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Geotechnical considerations for concurrent pillar recovery in close-distance multiple seams

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Abstract

Room-and-pillar mining with pillar recovery has historically been associated with more than 25% of all ground fall fatalities in underground coal mines in the United States. The risk of ground falls during pillar recovery increases in multiple-seam mining conditions. The hazards associated with pillar recovery in multiple-seam mining include roof cutters, roof falls, rib rolls, coal outbursts, and floor heave. When pillar recovery is planned in multiple seams, it is critical to properly design the mining sequence and panel layout to minimize potential seam interaction. This paper addresses geotechnical considerations for concurrent pillar recovery in two coal seams with 21 m of interburden under about 305 m of depth of cover. The study finds that, for interburden thickness of 21 m, the multiple-seam mining influence zone in the lower seam is directly under the barrier pillar within about 30 m from the gob edge of the upper seam. The peak stress in the interburden transfers down at an angle of approximately 20°away from the gob, and the entries and crosscuts in the influence zone are subjected to elevated stress during development and retreat. The study also suggests that, for full pillar recovery in close-distance multiple-seam scenarios, it is optimal to superimpose the gobs in both seams, but it is not necessary to superimpose the pillars. If the entries and/or crosscuts in the lower seam are developed outside the gob line of the upper seam, additional roof and rib support needs to be considered to account for the elevated stress in the multiple-seam influence zone.

Keywords

Pillar recovery; Room-and-pillar; Retreat mining; Multiple seam; Mining sequence; Pillar design

1. Introduction

Room-and-pillar mining accounted for about 40% of underground coal production in the United States in 2016. Pillar recovery, practiced in about one-third of the room-and-pillar

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mines, represents about 10% of the coal mined underground, yet it has historically been associated with more than 25% of all ground fall fatalities [1]. In some U.S. coal fields, particularly central Appalachia, many coal mines are operating under geological conditions with multiple coal seams. The risk of ground falls during pillar recovery increases under multiple-seam mining conditions [2,3]. The hazards of pillar recovery associated with multiple-seam mining include roof cutters, roof falls, rib rolls, coal outbursts, and floor heave [4-11]. Pillar retreating creates abutment pressure, not only in the currently mined seam, but also in the overlying or underlying seams. Multiple-seam interactions become more pronounced as overburden depth increases and interburden thickness decreases. To safely recover the pillars in multiple seams, it is critical to properly plan the mining sequence and panel layout to minimize potential multiple-seam interaction.

The degree of multiple-seam interaction can be influenced by the sequencing of seams, pillar and entry design, and the layout of workings [12]. Seams can be mined by two basic seam sequences: in descending order with mining completed in the upper seams before any mining is initiated in the lower seams, or in ascending order with mining completed in the lower seams before any mining is initiated in the upper seams. A descending order of pillar recovery is considered the most preferable practice to minimize multiple-seam interactions. Seams mined in this order are influenced by the abutment stress transferred from the overlying pillars, gob-solid boundaries, and barrier pillars. Seams mined by ascending order can also experience interactions resulting from subsidence fractures if full pillar extraction is previously conducted in the lower seams. Multiple-seam interactions could become more complicated where mining is between previously mined seams. Multiple-seam interaction can be minimized if the pillars in the lower and upper seams are designed concurrently to account for the stress transfer through the interburden. In planning, the layout of workings in multiple seams, there are two basic approaches to laying out room-and-pillar panels in successive seams: superposition or offset of panels or workings. Superposition of panels is optimal when the upper seams are developed first and then pillared. The pillars developed under the upper seam gob can be designed for single-seam conditions [12]. However, the outer entries in the lower seam are influenced by the load transferred from the overlying barrier.

Although mining sequence, panel layout, and pillar size are critical for the planning of concurrent pillar recovery in multiple seams, the size of leave blocks, stump size, and roof and rib support should also be carefully designed to minimize multiple-seam interaction during pillar recovery. This paper addresses geotechnical considerations for concurrent pillar recovery in two coal seams with 21 m of interburden under about 305 m depth of cover at the lower seam.

2. Panel layout for pillar recovery in two coal seams

This study concerns concurrent pillar recovery of two adjacent panels in two coal seams. Fig. 1 shows the overlay of the panel layout in both seams. The upper seam is the peerless coal seam and the lower seam is the Powellton Seam. Fig. 2 shows a typical geologic column of the interburden strata. The interburden consists of shale, sandstone, and the 2-gas coal seam. The maximum overburden depth is 284 min the upper seam and 305 min the lower seam where the interburden between the two seams is about 21 m.

The panels in the upper seam were developed with a 6–9-entry system and 21 m by 27 m center-to-center pillars. The overburden depth over the two panels ranges from 152 to 284 m. The barrier pillar between the two panels is 27–43 m center-to-center. The entry width is about 5.8–6.1 m, and the entry height is about 1.8 m. The immediate roof consists of shale and sandyshale. The roof is supported by four 1.5-m, 19-mm-diameter, fully grouted resin bolts on 1.2-m spacing for primary support and five 3-m, 15.2-mm cable bolts at intersections for supplementary support.

The panels in the lower seam were developed with a 9-entry system and 21-m by 27-m center-to-center pillars. A barrier pillar of 61 m center-to-center was left between the two panels. The immediate roof is dark shale and sandstone, and the immediate floor is dark gray fireclay. The entry width is about 6.1 m, and the mining height is 1.8 m. The coal in the Powellton Seam is about 1.2 m thick, and about 0.6 m of top rock is mined to make a mining height of 1.8 m. The roof is supported by four 1.5-m, 19-mm-dia., fully grouted resin bolts on 1.2-m spacing for primary support and five 3.6-m, 15.2-mm-diameter cable bolts at intersections for supplementary support.

The panels in the two seams were developed with different numbers of entries, and the workings were offset 6–21 m. Fig. 3 shows the vertical layout of the entries in the upper and lower seams. Fig. 4 shows the sequence of development and retreating in the upper and lower seams. The multiple-seam mining took place in the two coal seams in descending order. The first panel in the upper seam was developed and then retreated first. The concurrent mining took place in the second panel in the upper seam and in the first panel in the lower seam. The two panels were developed first and then retreated. The second panel in the lower seam was developed and retreated last.

The pillars in the retreat panels were designed by the mine engineers using the NIOSH-developed software, Analysis of Retreat Mining Pillar Stability (ARMPS) (NIOSH, 2010) and the numerical modeling software, LaModel (West Virginia University, 2011). LaModel was used to calculate the stability factor of the pillars over the area under maximum overburden depth of 305 m in the lower seam. The pillar sizes in both seams in the study meet the stability factor requirements established in the ARMPS and LaModel software programs.

3. Numerical modeling of multiple-seam interaction

LaModel software was used to model the distribution of abutment pressure around the retreat panels [13]. Figs. 5 and 6 show the modeled area and dimensions of the models in the upper and lower seams. To make the model conservative, the highest overburden depths of 284 m in the upper seam and 305 m in the lower seam were used. To model the effect of retreat mining in the upper seam on stress change in the lower seam, the model was set up with both panels in the upper seam retreated, but with Panel I in the lower seam developed. The model used 3-m element and symmetrical boundary conditions. The gob model was calibrated with lamination thickness and gob pressure. Lamination thickness of 15.2 m and final gob modulus of 2069 MPa were set in the model as the resulting extent of abutment pressure in the upper seam as well as multiple-seam stress transferred to the lower seam, which reasonably agrees with the field observations.

Fig. 7 shows the vertical stress distribution over the two retreat panels in the upper seam. High stress can be seen over the barrier pillars and bleeder pillars adjacent to the barrier pillars. Fig. 8 shows the vertical stress distribution across the two panels in the lower seam. This chart shows that the peak stress reaches about 27.6 MPa over a solid barrier pillar and about 34.5 MPa over the bleeder pillars adjacent to the barrier pillar. LaModel also predicts that pillar yielding is about 4.6–6.1 m deep, and the abutment pressure extends for about 30 m over the barrier pillar from the edge of the gob.

Fig. 9 shows the vertical stress distribution in the pillars over the developed Panel I and in the projected panel II in the lower seam. The peak stress is about 17.2 MPa over Panel I and about 10.3 MPa over the projected Panel II in the lower seam. The stress is lower than the overburden stress under the middle of the upper seam gob in Panel II. LaModel predicted about a 2.76 MPa increase of peak vertical stress under the edge of the upper seam barrier pillar, and about a 0.7–2.1 MPa decrease of vertical stress under the middle of the upper seam gob before the panels are developed in the lower seam.

The retreat mining in the upper seam creates abutment pressure in the pillars adjacent to the gob, which transfers through the interburden to the pillars in the lower seam. The amount and extent of abutment pressure in the upper seam is related to the width of the gob, the gob material properties, and the overburden characteristics. The distribution of the abutment pressure over the barrier pillars, as well as the depth of yielding in the barrier pillar, largely determines the stress transferred into the interburden. Understanding how the abutment pressure transfers to the lower seam through the interburden is critical for optimal design of a multiple-seam mining layout.

This study also uses the FLAC3D numerical software to model the stress transfer through the interburden under the abutment pressure created from pillar retreating in the upper seam [14]. The model was set up based on the interburden geology shown in Fig. 2. To simplify the modeling process, the FLAC3D model only consisted of the interburden, lower seam, and underlying floor. Table 1 shows the rock properties used in the FLAC3D model. The pressure on the interburden was simulated by applying the abutment pressure from LaModel onto the top of the interburden. The vertical stress distribution over a barrier pillar in Panel I in the upper seam, as shown in Fig. 10, was used to apply the pressure on the top of the interburden.

