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TECHNICAL COMMUNICATION

Key Aquiclude Strata Reconstruction and Fluid–Solid Coupled Deformation Mechanism Study for Backfill Coal Mining

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Abstract

Safety assessments of conventional coal mining under aquifers mainly use the height of the water-conducting zone (HWCZ) above the mining panel as the empirical safety criterion. However, this criterion alone fails to account for mining-induced permeability and porosity variations of key aquiclude strata (KAS) in backfill mining. Backfilling can compact and close developed fractures in the KAS, making it less permeable. In this paper, based on an analysis of KAS's regional geological and hydrogeological patterns, new concepts and methods of KAS reconstruction by backfill mining technology are introduced to provide safe mining of coal resources and protect water resources. The nature, reconstruction techniques, primary mode, and principle of KAS reconstruction by backfill mining are discussed in detail. The coupling deformation mechanism of single KAS and composite layered KAS in backfill mining are theoretically analyzed and numerically simulated. The results will aid theoretical analysis of safe coal mining design and water protection under surface water bodies and aquifers.

Keywords Backfill mining · Key aquiclude strata · Reconstruction method · Seepage and water inrush · Water protection

Introduction

Nearly half of China's principal coal mines (47.5%) are threatened by surface and underground water sources and water accumulation in the goaf (Li 2018; Meng et al. 2009). The main techniques used in such mining areas to maintain rock integrity and limit water inrush risk involve large coal pillars, strip mining, limited thickness mining, and drainage or depressurization. However, these all waste large amounts of coal and water resources. In the Shanxi Province of China, the area impacted by coal mining in 2013 has reached over 1150 km^2, with poor water management resulting in surface vegetation destruction, aquifer water level decline, ground collapse, landslides, debris flows, and other geological disasters. According to available statistical data, the annual water inflow of mines in western China is about 1.4 billion m^3; less than 40% of this water is treated and less than 15% utilized (Liu and Ren et al. 2009). In addition to poor water resource management, coal mining under aquifers can cause water inrush disasters. In the past 20 years, there have been more than 800 mine water disasters, with a toll of more than 4000 deaths (Huang et al. 2016). Another side-effect is the accumulation of coal gangue in surface waste dumps. Coal gangue, a significant waste product of coal processing and washing, accounts for about 10 ~ 25% of raw coal production (Wang et al. 2012). Over 50 billion t of coal gangue has accumulated in about 2600 gangue dumps in China: the dumps cover an area of 15,000 hm^2 with an annual growth rate of about 3.0 ~ 3.5 billion t/a. About 70% of the coal gangue can be reprocessed for power generation or other purposes (Yang 2015). Thus, better mining methods for areas with aquifers can improve the recovery rate of coal resources, reduce gangue tonnage, and protect water resources.

In this respect, fully mechanized solid backfill mining (SBM) technology is increasingly being used in coal mining areas under large rivers and aquifers in China. Theoretical research and field measurement results show that backfilling protects the surrounding rock, thus suppressing the height of the water-conducting zone (HWCZ) in the overlying strata. Rock fractures in the surrounding rock become compacted

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and closed, reducing the risk of water inrush at the backfilled mining face. SBM also improves the recovery rate of coal resources and enhances the protection of water resources. SBM technology combines water conservation mining with groundwater environmental protection and restoration.

Studies conducted on controlling HWCZ development in overlying strata to protect water resources (Li 2013; Wang et al. 2013) have indicated that the maximum HWCZ should not reach overlying aquifers or water bodies, thus creating a criterion for protecting aquifers and water bodies. However, other researchers (Huang et al. 2010; Qu et al. 2014) have shown that fractures in many aquicludes (Quaternary clay, mudstone, soft rock, etc.) that act as key aquiclude strata (KAS) can be repaired. Even after damage to rock structure, mining-induced fractures can often be easily compacted and closed by the coupled interaction of pressure and stresses. If no water inrush passage is formed, the aquifer system will remain stable.

In SBM, backfilling the void with densely compacted waste can effectively support the overlying strata load, weaken the development of HWCZ fracture channels, and promote fracture repair in the surrounding rock environment. Given the evolution of mining fractures, the KAS system can become a time-varying non-linear seepage system under the combined action of seepage and stress fields. Whether or not seepage instability occurs after compaction, system stability needs further in-depth analysis and verification; we cannot rely on HWCZ development as a robust and accurate field evaluation index during SBM. However, there is little research on backfill mining with KAS as the control object. To the best of the authors' knowledge, no comprehensive study on the mechanism of non-linear seepage and KAS stability in backfill mining has yet been done.

Therefore, this study used backfill mining as the technical method and KAS as the primary research object. The concepts and methods of KAS reconstruction by backfill mining technology are put forward for the safe mining of coal resources and water resources protection. The coupled deformation mechanism of KAS in backfill mining is explored by theoretical analysis and numerical simulation. The research results provide a theoretical basis for the robust and accurate evaluation of safe coal mining under surface water bodies and aquifers.

Strata Movement Control Theory in Solid Backfill Mining with Water Protection

Current SBM research efforts are mainly guided by the theory of "equivalent mining height", which relies on HWCZ development as the basic control index, without considering formation fractures, water inrush channels, or the effects of the water-resistance of the rock strata and fluid-solid coupling. Based on the seepage aspect of the mining rock mass and the key strata theory in ground control, the KAS principle was formulated for use in the design of water-preserved mining technology at the beginning of the century who also described a mechanical model of KAS (Miao et al. 2008). According to the structural characteristics of the coal seam and overlying strata, KAS are subdivided into three categories, namely: (i) thick-soft KAS, (ii) structural hard rocks, and (iii) soft-hard composite KAS (Miao et al. 2007, 2009; Pu 2010). The aspects of KAS location, structural stability, seepage stability, and their impact on seepage inrush control were also explored (Miao et al. 2007).

