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ORIGINAL PAPER

Coal mining method with near-zero impact on the ecological environment in a high-intensity mining area of Northwest China

Erhu Bai[1,2,3] · Wenbing Guo[1,2,3] · Hebing Zhang[4] · Yi Tan[1,2,5] · Zhibao Ma[1] · Dongtao Wu[1] · Mingjie Guo[1] · Peng Wen[1]

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Abstract
In order to avoid the destruction of underground aquifers in the eco-environment frangible area caused by the exploitation of coal resources, a new coal mining method with near-zero impact on aquifers (MNIA) was proposed according to the advantages of strip mining and backfill mining methods to effectively control overburden, which is coordinated with the eco-environment. First, the ecological fragile status of the high-intensity mining area is studied. This is followed by the basic principle, technical steps, and its characteristics and advantages of MNIA. Combined with specific mining conditions, theoretical analysis and physical simulation are adopted. Then, the determination principle of strip mining parameters, filling width along the strip coal pillar, width of the narrow pillar in the recovery strip residual pillar and filling rate are given. The MNIA is more effective in thin- and medium-thick coal seams. Based on the long-term stability evaluation method of the strip pillar, it is determined that the narrow coal pillar and backfill body have long-term stability. In addition, the development and utilization of the underground space is proposed, which provides a new solution for the in situ protection of aquifers, effective utilization of underground space, and coordinated development of ecological environment and coal resource exploitation in the eco-environment frangible area.

Keywords Aquifers · Eco-environment frangible area · Environment protection · Near-zero impact · Underground space

Introduction

Water is the basis for human survival and development and is of great significance to the ecosystem (Zhang and Anadon 2014; Sotomayor et al. 2018). In general, the ecosystem is in a relatively stable dynamic equilibrium state. Once broken, it will make corresponding "expressions," such as smile (to benefit or improve the ecological environment), or anger (to harm or destroy it). The ecosystem expression for coal mining belongs to the latter. During the process of coal exploitation, the mining driving force breaks the original balance of the overlying strata, and the overburden breaks and forms fissures, which leads to the formation of cracks, nutrient loss, and biodiversity reduction in the pedosphere (Hu et al. 2010, 2016; Yang et al. 2016a, b; Zhang et al. 2016a, b; Sun et al. 2017). Because the hydrosphere is mainly dependent on the lithosphere and pedosphere, the mining driving force not only affects the surface water system of the mining area, but also causes serious damage to the groundwater resources, increasing the probability of water inrush in the mine, especially in the Northwest mining area of China, and aggravates the fragile ecological environment (Zhang and Peng 2005; Sui et al. 2011; Zhang et al. 2015a, b; Yang et al. 2016a, b; Wang et al. 2019), as shown in Fig. 1. Therefore, it is imperative to study a water-preserved mining method in China's Northwestern eco-environment frangible area.

In recent years, with the strategic adjustment of coal resources, the Northwestern high-intensity mining area has

✉ Yi Tan
tanyi@hpu.edu.cn

1 School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan, China

2 Henan Key Laboratory for Green and Efficient Mining & Comprehensive Utilization of Mineral Resources, Henan Polytechnic University, Jiaozuo 454003, China

3 State Collaborative Innovation Center of Coal Work Safety and Clean-Efficiency Utilization, Jiaozuo, Henan, China

4 School of Surveying and Land Information Engineering, Henan Polytechnic University, Jiaozuo, Henan, China

5 Department of Mining Engineering, West Virginia University, WV 26506 Morgantown, USA

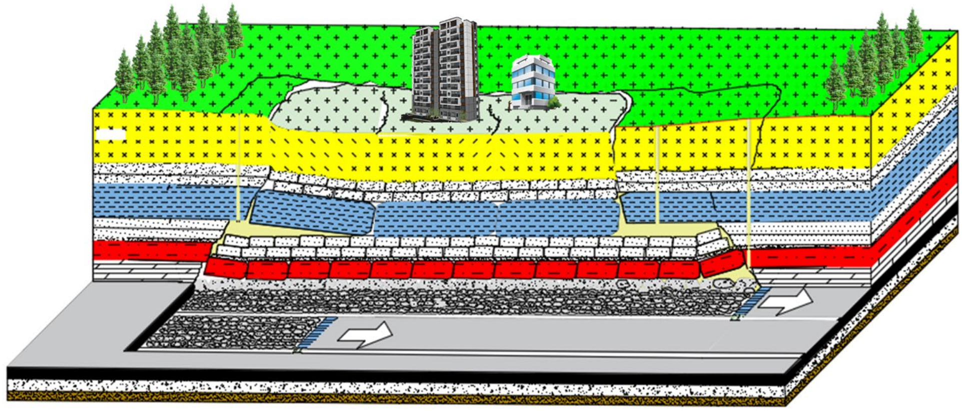


Fig. 1 Schematic diagram of the mining impact on the eco-environment in a high-intensity mining area

become China's main coal supply base (in 2017, the coal output of Shanxi, Shaanxi, and Inner Mongolia accounted for 66.82% of the country's total) (Guo et al. 2018). Meanwhile, with the acceleration of ecosystem protection proposed in the 19th National Congress and scholarly attention to geological hazards in high-intensity mining areas in Western China, green mining in harmony with the ecological environment has become the current theme (Zhang et al. 2009; Bai et al. 2017; Liu et al. 2017). In order to perform safe mining under aquifers and to protect groundwater and the ecological environment, Zhang et al. (2011) pointed out that the main task of scientific development of coal resources in Western China is to transform passive recovery into active protection. Fan and Ma (2018) proposed a new definition of water-preserved mining to protect the environment and summarized its latest progress and existing scientific problems at different stages in ecologically fragile mining areas in Western China. Ma et al. (2013) the water-preserved mining technology of longwall mining by speeding the face advance rate, which has been successfully applied. Ning et al. (2015) constructed the evaluation model of water-preserved mining in a shallow coal seam with a sandy mudstone roof and proposed its evaluation method. By studying the structural stability of the main key strata, Wang et al. (2012) suggested control measures to prevent the structural sliding and instability of the main key strata in order to achieve water retention. Meanwhile, with the concept of active aquifer protection gaining popularity, backfill mining has become an effective method for safe mining under aquifers to reduce the development height of the water flowing fracture zone (Sui et al. 2015; Zhang et al. 2015a, b; Zhou et al. 2016; Zhu et al. 2017; Bai et al. 2018a; Sun et al. 2018). In fact, many mining areas have successfully applied backfill mining technology to protect the aquifers, achieving the win–win goal of coal mining and water conservation.