Fig. 11 shows the vertical stress distribution in the interburden under a barrier pillar in the upper seam. The vertical stress under the barrier pillar reduces with increasing distance from the upper seam. The peak stress in the barrier pillar concentrates at about 4.6 m from the gob edge (at the edge of the yield zone) and transfers with reduction through the interburden along a line at an angle of 20° away from the gob. At the lower seam level, the peak stress decreased to about 12 MPa and also shifted to about 12 m from the gob edge of the upper seam. The influence zone in the lower seam is directly under the barrier pillar and mainly within about 30 m from the gob edge of the upper seam. The vertical stress at the lower seam within 30 m of the gob edge of the upper seam is 9.0–10.0 MPa, which is about 1.18–1.54 times the overburden stress at the lower seam level. This finding suggests that the entries and crosscuts developed into the influence zone are subjected to the elevated stress resulting from mining in the upper seam. They will be further subjected to the front abutment pressure from mining in the lower seam if the pillars in the influence zone are retreated.

4. Observations of multiple-seam interactions during pillar recovery

Full pillar recovery was conducted in both seams during the study. Right and left lifts, called Christmas trees, were used for pillar recovery in both seams, and coal stumps were left to support the roof during pillar recovery. Two mobile roof supports (MRS) were used for roof support inby the pillaring face, and 8–10 timbers were set up in the crosscuts as turn posts, as well as in the entries as breaking posts. The depth of cut for retreating was 9.8 m in both seams. The conditions of the pillar, roof, and floor were carefully monitored during mining of both seams.

Fig. 12 shows the observations of roof and pillar conditions during pillar recovery of Panel II in the upper seam. The overburden depth in Panel II ranges from 152 to 274 m. Fig. 13 shows the roof condition outby the pillaring line in the upper seam. The condition of the immediate roof changed little in the active pillaring area, and the scope holes at the intersections within one block from the gob line showed no separations. The pillar retreating was conducted from right to the left of the panel with one continuous miner. Fig. 14 shows the pillaring plan in the upper seam. Four lifts were made at each side of the pillar in the entries, and one lift was made in the crosscut. Coal stumps left for supporting the roof during retreating measured a minimum of 1.8 m at the inby corners and 2.4 m at the outby corners from the entries. The roof caved fully, inby the pillaring line, although the caving delayed for about 3 blocks in the two entries adjacent to the outside bleeder entries. Generally, roof caving around the middle of the panel occurred within 6–12 m inby the coal stumps by the pillaring line, and the intersections and crosscuts at the pillaring line remained open until each pillar at the next row was retreated. The coal stumps generally squeezed at the intersections by the pillaring line and crushed further inby in the gob.

The coal rib in the upper seam has about 43 cm of weak fireclay at the mid-height and a mudstone streak above the fireclay. The mudstone streak is very weak and becomes muddy after absorbing moisture. Rib sloughage was observed at the outby pillars within one block from the pillaring line. The severity of rib sloughage varied with overburden depth. The rib sloughage was 30–60 cm under 213–274 m depth of cover, and 15–30 cm under 183–213 m depth of cover. Only minor rib sloughage occurred under less than 183 m of cover in the active pillaring face. Rib sloughage of 30–60 cm also occurred at the rib of the barrier pillar under overburden depth of 152–213 m where the barrier width between the gob lines was about 30 m. The rib failure mode is largely controlled by the weak fireclay and the mudstone streak above it. With sliding at the mudstone streak and breaking of the fireclay, the rib normally spalled below the fireclay. Fig. 15 shows the rib sloughage outby the pillaring line during retreating in the upper seam.

Fig. 16 shows the observations of roof, pillar, and floor conditions during pillar recovery of Panel I and Panel II in the lower seam. The overburden depth over the two panels ranges from 183 to 305 m. The immediate roof was sandyshale, and no roof sagging was observed during development and retreating. The scope holes showed minor separations in the immediate roof. Fig. 17 shows the roof and pillar conditions outby the pillaring line in the lower seam. Fig. 18 shows the pillaring plan in the lower seam. Five lifts were made at each side of the pillar from the entries, and no lift was made in the crosscuts. Small coal stumps were left at the inby pillar corners, and a triangular coal stump was left by the outby crosscut. The roof caved well inby the triangular stumps around the middle of the panel, but the caving delayed for 2–3 blocks in the two outside entries adjacent to the outside bleeder entries in Panel I. With half blocks left on each side of Panel I, the two outside bleeder entries remained open for ventilation during retreating. The first caving occurred after three rows of pillars were retreated in Panel I, and after four rows of pillars were retreated in Panel II. Delayed roof caving in the lower seam is related to the lower pressure under the upper seam gob and the relatively large triangular stumps left behind. The intersections and the crosscuts at the pillaring line remained open until each pillar at the next row was retreated.

The right side of Panel I was extended by developing one block into the northern barrier pillar during retreating. The new pillars developed were under the barrier pillar of the upper seam and were retreated with half blocks where overburden depth was less than 274 m. Significant rib sloughage was observed at those pillars outside the gob line of the upper seam, but no significant rib sloughage occurred within the gob line of the upper seam. One row of the pillars at the right side of Panel II was also developed under the barrier pillar of the upper seam. Severe sloughage was observed at the pillar rib outside the gob line of the upper seam within two blocks of the pillaring line in Panel II under depth of cover of about 244 m. Figs. 19 and 20 show the rib sloughage at the panel side and the barrier side, respectively, in the bleeder entry outby the pillaring line in Panel II in the lower seam. The rib sloughage is more severe at the panel side than at the barrier side. The rib sloughage within the gob line of the upper seam was very insignificant. Floor heave of 15–30 cm was also observed in the bleeder entry in Panel II in the lower seam. Fig. 21 shows the floor heave outby the pillaring line in the bleeder entry in Panel II in the lower seam. The observed rib sloughage and floor heave in the bleeder entry were caused by the multiple-seam stress transferred from the upper seam, as well as the front abutment pressure from pillaring of the current seam. The manifest of elevated pressure in the bleeder entries in the lower seam demonstrated that the multiple-seam influence zone is directly under the barrier pillar outside the gob line of the upper seam.

5. Geotechnical considerations for pillar recovery in close-distance multiple seams

Pillar recovery can be conducted safely in close-distance multiple seams with proper planning and adequate ground support. Mining sequence, panel layout, and pillar sizing are primary considerations to minimize multiple-seam interactions, but depth of cut, stump size, leave blocks, and roof and rib support are also important in reducing the risk of ground falls during pillar recovery.

Mining sequence concerns the sequence of mining in seams and panels. For full pillar recovery in close-distance multiple seams, descending order from the upper seam to the lower seam is the optimal sequence, as under-mining greatly reduces multipleseam interaction in comparison with over-mining. Mining sequence in panels should be planned in such an order that pillar retreating between two gobs can be avoided unless large barrier pillars are left.

For panel layout in close-distance multiple seams, superposition of panels and columniation of pillars minimize multipleseam interaction. If the interburden strata is fairly strong with sandstone and sandyshale comprising the majority of the strata, as in this studied case, columniation of pillars are not necessary. If the panels in the upper and lower seams are not the same size, it is important to superimpose the retreated gobs, especially when the overburden is greater than 245–274 m deep. Mining within the gob lines of the upper seam always puts the pillar and roof under the de-stressed gob zone, and can be practiced if adverse roof conditions are encountered in the lower seam. Based on this study, it is important to note that the highest stress under the barrier pillar of the upper seam is not directly under the edge of the upper seam gob, but is at an angle of 20° away from the gob edge, considering a close-distance interburden of 15–30 m. Any workings developed within about 30 m outside the upper seam gob line are located in the multiple-seam influence zone. Depending on overburden depth and the strength of the roof and rib, development or pillar retreating in the influence zone may be possible, but potential rib sloughage, roof cutters, or floor heave should be anticipated. Retreat mining outside the upper seam gob line under deep cover also significantly increases the risk of coal outburst and, therefore, should be practiced with caution.

Pillar design for multiple-seam mining should consider development loading, abutment loading, and additional loading caused by multiple-seam mining. Generally, for mining in close-distance multiple seams, pillars should be designed based on the overburden depth in the lower seam. If the panels in the lower seam stay within the gob lines of the upper seam, ARMPS can be used for pillar design as the pillars in the lower seam are generally under destressed zone as a result of pillaring in the upper seam [5]. If the pillars in the lower seam are developed and/or retreated beyond the gob lines of the upper seam, the stability of the pillars within the multiple-seam influence zone can be evaluated by the NIOSH-developed software, Analysis of Multiple Seam Stability (AMSS) or by numerical modeling [15].

With full pillar recovery, it is important to plan the slab cut into the barrier pillar to maximize extraction and the size of leave blocks, if necessary, to be left for bleeder ventilation. The barrier pillar and leave blocks define the gob line. The planned leave blocks in the retreat panel help support the roof in the bleeder entries. Either whole blocks or half blocks can be left at one or two sides of the panel, depending on the requirements for ventilation and the stability of the roof and remaining pillars. If the leave blocks in the lower seam are outside the gob line of the upper seam, whole blocks should be considered because those pillars will be subjected to elevated stress resulting from mining in both seams. To reduce the stress transferred from the upper seam, the size of the stumps left in the gob should be designed to facilitate caving. Excessive coal stumps left in the upper seam, if not squeezed or crushed in the gob, may behave as remnant pillars and create high stress in the lower seam. This situation may occur with strong roof in the upper seam under shallow cover. To eliminate multiple-seam interaction caused by the remnant pillars left within the gob in the upper seam, it is important to recover the projected retreat pillars in the upper seam as much as possible. If certain pillars in the upper seam have to be left without retreating due to local adverse roof conditions, the pillars at the same area in the lower seam should be evaluated for their stability under additional stress.

If entries and crosscuts are developed outside the gob line of the upper seam, additional roof and rib support should be considered for those entries and crosscuts in the multiple-seam influence zone, depending on the overburden depth in the area and strength of the roof and rib.

