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Qian Lecture

Innovation and future of mining rock mechanics

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A B S T R A C T

The 121 mining method of longwall mining first proposed in England has been widely used around the world. This method requires excavation of two mining roadways and reservation of one coal pillar to mine one working face. Due to considerable excavation of roadway, the mining roadway is generally destroyed during coal mining. The stress concentration in the coal pillar can cause large deformation of surrounding rocks, rockbursts and other disasters, and subsequently a large volume of coal pillar resources will be wasted. To improve the coal recovery rate and reduce excavation of the mining roadway, the 111 mining method of longwall mining was proposed in the former Soviet Union based on the 121 mining method. The 111 mining method requires excavation of one mining roadway and setting one filling body to replace the coal pillar while maintaining another mining roadway to mine one working face. However, because the stress transfer structure of roadway and working face roof has not changed, the problem of stress concentration in the surrounding rocks of roadway has not been well solved. To solve the above problems, the conventional concept utilizing high-strength support to resist the mining pressure for the 121 and 111 mining methods should be updated. The idea is to utilize mining pressure and expansion characteristics of the collapsed rock mass in the goaf to automatically form roadways, avoiding roadway excavation and waste of coal pillar. Based on the basic principles of mining rock mechanics, the "equilibrium mining" theory and the "short cantilever beam" mechanical model are proposed. Key technologies, such as roof directional presplitting technology, negative Poisson's ratio (NPR) high-prestress constant-resistance support technology, and gangue blocking support technology, are developed following the "equilibrium mining" theory. Accordingly, the 110 and N00 mining methods of an automatically formed roadway (AFR) by roof cutting and pressure releasing without pillars are proposed. The mining methods have been applied to a large number of coal mines with different overburdens, coal seam thicknesses, roof types and gases in China, realizing the integrated mode of coal mining and roadway retaining. On this basis, in view of the complex geological conditions and intelligent mining demand of coal mines, an intelligent and unmanned development direction of the "equilibrium mining" method is prospected.

1. Introduction

Coal is an important source for energy consumption around the world, accounting for 27% of the global primary energy consumption in 2019. In China, coal consumption accounts for 57% of the primary energy consumption in 2019 (National Statistical Bureau of China, 2020). For coal extraction, the coal mining methods mainly include shortwall and longwall mining methods. The longwall mining method has been widely used due to its high productivity and good ventilation.

The 121 mining method belonging to longwall mining method (gob-side entry driving with coal pillar) was first proposed in England in 1706 (He et al., 2019). The 121 mining method represents mining one working face, excavating two mining roadways, and reserving one protective coal pillar (Wang et al., 2014; Li et al., 2016; Konicek and Schreiber, 2018). Two mining roadways are used for coal transportation and ventilation of the working face (working

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face I). The coal pillar maintains the stability of the mining roadway of the next working face (working face II). A schematic diagram of the 121 mining method is shown in Fig. 1.

The 121 mining method has been widely used in coal mining (Majdi et al., 2012; He, 2014; Islavath et al., 2016), but it has the following drawbacks: (i) Considerable roadway excavation is required. Approximately 13,000 km of roadways are excavated in China each year (He, 2017), with significant excavation cost. In addition, it is easy to cause inequilibrium between coal mining and roadway excavation. Moreover, the excavation process mostly focuses on artificial construction, which restricts the development of intelligent and unmanned coal mines. (ii) The collapsed gob roof can easily compress the coal pillar of the roadway, resulting in stress concentration at that location (Shabanimashcool and Li, 2012; Li et al., 2015; Rezaei et al., 2015a, b), which easily leads to deformation and damage to the surrounding rocks of roadway (He et al., 2002, 2005, 2010; Wang et al., 2019a, 2021). In this method, the coal pillar reserved cannot be recovered, and a number of coal pillar resources are wasted. China's annual resource loss due to coal pillars reaches 400×10^6 t, exceeding 200 billion yuan (He et al., 2018a). (iii) The coal mining process is basically accompanied by significant mining pressure. Thus, high-strength support has to be used in mining roadways to resist large mining pressure, which can easily cause failure of the support components and surrounding rocks of roadway (He, 2014; Ghabraie et al., 2015; Wang et al., 2017). The accidents reported in the mining roadway account for 80%–90% of all coal mine accidents (He et al., 2017b). (iv) A broad range of goaf is formed along with coal mining. Due to coal pillar support, the fracturing and collapsing patterns of overlying strata between the goaf and coal pillar are different. The fractures continue to expand to the ground surface, leading to uneven ground surface subsidence and environmental damage (Chen et al., 2016). The total area of ground surface damage caused by coal mining in China is expected to be 18,000 km^2 from 1994 to 2020 (Yang et al., 2015), with an increasing rate of 700 km^2 annually.

In 1937, the 111 mining method (gob-side entry retaining with filling body) was proposed in the former Soviet Union in view of coal resource waste caused by the 121 mining method. The 111 mining method (Al Heib et al., 2010; Poulsen and Shen, 2013; Sun et al., 2018) means mining one working face, excavating one mining roadway, and setting one filling body to replace the coal pillar for maintaining another mining roadway, as shown in Fig. 2. The 111 mining method abandons coal pillar, in order to improve coal recovery rate and reduce excavation of the mining roadway. However, there still are some problems (Tan et al., 2015; Luan et al., 2018; Wang et al., 2018a; Zhang et al., 2020) that should be resolved, such as stress concentration in surrounding rocks of roadway and mine ecological damage, which are also reported in the 121 mining method. These problems hinder the applications of the 111 mining method.

In view of the above-mentioned problems, extensive studies have been performed on roadway excavation, coal pillar and filling body control, roadway support, and mine ecological protection, such as "broken rock zone theory" (Dong et al., 1994), "stress control theory" (Li and Sang, 1997), "combining support theory" (Lu, 1986), "intensity weakening theory for rockburst" (Dou et al., 2005), and "strip-filling to controlling subsidence theory" (Xu et al., 2007). However, these theories and technologies mainly focus on the systems utilizing high-strength support to resist the mining pressure. There is no unified research on all kinds of problems, and there are few revolutionary innovations in mining theory. As a result, it is difficult to solve the abovementioned coal mining problems from the source. The fundamental approach to solve the coal mining problems in the 121 and 111 mining methods lies in the reform of mining methods by using mining rock mechanics.

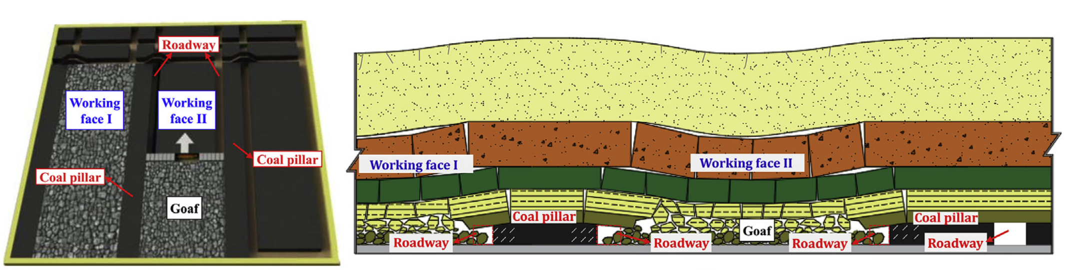
Mining rock mechanics plays an important role in reform of the coal mining method and development of mechanized intelligent equipment and technology. For this, the authors first analyzed the mining pressure law of the 121 mining method in view of mining rock mechanics. Next, the "equilibrium mining" theory was proposed, and the "short cantilever beam" mechanical model was established (He and Qian, 2010; He et al., 2015). Then, a new concept was proposed, which utilizes the mining pressure and expansion characteristics of the collapsed rock mass in a goaf to automatically form roadways. This means that neither roadway excavation nor the coal pillar is needed. On this basis, the 110 mining method of an automatically formed roadway (AFR) by roof cutting and pressure releasing (He et al., 2017c) was proposed in 2009. The mining method represents mining one working face, excavating one mining roadway, without coal pillar or filling body. The stress transfer between the goaf and roadway is cut off by roof directional presplitting. The roof directional collapse and automatic roadway formation are realized through mining pressure and broken expansion characteristics of the collapsed rock mass. Based on successful application of the 110 mining method, the N00 mining method was proposed in 2016 (He et al., 2018a; Wang et al., 2018b). In the N00 method, no roadway excavation or coal pillar is needed, and the integrated mode of coal mining and roadway retaining can be realized. This lays a foundation for achieving the goal of safe, efficient and intelligent mining.

2. Characteristic analysis of traditional 121 mining method

2.1. Analysis of mining pressure

In the traditional 121 mining method, the mining pressure law of the working face is generally divided into the following five stages, as shown in Fig. 3 and described as follows:

(1) Stage I: before immediate roof collapse. The immediate roof consists of unstable rock strata located directly above the



(a) (b)

Fig. 1. Diagram of the 121 mining method (UK, 1706): (a) Three-dimensional (3D) diagram of the working face; and (b) Profile of the working face.

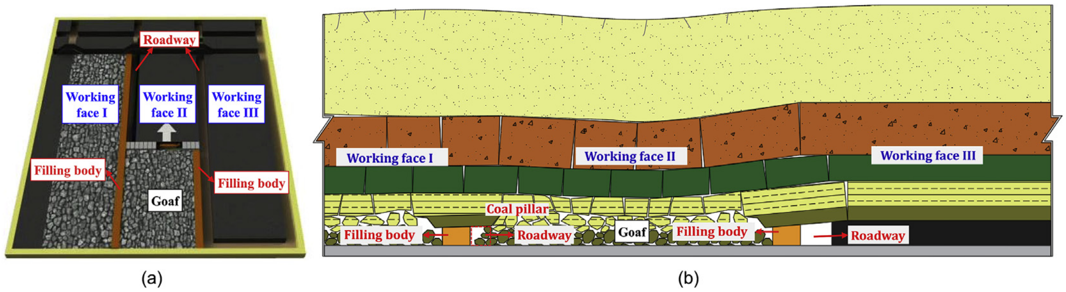


Fig. 2. Diagram of the 111 mining method (former Soviet Union, 1937): (a) 3D diagram of working the face; and (b) Profile of the working face.

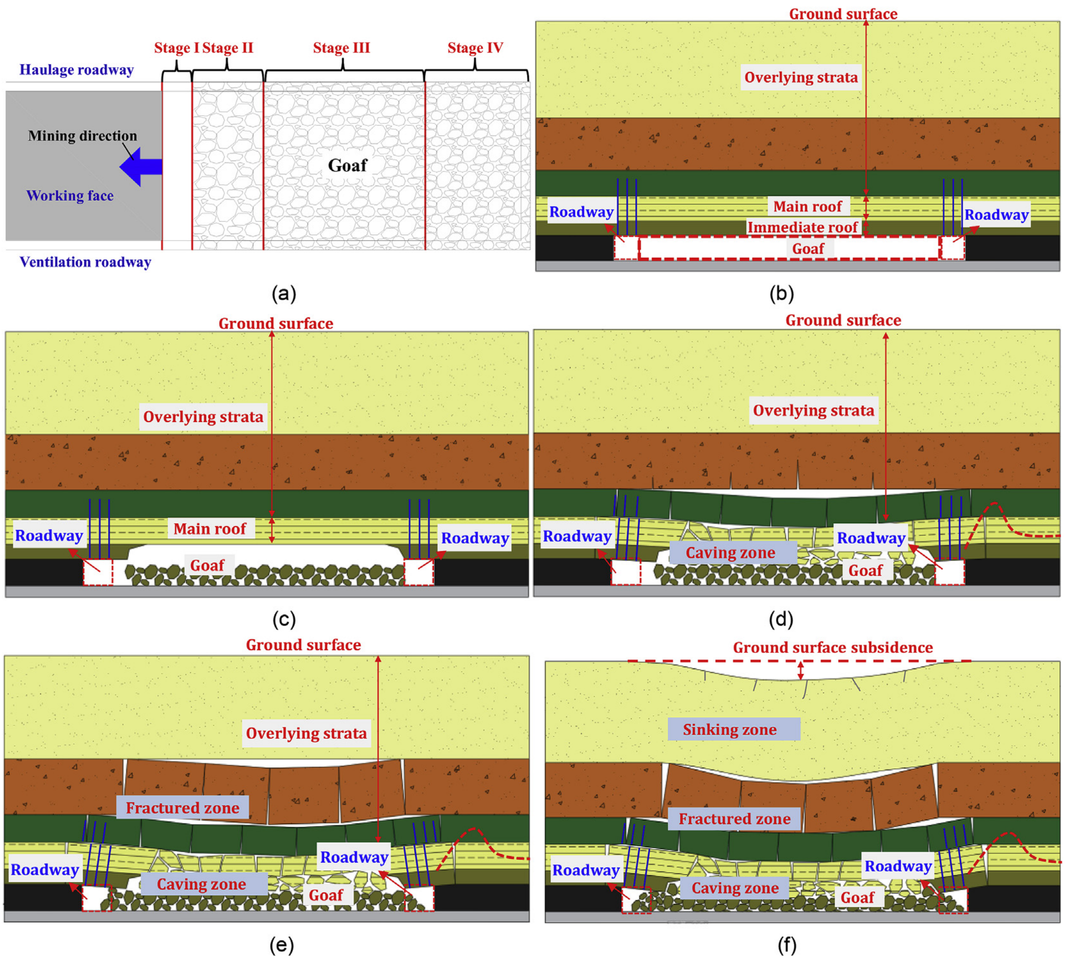


Fig. 3. Schematic diagrams of mining process of the 121 mining method: (a) Plane diagram of coal mining; (b) Stage I; (c) Stage II; (d) Stage III; (e) Stage IV; and (f) Stage V.

coal seam. The surrounding rock stress within the gob roof is redistributed during coal mining. However, the immediate roof does not collapse in a short period of time, with no obvious deformation of the rock strata above it (Fig. 3b).