The above research not only provides the theoretical basis and technical methods for green mining in fragile ecological environments, but also promotes the development of water-preserved mining technology. However, fundamentally speaking, although mining safety is guaranteed by reducing the disturbance to an aquifer, it does not really protect the aquifer structure. In addition, shut-down coalmines after coal resources depletion will result in a huge waste of underground space, while the value of fixed assets, such as some equipment and pipeline facilities, will suddenly become zero. Therefore, based on previous studies, a new mining technology of in situ protection for aquifers with near-zero ecological environment impact is proposed. Combining the advantages of strip mining and backfill mining, the backfilling body is used to reinforce strip pillars during the strip mining, and then the strip pillars are recovered by retaining narrow coal pillars, and finally, the goal of supporting overlying strata and roof stability by backfilling and narrow coal pillars is achieved. Moreover, the underground space should be planned reasonably so as to facilitate the later transformation. In this way, the in situ protection of aquifers is fundamentally realized, which is vital for the sustainable development of the mining industry and economic growth in ecologically fragile areas.

Ecologically fragile status of a high-intensity mining area

The northwestern region of China is an arid and semi-arid, and its eco-environment is fragile due to its low precipitation and high evaporation. Therefore, water resources are particularly important in the ecological environment of Northwest China. For the high-intensity mining area, the response of the ground surface to mining is one of the negative externalities of high-intensity mining, mainly manifested in the discontinuous deformation of the ground surface (surface cracks) and the destruction of the surface buildings (Bai et al. 2019). A tensile downward crack formed on the surface is the main factor reducing the soil moisture and also the essential factor affecting the soil nutrients, microorganisms, plant biomass, and coverage in the mining subsidence area. Therefore, the soil water content in the mining area is used as an indicator of the mining impact on the surface ecological environment.

The geological conditions of the 22407 working face in Halagou coalmine are as follows: the coal seam is 5.4 m thick on average and dips 1–3° with an average buried depth of 136 m. Its immediate roof is siltstone with a thickness of 6.7 m, and the same lithology makes up the immediate floor with a thickness of 5.8 m. According to the definition and distinguishing method of high-intensity mining (Bai et al. 2019), combined with the mining conditions of the 22407 working face, the working face has few geological structures, a large working face size (3224 m long and 284 m wide), fast advanced speed (average 15 m/day), excellent technical equipment level, and high mining efficiency (805.5 t/person), which is in line with the scope of high-intensity mining in geological mining technology. Meanwhile, based on the mining influence of other working faces, the overburden is seriously damaged, and the surface appears to have a serious discontinuous deformation, as shown in Fig. 2. Additionally, the ratio of mining depth to thickness is 12.6, which is in line with the category of mining impact and damage of high-intensity mining. Therefore, the 22407 working face is high-intensity mining working face.

The six soil samples collected from mining subsidence and the unaffected area of the Halagou coalmine were dried using the DHG-9055A dryer in the laboratory. The soil water content data obtained from the test are shown in Fig. 3.

As shown in the above figure, the average soil water content in the unaffected area is 5.02%, and that in the Halagou coalmine is 3.89%, a decrease of 22.51%. Combined with the surface cracks, the data show that the cracks increase the porosity in the soil, accelerate the water evaporation, and reduce the soil moisture content. Therefore, it is necessary to further study the influence of surface downward cracks on soil moisture content.

Combined with the surface topography of the mining area, the soil samples were collected in the gully slope topography and dune topography respectively. The soil samples within 1 m were taken by the soil drill at an interval of 0.1 m and sealed in a special plastic bag. Based on the development of surface cracks on the site, it was divided into large crack areas (1–2 m) and small crack areas (< 0.5 m) according to their length. The depth distribution of soil water content in the crack and non-crack area is shown in Fig. 4.

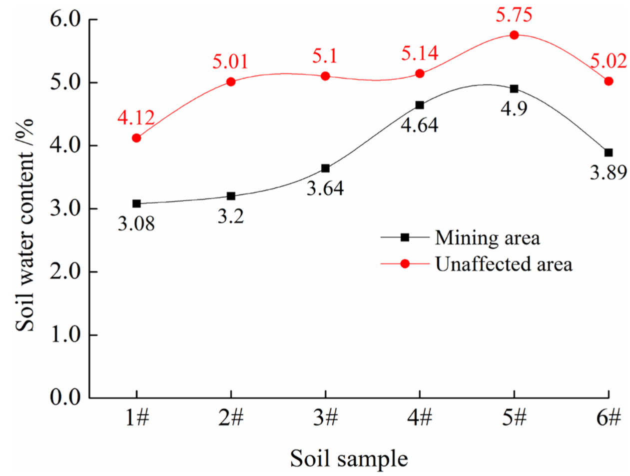


Fig. 3 Soil water content at sampling sites

From Fig. 4a, for the gully slope area, the soil water content in the crack zone is lower than that of the non-crack zone range of 0–1 m. In the range of 0–0.2 m, the soil moisture content in the crack zone is basically the same as that in the non-crack zone; the evaporation depth of soil moisture in this terrain is about 0.2 m. However, in the range of 0.2–1 m, the water content changes significantly, as follows: (1) the soil water content in the non-crack zone presents an "increase–decrease-increase" trend. (2) For 0.2–0.5 m, the water content in the small and large crack zones is basically the same, indicating that the impact of different cracks on the soil water content is basically the same. (3) From 0.5 to 0.9 m, the soil water content in the large crack zone is obviously lower than that in the small crack zone, which is mainly caused by the larger width and depth of the crack

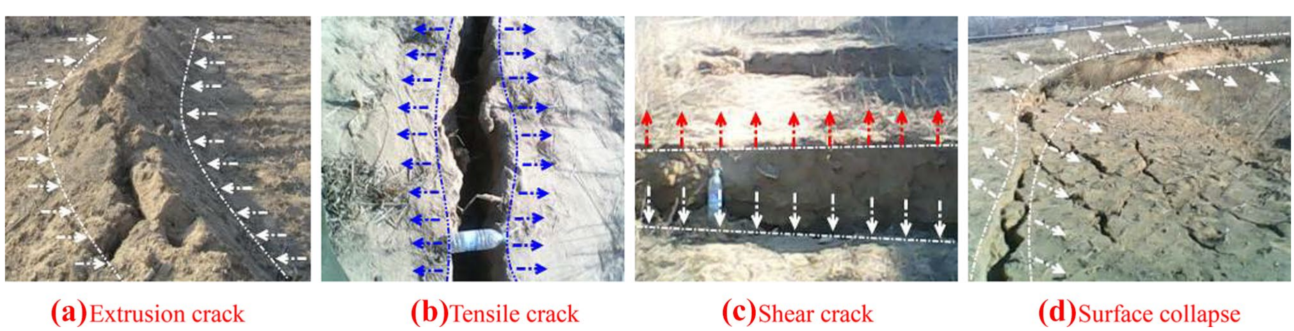


Fig. 2 Classification of surface cracks in the high-intensity mining working face of Halagou coalmine. **a** Extrusion crack. **b** Tensile crack. **c** Shear crack. **d** Surface collapse