6. Conclusions

Based on the case study described in this paper of concurrent pillar recovery in two close-distance multiple seams, the following conclusions are made:

1. Pillar recovery can be conducted concurrently and safely in close-distance multiple seams through proper planning and adequate ground support. Mining sequence, panel layout, and pillar size are the primary considerations to minimize multiple-seam interaction, but depth of cut, stump size, leave blocks, and roof and rib support are also important in reducing the risk of ground falls during pillar recovery.
2. Interburden thickness and characteristics are the most important factor in determining the degree of multipleseam interaction. The multiple-seam interaction also increases significantly with the increase of overburden depth.
3. For full pillar recovery in close-distance multiple seams, it is optimal to superimpose the gobs, but it is not necessary to superimpose the pillars depending on the thickness and strength of the interburden.
4. For interburden thickness of 21 m, the influence zone in the lower seam is directly under the barrier pillar and mainly within about 30 m from the gob edge of the upper seam. The entries and crosscuts developed outside the gob line of the upper seam are subjected to elevated stress resulting from multiple-seam mining.
5. If entries and crosscuts are developed in the lower seam outside the gob line of the upper seam, additional roof and rib support should be considered to accommodate the elevated stress in the multiple-seam influence zone.

References

1. Mark C, Chase FE, Pappas DM. Reducing the risk of ground falls during pillar recovery. SME Trans. 2003; 314:153–60.
2. Zhang P, Peterson S, Neilans D, Wade S, McGrady R, Pugh J. Geotechnical risk management to prevent coal outburst in room-and-pillar mining. Int J Mining Sci Technol. 2016; 26:9–18.
3. Mark C, Gauna M. Evaluating the risk of coal bursts in underground coal mines. Int J Mining Sci Technol. 2016; 26(1):47–52.
4. Mark, C., Tuchman, RJ. Inform Circ. Vol. 2017. Pittsburgh, PA: National Institute of Occupational Safety and Health; 9495. New technology for ground control in multiple-seam mining; p. 88
5. NIOSH. ARMPS software, version 6.0.29. National Institute for Occupational Safety and Health; 2010. Analysis of retreat mining pillar stability. https://www.cdc.gov/niosh/mining/works/coversheet1813.html
6. NIOSH. Response to FY 2008 appropriation (Public Law 110-161). Pittsburgh, PA: National Institute of Occupational Safety and Health; 2010. Research report on the coal pillar recovery under deep cover; p. 79
7. Klemetti TM, Sears MM, Tulu IB. Design concerns of room and pillar retreat panels. Int J Mining Sci Technol. 2017; 27:29–35.
8. Westman ED, Molka RJ, Conrad WJ. Ground control monitoring of retreat room-and-pillar mine in Central Appalachia. Int J Mining Sci Technol. 2017; 27:65–9.
9. Mark C, Gauna M. Preventing roof fall fatalities during pillar recovery: a ground control success story. Int J Mining Sci Technol. 2017; 27:107–13.
10. Gauna M, Mark C. Unanticipated multiple seam stresses from pillar systems behaving as pseudo gob–case histories. Int J Mining Sci Technol. 2017; 27:131–7.
11. Tulu IB, Esterhuizen GS, Klemetti T, Murphy MM, Sumner J, Sloan M. A case study of multi-seam coal mine entry stability analysis with strength reduction method. Int J Mining Sci Technol. 2016; 26:193–8.
12. Chekan, GJ., Listak, JM. Technology News 443. Bureau of Mines, United States Department of the Interior; 1994. Design practice for multiple-seam room-and-pillar mines; p. 2
13. West Virginia University. LaModel software, version 3.0.05. 2011
14. ITASCA. FLAC3D software, version 5.0. ITASCA Consulting Group; 2016. Fast lagrangian analysis of continua in 3 dimensions. http://www.itascacg.com/software/flac3d
15. NIOSH. AMSS software, version 2.1.02. National Institute for Occupational Safety and Health; 2013. Analysis of multiple seam stability. https://www.cdc.gov/niosh/mining/works/coversheet1808.html

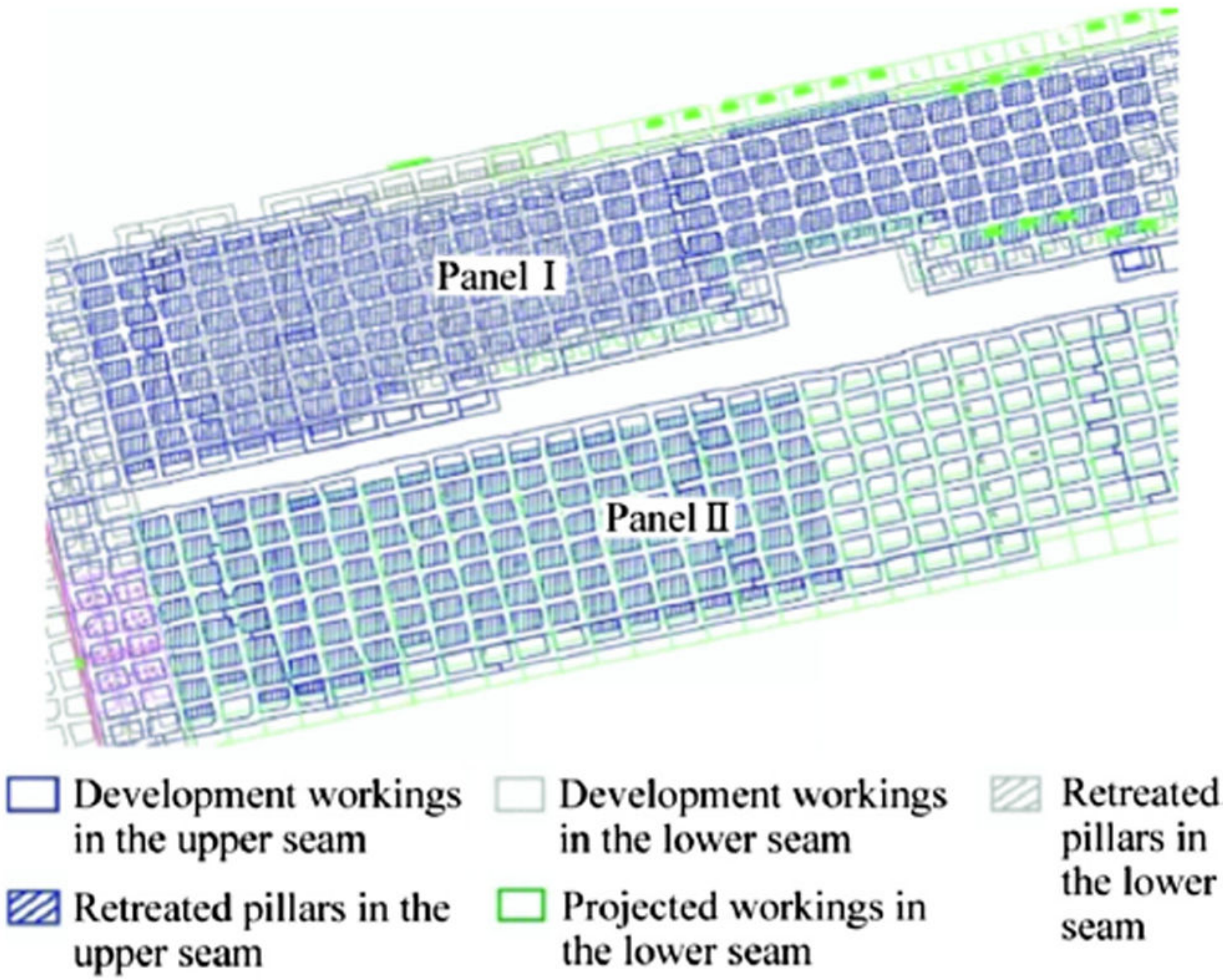

Fig. 1.
Overlay of panel layout in the upper and lower seams.

