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Full Length Article

A green coal mining method for protecting roadways and overlying strata

Shilin Hou [a], Manchao He [a], Jun Yang [a], Jun Zhang [c], Yajun Wang [b,*], Xuhui Kang [a], Zijie Han [d], Fukang Du [b]

[a] State Key Laboratory for Tunnel Engineering, China University of Mining & Technology Beijing, Beijing, 100083, China
[b] School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing, 100083, China
[c] Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai, 200092, China
[d] Capital Airports Holdings Co., Ltd., Beijing Construction Project Management Headquarters, Beijing, 100083, China

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ABSTRACT

The non-pillar mining method with automatically formed roadway (NPM-AFR) is an innovative mining method. This paper provides a detailed description of how this method achieves the cancellation of pillar retention and the advance excavation of roadways through optimized mining processes. Based on mining mechanics modeling, the paper explains how the NPM-AFR compensates for mining-induced damage by utilizing the bulking of the goaf gangue and uses directional roof cutting technology interrupt the stress transmission path from the goaf to the roadway, thereby enhancing the protection of both the overlying strata and the roadway. Geological and mechanical model tests were conducted based on the Ningtiaota coal mine to compare the NPM-AFR and traditional mining method. The results show that under the NPM-AFR, the development height of overlying strata damage is reduced by 36.14 % compared to traditional mining method, and overlying strata stress is reduced by 25 %. The overlying strata is effectively protected in the NPAFR mining area. In both mining methods, the roadways remain in a low-stress zone, but the peak stress on the coal pillar side in the NPM-AFR is reduced by 40.6 % compared to the traditional method, significantly reducing the safety risks of the roadway. Field verification tests further demonstrate that the NPM-AFR, along with its supporting processes, successfully achieves the goals of pillar-free mining, surface protection, and safe roadway preservation. This technology represents a sustainable, green mining approach that protects both the overburden and the roadway, providing new solutions for safe and efficient coal mining.

1. Introduction

As a major non-renewable energy source for human development, the safe and efficient extraction of coal resources has always been a focal point of research. Qian et al. (1994, 1995, 1996) established the masonry beam theory, which clarified the breaking and evolution laws of the overlying strata, laying a theoretical foundation for the control of mining roadways and surrounding rock masses in coal mining. Song et al. (1984, 1986, 1996) proposed the transmission rock beam theory and suggested that by leaving small coal pillars, roadways could be positioned in low-stress areas where stress concentration is minimal. This approach achieves roadway protection while relatively conserving coal pillar resources. Based on these two theories, the longwall mining method with retained coal pillars and the artificial support-based mining method with roadway preservation have been widely applied in the coal mining sector, making outstanding contributions to the advancement of coal mining technologies (Peng et al., 2019; Wang et al., 2022).

However, these methods essentially rely on pillars to bear or isolate the mining-induced stress, without effectively relieving the stress generated in the mining area. Furthermore, traditional methods do not implement appropriate measures to compensate for mining-induced damage after coal extraction, resulting in significant destruction of the overlying strata. In addition, the need for premature excavation of the recovery roadways means that the surrounding rock is repeatedly impacted by the excavation of the roadway and the mining operations, leading to considerable safety risks for the roadways (He et al., 2018). As mining depths and intensities increase, the heightened damage to the overlying strata leads to a sharp accumulation of mining-induced stress, making the mining area more prone to safety issues such as roadway floor heaving and rock bursts under mining disturbances (Ranjith, 2017; Hu

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et al., 2019; Chen et al., 2019; He et al., 2023). Additionally, severe surface subsidence and ecological damage occur, posing significant challenges to coal mine safety and green mining practices (Guo, 2019; Wei et al., 2022; Cai et al., 2023).

To address the above issues, the author's team proposed the non-pillar mining method with automatically formed roadway (NPM-AFR) (He et al., 2021). This method utilizes the bulking characteristics of gangue to compensate for mining-induced damage, replaces premature roadway excavation with coal cutter cutting, reduces the disturbance of roadway excavation and coal mining, and uses directional roof cutting technology for the roof strata to interrupt the stress transmission path between the mined-out area and the roadway roof, further reducing the impact of mining-induced stress on the roadway. For this mining method, researchers such as He et al. (2020), Wang et al.,(2022) and Zhang et al. (2011) developed supporting equipment, including a new type of end-supporting device and an efficient anchor drilling machine, to provide the necessary equipment support for coal cutter roadway cutting. Zhang et al. (2020), Sun et al. (2024), Gao et al. (2023) and Guo (2024) verified the protective effect of directional roof cutting technology on the roadway, and summarized its optimization design methods. He et al. (2023), Tao et al. (2018), and Ren et al. (2023) proposed a high-extension support anchor and verified its high support performance in roadway protection, ensuring the safety of roadway retention and reuse. Wang et al.,(2022), Yang et al. (2019), Yang et al. (2023), and others analyzed the mining pressure manifestation throughout the entire process of non-pillar mining and proposed a dynamic pressure-bearing temporary support technology during goaf pressure influence. Existing research has mainly focused on the supporting technologies and parameter designs for the non-pillar mining method. However, fundamental theoretical studies on overlying strata damage and mining-induced stress evolution characteristics during this mining method are relatively lacking, which is insufficient to support the engineering design and practical application of the method.

Therefore, this paper clarifies the layout and supporting processes of the NPM-AFR and provides a detailed description of the process for eliminating coal pillars and roadway excavation. Based on damage and mechanical analysis models, this study reveals the technical mechanism by which the NPM-AFR achieves overlying strata protection and roadway roof protection through the utilization of rock bulking, directional roof cutting technology, hydraulic support control, and other series of technologies. Furthermore, geological and mechanical model tests were conducted based on the Ningtiaota coal mine to analyze in detail the differences and similarities in overlying strata damage and surrounding rock stress evolution between the new and traditional mining method. The results verified the protective effects of the NPM-AFR on the overlying strata and roadways. The successful implementation of field trials at Ningtiaota coal mine fully demonstrates that this mining method can effectively achieve the goals of eliminating coal pillars, eliminating premature excavation, and protecting both the overlying strata and the roadway. The green mining theory of the non-pillar mining method with automatically formed roadway has been significantly improved, providing a theoretical foundation for the further promotion and application of this new green mining method, and offering new solutions for safe, efficient, and green coal mining.

2. Mechanism of overlying strata and roadway protection in NPM-AFR

2.1. Layout and technology of NPM-AFR

The non-pillar mining method with automatically formed roadway (NPM-AFR), as a new mining method, differs significantly from traditional mining method in terms of mining layout, roadway retention, and other aspects. In traditional mining method, after the coal extraction in a working face, the roadways and mined-out areas are managed using a free collapse approach, meaning that all production roadways are destroyed and abandoned after mining (working face I). The adjacent mining faces are separated by safety coal pillars (working face II). For adjacent planned working faces, two recovery roadways (a_2, b_2) must be pre-excavated, and one safety coal pillar is retained (Fig. 1a). In contrast, when using the new mining method, measure roadway c needs to be preconstructed around the entire periphery of the panel area to ensure the integrity of the ventilation and transportation systems of the working faces within the panel (Fig. 1b). Similarly, the goaf is managed using the free collapse method. Meanwhile, the roadways are cut by a coal cutter and then preserved using directional roof cutting technology so that they can be reused in subsequent working faces (d_1, d_2). These roadways can be reused in the next mining face without leaving a safety coal pillar. This method allows for the mining of N working faces without needing to pre-excavate any roadways or leave any safety coal pillars.

