

Mining-Height Effects On Pressure Relief And Gas Outburst Control In Long-Distance Ultra-Thin Lower Protective-Seam Mining

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Mining an ultra-thin lower protective seam alone may provide insufficient pressure relief because of the limited mining height, whereas excessive co-mining of adjacent rock increases the engineering burden associated with rock excavation, transportation, hoisting, waste-rock handling, and coal-quality control. To address this problem, this study investigates a reasonable coal–soft-rock co-mining height for the long-distance ultra-thin lower protective Seam I-8 at Zhongtai Mine. The heights of the overburden failure zones were first estimated theoretically under different mining heights. RFPA2D simulations were subsequently conducted for three representative mining heights of 0.5, 1.0, and 1.5 m to compare the evolution of overburden failure, the gas permeability response, and the expansion strain of Seam II-1. Among the three simulated cases, increasing the mining height from 0.5 to 1.0 m markedly enhanced the pressure-relief response of the protected seam, whereas the additional improvement from 1.0 to 1.5 m was comparatively limited. At a mining height of 1.0 m, the maximum gas permeability coefficient of Seam II-1 reached approximately $160 \text{ m}^2 \cdot \text{MPa}^{-2} \cdot \text{d}^{-1}$, and the maximum expansion strain reached 6.13%. Considering the pressure-relief performance and the additional rock excavation associated with a larger mining height, a mining height of 1.0 m was selected for field implementation. The field scheme consisted of mining the 0.5 m-thick Seam I-8 together with approximately 0.5 m of soft roof rock and applying pressure-relief gas drainage. The maximum pure methane drainage rate reached $14 \text{ m}^3/\text{min}$, and the maximum gas content measured after drainage was $1.83 \text{ m}^3/\text{t}$. These results indicate that the 1.0 m coal–soft rock co-mining scheme can provide effective pressure relief and regional gas outburst control under the geological and mining conditions investigated in this study.

Keywords: ultra-thin lower protective seam; coal–soft-rock co-mining; mining height; gas outburst control

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1. Introduction

Protective seam mining is one of the main regional measures for coal and gas outburst control, and long-distance lower protective-seam mining combined with pressure-relief gas drainage has been applied in Chinese coalfields [1–3]. Ultra-thin protective seams with thicknesses of approximately 0.3 – 0.5 m have been investigated and applied in several Chinese coalfields [4, 5]. However, when only

the ultra-thin coal seam is mined, the limited mining height may provide insufficient pressure relief for the protected seam. Mining part of the roof or floor rock together with the coal seam can increase the effective mining height, but additional rock excavation also increases the rock-mining and handling workload [6, 7]. Therefore, while meeting the pressure-relief requirement of the protected seam, the thickness of the rock mined together with the coal seam should be kept as small as possible. A reasonable mining height is

required for this type of ultra-thin protective seam.

Previous studies on protective-seam mining have evaluated the pressure-relief range and gas-drainage performance of protected seams [8]. Numerical and field investigations have also examined mining-induced stress redistribution and fracture evolution in the overburden and protected seam [9, 10]. Changes in the permeability of protected coal during mining-induced unloading have likewise been reported [11]. However, relatively few studies have focused on how much adjacent rock should be mined when an ultra-thin coal seam is used as a protective seam. The mining height should therefore be selected by considering both the pressure-relief response of the protected seam and the additional rock excavation.

At Zhongtai Mine, the ultra-thin Seam I-8 is located below the outburst-prone Seam II-1, with an average vertical separation of 44.5 m. Seam I-8 is approximately 0.5 m thick. Because Seam I-8 is only approximately 0.5 m thick, mining it alone is difficult and may not provide the expected pressure-relief effect; therefore, a controlled thickness of adjacent soft roof rock was considered for co-mining with the seam. Based on the geological and mining conditions of Zhongtai Mine, this study used theoretical calculation and RFPA2D numerical simulation to compare the pressure-relief responses under different total mining heights. Total mining heights of 0.5, 1.0, and 1.5 m were considered to compare overburden failure and the deformation and gas permeability of Seam II-1. The mining scheme selected from the comparison was then applied at the 3307 working face and evaluated using field gas-drainage and gas-content measurements. The purpose was to determine a reasonable mining height that could provide the required pressure-relief effect while reducing unnecessary rock excavation.

2. Materials and methods

2.1. Factors Affecting Pressure Relief and Gas Outburst Control

Mining height has an important influence on roof movement and the pressure-relief response of a protected seam [12]. Overburden lithology and thick or hard key strata can constrain the transmission of mining-induced unloading and the associated gas-drainage response [13]. Working-face geometry and seam dip also influence the pressure-relief protection effect of an underlying protective seam [14].

For the 3307 working face studied here, the interseam spacing, seam dip, working-face dimensions, and lithological conditions were fixed by the site conditions. Mining height, however, could be adjusted by mining part of the

adjacent rock together with Seam I-8. Therefore, mining height was selected as the main engineering variable for the subsequent theoretical and numerical comparison.