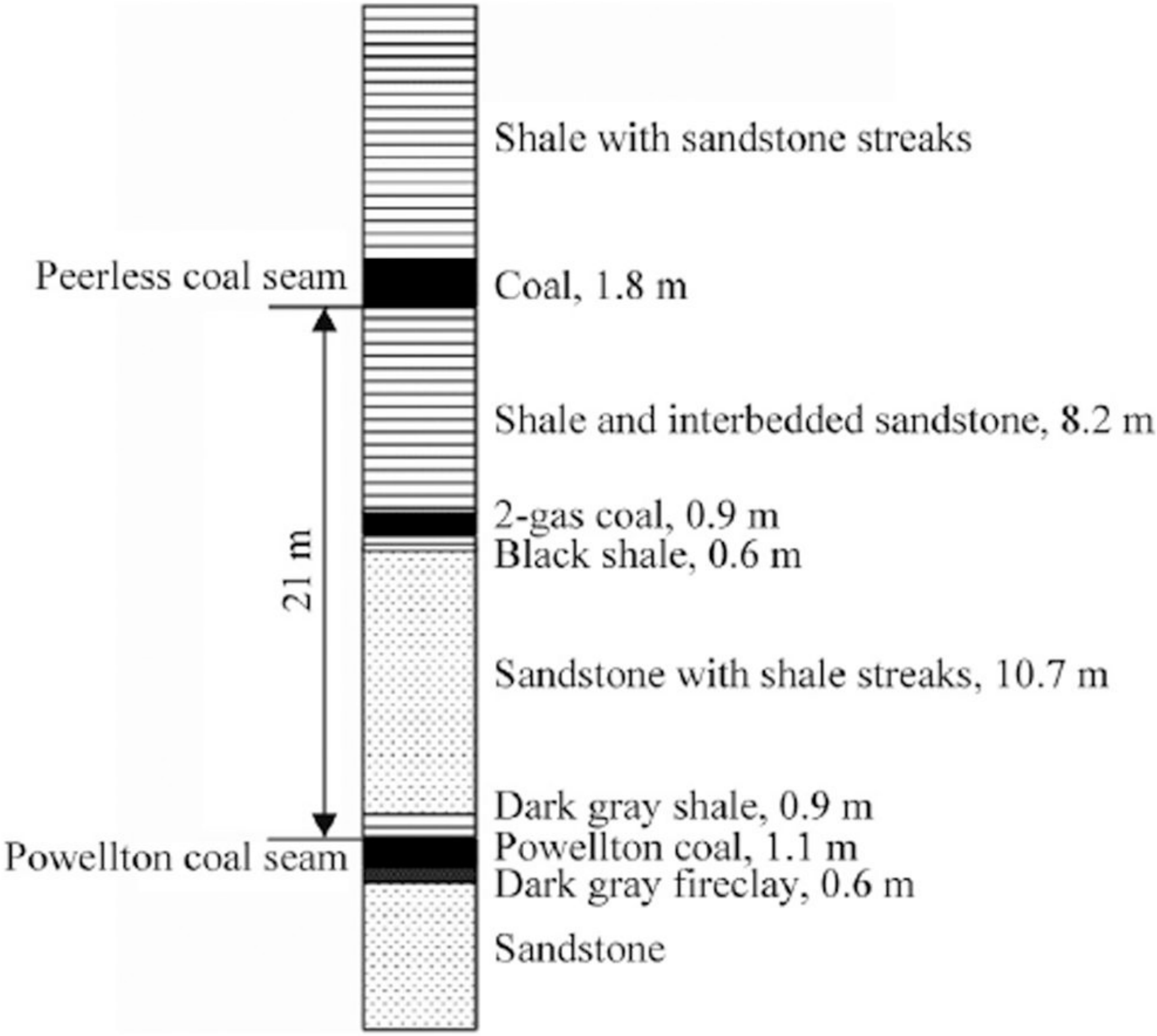

Fig. 2.
Geological column of the interburden strata.

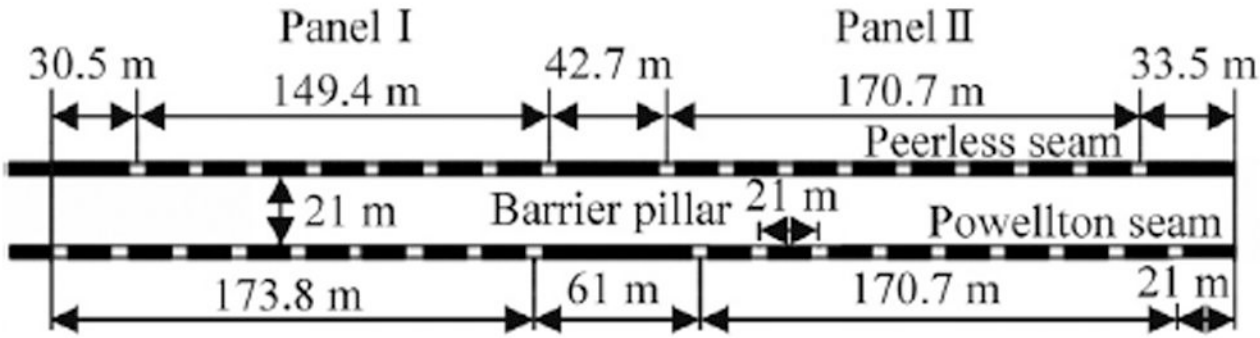

Fig. 3.
Entry layout in the upper and lower seams.

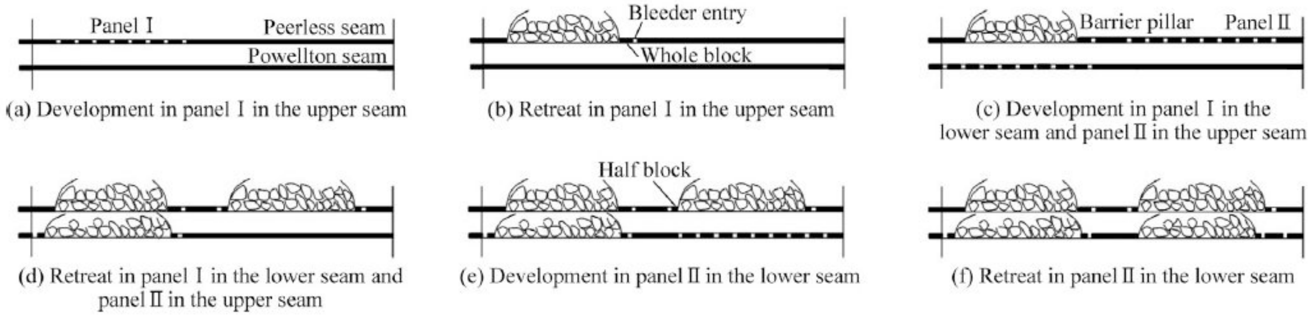

Fig. 4.

Sequence of development and retreating in the upper and lower seams.

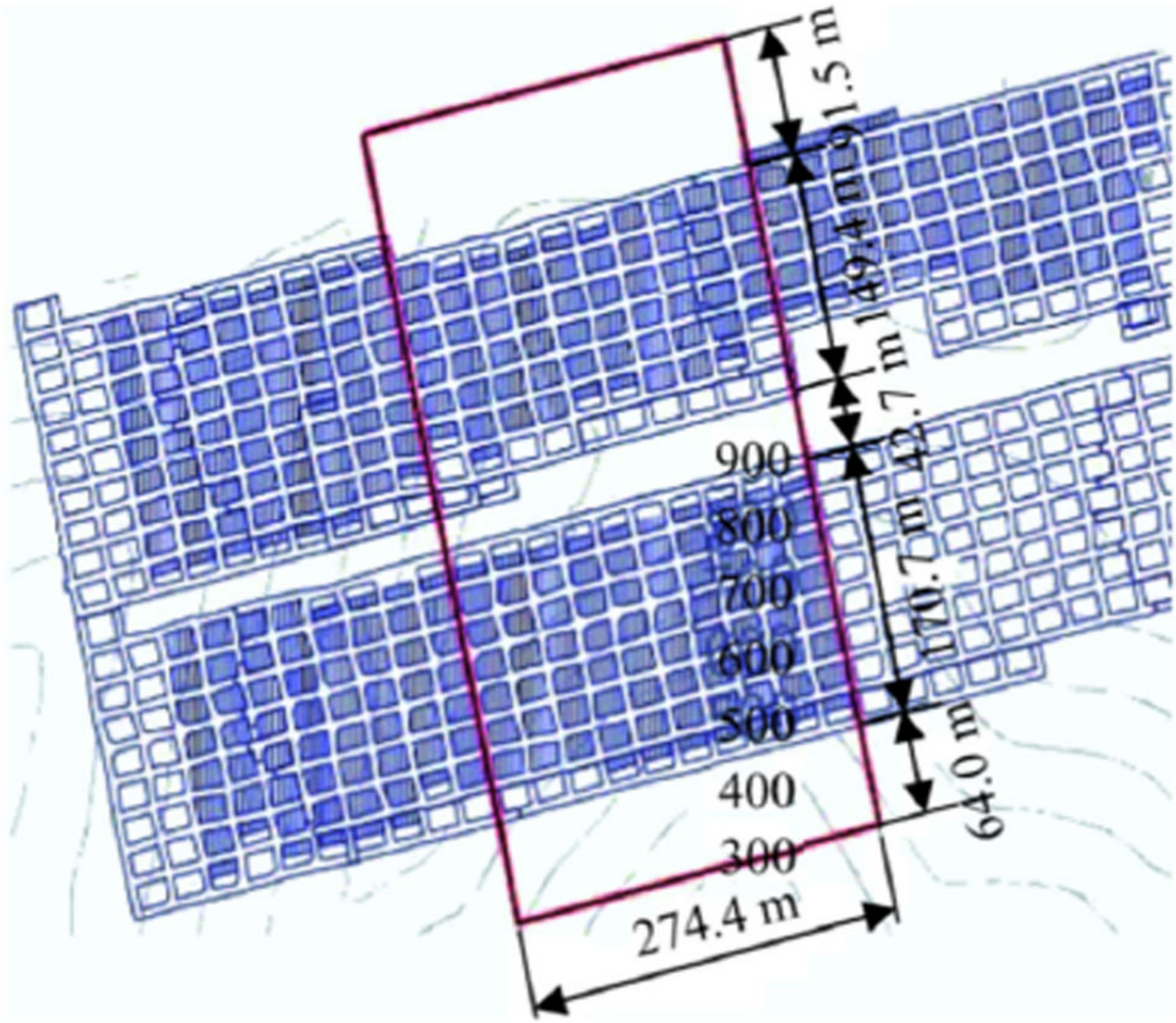

Fig. 5.
Modeled area in the upper seam.

