Geoenvironmental Disasters

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Experimental investigation on stress distribution and migration of the overburden during the mining process in deep coal seam mining

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Abstract

Coal mining has a significant impact on the movement of the overburden, leading to potential safety hazards in the working face. In this paper, a similarity simulation experiment was conducted to investigate the migration of overburden during the mining process of a specific working face in the Liuzhuang Coal Mine located in southern China. Sand and gravel were used to simulate the geological environment of each rock stratum. The deformation of the stratum was monitored using strain gauges, the fracture and displacement changes of the overburden stratum were recorded using cameras, and the characteristics of roof collapse was monitored using infrared thermal imager. The experimental model fully simulated the situation of the working face, and the actual working face size was obtained by enlarging the model by 100 times. The experiment found that during the initial stage of mining, there was no significant subsidence of the roof. In the course of the advancement of the working face, the primary roof intermittently fractured behind the working face, with subsequent propagation of upper cracks in an upward direction. The overburden rock layer above the goaf experienced continuous compaction, leading to the gradual closure of the separation layer. Simultaneously, new cracks constantly emerged in front of the working face, resulting in the progressive stabilization of the height of the crack zone. The stress measurements at each point exhibit a pattern of initial increased, followed by decrease, and ultimately stabilization. By considering the stress variation law of the overburden rock, the stress changes in key layers of the bedrock during mining could be categorized into four zones: the stress stable zone, stress increasing zone, stress reducing zone, and compaction stable zone. During the initial phase of coal seam mining, the presence of rock layers provided support, resulting in minimal subsidence of the overburden rock. However, as the mining operation progressed, the disturbance force and collapse of the overburden rock leaded to further downward subsidence. When the working face reached the stop line, the collapsed overburden rock gradually consolidates, resulting in a deceleration of energy release and the formation of a pressure relief zone. Consequently, the overburden rock above the working face underwent a slight additional subsidence, reaching its maximum level. A short cantilever rock beam structure was formed in the experiment. This study will provide valuable reference for future coal mining and serve as a vital theoretical basis for roof control in deep coal seam mining.

Keywords Coal seam, Overburden, Migration, Collapse, Roof

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Introduction

During the mining process of coal seams, the overburden pressure can cause support break-off, leading to serious safety hazards in the working face. The ability of safely and efficiently mining a stope is closely related to the deformation, fracture, and migration of the overburden strata, which are influenced by various factors (Lv et al. 2022; Xie et al. 2023).

After mining, the overburden above the goaf will form a certain shape and relatively stable structure with rock pressure manifestations. The selection of support for the mining face, the deformation and destruction of the overburden, as well as the distribution of each separation fissure zone and the characteristics of surface subsidence and deformation, are all influenced by this structure and rock pressure manifestations (Lv et al. 2022; Zhu et al. 2022). Theoretical achievements proposed by many experts and professors at home and abroad include the cantilever beam hypothesis, the pressure arch hypothesis, the pre-formed crack hypothesis, the "transmission rock beam" hypothesis, the "masonry beam" hypothesis, and the "key layer" theory (Peng 2015; Wang et al. 2022). Gao et al. (2000) established a mechanical model for the deformation and failure of overburden based on the theory of masonry beam structure, under the complex mechanical problems of forming a direct roof under the deformation and failure of the main roof. Hou (2008) deduced a theoretical formula for determining the main roof of a crack zone based on the mechanical conditions for rock mass equilibrium of masonry beam structures. Tu et al. (2011) studied the deformation and failure of overburden caused by coal mining, the support break-off mechanism, and the law of surface movement, and proposed reasonable and effective solutions. Kong et al. (2015) used the microseismic monitoring system to predict the subsidence movement of the overburden strata in the stope, and the characteristics of overburden strata in the top coal caving face with large mining height in Tashan Coal Mine. Wang et al. (2019) established a mechanical model of the loose layer arch bearing structure and obtained the law of movement of the loose layer arch on mining overburden through similar simulation tests. The above research shows that physical similarity simulation experiments can reveal the behavior and structural evolution of overburden strata during coal mining.

Coal mining has been found to have a significant impact on the movement of overburden, and numerous studies have been conducted to analyze the factors and processes that influence the migration and destruction of overburden (Li et al. 2022; Ma et al. 2023a). Xu et al. (2005) conducted a comprehensive analysis on the impact of key layers of overburden strata during mining and found that these layers played a crucial role in controlling the deformation, fracture and migration of overburden strata. Wang and Wang (2015) conducted the research on the Ulanmulun Coal Mine and found that increasing the thickness of the load layer, mining height, and length of the working face could lead to an increase in the height to length ratio of the roof failure rock block and the maximum position of the rock beam rotational instability. Wang et al. (2015) studied the movement law of overburden strata in shallow coal seams and found that a reasonable mining height could control the impact of mining on the overburden strata. Zhou et al. (2016) used simulation experiments to study the movement of various parts of the overburden interior. Wu et al. (2017) studied the impact of different coal seam dip angles on mining-induced overburden movement and found that the maximum collapse height and the maximum uplift height of the middle floor of the working face had a certain relationship with the dip angle. Based on large-scale true 3D similar physical simulation tests, Yang et al. (2021) obtained the movement law of overburden crack in thick coal seam mining under the condition of thick and hard roof. Their research indicated that the weak rock stratum moved synergistically with the deformation and fracture of thick and hard key layers. Ma et al. (2023b) analyzed the evolution law of mining stress and the impact of dynamic pressure, and identified the roof plastic zone and roof subsidence characteristics in deep adjacent working faces by numerical simulation. Wang et al. (2023) analyzed the characteristics of strong ground pressure of thick loose bed and thin base rock, and revealed cause of mining-induced roof broken and instability by similar experiment and mechanic modeling. Based on the above research, it was clear that mining overburden had many impact factors (Ti et al. 2021; Zhang et al. 2021). Therefore, when analyzing specific issues, it was necessary to identify the main impact factors based on the actual situation.