2.2. Geological and Mining Conditions and Theoretical Analysis

At Zhongtai Mine, the protected Seam II-1 has an average thickness of 7.5 m and an average dip of 13° , with elevations ranging from -358 to -402 m. The gas content of Seam II-1 ranges from 15.8 to 20.8 m^3/t , the gas pressure ranges from 0.73 to 2.13 MPa, and the gas permeability coefficient is $1.2 - 1.8 \text{ m}^2 \cdot \text{MPa}^{-2} \cdot \text{d}^{-1}$. Seam II-1 contains soft coal and is classified as an outburst-prone seam. The underlying Seam I-8 is approximately 0.5 m thick and is classified as a non-outburst-prone seam. The average vertical separation between the two seams is 44.5 m. Panel 3307 in Seam I-8 was selected as the trial panel for ultra-thin lower protective seam mining. The panel is 256.5 m long along strike and 106 m wide along dip. The spatial relationship between the protective Seam I-8 and the protected Seam II-1 is shown in Fig. 1. The strata between the two seams consist mainly of sandy mudstone and medium-grained sandstone and are generally classified as medium-hard strata.

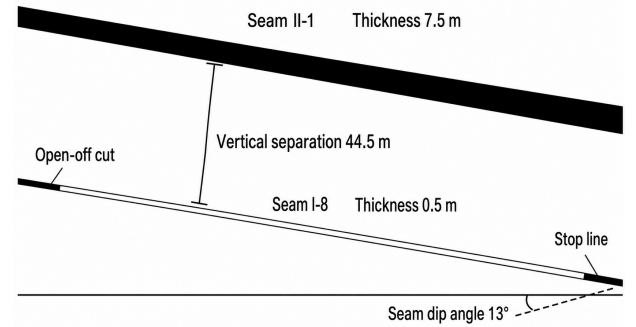


Fig. 1. Spatial relationship between the protective and protected seams.

Based on the geological conditions at Zhongtai Mine, the caving-zone height for medium-hard overburden was estimated using Eq. (1), in which the ± 2.2 term represents the mean error [15]:

$$H_k = \frac{100\Sigma M}{4.7\Sigma M + 19} \pm 2.2 \quad (1)$$

The height of the water-conducting fractured zone was estimated using Eq. (2) [16]:

$$H_{li} = 20\sqrt{\Sigma M} + 10 \quad (2)$$

In these equations, H_k is the estimated height of the caving zone, H_{li} is the estimated height of the water-conducting fractured zone, and $\sum M$ is the cumulative mining thickness. The reported application range of these empirical relations is a single-layer mining thickness of 1-3 m, with the cumulative mining thickness not exceeding 15 m [17]. Therefore, the calculations for mining heights of 0.5, 0.6, and 0.8 m fall outside the stated single-layer mining-thickness range and are used only as extrapolative estimates for comparison. In addition, because the present study involves an ultra-thin coal seam co-mined with adjacent rock, these empirical calculations are treated as preliminary theoretical estimates rather than precise predictions of the actual overburden failure height.

The calculated results are presented in Table 1. Here, Effective vertical distance denotes the vertical distance from the upper boundary of the mined space to the floor of Seam II-1. For the 0.5 m case, in which Seam I-8 is mined alone, this distance is approximately 44.5 m; it decreases progressively as additional roof rock is included in the total mining height.

The results show that the estimated height of the fractured zone increases with mining height, whereas the effective vertical distance between the mined space and Seam II-1 decreases. At mining heights of 0.5, 1.0, and 1.5 m, the estimated fractured-zone heights are 24.14, 30.00, and 34.49 m, respectively, while the corresponding effective vertical distances are 44.5, 44.0, and 43.5 m. Thus, the vertical separation between the estimated upper boundary of the fractured zone and Seam II-1 decreases progressively with increasing mining height. This trend indicates that a larger mining height allows the mining-induced fracture zone to develop closer to the protected seam.

In Eq. (2), H_{li} represents the height of the water-conducting fractured zone measured upward from the mined seam and therefore directly defines the upper extent of the fractured zone. Thus, H_k and H_{li} are not added together. The theoretical calculation is used only to compare the influence of mining height on overburden failure and is not used alone to determine whether sufficient pressure relief has been achieved in Seam II-1.

The average vertical separation between Seam I-8 and Seam II-1 is approximately 44.5 m. A reference maximum vertical protection distance of 100 m has been reported for gently inclined lower protective-seam mining [18]. The interseam spacing at Zhongtai Mine is below this reference value; however, the actual pressure-relief effect and effective protection range still require evaluation under the site-specific geological and mining conditions.

Mining heights of 0.5, 1.0, and 1.5 m were subsequently

selected for the RFPA2D numerical simulations. The actual pressure-relief response of Seam II-1 was further evaluated by comparing overburden failure, protected-seam deformation, and gas permeability under these three mining heights, followed by field evaluation of the selected mining scheme.

2.3. RFPA2D Numerical Model and Mechanical Parameters

RFPA2D was used to simulate the failure and deformation of the overlying protected Seam II-1 induced by mining Panel 3307 in Seam I-8. The average vertical separation between the two seams was approximately 44.5 m, and the elevation of Seam II-1 ranged from -358 to -402 m.