Researchers have also studied water inrush mechanisms caused by fault activation and the influence of faults on floor aquifer stability (e.g. Molina and Zeidouni 2018; Sun and Wang 2013). Thus, Ma et al. (2018) analyzed KAS's yield failure mechanism under local high-confined water pressure and obtained the yield state of KAS for different critical water pressure ranges. Floor water inrushes in deep mines was categorized into three modes/types based on the formation mechanism of a floor water-conducting fracture channel and the catastrophic characteristics and spatio-temporal evolution process of water inrush disasters in deep mine floors were analyzed (Chen et al. 2015; Wang et al. 2009). Based on an analysis of the spatial distribution relationship between aquifer and aquiclude, Wang et al. (2010) identified and classified various water-preserved mining condition zones and gave recommendations on coal resource exploitation in ecologically fragile mining areas. Thus, research has promoted the application and development of KAS theory in water-preserved mining. However, previous studies were mainly focused on conventional caving mining methods; this study attempts to analyze KAS's structural characteristics in different regions for the SBM method and elaborate a new reconstruction theory of KAS for water-preserved coal mining.

Method and Principle of KAS Reconstruction by Backfill Mining

Based on the differences between strata movement and the evolution characteristics of fractures in caving and backfill mining methods, the mining-surrounding rock environment can be modified and restored by specific technical means or methods with time effect to achieve safe and efficient mining. Based on the relevant literature (Jia 2012; Fan 2017; Zhu 2013), the term "reconstruction" is used in this paper for time-dependent recreation or reconditioning of rock surrounding the mining void. The underlying connotation of KAS reconstruction by backfill mining is to take KAS as the control object. The reconstruction effectiveness may differ depending on the backfilling characteristics, such as backfill material compaction ratio (BMCR) (Zhang et al. 2015).

This paper combines the current research status on the progression of KAS. According to the reconstruction characteristics of KAS in backfill mining, the primary structural types of KAS in backfill mining are summarized as: (I) thicker KAS in soft rock; (II) structural hard KAS from the hard rock; (III) composite KAS with complex soft and hard rock strata; (IV) multi-KAS (mixed cases I + II); and (V) no KAS. According to KAS's structure types and reconstruction characteristics depicted in Fig. 1, combined with the definition and connotation of KAS reclaimed by backfill mining, five basic patterns of KAS reconstruction by backfill mining are put forward in this paper, which are described as follows.

The soft KAS (type I) often has low permeability, excellent creep property, high adsorption, and can often self-repair when damaged. The key to realizing the reconstruction of such KAS lies in controlling the goaf's backfilling effect, exerting the effective bearing capacity of backfilling materials, reducing the deformation and destruction of such KAS. Under the joint action of backfilling materials and overlying strata, the characteristics of the KAS's self-repairing and regenerating ability must ensure that no seepage or instability occurs during the mining process.

According to conventional water protection theory, a single structural key stratum with good water-resistance capacity can be treated as a KAS (type II). However, previous studies have revealed that the hardness of this stratum can be a significant problem. Once damaged, fractures in hard rock resist recompaction and are difficult to close and repair. These fractures, once developed, become pathways for water inrush disasters. Therefore, for backfill mining under such conditions, the BMCR of the goaf must be controlled and the stress environment in the surrounding rock must be managed so that the KAS is not significantly structurally damaged. If damage does occur, then remediation by curtain grouting technology is needed to recreate the KAS at later stages of mining to ensure continued safe mining.

Composite KAS comprises soft and hard rocks (type III), which strongly differ by their thickness ratios and composite types. After backfilling, the goaf's backfill body can bear the subsidence and deformation of the overlying strata to a certain extent. Also, when the structural hard rock in the middle and lower parts of a composite KAS is damaged, it can still have residual bearing capacity. The fractures are backfilled and compacted by the adjacent soft strata, forming a composite KAS without seepage loss or instability since the composite KAS still has excellent water-resisting performance and water-retaining function. The key to reconstruction of a composite KAS is to understand the interaction between the hard and soft strata and improve the compaction of fractures in the KAS.

