution characteristics and the laws governing overlying rock movement and failure during the panel's mining process were investigated. The research results indicate a clear pattern of complex, asymmetric mining pressure during the panel's mining process. When the panel was close to the 1202-1 goaf, energy accumulation led to a significant increase in mining pressure intensity, with the maximum stress reaching 28 MPa and a stress concentration factor of up to 4.48. The lower area of the 1202-2 panel, along the dip direction, experienced overall pressure relief, with a stress peak of 50% of that in the upper area, while the transition area showed stress-concentration characteristics. The stress variations in the 14 m coal pillar (where the headgate was located) were complex, manifested as stress concentrations in the area of coal seam thickness variation, in the coal pillar area between the 1201 and 202-1 goafs, and in areas of high mining pressure. Based on the research results, the key influencing factors of the law of mining pressure and strata movement in the isolated panel were discussed and analyzed. The results obtained provide theoretical substantiation for the study of mining pressure laws and control in similar isolated panels.

Keywords Island panel, Mining pressure evolution, Asymmetric fracture, Numerical simulation, Physical analog modeling

Coal, as China's primary energy source, accounts for approximately 60% of the energy mix ¹. In 2025, China's raw coal production reached 4.85 billion tons. Still, long-term large-scale development has led to a gradual reduction in recoverable resources and a decline in the reserve-to-production ratio. Due to technological limitations and other factors, the mining method of "mining thick and discarding thin" in some mining areas has resulted in significant resource waste ^{2,3}, with abandoned resources in thick coal seams particularly widespread. In this context, re-mining of residual coal resources has become an important means to extend mine service life and improve resource recovery rates. The reserves of thick coal seams account for 38% of the country's recoverable resources, with an annual output of over 1.5 billion tons, and their resource value is increasingly prominent ⁴. The isolated panel of thick coal seams is generally under high stress concentration. The mining of the panel faces severe challenges: the irregular distribution of old goaf areas leads to a reduction in the effective bearing width of coal pillars, and significant stress concentration in the surrounding rock of the roadway; Due to the synergistic effect of the overlying rock structure in multiple goaf areas, the isolated coal body is in a bi-directional or triaxial stress superposition environment, forming a "dual force source" structural feature, with a high peak value of advanced support pressure and a large impact range. Research has shown that the mining pressure intensity of an isolated panel is 2.3 to 3.5 times that of an ordinary panel. During the mining period, the deformation rate of the surrounding rock of the roadway increases significantly, which can easily trigger dynamic disasters such as rock bursts.^{5,6}

Regarding mining pressure laws and control in isolated island panels, relevant scholars have conducted some research. Some scholars used a combination of numerical simulation and on-site measurements to analyze the asymmetric expansion law and the evolution mechanism of the plastic zone in the surrounding rock of the mining roadway in an isolated island panel. They revealed the damage mechanism of the roadway surrounding rock.⁷ Researchers developed a high-level rock fracture rotation mechanics model, revealing a positive correlation between the size of the overlying rock fracture block and the coal pillar support stress in an isolated panel of thick coal seams.⁸ Researchers studied the stress evolution law of the middle coal seam in the mining process of the isolated island panel, revealed the occurrence mechanism of rock burst when the panel was in overall instability, and deduced the limit advance distance when the panel was in a critical instability state.⁹ Researchers established a mechanical model of the overlying rock structure of an isolated panel, studied the movement characteristics of the overlying rock structure of an isolated panel, and determined the reasonable width of coal pillars.¹⁰ Researchers studied the mining pressure behavior of an isolated panel in the goaf of deep, close-range coal seams, revealing differential characteristics in advanced support pressure and roof displacement between the overlapping and non-overlapping sections of the panel and the upper goaf.¹¹ Researchers analyzed the dynamic changes and mechanical response of the roof structure of the goaf on both sides of the isolated panel under mining disturbance. They established a dynamic and static load estimation model and a support pressure estimation method.¹² Existing research mostly focuses on the mining pressure law of a single isolated panel, the geological conditions are relatively simple, most of them are medium thick coal seams. There are very few studies investigating the spatiotemporal evolution of mining stress, roof fracture mechanism, and coordinated control of surrounding rock under complex isolated conditions. During repeated mining, a large number of irregulars, old goafs are present in the surrounding rock of the two roadways, and the load-bearing structure of the coal pillars in the sections is damaged. The residual coal pillars result in a complex stress distribution, and the movement law of the roof is difficult to predict. Therefore, systematic research on the mining pressure law of complex isolated panels in thick coal seams, revealing the interaction mechanism between overlying rock structure and mining stress, exploring targeted surrounding rock control technology, has important theoretical significance and engineering value for ensuring the safe and efficient recovery of residual coal resources in mines and promoting sustainable development of mining areas.

This study was organized into the following sections: a review of rock mechanics and engineering geology conditions, a panel roadway layout. Using numerical and physical modeling, we investigated the laws governing mining stress and overlying rock movement during panel advancement. Then, the key factors affecting the mining pressure law of isolated mining faces in thick coal seams were analyzed and discussed in detail. The research results can serve as a reference for the safe and efficient mining of isolated panels in thick coal seams, especially affected by adjacent multiple goafs.

Background and methods

Research background

The Yangchangwan Coal Mine is located in north-west China, in the Ningxia Hui Autonomous Region, China (about 60 km from the regional capital Yinchuan. It belongs to the Ningdong Coalfield and contains nearly horizontal #2 coal seams with an average thickness of 8.0 m and an average burial depth of 227 m. The roof of the coal seam is composed of siltstone and medium sandstone, with a thickness of 9.39 m, and is of medium-hard rock type and moderate stability. The coal seam floor is composed of siltstone and fine sandstone, with a few units belonging to the medium-hard rock type and a moderately stable rock layer. When the advancing distance of the 1202-2 panel to be studied is 0~250 m, the coal seam thickness is 8.0 m; when the advancing distance of the panel is 250~1164 m, the

coal seam thickness is 5.0 m, which belongs to the panel with varying coal seam thickness. The goaf of the 1202-1 panel is located 250 m in front of the open-off cut of the 1202-2 panel. The advancing length of the panel is 914 m, and the coal seam mining height is 3 m. The west side of the 1202-2 panel is adjacent to the goaf of the 1201 top coal caving panel (with a mining height of 8 m), the east side is adjacent to the goaf of the 1204 panel (with a mining height of 3 m), and the south side is adjacent to the goaf of the 1209 panel (with a mining height of 8 m). The north side is adjacent to major transportation and return air roadways.

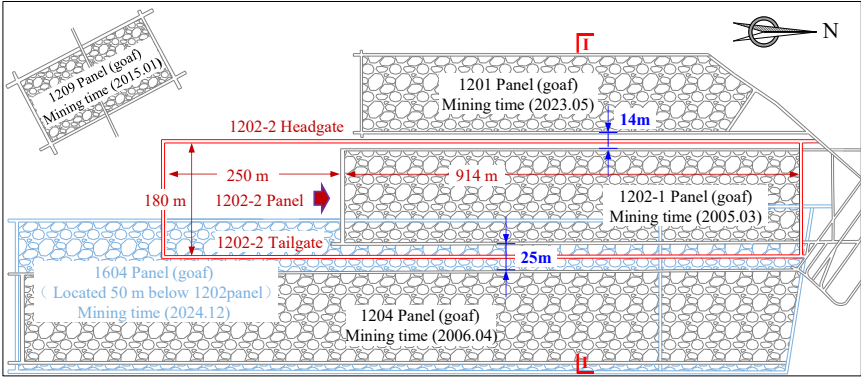


Fig. 1. The panel layout of the study area

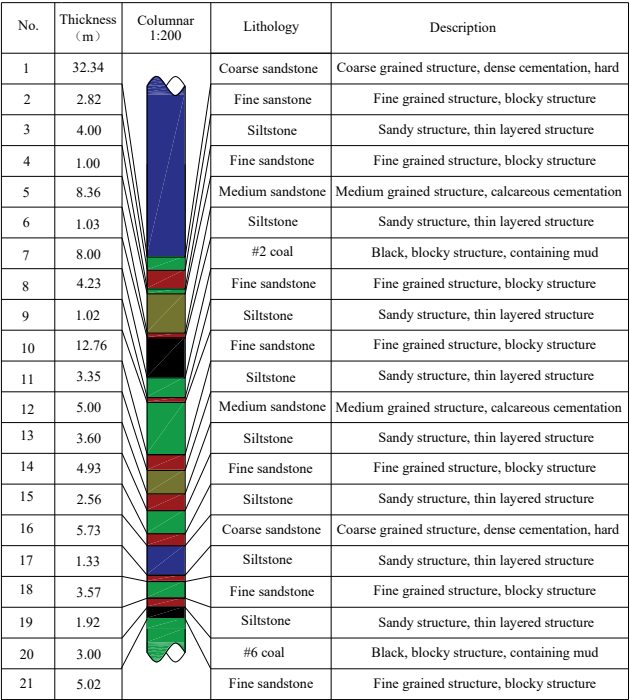


Fig. 2. Generalized stratigraphic column

Numerical simulation

FLAC3D, a commercial software package developed by Itasca Consulting Group, Inc., is widely used in mining engineering. The conventional Mohr–Coulomb model is used to summarize the problems causing damage to coal and rock. ¹³⁻¹⁵ As shown in Fig. 3, the numerical model assumes a length of 750 m in the strike direction, a width of 530 m in the dip direction, and a height of 130 m based on the geological conditions of panel 1202-2. In the model, boundary coal pillars were considered and left to avoid the influence of model boundaries. The horizontal

displacements of four vertical planes of the model are restricted in the normal direction, and the vertical displacement at the base of the model is set to zero. According to the calculation of coal seam burial depth, a uniform equivalent load of 4.44 MPa is applied above the model. To determine the mechanical properties of rock and coal samples, different parameters were employed, adjusted, and scaled in a laboratory. The final parameters are presented in Table 1.

