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Experimental investigation into stress-relief characteristics with upward large height and upward mining under hard thick roof

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Abstract According to geological conditions of No. 3 and No. 4 coal seams (namely A3 and B4) of the Pan'er coal mine and the parameters of panels 11223, 11224, and 11124 with fully-mechanical coal mining, we built 2D similar material simulation and FLAC^{3D} numerical simulation models to investigate the development of mining-induced stress and the extraction effect of pressure-relief gas with large height and upward mining. Based on a comprehensive analysis of experimental data and observations, we obtained the deformation and breakage characteristics of strata overlying the coal seam, the development patterns of the mining-induced stress and fracture, and the size of the stress-relief area. The stress-relief effect was investigated and analyzed in consideration with mining height and three thick hard strata. Because of the group of three hard thick strata located in the main roof and the residual stress of mined panel 11124, the deformation, breakage, mining-induced stress and fracture development, and the stress-relief coefficient were discontinuous and asymmetrical. The breakage angle of the overlying strata, and the compressive and expansive zones of coal deformation were mainly controlled by the number, thickness, and strength of the hard stratum. Compared with the value of breakage angle derived by the traditional empirical method, the experimental value was lower than the traditional results by 3°–4° below the hard thick strata group, and by 13°–19° above the hard thick strata group. The amount of gas extracted from floor drainage roadway of B4 over 17 months was variable and the amount of gas per month differed considerably, being much smaller when panel 11223 influenced the area of the three hard thick strata. Generally, the stress-relief zone of No. 4 coal seam was small under the influence of the hard thick strata located in the main roof, which played an important role in delaying the breakage time and increasing the breakage space. In this study we gained understanding of the stress-relief mechanism influenced by the hard thick roof. The research results and engineering practice show that the main roof of the multiple hard thick strata is a critical factor in the design of panel layout and roadways for integrated coal exploitation and gas extraction, provides a theoretical basis for safe and high-efficient mining of coal resources.

Keywords Integrated coal exploitation and gas extraction · Large mining height · Stress-relief effect · Hard thick strata · Mining-induced stress

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1 Introduction

Coal mining disasters involving gas will result in severe safety accidents during high-efficient exploitation for coal resources. With coal production and mining depth increasing, gas leak prevention and control in gassy coal seams with low permeability and high occurrence of outbursts have become extremely important and high-cost issues (He et al. 2005; Zhou et al. 2005; Yuan 2008). In recent years, scholars and engineers have developed effective methods, with significant progress in integrated coal and gas extraction with stress-relief mining, such as mining program selection, roadway design, and gas extraction drilling layout (Cheng et al. 2003; Xu et al.2004; Tu et al. 2006; Shi and Liu 2008). Stress-relief mining has proved to be a successful method in gassy coal mining. It uses strata movement to release elastic energy, increase coal permeability, change the methane state in the pressure-relieved coal body (to prevent coal and gas outburst), and increase the gas extraction rate. Research results show that the distribution and deformation characteristics of the stress-relieved zone in the depressurized coal seam depend on the panel layout, the spacing of the layers and their thickness, the lithology, and the roof structure between the mining seam and stress-relief seam; however, few investigations have examined large mining height with multiple hard thick strata at long intervals (Xu et al. 2004; Tu et al. 2006, 2007; Shi and Liu 2008; Liu 2010; Shao 2012; Xie et al. 2012; Chen et al. 2013; Guo 2014). In this study, we investigate the geological and engineering conditions of No.3 and No.4 seams (seams A3 and B4) in the Pan'er coal mine, Huainan Coalfield, Anhui Province, China. A numerical simulation model is established to investigate the stress-relief distribution, deformation, and breakage characteristics in the overlying strata and coal seam with large height and upward mining.