(2) Stage II: immediate roof collapse. The immediate roof collapses instantly when it lags behind the working face to a certain distance under the influence of its deadweight and mining pressure. The roof collapse affects the stability of the roadway. At this stage, the gangue formed by the immediate roof collapse fails to fill the goaf, and there are no obvious fractures in the rock strata above the immediate roof (Fig. 3c).

(3) Stage III: main roof collapse. The main roof is stable rock strata located in the upper section of the immediate roof and can maintain a large exposed area. Because the goaf is not filled with gangue by immediate roof collapse, the fractures of the main roof occur and the fractured roof sinks above the roadway or coal wall under the deadweight and overlying load. The caving zone forms above the goaf. Marked fractures appear in its interior structure, and begin to expand to the overlying strata (Fig. 3d). At this stage, the stress in the surrounding rocks of roadway increases considerably due to main roof rotary extrusion. The stress concentration area appears at the roadway solid coal side.

(4) Stage IV: fracture and subsidence of overlying strata. The main roof collapses periodically along the mining direction of the working face, with fracture and subsidence in the overlying strata. Fractures quickly expand in the overlying strata and the fractured zone forms. At this stage, the stress concentration area of the roadway solid coal side still exists, but the peak stress gradually transfers to the depth of the solid coal side (Fig. 3e).
(5) Stage V: ground surface subsidence. The strata above the fractured zone appear to sink after coal mining, and the sinking zone forms. Ground surface subsidence and fracture damage begin to occur as time elapses (Fig. 3f).

2.2. Analysis of the inequilibrium state

To understand the movement of the overlying strata and the mechanical state at different positions when applying the 121 mining method, the force characteristic of the coal pillar, movement of the overlying strata structure, and force state of the roadway support system are analyzed, as shown in Fig. 4. The analysis process is described as follows:

(1) Force characteristic of coal pillar. Periodic collapse and fracture subsidence occur along with coal mining in the overlying strata of the goaf. The long cantilever beam structure forms above the roadway on both sides of the coal pillar. The long cantilever beam revolves and sinks to squeeze the coal pillar of the roadway, resulting in stress concentration in this area. The stress in the coal pillar is in an inequilibrium state and cannot be released. The coal pillar can be easily crushed over time.
(2) Movement law of overlying strata structure. Due to the coal pillar support, tensile fracturing failure gradually occurs along the strata above the coal pillar after coal mining. The fracture and collapse patterns of the overlying strata between the goaf and coal pillar are different. The overlying strata in the mining area are constantly moving and are of an inequilibrium state. The time to reach the overall stability of the structure is significantly long. Fractures in the overlying strata gradually extend to the ground surface with time, leading to uneven ground surface subsidence and environmental damage.
(3) Force state of roadway support system. The 121 mining method adopts high-strength support to resist mining pressure to ensure the stability of roadway. The force of the roadway support system is in an inequilibrium state under substantial mining pressure, which is prone to causing support system failure and roadway instability.

According to the above analysis, it can be concluded that the stress in the coal pillar reserve is highly concentrated when the 121 mining method is adopted. Overlying strata structure movement above the coal pillar and two sides creates an uncoordinated and unstable state. When high-strength support is used to resist the mining pressure, the inequilibrium force is induced in the roadway support system. Thus, the stope using the 121 mining method is in an inequilibrium state in consideration of the force characteristic of the coal pillar, movement law of the overlying strata structure, and force state of the roadway support system.

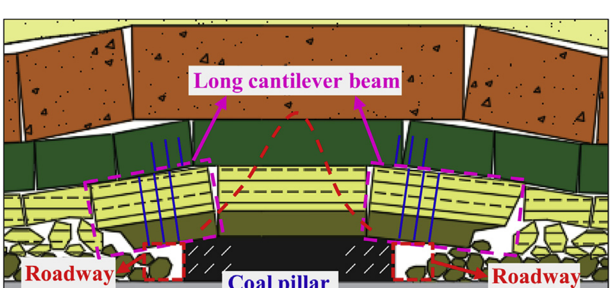


Fig. 4. Diagram of the long cantilever beam structure used for the 121 mining method.

3. The "equilibrium mining" theory

3.1. The mining damage invariant equation

To understand the cause of the above "inequilibrium state" of the 121 mining method, rock strata damage at each stage of mining activity is analyzed based on the mining rock mechanics. Mining activities generally lead to large area collapse and fracture expansion in rock strata above the goaf. Caving zone, fractured zone and sinking zone form in the roof strata, resulting in ground surface subsidence. Rock strata damage in these three zones causes continuous changes in the ground surface subsidence variable volume ΔV_S, the roof strata fracture increasing volume ΔV_C and the broken expansion volume of the collapsed rock mass ΔV_B. These three types of volumes are closely related to the mining volume ΔV_m in mining activities, as shown in Fig. 5.

Combining the 121 mining method (Fig. 3) and rock strata damage (Fig. 5), the mining process at each stage is described as follows:

(1) Stage I (before immediate roof collapse): $\Delta V_B = \Delta V_C = \Delta V_S = 0$.
(2) Stage II (immediate roof collapse): $\Delta V_B < \Delta V_m$, $\Delta V_C = 0$.
(3) Stage III (main roof collapse): ΔV_B continues to rise. At this stage, $\Delta V_B < \Delta V_m$ and ΔV_C begins to increase.
(4) Stage IV (overlying strata fracture and subsidence): ΔV_B remains unchanged, and ΔV_C increases rapidly.
(5) Stage V (ground surface subsidence): ΔV_S begins to increase.

Three types of rock strata damage variables are defined to describe the damage state of different rock strata. K_1 is defined as the damage variable of ground surface subsidence caused by coal mining, which is the ratio of the ground surface subsidence variable volume to the mining volume (Eq. (1)). K_2 is defined as the damage variable of roof strata fracture, which is the ratio of the roof strata increasing fracture volume to the mining volume (Eq. (2)). K_3 is defined as the damage variable of the broken expansion of the collapsed rock mass, which is the ratio of the broken expansion volume of the collapsed rock mass to the mining volume (Eq. (3)).

$$K_1 = \Delta V_S / \Delta V_m \tag{1}$$

$$K_2 = \Delta V_C / \Delta V_m \tag{2}$$

$$K_3 = \Delta V_B / \Delta V_m \tag{3}$$

Under different geological conditions, the above three types of rock strata damage variables constantly change. Although the changes in the three damage variables are complicated, their sum is always equal to 1. All mining engineering approaches follow this rule, which is called the invariant equation of the sum of the mining damage variables (referred to as the mining damage invariant equation):

$$K_1 + K_2 + K_3 = 1 \tag{4}$$

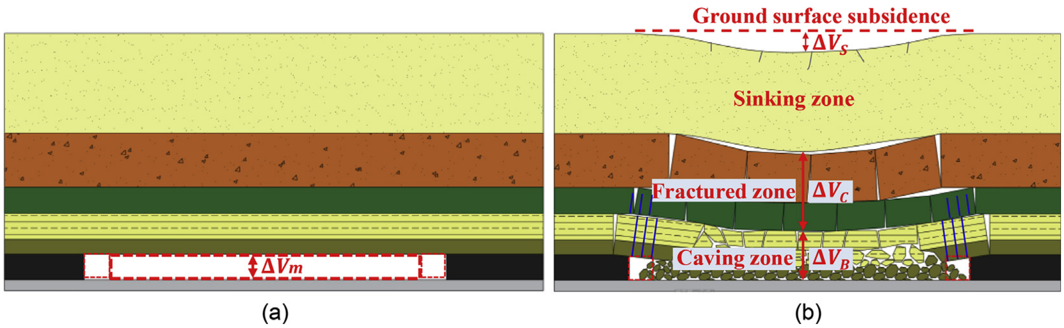


Fig. 5. Rock strata damage diagram for the 121 mining method: (a) before and (b) after roof collapse.

In Eqs. (1)–(4), the mining volume ΔV_m of the 121 mining method is known. ΔV_S can be obtained by measurement to determine the value of K_1. However, ΔV_C and ΔV_B are not controllable, and the corresponding mining damage variables K_2 and K_3 cannot be determined. Thus, the mining damage invariant equation (Eq. (4)) of the 121 mining method cannot be solved. Combined with the inequilibrium state analysis, the 121 mining method cannot be used for the equilibrium control of mining activities, hence this method is a typical "inequilibrium mining" system.

The broken rock mass exhibits expansion characteristics. If these characteristics can be used to realize equilibrium between the broken expansion volume of the collapsed rock mass and the mining volume, ΔV_B can be equal to ΔV_m. By substituting this value into Eqs. (3) and (4), K_3 is calculated as 1, and $K_1 = K_2 = 0$. The mining damage invariant equation (Eq. (4)) could be solved, which can be used to control the equilibrium of mining activities, forming an "equilibrium mining" system.

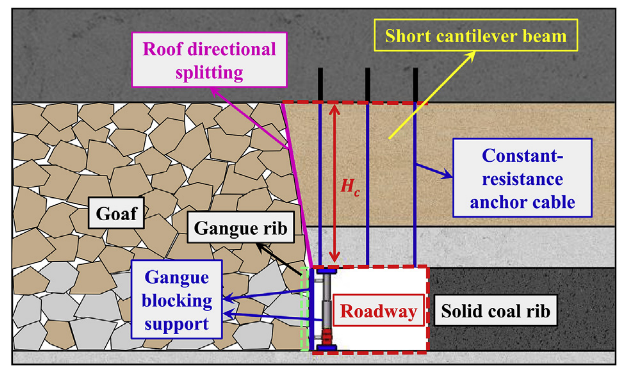


Fig. 6. Model of the "short cantilever beam" for coal mining (He, 2009).

3.2. The model of the "short cantilever beam"

A "short cantilever beam" (He et al., 2017b) model was established in 2008 for coal mining based on the above concept of "equilibrium mining", as shown in Fig. 6. The model combines the idea of utilizing the expansion characteristics of the broken rock mass and converting the resistance to mining pressure into the utilization of mining pressure. On one hand, through directional splitting on the gob-side roof, the directional collapse of roof rock strata towards the goaf is realized by utilizing the mining pressure, and the goaf is filled with the gangue by utilizing the expansion characteristics of the gangue. Therefore, the gangue rib automatically forms in the underground space obtained during coal mining. On the other hand, gangue blocking support is used to maintain the gangue rib, and the high-prestress constant-resistance anchor cable is used to control the roadway roof to ensure the stability of the surrounding rocks of roadway. It can be seen that the mining pressure and the expansion characteristics of the collapsed rock mass are utilized, and eliminations of coal pillar and roadway excavation are realized. Based on the "short cantilever beam" model, the "equilibrium mining" theory of "utilization of two aspects and elimination of two aspects" with an integrated mode of coal mining and roadway retaining is formed.

The overlying strata of the working face can collapse directionally, and the goaf can be filled with gangue using the "equilibrium mining" theory. Thus, rapid equilibrium of the overlying strata structure and the equilibrium force of the roadway support system can be realized. Based on the above theory, the mining method of AFR by roof cutting and pressure releasing without pillars (referred to as AFR without pillars) is proposed. According to the expansion control equation of the collapsed rock mass (Eq. (5)) and the equation of broken expansion (Eq. (6)) obtained from field measurement, a reasonable roof cutting height is designed to control the broken expansion volume of the collapsed rock mass. It realizes equilibrium between the broken expansion volume and mining volume, where $\Delta V_B = \Delta V_m$, $\Delta V_C = 0$, and $\Delta V_S = 0$. The overall equilibrium of each roof cutting area can be realized by the above mining method, as shown in Fig. 7.

The expansion volume ΔV_B of the collapsed rock mass of the AFR without pillars is determined by the broken expansion control equation (Wang et al., 2020a):

$$\Delta V_B = (K-1)\, H_C S \tag{5}$$

where K is the expansion coefficient of the collapsed rock mass, H_c is the height of roof splitting, and S is the area of coal mining.