The numerical model was 300 m wide and 130 m high and consisted of 25 strata. It was discretized into 600×260 elements, giving a total of 156,000 elements. The nominal element size was therefore $0.5 \text{ m} \times 0.5 \text{ m}$. The upper two layers were each represented by a 15 m-thick equivalent stratum to account for the overburden outside the modeled domain. Joints were inserted between adjacent strata to represent the layered structure of the coal and rock mass. The mechanical parameters used in the model are listed in Table 2. Horizontal displacement was constrained at the lateral boundaries, and self-weight loading was applied vertically. The numerical model is shown in Fig. 2. Grayscale represents the elastic modulus of the strata; brighter layers have higher elastic moduli, whereas darker layers have lower values.

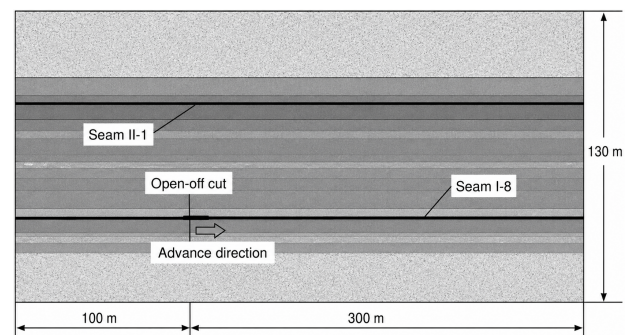


Fig. 2. Numerical simulation model

To represent the overburden load outside the modeled domain, equivalent numerical densities of 35,000 and 26,000 kg/m^3 were assigned to the two upper layers. Their combined self-weight corresponds to a vertical stress of approximately 8.98 MPa:

$$\sigma_{eq} = \rho_1 g h_1 + \rho_2 g h_2 = 8.98 \text{ MPa} \quad (3)$$

Table 1. Estimated overburden failure-zone heights at different mining heights

Mining height (m)	Height of caving zone (m)	Height of Water-conducting fractured-zone (m)	Effective vertical distance (m)
0.5	2.34 ± 2.20	24.14	44.5
0.6	2.75 ± 2.20	25.49	44.4
0.8	3.51 ± 2.20	27.89	44.2
1	4.22 ± 2.20	30	44
1.2	4.87 ± 2.20	31.91	43.8
1.4	5.47 ± 2.20	33.66	43.6
1.5	5.76 ± 2.20	34.49	43.5

Table 2. Mechanical parameters of rock

Lithology	Elastic modulus (GPa)	Compressive strength (MPa)	Poisson's ratio, ν	Bulk density (kg/m ³)	Thickness (m)
Equivalent overburden layer 1	50	120	0.4	35000	15
Equivalent overburden layer 2	50	150	0.32	26000	15
Medium-grained sandstone	18	85	0.29	2500	9.5
Sandy mudstone	14	63	0.32	2300	3
Mudstone	6	35	0.31	2700	0.5
Seam II-1	5	25	0.38	1400	7.5
Sandy mudstone	14	68	0.36	2900	5
Medium-grained sandstone	20	85	0.29	2500	4.5
Sandstone-mudstone	15	68	0.36	2900	7.5
Medium-grained sandstone	20	77	0.29	2500	3
Limestone	40	120	0.28	2600	1
Sandy mudstone	15	65	0.38	2700	2
Medium-grained sandstone	21	85	0.27	2400	3.5
Sandy mudstone	16	67	0.36	2700	5
Medium-grained sandstone	20	83	0.27	2500	3
Sandy mudstone	14	80	0.35	2600	5.5
Limestone	40	125	0.28	2600	4.5
Sandy mudstone	12	40	0.31	2500	0.5
Seam I -8	5	25	0.38	1400	0.5
Sandy mudstone	16	78	0.34	2700	5.5
Medium-grained sandstone	22	87	0.28	2500	1.5
Sandy mudstone	16	66	0.34	2700	0.5
Limestone	40	130	0.25	2600	3.5
Medium-grained sandstone	25	84	0.29	2500	3.5
Bottom rock	50	150	0.28	3000	20

where ρ_1 and ρ_2 are the equivalent densities of the two strata, h_1 and h_2 are their thicknesses, and g is gravitational acceleration.

RFPFA-based formulations combine finite-element stress analysis with damage evolution and have also been extended to coupled flow-stress-damage analysis of rock failure [19]. At the mesoscopic scale, the spatial variability of material properties is commonly described by a Weibull distribution :

$$f(u) = \frac{m}{u_0} \left(\frac{u}{u_0} \right)^{m-1} \exp \left[- \left(\frac{u}{u_0} \right)^m \right] \quad (4)$$

where u represents a mechanical property of a mesoscopic element, u_0 is the scale parameter of the Weibull distribution, and m is the homogeneity index. Tensile and

shear failures are governed by the maximum tensile strain criterion and the Mohr-Coulomb criterion, respectively. After damage initiation, the elastic modulus decreases according to Eq. (5). These mesoscopic heterogeneity and damage relations follow the RFPFA micromechanical fracture formulation [20].

$$E = (1 - D)E_0 \quad (5)$$

where E_0 and E are the elastic moduli of the undamaged and damaged elements, respectively, and D is the damage variable. In this way, the progressive initiation, propagation, and coalescence of mining-induced fractures can be represented.