2 Geotechnical conditions

In the Pan'er coal mine, coal seams A3 and B4 (consisting of coal seams 4-1 and 4-2) are gassy and outburst prone, making the mining work geotechnically complex. The average thickness, methane content, and methane pressure of seam A3 are 5 m, 11 m^3 per ton, and 2.6 MPa, respectively. And those of seam B4 are 3 m, 7.79 m^3 per ton, and 1.5 MPa, respectively. The average distance between seams A3 and B4 is 80 m and the average inclination angle of the seams is 13°. The permeability of A3 and B4 coal is about 0.0023 mD. Panel 11223 is located in seam A3 and panels 11224 and 11124 are located in seam B4 (Fig. 1). The distance between the head-entry of panel 11124 and the tail-entry of panel 11223 is about 90 m and the pillar width between panels 11124 and 11224 is 7 m. The elevation of panel 11223 is from −460 to −500 m, and the width of panels 11124, 11224, and 11223 is 140, 180, and 180 m, respectively. The gas drainage roadway is in the middle location above panel 11223 and about 40 m from the floor of B4.

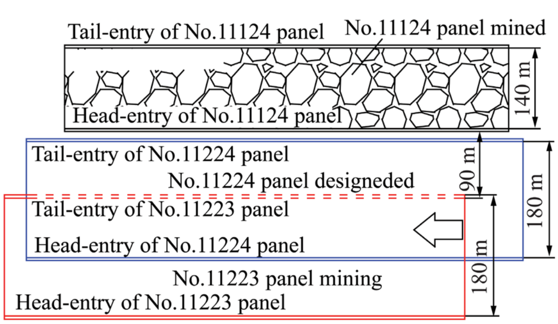


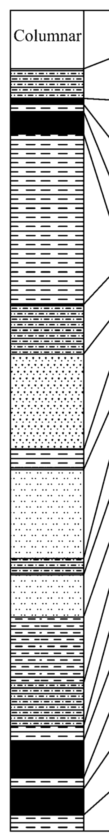
Fig. 1 Layout of the longwall panels of seams A3 and B4

Based on the stratigraphic column (Fig. 2), the main roof consists of three groups of hard thick strata. The thickness of the sandstone is 5.7, 12, and 12.8 m and the three layers are located 16.7, 24.6, and 39.4 m from the roof of seam A3, respectively. All the sandy strata are generally hard and thick, which strongly affects coal extraction. The sandy rock has a tensile strength of 5.6–6.3 MPa and compressive strength of 61.4–75.6 MPa.

3 Similar material modeling

3.1 General model

To investigate the scope of the depressurized zone of the inclined seam B4, a rotational experimental platform was used to construct the model. The length, width, and height of the platform are 2, 0.2, and 2 m, respectively. Because of the size limitation of the model, the overlying strata



Rock	Thickness (m)	Density (kg/m^3)	Tensile strength (MPa)	Compressive strength (MPa)
Sandy mudstone	4.0	2605	2.0	24.0
B4-2 coal	0.8	1460	0.4	4.2
Mudstone	1.0	2433	1.9	22.8
B4-1 coal	3.0	1460	0.4	4.2
Mudstone	20.3	2433	1.9	22.8
Sandy mudstone	6.7	2565	1.7	20.4
Gritstone	12.8	2704	5.6	61.4
Mudstone	2.8	2433	1.5	18.0
Fine sandstone	12.0	2684	6.3	75.6
Sandy mudstone	2.2	2505	2.7	32.4
Fine sandstone	5.7	2684	6.3	75.6
Mudstone	8.9	2565	1.7	20.4
Sandy mudstone	5.8	2460	1.6	24.4
Mudstone	2.0	2389	1.4	16.8
A3 coal	5.0	1460	0.3	4.1
Mudstone	1.5	2389	1.4	16.8
A1 coal	3.5	1400	0.3	4.1
Mudstone	2.2	2389	1.4	16.8

Fig. 2 Stratigraphy and rock property parameters of the study site

were represented by an additional compensation load modeled as lever and gravity loading. Taking into account the friction between the material and the steel baffle, the additional load was set as 20 kN.

In the model, resistance strain gauges of BX120-50AA were used as stress sensors to record the evolution of the mining-induced stress in the coal and rock. The data acquisition system No. 7v14 was used to collect and transmit data to the computer. The system consists of data acquisition equipment, data communications equipment, a computer, and data analysis software. The pulse laser station EDM NIKON NPL-821 was used to survey the displacement of the overlying strata using the cross-distribution point method.