The parameter K can be determined from the equation of broken expansion obtained via field measurement:

$$K = K_0 e^{-\alpha t} \tag{6}$$

where K_0 is the initial broken expansion coefficient, α is the fitting coefficient, and t is the time.

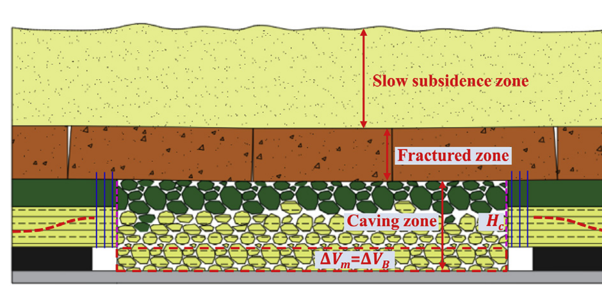


Fig. 7. Analysis model of the mining damage invariant of the AFR without pillars (He, 2009).

The coefficient K varies under different rock characteristics conditions. According to the test results in the Ningtiaota coal mine in China, the curves of expansion coefficient K in different monitoring sections obtained by Eq. (6) are shown in Fig. 8.

3.3. Characteristics of "equilibrium mining" of the AFR without pillars

The characteristics of the "equilibrium mining" system of the AFR without pillars are shown in Fig. 9. The equilibrium state of the working face after coal mining is mainly manifested in three aspects: automatic equilibrium of goaf, roadway equilibrium by artificial intervention, and overall equilibrium of multiple working faces, which are described as follows:

(1) Automatic equilibrium of goaf. The overlying strata of the goaf presents the broken expansion equilibrium during coal mining, which belongs to the automatic equilibrium state formed by utilizing the mining pressure and expansion characteristics of the collapsed rock mass. The directional splitting is carried out on the gob-side roof so that the overlying strata can collapse within the roof splitting height under its deadweight and mining pressure. The goaf is filled by continuous collapse of strata and broken expansion of gangue, which ensures that the broken expansion volume is equal to the mining volume. Therefore, goaf automatic equilibrium can be realized.

(2) Roadway equilibrium by artificial intervention. The specific performance is as follows:

(a) The structure of the "short cantilever beam" is formed under roof splitting so that the influence of gob roof movement and collapse on the roadway is reduced.

(b) The collapsed rock mass in the goaf plays a certain supporting role in the "short cantilever beam" of the roadway roof based on the expansion characteristics of the collapsed rock mass.

(c) The gangue blocking maintenance is carried out for the gangue rib of the roadway, and a high-prestress constant-resistance anchor cable is adopted to control the roof so that the roadway roof and the stable main roof form an integral structure. Therefore, roadway equilibrium by artificial intervention is realized.

(3) Overall equilibrium of multiple working faces. The multiple working faces present overall equilibrium after coal mining, which avoids the influences of coal pillar and roadway excavation on working faces. The specific performance is as follows:

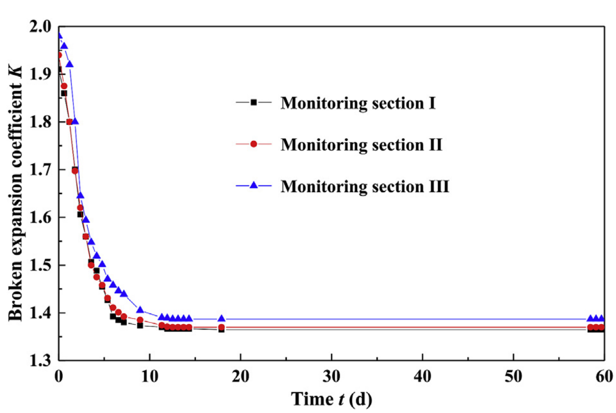


Fig. 8. Curves of broken expansion coefficient K in different monitoring sections.

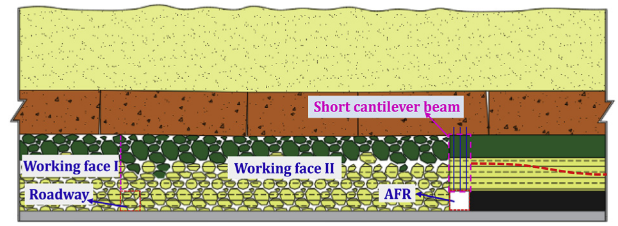


Fig. 9. Mining diagram of the adjacent working face of the AFR without pillars.

(a) The coal pillar is eliminated. The influence of the stress concentration and the large shear force at the coal pillar are eliminated when fracturing and collapsing occur in the rock strata so that uneven ground surface subsidence is avoided.

(b) The excavation of the roadway is not needed. The influence of roadway excavation in the adjacent working face (working face II) on the equilibrium area of the previous working face (working face I) can be avoided, which greatly reduces the overall equilibrium time of the mining area. Therefore, the overall equilibrium of multiple working faces can be realized.

It is then required to develop associated key technologies based on the "equilibrium mining" theory to realize the coal mining of the AFR without pillars. To realize automatic equilibrium of goaf, roof directional splitting technology of roadways should be developed to realize roof directional collapsing and gangue filling with broken expansion. To realize roadway equilibrium by artificial intervention, high-prestress constant-resistance support technology and gangue blocking support technology should be developed to realize stable control of the roadway and equilibrium mining. Based on the above key technological developments, "equilibrium mining" technology and intelligent studies on matching equipment should be conducted to realize the unmanned overall equilibrium mining of multiple working faces.

4. Key technologies of mining method of the AFR without pillars

Three key technologies are developed based on the technical requirements of the AFR without pillars, including roof directional presplitting technology, negative Poisson's ratio (NPR) high-prestress constant-resistance support technology, and gangue blocking support technology.

4.1. Roof directional presplitting technology

To control the collapsing height of the gob roof and make it collapse directionally to fill the goaf, a new presplitting technology is proposed to realize effective roof cutting. In consideration of the rock mass characteristics of high compressive strength and low tensile strength, directional presplitting technology is proposed. It consists of the bidirectional energy cavity tension blasting technique and instantaneous splitting with a single fracture surface technique.

4.1.1. Bidirectional energy cavity tension blasting technique

Roof directional presplitting is realized by bidirectional energy cavity tension blasting equipment (He et al., 2017d; Gao et al., 2019). The initial fracture is formed at the blast hole wall according to the preset direction when the hole is blasted. The surrounding rocks of the blast hole are uniformly compressed. The

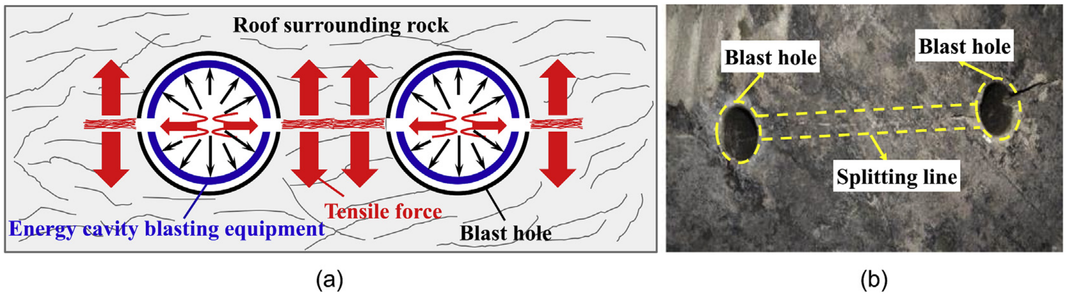


Fig. 10. Bidirectional energy cavity tension blasting: (a) Technical principle; and (b) Field application (He, 2009).

tensile stress is generated in the vertical direction of the initial fracture. The rock mass is fractured along the presplitting direction, leading to further expansion and extension of the fracture, as shown in Fig. 10a.

Directional fractures appear along the interior and surface of the blast hole by adopting the bidirectional energy cavity tension blasting technique, with fracture rate greater than 90%. The technique can produce roof presplitting according to the preset position and direction, which causes the gob roof to be cut down along the presplitting line based on the design height. The field application of the technique is shown in Fig. 10b.

4.1.2. Instantaneous splitting with a single fracture surface technique

Roof directional presplitting is realized by instantaneous splitting with a single fracture surface technique. It utilizes instantaneous splitting equipment, which can produce a single fracture surface instantaneously without blasting and can replace the bidirectional energy cavity tension blasting technique. The new splitting equipment is mainly composed of a (i) directional splitting tube, (ii) coupling medium, (iii) special splitting agent, and (iv) current initiating device, as shown in Fig. 11. The coupling medium fixes the special splitting agent and transmits energy. The special splitting agent has high ignition point. When it is triggered by the current initiating device, a large amount of gas is produced in a short period of time. The gas is discharged in the direction of the energy gathering hole at the directional splitting tube, which fractures the surrounding rocks in the direction of gas pressure.

The field test of instantaneous splitting with a single fracture surface technique is carried out in a deep coal mine (overburden of 890 m). The immediate roof of the test working face is composed of fine sandstone with an average thickness of 11.05 m and average uniaxial compressive strength of 86.3 MPa. The instantaneous splitting equipment is successful in field applications, and the fracture rate can be up to 90%, meeting the requirements of directional splitting. The field test process and effects of instantaneous splitting are shown in Fig. 12. The indices of two kinds of roof splitting equipment applied for roof directional presplitting techniques are shown in Table 1.

4.2. NPR high-prestress constant-resistance support technology

The commonly used support anchor cable exhibits the Poisson's ratio (PR) effect, characterized by "local plasticity and obvious necking". Its elongation is approximately 3%–5% (Dong et al., 2018), leading to poor energy absorption effect and susceptibility to failure when the deformation of the surrounding rocks is large, as shown in Fig. 13.

During the collapsing process of the gob-side roof, large friction stress is generated on the formed "short cantilever beam" after roof directional splitting. The surrounding rocks of the roadway roof deform easily and release large amounts of energy. The traditional anchor cable can easily fail due to the sudden increase in stress and

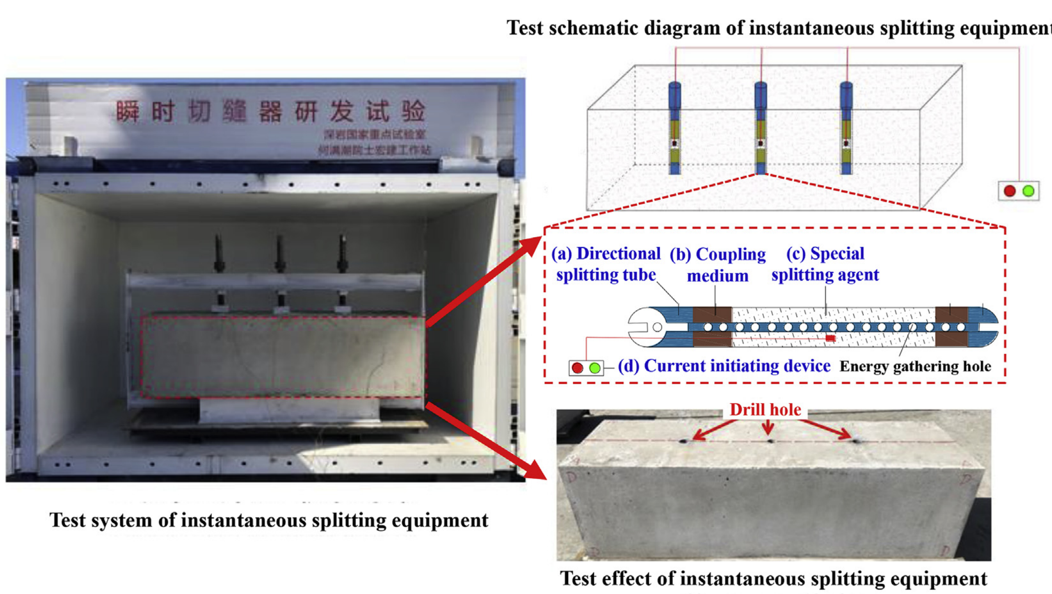


Fig. 11. Laboratory test of instantaneous splitting equipment (He et al., 2019).

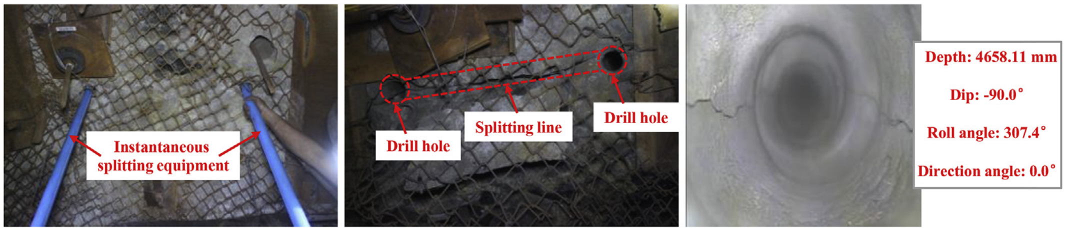


Fig. 12. Field test process and effects of instantaneous splitting: (a) Installation; (b) Splitting effect of the hole surface; and (c) Splitting effect of the hole interior.

