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TECHNICAL COMMUNICATION

Study of Water-Controlled and Environmentally Friendly Coal Mining Models in an Ecologically Fragile Area of Northwest China

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Abstract
Striking a balance between high-intensity coal mining and environmental protection has been a challenge in the Yushen mining area, which is an important coal production base in China located in an arid and semi-arid ecologically fragile environment. The 122,109 working face of the Caojiatan coal mine was used as a model to coordinate coal production with ecological protection. Theoretical analysis and field monitoring revealed that the maximum surface subsidence was 5.6 m, and the development height of the diversion fracture zone was 21 times the coal seam thickness. The influence of mining process parameters and mining methods on surface ecological damage and water loss was further analyzed using the fluid–solid coupling method. The results showed that exclusive pursuit of high-intensity mining would induce irreversible disasters including aquifer water loss and cultivated land damage; the degree of influence was directly proportional to the working face length, mining height, and mining method. Proper adjustments of these parameters could help realize water-controlled coal mining. The results provide an empirical basis for allowing both exploitation of coal resources and protection of the environment in ecologically fragile areas.

Keywords Mining intensity · Coordinated mining · Ecological environment · Aquifer water loss intensity

Introduction

In recent years, with the exhaustion of coal resources in the central and eastern parts of China, the focus of coal mining has gradually shifted west (Bai et al. 2019; Ju and Xu 2013; Li et al. 2020; Yang et al. 2014; Zeng et al. 2018). In 2020, the coal output in western China was estimated to be 2.3 billion tons, accounting for 59.2% of the national total, and an important component of China's economy. However, at the same time, this has caused extremely negative impacts on the ecological environment. For example, coal mining has deteriorated the fragile ecological environment of the Yushen mining area of western China, resulting in "secondary disasters," as shown in supplemental Fig. S-1. According to researchers (Bai et al. 2010; Candeias et al. 2015; Cui et al. 2021; Duan et al. 2019; Fang et al. 2021; Liu et al. 2019a, b; Peter et al. 2021; Zhang et al. 2021), the main reason for this is the high-intensity longwall mining method currently used in the area, which not only causes a great degree of disturbance and damage to the overlying strata of the coal seam, but greatly impacts the aquifer and surface ecosystem. Because such mining produces coal efficiently but causes secondary disasters, it is classified as a "high efficiency and low benefit" mining method, indicative of mining coal resources at the expense of the ecological environment. In contrast, filling and short-walled height-limiting mining methods can reduce the surface ecological damage, but their production efficiency is much lower, causing them to be classified as "low efficiency and high benefit" mining methods (Dong et al. 2020; Al Heib et al. 2010; Huang et al. 2017;

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Piao et al. 2019; Zhang et al. 2020). Therefore, when mining in areas with fragile ecological landforms, such as the Yushu mining area, it is important to select the appropriate mining structure and guide the mining area to coordinate resource recovery and environmental protection.

Studies have been conducted on how to coordinate exploitation of resources and environmental protection in western China. Fang et al. (2019) proposed the concept of water conservation mining to reduce damage to the Salawusu Formation aquifer and deterioration of the ecological environment during the mining of thick coal seams in western China. Wu et al. (2017) proposed the construction of a "coal-water" dual-resource mine based on the concept of coordinated mining of coal and water. Li et al. (2018) proposed the concept of aquifuge reconstruction based on protection and management of the eco-geological environment in the mining area.

Using field monitoring and statistical analysis, researchers have dynamically analyzed how surface ecological landforms and stratum structures respond to high-intensity mining and explored how high-intensity mining causes the decline of groundwater levels, vegetation degradation, land desertification, and geohazards (Liu et al. 2019a, b; Salmi et al. 2017; Qiao et al. 2017; Wu et al. 2017; Wang et al. 2019, 2020).

Researchers have also used geographic information systems (GIS), physical detection, and other technical means to study how the surface ecological environment in different regions responds under high-intensity mining conditions and proposed appropriate measures for each area. For example, Liu et al. (2020) developed a suitability analysis system to evaluate the suitability of water conservation mining in a study area using GIS and the analytic hierarchy process (AHP). Li and Wu (2019) proposed an eco-geological environment zoning method based on evaluating the ecological characteristics of mining areas before mining, which aims to protect and improve the regional ecological environment. Xu et al. (2020a, b) proposed a water-saving mining method to better protect the ecological environment during large-scale underground coal mining in northwest China.