This paper aims to conduct a similarity simulation experiment on the overburden migration during the mining process of a specific working face in Liuzhuang Coal Mine, southern China. The study will focus on the development of overburden crack and subsidence process of overburden during the mining process, as well as the stress distribution and evolution of the overburden rock in the stope. The results of this study will provide valuable reference for future coal seam mining.

Methods

Combined with the construction drawing and the comprehensive geological histogram of the mine, the two-dimensional physical similar material simulation was carried out. The determination of the appropriate similarity ratio for the research object and task was based

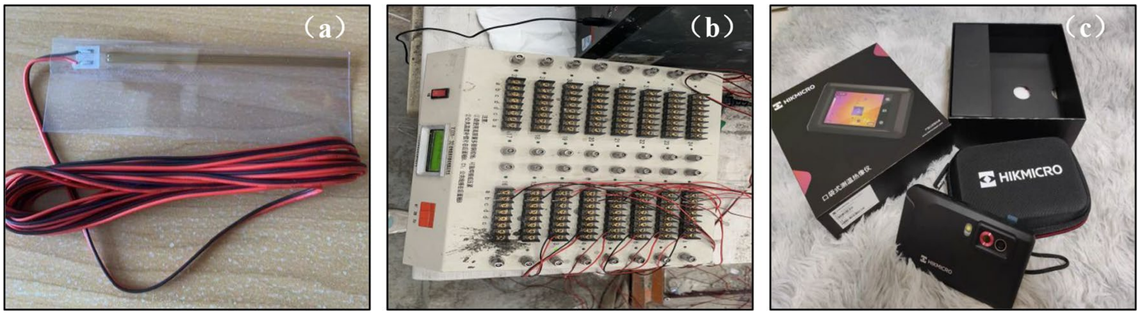

Fig. 1 Monitoring devices. **a** Strain gauge, **b** Strain instrument, **c** Infrared thermal imager

Table 1 Rock layer simulation parameters and material ratio

Number	Name of rock layer	Thickness/cm	Ratio No.	Weight of each component material (kg)		
				Sand	lime	gypsum
9	Aluminum mudstone	14	864	44.8	3.36	2.24
8	Sandy mudstone	17	773	53.55	5.22	2.32
7	Coarse sandstone	5	775	16.35	1.20	1.20
6	Medium fine Sandstone	18	655	60	5.10	5.10
5	Medium sandstone	21	564	68.25	8.19	5.46
4	11 − 2 Coal	4.6	1055	8.78	0.44	0.44
3	Mudstone	4	864	6.40	0.48	0.32
2	Siltstone	6	955	21.04	1.18	1.18
1	Sandy mudstone	9	773	28.35	2.82	1.23

on the principle of similarity condition experiment. The experiment was conducted at China University of Mining and Technology. In the experiment, a planar model platform with long × wide × high (1500 mm× 100 mm × 1000 mm) was used to simulate the geological environment of various rock layers by mixing sand, lime, gypsum, and water in different proportions. The strain gauges (BX120-30AA) connected to the strain instrument to monitor the stress change data, and the data was collected every five minutes. The cameras (Canon) were used to take photos of the fracture and displacement changes of the overburden strata. The infrared thermal imager (Haikang, HIKMICRO-TPK20) was used to monitor the characteristics of roof caving during mining in the working face (Fig. 1).

Based on the rock stratum histogram, mechanical parameters of coal and rock mass, and similar conditions of the working face in Liuzhuang Coal Mine, the layer weight of each rock stratum was computed. The amount of sand, lime, gypsum, and water was determined based on the ratio number (Table 1). Fine sand was utilized as an aggregate, while lime and gypsum were utilized as cements. Water was used for dilution and easy mixing. Additionally, mica powder was chosen as the layered material, with a layer thickness of 3 cm for each layer.