Table 1
Comparison of two kinds of roof splitting equipment (He and Zhang, 2018).

Performance index	Bidirectional energy cavity tension blasting equipment	Instantaneous splitting equipment
Explosiveness	Yes	No
Working method	Blasting by detonator	Seal ignition
Required time	Millisecond	0.05–0.5 s
Amount of raw material required for same rock mass	1.15 kg	1 kg
Working mechanism	Detonation wave, shock wave	Expansion of high-temperature gas
Heat of combustion	2600–3500 kJ/kg	14,248 kJ/kg
Specific volume	>700 mL/g	306.2 mL/g
Explosion speed	2000–4000 m/s	Non-explosion
Ignition point	<260 °C	503 °C
Apparent density	>1 g/cm^3	0.49 g/cm^3
Moisture	<0.5%	0.4%
Flame density	2–8 cm	16.7 cm

the PR effect, which cannot meet the control requirements of the roadway roof.

To control the deformation of surrounding rocks and absorb released energy effectively, a new anchor cable must be developed. It should have good energy absorption ability, and bear large deformation of the rock mass under high prestress. The NPR high-prestress constant-resistance support technology for the AFR without pillars is then developed. The key components of this technology include macro- and micro-NPR anchor cables.

4.2.1. Macro-PR high-prestress constant-resistance anchor cable

A series of macro-NPR anchor cable support products with a new type of NPR constant-resistance structure was developed in 2008. To compare the mechanical properties of the macro-NPR anchor cable with those of traditional anchor cables, numerous static tensile tests (Sun et al., 2017) and dynamic impact tensile tests (He et al., 2015, 2017e) have been carried out. The test results show that the macro-NPR anchor cable has significant constant-resistance characteristics, and the maximum displacement of the NPR constant-resistance structure can be up to 1000–2000 mm. The macro-NPR anchor cable is more effective than the traditional anchor cable in terms of the supporting force and maximum displacement, as shown in Fig. 14.

4.2.2. Micro-NPR high-prestress constant-resistance anchor cable

The micro-NPR support material was developed in 2014 which is a quasi-ideal plastic material with following advantages: (i) The material has NPR effect, i.e. the PR can reach the magnitude of 10^{-3}; (ii) The yield plateau of the material disappears; and (iii) The maximum strain of the material is larger than 20%.

The laboratory test results show that the hysteretic energy capacity of the micro-NPR support material is 7–8 times that of the PR support material (Q235 thread steel). The elongation of the new support material can be up to 35%–70%, and the tensile strength ranges from 900 MPa to 1100 MPa. The new support material has better elongation and strength characteristics, and the fracture surface basically has no necking phenomena, as shown in Fig. 15. The material also has unique properties of non-magnetic, anti-strong magnetic field magnetization and strong anti-corrosion effect.

The micro-NPR high-prestress constant-resistance anchor cable is developed using this new material. This study first realized the NPR effect of anchor cable support products in terms of the material. The design concept of the micro-NPR high-prestress constant-resistance anchor cable in engineering application is described as follows:

(1) The roof anchor cable length. The length of the high-prestress constant-resistance anchor cable can be calculated by

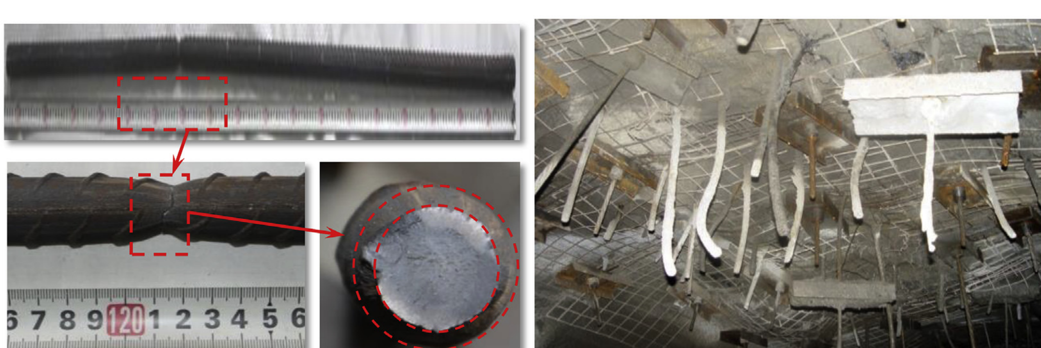
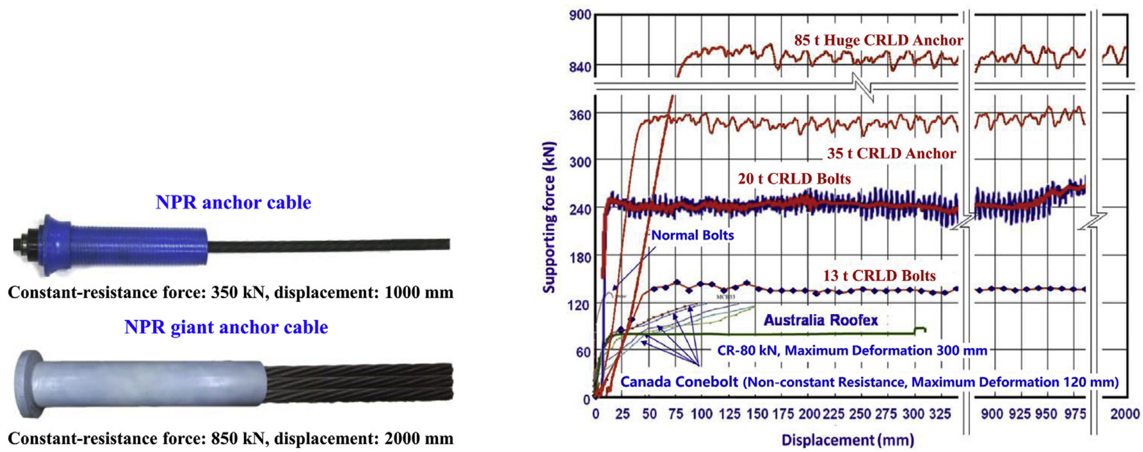


Fig. 13. PR effect and failure of traditional anchor cables.



(a) (b)

Fig. 14. Macro-NPR anchor cable (a) and tensile deformation curve (b) (He, 2006). CRLD represents the constant-resistance large deformation.

$$L_H = H_C + 2 \tag{7}$$

where L_H is the anchor cable length (m), and H_C is the pre-splitting height (m).

(2) The high prestress. The applied prestress of the high-prestress constant-resistance anchor cable should be 80%–90% of its ultimate constant-resistance value.
(3) The anchor cable number per unit area. The number per unit area of the high-prestress constant-resistance anchor cable, N, can be calculated by

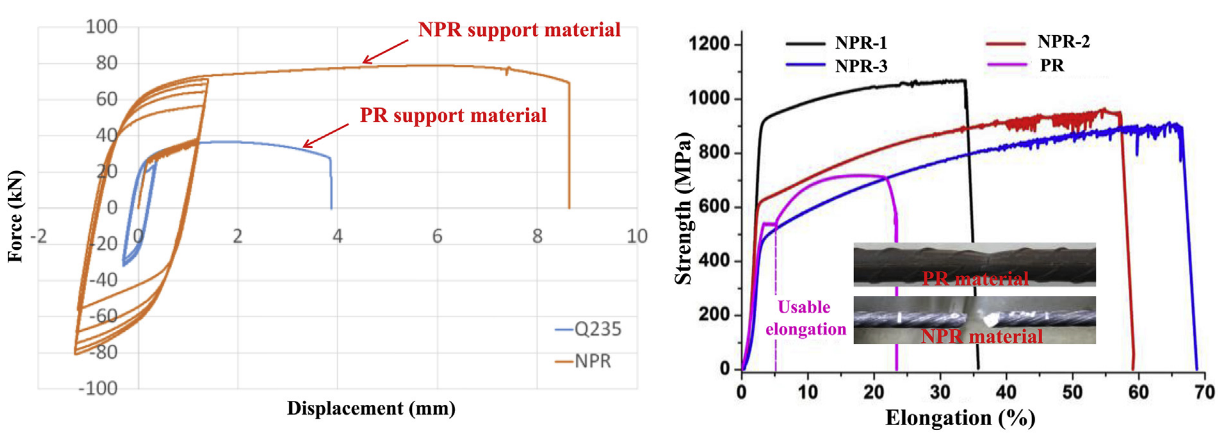
$$N = K_c\,(P_n/P_0) \tag{8}$$

where P_n is the roof pressure per unit area (kN); P_0 is the constant-resistance stress of anchor cable (kN); and K_c is the safety coefficient, with the value of 1.1–1.3.

4.3. Gangue blocking support technology

High vertical pressure appears on the AFR before the gob roof collapses, and high dynamic pressure will be generated during the collapsing process of the gob roof. For this, the traditional gangue blocking support is prone to bending and slipping, as shown in Fig. 16. Therefore, a new support technology should be developed, which can resist large forces and control surrounding rock deformation to ensure the stability of the gangue rib. The gangue blocking support technology (Wang et al., 2018c) for the gangue rib is proposed herein in view of the above problems. The roof and rib support equipment, gangue blocking mesh and retractable U-steel are used for the combined support technology, as shown in Fig. 17.

The roof and rib support equipment is composed of two parts. The first part includes the top beam, bottom beam, push plate and column, which can provide large supporting force to resist roof deformation and maintain yield pressure to adapt to the given deformation of the main roof with the movement process of the overlying strata. The second part includes the upper and lower push plates, providing a large lateral thrust to resist the lateral



(a) (b)

Fig. 15. Properties of the micro-NPR support material: (a) Hysteretic energy curve; and (b) Mechanical property curve (He and Xia, 2016).

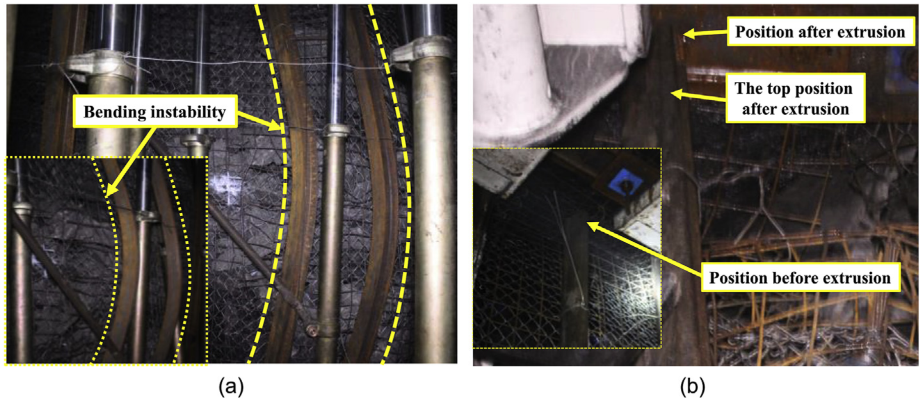


Fig. 16. Instability types of common gangue blocking support: (a) Bending instability, and (b) Slipping instability.

dynamic load of gangue blocking support during the collapsing process of the gob roof.

The retractable U-steel produces a relative displacement under the extrusion action generated by roof subsidence, actively yielding pressure with high resistance to prevent bending instability in the gangue blocking support structure. The collapsed rock mass is piled up to form the wall under the joint cooperation of the roof and rib support equipment, retractable U-steel and gangue blocking mesh. The gangue rib is formed after the gangue is compacted and stable.

5. Mining method of the AFR without pillars

The 110 and N00 mining methods are established based on the "equilibrium mining" theory and the comprehensive application of the key technology of the AFR without pillars.

5.1. 110 mining method of the AFR without pillars

The roof presplitting, roof anchor cable support and gangue blocking support are carried out for the reserved roadway in the

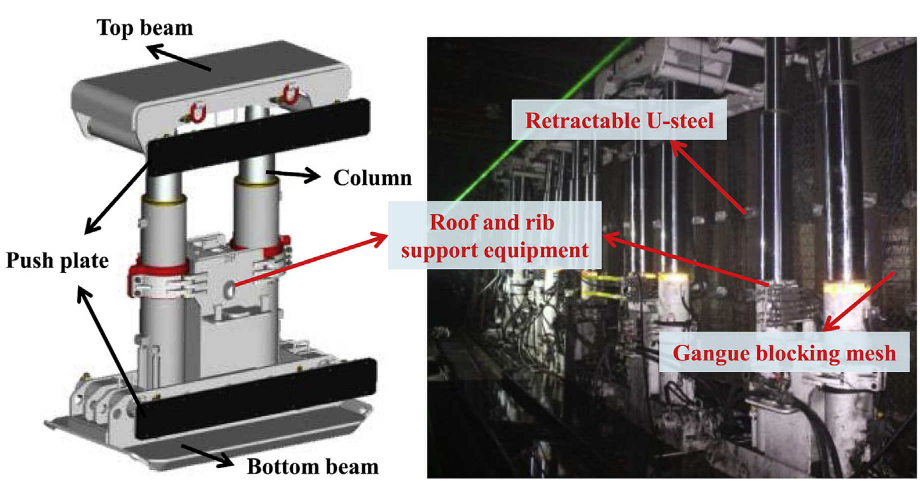


Fig. 17. Gangue blocking support equipment of the gangue rib.