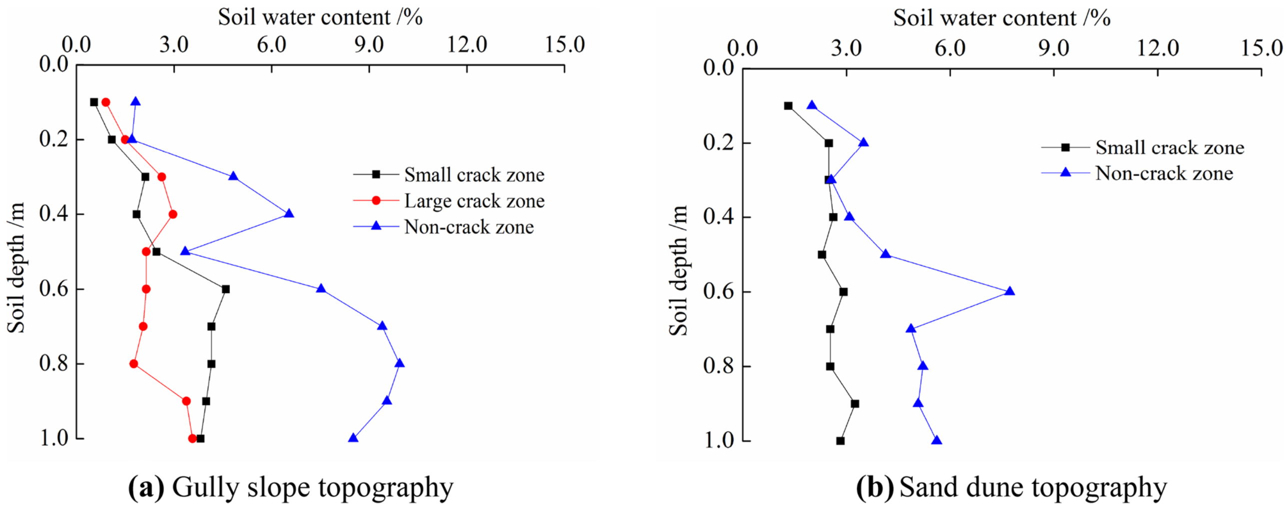


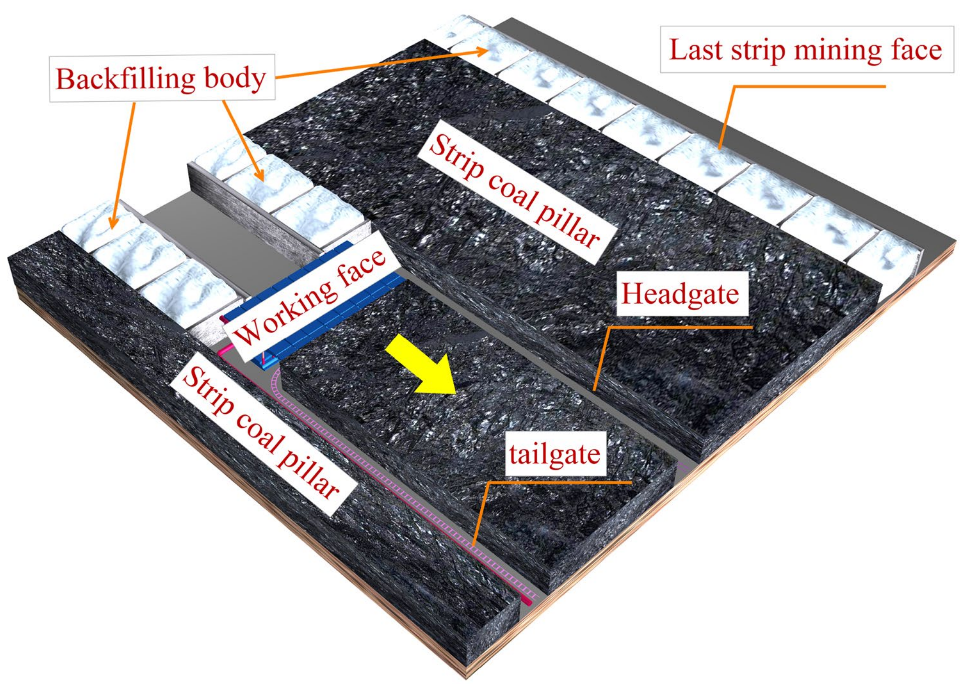
Fig. 4 Depth distribution of soil water content in the crack area. **a** Gully slope topography. **b** Sand dune topography

increasing the water evaporation, indicating that its impact on soil water content is 0.4 m deeper than that in the small crack zone. (4) From 0.9 to 1 m, the soil water content in each crack zone tends to be the same, which indicates that the crack effect on soil moisture content has become weak. At this time, the lower water content is mainly caused by the surface movement and deformation under coal mining, which changes the soil structure and compactness, resulting in water loss.

For the subsidence area under the dune terrain, due to the sand fluidity, sand will automatically fill the surface cracks, resulting in the inability to measure the actual crack length. Therefore, only the small and non-crack zones are compared. From Fig. 4b, the evaporation depth of soil water is about 0.3 m, and the crack influence on soil water content is mainly in range of 0.3–1 m. Its change trend is similar to that of the gully topography.

Based on the above analysis, the surface cracks not only cause water loss by increasing evaporation, but also affect the water retention capacity by changing soil structure and compactness, thereby deteriorating the surface eco-environment. Therefore, in order to prevent the occurrence of surface cracks and protect the eco-environment, an in situ protection technology with near-zero ecological impact is proposed, which

Fig. 5 Strip mining with reinforced strip coal pillars



provides a reference for the in situ protection of aquifers, development and utilization of the underground space, and transformation of mines.