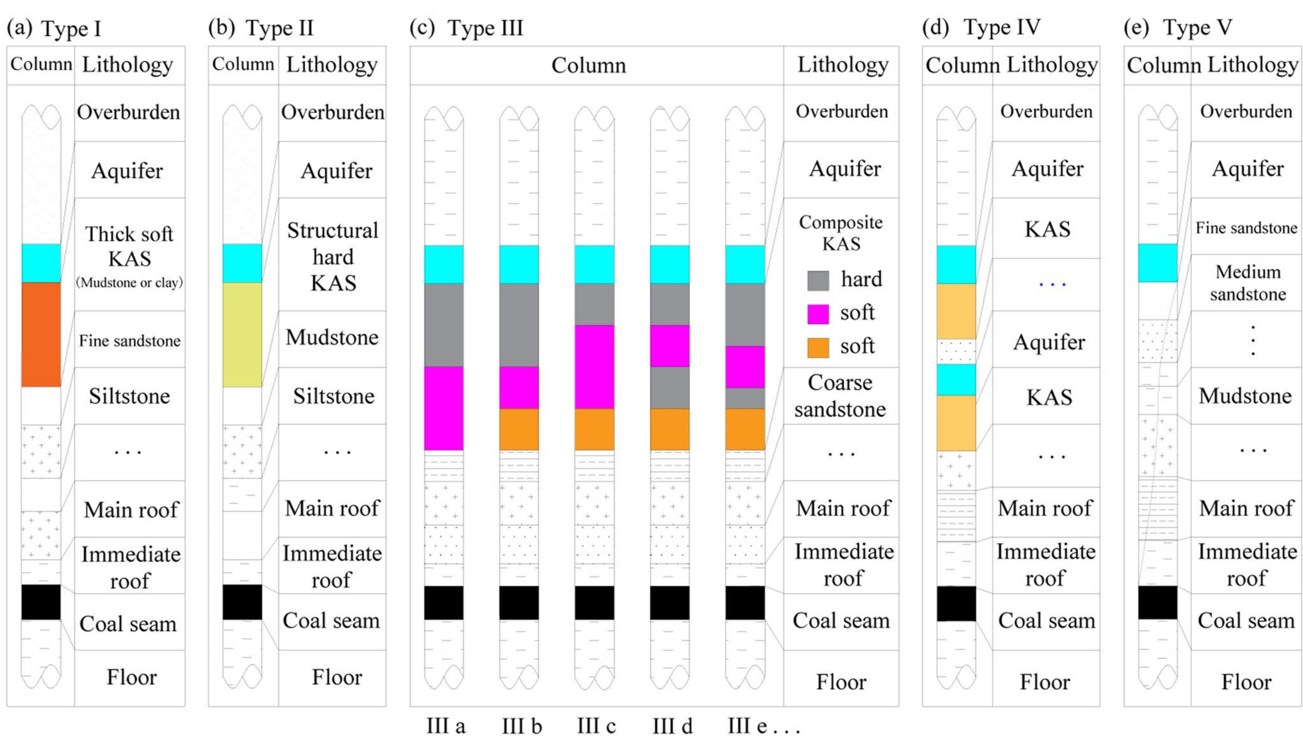

Fig. 1 Basic structure characteristics of KAS

For the complex hydrogeological conditions of multi-aquifer and KAS (type IV), it is sometimes necessary to consider how characteristics of the different aquifer strata and KAS affect the reconstruction, including the structural characteristics of varying aquifer strata and KAS, the interval distances between layers, thickness ratios, water pressure ratios, etc. Thus, the interaction between aquifer strata and KAS affects the reconstruction's structural and seepage stability, which has to be considered to achieve backfill mining with water protection.

For type V, with the development of initial fractures and no KAS, a water-resisting backfill material (such as clay) can be used to densely backfill the goaf and compact adjacent rock layers to form a KAS. Moreover, curtain grouting technology can be used to construct an artificial KAS, protect groundwater resources, and keep the original water level stable.

The above five types of KAS structure can be ranked in decreasing order by the difficulty of their overall reconstruction after backfill mining: type I > type III > type IV > type II > type V. Based on the classification and evaluation analysis of reconstruction KAS in backfill mining, this study substantiates the recommendations on the crucial reclaimed aquifer formation by the backfill mining.

Deformation Mechanism Analysis of KAS Reconstruction under Fluid-solid Interaction in Backfill Mining

Deformation Mechanism of KAS

For KAS types I, II, and III, the reconstruction effect is controlled by multiple factors, including the characteristics of KAS rock mass, geological conditions, and the design parameters of backfill mining. KAS rock mass characteristics mainly refer to the inherent thickness, strength, porosity, and permeability of the KAS rock mass. Geological conditions mainly include the burial depth load, pore water pressure, dip angle, and spatial distribution relationship between the coal seam and KAS. Backfill mining's design parameters mainly include mining height, mining area, BMCR, backfill material properties, backfill technology, and equipment. Other factors are faults, karst collapse columns, etc.

FLAC3D numerical simulation software was used to analyze the fluid-solid coupled deformation characteristics of the KAS, making it possible to study the rock failure, stress distribution, pore water pressure, and deformation characteristics of a single KAS during backfill mining and reconstruction (Ma et al. 2016). According to the mine's geological conditions under study, basic mechanical and numerical models were developed (Fig. 2). The thickness of the KAS was set at 25 m and the aquifer strata's water pressure was 2.0 MPa. The simulation model dimensions were 200 m × 200 m × 120 m (length × width × height). The model mesh consisted of 499,041 nodes and 480,000 elements and the model upper layer was subjected to a vertical load ($P = 3.0$ MPa). The horizontal displacements of the model vertical planes were restricted and the vertical displacement at the base of the model was set to zero. The Mohr-Coulomb model was used in this study, while the mechanical and seepage parameters applied in the simulation were mainly experimentally determined via laboratory tests, as shown in Table 1.

The numerical simulation focused on varying two key factors: (i) working face advancing distance and (ii) BMCR. The first simulation test series assumed a constant BMCR of 80% and four different advancing distances (25, 50, 75, and 100 m, respectively). In the second test series, the working face's advancing distance was 100 m, while BMCR values were 90, 80, 70, and 60%, respectively. The plastic zone's development characteristics in the KAS with different advancing distance and BMCRs are plotted in Fig. 3. The pore water pressure and subsidence curves of KAS with different advancing distance and BMCRs are plotted in Fig. 4. The vertical stress, pore water pressure, and subsidence