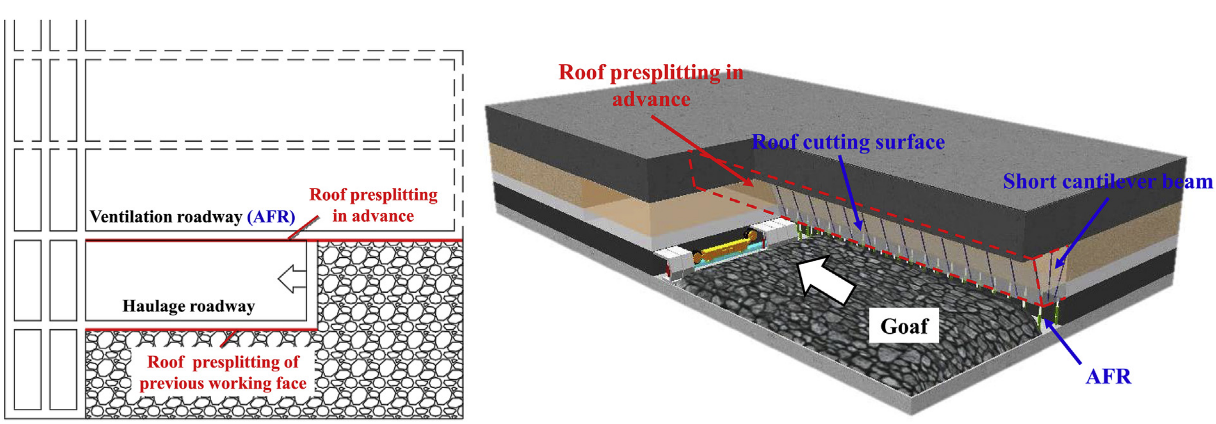


Fig. 18. Schematic diagram of the 110 mining method of the AFR without pillars (He, 2009).

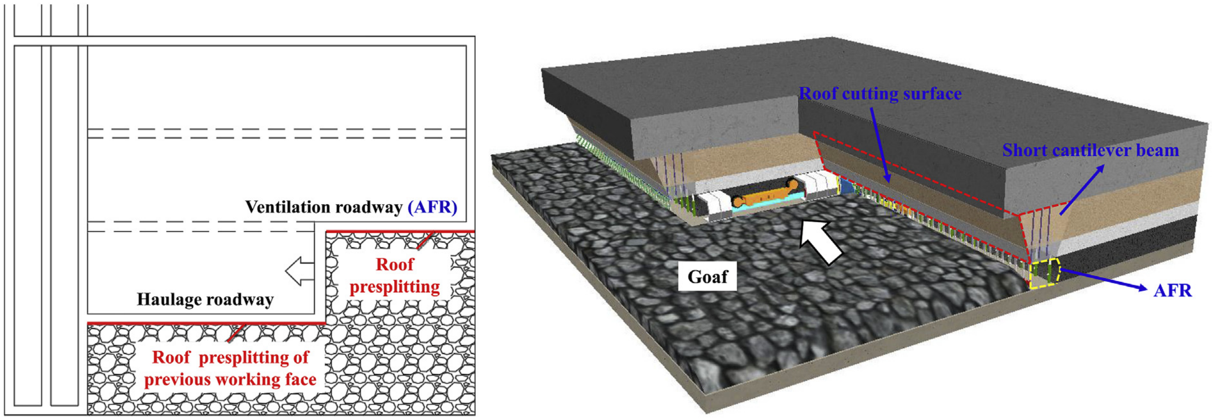


Fig. 19. Schematic diagram of the 1G N00 mining method of the AFR without pillars (He and Wang, 2016).

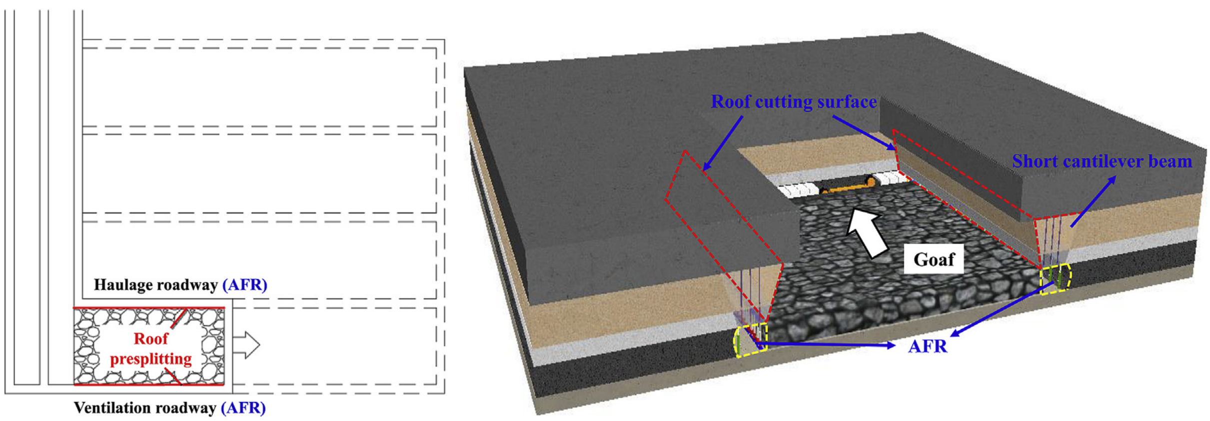


Fig. 20. Schematic diagram of the 2G N00 mining method of the AFR without pillars (He and Wang, 2018).

110 mining method (Wang et al., 2020b, c). The reserved roadway is retained for the next working face, as shown in Fig. 18. The method can reduce half of the excavation amount of roadway and the coal pillar is not needed, which is beneficial for reducing the stress concentration in the surrounding rocks of roadway. This is an important transition from “inequilibrium mining” to “equilibrium mining”.

5.2. N00 mining method of the AFR without pillars

5.2.1. 1G N00 mining method of the AFR without pillars

The 1G N00 mining method of the AFR without pillars is proposed based on the 110 mining method. In this method, the roadway excavation for the working face is not needed and the integrated mode of coal mining and roadway retaining can be realized, as shown in Fig. 19. The mining technique, equipment system, and layout of the working face and roadway are changed (He et al., 2019; Wang et al., 2020d, e). The roadway is automatically formed and retained by roof cutting on one side of the working face, and the roadway excavation (except the boundary roadway) and coal pillar reserved in the panel are not required.

5.2.2. 2G N00 mining method of the AFR without pillars

The concept of the 2G N00 mining method of the AFR without pillars is proposed based on the 1G N00 mining method to eliminate all roadway excavations in the whole panel, as shown in Fig. 20. The working face transportation and conveyor systems are turned and overlapped with the 2G N00 mining method. The support time of roof and rib support equipment is advanced, and the integrated design of the drilling and the support is carried out. The roadway is automatically formed and retained by roof cutting on two sides of the working face, and all mining roadway excavations in the whole panel are eliminated. The application of this method is being carried out in the Xintai coal mine in China.

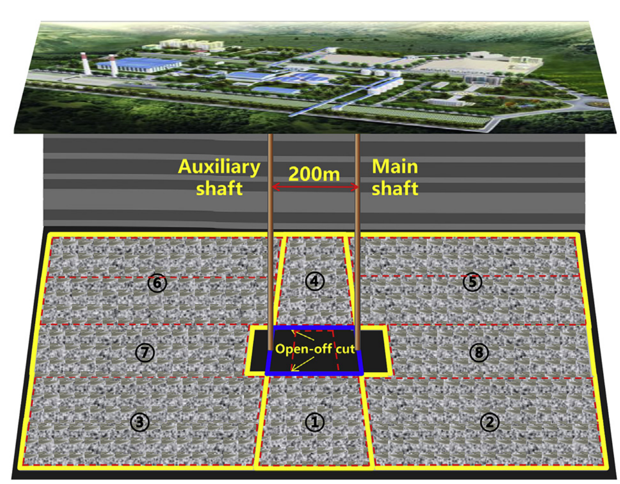


Fig. 21. Schematic diagram of the 3G N00 mining method of the AFR without pillars (He and Wang, 2019).

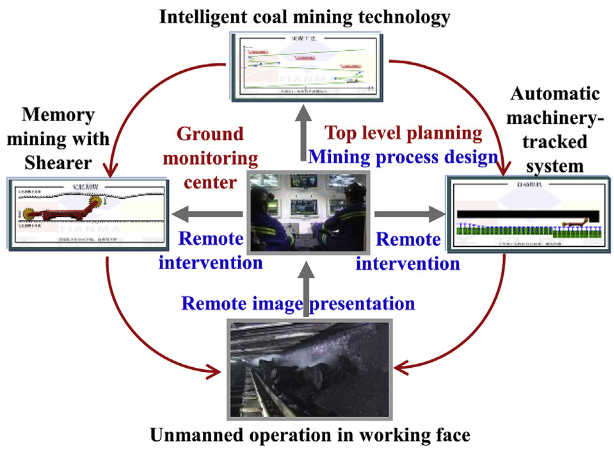


Fig. 22. Schematic diagram of the 4G N00 mining method of the AFR without pillars (He and Wang, 2020).

5.2.3. 3G N00 mining method of the AFR without pillars

The concept of the 3G N00 mining method of the AFR without pillars is proposed based on the 2G N00 mining method to eliminate roadway excavation in the whole coal mine and realize a new concept of mine construction, as shown in Fig. 21. The transportation and ventilation systems are formed through the mining of the working face in the 3G N00 mining method. The mine construction is greatly simplified due to the reduction in the mine construction duration, the simplification of the shaft station, and the elimination of the main roadway excavation. The mode of no coal pillar reserve and roadway excavation is realized in the whole mine. All the coal resources can theoretically be mined out, providing that the intelligent and unmanned mining is realized in the whole mine. The application of this method is being carried out in the Xiaohaotu coal mine in China.

5.2.4. 4G N00 mining method of the AFR without pillars

The concept of the 4G N00 mining method of the AFR without pillars is proposed based on the 3G N00 mining method to realize intelligent unmanned mining and eliminate mine ventilation, as shown in Fig. 22. Memory mining with shearers, automatic machinery-tracked systems of hydraulic support and visual remote monitoring are the basis of the 4G N00 mining method. The intelligent control platform is adopted to realize the intelligent control of the whole mine to ensure the continuous, safe and efficient mining of the working face. Mine ventilation will be eliminated, and gas disasters will be transformed into natural gas resources. The intelligent and unmanned simultaneous extraction of coal resources and natural gas resources will be realized.

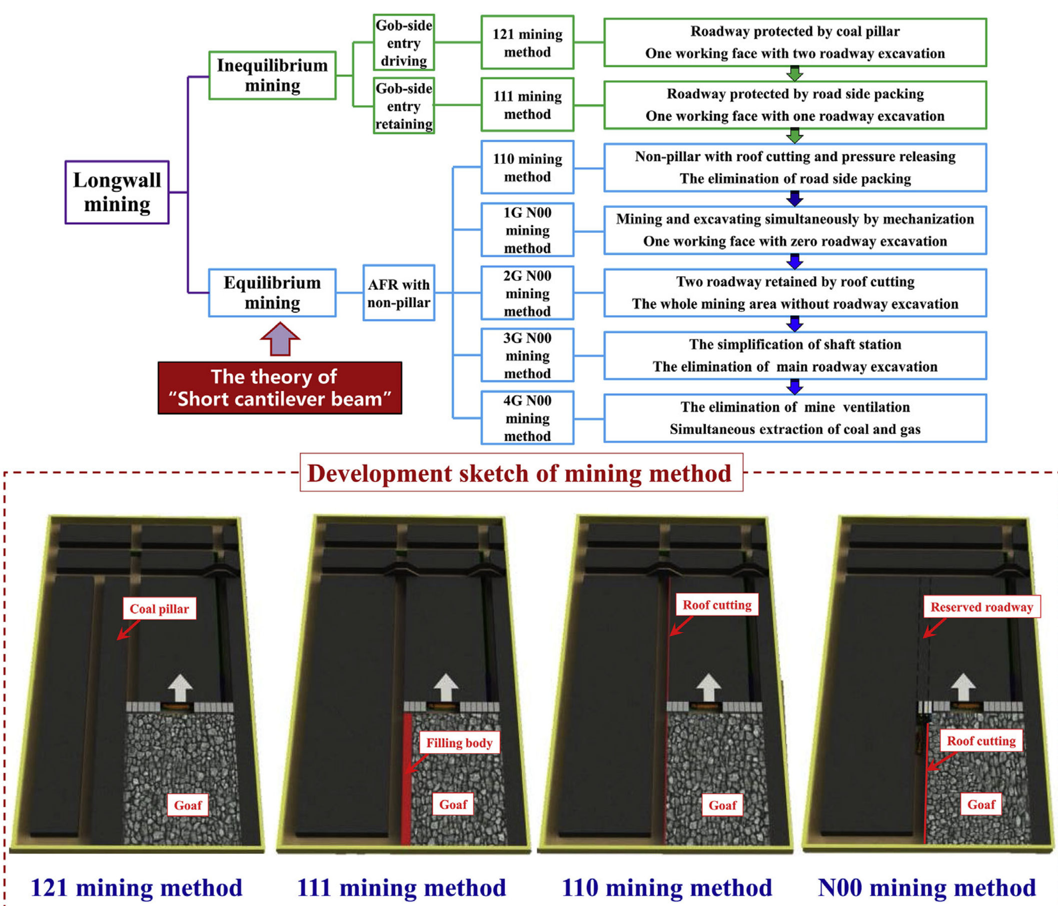


Fig. 23. Development and planning of the longwall mining method.