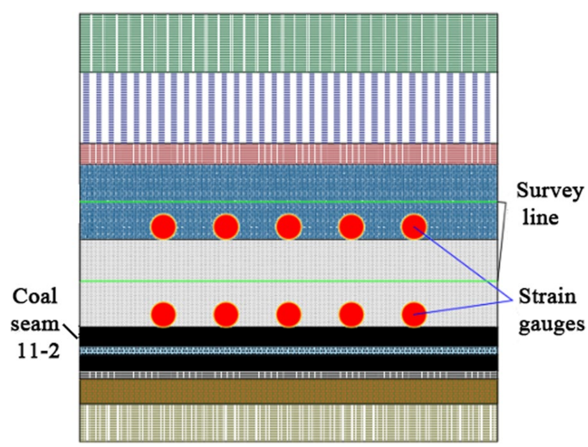

Fig. 2 Layout Plan of Strain Gauge

Two layers of strain gauges were laid in the model. The first layer was arranged in medium sandstone, 3 cm away from the top of coal seam 11–2. They were arranged from 30 cm away from the left coal pillar, and arranged every 25 cm. A total of 5 strain gauges were buried, numbered

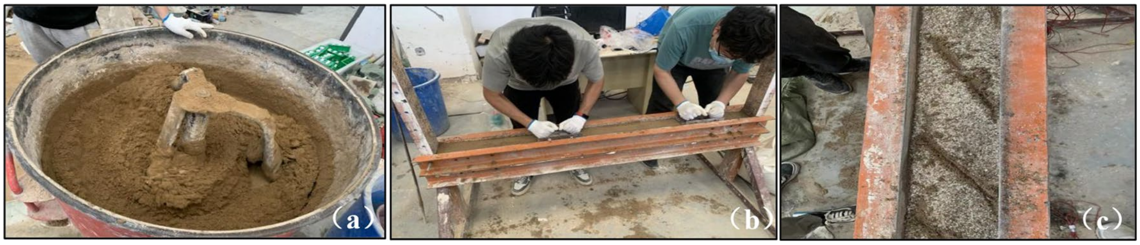

Fig. 3 The process of experiment. **a** Mixing materials, **b** Tamping the rock layer, **c** Scattering mica powder and joints

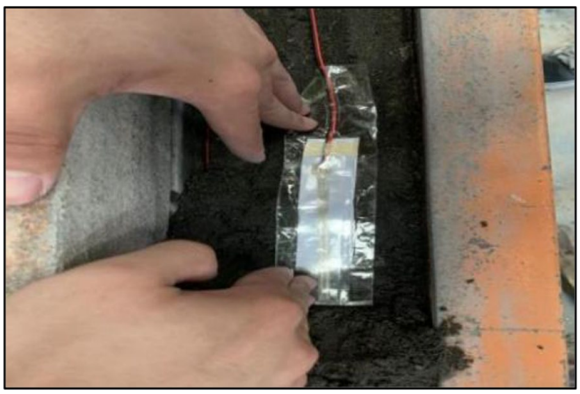

Fig. 4 Laying Strain Gages

Fig. 5 Whitening the model

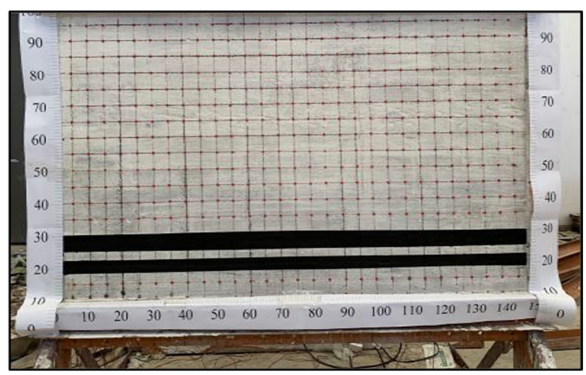

Fig. 6 Rendering of the actual model

1, # 2, # 3, # 4, and # 5 (Fig. 2). The second layer was arranged in medium fine sandstone, 21 cm from the top of coal seam 11–2, in the same manner as the first layer, numbered # 6, # 7, # 8, # 9, and # 10. A total of 10 strain gauges were arranged at the two measuring points.

Before the experiment, it was necessary to dry the sand to remove its own moisture, and then screened it to remove larger particles. Then weigh a certain weight of sand, lime, and gypsum in proportion, pour them into a mixer, and add an appropriate amount of water to make them fully mixed and stir evenly. In addition, four steel plates needed to be installed on the base and top of the planar model platform to support and stabilize it. Finally, pour the mixed material onto the base, evenly spread and compact it. Mica powder needed to be sprinkled between layers, and its joints should be compacted layer by layer upward, with each layer of 3 cm (Fig. 3).

When arranging strain gauges, we fixed the welded joints of the strain gauges with adhesive tape in advance, and buried them in sequence according to the positions determined in advance. Each strain gauge number was labeled for later identification and data processing (Fig. 4).

After the completion of the construction of the planar model platform, it was necessary to air dry it and let it stand for 3–4 days. And then it needed gradually remove some steel plates to undergo processes such as whitewashing, snapping lines, and tracing coal seams. The final physical model image was shown in the following figure (Figs. 5 and 6). Based on the daily mining progress and a time similarity ratio of 1/10 at the working face site, the planar model platform was excavated every 30 min, with each knife advancing 5 cm. The model was excavated from left to right, and the open-off cut was located 20 cm from the left end of the model platform.