To achieve the technical objectives of the NPM-AFR, which include eliminating coal pillars and eliminating the need for roadway advance excavation, the author's team developed an integrated key process system. This system features core technologies such as coal cutter roadway formation technology, directional roof cutting technology, and gangue retaining support technology. The specific details are as follows:

(1) Coal cutter roadway formation technology: When the coal cutter reaches the roadway position, it uses the modified tail auxiliary device of the scraper conveyor to cut coal beyond the working face, creating the necessary space for the roadway. Simultaneously, Negative Poisson's Ratio (NPR) anchor cables and other support facilities are installed for the roof to ensure the safety of the newly formed roadway's roof (Fig. 2a).
(2) Directional roof cutting technology: The directional roof cutting technology is used to precisely cut the roof of the roadway within a designated range, thereby expanding the height of roof caving. At the same time, the roof forms a short arm beam, cutting off the stress transmission path between the gangue in the goaf and the roadway roof, significantly improving the stress environment (Fig. 2b).
(3) Gangue retaining support technology: Following the hydraulic support at the working face, gangue blocking equipment is used to prevent gangue from collapsing into the roadway while simultaneously forming a gangue sidewall along the roadway (Fig. 2c).

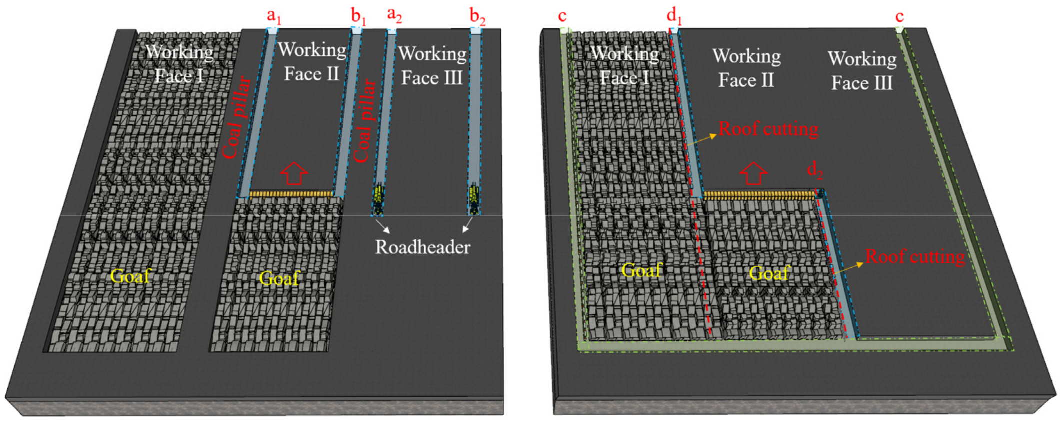
After the above processes are completed, the equipment at the working face and the coal extraction machinery will advance, and the new mining and roadway retention operations will proceed in succession (Fig. 2d).

2.2. Mechanism of overlying strata protection of NPM-AFR

Based on the overall process of overlying strata damage development after coal mining the author's team proposed the mining damage invariant equation (Eq. (1)). After coal mining in the working face, a space with a volume of ΔV_M is created. Following a series of movements of the overlying strata in the mining area, a caving zone, a fracture zone, a fissure zone and a subsidence zone are formed. Among these, the caving zone generates a bulking volume ΔV_B due to the collapse and bulking accumulation of gangue; the fracture zone and fissure zone generate a detachment volume ΔV_C due to diastrophism between strata layers; the subsidence zone undergoes overall subsidence, leading to a subsidence volume ΔV_S at the surface. The generation of these variables compensates for the damage volume ΔV_M caused by coal extraction. Therefore, the three variables should satisfy the following equation:

$$\Delta V_M = \Delta V_B + \Delta V_C + \Delta V_S \tag{1}$$

For traditional mining method, measures are taken to increase the bulking rate of the goaf rock, the mining damage volume ΔV_M caused by coal mining is not effectively compensated. The overlying strata has a



a. Traditional mining method b. NPM-AFR

Fig. 1. Layout of working faces for two mining methods.

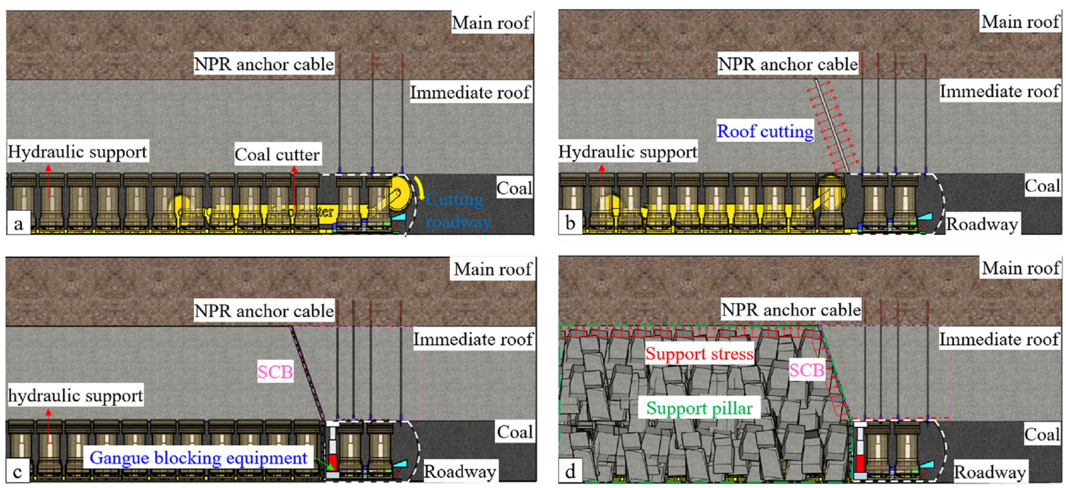


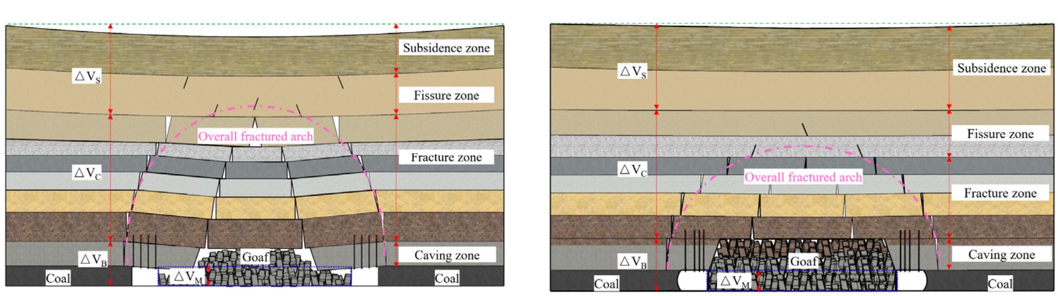
Fig. 2. Key technologies and implementation process of NPM-AFR.

large rotational space. According to Eq. (1), with a smaller ΔV_B, both ΔV_C and ΔV_S will be larger. This results in significant damage in the fracture zone, fissure zone and subsidence zone of the overlying strata. The overall fractured arch of the overlying strata is higher, which leads to larger mining pressure, and serious surface subsidence and damage (Fig. 3a).

In contrast, for the NPM-AFR, the use of technologies such as directional roof cutting and hydraulic support control has increased the height of the caving roof and enhanced the bulking of the collapsed goaf rock. As a result, the mining damage volume ΔV_M caused by coal mining is compensated by ΔV_B, effectively alleviating the development of ΔV_C and ΔV_S. The damage in the fracture, fissure and subsidence zones of the overlying strata is significantly reduced compared to traditional mining method. The height of the overall fractured arch of the overlying strata is greatly lowered, and surface subsidence, along with subsequent environmental issues, is effectively mitigated (Fig. 3b).