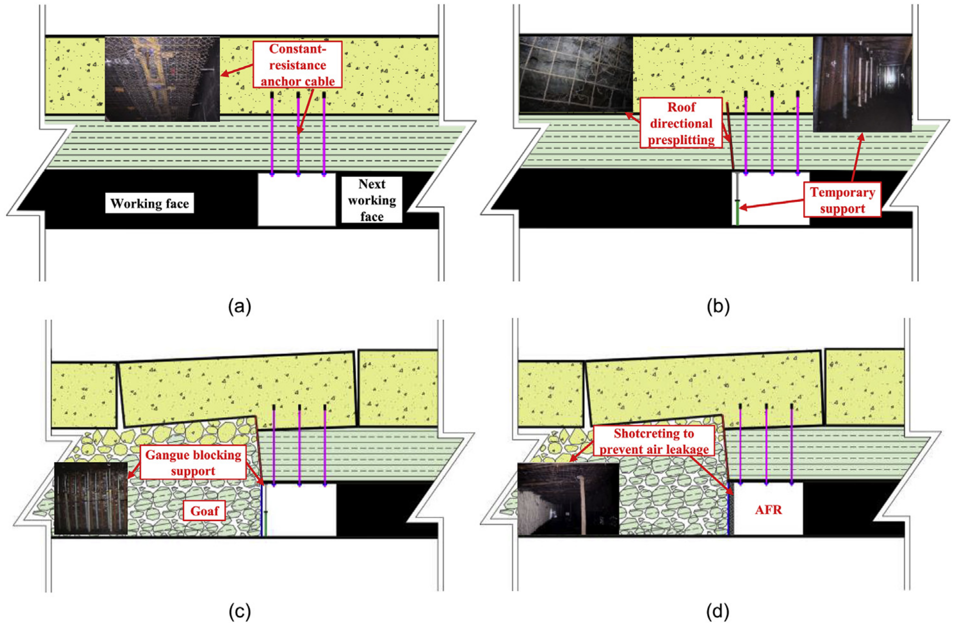


Fig. 24. Technique flowchart of the 110 mining method of the AFR without pillars: (a) Installation of NPR constant-resistance anchor cables; (b) Roof directional presplitting and temporary supporting; (c) Installation of gangue blocking support; and (d) Shotcreting for the gangue.

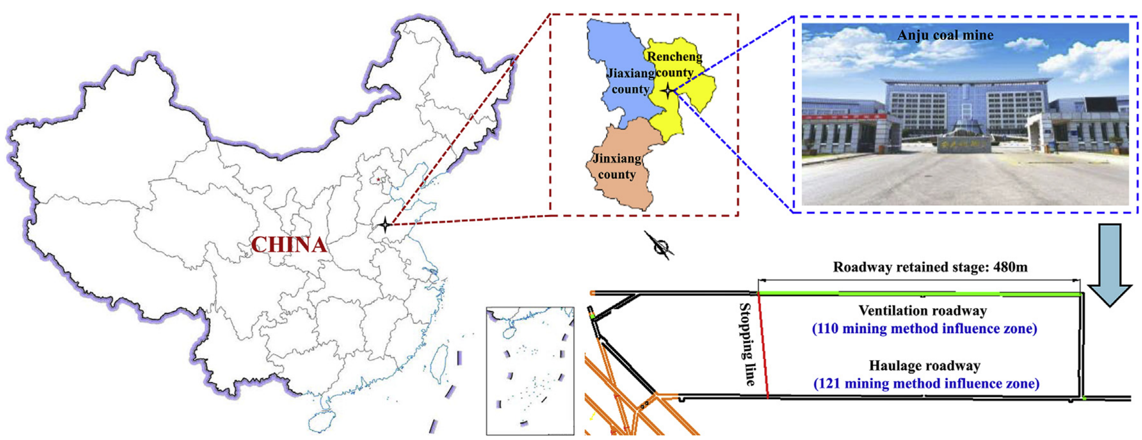


Fig. 25. The geographic location and roadway layout of the 5307 working face.

5.3. Development of the mining method

The 110 and N00 mining methods of the AFR without pillars are coal mining innovations in China, in addition to gob-side entry driving (121 mining method) and gob-side entry retaining (111 mining method). The 121 mining method generally adopts the "masonry beam theory" (Qian, 1981) and "transfer rock beam theory" (Song, 1979). The mining method of the AFR without pillars follows the "short cantilever beam theory". The 110 mining method (Yang et al., 2019a; Wang et al., 2020f) and 1G N00 mining method (Wang et al., 2019b, 2020g) have been successfully applied in the field. The 2G and 3G N00 methods are being carried out in two coal mines in China. The technical characteristics of the 121 mining method, 110 mining method and each stage of the N00 mining method are compared and summarized in Fig. 23.

6. Field application of the mining method of the AFR without pillars

6.1. Field application of the 110 mining method

6.1.1. Technique system of the 110 mining method

The technique flowchart of the 110 mining method of the AFR without pillars is shown in Fig. 24 and described as follows:

(1) The NPR high-prestress constant-resistance anchor cables are used as the main support component to support the mining roadway roof (Fig. 24a).
(2) During coal mining, roof directional presplitting is carried out along the gob-side of the roadway based on predesigned roof cutting parameters. At the same time, the hydraulic props are used at the gob-side of the roadway as a temporary support (Fig. 24b).

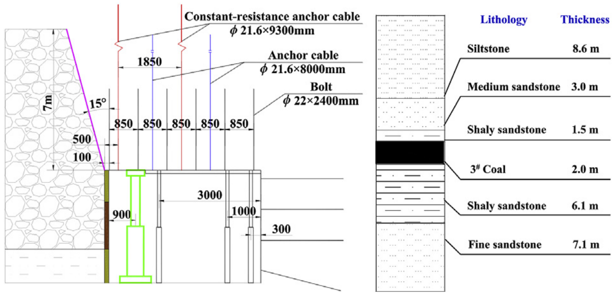


Fig. 26. Parameters of roadway roof cutting and support for the 110 mining method (unit: mm).

(3) Gangue blocking support is provided in a timely manner at the gob-side of the roadway behind the working face along with coal mining (Fig. 24c).
(4) The gob roof collapses, and the collapsed rock mass is gradually compacted along with coal mining under its deadweight and mining pressure. The goaf is filled to form a gangue rib on the gob-side of the roadway due to the expansion characteristics of the collapsed rock mass, and the roadway is formed automatically. Temporary support can be withdrawn when the surrounding rocks of the AFR are stable. Shotcreting should be carried out for the gangue rib to prevent air leakage, forming a closed roadway rib (Fig. 24d).

6.1.2. Typical application of the 110 mining method

The 110 mining method of the AFR without pillars has been successfully applied in the Anju coal mine located in eastern China, which is more than 1000 m in depth. The average burial depth of the 5307 working face is 1195 m. It has a dip length of 150 m and a strike length of 480 m. The average dip angle of the coal seam is 7°, and its average thickness is 2 m. The immediate roof is composed of shaly sandstone and medium sandstone with average thicknesses of 1.5 m and 3 m, respectively. The main roof is siltstone with an average thickness of 8.6 m. The immediate floor is shaly sandstone with an average thickness of 6.1 m, and the main floor is fine sandstone with an average thickness of 7.1 m. The 110 mining method is applied to the track roadway (ventilation roadway), and the 121 mining method is applied to the belt roadway (haulage drift) in the test working face. The geographic location and roadway layout of the coal mine are shown in Fig. 25.

The design parameters of roadway roof cutting and support for the 110 mining method are shown in Fig. 26 and listed as follows:

(1) Roof cutting parameters: the roof cutting height of 7 m, and the roof cutting angle of 15°.
(2) Roof support parameters: the roadway roof is supported by the NPR high-prestress constant-resistance anchor cable, anchor cable and high-strength bolt. The parameters of the constant-resistance anchor cable, the anchor cable, and the high-strength bolt are ϕ21.6 mm × 9.3 m, ϕ21.6 mm × 8 m, and ϕ22 mm × 2.4 m, respectively.
(3) Gangue blocking support parameters: the hydraulic unit support and "one beam and three columns" are adopted. The field application effect is shown in Fig. 27.

(1) Deformation monitoring of the AFR surrounding rocks

The displacement monitoring station is located 80 m away from the open-off cut in the 5307 track roadway to monitor the roof and floor convergence deformation of the roadway roof cutting side, solid coal side and middle of the roadway, as shown in Fig. 28.

Fig. 28 shows that the roof and floor convergence deformation is compared as follows: middle of roadway > roof cutting side > solid coal side. The variation in the roof and floor convergence deformation of the three parts can be divided into three stages:

(i) The rapid deformation stage. The roof and floor deformation increases rapidly in the range of 0–200 m behind the working face. The displacement in the middle of the roadway roof is the largest (826 mm).
(ii) The slow deformation stage. The roof and floor deformation increases slowly in the range of 200–250 m behind the working face.
(iii) The stable deformation stage. The roof and floor deformation basically does not change, and the deformation in the middle of the roadway roof is the largest (976 mm) after lagging behind the working face by approximately 250 m. The results show that the mining method effectively controls the surrounding rocks of the high-stress roadway and meets the engineering requirements.

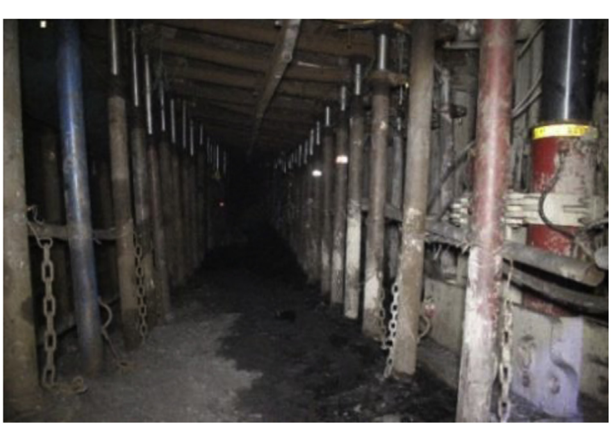


Fig. 27. Field application effect for the 110 mining method.

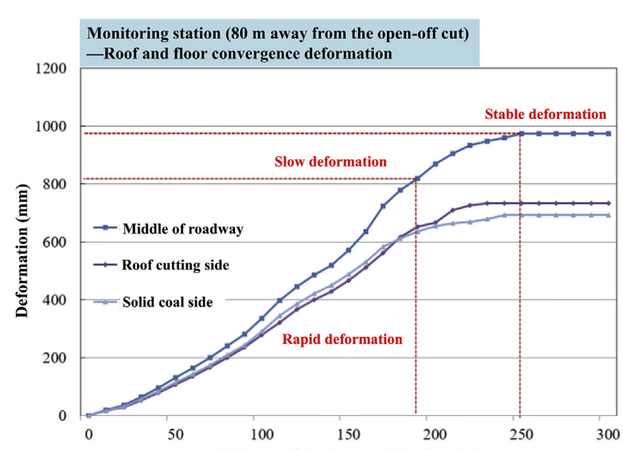


Fig. 28. Variation curves of the roadway roof and floor convergence deformation.

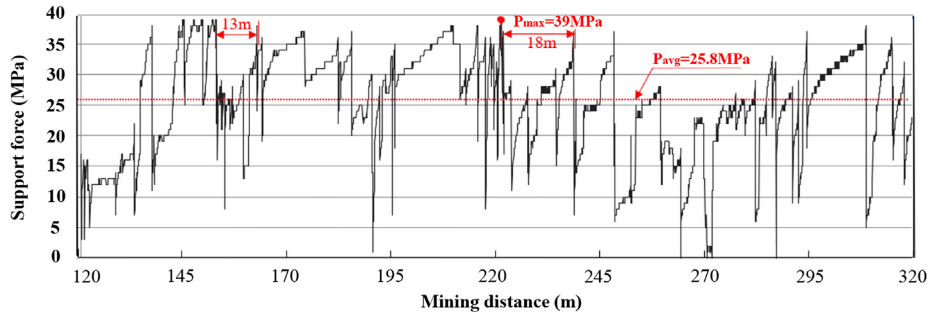


Fig. 29. The load curve of hydraulic support #4 in the influence zone without roof cutting.