The numerical simulation process contained the following steps: (i) calculate the initial state induced by gravity; (ii) model the excavation of panels 1202-1, 1204, 1209, 1201, and 1604; (iii) model the excavation of panel 1202-2 step by step. During the mining process of the 1202-2 panel, four stress monitoring lines (Y=150 m, Y=347.5 m, Y=278 m, Y=195 m) are arranged along the strike direction to monitor the stress changes in the 14 m coal pillar, mining stope, mining stope above the 1604 panel goaf, and the 25m coal pillar, respectively. Four stress monitoring lines (X=350 m, X=455 m, X=485 m, X=505 m) are arranged along the dip direction to monitor the stress changes in front of the 1202-2 panel during mining, as shown in Fig. 3.

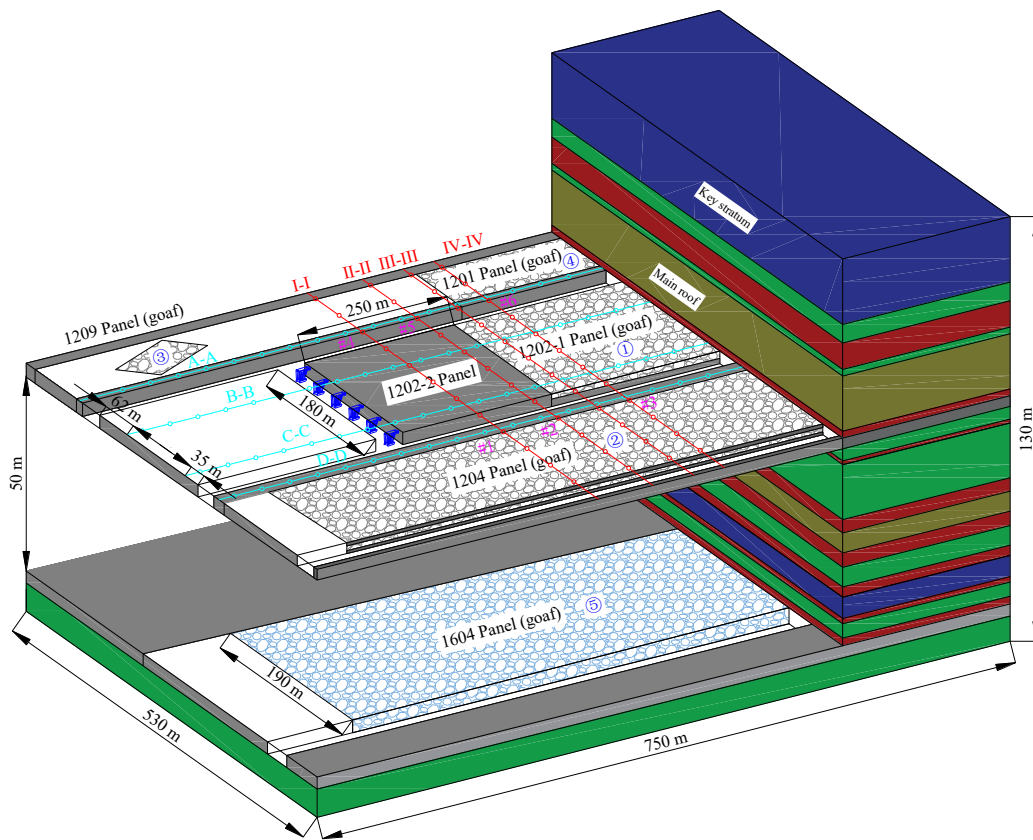


Fig. 3. Conceptual numerical simulation model

Table 1. Physical and mechanical parameters of rock strata used in numerical simulations.

Strata	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Tensile strength (MPa)	Internal friction angle (degrees)	Density ($\text{kg}\cdot\text{m}^{-3}$)
Coarse sandstone	1.63	0.79	3.31	4.3	35.1	2630
Fine sandstone	4.10	2.81	3.58	4.525	36.2	2721
Siltstone	1.30	0.67	1.39	0.545	34.7	1860
Fine sandstone	4.10	2.81	3.58	4.525	36.2	2721
Medium sandstone	3.47	1.31	3.07	0.6	25.1	1576
Siltstone	1.30	0.67	1.39	0.545	34.7	1860

#2 coal	3.51	1.41	2.22	0.71	25.45	1370
Fine sandstone	4.10	2.81	3.58	4.525	36.2	2721
Siltstone	1.30	0.67	1.39	0.545	34.7	1860
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Fine sandstone	4.10	2.81	3.58	4.525	36.2	2721
Siltstone	1.30	0.67	1.39	0.545	34.7	1860
#6 coal	3.51	1.41	2.22	0.71	25.45	1370
Fine sandstone	4.10	2.81	3.58	4.525	36.2	2721

Physical analog modeling

In this study, a 2-D physical analog model (PAM) was established to investigate the characteristics of strata movement further and analyze stress evolution after coal seam mining. The PAM dimensions were as follows: a length of 2500 mm in the strike direction, a width of 300 mm in the dip direction, and a height of 1500 mm; the geometric similarity of simulation model was 1:200. According to the rock strength and PAM similarity theory, each rock was composed of different proportions of sand, calcium carbonate, gypsum, and water,^{16, 17} with a density similarity ratio is 1.667:1 and a stress similarity ratio is 333:1. A uniform equivalent load of 8.03 kPa was applied above the model. In this section, the mining scheme was designed similarly to that described earlier in section: first, mining was carried out on the 1202-1 panel, then on the 1604 panel, and finally on the 1202-2 panel. Each mining cycle involved excavating a length of 5.0 cm. During coal mining, 11 diaphragm earth pressure cell were installed every 210 mm at the main roof position to monitor stress changes. At the same time, BZ2205C static resistance strain gauge was used to record experimental data. Displacement in the overlying strata was monitored using the Matchid-ID non-contact full-field strain measurement system.¹⁸ Physical analog model (PAM) and modeling process can be seen in Fig. 4. The similar materials and ratios of the main rock layers are shown in Table 2.

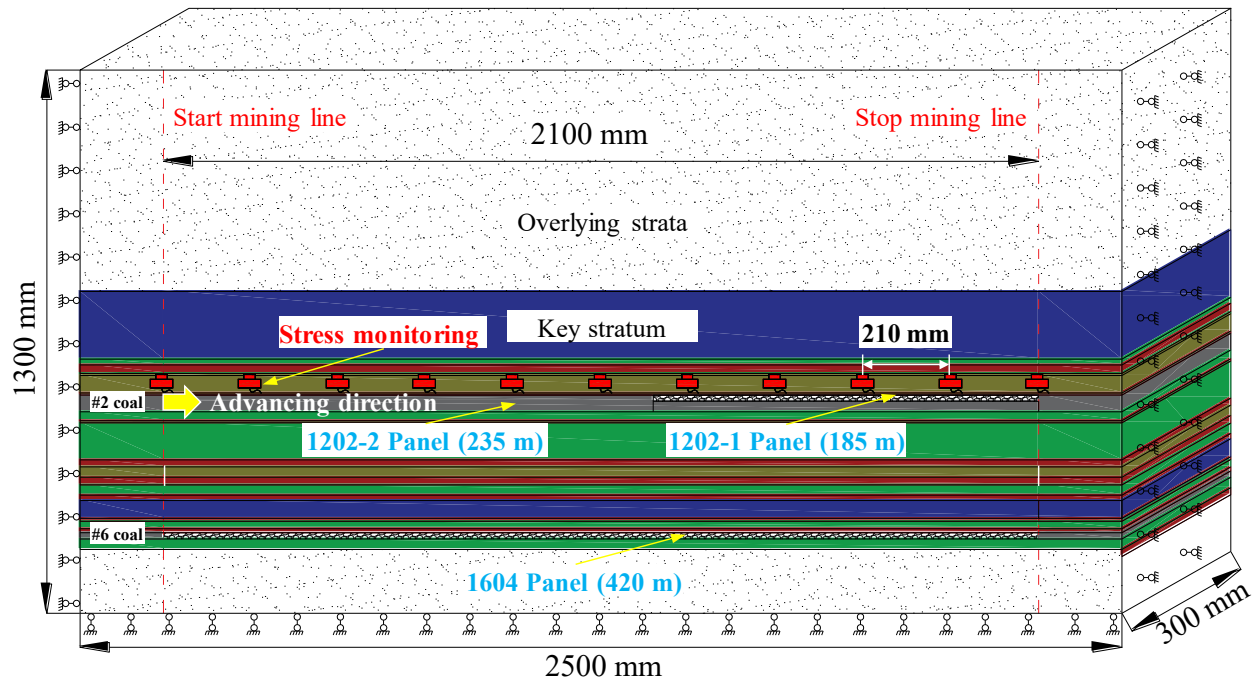


Fig. 4. Physical analog model (PAM) and modeling process.