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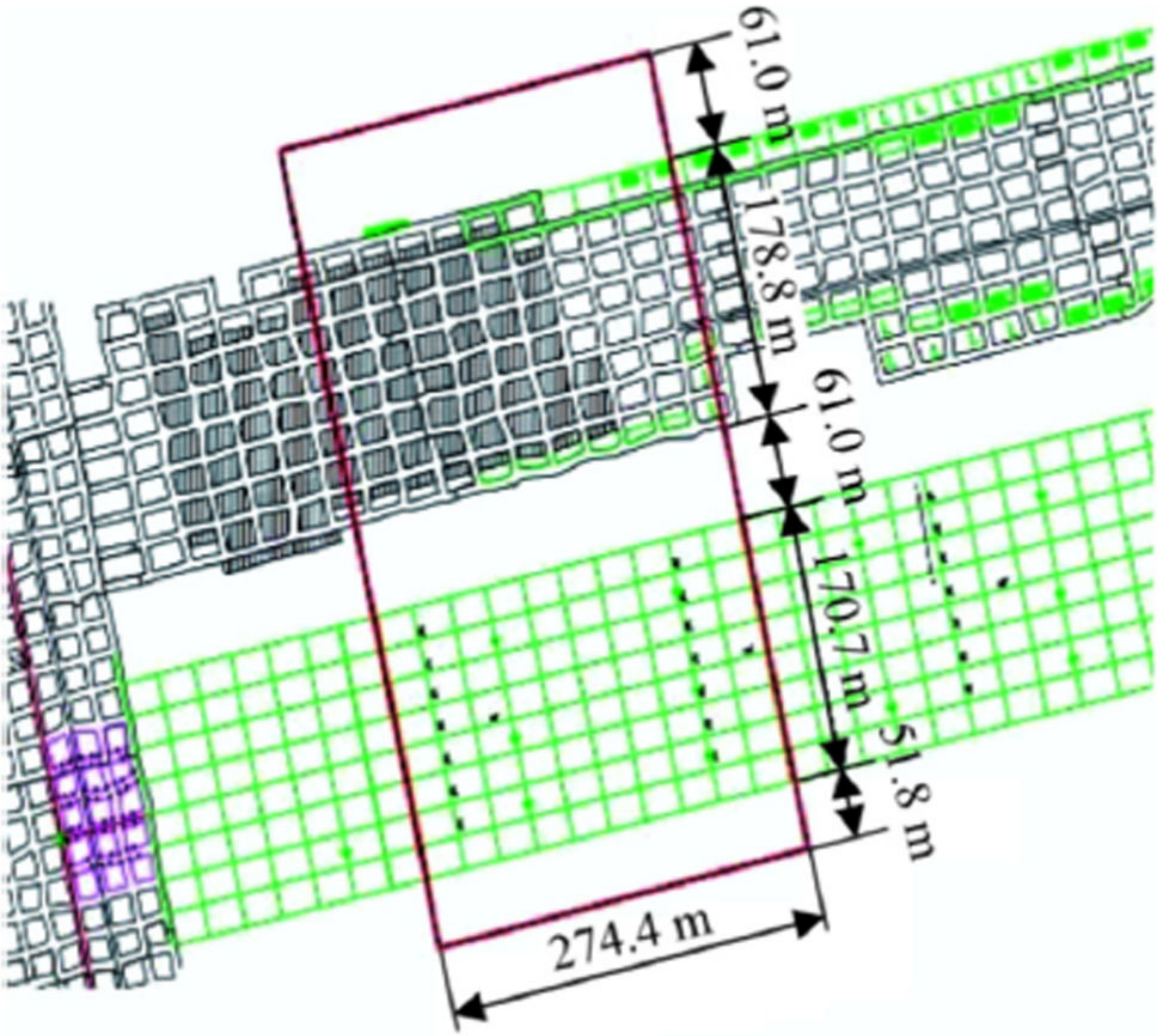

Fig. 6.
Modeled area in the lower seam.

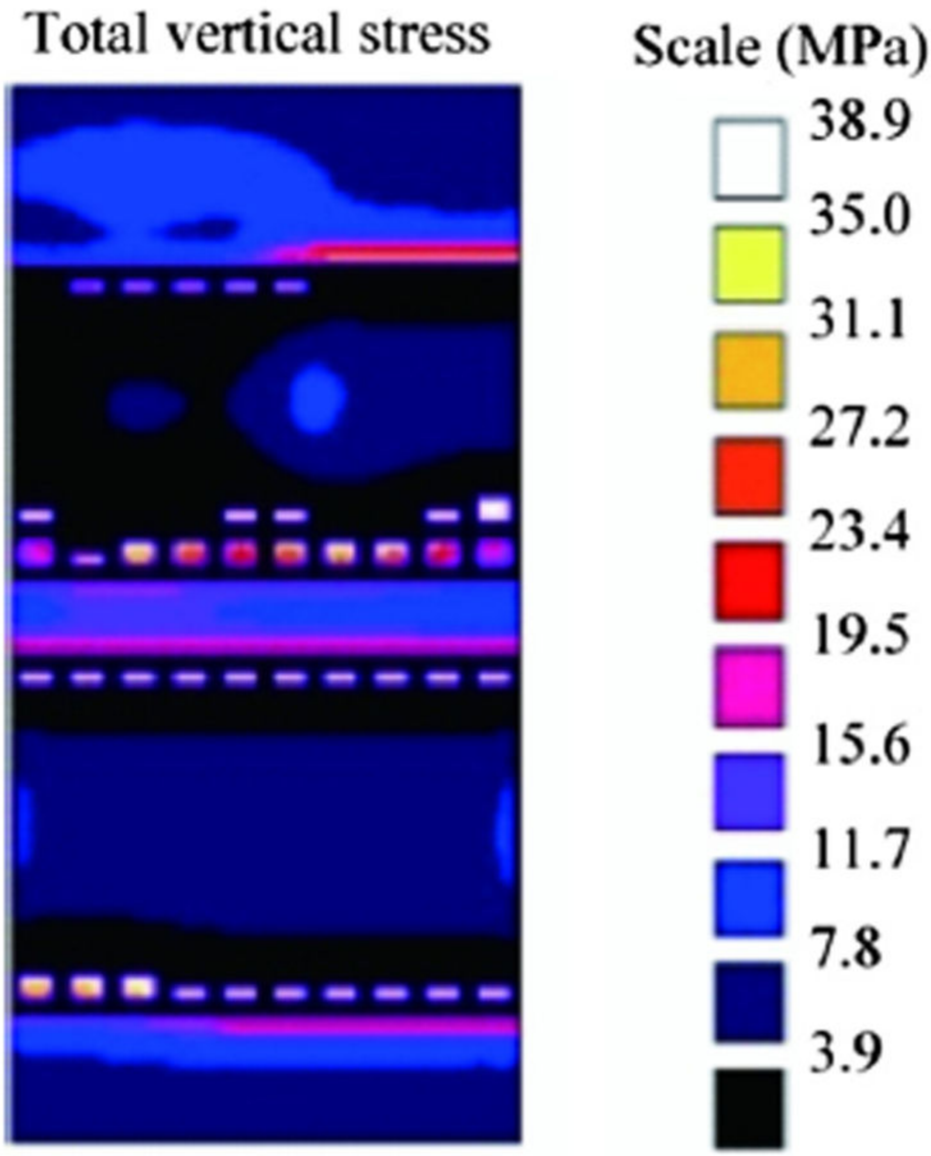

Fig. 7.
Vertical stress distribution over the retreat panels in the upper seam.

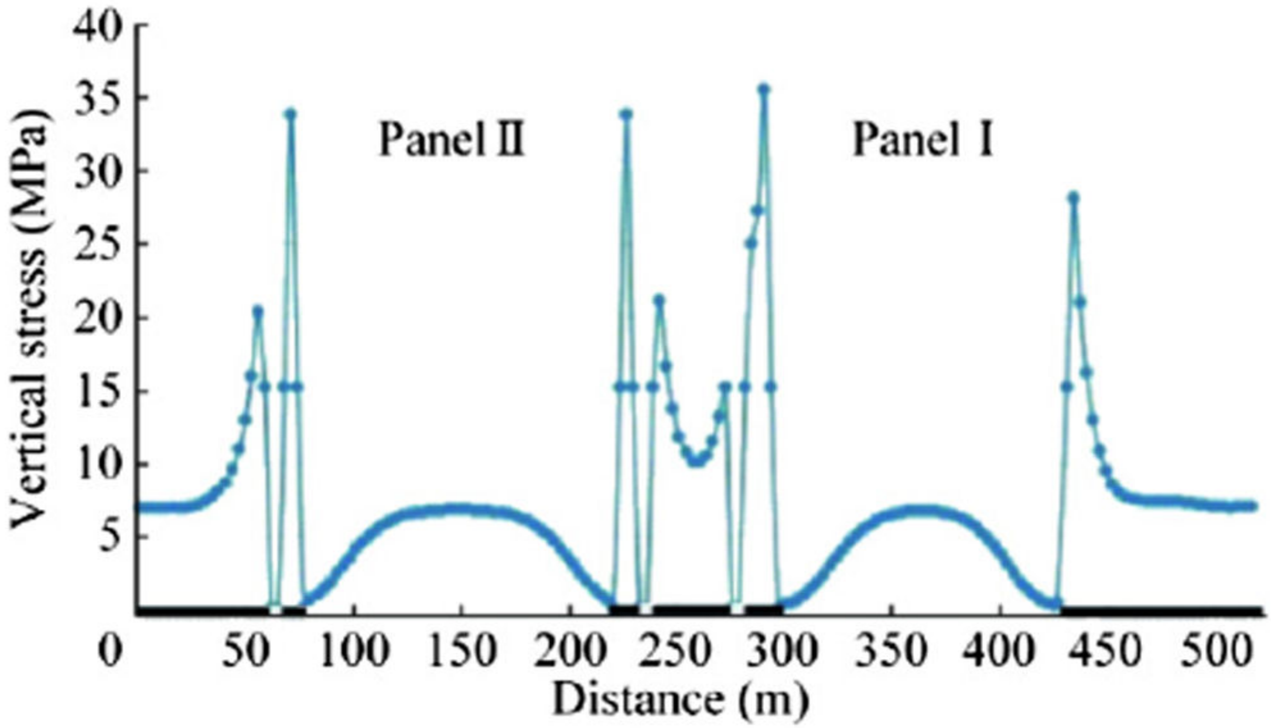

Fig. 8.
Vertical stress distribution across the panels in the upper seam.