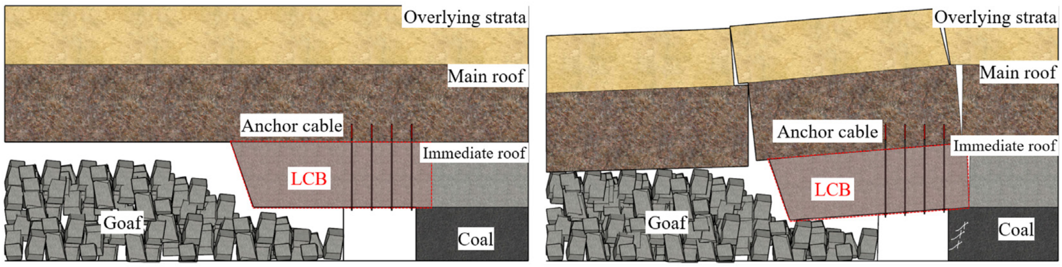
2.3. Mechanism of roadway protection of NPM-AFR

For traditional mining method (Fig. 4), after coal is extracted from the working face, the roof is managed by the free-fall method, where the direct roof collapses freely into the goaf. Initially, the collapsed roof



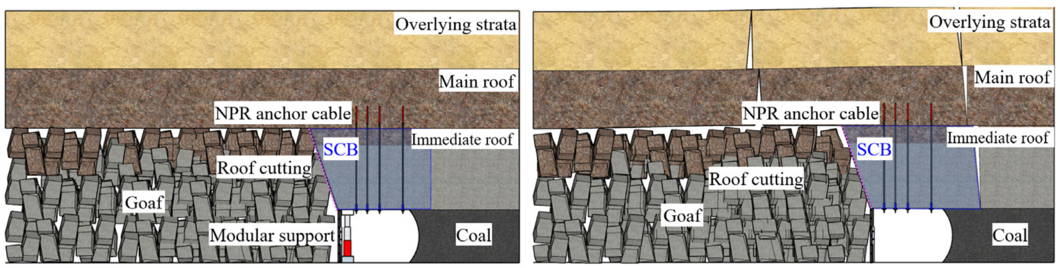
a. traditional mining method b. NPM-AFR

Fig. 3. Overlying structure figure of two mining methods.



a. before the main roof fracturing b. after the main roof fracturing

Fig. 4. Roof caving structure of traditional mining method.



a. before the main roof fracturing b. after the main roof fracturing

Fig. 5. Roof caving structure of NPM-AFR.

forms a long cantilever beam (LCB) structure. After the direct roof falls, its accumulated height, due to the bulking characteristics of the rock mass, is greater than its original height. However, this accumulated height is insufficient to compensate for the mining damage volume created by coal mining. There is a significant displacement gap between the accumulated goaf gangue, and the main roof. During the continued mining of the working face, the overlying main roof gradually begins to bend and break under the condition of a large displacement gap. The original balance of the overlying strata is disrupted, and the roof undergoes severe displacement and rotation until the main roof contacts and compresses the goaf gangue, restoring stability. Due to the presence of unfilled space, the roof collapse is more intense. Moreover, because the roadway roof forms a LCB structure, a significant amount of mining pressure is transmitted through this structure, accumulating in the roadway roof and coal pillar (Fig. 5).

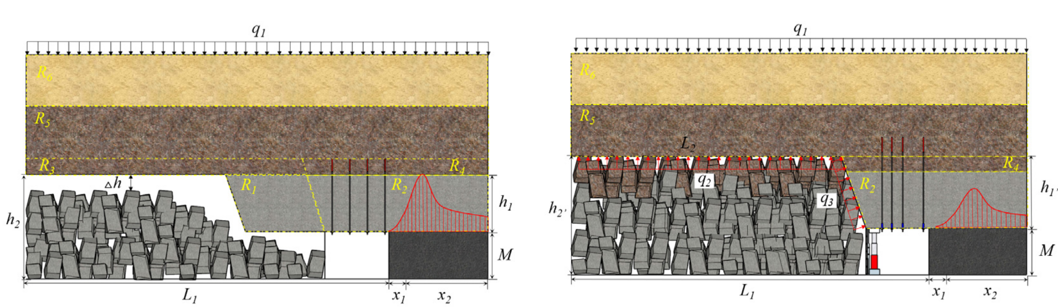
To ensure the overall safety and usability of the roadway, the NPM-AFR uses directional roof cutting technology to sever the stress transmission path between the roadway roof and the goaf roof. This results in the formation of a short cantilever beam (SCB) structure in the roadway roof. Additionally, by adjusting the roof cutting height and the hydraulic support pressure, the height of the immediate roof caving is expanded, the bulking rate of the gangue is increased. The bulking characteristics of the collapsed goaf gangue are leveraged to maximize the compensation for the coal mining damage space. During the initial phase of coal mining, a support pillar is formed for the overlying strata, providing upward support to the main roof. In subsequent mining, because the deformable space is smaller, the extent of damage to the overlying strata is greatly reduced, and as a result, the mining pressure in the working face is effectively alleviated. Furthermore, due to the LCB structure of the roadway roof, the stress transmission is significantly reduced compared to the condition without roof cutting, improving the stress environment in the roadway.

To more clearly analyze the protective effect of the NPM-AFR on the roadway, a comparative analysis of the overall support force in the roadway was conducted. As shown in Fig. 6a, before the application of protection techniques such as directional roof cutting and hydraulic support control, after the immediate roof collapse, there was still a significant displacement space between the collapsed goaf gangue and the main roof. This satisfies the following relationship:

$$\triangle h = h - \sum_{i}^{x} K_i h_i \tag{2}$$

In the equation, K_i is the swelling coefficient of rock layer.

In Fig. 6, x_1 is the range of the plastic zone, m; x_2 is the range of the elastic zone, m; L_1 is the sum of the goaf width and the roadway width, in meters; L_2 is the support range of the caved gangue on the overlying rock strata roof, m; h_1 is the direct caving height of the immediate roof, m; h_2



a. without using protection techniques b. using protection techniques

Fig. 6. Stress distribution in roadways in different working conditions.

is the total height of the goaf, m; Δh is the height of the caved gangue from the main roof in the goaf, m; R_x is the block number in the overlying rock strata; M is the thickness of the coal seam being mined in the working face, m. q_1 is the uniformly distributed pressure borne by the overlying strata, kN/m; q_2 is the support pressure provided by the caved gangue of the goaf to the main roof, kN/m; q_3 is the lateral support pressure of the caved gangue of the goaf on the roadway roof, kN/m.

From Eq. (2), it can be seen that if the h tends to 0, the most intuitive methods are to increase the height of the caving rock layer and to increase the bulking coefficient of the caving gangue. The NPM-AFR uses technologies such as directional roof cutting and hydraulic support control to achieve the goal of the h tending to 0 (Fig. 6b). According to Eq. (2), the calculation formula for the height of the directional roof cutting is as follows:

$$h_{1'} = \sum_{i}^{x} h_i, \text{wherein}, x \text{ satisfies} : h - \sum_{i}^{x} K_i h_i = 0$$

Under the same mining conditions, without the use of roadway protection techniques, the support resistance required to maintain the stability of the roadway roof is:

$$\begin{aligned} Q_1 &= \overline{\sigma_{y1}}(x_1 + x_2) \\ &= q_1(L_1 + x_1 + x_2) + \gamma_1(S_{R_1} + S_{R_2}) + \gamma_2(S_{R_3} + S_{R_4}) + \gamma_3 S_{R_5} + \gamma_4 S_{R_6} \end{aligned} \tag{3}$$

After using protection techniques, the support resistance required to maintain the stability of the roadway roof is:

$$\begin{aligned} Q_2 &= \overline{\sigma_{y1}}(x_1 + x_2) \\ &= q_1(L_1 + x_1 + x_2) + \gamma_1 S_{R_2} + \gamma_2 S_{R_4} + \gamma_3 S_{R_5} + \gamma_4 S_{R_6} - q_2 h_c \sin\theta - q_3 L_2 \end{aligned} \tag{4}$$

It can be concluded that:

$$Q_1 - Q_2 = \gamma_1 S_{R_1} + \gamma_2 S_{R_3} + q_2 h_c \sin\theta + q_3 L_2 \tag{5}$$

In the above formula, γ_x is the unit weight of the R_x area, kN/m^3, S_{R_x} is the total area of the R_x area, m^2, and Q_x is the support stress required to maintain the stability of the roadway roof, kN.