(2) Analysis of mining pressure monitoring in the field

According to the zoning conditions of the working face by the 110 mining method, hydraulic supports #4 and #104 are selected for mining pressure monitoring. Hydraulic support #4 is located in the influence zone without roof cutting, and hydraulic support #104 is located in the influence zone of roof cutting. The load curves of hydraulic supports #4 and #104 are displayed in Figs. 29 and 30, respectively. The following results are obtained:

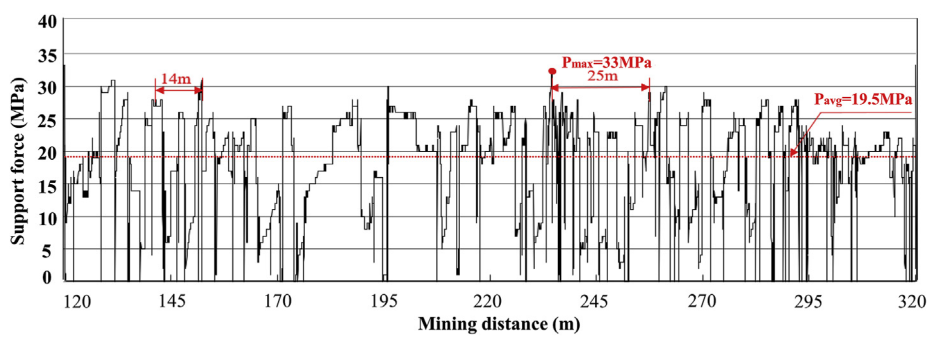


Fig. 30. The load curve of hydraulic support #104 in the influence zone of roof cutting.

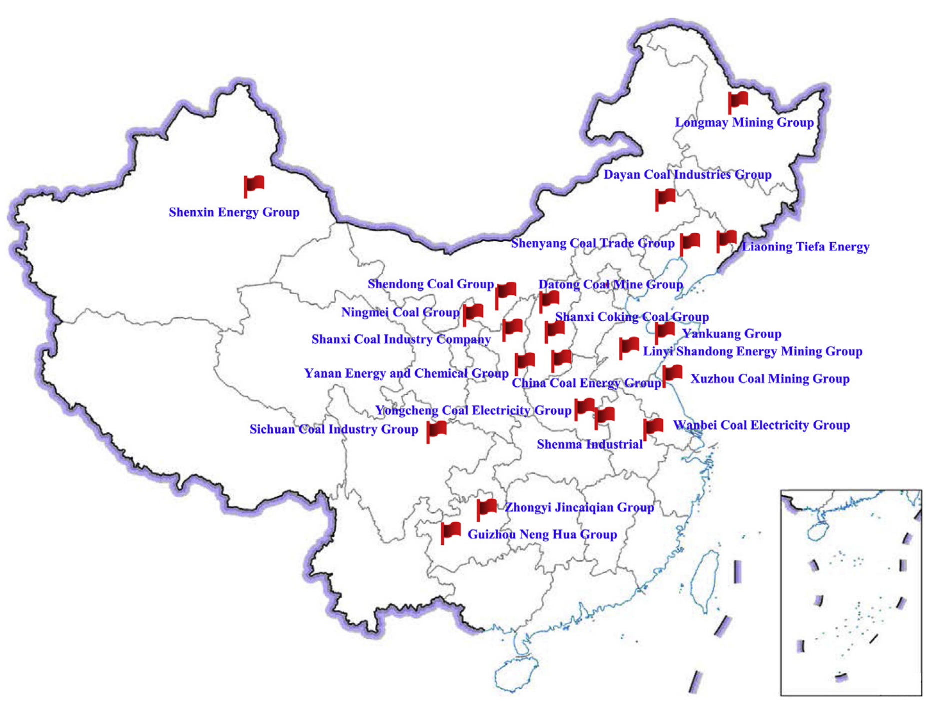


Fig. 31. Application of the 110 mining method of the AFR without pillars.

(i) The maximum pressures (P_{max}) of the hydraulic support on the side of the track roadway (influence zone of 110 mining method) and belt roadway (influence zone of 121 mining method) are 33 MPa and 39 MPa, respectively. The maximum pressure of the former decreases by 6 MPa relative to the latter with a decreasing rate of 12.8%.
(ii) The average pressures (P_{avg}) of the hydraulic support on the side of the track roadway and belt roadway are 19.5 MPa and 25.8 MPa, respectively. The average pressure of the former decreases by 6.3 MPa relative to the latter with a decreasing rate of 24.4%.
(iii) The maximum periodic weighting distances of the track roadway side and belt roadway side are 25 m and 18 m, respectively. The maximum periodic weighting distance of the former increases by 7 m relative to the latter.

It can be concluded that the 110 mining method can effectively release the stress imposed on surrounding rocks of roadway roof. This reduces the force of the supporting components and maintains the stability of the surrounding rocks of roadway. Moreover, the mining method eliminates the coal pillar reserve and reduces roadway excavation, realizing the stable equilibrium of the roadway support system.

6.1.3. Application status of the 110 mining method

In recent years, the 110 mining method of the AFR without pillars has been applied to 21 mining areas in China, as shown in Fig. 31. More than 600 km of roadways have been automatically formed in more than 500 mining working faces, and more than 40×10^6 t of coal pillar resources have been recovered. The association standard of the “Code for Non-pillar Mining with Gob-entry Retaining of the 110 Method” has been formed with the establishment and improvement of the 110 mining method.

Application of the 110 mining method is classified (He et al., 2017e) according to different geological and mining conditions. The classification is conducted as follows:

(1) According to splitting roof strata combinations and structural states, it can be divided into 110 mining methods with composite roof, broken roof and hard roof.
(2) According to the thickness of the mining coal seam, it can be divided into 110 mining methods with thin coal seams (mining thickness $\leq$ 2 m), medium thick coal seams (2 m $<$ mining thickness $\leq$ 4 m), and thick coal seams (mining thickness $>$ 4 m).
(3) According to the mining depth, it can be divided into 110 mining methods with shallow (mining depth $\leq$ 300 m), medium (300 m $<$ mining depth $\leq$ 600 m), and large burial depth (mining depth $>$ 600 m).

According to the above classification, typical applications of the 110 mining method include the Baijiao coal mine with a composite roof and thin coal seam (Zhang et al., 2011), Ningtiaota coal mine with a hard roof and thick coal seam (Gao et al., 2017), Halagou coal mine with a composite roof (Ma et al., 2018), Tangshangou coal mine with a hard roof (Sun et al., 2020), Tashan coal mine with a composite roof and medium thick coal seam (He et al., 2019b), Hecaogou No. 2 coal mine with a broken roof (Li et al., 2018), Chengjiao coal mine with a large burial depth (He et al., 2018b), and so on (Hu et al., 2019; Liu et al., 2019; Sun et al., 2014, 2019; Yang et al., 2019b, 2020). A remarkable roadway formation effect has been achieved in the above coal mines. The typical coal mines applying the 110 mining method in the field are shown in Table 2 and Fig. 32.

6.2. Field application of the 1G N00 mining method

6.2.1. Equipment systems

The equipment systems include three coal mining equipment systems and four roadway forming equipment systems. The integrated production mode of coal mining and roadway forming is realized by improving matching construction among the three coal mining equipment systems. The roadway is retained by utilizing four roadway forming equipment systems. Automatic roadway forming and coal mining without pillars are realized.

(1) Coal mining equipment systems

The three coal mining matching equipment systems include the N00 mining shearer, N00 scraper and N00 hydraulic support, as shown in Fig. 33. This system differs from traditional coal mining systems with its improved matching construction between the mining shearer and scraper, which creates conditions for the integrated mode of coal mining and roadway forming.

The improved mining shearer in the 1G N00 mining method can move past the tail of the scraper and carve the coal wall into an arc-shaped solid coal rib in the roadway by a drum, formulating an

Table 2
List of typical coal mines applying the 110 mining method in the field.

Year	Coal mine and working face	Surrounding rock conditions	Coal seam dip (°)	Roof cutting parameter: Height (m)	Roof cutting parameter: Angle (°)
2010	Baijiao coal mine 2422 working face	Composite roof Thin coal seam	8–10	5	0
2013	Tangshangou coal mine 8820 working face	Hard roof Thin coal seam	3–5	6	20
2013	Nantun coal mine 1601 working face	Hard roof Thin coal seam	3	5	20
2014	Jiayang coal mine 3118 working face	Broken roof Thin coal seam	3	4	20
2015	Halagou coal mine 12201 working face	Composite roof Medium thick coal seam	2	6	10
2015	Chengjiao coal mine 21304 working face	(Large buried depth) broken roof Medium thick coal seam	3	8	15
2015	Ningtiaota coal mine S1201 working face	Hard roof Thick coal seam	0–2	9	10
2015	Hecaogou No. 2 coal mine 1105 working face	Broken roof Thin coal seam	1–3	4	20
2017	Fucheng coal mine 1906S working face	(Large buried depth) hard roof Thick coal seam	0–3	11	20
2017	Guandi coal mine 12605 working face	Composite roof Medium thick coal seam	5	7	15
2017	Tashan coal mine 8304 working face	Composite roof Medium thick coal seam	2–6	7.7	15
2019	Jining No. 3 coal mine 5312 working face	Hard roof Medium thick coal seam	3–6	5	15
2019	Zhongxing coal mine 1200 working face	Composite roof Medium thick coal seam	7.6	6	15
2019	Hongqinghe coal mine 3^{-1}101 working face	Hard roof Thick coal seam	0–3	10	15

Fig. 32. Field applications in typical coal mines using the 110 mining method.

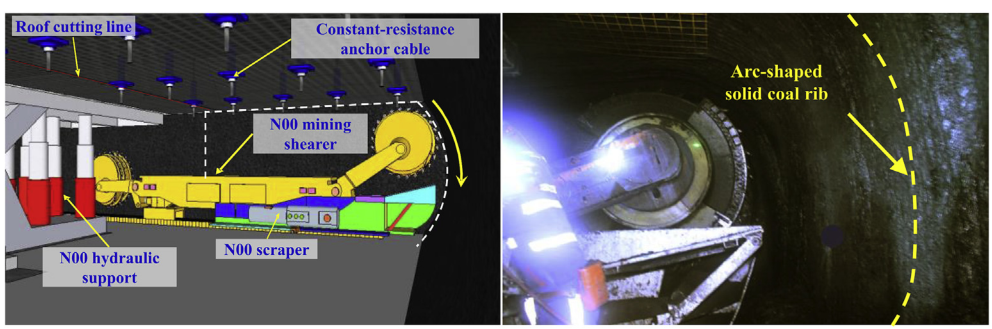


Fig. 33. Three coal mining matching equipment systems of the 1G N00 mining method (He, 2016).

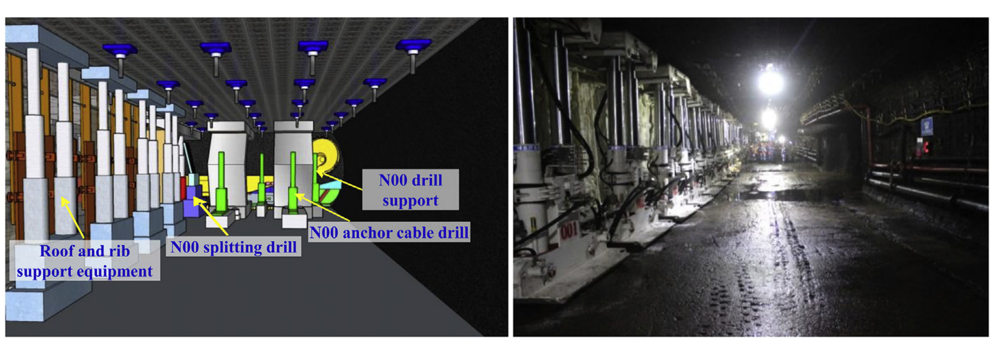


Fig. 34. Four roadway forming matching equipment systems of the 1G N00 mining method (He, 2016).

integrated mining mode of coal mining and roadway forming. A new type of scraper with a coal blocking and coal collecting device is included by adding a retractable coal blocking plate and a coal shoveling plate at the scraper tail to reduce the waste of coal resources.

(2) Roadway forming equipment systems

The four roadway forming matching equipment systems include the N00 anchor cable drill, N00 splitting drill, N00 drill support, and roof and rib support equipment, as shown in Fig. 34.