Table 2 Similar materials and ratios of the main rock layers

No.	Lithology	Similar materials and weight			Thickness /cm
		Sand/kg	Calcium carbonate/kg	Gypsum/kg	
1	Coarse sandstone	234.79	54.79	23.47	16.17
2	Fine sandstone	19.03	3.33	1.43	1.41
3	Siltstone	27.46	4.81	2.06	2.00
4	Fine sandstone	6.75	1.18	0.51	0.50
5	Medium sandstone	58.79	8.23	3.53	4.18
6	Siltstone	7.14	1.25	0.54	0.52
7	#2 coal	74.43	6.62	1.65	4.00
8	Fine sandstone	28.63	5.01	2.15	2.12
9	Siltstone	7.00	1.23	0.53	0.51
10	Fine sandstone	86.15	15.08	6.46	6.38

11	Siltstone	22.76	3.98	1.71	1.68
12	Medium sandstone	35.16	4.92	2.11	2.50
13	Siltstone	24.72	4.33	1.85	1.80
14	Fine sandstone	33.35	5.84	2.5	2.47
15	Siltstone	17.58	3.08	1.32	1.28
16	Coarse sandstone	41.67	9.72	4.17	2.87
17	Siltstone	9.13	1.60	0.69	0.67
18	Fine sandstone	24.17	4.23	1.81	1.79
19	Siltstone	13.18	2.31	0.99	0.96
20	#6 coal	29.62	2.63	0.66	1.50
21	Fine sandstone	33.89	5.93	2.54	2.51

Results

Numerical Simulation Results

After the formation of adjacent goafs on the panel, the stress distribution in the mining area is shown in Fig. 2. After the adjacent panels of the 1202-2 panel are sequentially mined, the stress evolution process of the surrounding rock in the goaf is shown in Fig. 5.

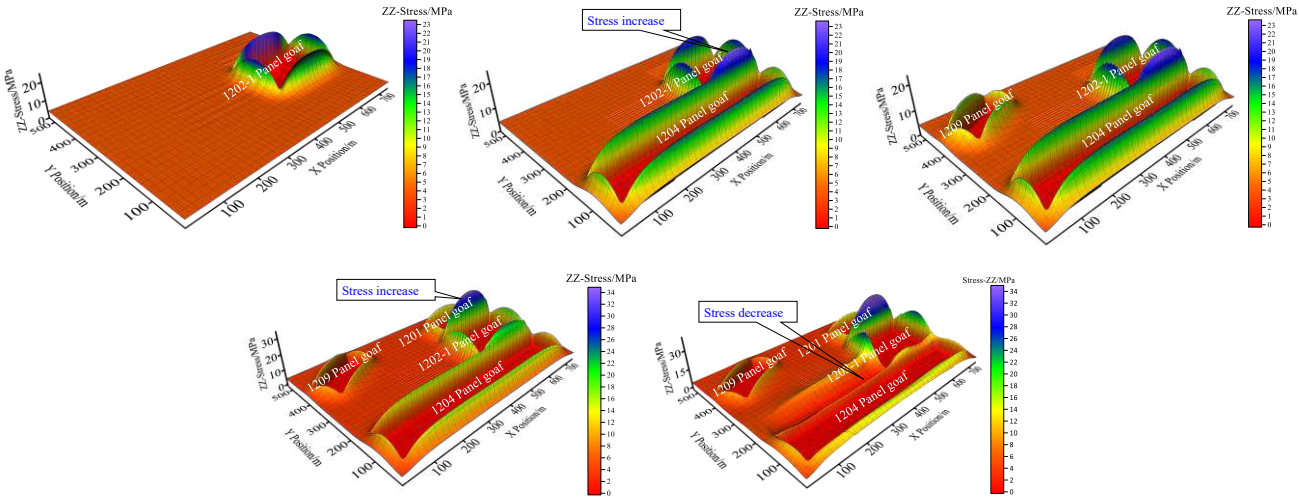
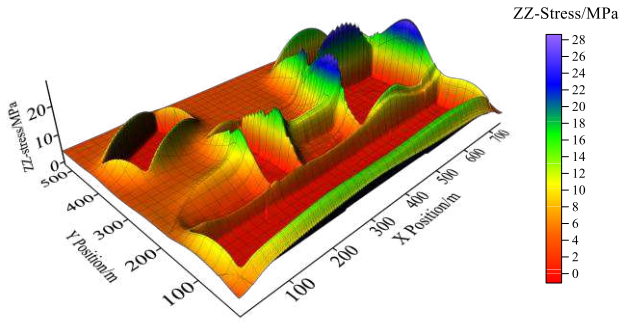


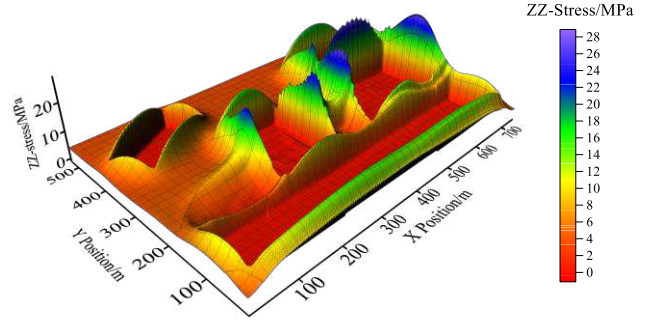
Fig. 5. Evolution process of surrounding rock stress in the goaf

According to Fig. 5, after the mining of the 1202-1 panel, there is a significant concentration of stress in the surrounding coal and rock mass of the goaf, with a peak vertical stress range of about 18~22 MPa. After mining the 1204 panel, stress increased and transferred, mainly concentrated in the 25 m coal pillar between the two panels, reaching a peak of 23 MPa. After mining the 1209 panel, due to the relatively large distance, the stress values and the impact range of the surrounding rock are relatively small. After mining the 1201 panel, the overall surrounding rock stress in the mining area increased, particularly along the 14 m coal pillar between the goaf of the 1201 panel and the goaf of the 1202-1 panel, with a peak stress of 34 MPa and a stress concentration factor of 5.6. Finally, after the mining of the 1604 panel, the stress in the upper 1204 panel goaf, 25 m coal pillar, and some areas of the 1202-1 goaf decreased significantly, with a peak stress of about 10~12 MPa, indicating that the mining of this panel has a certain press. relief effect on the overlying rock strata.

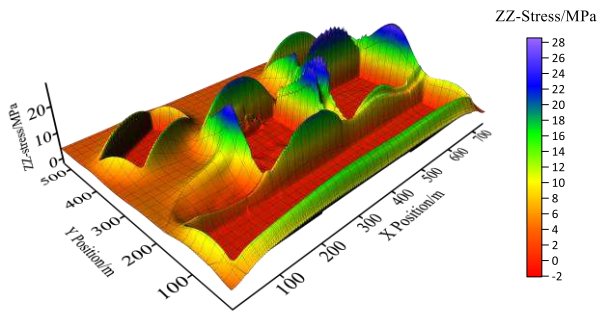
The stress distribution and evolution of the 1202-2 panel when advancing to 75 m, 150 m, 200 m, 250 m, 300 m, and 350 m are shown in Fig. 6. The stress distribution along the vertical sections of A-A, B-B, C-C, and D-D during the progress of the panel is shown in Fig. 7. The corresponding stress evolution curve is shown in Fig. 8.