Three mining heights of 0.5, 1.0, and 1.5 m were sim-

ulated. The 0.5 m case corresponded to mining Seam I-8 alone, whereas the 1.0 and 1.5 m cases involved Seam I-8 and adjacent rock. The mined section extended from $x = 100$ to 200 m in the 300 m wide model. The overburden failure process was compared at working-face advances of 40, 70, 80, and 100 m. The vertical displacement of Seam II-1 was analyzed at advances of 30, 50, 60, 80, and 100 m, and its gas permeability coefficient was evaluated after an advance of 100 m.

$$R_\lambda = \frac{\lambda_{\max}}{\lambda_0} \quad (6)$$

where $\lambda_{\max}$ is the maximum gas permeability coefficient obtained from the extracted permeability profile of Seam II-1 after mining, and λ_0 is the representative premining gas permeability coefficient. A value of $1.5 \text{ m}^2 \cdot \text{MPa}^{-2} \cdot \text{d}^{-1}$, corresponding to the midpoint of the measured pre-mining range of $1.2 - 1.8 \text{ m}^2 \cdot \text{MPa}^{-2} \cdot \text{d}^{-1}$, was used for the relative permeability-enhancement calculation.

3. Results and discussion

3.1. Overburden Caving and Fracture Evolution

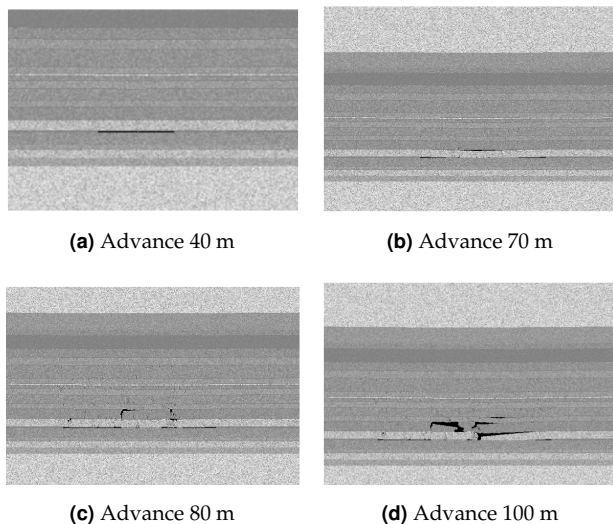


Fig. 3. Overburden failure process at a mining height of 0.5 m

Fig. 3 shows the overburden failure process at a mining height of 0.5 m. At an advance of 40 m, no obvious overburden failure is observed. When the working face advances to 70 m, the roof strata begin to cave, accompanied by bending and subsidence of the overburden and the development of bedding-separation fractures. At 80 m, roof caving becomes more pronounced, fractures continue to propagate upward, and the caved rock gradually fills the

goaf. At an advance of 100 m, the overburden failure continues to develop upward, and the strata close to Seam I-8 are seriously damaged, whereas no obvious failure occurs in Seam II-1.

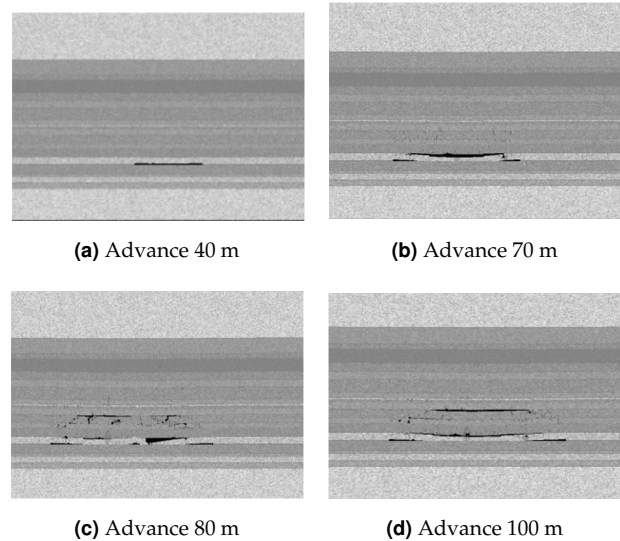


Fig. 4. Overburden failure process at a mining height of 1.0 m

Fig. 4 shows the overburden failure process at a mining height of 1.0 m. At an advance of 40 m, slight damage occurs in the immediate roof, but no obvious caving is observed. At 70 m, the immediate roof bends and fractures, with pronounced failure occurring in its central part, while bedding separation begins to develop in the overburden. At 80 m, the bedding-separation fractures become more pronounced and the degree of overburden failure increases. At an advance of 100 m, large bedding-separation fractures develop in the overburden, and the vertical and bedding-separation fractures become well developed and connected.