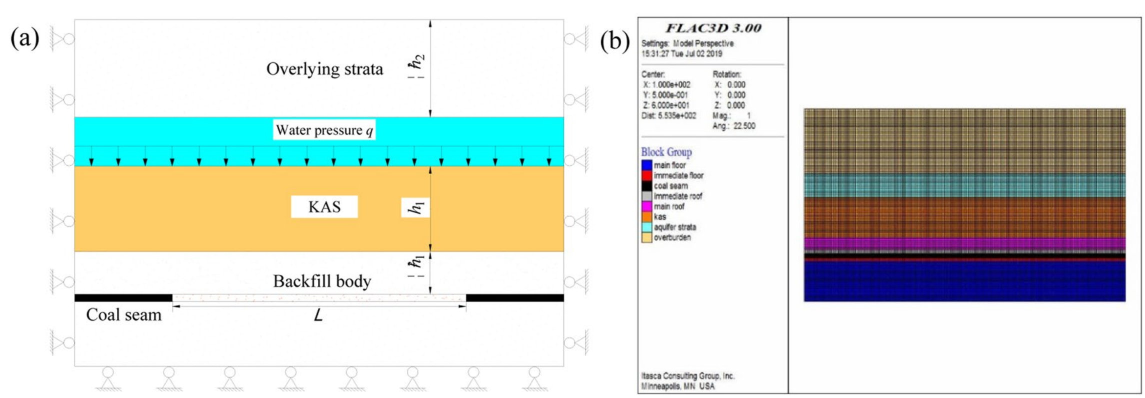

Fig. 2 Mechanical and numerical models of the single KAS: **a** mechanical model; **b** numerical model

Table 1 Physical and mechanical parameters of the single KAS

Strata	Thickness (m)	Elastic modulus (GPa)	Poisson's ratio (−)	Cohesion (MPa)	Tensile strength (MPa)	Internal friction angle (°)	Density (kg/m^3)	Permeability (10^{-9} $m \cdot s^{-1}$)	Porosity
Overburden	40.0	8.5	0.28	3.2	3.2	30	2400	0.072	0.10
Aquifer strata	15.0	22.0	0.25	2.8	2.5	34	2600	1.580	0.25
KAS	25.0	25.0	0.32	5.5	6.0	35	2300	0.015	0.05
Main roof	8.0	20.0	0.26	3.2	3.0	32	2600	0.072	0.15
Immediate roof	2.0	7.2	0.32	2.4	2.4	28	2200	0.035	0.10
Coal seam	3.0	5.5	0.30	1.5	1.5	26	1400	0.153	0.20
Immediate floor	2.0	15.0	0.25	2.8	2.4	32	2200	0.025	0.08
Main floor	25.0	25.0	0.32	3.5	3.2	25	2400	0.068	0.12

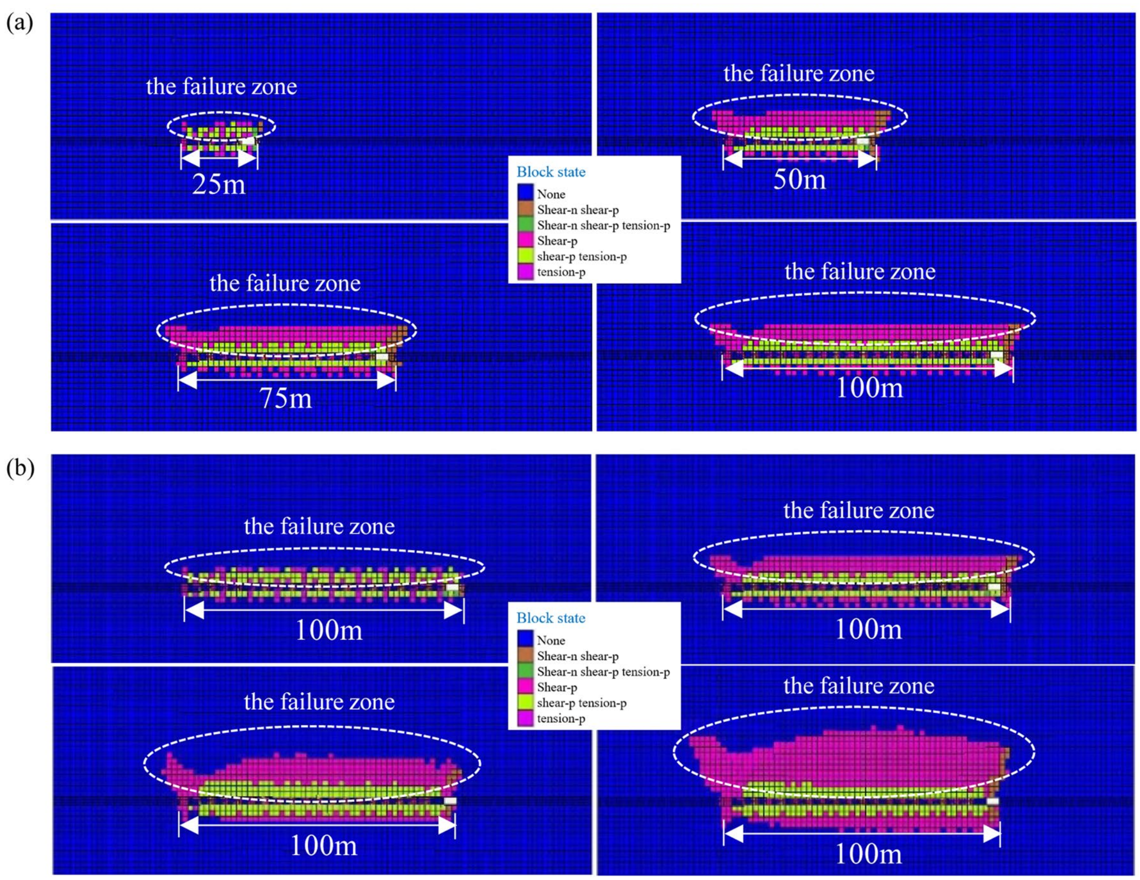

Fig. 3 Plastic zone development characteristics of KAS with different advancing distance and BMCR: **a** advancing distance; **b** BMCR

monitoring points are in the middle of the KAS along the face advancing direction.