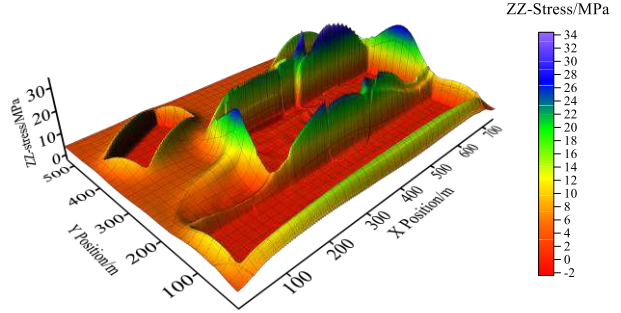
(a) advancing 75 m



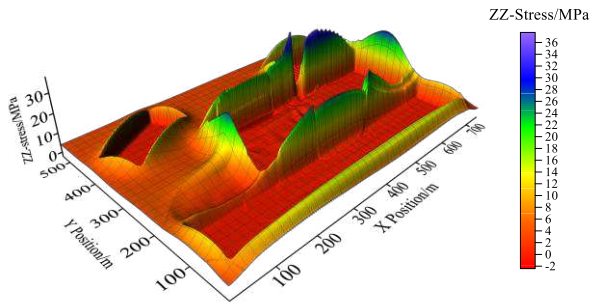
(b) advancing 150 m



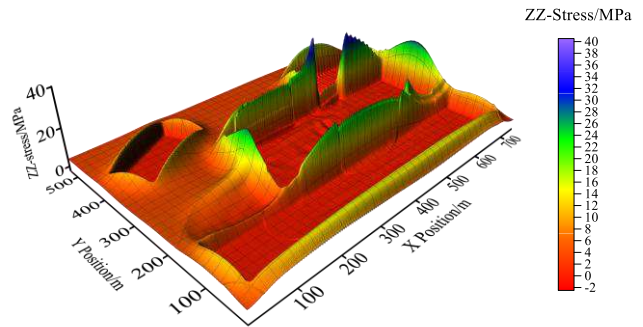
(c) advancing 200 m



(d) advancing 250 m

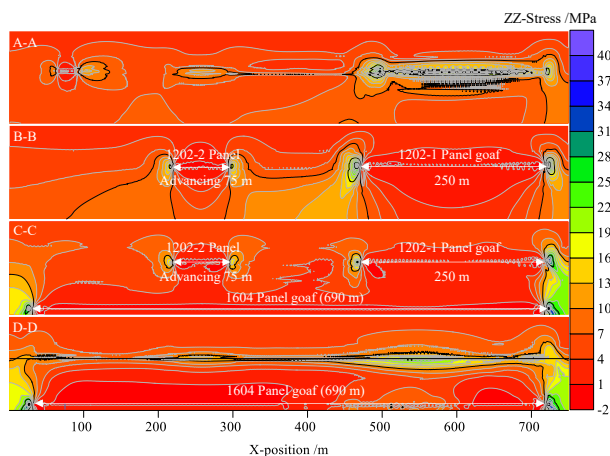


(e) advancing 300 m

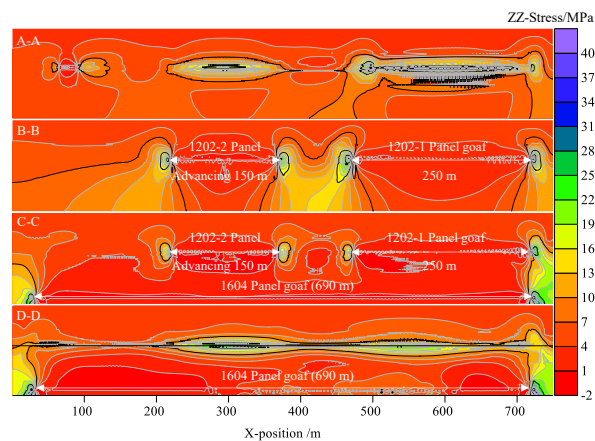


(f) advancing 350 m

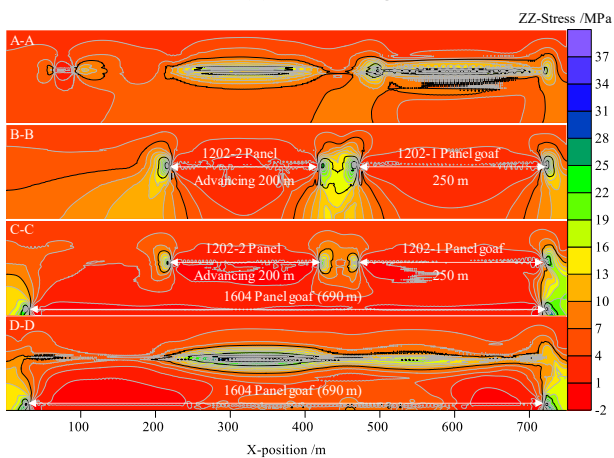
Fig. 6. Stress distribution and evolution during the 1202-2 panel mining



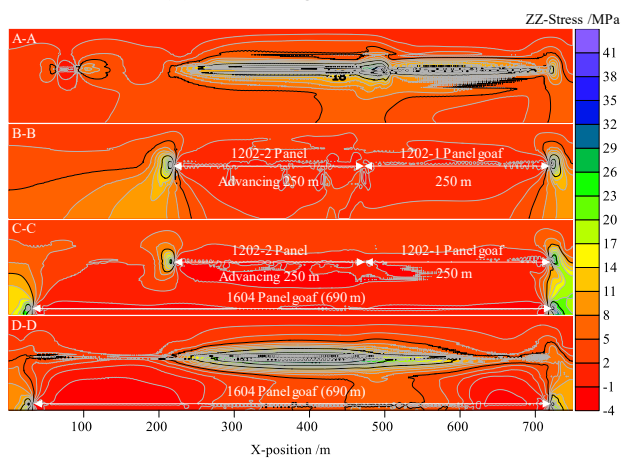
(a) advancing 75 m



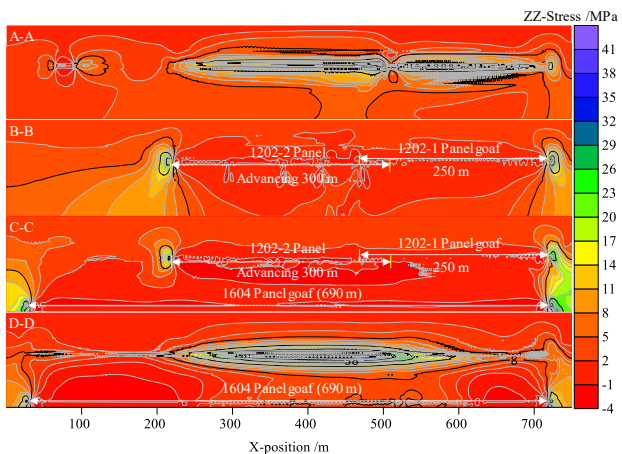
(b) advancing 150 m



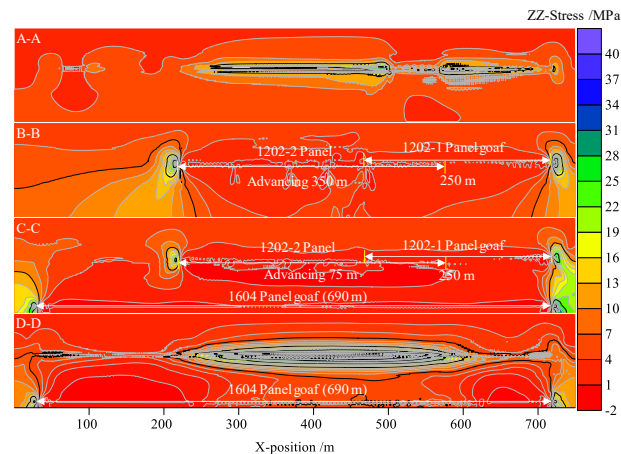
(c) advancing 200 m



(d) advancing 250 m



(e) advancing 300 m



(f) advancing 350 m

Fig. 7. Sectional diagram of stress distribution along the strike of the panel

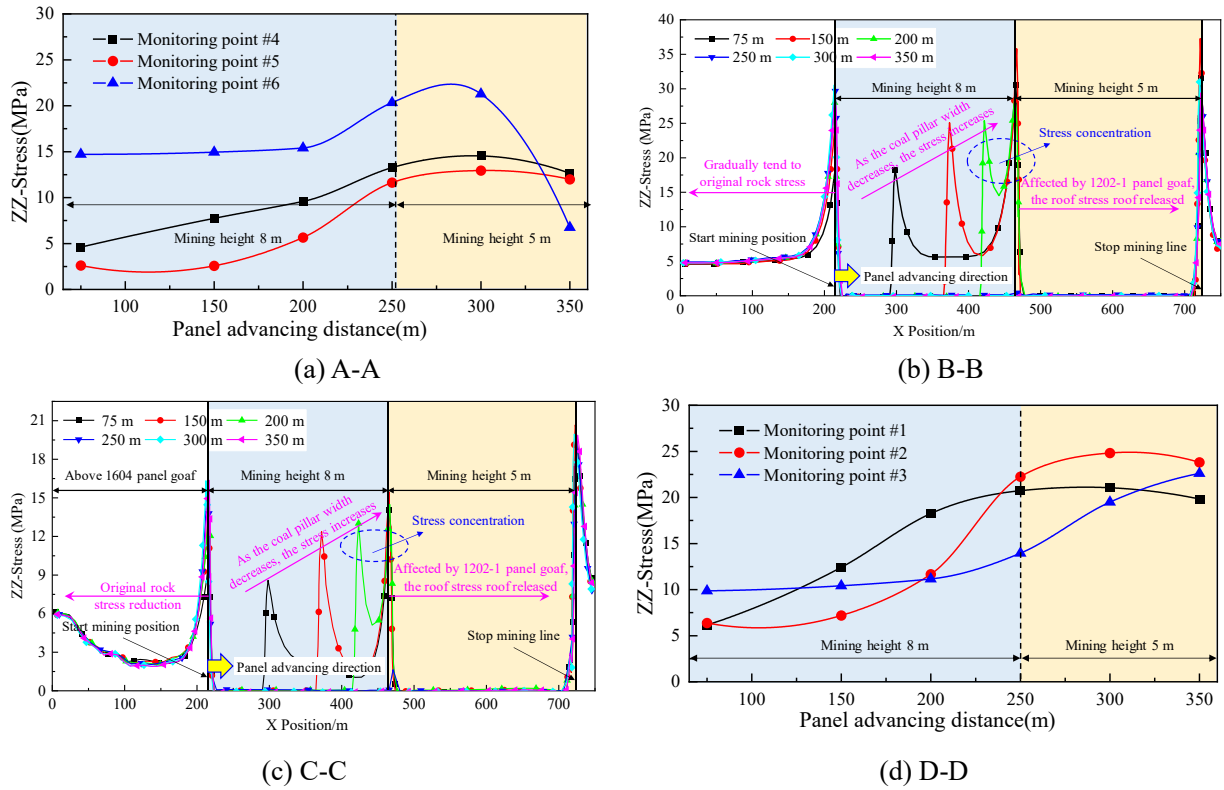


Fig. 8. Stress curves of different profiles during the 1202-2 panel mining

Fig. 6 shows that when the 1202-2 panel is advanced to 75 m, the peak stress at the advanced support of the panel is about 20 MPa, and the stress concentration factor is 3.20, located about 10 m in front of the panel's coal wall. When the panel is advanced to 150 m, the peak stress at the advanced support further increases to 26 MPa, and the stress concentration factor increases to 4.16. When the panel is advanced to 200 m, the stress in the coal seam ahead increases further, and the stress concentration is significant, with a maximum factor of 4.48, mainly due to the decrease in coal pillars near the 1202-1 goaf. When the panel advanced to 250 m, the coal seam with a thickness of 8 m was fully mined, and a significant triangular stress concentration zone was formed in the open-off cut area of the 1201 goaf on the west side. When the panel advances to 300 m, the coal seam mining thickness is 5 m, and the stress is significantly reduced. The stress on both sides of the coal pillars shows clear asymmetry, with the peak vertical stress in the west coal pillar about 28 MPa and in the east coal pillar about 22 MPa. When the panel advances to 350 m, the surrounding rock stress is relatively stable.