Fig. 5 shows the overburden failure process at a mining height of 1.5 m. At an advance of 40 m, slight roof damage occurs, mainly above the central part of the goaf, while the immediate roof has not yet caved. At 70 m, the immediate roof caves, bends, and subsides into the goaf, and a large number of bedding-separation fractures develop in the overburden. At 80 m, roof caving becomes more extensive and the caved rock fills the goaf. The overburden is clearly damaged, with well-developed bedding-separation and vertical fractures. At an advance of 100 m, the caved overburden is gradually compacted under the in-situ stress field. Fractures above the open-off cut are compressed and the number of bedding-separation fractures decreases, whereas fracture development above the working face in-

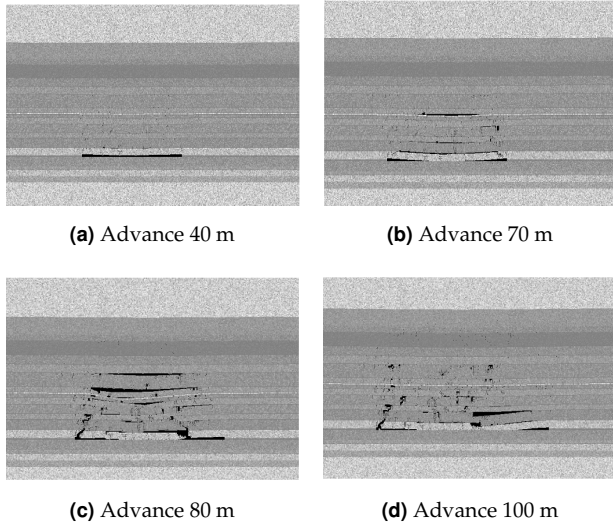


Fig. 5. Overburden failure process at a mining height of 1.5 m

creases.

Comparison of Figs. 3 to 5 shows that the degree of overburden failure generally increases with mining height. At the same working-face advance, increasing the mining height promotes roof caving and the upward development of mining-induced fractures. The difference in fracture development is particularly evident when the mining height increases from 0.5 to 1.0 m.

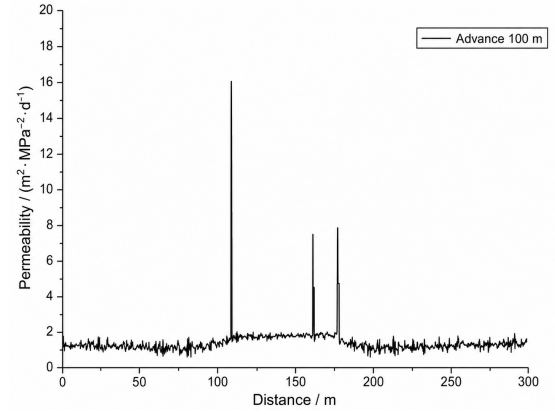
3.2. Gas Permeability Evolution of the Protected Seam

Fig. 6 shows the distribution of the gas permeability coefficient in Seam II-1 at a working-face advance of 100 m. The gas permeability coefficient of the protected seam varies significantly under different mining heights.

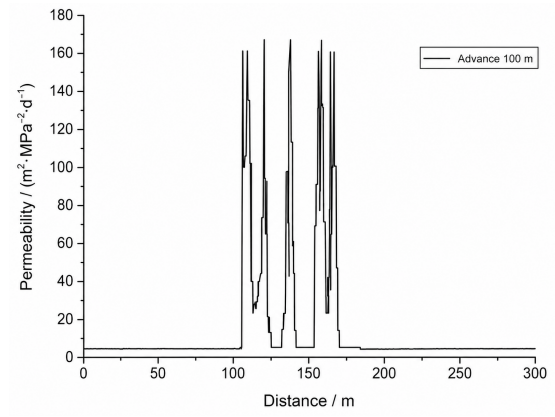
At a mining height of 0.5 m, the gas permeability coefficient of Seam II-1 changes slightly in most areas. The maximum value appears near the open-off cut and reaches approximately $16 \text{ m}^2 \cdot \text{MPa}^{-2} \cdot \text{d}^{-1}$, corresponding to a permeability enhancement factor of approximately 10.7. The pressure-relief effect on the protected seam is relatively limited.

At a mining height of 1.0 m, the gas permeability coefficient of Seam II-1 increases significantly. The maximum value in the pressure-relief area reaches approximately $160 \text{ m}^2 \cdot \text{MPa}^{-2} \cdot \text{d}^{-1}$, corresponding to a permeability enhancement factor of approximately 106.7. Compared with the 0.5 m mining-height condition, the permeability enhancement of the protected seam is markedly greater.

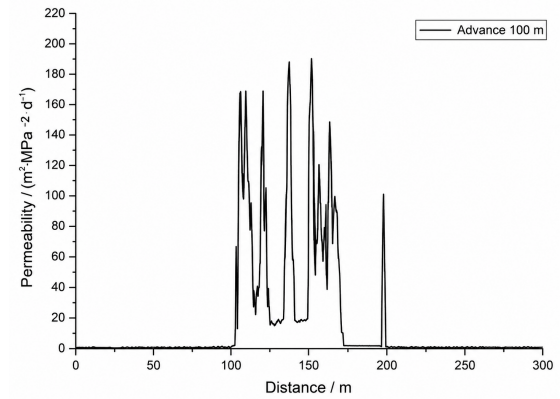
At a mining height of 1.5 m, higher gas permeability coefficients appear above the open-off cut, near the working face, and above the central part of the goaf. The maxi-



(a) Permeability of Seam II-1 at a mining height of 0.5 m



(b) Permeability of Seam II-1 at a mining height of 1 m



(c) Permeability of Seam II-1 at a mining height of 1.5 m

Fig. 6. Gas permeability of Seam II-1 after 100 m of face advance.

imum value reaches approximately $180 \text{ m}^2 \cdot \text{MPa}^{-2} \cdot \text{d}^{-1}$, corresponding to a permeability enhancement factor of approximately 120.