Materials and methods

Mining method with near-zero impact on aquifers (MNIA)

Basic principle and technical steps

In process of coal mining, due to the roof overhanging a large area, the strata collapse when the roof reaches the limit breakage interval. As the mining advances, the breakage process will gradually develop upwards from key strata until it affects the aquifer or develops to the surface, causing damage to the buildings and eco-environment. Therefore, preventing the roof from breaking is the fundamental purpose of the MNIA, which is based on the idea of coordinated mining, subcritical mining, replacement of coal pillars by the backfilling body, and "strip mining roadway backfilling method" mining (Bai et al. 2018b). The methods of reasonable working face size of subcritical mining, reinforcement strip pillar, and backfill mining of the strip residual coal pillar are adopted to control the gob roof and achieve the purpose of the MNIA. Consequently, its basic principle is to control the working face roof integrity of subcritical mining and replace the coal pillars with a backfilling body to maintain the stability of the overlying strata.

Based on the basic principle of the MNIA, the applicable conditions are generally that the roof of a coal seam is sub-key strata, because its limit breakage interval is larger than that of a weak roof, making it easier to achieve efficient coal mining. The technical steps are as follows:

(1) Strip mining with reinforced strip coal pillars: according to the actual geological mining conditions, the strip mining parameters are selected on the premise that the mining width is less than the initial breakage interval of the roof. When strip mining is performed, the strip pillars on both sides of the working face are reinforced by the backfilling body. Considering the safety of underground space, the necessary supporting measures can be taken to support the roof, and the coupling support of the strip coal pillar and backfilling body can be constructed to keep the original coal pillar within the core area, ensuring the stability of the overlying strata. The schematic diagram of this step is shown in Fig. 5.
(2) Backfill mining of the residual coal pillar: after completion of step 1, due to the adoption of the backfilling body to reinforce the strip pillars and necessary supporting measures, strip mining has less disturbance to the overburden and only minor roof subsidence. After the reasonable narrow coal pillars are reserved, backfill mining of strip coal pillars can be performed. However, according to actual mining conditions, the filling location and flow rate during backfill mining should be well controlled, so as to improve the filling rate and promote coordinated and orderly progress. In order to ensure the filling effect, the isolation zone can be applied behind

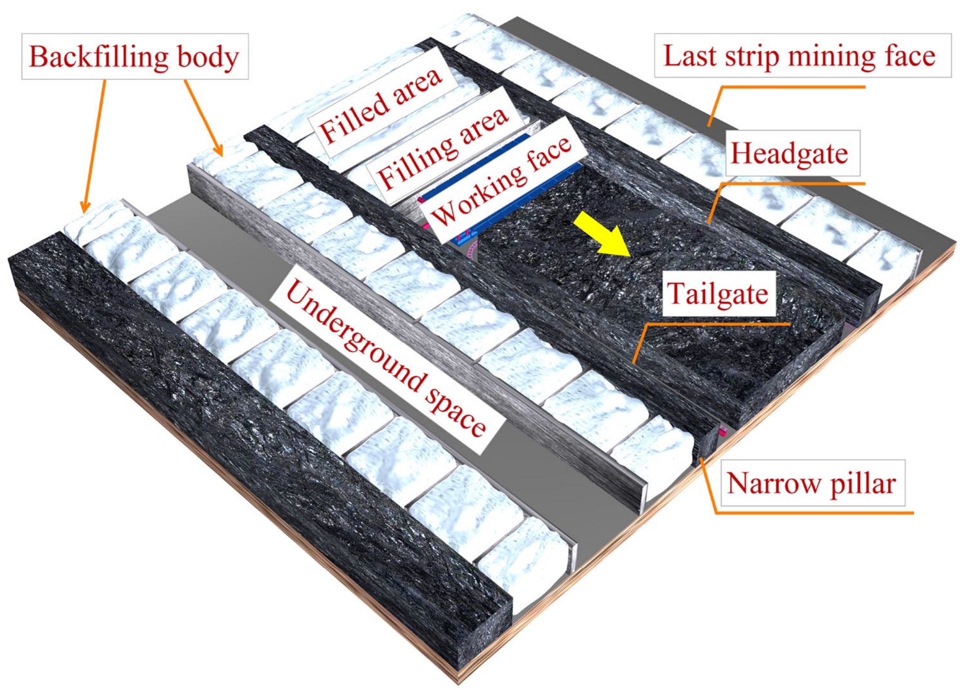


Fig. 6 Strip mining with reinforced strip coal pillars

the working face after advancing a reasonable distance to form the filling space. The solidified backfilling body and the reinforced coal pillars support the overlying strata to prevent large deformation, so as to control the overlying strata, protecting the aquifers and the surface ecological environment in situ. A schematic diagram of this step is shown in Fig. 6.

Characteristics and advantages

Based on the above analysis, the main characteristics of the MNIA are as follows: (1) in situ protection of aquifers, (2) near-zero ecological environment impact, and (3) development and utilization of underground space.

In order to clarify the advantages of the MNIA, it is necessary to compare this technology with strip mining, complete backfilling of the gob, and longwall mining. Table 1 shows the comparison of the different mining methods.

From the comparison and analysis of the recovery ratio of coal mining parameters and the impact on the ecological environment, it can be see that (1) compared with strip mining, the width of the backfilling body and coal pillars is larger than that of the strip coal pillar. Under the condition of guaranteed filling rate, the roof is not broken, achieving aquifer protection. In addition, the recovery ratio is higher than strip mining, and the underground space can be developed and utilized, which is conducive to the later transformation. (2) Compared with complete backfilling of the gob, the MNIA adopts the partial backfilling mode, which reduces the backfilling cost without breaking the roof. Although a small number of coal pillars have been sacrificed, the fragile ecological environment has been effectively protected, and the effective utilization of the underground space has facilitated the later transformation. (3) Compared with longwall mining, the recovery ratio of the MNIA is smaller. However, in the aspect of the eco-environment impact, the MNIA has little disturbance to the overburden and provides conditions for the utilization of the underground space. Therefore, the MNIA is better than longwall mining.

In addition, from the comparison of environmental benefits, the MNIA has characteristics of reducing tailing discharge and aquifer damage after mining, avoiding the surface subsidence, damage to surface buildings and eco-environment, and making full use of underground mining space. Its potential economic benefits are mainly reflected in the saving of environmental costs and the utilization of underground space, which usually cannot be directly expressed as currency. Generally, the benefits can be obtained indirectly by measuring the losses caused by various environmental hazards that are avoided, such as the compensation cost of land resources, natural landscapes or buildings, water resources and the loss of human capital. More importantly, as economics has not yet formed a unified understanding of the irreversible environmental damage caused by coal mining, the environmental cost of the MNIA is underpredicted because this irreversible environmental damage will remain for a long time and constitutes a continuous negative effect on production and life.