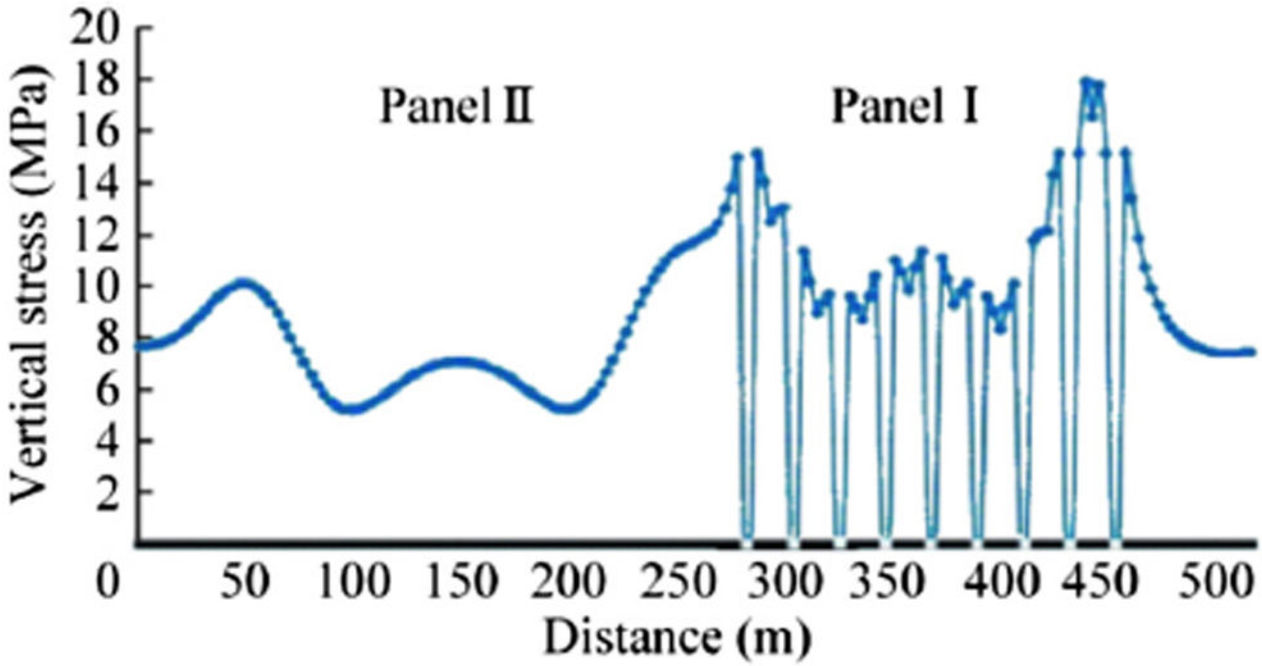

Fig. 9.
Vertical stress distribution across the panels in the lower seam.

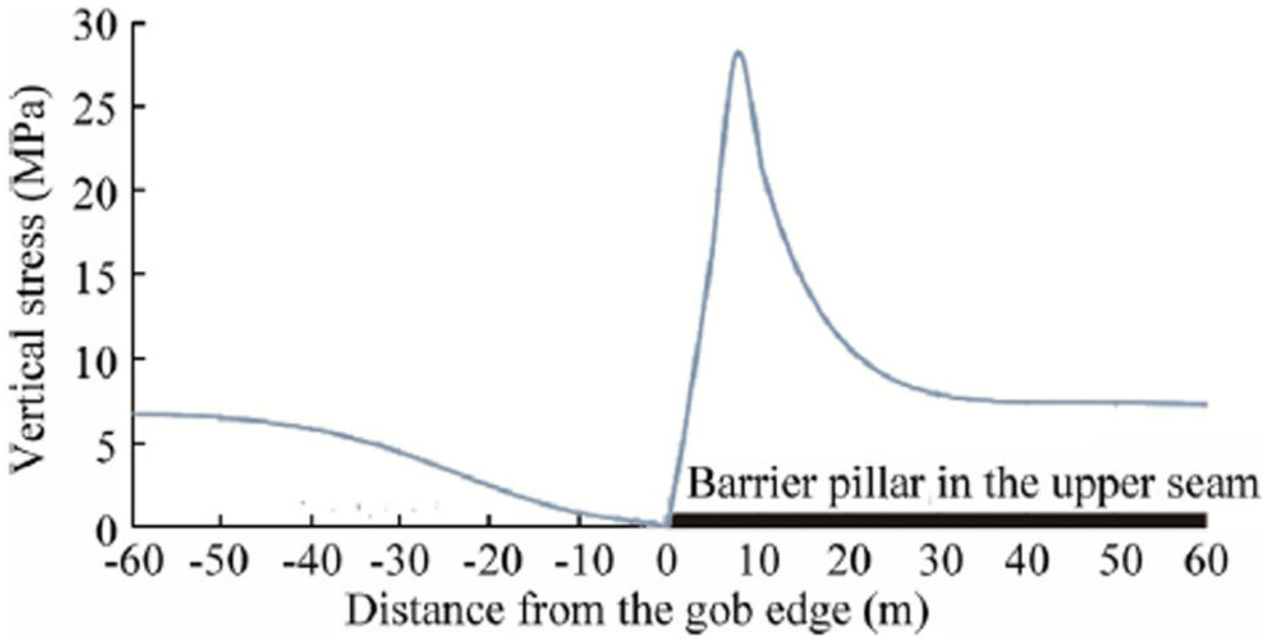

Fig. 10.
Vertical stress distribution over a barrier pillar in the upper seam.

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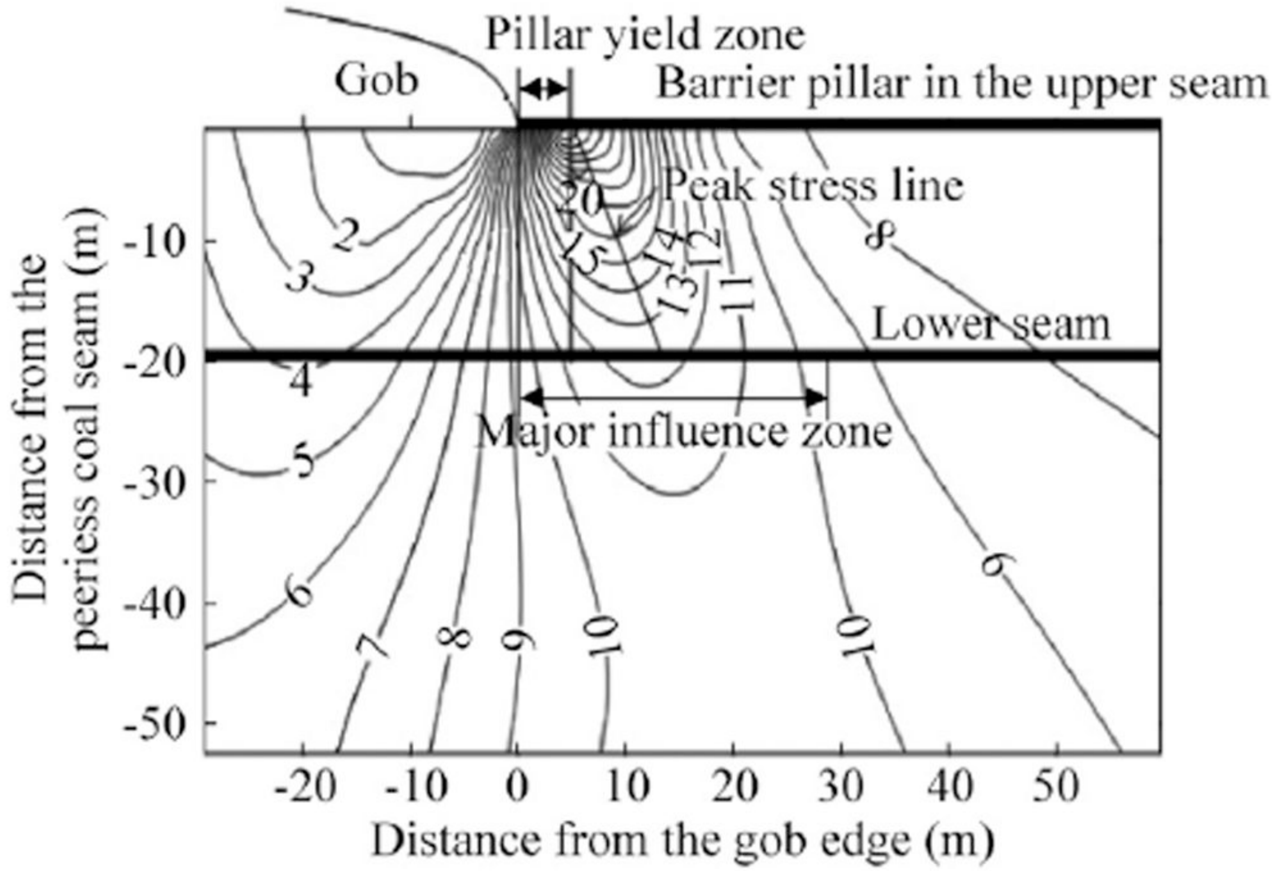

Fig. 11.
Vertical stress distribution in the interburden under a barrier pillar in the upper seam.