Results

The experimental model fully simulated the situation of the working surface in Liuzhuang Coal Mine, and the actual working surface size was obtained by enlarging the model by 100 times. The following experimental process was analyzed based on the actual working surface size. A 20 m boundary coal pillar was reserved on the left side of the working face, and the working face advanced from left to right. By analyzing the evolution form of overburden migration, the deformation and failure law of overburden caused by mining in deep mining face could be obtained. When the working face was advanced to 10 m from the open-off cut, a weak crack appeared on the direct roof for the first time, and the crack was approximately 5.5 m away from the coal seam roof (Fig. 7).

As the working face was advanced, the cracks further developed. When the working face was advanced to 15 m from the open-off cut, a second segment of cracks appeared on the direct roof at a distance of 9 m from the coal seam roof (Fig. 8a). When the working face was advanced to 20 m from the open-off cut, a third segment of crack appeared on the direct roof, which was about 18 m from the coal seam roof, and the direct roof began to fall downward (Fig. 8b). When the working face was advanced to 25 m from the open-off cut, cracks appeared for the first time on the basic roof stratum, which was about 28 m from the coal seam roof, and there was a trend of further development and expansion of the cracks (Fig. 8c). When the working face was advanced to 35 m from the open-off cut, the cracks on the direct roof rock stratum were fully developed, and the cracks continued to expand. The direct roof began to fall for the first time and the key layer masonry beam began to appear. After about half an hour of development, the direct roof fully collapsed for the first time (Fig. 8d). When the working face was advanced to 40 m from the open-off cut, the cracks on the basic roof rock stratum continued to increase. When the basic roof was first pressed, the rock stratum began to partially fall. After about half an hour of development, the basic roof collapsed completely, and the key rock stratum above the basic roof began to appear cracks (Fig. 8e). When the working face was advanced to 60 m from the open-off cut, the direct roof dropped for the second time, and the cracks in the underlying roof rock above continued to develop, further expanding. Crack zone began to appear. Three segments of cracks appeared above the key layer, with the distances from the cracks to the roof of 11−2 coal seams being 48 m, 53 m, and 57 m, respectively (Fig. 8f). When the working face was advanced to 70 m from the open-off cut, the cracks on the direct roof rock stratum further expanded, and the lateral cracks in the rock stratum above the basic roof further expanded. There was a separation layer above the basic roof, and the separation layer continued to expand (Fig. 8g). When the working face was advanced to 75 m from the open-off cut, the direct roof collapsed for the third time, and the basic roof also began to collapse. The separation layer on the key layer showed a significant downward collapse trend, and the roof collapsed completely (Fig. 8h).

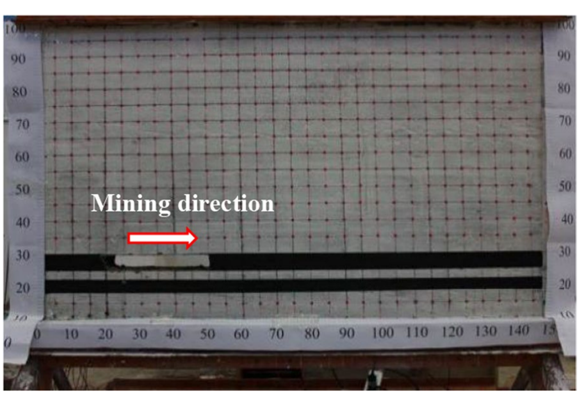

Fig. 7 The working face was advanced to 10 m from the open-off cut

Discussion

Analysis of collapse characteristics

The infrared thermal imager was used to monitoring the initial and periodic weighting of the basic roof during excavation, and analyzed the collapse characteristics from the roof collapse height and angle (Fig. 9). During the initial phase of the working face advancement, the overburden rock layer underwent gradual bending and deformation, leading to the progressive development of internal lateral cracks, ultimately resulting in separation. As the advancement continued, longitudinal cracks emerged along the sides and center of the goaf. Furthermore, both transverse and longitudinal cracks continued to expand with the ongoing progression of the working face. When the working face was advanced to 40 m from the open-off cut, the initial weighting of the basic roof was carried out with a collapse step of 30 m and a periodic weighting step of 18 m (Fig. 9a). When the working face was advanced to 110 m from the open-off cut, the roof collapse of the goaf tended to stabilize, with a maximum collapse height of 17.6 m, a maximum height of 45.2 m for the development of the crack zone, and a front collapse angle of 70° and a rear collapse angle of 75° for the overlying strata (Fig. 9b).