In summary, the MNIA is dominant in both recovery ratio and eco-environment protection. It can easily achieve the purpose of protecting the groundwater and surface eco-environment. Furthermore, the development and utilization of the underground space can also provide conditions for the sustainable development and transformation of coalmines.

Strip coal pillar reinforcement and backfill mining technology

Strip coal pillar reinforcement

The key goal of the MNIA is to keep the hard roof from breaking. In strip mining, it uses strip coal pillar as a "pier-like body" to support overburden and prevent the surface from experiencing wavy subsidence. The core zone with large bearing capacity is key to the stability of the strip coal pillars, while the plastic zone formed at the edge of the coal pillars has only a small bearing capacity, which wastes a certain amount of coal resources. Therefore, in order to avoid the waste of coal resources, the method of coal pillar reinforcement is used to make the coal pillars in the core zone.

By filling the reasonable width along the strip pillar, the plastic zone is entirely borne by the backfilling body. At this time, the edge pillar is in a three-dimensional stress state, which indirectly improves the performance of the strip coal

Table 1 Comparison of different mining methods

Mining method	Mining	Environment	Other
Strip mining	Recovery ratio: 40 ~ 60%	Certain influence	Instability of coal pillar will cause serious disaster
Complete backfilling	Recovery ratio: nearly 100%; Higher cost than other methods;	Little influence	/
Longwall mining	Recovery ratio: nearly 100%;	Serious influence	Tension relation between workers and residents
MNIA	Recovery ratio: 80 ~ 90%; Certain backfill cost	Near-zero influence	Development and utilization of underground space

pillar and gives full play to the bearing capacity of the in situ coal pillar (Zhang et al. 2016a, b). When reinforcing strip coal pillars, the overlying strata are jointly supported by coal pillars and props, and the width of the backfilling body along the coal pillars can be determined.

For longwall mining, with the advance of the working face, the main roof breaks into key blocks at the edge of the gob and forms an articulated structure with adjacent blocks. The abutment pressure of the overburden transferred to the coal is divided into two parts according to the fracture line, i.e., internal stress zone between the fracture line and coal, and the external stress zone in the deep region of the fracture line (it becomes the original stress zone beyond a certain point), thereby establishing a broken roof model in the width direction of the working face, as shown in Fig. 7. Therefore, under certain safety factors and supporting overburden with props, it can be considered that the width of the backfilling body determined by the width of the internal stress zone can satisfy the stability of the overlying strata.

For auxiliary support measures, Hancheng Mining Company has solved the surrounding rock control problems of the retained gob-side roadway with a height of 6–7 m, as well as provided effective support equipment for in situ aquifer protection mining in the coal seam below 6 m and the basis for transformation through the reuse of the underground space in the later stage. For deep coal seams, high-intensity concrete with gangue as the aggregate can be used for backfilling material, supplemented by roof bolt and anchor cable support (Xie et al. 2013). For the shallow seam in the western mining area, backfilling with rich aeolian sand as the aggregate can be adopted, and other supporting measures are also needed to ensure safety. That is, its technical principle is valid.

Backfill mining of strip residual coal pillar

The essence of the MNIA is to design strip mining to control the roof integrity. After the first step is completed, due to the strip pillar reinforcement and the gob-side roadway retained support technology being adopted, the backfilling body and strip pillar can effectively maintain the stability of the overlying strata, and the strip pillars are all in the core zone. Then, in order to increase the recovery ratio, it is necessary to recover the strip coal pillar. Considering the roof stability and the development and utilization of the underground space in the later stage of mine transformation, the backfill mining method, which can effectively control the overburden movement and deformation, is selected to recover the residual strip pillars. As there is a certain amount of defective distance of roof-contact, based on the theory of "equivalent mining height" (Guo et al. 2014), the roof will bend and subside to a certain extent. In order to avoid the disturbance caused by step 2 to the adjacent gob, the backfill mining method with retained narrow coal pillars is adopted. Its purpose is to provide partial support for the defective distance of the roof-contact of the backfilling body. For backfill mining, since it weakens the mining effect significantly, the overburden will maintain its internal stress dynamic balance as long as the filling parameters are reasonable. At the same time, it ensures that the roof produces less deflection and does not break.

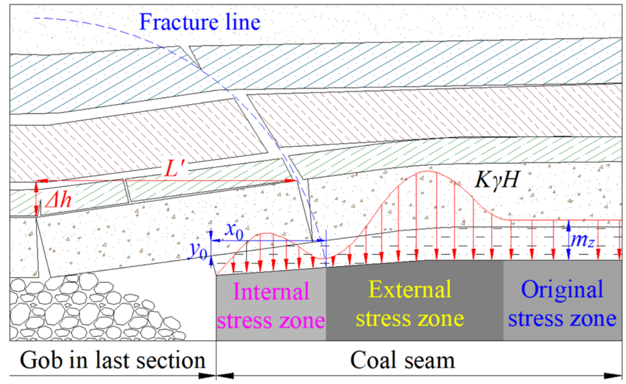


Fig. 7 Breakage model of the immediate roof in longwall mining

According to relevant engineering practice (Bai et al. 2018b), the strength of the paste filling body with aeolian sand is about 5 MPa in general, and it can reach 7 MPa in the later period. Under reasonable filling parameters, it can fill the gob in time. The synergistic action of the panel advancing speed and backfilling body's rapid resistance increase can make the bearing capacity reach the cutting resistance before the roof subsidence and weighting, supporting the overburden in time to avoid breaking or smaller separation, which can also reduce the load on the coal pillar and backfilling body. When the overburden load is lower than the compressive strength of the backfilling body, and the backfilling body achieves its later strength due to its strain strengthening characteristics, it is more conducive to preventing the movement and deformation of the roof strata and can effectively guarantee the stability of the backfilling body and overburden. Therefore, backfill mining of the strip residual coal pillar is theoretically feasible.

Results and discussion

Key parameters of the MNIA

According to the above analysis, the geological condition of the 22407 working face of the Halagou coalmine in the Shendong mining area is taken as an example to analyze the new coal mining method. Based on the near borehole of the 22407 working face, the overburden parameters are shown in Table 2.

Based on the key strata theory, the calculation formula of the loads on the movement combination layer is given in formula (1). If the first layer is the key strata and its control reaches the nth layer, then the $(n+1)$th layer becomes the second key strata, which must agree with the formula (2).

$$(q_n)_1 = \frac{E_1 h_1^3(\gamma_1 h_1 + \gamma_2 h_2 + \cdots + \gamma_n h_n}{E_1 h_1^3 + E_2 h_2^3 + \cdots + E_n h_n^3} \quad (1)$$

$$(q_{n+1})_1 < (q_n)_1 \quad (2)$$

where $(q_n)_1$ is the load imposed by n layers of strata controlled by the first sub-key strata, Pa; E_n is the elastic modulus of the nth layer rock strata, Pa; γ_n is the volumetric weight of the nth layer rock strata, N/m^3; and h_n is the thickness of the nth layer rock strata, m.