The results presented in Figs. 3 and 4 strongly indicate that the plastic zone in the goaf's upper strata slowly and gradually stabilize during the continuous mining and backfilling of the working face. When the working face advances to 100 m, the plastic zone develops to the middle and lower parts of the KAS and tends to be steady. The disturbance of the key aquifer increases gradually as the working face continues to advance.

As the working face advances to 50 and 100 m, the vertical stress peak values of KAS are 5.25 and 5.92 MPa, respectively, and the stress concentration coefficients are 1.11 and 1.25, respectively. With an increase in the working face's advance, the pore water pressure of KAS in the upper part of the corresponding mining area gradually

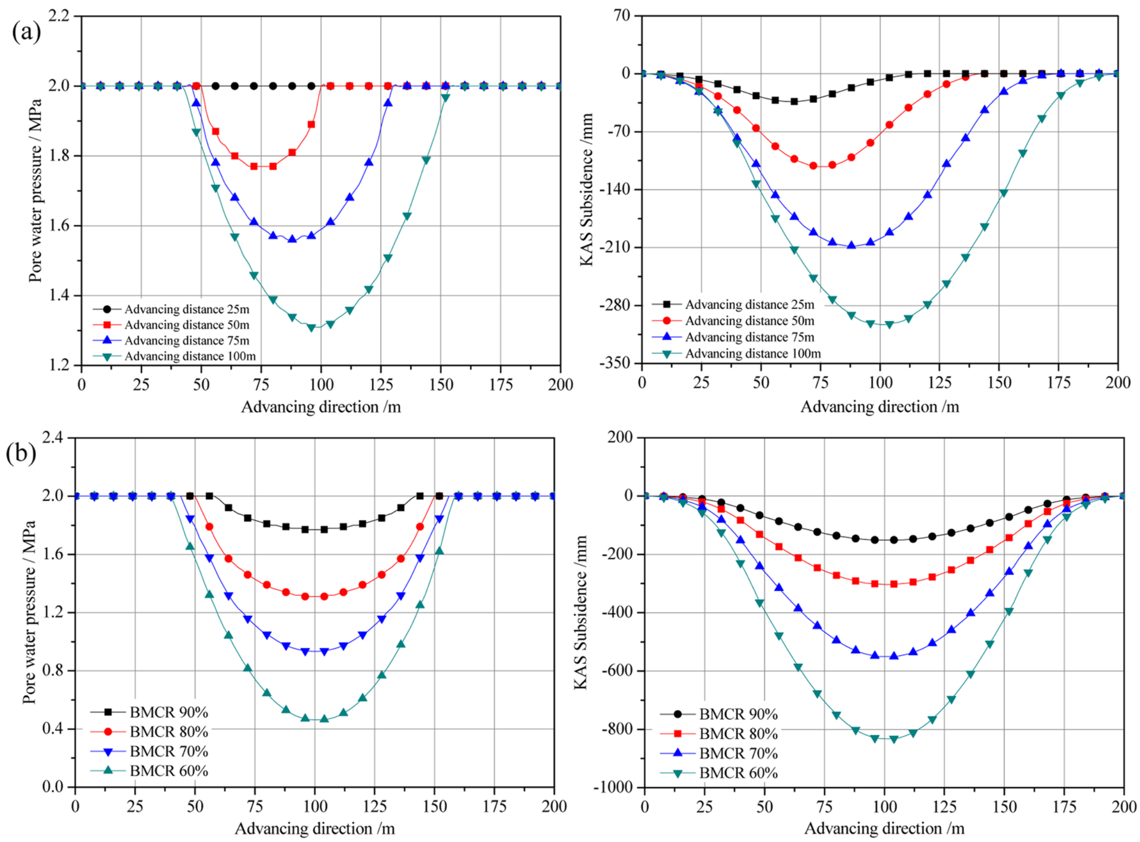

Fig. 4 Pore water pressure and subsidence curves of KAS with different advancing distance and BMCR: **a** advancing distance; **b** BMCR

decreases and is funnel-shaped. The influence range of the pore water pressure increases gradually; at 100 m, the minimum pore water pressure is 1.31 MPa. The maximum vertical displacement of the KAS is 34 ~ 303 mm with the corresponding advancing distance of 25 ~ 100 m.

At 100 m, the height and scope of plastic zone development in the upper strata of the goaf gradually increased with decreasing BMCR values. For example, at BMCR = 60%, most of the KAS was destroyed. Furthermore, as the BMCR dropped from 90 to 70%, the KAS's vertical stress peak values increased from 5.20 to 6.85 MPa, respectively, while stress concentration factors rose from 1.09 to 1.44. As the BMCR decreased, the KAS's pore water pressure in the upper part of the corresponding mining area gradually decreased as well, while the influence range of the pore water pressure grew correspondingly. At BMCR = 60%, the minimum pore water pressure was reduced to 0.46 MPa. As BMCR values dropped from 90 to 60%, the KAS maximum vertical displacement changed from 151 to 832 mm, respectively.