According to similar simulation criteria, the geometric similarity ratio, time similarity ratio, and the stress similarity ratio of the model were set as 1:100, 1:10, and 1:160, respectively. The stress and displacement schemes are shown in Fig. 3 and Table 1. In the model, four displacement survey lines and four stress observation lines were designed and arranged in each layer. 19 survey points at 10 cm intervals were set in each displacement line and seven observation points were set in each stress line. Additionally, three points were arranged in the pillar sides and one point in the middle region based on theory estimating.

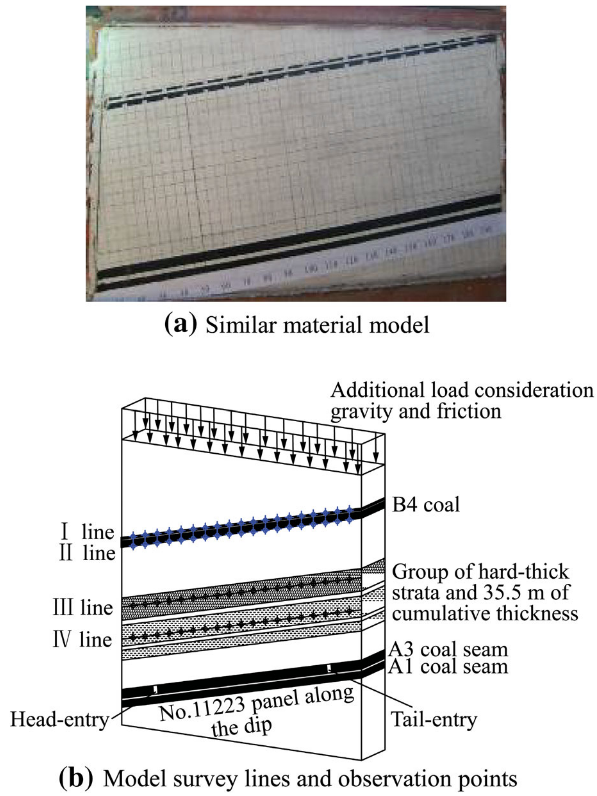


Fig. 3 Model design and survey points arrangement

3.2 Stress-relief coefficient characteristics

To analyze the mining-induced stress evolution and stress-relief characteristics of the B4 coal seam, we used the stress-relief coefficient (Yuan et al. 2011).

$$r = 1 - \frac{\sigma_z}{\sigma_{z0}} \tag{1}$$

where σ_z is the vertical mining-induced stress and σ_{z0} is the initial stress. $r > 0$ and $r < 0$ represent stress relief and stress increase, respectively.

The advance of panel 11223 creates a range of mining-induced fractures including vertical breakage fissures and separation fissures in the strata (Figs. 4 and 5), which develop at different heights. The vertical breakage fissures are mainly under the hard thick sandstone group while the separation fissures are in B4 coal seam. The stress data from the strain gauges show that the stress-relief coefficient and stress-increase coefficient are variable and asymmetric in the overlying strata. In line IV, the stress-relief zone is 125 m wide (between 10 and 135 m) above the mined area of panel 11223 and the maximum coefficient is 0.9. As the strata elevation increases, the stress-relief zones become smaller, decreasing in size to 93 m and 65 m in the strata of line III and B4 coal seam (lines I–II), respectively. The maximum coefficients are reduced to 0.8 and 0.2 in the strata of line III and coal seam B4 (lines I–II), respectively, with a considerable decrease in B4.

With the effect of strata structure and layer location, the values of the stress-relief coefficient and breakage angle vary considerably and asymmetrically in the overlying strata as the strata structure and layer location change. The breakage angles differ from the dip angle in the hard thick strata below and above the coal seam. Along the head-entry and tail-entry of panel 11223, the breakage angle (the angle between the direction of the breakage line and the dip line of the coal seam) is 72° and 81°, respectively, below the hard thick strata group. Above the strata group, the breakage angles of the head and tail entries are 63° and 65°, respectively. The difference in breakage angle between the lower and upper strata is 9°–24°. The results indicate that the asymmetric characteristics are closely related and mainly influenced by the hard thick strata group that play an important role in delaying the breakage time and increasing breakage spacing.