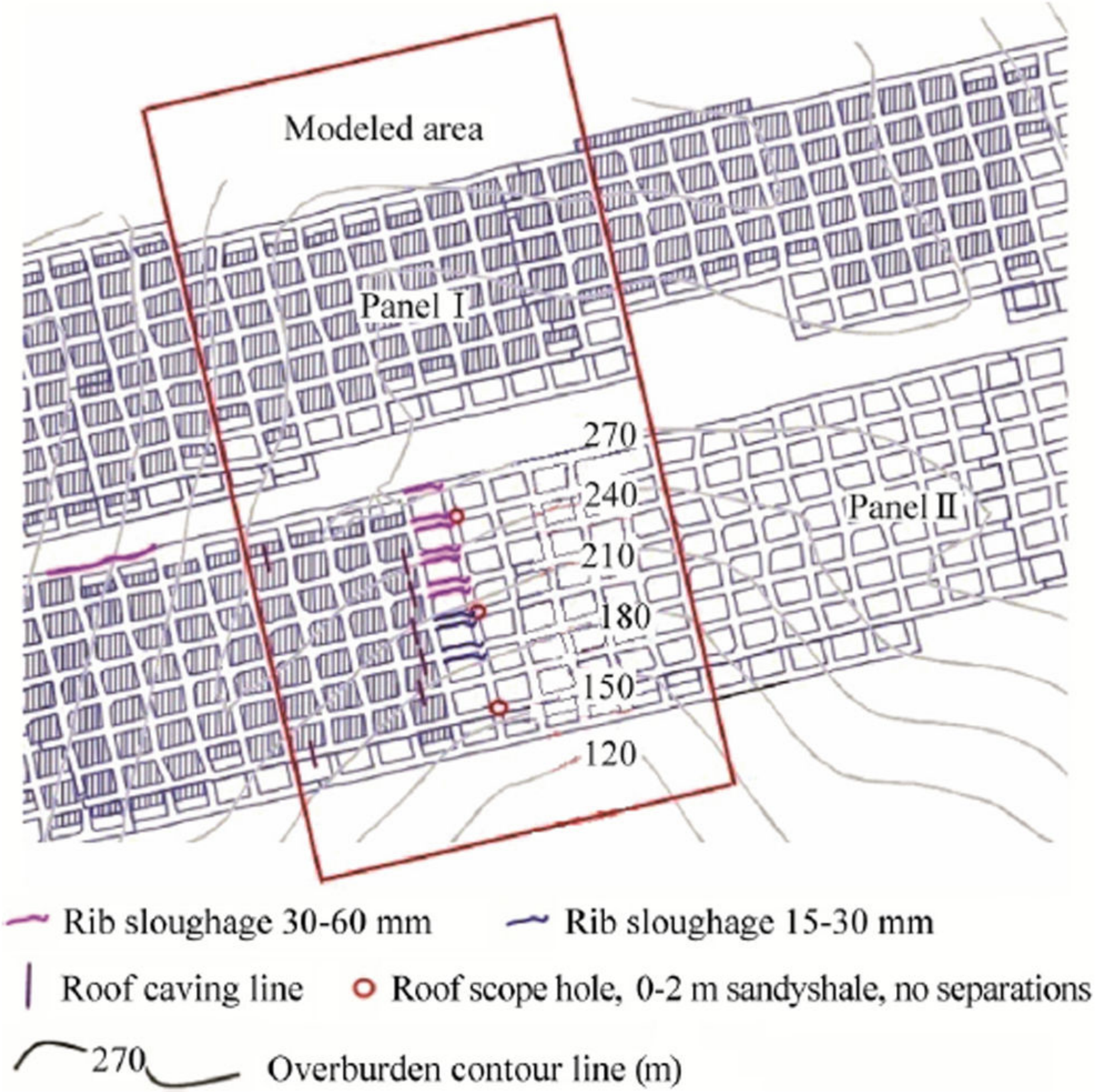

Fig. 12.
Observations during pillar recovery in the upper seam.

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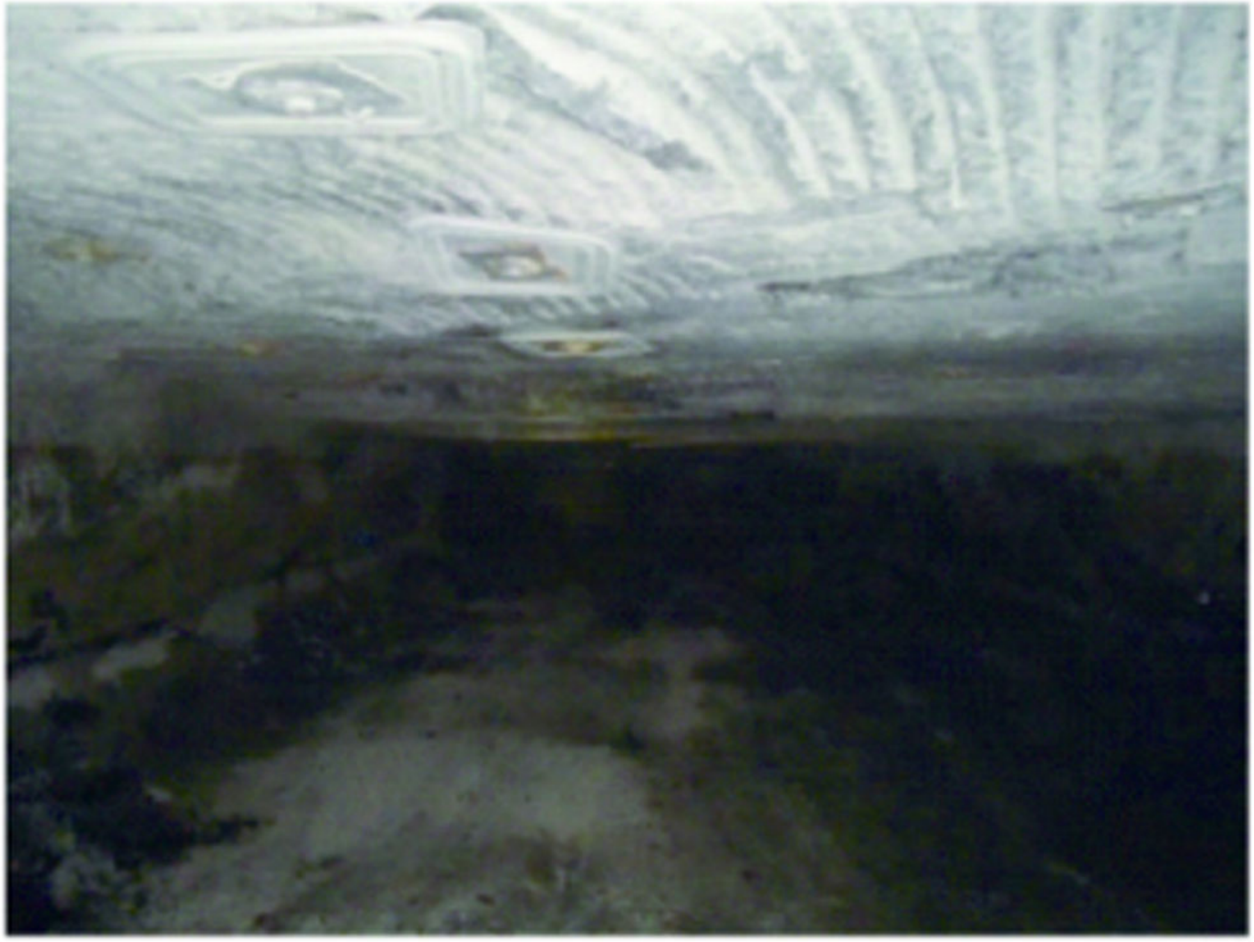

Fig. 13.
Roof condition outby the pillaring area in the upper seam.

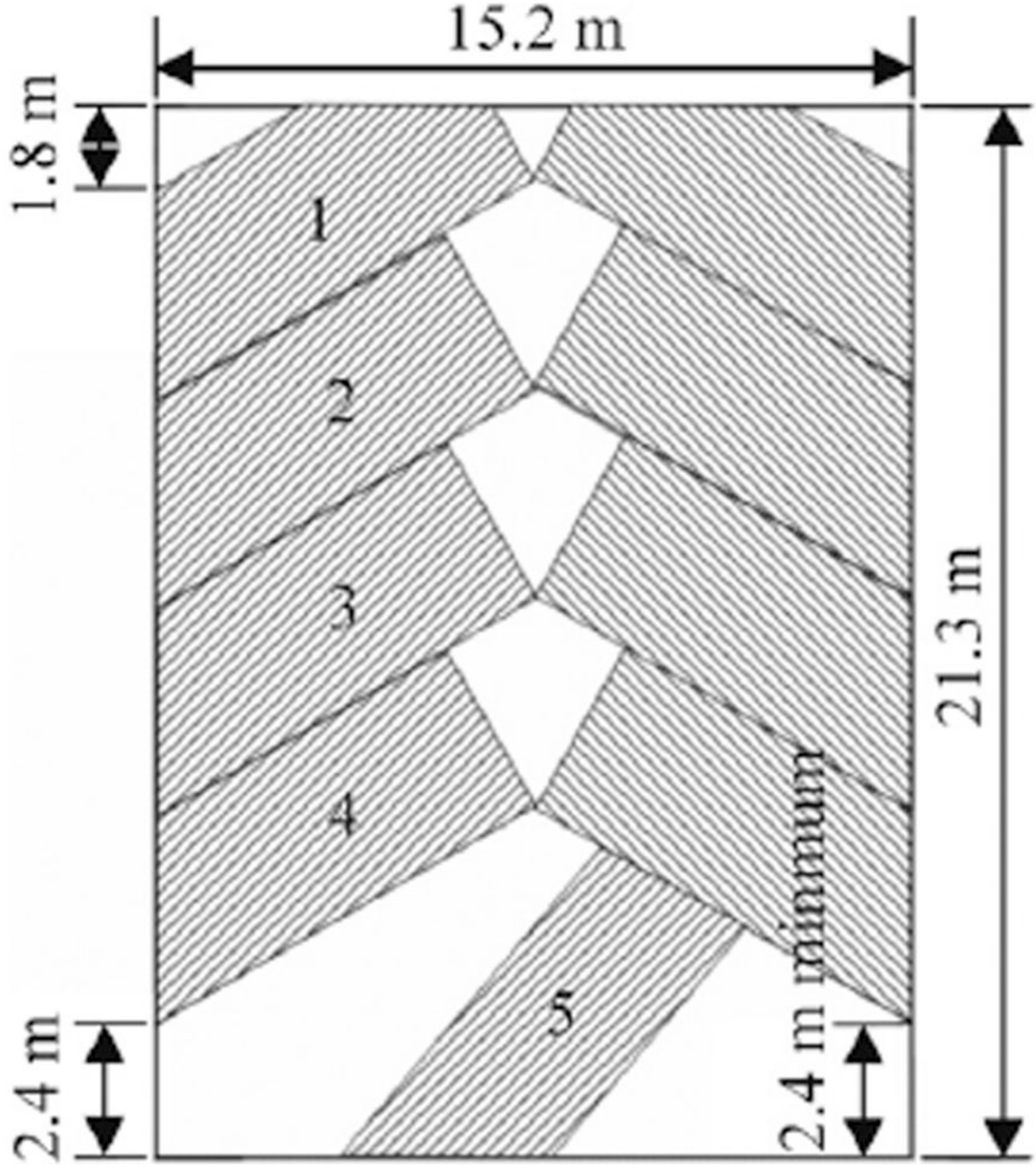

Fig. 14.
Pillaring plan in the upper seam.