Therefore, using key strata discriminant software to analyze the key strata of the overburden, it can be seen that the immediate roof is the sub-key strata ($(q_4)_1 = 262.3$ kPa $< (q_3)_1 = 266.1$ kPa), which meets the applicable conditions of the MNIA. In order to ensure safe implementation, the key parameters need to be determined, which are mainly the strip mining parameters, the filling width along the strip coal pillar, the width of the narrow pillar and the filling rate for the strip residual coal pillar.

Determination of strip mining parameters

In order to ensure that the sub-key strata do not break after strip mining, it is necessary to know its initial breakage interval. According to the observation of ground pressure in longwall mining, the gob roof does not break at a long distance as working face advances from the setup room. In order to prevent damage to equipment and personnel caused by high-pressure wind formed by sudden roof collapse at the limit breakage interval, deep-hole pre-split blasting was used to force roof caving after the working face advances 14 m, and the initial breakage interval could not be measured from underground. Therefore, laboratory simulation is selected to analyze longwall mining, and the periodic weighting interval, surface subsidence, and surface step crack are compared with field measurements (as shown in Fig. 8) to obtain the initial breakage interval of the immediate roof. Considering the safety of the underground space in the later stage, the parameters of strip mining are determined based on smaller values by comparing the obtained step distance from the key strata theory.

As shown in the above figure, the measured periodic weighting interval is 7.4–12.9 m; the maximum surface subsidence is 3.35 m, accompanied by a step crack of 0.2 m. The physical simulation values are basically the same as the measured. Therefore, the initial breakage interval of the immediate roof obtained by the physical simulation basically reflects the actual situation.

Based on the key strata theory, there are five key strata in the overlying strata, among which the immediate roof of the coal seam is the first sub-key stratum, and its initial breakage interval is 28.2 m. In order to reduce the uncertainty of the actual strata and improve the safety of the later stage, the strip mining width is determined to be 25 m with the limit of the initial breakage interval. According to the design principle of strip mining parameters and the safety of recovering residual coal pillars, the width of the strip coal pillar is determined to be 30 m. At this time, the safety factor of the coal pillars is 2.06, and the ratio of coal pillar core zone is 75.9%. Due to the reinforcement and support measures taken near the coal pillar, the determined strip mining parameters meet the requirements.

Determination of filling width along the coal pillar

Generally speaking, the smaller the suspended area of the immediate roof is, the stronger the stability of overlying strata. Although the strip mining parameters determined can

Table 2 The mechanical parameters of some overlying strata above the coal seam

No	Lithology	Thickness (m)	Density (kN/m^3)	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)	Poisson's ratio
7	Siltstone	6.87	24.6	40.6	2.3	35	0.25
6	Fine sandstone	3.64	25.0	44.6	2.8	32	0.28
5	Medium sandstone	4.42	23.9	45.3	2.5	33	0.25
4	Fine sandstone	5.66	25.0	44.6	2.8	32	0.28
3	sandy mudstone	3.29	22.5	22.8	3.53	23	0.28
2	Medium sandstone	2.84	23.9	45.3	2.5	33	0.25
1	Siltstone	6.68	24.6	40.6	2.3	35	0.25
0	Coal seam	5.40	14.3	10.5	0.6	15	0.35

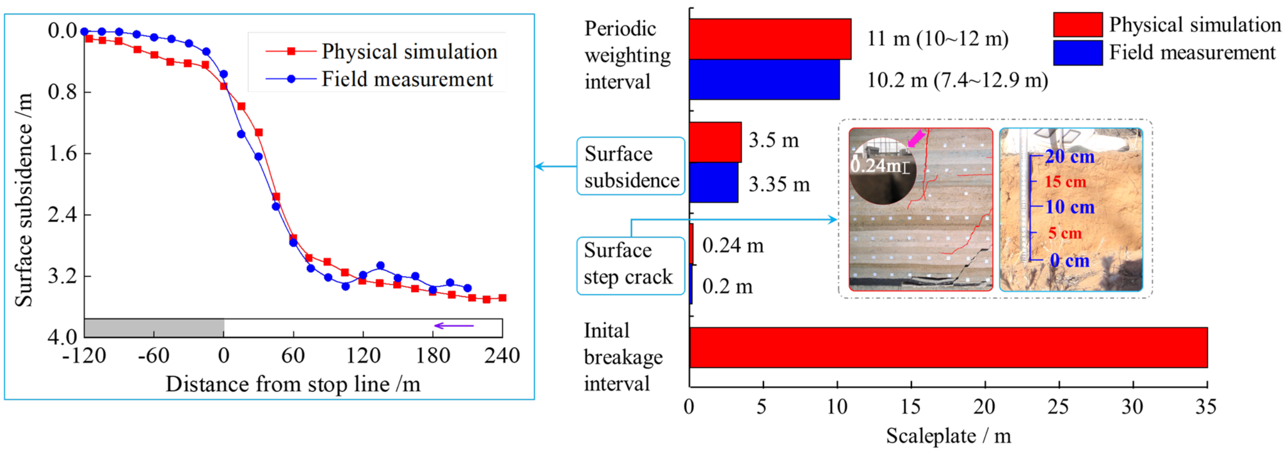


Fig. 8 Comparison of similar simulation and field measured parameters

ensure the stability of the overlying strata, considering the long-term safety, a backfilling body of reasonable width can be filled along the coal pillar to ensure that the coal pillar is within the scope of the core zone. Then, it is necessary to determine the filling width along the coal pillar.

According to the strip coal pillars reinforcement and Fig. 7 above, in the direction from the gob to the coal pillar, the stiffness of the coal pillar increases gradually and its compression decreases gradually as the stress state of coal pillar changes from two-dimensional to three-dimensional. For the convenience of calculation, the stiffness and compression of the coal pillars are regarded as linear changes. Combining the theory of internal and external stress zones and geometric similarities, the range of the internal stress zone could be obtained by the following formula:

$$\frac{Gx^2h}{6l} = WLm\gamma \tag{3}$$

where G is the maximum coal stiffness in the internal stress zone, Pa; x is the range of internal stress zone, m; h is the thickness of the coal seam, m; l is the suspension span of the rock beam, approximately equal to the periodic weighting interval of the longwall mining face, m; W is the length of the working face, m; L is the first roof weighting interval of the adjacent working face, m; and m and γ are the main roof strata thickness and bulk density, respectively.