From Eq. (5), it can be concluded that after the implementation of roadway protection technologies such as directional roof cutting and hydraulic support control, the effective volume force acting on the roadway roof is significantly reduced, the stress transfer lever arm is effectively shortened, and the stress on the support structure within the roadway is effectively alleviated. The stress relief effect of the NPM-AFR on the surrounding rock of the roadway is evident.

In summary, the NPM-AFR, by improving the layout of the working face and supporting key technologies, achieves the cancellation of coal pillar setting and the elimination of roadway advance excavation within the mining area. Within the working face, it increases the caving height of the goaf roof, allowing the caved gangue to form a support pillar structure, significantly compensating for the damage caused by coal mining and alleviating the degree of overlying strata destruction. At the same time, it forms a SCB structure on the roadway roof, cutting off the stress transfer path between the roadway roof and the goaf roof, reducing stress concentration on the roadway roof and the sides of the coal pillars, ensuring the safe use of the roadway. This mining method provides a new innovative approach for the safe, green, and efficient extraction of coal.

3. Geological and mechanical model tests

To further clarify the protective effect of the NPM-AFR on the surrounding and overlying strata during the mining process, geological and mechanical model tests were conducted with the Ningtiaota coal mine as the engineering background. The model tests were carried out in two setups: one using the traditional mining method and the other using the NPMAFR. By comparing and analyzing the overlying strata damage and migration patterns, as well as the stress distribution in the surrounding rock of the roadway during the mining process, the protective effect of the NPM-AFR on the overlying strata and roadway was comprehensively verified.

3.1. Engineering background

The Ningtiaota coal mine of Shaanxi coal and chemical group, located in Shenmu City, Yulin, Shaanxi Province, China, is the world's first field test site for the NPM-AFR. The S12012 test working face primarily extracts the 2-2 coal seam, which has an average thickness of 4.11 m. The working face has a dip length of 280 m, a strike length of 2344 m, and a burial depth ranging from 90 m to 165 m. The coal seam is stable and nearly horizontal. The layout of the test face and the geological column diagram are shown in Fig. 7. According to borehole SB01 data for the S12012 working face, the roof consists of medium sandstone, with a thickness ranging from 5.4 m to 21.5 m. The composition is mainly quartz, with large-scale cross-bedding. The immediate roof is siltstone, with a thickness ranging from 0.78 m to 4.05 m, and its composition is primarily quartz with large-scale cross-bedding. The immediate floor is siltstone, with a thickness of 1.8 m–16.3 m. The outer section of the test face has a local bottom plate of carbonaceous mudstone. The old floor consists of fine sandstone, with a thickness of 3.2 m–19.6 m, containing feldspar-quartz sandstone with white mica fragments and wave-like bedding.

3.2. Overall test plan

3.2.1. Selection of key test parameters

The model test is conducted using a two-dimensional indoor model test frame. The frame dimensions are 3726 mm in length, 200 mm in width, and 2000 mm in height. The entire test frame is made of high-strength steel, with the outer sides formed into ribs using high-strength steel. The effective test range of the model frame is 3600 mm × 200 mm × 1440 mm. Based on the conditions of the S12012 test face, the geometric similarity ratio (C_l) for the model test is chosen as 80, and the density similarity ratio is 1.2. Other similarity ratios are derived from similarity theory:

$$C_\sigma = C_E = C_c = 96$$

$$C_\varepsilon = C_f = C_\mu = 1$$

In the equation: C_σ is the stress similarity ratio, C_E is the elastic modulus similarity ratio, C_c is the cohesion similarity ratio, C_ε is the strain similarity ratio, C_f is the Poisson's ratio similarity ratio, and C_μ is the angle of internal friction similarity ratio.

According to the research requirements, two model tests are planned to be conducted. To accommodate subsequent research work, the model tests are designed to simulate the mining of two working faces. For the NPM-AFR model test, working Face 1 is designed with a width of 1140 mm, and working face 2 with a width of 1800 mm. There is one roadway arranged between the working faces, with dimensions of 78 mm. this roadway adopts directional roof cutting technology during the test process, with roof cutting heights of 112.5 mm and an inclination angle of 10° (Fig. 8). For the traditional mining method model test, working face 1 is designed with a width of 1140 mm, and working face 2 is designed with a width of 1600 mm. There is one safety coal pillar and two roadways arranged between the working faces. Since the focus of this study is on a single mining field, subsequent data analysis will concentrate on the mining process of working face 1.

3.2.2. Test materials and excavation plan

The model test overall utilizes river sand, barite powder, and gypsum as simulated rock layer aggregates. River sand and barite powder serve as rock aggregates and density adjustment materials, respectively, while gypsum acts as a bonding material for the aggregates, providing mechanical strength for the analogous simulated rock body. Since the coal

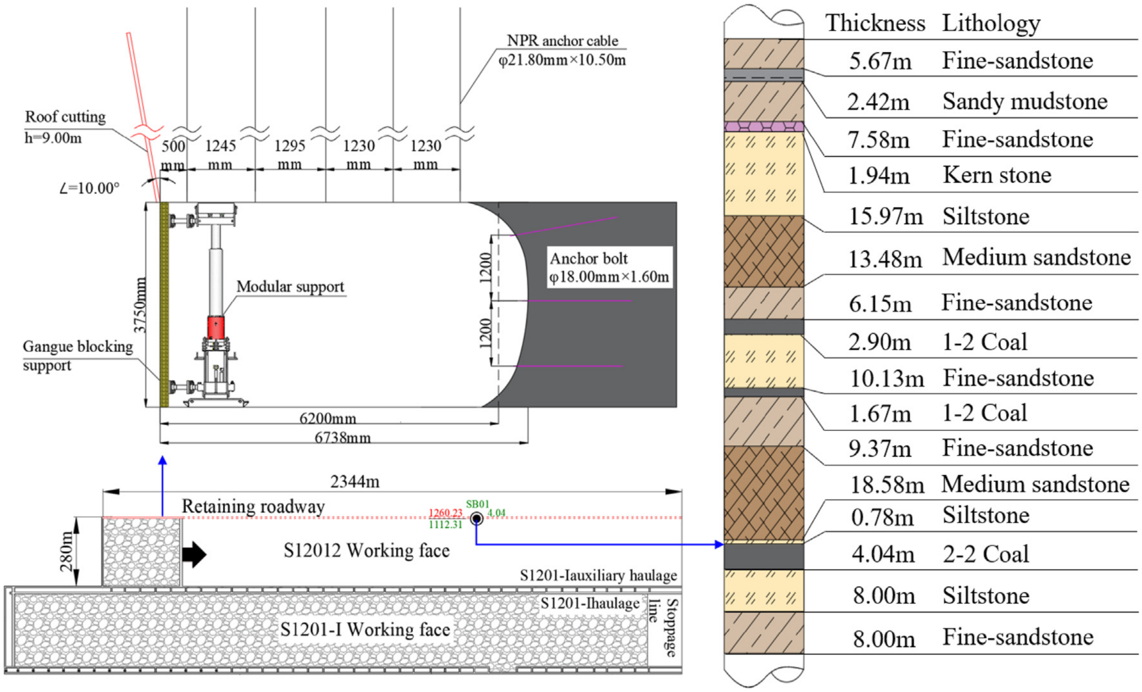


Fig. 7. S12012 working face layout and borehole column chart.