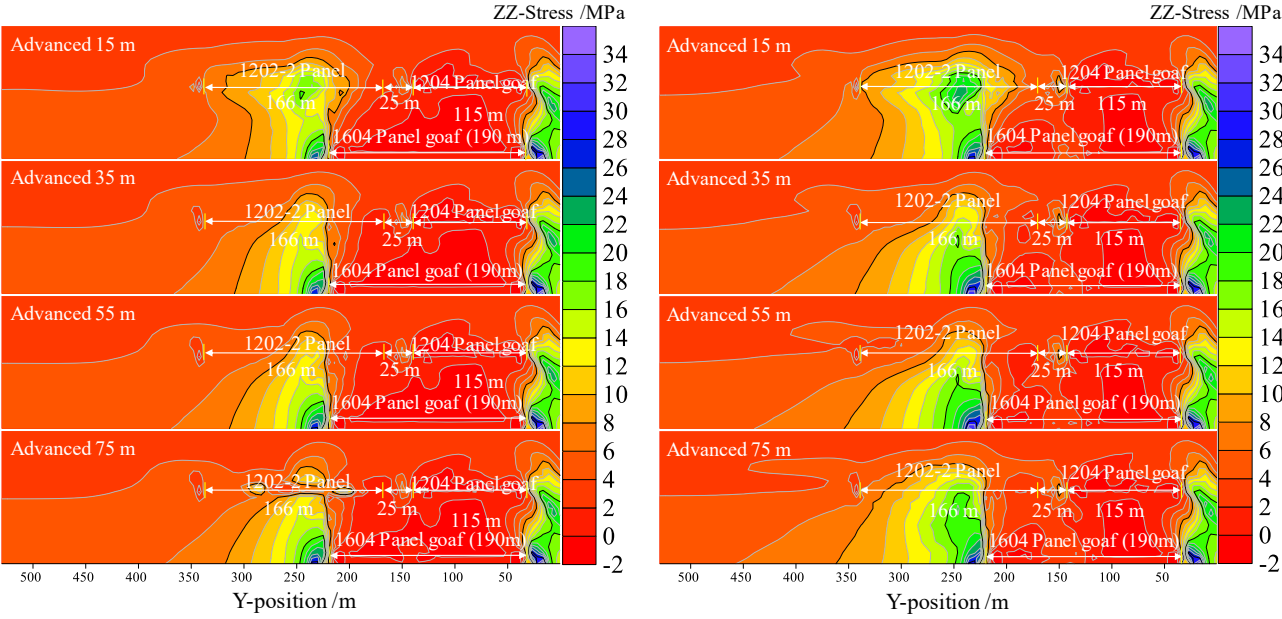
From Fig. 7, it can be seen that when the advancing distance of the panel is 0~200 m, as the advancing distance increases, the peak value of the advance support pressure shifts forward, and the range of the high-stress zone gradually expands. When the panel advanced to 200 m, only 50 m of coal pillars remained from the 1202-1 goaf, and the peak support stress ahead of the panel in the B-B section increased to 30 MPa. Comparing the vertical stress between the B-B and C-C profiles, the C-C profile is affected by the lower 1604 panel goaf, which releases the stress in the coal rock mass and reduces the overall stress level compared to the B-B profile. When the advancing distance is 250~350 m, the roof becomes a 1202-1 goaf, forming a stress relief mining area. At this point, the peak and range of front stress in front of the panel have significantly decreased, and the stress concentration factor is close to 1.0.

It can be inferred from Fig. 8 that the 1202-2 panel is affected by the 1604 panel goaf, and the stress peak in the C-C profile stress monitoring curve is significantly lower than that in the B-B profile, by 50%. The initial stress of the 25 m coal pillar is generally high due to the 1204 panel goaf effect, and shows an upward trend as the panel

193 advances. The stress at measuring point #2, located in the transition section, rapidly increased from 12 MPa to about
 194 27 MPa, indicating a significant local stress concentration near the coal thickness change during mining. In contrast,
 195 the stress evolution on the 14 m coal pillar side is more complex. The initial stress at measuring point #6, located
 196 between two goaf areas, is significantly higher than that at measuring points #4 and #5. The stress growth of the
 197 measuring point on the 14 m coal pillar is slow before the coal thickness changes as the panel advances. When the
 198 panel advances to 300 m, and both sides are goaf areas, the stress increases to 21.2 MPa.

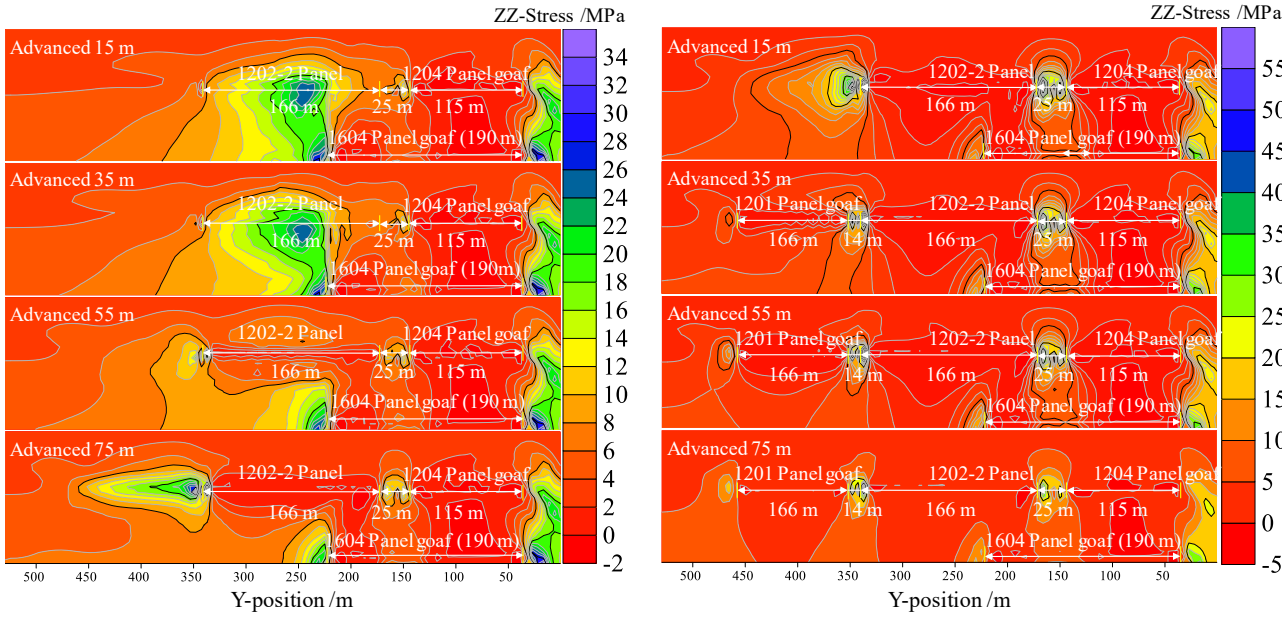
199 The stress at positions 15 m, 35 m, 55 m, and 75 m ahead of the panel during the mining, the different sectional
 200 diagrams of stress distribution along the dip of the panel can be seen in Fig. 9. The lateral stress distribution curves
 201 of I-I, II-II, III-III, and IV-IV profiles are plotted in Fig. 10.