Fig. 15.
Rib sloughage outby the pillaring line during retreating in the upper seam.

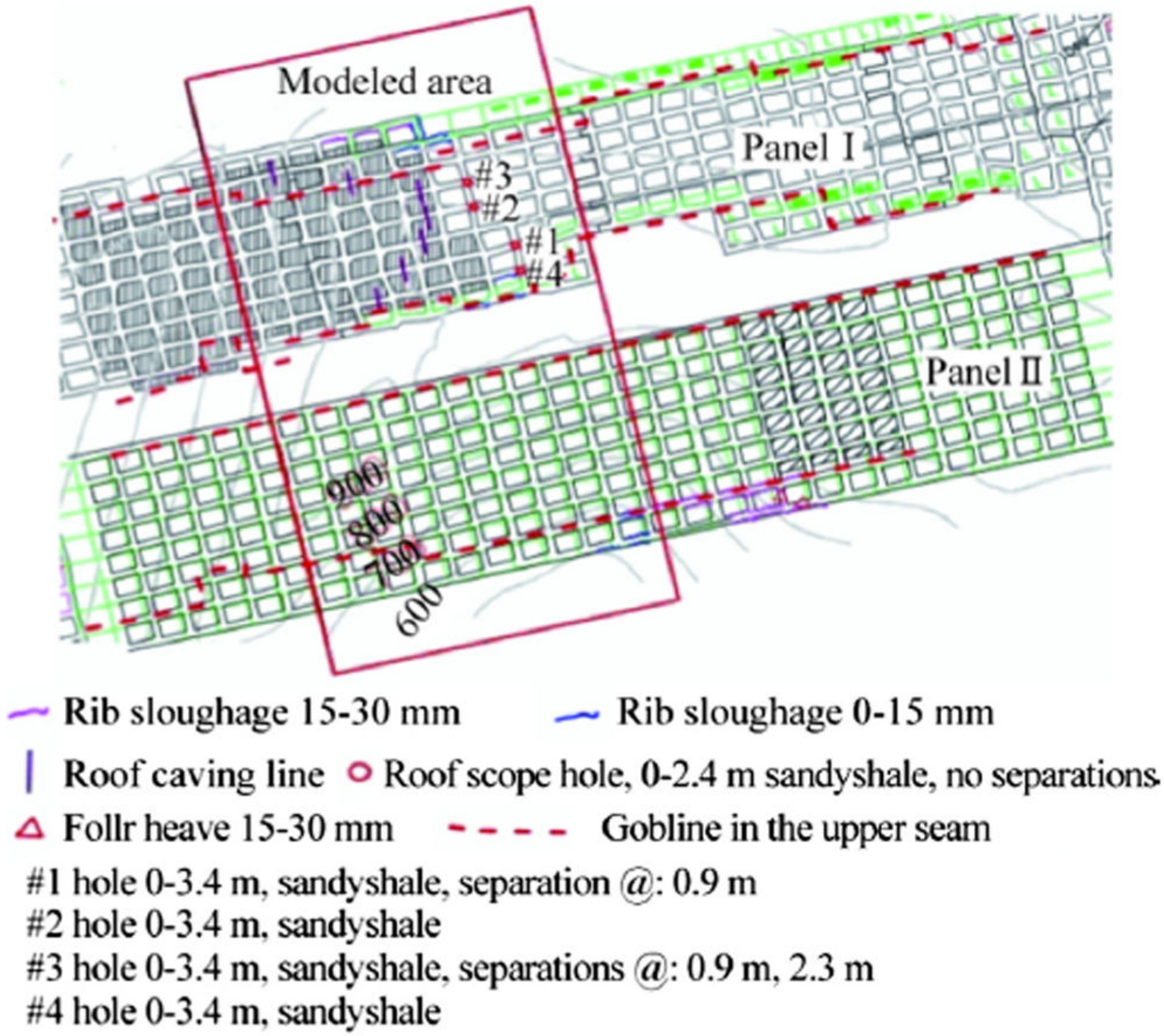

Fig. 16.
Observations during pillar recovery in the lower seam.

Fig. 17.
Conditions of roof and pillar in the lower seam before retreating.

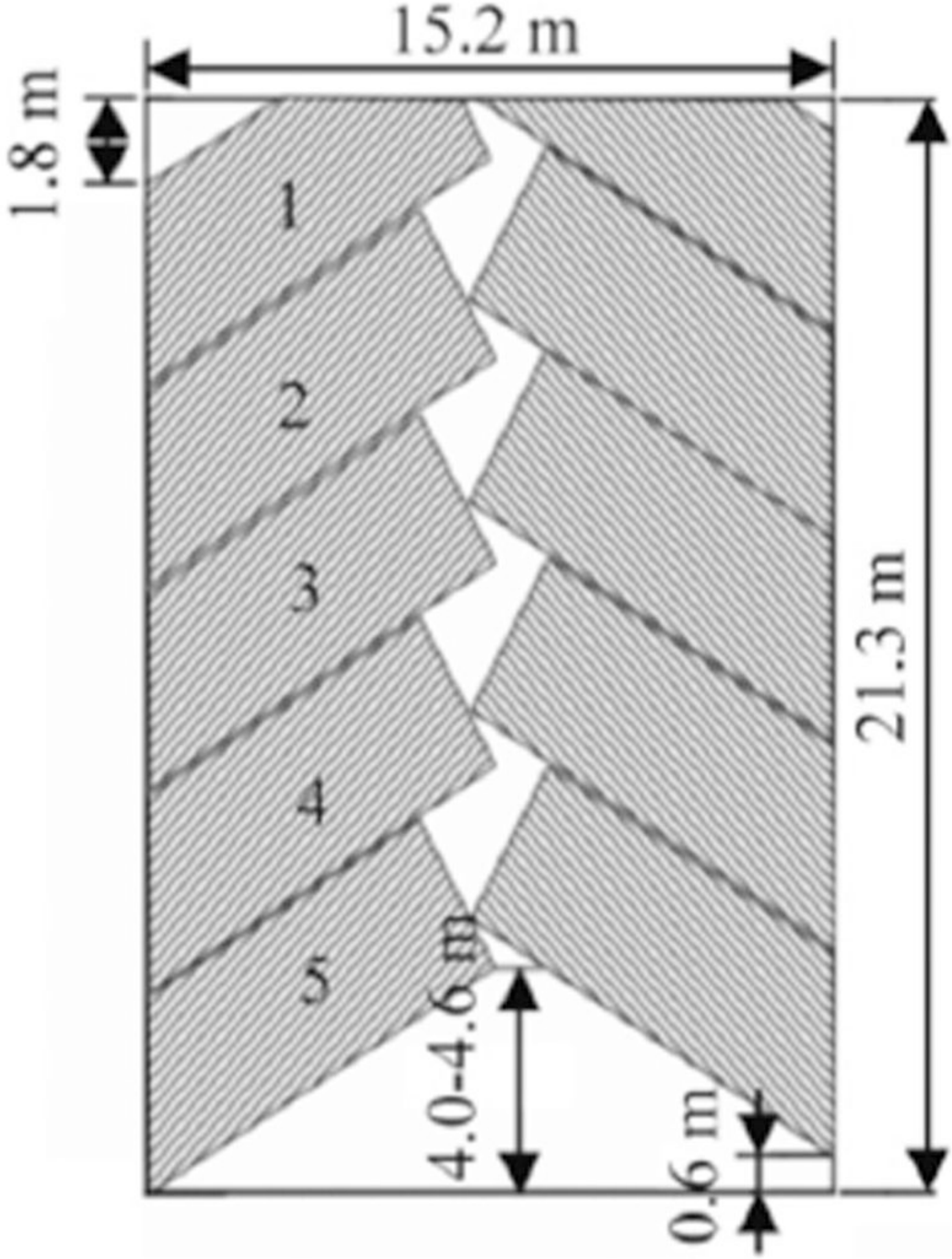

Fig. 18.
Pillaring plan in the lower seam.

Fig. 19.
Rib sloughage at the panel side in the bleeder entry of Panel II in the lower seam.

Fig. 20.
Rib sloughage at the barrier side in the bleeder entry of Panel II in the lower seam.

Fig. 21.
Floor heave in the bleeder entry of Panel II in the lower seam.

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Table 1

Rock properties used in the FLAC3D model.

Rock type	Young's modulus (GPa)	Poisson's ratio	UCS from lab (MPa)	UCS in model (MPa)	Tensile strength (MPa)	Cohesion (MPa)	Internal friction angle (°)
Sandstone	13.8	0.20	82.8	41.4	5.0	11.9	30
Shale	13.8	0.20	41.4	20.7	3.3	6.0	30
Coal	2.1	0.30	24.8	6.2	0.3	1.9	28
Fireclay	13.8	0.30	20.7	10.3	1.2	3.1	28