According to inclusion theory, the expression of coal stiffness G in the plastic state is (Song et al. 2000):

$$G = \frac{E}{[2(1+v)\varphi]} \tag{4}$$

where E is the elastic modulus of coal, Pa; ν is Poisson's ratio; and φ is the influence coefficient, which is related to the development of fissures in coal.

Therefore, the distribution range of internal stress field can be obtained by simultaneous two formulas above.

$$x = \sqrt{\frac{12WLlm\gamma\varphi(1+v)}{Eh}} \tag{5}$$

Combining the geological conditions, theoretical analysis, laboratory tests, and field measurements of the 22407 working face, the parameters are as follows: $W = 284.3$ m, $m = 6.7$ m, $h = 5.4$ m, $\gamma = 25$ kN/m^3, $E = 1.5$ GPa, $\nu = 0.35$; $L = 28.2$ m, $l = 7.4$–12.9 m, $\varphi = 0.8$. The range of internal stress zone is 3.99–5.26 m by substituting the parameters into the formula above; i.e., the position of the immediate roof broken is 3.99–5.26 m away from the coal pillar.

Considering that the overlying strata in strip mining have not collapsed, the range of the stress-concentration area will increase correspondingly, and the revised plastic range is $Y = 0.0057Hh = 4.193$ m. However, as the microstructure of the backfilling material is condensed to form a compact backfilling body, the compressive strength will gradually increase. In order to ensure that the coal pillar is in the core zone, the filling width is determined by the range of the internal stress zone with a safety factor of 1.5 times, i.e., 5.99–7.89 m. Overall, the filling width is determined to be 8 m. It not only satisfies that part of the filling body is within the scope of the strip mining core area but also further ensures the stability of the overlying strata.

Determination of narrow pillar width

Due to the influence of the filling rate, it is necessary to retain narrow pillars to support the overburden when mining strip residual pillars. In order to maintain the stability of the overlying strata effectively in the early stage of the narrow coal pillars, bolt support can be used when the strip coal pillars are recovered. Therefore, the narrow coal pillar width can be determined as shown in Fig. 9.

As can be seen from the above figure, the narrow coal pillar width consists of three parts; namely, the support width W_1 is 1.6 m; W_2 is the stable width of the narrow coal pillar, which is usually 0.4 times of the sum of the other two parameters; and W_3 is the width of the plastic zone formed by the stress change at the junction of the backfilling body and coal pillar, and its calculation is as follows:

$$W_3 = \frac{Ah}{2\ \tan_{\varphi 0}} In\left(\frac{\frac{C_0}{\tan_{\varphi 0}} + K\gamma H}{\frac{C_0}{\tan_{\varphi 0}} + \frac{P_x}{A}} \right) \quad (6)$$

where h is the coal seam thickness, 5.4 m; φ_0 is the internal friction angle, 24.5°; C_0 is the cohesive force, 2.3 MPa; γ is the rock bulk density, 25 kN/m^3; H is the buried depth, 136 m; K is the stress concentration factor, 2.2; A is the lateral pressure coefficient, $A = \nu/(1-\nu)$, ν is 0.35; and P_x is the support strength of the backfilling body, 5 MPa.

Then, it can be obtained that $W_3 = -0.43$ m by substituting parameters into formula 6. From the negative number of W_3, the backfilling body plays a supporting role in the overlying strata at the junction of the coal pillar and the filling, and there is no plastic zone in the strip coal pillar. Therefore, the narrow coal pillar width W_0 is 2.24 m. In order to ensure the supporting effect of the bolts and the stability of the coal pillar, the narrow coal pillar width on both sides is 2.5 m when the strip residual coal pillars are recovered.

Determination of filling rate

In the process of recovering the strip residual coal pillars, the strength and filling rate of the backfilling body are the most important factors for maintaining the stability of the immediate roof effectively. For the strength of the backfilling body, according to the mechanical parameters of the strata above the working face, the load of the overlying strata is 3.27 MPa, while the compressive strength of the paste backfilling body is usually 5 MPa, and the later strength will be greater. It is only necessary to coordinate the advance speed of the working face and the curing time of the backfilling body. Therefore, the strength of the backfilling body is able to support the overlying strata. The filling rate is a reflection of the actual filling in the gob, which is directly related to the support effect on the immediate roof. For the stope with the same conditions, the higher the filling rate is, the thinner the coal seam, and the smaller the free space of the immediate roof is, the better the effect on controlling the stability of the overburden. If the filling rate is low, the stress redistribution in the overburden caused by the immediate roof collapses may seriously affect the stability of the last gob, threatening the successful implementation of the MNIA and safety of the utilization of the underground space. Therefore, it is necessary to determine the filling rate of the backfill mining.

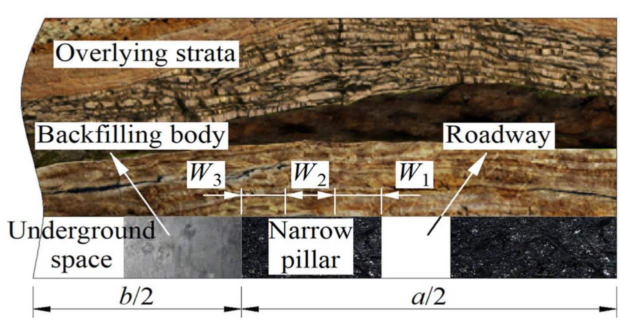


Fig. 9 Schematic diagram for calculating the narrow pillar width

Based on the definition of limited thickness mining, in order to ensure that the immediate roof does not break, it can be assumed that its maximum allowed horizontal deformation is the same as that of buildings, and the equivalent mining depth is the sum of the roof strata thickness and the coal seam thickness. Therefore, it can be concluded that the formula of the filling rate when the immediate roof is unbroken is as follows.

$$\eta \geq 1 = \frac{[\varepsilon]H'}{1.52hbq \tan\beta \cos\alpha} \quad (7)$$

where η is the filling rate; h is the thickness of the coal seam, 5.4 m; H' is the equivalent mining depth of the coal seam, 12.1 m; $[\varepsilon]$ is the maximum allowable horizontal deformation value of the immediate roof, 2 mm/m; b is the horizontal movement coefficient, 0.25; q is the subsidence factor, 0.1; tanβ is the tangent of the major influence angle, 1.8; and α is the coal seam dip, 3°.