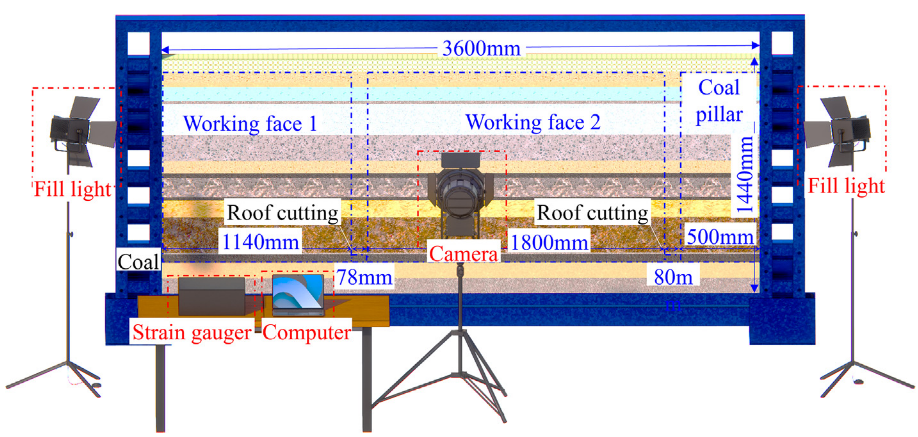


Fig. 8. Model test design plan.

seam parameters are lower compared to the rock layers, perlite is added to the above materials as a density adjustment material. Additionally, industrial alcohol is used as a binder to promote the strengthening of the similar materials in a short period. The mechanical parameters of the overlying strata in the S12012 test face are obtained through a series of laboratory tests, with specific values shown in Table 1.

For the traditional mining method model test, after the model is prepared, the first workface R_1 roadway is excavated, followed by excavation of the R_2 roadway. Once the roadway is fully stabilized, the excavation of the test face starts from the W_1 module, with each excavation step being 100 mm, completed in 11 steps (Fig. 9).

For the NPM-AFR model test, after the model is prepared, the first workface R_1 roadway is excavated, followed by cutting the R_2 surface with a saw blade to create the directional roof cutting surface. Afterward, the excavation of the test face begins from the W_1 module, with each excavation step being 100 mm, completed in 11 steps. The remaining 40 mm is used to compensate for manual excavation errors.

Table 1
Main rock strata mechanical parameters.

Stratum name	Bulk modulus/ GPa	Shear modulus/ GPa	Tensile strength/ MPa	Cohesion/ MPa	Density/ (kg·m^{-3})
Siltstone	4.81	3.92	1.26	1.27	2440
Fine	3.78	3.08	1.32	1.55	2250
Sandstone	5.46	4.27	1.46	1.47	2490
Medium	4.81	3.92	1.09	1.31	2330
Sandstone	3.95	3.22	0.36	0.81	1280
Siltstone	8.23	7.33	1.62	1.96	2410

3.2.3. *Monitoring plan*

The overall displacement of the model test is monitored using digital speckle displacement measurement methods. After the similar materials are air-dried, digital speckle displacement monitoring points are applied within the area of 1440 mm × 3600 mm on the front surface of the model body. After each excavation step, the model is left static to collect the dynamic changes in the speckle pattern. During the excavation process, the stress in the surrounding rock of the roadway and the overlying strata

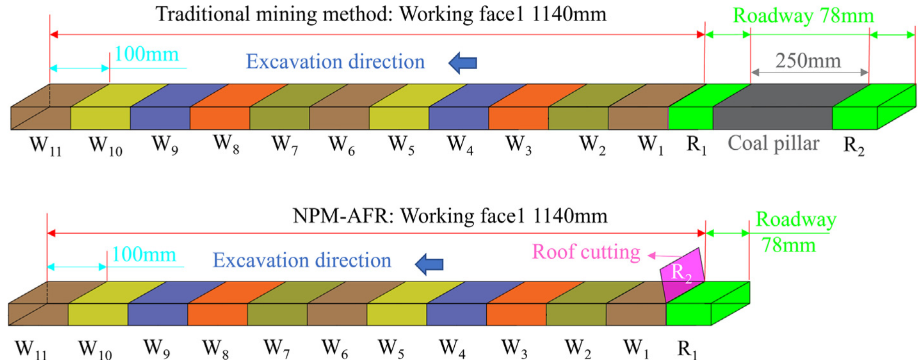


Fig. 9. Model test excavation plan.

of the test face is measured using strain bricks and a stress-strain data collection system. The specific monitoring plan is shown in Fig. 10.

3.3. Analysis of test results

3.3.1. Comparative analysis of overlying strata failure patterns

The overlying strata destruction process for traditional mining methods is shown in Fig. 11a–c, and the overlying strata destruction process for the NPM-AFR is shown in Fig. 11d–f. The coal seam mining height (original damage height) is defined as h_m, and the immediate collapse height of the roof is defined as h_c.

By the 4th excavation step, for the traditional mining method (Fig. 11a), after the collapse of the immediate roof, the height of the bulking and collapsed spoil h_c is clearly insufficient to compensate for the mining damage caused by the mining height h_m, thus forming a damaged area of height Δh. For the NPM-AFR(Fig. 11d), due to the prior implementation of directional roof cutting technology, the collapse height h_c is significantly larger than that of the traditional mining method, and the damage area Δh is significantly reduced, resulting in better filling of the goaf.

By the 9th excavation step, the traditional mining method shows more significant damage to the overlying strata (Fig. 11b), with many fractures developed in the damaged area. The upper and central sides of the workface show large damage areas with significant fracture development, which undoubtedly increases the safety risks during the mining process. For the NPM-AFR, there is also noticeable fracture development (Fig. 11e), but the height of the developed fractures is significantly lower than that in the traditional mining method, and the quantity and intensity of the fractures are also considerably lower, indicating that the implementation of directional roof cutting technology helps the bulking spoil body in the goaf support the overlying strata, reducing the damage to the overlying strata.

By the 11th excavation step, when the workface excavation is completed, the area of fracture damage to the overlying strata for the traditional mining method significantly increases (Fig. 11c), with most of the damage concentrated in the upper part of the overlying strata, showing an obvious upward development trend. The damage area for the NPM-AFR also develops upward, but the height of the damage area is significantly smaller than that of the traditional mining method, with fewer fractures in the area. The degree of damage to the overlying strata is relatively lower than that of the traditional mining method.

The displacement data obtained from the digital speckle displacement measurement system was processed to derive the migration pattern of the overlying strata after excavation, as shown in Fig. 12.

According to Fig. 12, after the working face excavation is completed, both mining methods cause varying degrees of damage to the overlying strata. For the traditional mining method, the maximum displacement of the overlying strata reached 41 mm, while for the NPM-AFR, the maximum displacement was 26.5 mm, a reduction of 36.14 % compared to the traditional mining method.