In the course of the advancement of the working face, the primary roof intermittently fractured behind the working face, with subsequent propagation of upper cracks in an upward direction. The rock layer above the goaf experienced continuous compaction, leading to the

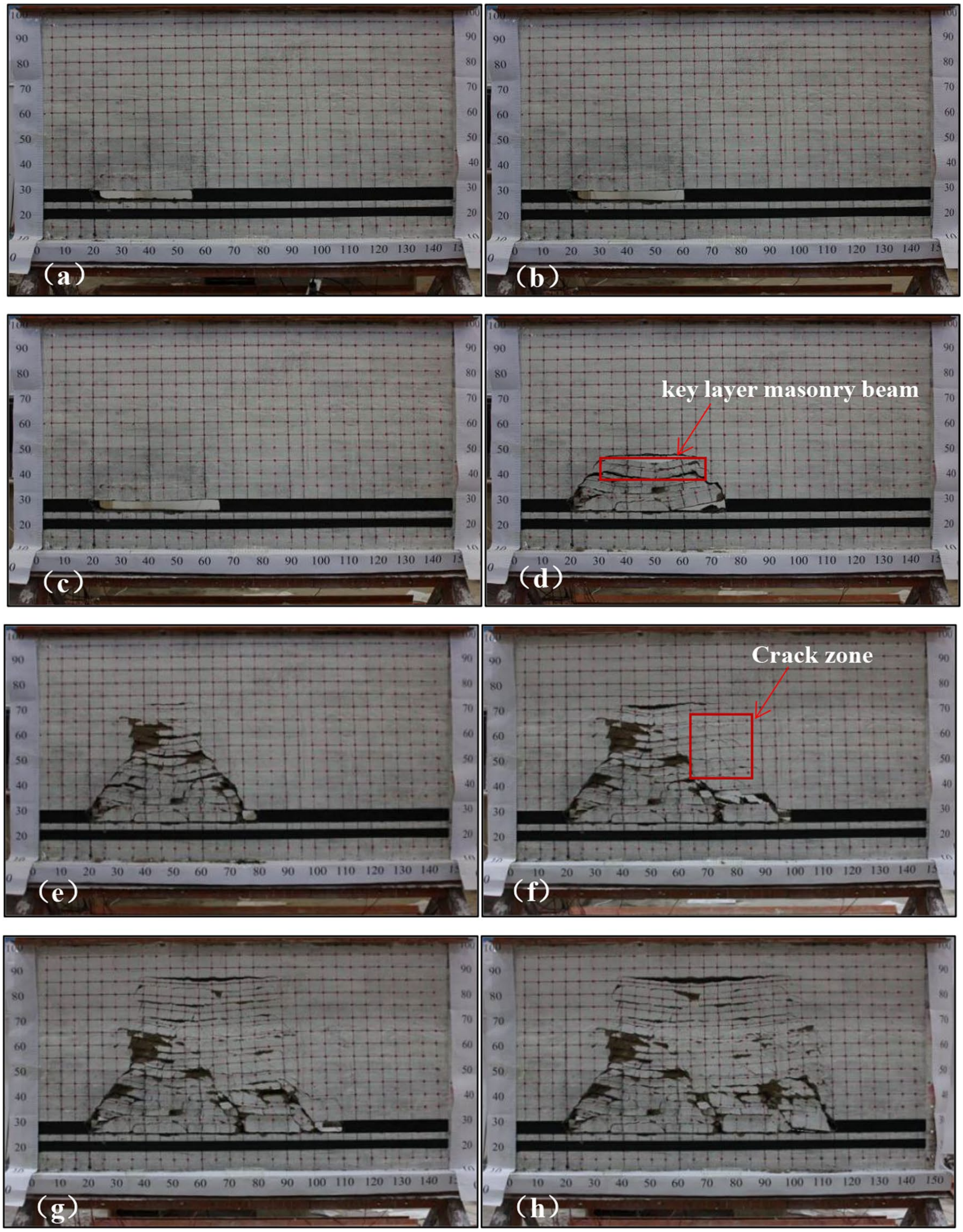

Fig. 8 Development of overburden crack and subsidence process of overburden during the mining process. **a** The working face was advanced to 15 m from the open-off cut, **b** The working face was advanced to 20 m from the open-off cut, **c** The working face was advanced to 25 m from the open-off cut, **d** The working face was advanced to 35 m from the open-off cut, **e** The working face was advanced to 40 m from the open-off cut, **f** The working face was advanced to 60 m from the open-off cut, **g** The working face was advanced to 70 m from the open-off cut, and **h** The working face was advanced to 75 m from the open-off cut