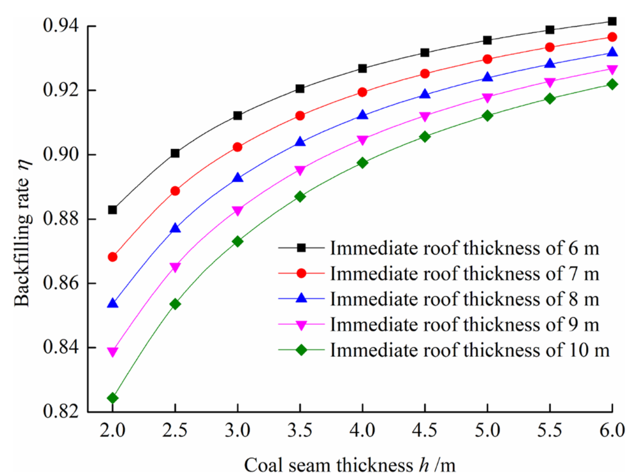


Fig. 10 Relationship of high-intensity mining characteristics

From the above parameters, it can be concluded that $\eta \geq 0.93$. The smaller the thickness of the coal seam and the larger the thickness of the immediate roof are, the lower the filling rate will be. Meanwhile, the sensitivity of the coal seam thickness to filling rate is greater than that of the immediate roof thickness, as shown in Fig. 10. Therefore, in backfill mining, it is easier to achieve the ideal effect for thin- and medium-thick coal seams under the same conditions. In order to control the roof deflection better, the filling rate should be increased as much as possible. The filling port can be selected on the high side of the terrain, or segment filling measures can be taken.

Long-term stability analysis of coal pillar and utilization of underground space

Theoretical analysis of long-term stability of coal pillars

In strip mining, in order to avoid the instability of coal pillars due to the effective size reduction and stability reduction caused by the overburden load and weathering, a paste material with better compactness is used to fill along the strip pillars. With the development, utilization, support, and timely maintenance of the gob in the later stage, no stripping phenomenon occurs in the backfilling body.

According to relevant research (Yu et al. 2017), the stripping phenomenon of the strip coal pillar is caused by other factors when strip mining is performed. The long-term safety factor of the coal pillar after stripping is only related to its initial safety factor, width-height ratio and stripping angle, as shown in formula 8.

$$F_1 = F_0 \frac{R_p - 2\tan\alpha}{R_p} \tag{8}$$

where F_1 is the safety factor of the coal pillar after stripping; R_p is the width-height ratio of the coal pillar; tanα is the tangent of the stripping angle of the coal pillar, that is, the ratio of the stripping width of the coal pillar to its height. Usually, the stripping angle is less than the repose angle and F_0 is the safety factor of the coal pillar before stripping.

After the completion of the MNIA, the long-term safety factor of the coal pillar is calculated according to the most unsafe consideration that the full stripping of the backfilling body, and $R_p = 6.48$, $\alpha = 35°$, and $F_0 = 2.06$ are substituted into formula 6. As can be observed, the safety factor of the coal pillar after stripping F_1 is 1.62, larger than 1.5. The coal pillar has long-term stability even when the backfilling body is stripped completely.

As the width of the backfilling body beside the coal pillar is 8 m and the height of the coal pillar is 5.4 m, the stripping angle is 56° for all stripping of the backfilling body. However, the repose angle of coal is generally 30°–45°. For natural stripping, the stripping angle is less than the repose angle. Then, the backfilling body will not be stripped completely; i.e., the stability of the coal pillar can meet the requirements under the most unfavorable assumptions mentioned above. In addition, with the development and utilization of the underground space in the later stage, its auxiliary support and maintenance can restrain the occurrence of the stripping phenomenon to a certain extent, so that the backfilling body can support the overburden more effectively. Therefore, the narrow coal pillars and backfilling body have long-term stability, and the underground space can be developed and utilized to facilitate the later transformation of the coalmines.

Development and utilization of underground space

With the development of the social economy, the transformation and upgrading of traditional industries, and the closure of a large number of coalmines due to capacity removal, the development and utilization of the underground space has received more and more attention (Liu and Li 2017). With the normalization of the development of subway and submarine tunnels and the application of tunnel boring machine in coalmine excavation, the underground space can also be further developed and utilized. The stability of the surrounding rock should be considered first in the development and utilization of the underground space in coalmines. It is the primary condition for planning and constructing underground buildings. Through short-term or long-term production planning, the rational utilization of the underground space can change it from wasteful to active scientific, comprehensive, and informational utilization, achieving the sustainable development of coalmines.

In the MNIA, the immediate roof only appears to be slightly subsided and unbroken after the exploitation of coal resources, and the backfilling body and coal pillar can effectively support the overburden, which is equivalent to strip mining with a mining width of 9 m and pillar width of 46 m. In the later application process, the corresponding parameters can be optimized to better utilize the underground space. Considering the surrounding conditions and coal seam thickness, the development and utilization of the underground space in a coalmine can be designed by the underground real estate industry, geological and mineral museums, underground agriculture or underground mine parks, etc. in accordance with the principle of synergy between underground space and ground resources, people-oriented safety and elastic design concept, such as Kailuan National Mine Park, the underground exploration scenic spot of Jinhuagong Mine in Datong city and mushroom cultivation in Zhangcun coalmine, etc. In addition, according to the analysis of the present situation and available space of Jingxi coalmine, Xie et al. (2018) have proposed a construction scheme of a high-tech research and development base by using an underground space that integrates teaching and scientific research, engineering experimentation, training, storage, tourism, recuperation, and entertainment, providing a demonstration and reference for the development and utilization of underground spaces in coalmines in China.

Conclusions

(1) In order to protect the underground aquifers without affecting the recovery of coal resources, an in situ aquifer protection technology for shallow buried coal seams in the Northwest mining area is proposed, which is coordinated with the ecological environment. Meanwhile, its basic principles and technical steps are expounded, and its characteristics and advantages are analyzed.

(2) Through the analysis of key parameters of in situ aquifer protection technology, the strip mining parameters and the filling width beside the strip pillar are determined. In strip coal pillars recovery, the theory of strip mining and limited thickness mining is used to determine the narrow coal pillar width and the minimum filling rate without breaking the roof. This technology has a better application effect in thin- and medium-thick coal seams.

(3) Considering the long-term stability of coal pillars, the stability of the underground space is analyzed based on strip mining theory and the long-term stability evaluation method, and the long-term stability of narrow coal pillars and a backfilling body is obtained. On this basis, the development and utilization planning direction of the underground space is proposed preliminarily to achieve the purpose of in situ protection of aquifers in the western area and the effective utilization of the underground space.

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Declarations

Conflict of interest The authors declare no competing interests.

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