After the excavation was completed, the overlying strata damage in the traditional mining method did not fully dissipate until measurement

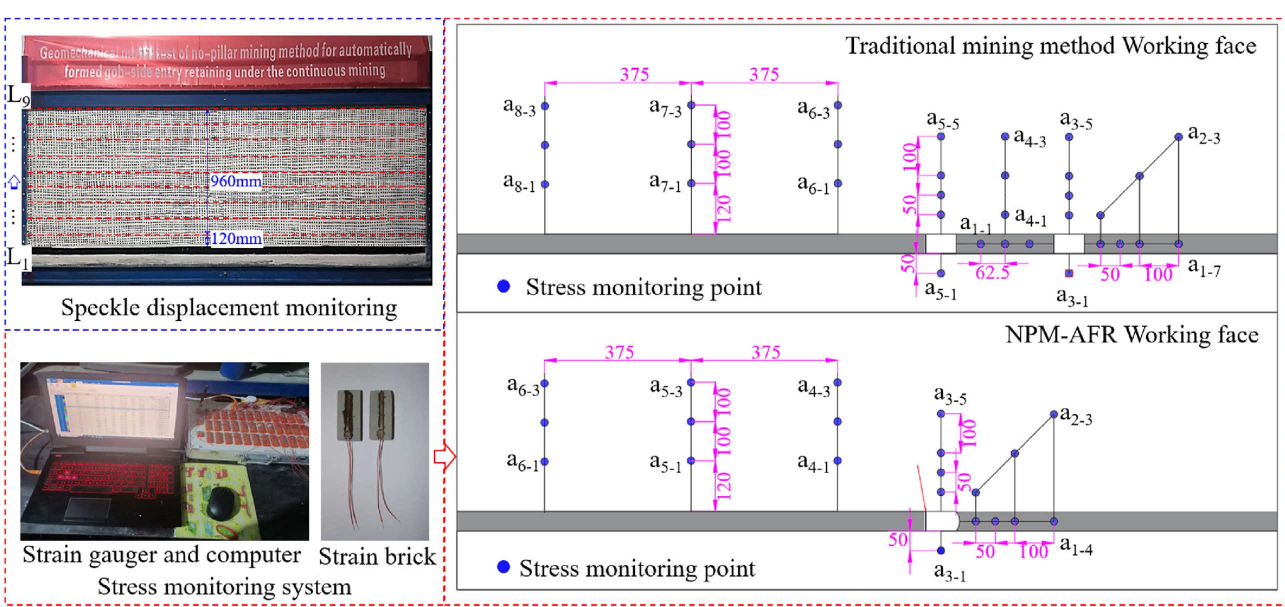


Fig. 10. Model test monitoring plan.

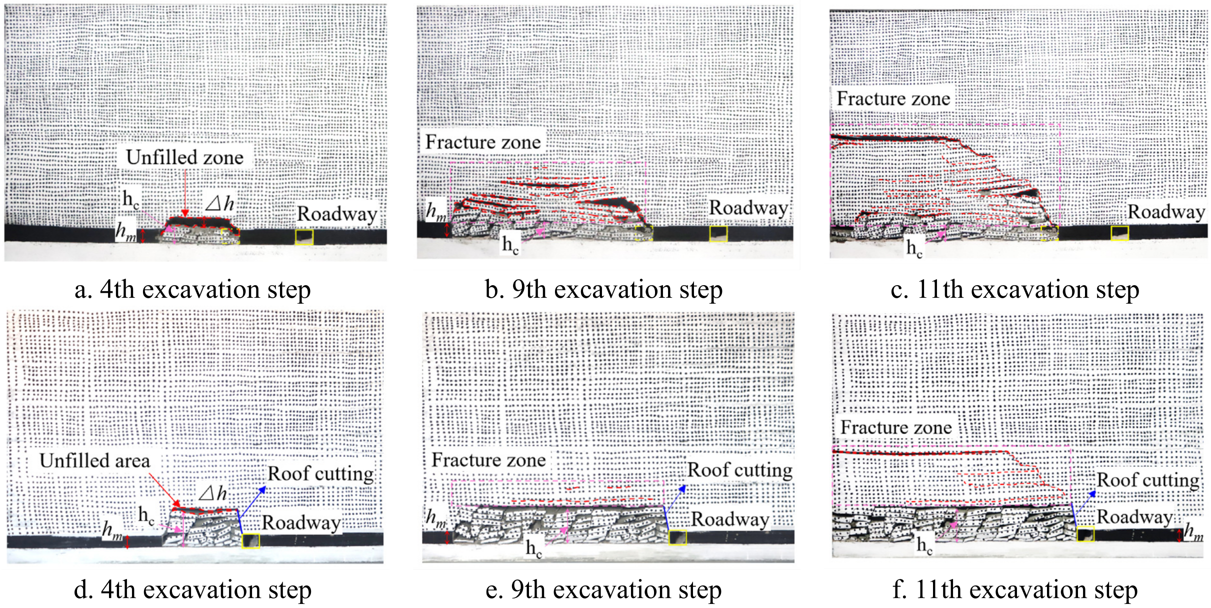


Fig. 11. Excavation process in geological and mechanical model tests.

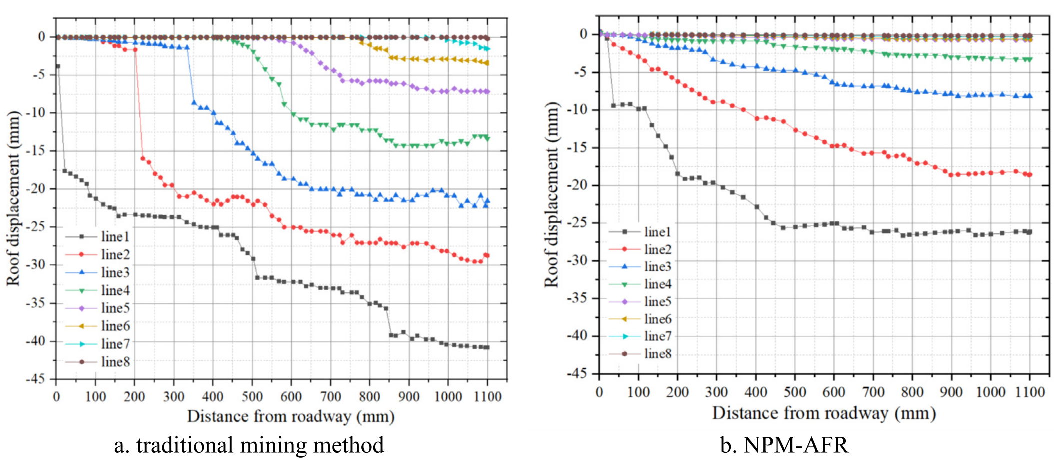


Fig. 12. Displacement data of overlying strata.

line 8, and displacement step changes were observed in measurement lines 1–3, indicating severe damage in higher regions. In contrast, the damage influence height of the overlying strata for the NPM-AFR essentially disappeared by measurement line 5, with only a stepwise subsidence phenomenon at measurement line 1, indicating that mining damage was effectively controlled and the overlying strata damage was relatively mild.

In conclusion, the NPM-AFR increases the bulking coefficient of the collapsed rock body, a supporting pillar capable of supporting the overlying strata has been formed. significantly reducing the degree of damage to the overlying strata and its influence height, thereby effectively protecting the overlying strata in the mining area.

3.3.2. Comparative analysis of stress distribution patterns in overlying strata

In the traditional mining method model test, monitoring points a_8-1, a_7-1, a_6-1, a_5-4, a_4-2, a_3-4, and a_2-2 were selected to form a measurement line. For the NPM-AFR model test, monitoring points a_6-1, a_5-1, a_4-1, a_3-4, and a_2-2 were selected to form a measurement line. The stress distribution patterns of the overlying strata after excavation completion for both mining methods are shown in Figs. 13 and 14.

From Fig. 13, it can be seen that after excavation with the traditional mining method, due to the presence of coal pillars, the overlying strata stress above the adjacent roadway is effectively relieved, with a stress of 0.012 MPa. However, because no effective measures were taken to compensate for the mining damage, most of the stress in the mining area is concentrated on the side of the coal pillars, with a peak stress value of up to 0.028 MPa.

From Fig. 14, it can be seen that for the NPM-AFR, although the roadway is a side road, the stress peak above the roadway is 0.012 MPa. This indicates that the implementation of roadway protection technology can effectively replace the safety role of coal pillars. At the same time, due to measures to interrupt the stress transmission path, the peak stress accumulated on the coal pillar side of the roadway is 0.021 MPa, which is 25 % lower than the traditional mining method. This shows that the NPM-AFR can effectively protect the roadway and reduce the safety risks during its application.