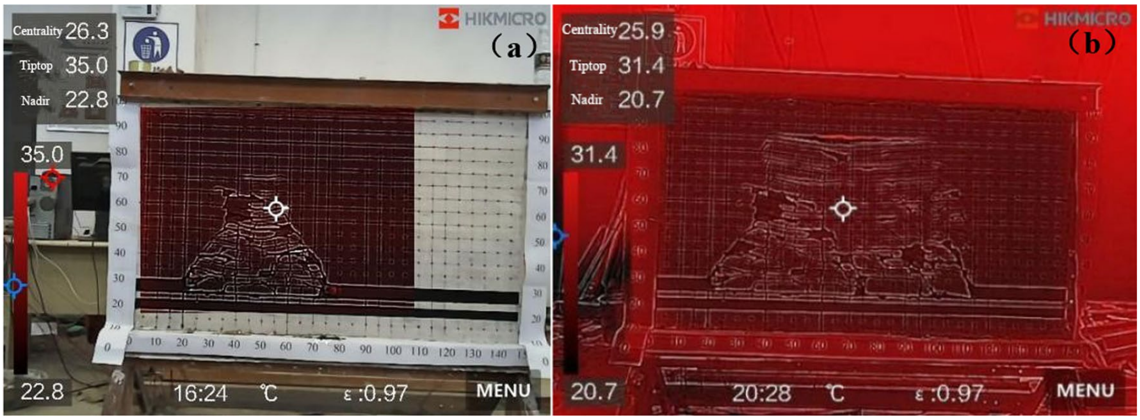

Fig. 9 Initial and periodic weighting of the basic roof during excavation. **a** Initial weighting of the basic top, **b** Periodic weighting of the basic top

gradual closure of the separation layer. Simultaneously, new cracks constantly emerged in front of the working face, resulting in the progressive stabilization of the height of the crack zone. The structural configuration of the working face roof could be described as a "cantilever beam," which exerted a significant influence on both the rock load borne by the working face support and the plastic zone of the coal wall.

Stress distribution and evolution characteristics of overburden rock in stope

To study the stress variation law of the overburden rock in the stope during mining, two layers strain gauges were placed in the model and there was a total of ten strain gauges. Before excavation, the strain gauge was connected with the data regulator. During excavation, we set parameters in advance and collected data every five minutes. After excavation, strain data were derived, and the stress evolution law of the overburden strata in the goaf was obtained through analysis and processing.

Based on the stress distribution of the overburden rock in the stope, the vertical stress of the #3 strain gauge remained relatively constant in the first 25 m section of advancing the working face. However, it gradually increased in the 25–65 m section and experienced a sudden change in the 65–70 m section, reaching a peak stress of 24.88 MPa (Fig. 10a). Similarly, the vertical stress of strain gauge 8# slowly increased with the increase of excavation distance in the first 40 m section, and then suddenly changed when the working face advanced to 60–65 m section, with a maximum value of 21.58 MPa. After the vertical stress of the overburden strata reached its peak, it gradually decreased and eventually stabilized as the working face continued to advance (as shown in

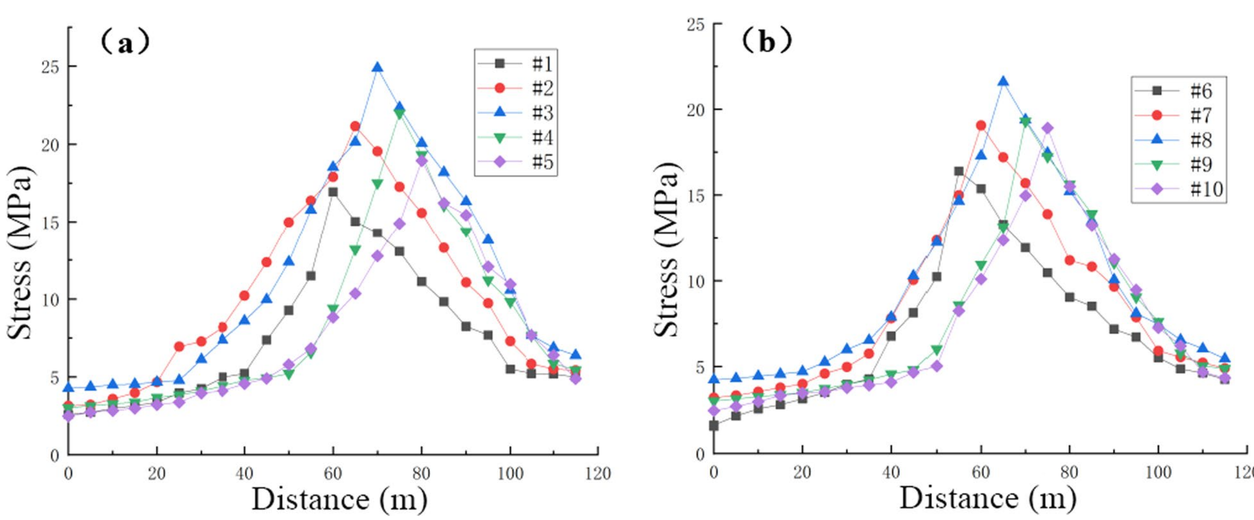

Fig. 10 Stress evolution of overburden strata in the goaf. **a** The first layer strain gauge of overburden strata, **b** the second layer strain gauge of overburden strata

Fig. 10b). During the excavation of the working face, the vertical stress at each measuring point of the overburden rock layer continuously increased. As the excavation depth approached the measuring point position, the vertical stress reached its peak value. Once the excavation progress exceeded the measurement point, the measured stress concentration was relieved, and the rear of the working face became a pressure relief zone. The vertical stress at each point gradually tended to stabilize.