3.3 Deformation characteristics of B4 coal seam

The displacement and breakage patterns of the coal bearing strata are shown in Fig. 4. The compressive and expansive deformation behavior in the various strata (Fig. 6) was obtained from analysis of the monitoring records of lines I and II.

Table 1 Arrangement of stress and displacement survey lines

Number	Location	Points number	Spacing (cm)
I	Roof of No. 4–2 coal seam	19	10
II	Floor of No. 4–1 coal seam		
III	45.8 m distance to roof of A3 coal seam		
IV	19 m distance to roof of A3 coal seam		

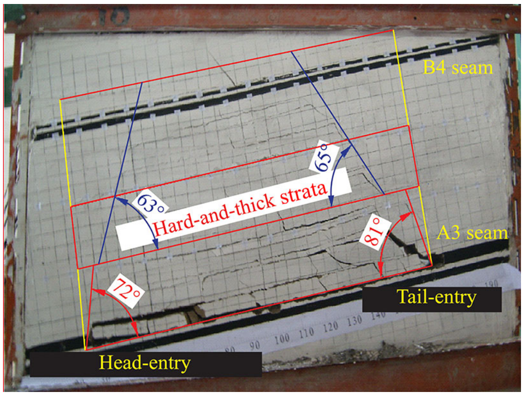


Fig. 4 Stress-released zone and mining-induced fracture in the coal bearing strata

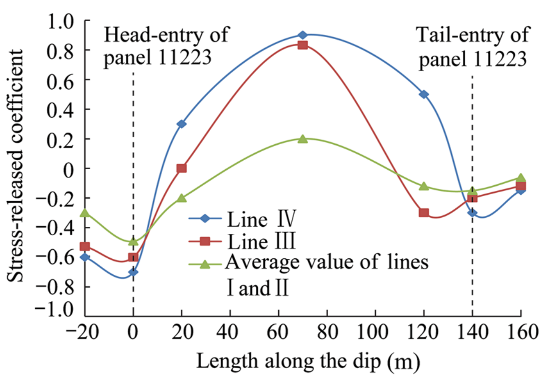


Fig. 5 Stress-relief coefficient curves in different strata

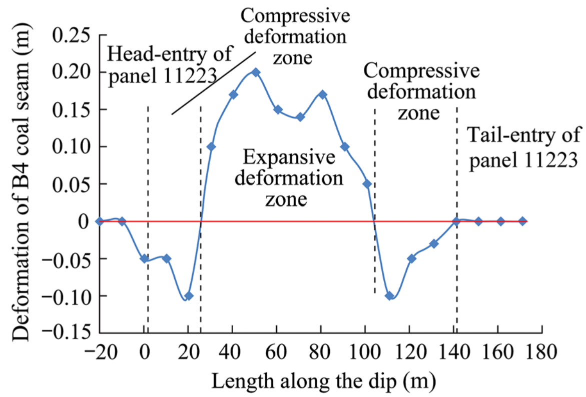


Fig. 6 Deformation curve of B4 coal seam

In B4 coal seam, the expansive deformation zones are from 25 to 103 m along the dip line and the curve is M-shaped, with two peaks and a depression between them. The maximum relative value of the expansive deformation is 4.17 %. The maximum relative value of the compressive deformation is 2.08 % and is located on the sides almost above the tail-entry and head-entry.

4 FLAC^{3D} numerical modeling

4.1 General model

We constructed the FLAC^{3D} model based on the geological conditions and panel layout to investigate the development of mining-induced stress and strata displacement. The model width, length, and height in the *x, y,* and *z* directions are 470,400, and 280 m, respectively, with *x–y* being the horizontal plane. The model includes 684456 units and 709920 nodes, and the Mohr–Coulomb criterion was adopted as the constitutive relation for the mechanical behavior of the coal and rock.