Finally, the importance of reconstructing the water-resisting layer and determining the critical mining water level to ensure safe mining was demonstrated by a combination of theoretical analysis and numerical simulation. Zhang et al. (2019) explained the mechanism of seepage induced by backfill mining and demonstrated the feasibility of rebuilding key aquifers to protect regional water. Xu et al. (2018) quantitatively analyzed the influence of the thickness and permeability of the aquitard on groundwater flow in a regional loose aquifer in a mining area.

Thus, research scholars have qualitatively and quantitatively evaluated the damage to surface ecology, geology, and water environment under high-intensity coal mining in the western mining areas, and provided a scientific basis for the coordinated and sustainable development of water-controlled coal mining. However, with the increasingly serious contradiction between environmental protection and coal mining in ecologically fragile mining areas, ensuring the coordinated development of "coal resources and ecological water environment" is still a major problem. Therefore, using the 122,109 working face of the Caojiatan coal mine of the Yushen mining area as a model, this paper discusses the response mechanism of overlying aquifers and aquifuges to high-intensity mining. On this basis, a coordinated "coal-water" mining framework is proposed. First, we conducted theoretical analysis and on-site monitoring and investigations and revealed the extent of ecological damage at the surface and the evolution of water-flowing fractures in response to high-intensity backstopping. Second, the influence of high-intensity mining parameters and mining methods on "coal-water" collaborative mining was analyzed using the fluid–solid coupling theory. Finally, a water-controlled mining framework is proposed for ecologically fragile areas based on the responses of strata and aquifers to high-intensity mining in the study area.

Study Site

The Yushen mining area is located north of Yulin City, Shaanxi Province, China (Fig. 1). It consists of four planning areas, which are designated as 1#, 2#, 3# and 4#. The 122,109 working face of the Caojiatan Mine in the 1# planning area was selected as the research site. The strata in this area include the Jurassic Yan'an, Zhiluo, and Anding Formations, as well as Neogene and Quaternary sediments (Fig. 2). The 122,109 working face mines the Yan'an Formation 2–2 coal seam. The design length of the working face is 260 m. The advance length is 6,004 m. The average thickness of the coal seam is 11.8 m, and the coal seam inclination angle is 0.4°. The coal mining method is thick coal seam longwall mining with sublevel caving. The aquifers affecting the mining of coal seam 2–2 is, from top to bottom, the: Quaternary Upper Pleistocene Salawusu Formation; a confined, fissured and weathered bedrock aquifer; a confined porous and fissures aquifer of the Middle Jurassic Zhiluo Formation; and a confined porous and fissured aquifer in the 2–2 coal bearing Middle Jurassic Yan'an Formation. The main water resisting layers are the Baode Formation laterite and the Neogene Anding Formation bedrock, followed by mudstone and siltstone in the bedrock.

Methodology

The water-controlled coal mining framework in ecologically fragile mining areas has three components: identifying the bearing capacity of the mining area's ecological environment; identifying the degree of surface ecological damage associated with coal mining; and identifying how the mining-induced water flowing fractured zone evolves and develops into the overburden.

Identifying the Bearing Capacity of the Mining Area's Ecological Environment

The main basis for ensuring the synergistic development of coal resources and environmental protection is the ecological carrying capacity of the mining area, which directly depends on the total water loss from the aquifers and the degree of key impervious layer destruction. A schematic diagram (Fig. 3) was established to visualize the relationship between the ecological environment carrying capacity and impervious strata, aquifers, and aquifer water loss. The x-axis in Fig. 3 is the mining direction; the z-axis is the deposition direction of the rock layer; and the origin O is the midpoint of the effective water barrier key layer. According to Fig. 3, as long as the water-conducting fracture zone does not penetrate the key water-impermeable layer, it can still carry the upper submerged aquifer, maintain the ecological water level, and ensure the survival of surface vegetation. Therefore, identifying the ecological carrying capacity characteristics requires identifying the ultimate carrying capacity of the critical impermeable layer and the maximum possible water loss of the aquifer.