Compared with the 0.5 m mining-height condition, both 1.0 m and 1.5 m mining heights produce a more significant

increase in the gas permeability coefficient of Seam II-1. However, the increase from 1.0 m to 1.5 m is relatively smaller than that from 0.5 m to 1.0 m.

3.3. Deformation of the Protected Seam

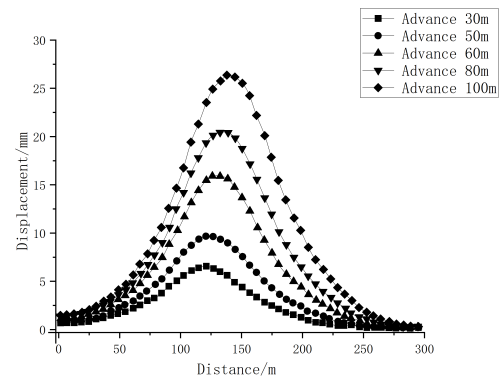
Fig. 7 shows the vertical displacement of Seam II-1 at mining heights of 0.5, 1.0, and 1.5 m when the working face advances 30, 50, 60, 80, and 100 m.

At a mining height of 0.5 m, the deformation of Seam II-1 is small during the early stage of mining. As the working face advances and the overburden gradually caves, the deformation of the protected seam increases. When the working face advances to 100 m, the maximum vertical displacement reaches 25 mm, corresponding to an expansion strain of 3.33‰. The deformation response remains relatively weak compared with those obtained at the larger mining heights.

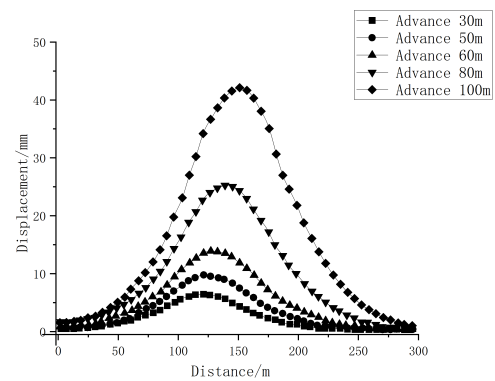
At a mining height of 1.0 m, the deformation of Seam II-1 is also relatively small during the early stage. When the working face advances to 80 m, extensive bedding-separation fractures develop in the overburden, and the maximum vertical displacement of the protected seam reaches approximately 25 mm. As the working face advances to 100 m, the deformation increases further, with a maximum displacement of 46 mm and an expansion strain of 6.13 ‰. The increase in deformation from 80 to 100 m corresponds to the continued development of overburden failure observed in Fig. 4.

At a mining height of 1.5 m, the deformation of Seam II-1 increases earlier and more strongly. A marked increase in the deformation of Seam II-1 occurs when the working face advances to approximately 50–60 m, with the maximum displacement reaching about 17 mm. At an advance of 80 m, the deformation range expands and the maximum displacement reaches approximately 32 mm. When the working face advances to 100 m, continued overburden caving further increases the deformation of Seam II-1, and the maximum displacement reaches 56 mm, corresponding to an expansion strain of 7.47‰.

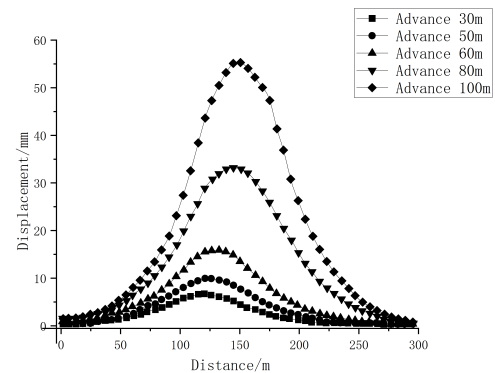
At an advance of 100 m, the maximum vertical displacements for mining heights of 0.5, 1.0, and 1.5 m are 25, 46, and 56 mm, respectively, and the corresponding expansion strains are 3.33‰, 6.13‰, and 7.47‰. Increasing the mining height therefore enhances the deformation response of the protected seam. The increase from 0.5 to 1.0 m is more pronounced than that from 1.0 to 1.5 m, which is consistent with the permeability variation described in Section 3.2.