The stress measurements at each point exhibit a pattern of initial increased, followed by decrease, and ultimately stabilization. By considering the stress variation law of the overburden rock, the stress changes in key layers of the bedrock during mining could be categorized into four zones: the stress stable zone, stress increasing zone, stress reducing zone, and compaction stable zone. The overburden rock in the stress stable zone experienced minimal impact from mining and remains in its original stress state. The overburden rock in the stress increasing zone fell within the range of support pressure ahead of the working face. The roof in the stress reducing zone directly collapses, causing the overburden rock layer to undergo pressure relief due to detachment. Our results were consistent with results of Liu et al. (2021), who found that the principal stresses of the coal seam in front of the working face are concentrated with the advance of the working face (Liu et al. 2021).

Movement and subsidence of overburden rock in the roof

In order to study the movement law of overburden rock in the roof during mining, two displacement survey lines were arranged in the roof of Coal Seam 11−2. The No. 1 survey line was 10 m from the top of Coal Seam 11−2, and the No. 2 survey line was 30 m from the top of Coal Seam 11−2 (see Fig. 2). At the initial stage of mining in the working face, there was no significant subsidence of the roof above the first survey line (Fig. 11a). When the working face was advanced to 45 m, the rock layer 10 m above the 11−2 coal seam began to sink with the part of the direct roof falling off, and the maximum deformation of the roof was 3.04 and 3.51 m, respectively. When the working face advanced to 75 m, the rock strata above Coal Seam 11−2 began to fall off in a large area along with the breaking of the basic roof, and the maximum subsidence of the roof was 3.45 and 4.13 m, respectively. When the working face was advanced to 90 m, there was a significant separation of the strata above the coal seam, and there was a trend of further expansion. When the working face was advanced to 105 m, the deformation of the strata further increased with the secondary crack of the basic roof, and the maximum subsidence of the roof were 4.14 and 4.58 m, respectively (Fig. 11a).

At the initial stage of mining, there was no significant subsidence of the roof above the second survey line (Fig. 11b). When the working face was advanced to 60 m, the maximum deformation of the roof was 3.05 and 3.39 m, respectively, as the part of the direct roof fell off. When the working face was advanced to 75 m, due to the impact of the basic roof crack, the cracks of the rock layer 30 m above the 11−2 coal seam continued to develop around. When the working face was advanced to 90 m, there was obvious separation of the strata above the coal seam with the breaking of the basic roof, and the maximum deformation of the roof was 3.84 and 4.15 m, respectively. When the working face was advanced to 105 m, the subsidence amount of the rock

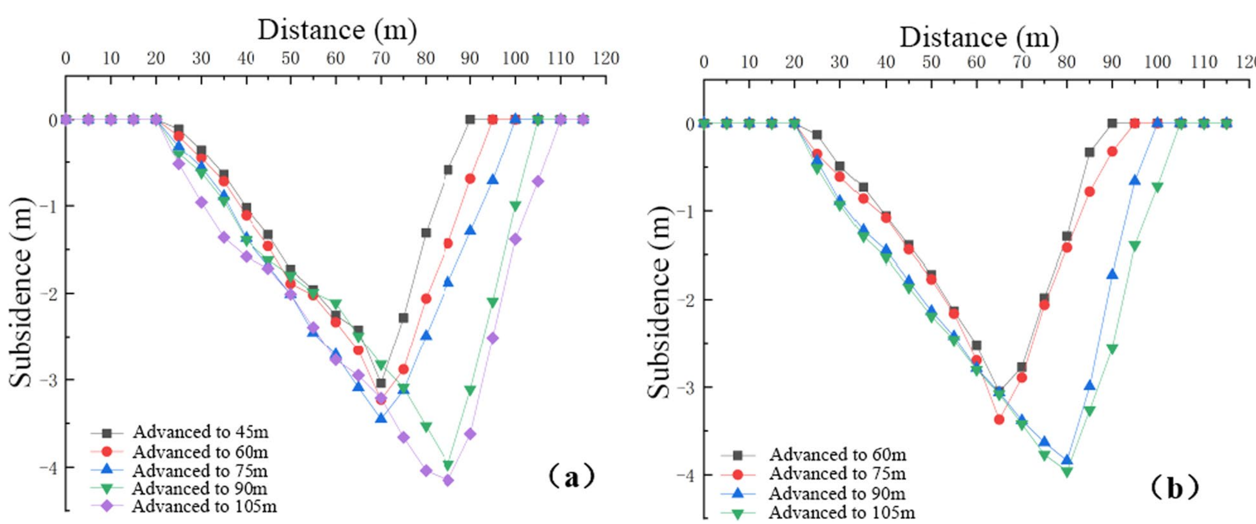

Fig. 11 Overburden movement law during mining process. **a** Overburden movement law of the first survey line, **b** Overburden movement law of the second survey line

stratum further increased with the separation layer and cracks above the coal seam continuing to develop, and the maximum subsidence amount of the roof were 3.96 and 4.36 m, respectively (Fig. 11b).