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203

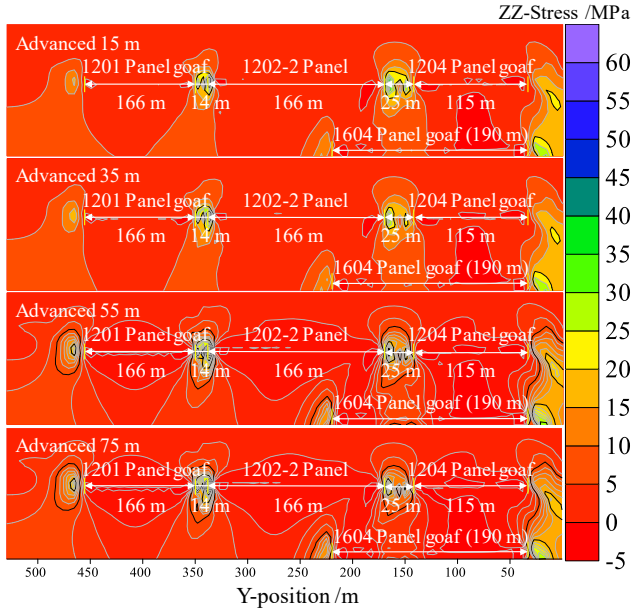


(a) advancing 75 m (b) advancing 150 m

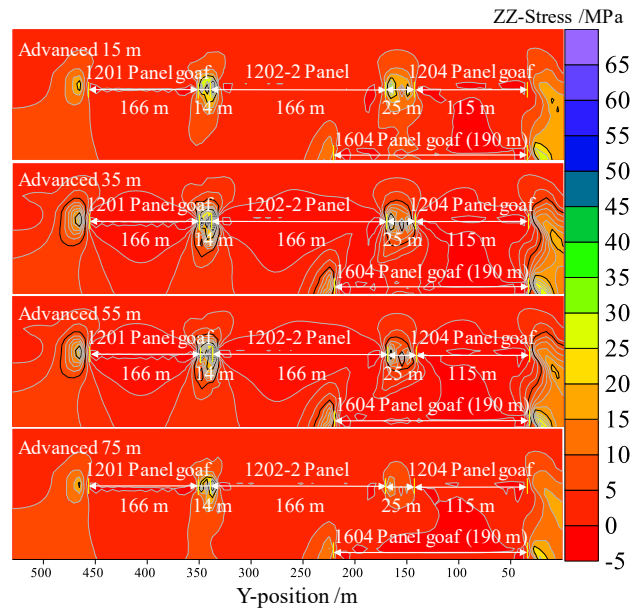
204
205



(c) advancing 200 m (d) advancing 250 m

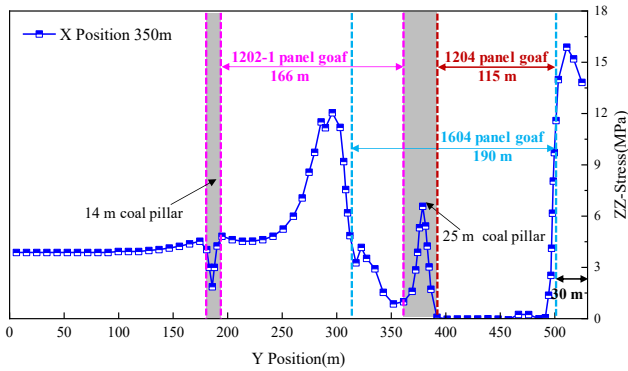


(e) advancing 300 m

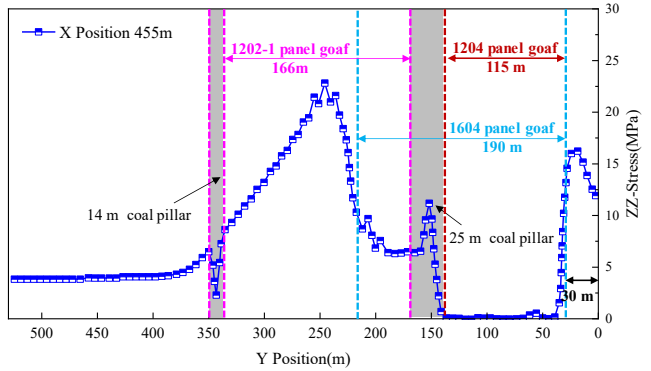


(f) advancing 350 m

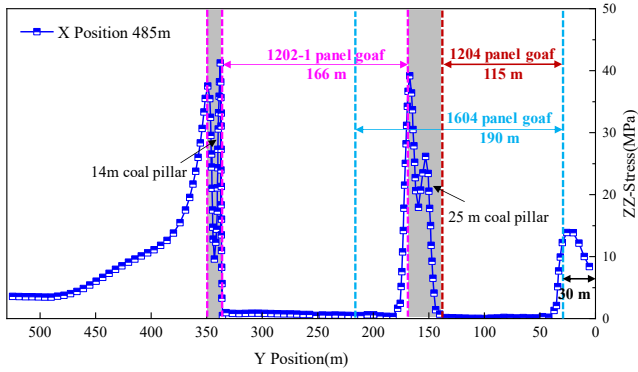
Fig. 9. Sectional diagram of stress distribution along the panel dip



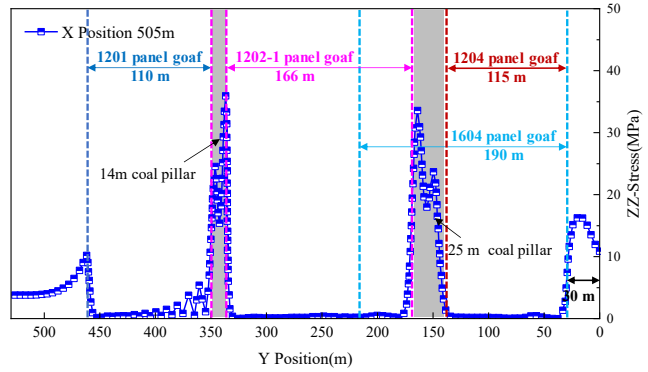
(a) I-I



(b) II-II



(c) III-III



(d) IV-IV

Fig. 10. Lateral stress distribution curves of different profiles

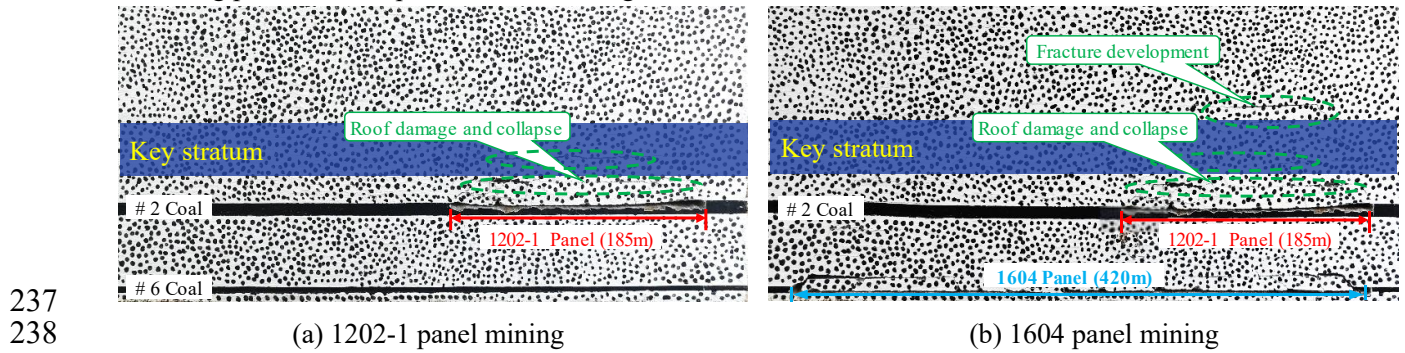
From Fig. 9, it can be seen that when the panel advances by 75 m, 150 m, and 200 m, the stress distribution shows a "low on both sides and high in the middle" pattern. As the mining distance increases, the stress concentration in the

216 panel's middle area becomes more pronounced. In contrast, the pressure relief in the panel's goaf area is more
 217 pronounced, with no stress concentration. When the panel advances to 250~350 m, the pressure relief effect of the
 218 goaf above significantly improves the surrounding rock environment, with stress ranging from 0 to 10 MPa. The
 219 stress from the overlying rock strata is transferred to the isolated coal pillars on both sides, resulting in stress
 220 concentration within them. At this stage, the coal pillars on both sides maintain a relatively stable, high-stress state
 221 at different positions. This indicates that after the overlying goaf structure stabilizes, the influence of the panel's
 222 advanced stress on the front coal wall is significantly reduced, and the lateral support stress becomes the dominant
 223 factor.

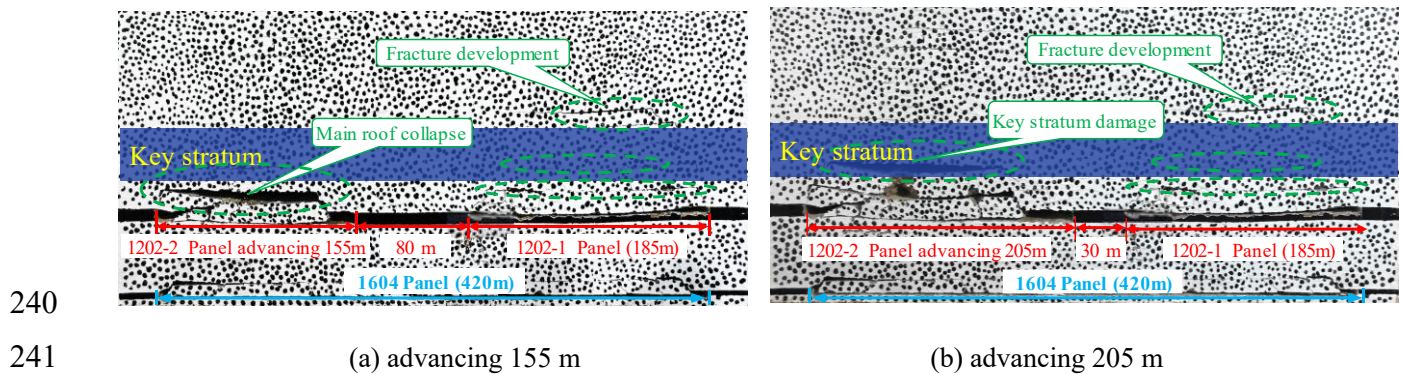
224 Fig. 10 shows that during the initial stage of advancing the panel, the peak support pressure in front of the coal
 225 gradually increases from 12.41 to 21.93 MPa, indicating a significant stress concentration. Due to the 1604 panel
 226 goaf, a significant trough appeared in the stress curve, resulting in stress concentration in the 25 m coal pillar. When
 227 the panel advances to 265 ~285 m, the roof load transfers to the boundary coal pillars on both sides, causing a sharp
 228 increase in the lateral support stress borne by the pillars. When the panel advanced to 265 m, it was located in the
 229 area of coal seam thickness variation. The stress peak in the 14 m coal pillar area reached about 36 MPa. When the
 230 panel advanced to 285 m, the west side became the 1201 panel goaf, and the vertical stress values in the coal pillars
 231 on both sides remained high.

232 PAM Experiment Results

233 The characteristics of overburden movement and damage after 1202-1 and 1604 panel mining and during 1202-2
 234 panel mining are shown in Fig. 11. For the advancing distances of the 1202-2 panel of 155, 205, 310, and 420 m, the
 235 characteristics of overburden movement and damage are shown in Fig. 12. The peak stress variation of the roof during
 236 the mining process of the panel is shown in Fig. 13.