To represent the weight of the overlying strata not included in the model, an additional vertical gravity stress was calculated and loaded on the model's upper surface. The displacement boundary constraints were added on the sides and bottom surface of the model. Based on the mining sequence of the three longwall panels, the numerical simulation process includes three steps: (1) Excavation of panel 11224 of B4 coal seam after initial equilibrium of the model; (2) Driving the head-entry and tail-entry of panel 11223 of A3 coal seam; (3) Excavation of panel 11223.

4.2 Stress-relief characteristics

The mining-induced stress was collected in the front and rear sections of longwall panel 11223 and the curves of the stress-relief coefficient were derived (Fig. 7). According to Eq. (1), the increased-stress (abutment pressure) zone that developed when panel 11224 was excavated is about 40 m to head-entry of panel 11124 in the 90 m coal pillar; the maximum stress-relief coefficient is 0.83. Then, the stress-relief scope gradually stabilized about 100 m along the rear of panel 11223 and the maximum stress-relief coefficient rose to 0.89.

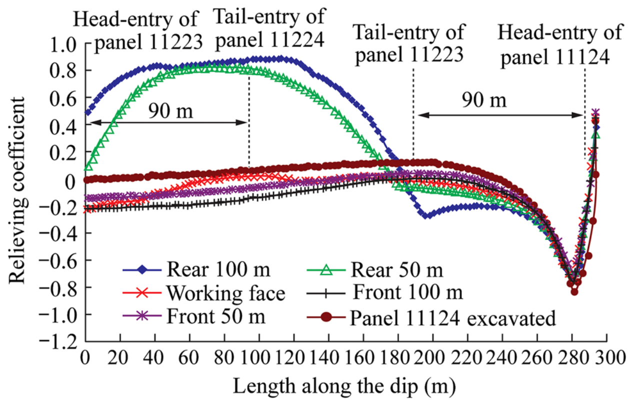
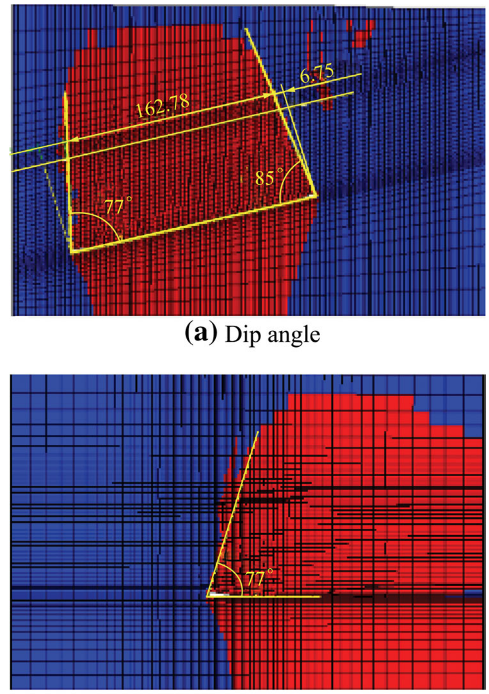


Fig. 7 Stress-relief coefficient curves in different dip sections

Figure 8 shows the distribution of the elastic and plastic zones in the model. The simulation shows that the breakage angles differ from the dip angle in panel 11223. Along the head-entry and tail-entry, the breakage angle is 77° and 85°, respectively. Along the strike, the breakage angle is 75°. The width of the depressurized zone developed in B4 coal seam when panel 11223 was excavated is 162.78 m.



(a) Dip angle

(b) Along the strike

Fig. 8 Distribution of the plastic zone (*blue* represents elastic zone and *red* indicates yield zone)

5 Gas extraction quantity

The gas extraction amount from the floor of the gas drainage roadway was variable during the advance of panel 11223 (Fig. 9). In the area under the influence of the three hard thick strata, only small amounts of gas were extracted in September, October, and November 2013, and in March and April 2014: the gas volume was 5247, 19640, 50512, 86293, and 98100 m^3, respectively. However, in August and September 2014, the amounts extracted were much higher, reaching 781369 m^3 in August. The maximum extracted volume is 8–150 times the volume in low-yield months.