(a) Mining Height of 0.5 m



(b) Mining Height of 1 m



(c) Mining Height of 1.5 m

Fig. 7. Vertical displacement of Seam II-1 during protective-seam mining

3.4. Selection of a Reasonable Mining Height

Table 3 summarizes the overburden failure, protected-seam deformation, and gas permeability under mining heights of 0.5, 1.0, and 1.5 m. Overall, the response of Seam II-

1 becomes stronger as the mining height increases. At a mining height of 0.5 m, only Seam I-8 is mined, and the deformation and permeability enhancement of the protected seam are relatively limited. Increasing the mining height to 1.0 m markedly strengthens the mining-induced response of Seam II-1, while a further increase to 1.5 m produces additional improvement.

Fig. 8 compares the changes in the maximum gas permeability coefficient and expansion strain under the three mining heights. When the mining height increases from 0.5 to 1.0 m, the maximum gas permeability coefficient increases by $144 \text{ m}^2 \cdot \text{MPa}^{-2} \cdot \text{d}^{-1}$ and the expansion strain increases by 2.80 ‰. When the mining height increases from 1.0 to 1.5 m, the corresponding increments are $20 \text{ m}^2 \cdot \text{MPa}^{-2} \cdot \text{d}^{-1}$ and 1.34 ‰, respectively. Thus, both the permeability and deformation responses of Seam II-1 continue to increase with mining height, but the changes from 1.0 to 1.5 m are smaller than those from 0.5 to 1.0 m.

Increasing the mining height requires more adjacent rock to be mined together with Seam I-8, thereby increasing the amount of rock cutting, transportation, and handling. Considering the pressure-relief response of Seam II-1 and the additional rock excavation, a total mining height of 1.0 m was selected for the 3307 working face among the three mining-height cases considered in this study. This mining scheme was subsequently adopted in the field test.

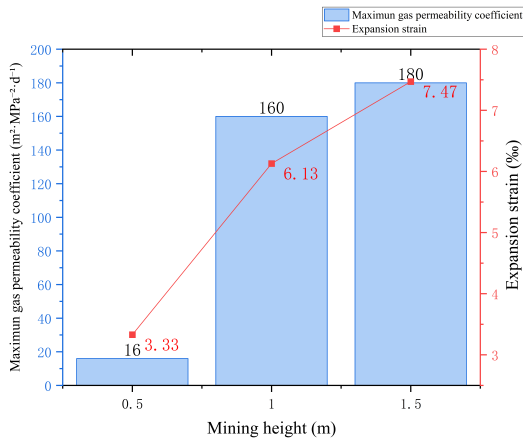


Fig. 8. Comparison of the maximum gas permeability coefficient and expansion strain of Seam II-1 at different mining heights.

3.5. Field Test

Based on the mining-height comparison, a total mining height of 1.0 m was adopted in the field test at Zhongtai Mine. The 0.5 m-thick Seam I-8 was mined together with

0.5 m of relatively soft mudstone from the false roof and immediate roof. Pressure-relief gas drainage was carried out simultaneously during protective-seam mining. The layout of the gas-drainage boreholes is shown in Fig. 9.

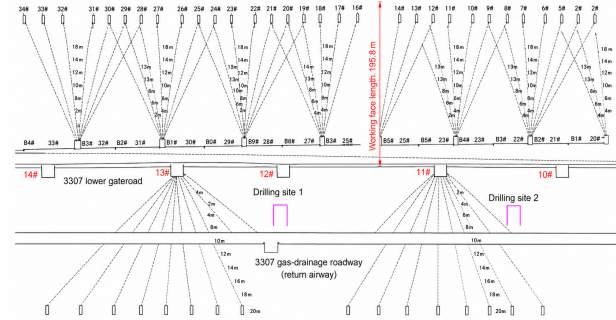


Fig. 9. Layout of gas-drainage boreholes

Fig. 10 shows the variation in gas-drainage parameters during working-face advance. At the initial stage of protective-seam mining, the pure methane drainage rate was only about $0.3 \text{ m}^3/\text{min}$, and the methane concentration was also relatively low. As the working face advanced, gas drainage gradually increased. After the face had advanced approximately 100 m, the pure methane drainage rate reached approximately $8 - 14 \text{ m}^3/\text{min}$ during the higher-drainage intervals, while the methane concentration reached 30-50%. Although pronounced fluctuations are present in the monitoring curves, the overall drainage response after approximately 100 m of advance was markedly stronger than that during the initial mining stage.

Gas-content measurements were subsequently conducted at six points in the protected Seam II-1. Table 4 lists the lost gas content, desorbed gas content, residual gas content, and total gas content measured at each point. The measured gas content after drainage ranges from 0.53 to $1.83 \text{ m}^3/\text{t}$, with the maximum value of $1.83 \text{ m}^3/\text{t}$ occurring at measurement point 4. At this point, the lost, desorbed, and residual gas contents are 0.02 , 0.16 , and $1.65 \text{ cm}^3/\text{g}$, respectively.

The field results show that the 1.0 m coal-soft-rock co-mining scheme, together with pressure-relief gas drainage, increased the gas-drainage performance and reduced the gas content of Seam II-1 under the investigated conditions. Because only the 1.0 m scheme was implemented in the field and pressure-relief gas drainage was applied simultaneously, these measurements provide engineering verification of the selected field scheme rather than independent validation of the mining-height responses predicted for all three simulated cases.