239 Fig. 11. Characteristics of overburden movement and damage after 1202-1 and 1604 panel mining



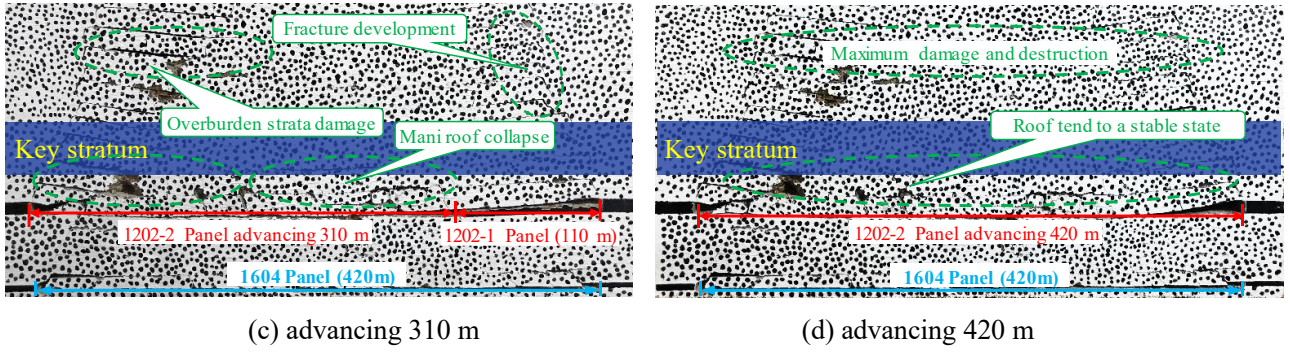


Fig. 12. Characteristics of overburden movement and damage during 1202-2 panel mining

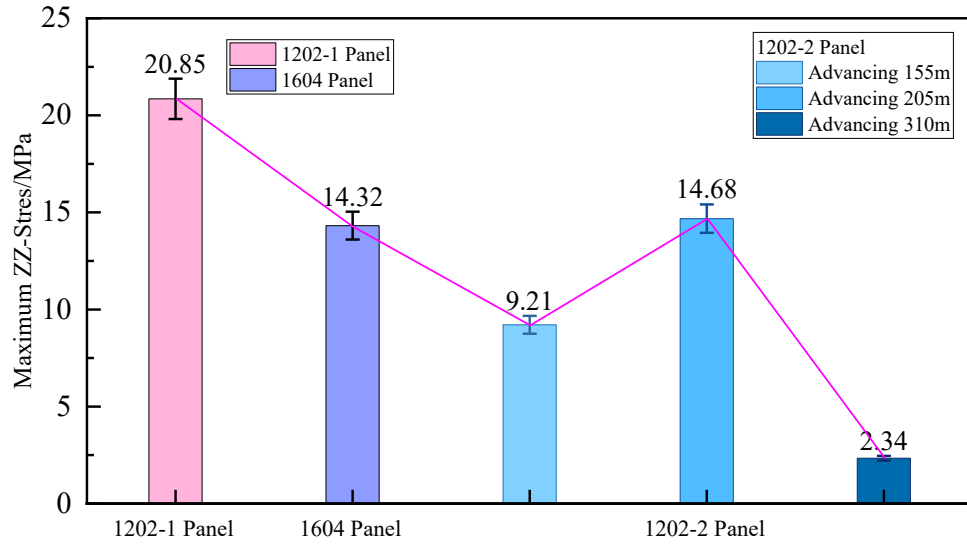


Fig. 13. The peak stress variation of the roof during the coal seam mining

According to Figs. 11 and 12: after mining the 1202-1 panel, the roof was damaged and collapsed, and the overlying rock strata developed longitudinal and transverse fractures, but the key stratum remained stable. After mining the 1604 panel, the damage to the overburden strata had a certain impact on the #2 coal seam. The overlying rock fractures of the 1202-1 panel have developed to the key stratum, and the overall overlying rock showed an asymmetric failure characteristic of "weak on the left and strong on the right". When the advancing distance of the 1202-2 panel ranged from zero to ~235 m, the coal seam mining thickness was 8.0 m. At the advancing distance range of the panel of 235~420 m, the coal seam mining thickness was 5 m. When the advancing distance of the panel was 155 m, the overlying rock strata were mainly characterized by the development of separation fractures and roof fractures, and the height of fracture development was relatively small. When the advancing distance of the panel was 205 m, the deformation and damage of the overlying rock were severe, and the disturbance deformation of the key stratum was strong. When the advancing distance of the panel reached 310 m, the key stratum had already broken, and the 1202-1 panel was in a state of repeated mining under relatively low mining pressure. After the panel was mined, the overlying rock fractures extended into the upper part of the key stratum, forming a typical three-zone development feature: "collapse, fracture, and bending subsidence zones".

According to Fig. 13, the maximum mining stress on the roof of the 1202-1 panel after mining reached 20.85 MPa, with a stress concentration factor of about 3.34, showing a high mining stress concentration. After the mining of the 1604 panel, the maximum mining stress of the roof of #2 coal seam was 14.32 MPa, and the stress concentration

factor dropped to about 2.29, indicating that the mining of the lower 1604 panel had a certain pressure relief effect on the overlying rock strata, verifying the conclusions of the previous research. At a 155 m advancing distance of the 1202-2 panel, due to the pressure relief effect of the goaf of the 1604 panel below, the maximum mining stress on the roof was 9.21 MPa, and the overall stress was relatively low. When the advancing distance of the panel was 205 m, the reduction in the width of the coal pillar in front caused stress concentration during mining. At this time, the maximum stress reached 14.68 MPa, and the stress concentration factor was 2.35. When the panel's advancing distance reached 310 m, it was simultaneously subjected to pressure relief from the 1202-1 and 1604 goaf zones. The maximum mining stress of the roof sharply decreased to 2.34 MPa, and the stress concentration factor dropped to 0.37, well below the original rock stress level. This strongly indicated that the surrounding rock in this area was under stable pressure relief.

Discussion

The 1202-2 panel is significantly affected by repeated mining across multiple panels, and the environmental conditions are complex. During the mining process of the panel, the mining pressure law is mainly influenced by key factors such as the stability of the overlying rock strata, disturbance of the same layer goaf, the lower goaf, and coal seam thickness. Combining the above numerical simulations and physical similarity experiments, the key influencing factors are analyzed as follows:

(1) Overlying key stratum

According to the theory of rock stratum control under mining pressure,¹⁹ the strata that exert full or partial control over the movement of overlying rock layers are referred to as key strata. The identification of key strata primarily involves assessing stiffness conditions and strength conditions: first, one needs to determine the position of hard rock layers within the overlying strata. The load $(q_n)_1$ exerted by the n -th stratum on the first stratum is derived as follows:

$$(q_n)_1 = \frac{E_1 h_1^3 (\gamma_1 h_1 + \gamma_2 h_2 + \dots + \gamma_n h_n)}{E_1 h_1^3 + E_2 h_2^3 + \dots + E_n h_n^3} \quad (1)$$

where E_i , h_i , and γ_i are the elastic modulus, thickness, and bulk density of the i -th rock layer, respectively. If $(q_{n+1})_1 < (q_n)_1$, this indicates that the $(n+1)$ -th layer of rock has high strength and small deformation, and is the first hard rock layer. Similarly, the location of all hard rock layers is identified. Then, the fracture distance analysis is performed, using the following formula:

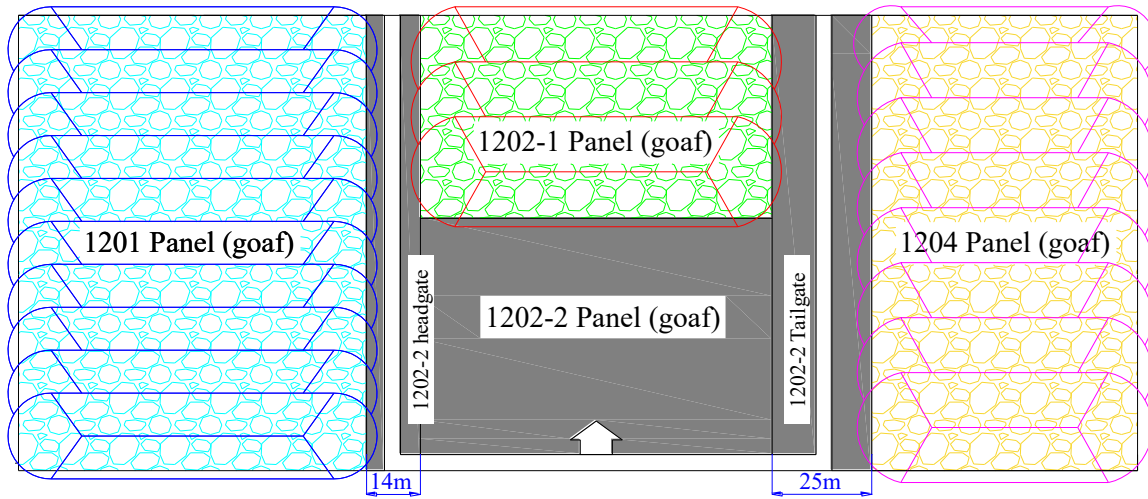
$$L_i = h_i \sqrt{\frac{2\sigma_i}{q_i}} \quad (2)$$

where σ_i is the tensile strength of the i -th hard rock layer, h_i is the thickness, and q_i is the load it bears. If $L_i < L_{i+1}$, this indicates that the i -th layer of hard rock has broken independently and is a key stratum.²⁰

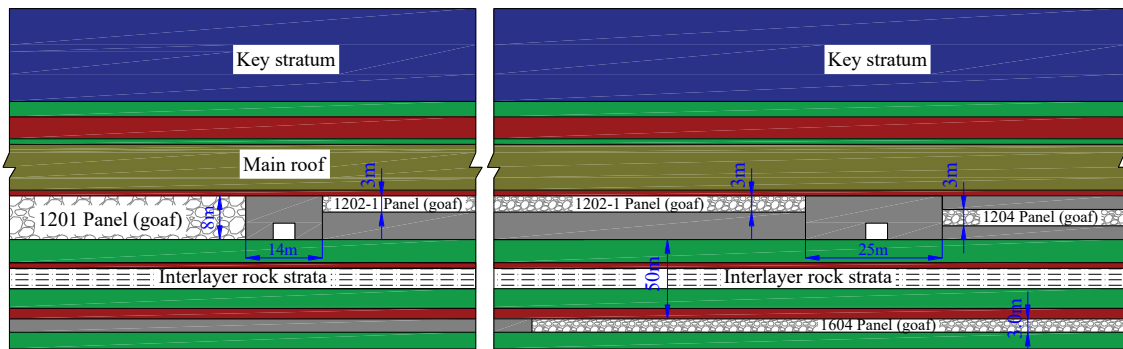
Based on the lithological information of the drilling rock layers in the 1202-2 panel area and the key stratum theory mentioned above, the sixth layer of coarse sandstone above the coal seam (17.21 m from the coal seam) was ultimately determined as the key stratum, which has a critical impact on roof failure and the mining pressure during mining. This conclusion can be verified from the numerical simulation and physical similarity experiments of mining pressure evolution and overlying rock failure characteristics in the previous section. Therefore, if necessary, roof pre-splitting techniques (such as drilling and blasting, hydraulic fracturing, etc.) can be adopted on site for key stratum to reduce the strength of mining pressure.