During the initial phase of coal seam mining, the presence of rock layers provided support, resulting in minimal subsidence of the overburden rock. However, as the mining operation progressed, the disturbance force and collapse of the overburden rock leaded to further downward subsidence. When the working face reached the stop line, the collapsed overburden rock gradually consolidates, resulting in a deceleration of energy release and the formation of a pressure relief zone. Consequently, the overburden rock above the working face underwent a slight additional subsidence, reaching its maximum level. Our results were consistent with others in overburden movement (Ti et al. 2021; Li et al. 2022).

Mechanical model of mining induced overburden rock fracture structure

According to the results of similarity simulation experiment, the main roof cantilever rock beam, which supported the weight of the overburden rock, experienced swift fracturing (Fig. 12). That leaded to the formation of a short cantilever rock beam structure. The front end of the short cantilever rock beam was firmly supported by the rock mass in front of the excavation, while the rear end was in frictional contact with the collapsed rock mass in the goaf (Wang et al. 2023). Due to the rigid and brittle nature of the rock mass, the bending and sinking of the mining overburden rock did not play a dominant role in the fracture of the short cantilever rock beam on the main roof. Instead, it only leaded to the generation and accumulation of micro cracks before the periodic fracture of the main roof rock layer. As the size of the main roof short cantilever rock beam increased, its bearing capacity also increased, and shear fracture occurred

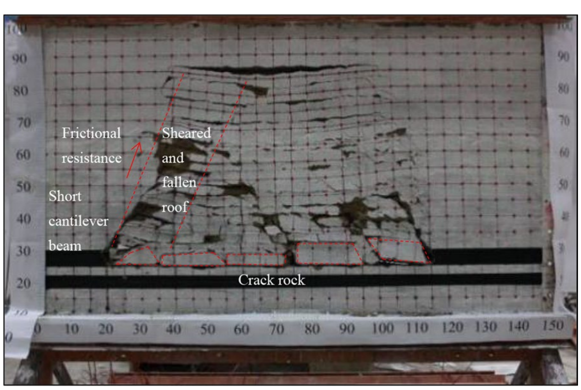

Fig. 12 Sheared and fallen roof structure (advanced to 75 m)

when the ultimate shear strength of the rock combination was reached.

The key layer, which is a hard rock layer, supports the overburden rock and served as the main structure controlling the fracture and migration of the overburden rock (Wang et al. 2023). Based on the theory of key layers and the characteristics of the overburden rock, the key layer above the working face was identified as a combination of medium sandstone and fine-grained sandstone. When the maximum shear stress of the overburden rock reached the ultimate shear stress of the key layer, the entire overburden rock collapses. From the mechanical conditions of the shear fracture of the main roof key layer, it could be observed that the load exerted on the key layer by the overburden rock and the distance between fracture steps were the determining factors influencing the fracture process.

Conclusions

This paper conducted a similarity simulation experiment on the overburden migration during the mining process of a certain working face in Liuzhuang Coal Mine, southern China. The experiment found that during the initial stage of mining, there was no significant subsidence of the roof. In the course of the advancement of the working face, the primary roof intermittently fractured behind the working face, with subsequent propagation of upper cracks in an upward direction. The overburden rock layer above the goaf experienced continuous compaction, leading to the gradual closure of the separation layer. Simultaneously, new cracks constantly emerged in front of the working face, resulting in the progressive stabilization of the height of the crack zone. The stress measurements at each point exhibit a pattern of initial increased, followed by decrease, and ultimately stabilization. By considering the stress variation law of the overburden rock, the stress changes in key layers of the bedrock during mining could be categorized into four zones: the stress stable zone, stress increasing zone, stress reducing zone, and compaction stable zone. During the initial phase of coal seam mining, the presence of rock layers provided support, resulting in minimal subsidence of the overburden rock. However, as the mining operation progressed, the disturbance force and collapse of the overburden rock leaded to further downward subsidence. When the working face reached the stop line, the collapsed overburden rock gradually consolidates, resulting in a deceleration of energy release and the formation of a pressure relief zone. Consequently, the overburden rock above the working face underwent a slight additional subsidence, reaching its maximum level. Mechanical model of the experiment was a short cantilever rock beam structure.

The mining process of coal involved the occurrence of significant overburden pressure on coal seams, leading to their susceptibility to movement, deformation, and fracture. Although, we investigated the migration patterns of the overburden during deep coal seam mining according to a certain working face, this research could contribute to the enhancement of the theoretical framework concerning the structural instability of the overburden. Furthermore, it could offer a crucial scientific foundation for effectively managing the overburden in deep mining regions. Consequently, these findings could serve as a vital theoretical basis for roof control in deep coal seam mining.

Author contributions

MZ and SM contributed to the conception, design and drafting of the work. ZT and MZ contributed to the acquisition, analysis, interpretation of data, and drafting of the work. SM contributed to the drafting of the work. LM, XL, ZS and SB contributed to the analysis. All authors read and approved the final manuscript.

Funding

Funding for the research has been supported by the Natural Science Foundation of Jiangsu Province (Grant No. BK20210527).

Availability of data and materials

All data, models, and code generated or used during the study appear in the submitted article.

Declarations

Competing interests

The authors declare no competing interests.

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Received: 2 July 2023 Accepted: 30 September 2023
Published online: 27 October 2023

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