3.3.3. Comparative analysis of stress distribution patterns in roadway surrounding rock

The stress monitoring results for the monitoring line consisting of points a1-1 to a1-7 in the traditional mining method model test are shown in Fig. 15.

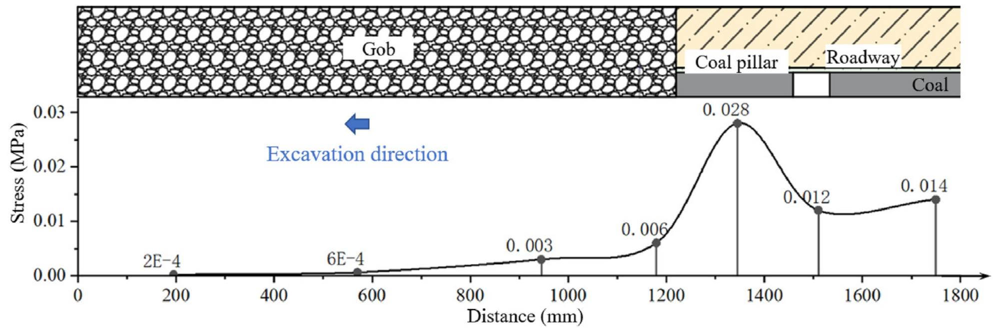


Fig. 13. Stress distribution patterns of the overlying strata (Traditional mining method).

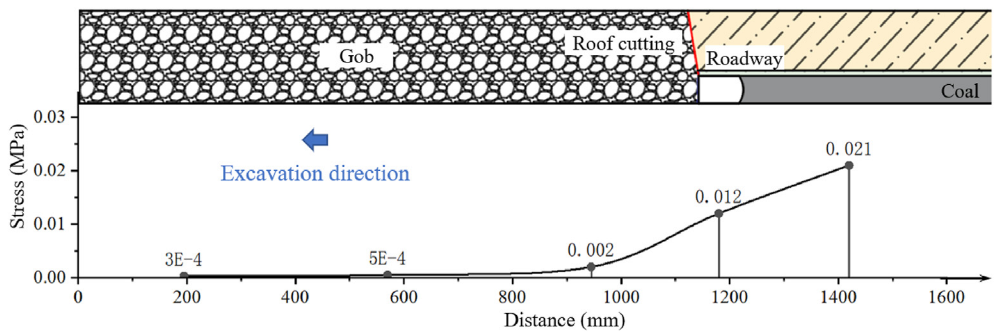


Fig. 14. Stress distribution patterns of the overlying strata (NPM-AFR).

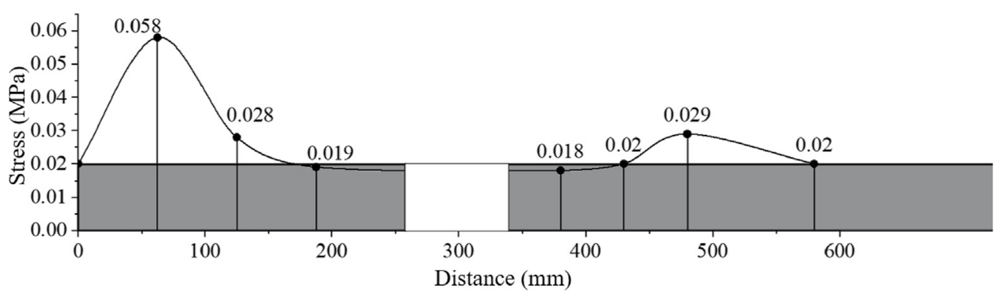


Fig. 15. Stress distribution patterns of the roadway surrounding rock (Traditional mining method).

From Fig. 15, it can be seen that after excavation in the traditional mining method model test, the coal pillar stress near the adjacent roadway shows a two-peak distribution. The safety coal pillar bears most of the stress in the mining area, with a peak stress of 0.058 MPa. The adjacent workface coal body bears another portion of the stress, with a peak stress of 0.029 MPa, while the adjacent roadway is in a low-stress area. This indicates that the safety coal pillar plays a good role in protecting the area.

The stress monitoring results for the measurement line consisting of points a1-1 to a1-4 in the non-pillar self-forming roadway mining method model experiment are shown in Fig. 16.

From Fig. 16, it can be seen that after excavation in the NPM-AFR model test, the stress in the coal pillar of the roadway shows a single-peak distribution, with a peak stress value of 0.035 MPa, which is 40.6 % lower than the traditional mining method. At the same time, the roadway is in a lower stress area, far from the peak stress, indicating that the series of roadway protection measures in the NPM-AFR play a good safety protection role.

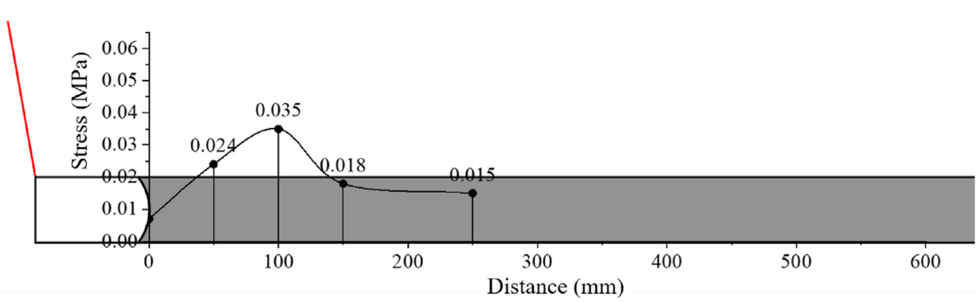


Fig. 16. Stress distribution patterns of the roadway surrounding rock (NPM-AFR).

Comparing Figs. 15 and 16, the roadway protection technology implemented by the NPM-AFR effectively achieves a significant reduction in the stress of the surrounding rock, fulfilling the purpose of protecting the roadway. This indicates that the NPM-AFR cuts off the stress transmission path of the roadway roof, improves the stress environment of the roadway, and thus makes the design for the repeated use of the roadway rational and feasible.

In summary, the overlying strata damage in the working face using the NPM-AFR is much lower than that in the traditional mining method. By utilizing the bulking characteristics of the collapsed rock body, the NPM-AFR effectively compensates for the original mining damage.

The overlying strata in the NPM-AFR experiences lower damage during the mining phase, and the stress in the overlying strata is greatly improved, providing a safer mining environment.

Compared to traditional mining methods, the overall surrounding rock stress in the mining field using the NPM-AFR is lower, avoiding the high stress accumulated on the coal pillar side in traditional mining methods, which could lead to a series of safety hazards in subsequent mining.

4. Field verification test

Building on the aforementioned research findings, the NPM-AFR was applied in the S12012 workface of the Negotiate coal mine. The test roadway has a width of 6.2 m and a height of 3.75 m, with a directional roof cutting height of 9 m and an angle of 10°. The roadway roof is supported by NPR anchor cables with dimensions of φ21.8 mm × 10.5 m. The coal pillar near the roadway is supported by fiberglass anchor rods of φ18 mm × 1.6 m, and the gangue side near the goal is supported by U-shaped steel and modular supports (Fig. 7).

Fixed monitoring points inside the roadway were selected for data extraction, and the roof and floor convergence and the stress evolution of the modular support in the S12012 workface are shown in Fig. 17.