(2) Adjacent panel goaf

301 The 1202-2 panel is adjacent to multiple panel goafs, and the surrounding rock environment is very complex. The
 302 surrounding goafs exhibit significant differences in formation time, spatial scale, and rock failure intensity, leading
 303 to asymmetric and asynchronous failure characteristics within the surrounding rock structure. The top and front views
 304 of the surrounding rock structure in the 1202-2 panel area are shown in Figs. 14 and 15.



305
 306 Fig. 14. Top view of the fractured overlying rock structure



307
 308 Fig. 15. Front view of adjacent goaf distribution in the 1202-2 panel

309 From Fig. 14 and Fig. 15, it can be seen that the adjacent 1201 panel is a top-coal-caving panel with a mining
 310 height of 8 m. The larger mining height leads to an increase in the goaf size, the hanging area and sinking space of
 311 the roof, and the bending moment and tensile stress, resulting in a significant reduction in the initial and periodic
 312 fracture distances of the overlying rock layer. The movement of high-level rock layers is more intense, the formation
 313 speed of "O" - shaped circles is accelerated, diagonal "X" - shaped cracks are more fully developed, and asymmetric
 314 fractures are more likely to occur, especially under isolated islands or asymmetric boundary conditions. An increase
 315 in mining height can easily trigger the breaking of overlying key layers, leading to upward extension of overlying
 316 rock movement and the simultaneous or alternating breaking of multiple rock formations, releasing energy and
 317 increasing the dynamic load coefficient, thereby triggering dynamic disasters such as strong mining pressure. The
 318 adjacent 1202-1 and 1204 panels have a mining height of 3 m. Due to the influence of mining height, their initial and
 319 periodic fracture distances are relatively large. Moreover, mining of the panel has been ongoing for nearly 20 years,
 320 and the overlying rock strata have remained stable. The rock damage caused by mining is relatively weak. The 1604
 321 panel is located directly below the 1202-2 panel, and this goaf provides some pressure relief in certain areas of the
 322 1202-2 panel. At the same time, it will cause the asymmetric distribution characteristics of the surrounding rock
 323 structure and stress field during the mining process of the 1202-2 panel. In addition, the coal pillar widths between

the goaf of panels 1202-1, 1201, and 1204 are 14 m and 25 m, respectively. The differences in mining height, mining time, and coal pillar width will further exacerbate the complex manifestation of mining pressure resulting from asymmetric damage to the surrounding rock structure during 1202-2 panel mining. This further validates and explains the conclusions drawn from the numerical simulation and physical similarity experiments.

(3) Lower panel goaf

The coal seam recovered from the 1604 panel is the # 6 coal seam, with an average thickness of 3 m. The roof rock layer is a medium-hard rock layer. Referring to the design and references,^{21, 22} the development height of the collapse zone and fracture zone after mining can be estimated as follows:

$$H_c = \frac{100M}{4.7M + 19} \pm 2.2 \quad (3)$$

$$H_f = \frac{100M}{1.6M + 3.6} \pm 5.6 \quad (4)$$

where H_c is the height of the collapse zone, H_f is the height of the fracture zone, and M is the thickness of the coal seam mining.

Based on the above calculations, H_c is 11.26 m and H_f is 41.31 m. According to the on-site measurement results, the collapse zone of the 1604 panel after mining is 15.90~16.50 m, and the height of the fracture zone is about 53.34~56.25 m. Taking the relatively larger value between the theoretical formula calculation and the on-site measurement results, the maximum height of the roof collapse zone and fracture zone after mining of the 1604 panel is about 72.75 m. The average vertical distance between the 1604 panel and the upper 1202-2 panel is 50 m, indicating that the goaf of the lower 1604 panel exerts a pressure-relief effect on the 25 m coal pillar and the 1202-2 panel. This will result in strong mining pressure in the upper half of the mining area and weaker pressure in the lower half during mining of the 1202-2 panel. This explains the main reason for the asymmetric mining pressure law of the 1201 working face.

(4) Coal seam thickness

The thickness of the coal seam in the 1202-2 panel has significantly changed during advancement, with the area divided into 8 m and 5 m thicknesses. Affected by the mining height, the closer the panel is to the 1202-1 panel goaf, the greater its mining-induced ground pressure (see Fig. 16).

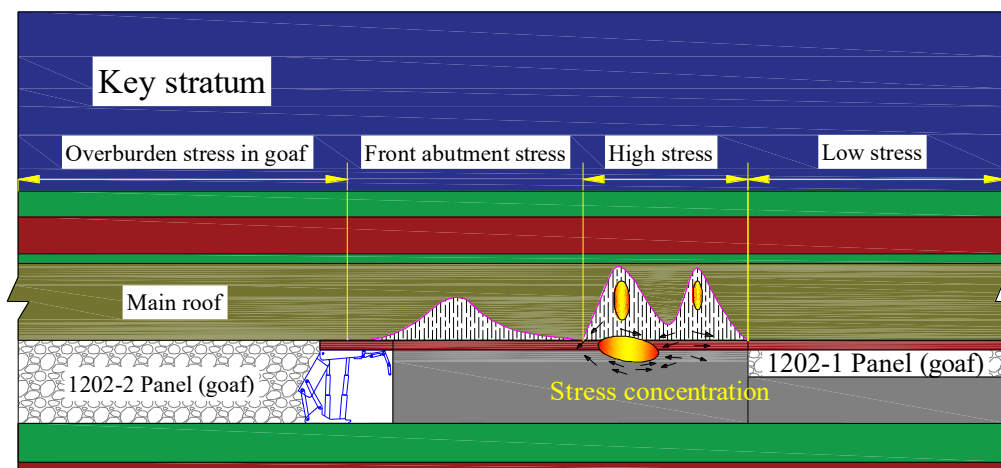


Fig.16. Changes in coal seam thickness and distribution and transmission of mining energy in the panel

As shown in Fig. 16, during the advancement of the 1202-2 panel, due to the influence of mining height, the stress in the coal wall ahead of the panel with an 8 m coal seam thickness is greater than that in the 5 m area. As the panel

gradually approaches the 1202-1 panel goaf, the stress concentration in the coal pillar in front of 1202-2 will intensify, and its stress peak curve will overlap with that of the 1202-2 panel goaf, leading to energy accumulation. As a result, the support's working resistance increases, and the deformation of the surrounding rock around the roadway intensifies, leading to strong mining pressure patterns. At the same time, due to the asymmetric influence of the two sides and the lower 1604 panel goaf, the mining pressure shows asymmetric differential characteristics, which, in turn, affects the safe and efficient mining of the 1202-2 panel.

Conclusions

The results obtained via numerical simulations and physical analog modeling of the case study coal mine made it possible to draw the following main conclusions:

1) The performed analysis of key influencing factors on the law of mining pressure in the case study panel shows that the sixth layer of coarse-grained sandstone above the coal seam (17.21 m away from the coal seam) was ultimately determined as the key stratum, having a critical impact on roof failure and the mining pressure during the mining. The 1202-2 panel was affected by the mining height, mining time, and coal pillar width, and the surrounding rock structure has asymmetric failure characteristics. Moreover, it was affected by the lower 1604 panel goaf, and some areas of the 1202-2 panel were within the pressure relief range. At the boundary between coal seam thickness variation, energy accumulation, and stress concentration, mining pressure was high.

2) After the formation of adjacent goafs, the 1202-2 panel reached a complex asymmetric stress state, with a maximum stress of 34 MPa, located in the 14 m coal pillar area between the 1202-1 and 1201 goafs. During the mining period of the 1202-2 panel, the maximum stress reached 28 MPa, with a stress concentration factor of up to 4.48. The lower area of the 1202-2 panel along the dip direction was under overall pressure relief, with a stress peak 50% of that in the upper area, while the transition area showed a pronounced stress concentration effect. During the mining period of the 1202-2 panel, the stress changes in the 14 m coal pillar (where the headgate was located) were complex, being manifested as stress concentration in the coal seam thickness variation area, the coal pillar area between the 1201 and 1202-1 goafs, and high mining pressure. The surrounding rock deformation and damage to the headgate in this area were severe, necessitating strengthening of its support.

3) Physical analog modeling experiments proved that during the mining period of the 1202-2 panel, near the 1202-1 goaf, the rock movement and damage were severe, and the stress concentration effect was strong. After mining the panel 1202-2, the overlying key layer (coarse sandstone) was fractured, while the observed mining pressure evolution pattern matched numerical simulation predictions. The research results obtained provide certain theoretical substantiation for the study of mining pressure laws and control in similar isolated panels and geological conditions.

Data availability

All data generated or analyzed during this study are included in this published article.

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436 **Author Contributions**

437 Q. S. conceived the research idea and drafted the original manuscript, and visualized the calculation results. Y.
438 H. designed the research methodology. X. L. organized the computational data. K. C. reviewed and revised the
439 initial draft. Q. S. conducted the final checks. All authors reviewed and approved the final manuscript.

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442 **Declaration**

443 **Competing interests**

444 The authors declare no competing interests.

445 **Additional information**

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