Table 3. Comparison of numerical results at different mining heights

Parameter	Advance distance	0.5 m	1.0 m	1.5 m
Overburden failure	40 m	No obvious failure	Slight roof failure	Slight roof failure
	70 m	Roof caving and bedding separation develop	Roof fracture and bedding separation develop	Roof caving with extensive bedding separation
	80 m	Roof caving increases	Overburden failure increases	Extensive caving and fracture development
	100 m	Severe overburden failure	Vertical and bed-ding-separation fractures develop	Caved strata gradually compact
Maximum vertical displacement	100 m	25 mm	46 mm	56 mm
Expansion strain	100 m	3.33 ‰	6.13 ‰	7.47 ‰
Maximum gas permeability coefficient	100 m	$16 \text{ m}^2 \cdot \text{MPa}^{-2} \cdot \text{d}^{-1}$	$160 \text{ m}^2 \cdot \text{MPa}^{-2} \cdot \text{d}^{-1}$	$180 \text{ m}^2 \cdot \text{MPa}^{-2} \cdot \text{d}^{-1}$

Table 4. Post-drainage gas-content measurements in Seam II-1

Measurement point	Lost gas content (cm^3/g)	Desorbed gas content (cm^3/g)	Residual gas content (cm^3/g)	Total gas content (m^3/t)
1	0.06	0.24	0.24	0.54
2	0.02	0.25	0.59	0.87
3	0.06	0.20	0.89	1.15
4	0.02	0.16	1.65	1.83
5	0.00	0.13	0.40	0.53
6	0.04	0.36	0.40	0.81

4. Conclusions

- (1) The theoretical analysis shows that increasing the mining height of the ultrathin lower protective seam promotes the upward development of mining-induced overburden failure. The calculated height of the water-conducting fractured zone increases with mining height, while it remains below the vertical separation between the mined seam and Seam II-1 for the mining-height range considered. Therefore, the theoretical calculation mainly reflects the increasing influence of mining height on overburden disturbance, and the pressure-relief response of Seam II-1 needs to be evaluated together with the numerical and field results.
- (2) RFPA2D simulations show that increasing the mining height enhances overburden failure and increases the deformation and gas permeability of Seam II-1. The changes in both expansion strain and gas permeability are much more pronounced when the mining height increases from 0.5 to 1.0 m than when it increases from 1.0 to 1.5 m. Considering the improvement in the protected-seam response together with the additional rock excavation required at larger mining heights, 1.0 m was selected as a reasonable mining height among the three investigated cases.
- (3) The 1.0 m mining-height scheme was implemented by mining the 0.5 m-thick Seam I-8 together with 0.5 m of relatively soft roof rock and combining protective-seam mining with pressure-relief gas drainage. After the working face had advanced approximately 100 m, the pure methane drainage rate reached $8 - 14 \text{ m}^3/\text{min}$ during the higher-drainage intervals, and the maximum gas content measured in Seam II-1 after drainage was $1.83 \text{ m}^3/\text{t}$. These field results support the engineering feasibility of the 1.0 m mining-height scheme under the conditions of the 3307 working face.
- (4) The results of this study are mainly applicable to the geological and mining conditions investigated at Zhongtai Mine. The numerical comparison included only three representative mining heights, and field implementation was conducted only for the 1.0 m scheme at one working face. In addition, the two-dimensional numerical model cannot fully represent three-dimensional boundary effects and the spatial evolution of mining-induced fractures. Further studies should examine in-

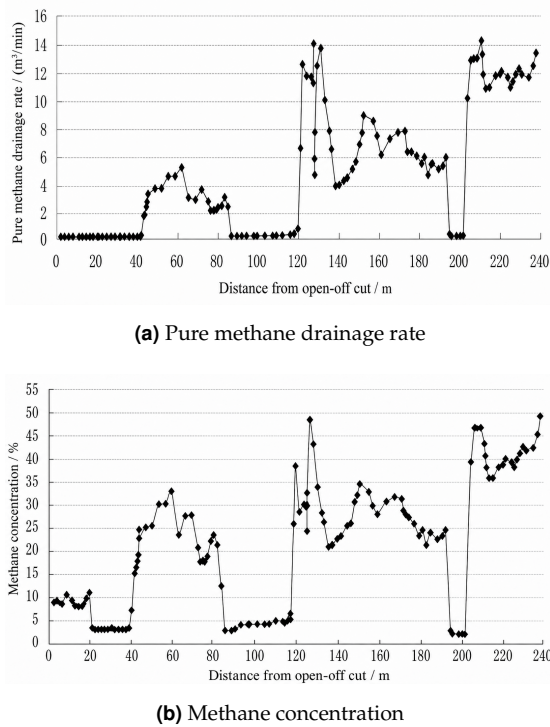


Fig. 10. Variation in gas-drainage parameters with working-face advance

intermediate mining heights and different interseam spacings, seam dips, overburden lithologies, key-stratum conditions, and gas occurrence conditions. Additional field deformation and stress monitoring would also help establish a more quantitative range of applicability for ultra-thin lower protective-seam mining.

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