Complex KAS Reconstruction

Coal mining often involves multiple aquifers or aquiclude strata, which makes reconstruction of the KAS more complex. In addition to the characteristics of the rock mass, geological conditions, backfill mining designs, and other factors in the single KAS, the KAS's composite effect on the backfill mining process should also be considered. As an example, we used the FLAC^{3D} numerical simulation software to analyze the fluid-solid coupled deformation characteristics for the case of two aquifers and two KAS. The basic mechanical and numerical models are shown in Fig. 5. The thickness of the lower KAS II was 10 m, and the water pressures of the lower and upper aquifer strata were set as 1.5 and 2.5 MPa, respectively. The simulation model dimensions were 250 m × 200 m × 135 m (length × width × height); the model was meshed using 724,626 nodes and 700,000 elements. A vertical load (P = 4.5 MPa) was applied to the top of the model. The horizontal displacements of the model's vertical planes were restricted and the vertical

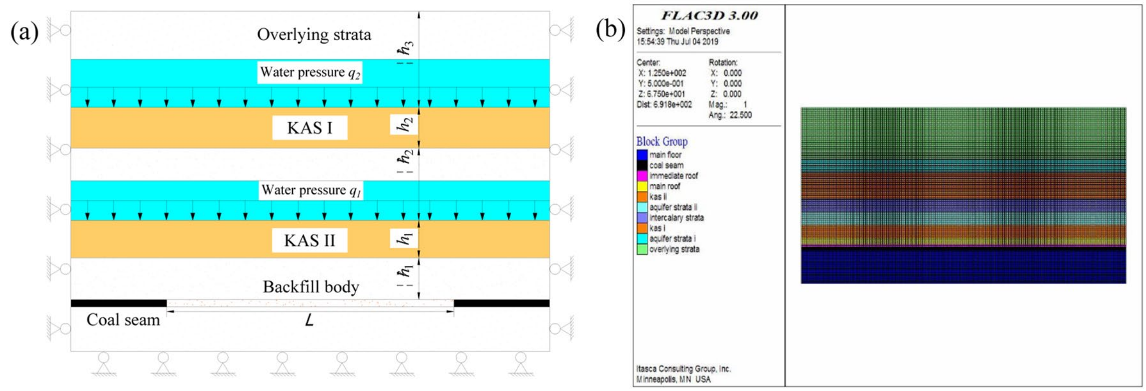

Fig. 5 Mechanical and numerical models of the KAS with a complex effect: **a** mechanical model; **b** numerical simulation model

Table 2 Physical and mechanical parameters of the KAS with a complex effect

Strata	Thickness (m)	Elastic modulus (GPa)	Poisson's ratio (–)	Cohesion (MPa)	Tensile strength (MPa)	Internal friction angle (°)	Density (kg/m^3)	Permeability (10^{-9} m·s^{-1})	Porosity
Aquifer strata I	10.0	30	0.25	2.8	2.5	28	2250	1.580	0.25
KAS I	–	35	0.35	5.5	5.0	35	2800	0.015	0.05
Intercalary strata	–	25	0.25	3.2	3.0	32	2500	0.072	0.10
Aquifer strata II	10.0	30	0.25	2.8	2.5	28	2250	1.580	0.25
KAS II	10.0	35	0.35	5.5	5.0	35	2800	0.012	0.06
Main roof	5.0	25	0.25	3.2	3.0	32	2500	0.072	0.10
Immediate roof	2.0	18	0.28	2.4	2.4	25	2200	0.035	0.15
Coal seam	3.0	5.5	0.32	1.5	1.5	28	1400	0.153	0.20
Main floor	25.0	25	0.35	3.5	3.2	25	2400	0.068	0.12

displacement at the base of the model was set to zero. The Mohr-Coulomb model was adopted and the mechanical and seepage parameters applied in this simulation were mainly based on the laboratory test results (Table 2).

The simulation covered variations of two key influencing factors, namely the KAS thickness ratios and the KAS interlayer thickness $\sum h_2$. The first numerical test series assumed a BMCR of 60%, an interlayer thickness of 20 m between the two KAS, and four different thickness values of KAS I (20, 30, 40, and 50 m, respectively). The second one assumed a BMCR of 60%, a 30 m thick KAS I, and various (20, 30, 40, and 50 m) interlayer thicknesses between the two KAS. The plastic zone's development characteristics for thickness ratios of 5:1, 4:1, 3:1, and 2:1 were calculated at an advancing distance of 150 m (Fig. 6a). The KAS plastic zone's development characteristics at a thickness ratio of 3:1 are shown in Fig. 6b for the four different interlayer thicknesses. The pore water pressure and subsidence curves of KAS II are depicted in Fig. 7. The monitoring points of vertical stress, pore water pressure, and subsidence are in the middle of the KAS II along the face advancing direction.

With an interlayer thickness between the two KAS of 20 m, the height and scope of plastic zone development in the upper strata of goaf increased gradually with a decline in KAS I thickness. The main reason is that the structural mechanical characteristics of KAS I allow it to bear the overlying load and water pressure to a certain extent, reducing the damage of the overlying strata. At thickness ratios of 5:1 and 3:1, the peak values of vertical stress of KAS II were 6.95 and 7.53 MPa, respectively, while stress concentration factors were 1.01 and 1.10, respectively. With a drop in the KAS thickness ratio, the KAS's pore water pressure in the upper part of the corresponding mining area decreased gradually and had a funnel shape. The influence range of the pore water pressure increased gradually. At a KAS thickness ratio of 2:1, the minimum pore water pressure was 0.14 MPa. As the working face advanced, the maximum vertical displacement of KAS changed in the range of 141 ~ 375 mm, with corresponding KAS thickness ratios of 5:1 ~ 2:1. At constant BMCR values, a rise in the interlayer thickness between the two KAS gradually enhances the plastic zone's development between the upper strata and the rock surrounding