From Fig. 17, it can be seen that the overall stress and deformation of the roadway in the S12012 workface during mining can be divided into three stages: the initial roadway formation stage, the mining-induced influence stage, and the consolidation and stabilization stage. In the initial roadway formation stage, the modular support forces inside the roadway remain at the initial support stress level. During this period, the overlying strata of the mining field does not experience significant damage under the support of the gangue support pillar. When the fixed monitoring point is 37.6 m behind the working face, the force on modular support begins to increase, it indicates that the overlying strata of the mining field starts to experience some degree of damage. During this period, the maximum force of the modular support is 39.9 MPa, which is far below the modular's support limit, and the roadway remains relatively stable. When the fixed monitoring point is 241.2 m behind the working face, the force of the modular support tends to stabilize, indicating that the roadway has been successfully retained, and at this point, the modular supports can be removed.

When the fixed monitoring point is 40.7 m behind the working face, the roof to floor convergence begins to increase rapidly, with the maximum convergence reaching 38.14 mm during this period, fully meeting the requirements for safe production. Unlike the force phase division of the modular support, the roof to floor convergence tends to stabilize when it is 161.0 m behind the working face, indicating that the modular support played a good control role on the roadway roof during the mining-induced influence stage.

The reserved roadway conditions in the S12012 working face are shown in Fig. 18. From Fig. 18b, it can be seen that there is no significant deformation of the roadway before or after the temporary support withdrawal, and the roadway reservation effect is good. This demonstrates that the theoretical basis of the NPM-AFR for surrounding rock protection is practical. From Fig. 18c, it can be seen that on the surface of the S12012 working face, most of the developed fractures are slow subsidence fractures with widths and heights around 10 cm. The overall strength of the fractures in the mining area is low, eliminating the large step-type subsidence fractures that occur in traditional mining method. This shows that the NPM-AFR plays a positive role in protecting the overlying strata in the mining area. The experiment of the NPM-AFR in the S12012 working face achieved good engineering results.

5. Conclusion

(1) The NPM-AFR through a series of key technologies such as directional roof cutting and hydraulic support control, as well as the balanced mining concept based on the mining invariant equation, makes full use of the broken expansion characteristics of gangue in the goaf, realizes the protection of the mining face's roadway and the overlying strata, and achieves the goals of eliminating the advance driving of roadways and the setting of coal pillars.

(2) The results of model tests show that, compared with the traditional mining method, the maximum displacement of the overlying strata in NPM-AFR is reduced by 36.14 %, and the overall stress is decreased by 25 %. Both mining methods place the roadway in the low-stress area, yet the stress peak beside the NPM-AFR roadway is 40.6 % lower than that of the traditional mining method. NPM-AFR effectively reduces the degree of damage to the overlying strata on the working face and the stress of the surrounding rock of the roadway, and significantly decreases the possibility of roadway disasters.

(3) Field monitoring results show that, for the working face roadways adopting NPM-AFR, the force on the support structure is stable.

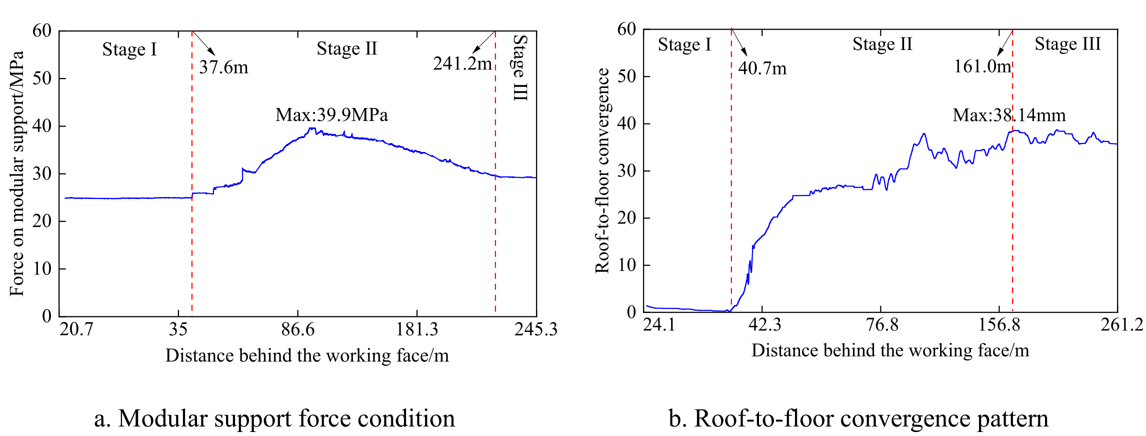


Fig. 17. Force on modular supports and roof-to-floor convergence patterns in the roadway.

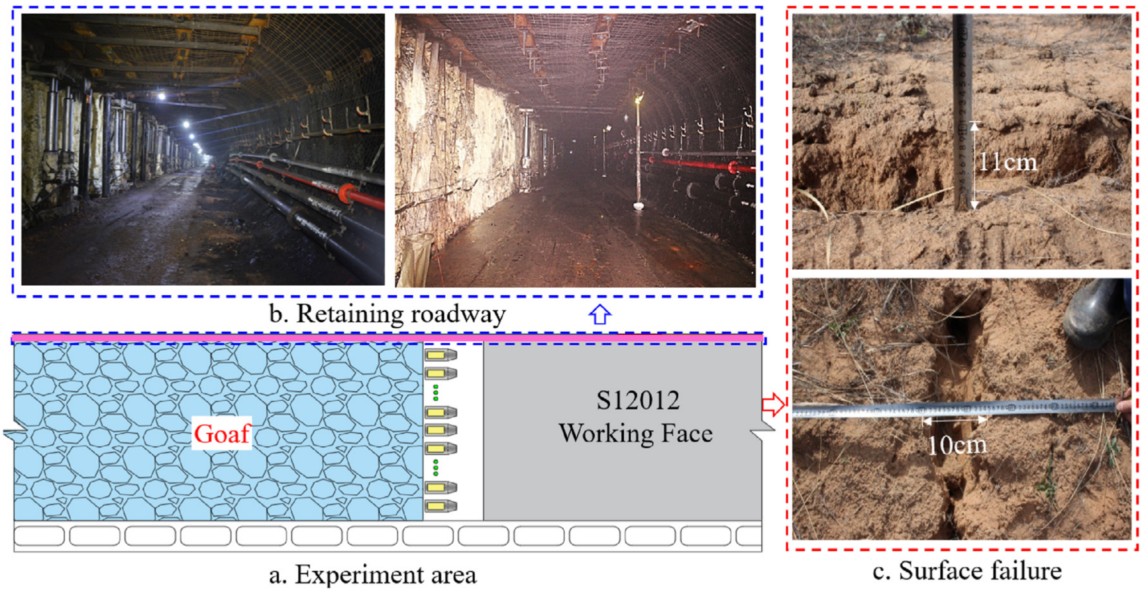


Fig. 18. The effect of roadway retention and surface fractures.

The maximum convergence between the roof and the floor is 38.14 mm, fully meeting the requirements for safe production. Most of the displacements of the surface cracks in the experimental area are around 10 cm, with overall minor damage, which significantly reduces the difficulty of ecological environment restoration in the mining area. The research results provide strong theoretical and data support for the study of overlying strata and roadway protection using the NPM-AFR, offering new innovative approaches for the safe, efficient, and environmentally friendly mining method.

CRediT authorship contribution statement

Shilin Hou: Writing – original draft, Methodology, Investigation, Formal analysis. **Manchao He:** Supervision, Methodology. **Jun Yang:** Supervision. **Jun Zhang:** Conceptualization. **Yajun Wang:** Methodology. **Xuhui Kang:** Conceptualization. **Zijie Han:** Formal analysis. **Fukang Du:** Visualization.

Declaration of competing interest

Manchao He is the Editor-in-Chief for Rock Mechanics Bulletin and was not involved in the editorial review or the decision to publish the article. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zijie Han is currently employed by Capital Airports Holdings Co., Ltd., Beijing Construction Project Management Headquarters, China.

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