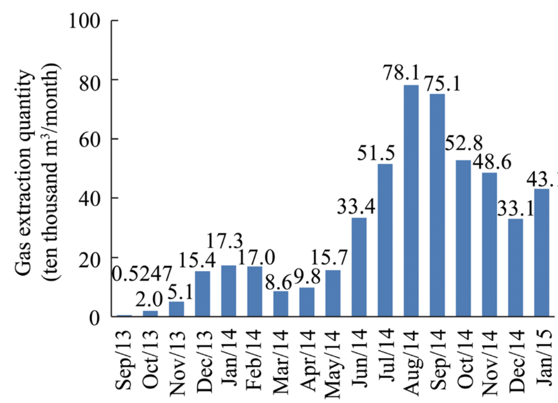


Fig. 9 Monthly gas extraction quantity

6 Discussion

According to the *Technical Criterion of Protective Coal Seam Exploitation* (AQ 1050—2008) and the geotechnical conditions, the depressurized zones were calculated and the depressurized angles (approximately equivalent to breakage angles) were derived: 76° and 84° inside the head-entry and tail-entry, respectively. These angles are consistent with the numerical simulation values but differ from the values obtained by similar material simulation (Table 2). Compared with the values of the breakage angle derived by using traditional empirical and numerical methods, the laboratory test results are smaller, with a deviation of 3°–4° below the hard thick strata group, and 13°–19° above the hard-thick strata group. The width of the depressurized zone is about 75 m in B4 coal seam when A3 coal seam is mined 140 m, but the width is 162.78 m when seam A3 is mined 180 m. Compressive analysis shows that those differences may be caused by test errors, because of limitations of platform size, selection of simulation parameters, and the simplification of the model.

The stress-relief mechanism has been qualitatively investigated and clarified to a certain extent; the deformation and displacement characteristics of the overlying strata, and the development of mining-induced stress and fissures are discontinuous and uncorrelated, and usually intermittent (Fig. 10). Insufficient stress-relief is the main reason for the fluctuation of the gas extraction, resulting in an inefficient supply.

Table 2 Breakage angles of the stress-relief area

Items	Empirical value	Numerical value	Below the hard-and-thick strata	Above hard-and-thick strata
Breakage angle of tail-entry side (°)	84	85	81	65
Breakage angle of head-entry side (°)	76	77	72	63

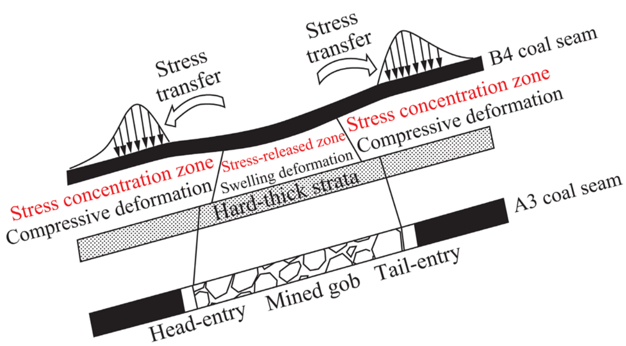


Fig. 10 Schematic diagram of the stress-relief area in upward relieving mining of hard thick strata

7 Conclusion

(1) The group of three hard and thick strata is one of the important factors in upward stress-releasing mining. To some extent, it plays a key role in delaying the time and the breakage spacing of the main roof and mitigating the discontinuous and asymmetrical deformation and breakage, especially the scope of the stress-relief area, where a clear difference exits below and above the hard thick strata.

(2) The breakage angles below the hard thick strata derived in the laboratory tests were 3°–4° lower than those derived by traditional empirical values, while those above the hard thick strata were 13°–19° lower.

(3) The widths of the stress-relief zones in B4 coal seam in the numerical simulation differed from those in the similar material simulation, but the stress-relief coefficient was symmetrical along the dip. The development pattern of the expansive deformation in B4 coal seam is M-shaped.

(4) Research results show that the evolving patterns of mining-induced stress and mining-induced fissures are critical factors when designing longwall panels, selecting gas extraction method, and arranging roadways. Effectively prolonging the time of gas extraction and applying the techniques of hole drilling and sealing to gas drainage may be effective and feasible processes in remote and upward stress-relief mining in hard thick strata between two coal seams.

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