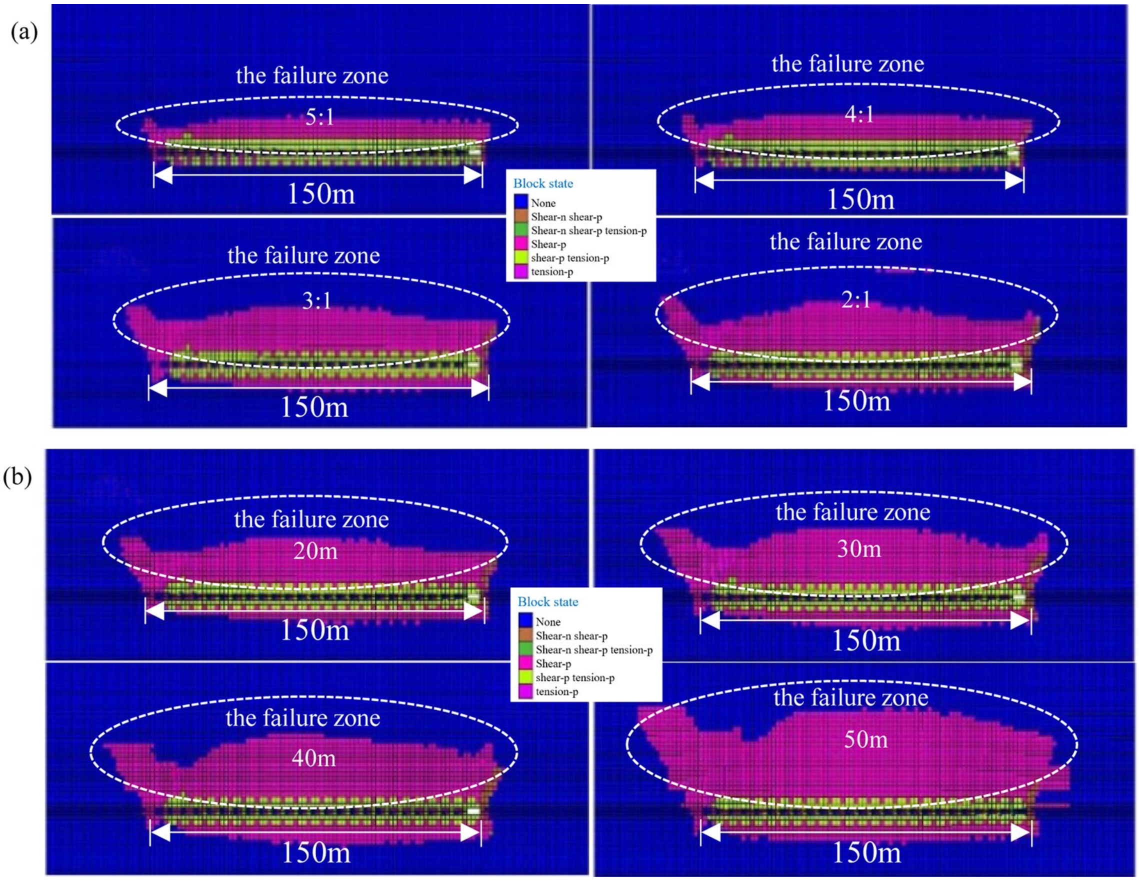

Fig. 6 Plastic zone development characteristics of KAS with different thickness ratios and interlayer thicknesses: **a** thickness ratio; **b** interlayer thickness

the goaf's KAS. This strongly indicates that an increase of interlayer thickness between the two KAS can weaken the influence of KAS II's damage degree and scope. At interlayer thickness values of 30 and 50 m, the peak values of vertical stress of KAS II were 8.05 and 9.42 MPa, and the respective stress concentration factors were 1.17 and 1.37. At an interlayer thickness of 50 m, the minimum pore water pressure dropped to zero. During the working face advance, the maximum vertical displacement of KAS II ranged from 288 to 18 mm, with corresponding interlayer thicknesses of 20 ~ 50 m.

The backfilling of the goaf directly affects the water-resisting performance of the KAS due to interaction and mutual influence. Based on the above numerical simulation results, the deformation mechanism of KAS reconstruction by backfill mining method under the effect of single and multiple KAS were summarized and further analyzed (Fig. 8).

As Fig. 8 illustrates, the mechanical structure and seepage system stability of KAS are mainly determined by the disturbance degree with different BMCRs. Mining activities will deform and destroy the KAS, decrease the overlying load, and increase the degree of deformation. When the BMCR drops to the critical value that corresponds to the KAS's seepage inrush, a water inrush disaster will occur in the working face. Therefore, in the case of single KAS reconstruction, the BMCR is the key influencing factor. The effective bearing capacity of backfill materials is crucial to preventing structural damage and seepage instability of the KAS. Meanwhile, the composite effect of KAS reconstruction by backfill mining is enhanced by smaller interlayer thicknesses and larger thickness ratios of KAS, as well as by a decline in BMCR. These findings are quite instrumental in determining the design for actual backfill mining at the mining sites.