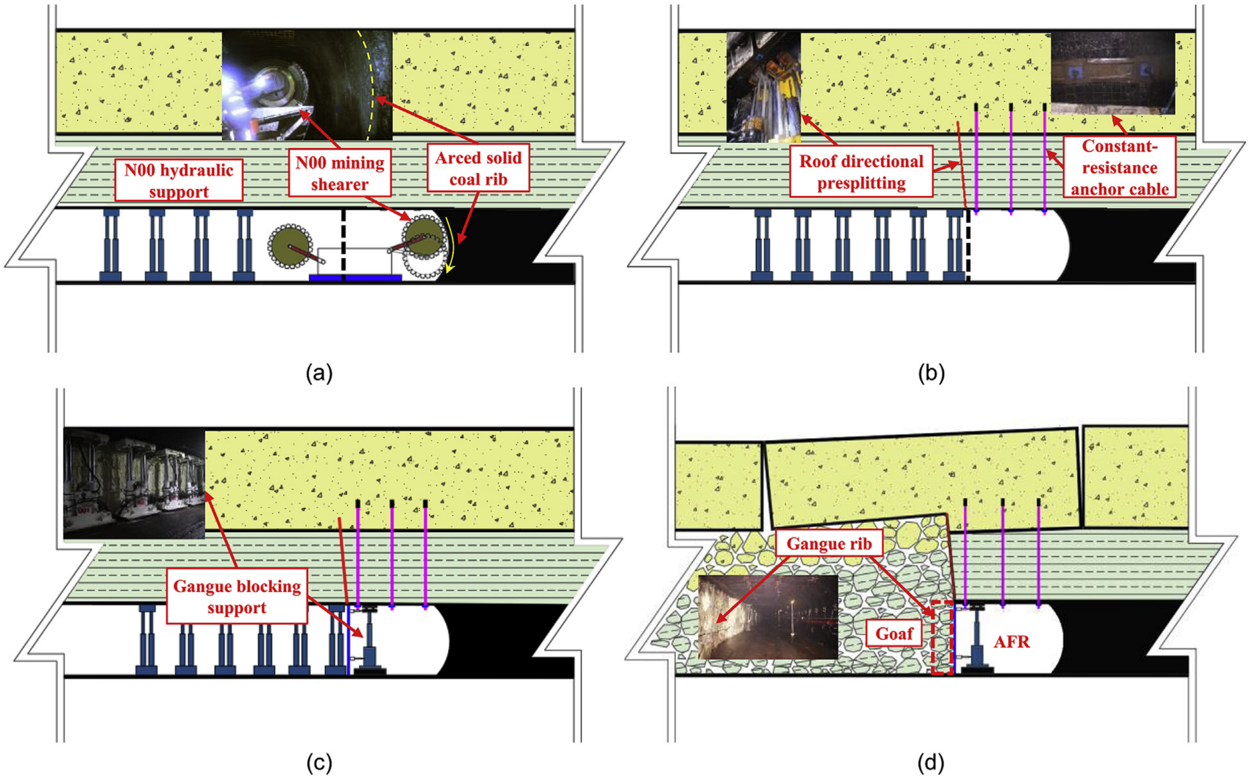


Fig. 35. Technique flowchart of the 1G N00 mining method of the AFR without pillars: (a) Roadway space formed by coal mining; (b) Constant-resistance anchor cable support and roof directional presplitting; (c) Gangue blocking support for roadway; and (d) Forming the gangue rib and AFR.

To meet the requirements of the 1G N00 mining mode, the corresponding functions and procedures of the original equipment are improved according to the technical characteristics of the mining method. The N00 drill support is arranged in the reserved roadway to provide an installation platform and working space for the N00 anchor cable drill and N00 splitting drill. The roof and rib support equipment is arranged along the gob-side of the roadway behind the working face, which can support the roof and gangue rib of the roadway.

Roof directional presplitting and roadway support are carried out by the linkages of the four roadway forming matching equipment systems. The stress transfer effect of the overlying strata on the roadway roof is weakened. The gob roof collapses along the roof cutting surface to form a gangue rib, thus forming a roadway automatically.

6.2.2. Specific technique

The specific technique flowchart of the 1G N00 mining method of the AFR without pillars is shown in Fig. 35 and described as follows:

(1) Combined with the improved scraper, the N00 mining shearer moves past the tail of the scraper and carves out a roadway space when arriving at the position of the reserved roadway. At the same time, the arc-shaped solid coal rib is formed (Fig. 35a).
(2) The matching construction equipment closely follows the working face. When the N00 mining shearer carves out the roadway space, the roadway roof is immediately supported by the constant-resistance anchor cable to keep the roadway roof stable. Meanwhile, the roof directional presplitting of the gob-side roadway roof is carried out (Fig. 35b).
(3) Gangue blocking support is arranged in a timely manner at the gob-side of the reserved roadway. The gangue formed by the collapse of the gob roof strata is gradually compacted and stabilized to form gangue rib under the support effect. When the gangue rib is stable, the shotcreting of closed materials is carried out to prevent air leakage to form a stable AFR structure (Fig. 35c and d).

6.2.3. Typical application

The 1G N00 mining method of the AFR without pillars has been successfully applied in the Ningtiaota coal mine, a shallow mine in western China. The depth of the S1201-II working face ranges from 90 m to 165 m. The dip length of the working face is 280 m, and the strike length is 2344 m. The dip angle is nearly horizontal, with an average thickness of 4.1 m. The immediate roof is siltstone with an average thickness of 2.2 m, and the main roof is medium sandstone with an average thickness of 17.2 m. The immediate floor is siltstone with an average thickness of 16.3 m, and the main floor is fine sandstone with an average thickness of 3.2 m. The geographic location and roadway layout of the coal mine are shown in Fig. 36.

The roadway roof cutting and support parameters of the 1G N00 mining method are shown in Fig. 37 and listed as follows:

(1) Roof cutting parameters: the roof cutting height is 9 m, and the angle is 15°.
(2) Roof support parameters: the roadway roof is supported by the NPR high-prestress constant-resistance anchor cable. The constant-resistance anchor cable parameters are ϕ21.8 mm × 10.5 m.

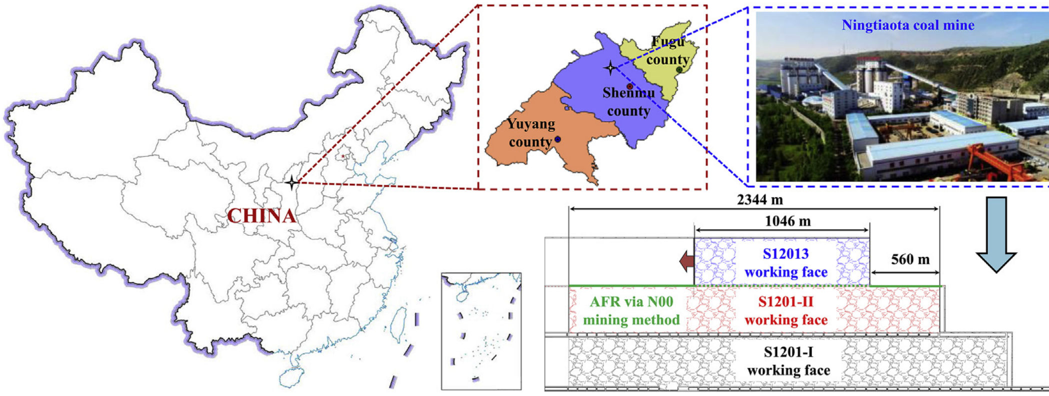


Fig. 36. General situation of the S1201-II working face.

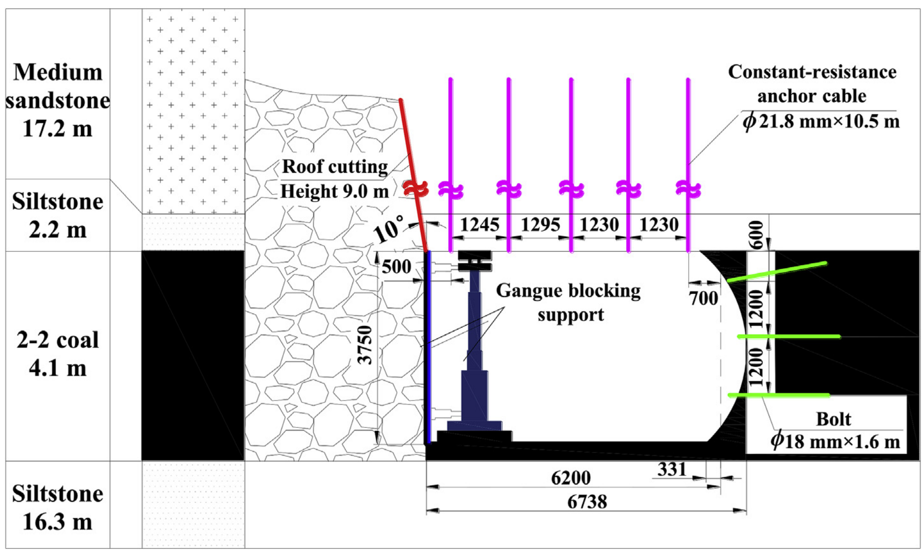


Fig. 37. Parameters of roadway roof cutting and support of the 1G N00 mining method (unit: mm) (He and Wang, 2016).

(3) Gangue blocking support parameters: the gob-side gangue rib support is provided by the roof and rib support equipment, retractable U-steel and gangue blocking mesh.

Combined with the field application effect of the 1G N00 mining method at the stages of roadway formation and reuse, it can be seen that the integrated mining mode of coal mining and roadway retaining is formed, which realizes roadway automatic forming and coal mining without pillars. This mining method effectively controls surrounding rocks of roadway, meeting the engineering requirements, as shown in Fig. 38.

The successful application of the 1G N00 mining method verifies the "equilibrium mining" theory using "utilization of two aspects and elimination of two aspects" concept with an integrated mode of coal mining and roadway retaining. The mining mode and technique of no coal pillar reserve and no roadway excavation are formed to ensure the safe and efficient mining of the working face, laying the foundations for intelligent and unmanned mining.

7. Conclusions and future prospects

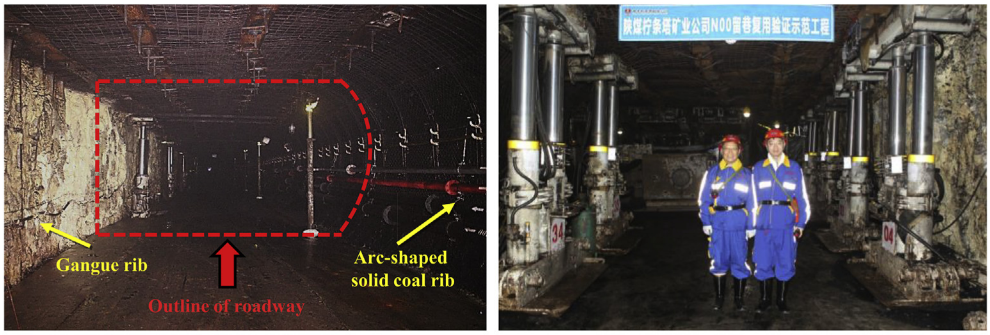
(1) Under the guidance of mining rock mechanics, the "short cantilever beam" model is established, and "equilibrium mining" theory is proposed. The equilibrium between the mining volume and broken expansion volume of the collapsed roof rock mass is realized, and a solution from the mining damage invariant equation is obtained, laying the theoretical foundation for the new coal mining methods.

(2) Based on "equilibrium mining" theory, a series of key technologies of the AFR without pillars is developed, and the 110 and N00 mining methods are formed. The integrated mining mode of coal mining and roadway retaining with no coal pillar reserve and no roadway excavation is formed.

(3) In view of the complex geological conditions and intelligent mining demand of coal mines, the concepts of the 2G–4G N00 mining method of the AFR without pillars are proposed based on the successful application of 110 and 1G N00 mining methods. These methods are expected to achieve the goal of the mining method of the AFR from no roadway excavation and no coal pillar reserve to intelligent and unmanned mining.

(4) The mechanical parameters of rock mass used in the "equilibrium mining" theory are the basis of calculation and design. The intelligent in situ test and real-time evaluation method should be established in the future to accurately measure the key mechanics parameters of rock mass. It is necessary to build an engineering database under various geological conditions, such as different rock mass properties and in situ stress levels, so as to improve the established theoretical calculation model.

(5) The dynamic disasters of deep mines can be effectively controlled by equilibrium mining. The mining rock mechanics



(a) (b)

Fig. 38. Field application of the 1G N00 mining method: (a) Roadway formation stage (He and Wang, 2016), and (b) Roadway reuse stage (He and Wang, 2019).

should be used to study the dynamic disaster mechanism in the future. On this basis, the surrounding rock strength and energy support design method under the "equilibrium mining" theory should be established, which could provide scientific guidance for the safety control of deep mines.

(6) The "equilibrium mining" theory and related technologies will be developed for different fields of mining industries in the future. The complete construction evaluation system and the corresponding engineering standards of different fields of mining industries should be established, which will promote the new mining technologies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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