Conclusions

In this study, the concept of KAS reconstruction by backfill mining was put forward. Analysis of various models of KAS damage with different backfill effects indicates that safe mining of coal resources under an aquifer can be realized by controlling and improving the relevant characteristics

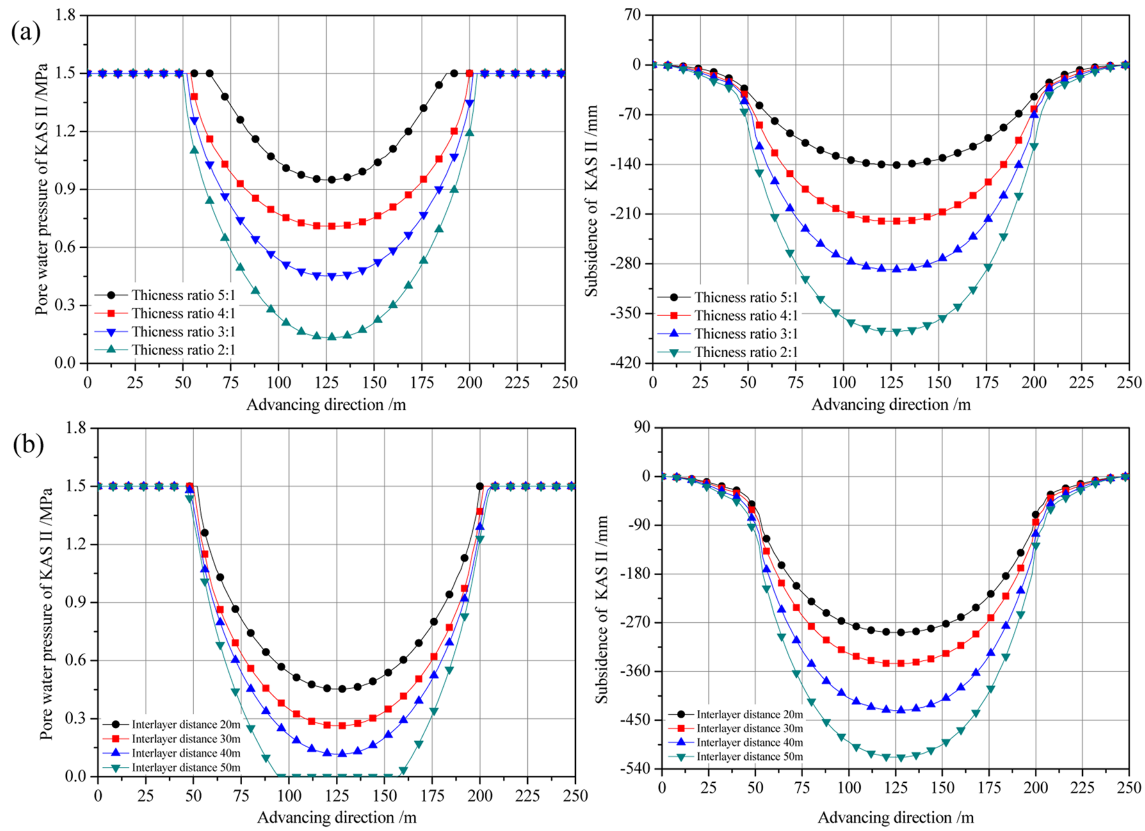

Fig. 7 Pore water pressure and subsidence curve of KAS II with different thickness ratios and interlayer thicknesses: **a** thickness ratio; **b** interlayer thickness

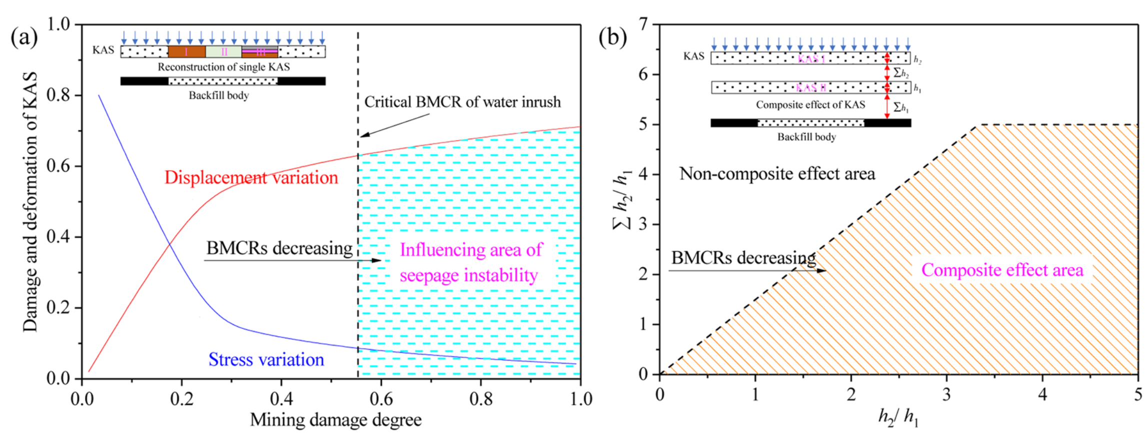

Fig. 8 Deformation mechanism of KAS reconstruction in backfill mining: **a** single KAS; **b** KAS composite

of backfilling materials during backfill mining, to create a surrounding rock environment with no structural damage or KAS seepage instability. KAS structures can be subdivided into five types, namely soft KAS (type I), hard KAS (type II), composite KAS (type III), multi-KAS (type IV), and no KAS (type V). These five types of KAS structure were ranked in decreasing order by the difficulty of their overall reconstruction after backfill mining as: type I > type III > type IV > type II > type V. The deformation mechanism of single and composite KAS reconstruction indicated that disturbance of the KAS increases with the advancing distance and decline in BMCR, whereas the pore water pressure of KAS in the upper part of the corresponding mining area decreases gradually and is funnel-shaped. With less interlayer thickness and an increase in the KAS's thickness ratio, the composite effect gets more pronounced, and the BMCR can aggravate the influence of seepage instability and composite effect of KAS to a certain extent. This research provides theoretical support for further use of SBM for water resources protection.

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