To further analyze whether the damaged key water barrier layer still has the strength to carry the overlying submerged aquifer, we calculated the bearing strength of the water barrier key layer based on the solid support beam theory. According to the theoretical calculations in material mechanics (Huang et al. 2020), the maximum bending moment M_{max} occurs at both ends of the beam, $M_{max} = -\frac{qL^2}{12}$. Therefore, the maximum tensile stress σ_{max} at this location is:

$$\sigma_{max} = \frac{qL^2}{2h^2} \tag{1}$$

where q is the load borne by the key impervious stratum, MPa; L is the span limit length of rock beam, m; and h is the thickness of the key impervious strata, m. When $\sigma_{max} \geq R_T$, that is, when the maximum tensile stress to which the key impervious stratum is subjected exceeds the ultimate tensile strength R_T of the rock beam, breakage of the key impervious strata occurs. The key impervious stratum loses its water barrier function, resulting in a drop in the aquifer's water level and ultimate destruction of the groundwater environment. At the time when the breakage occurs, the load borne

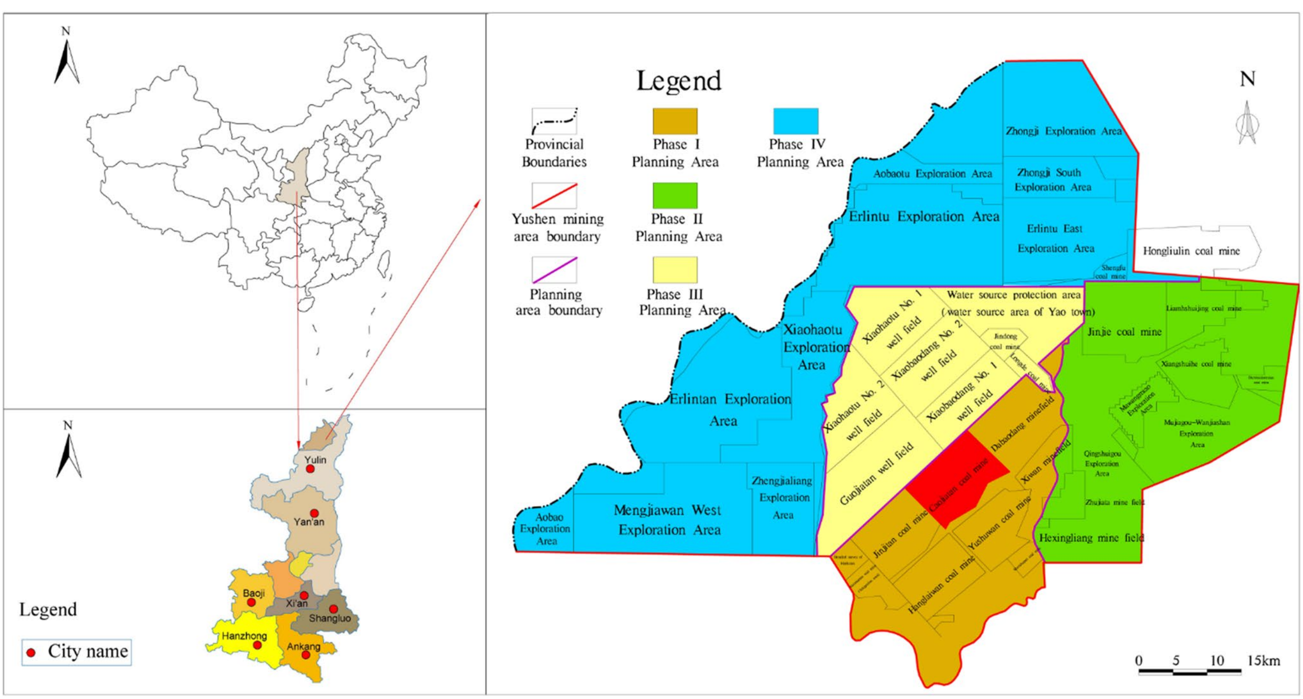


Fig. 1 Location of the study site

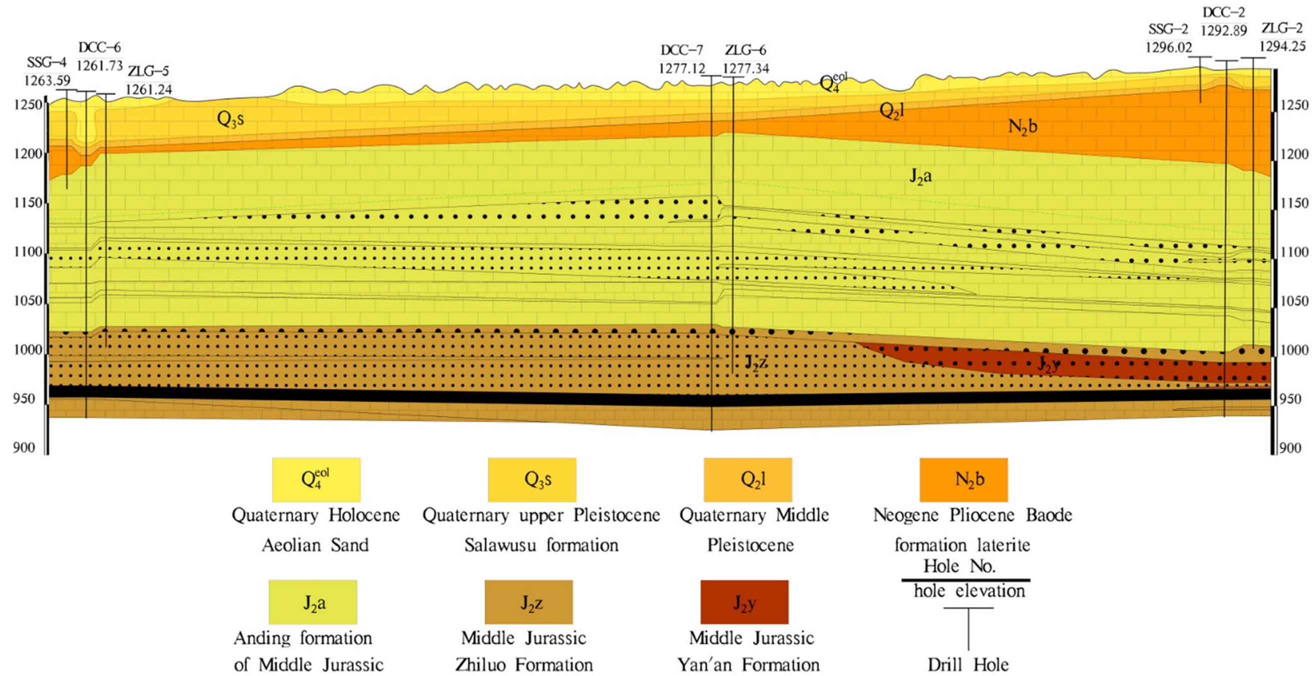


Fig. 2 Comprehensive hydrological profile

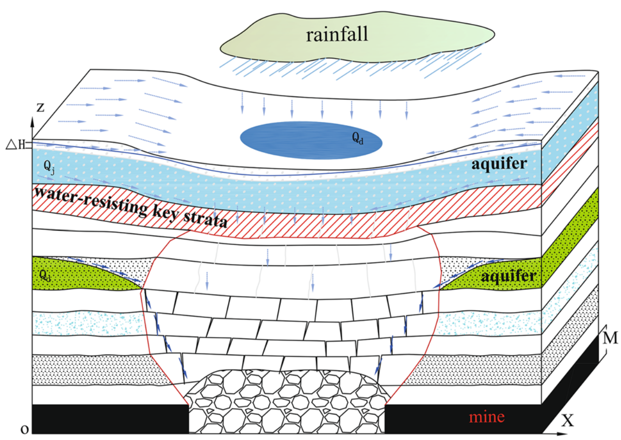


Fig. 3 Schematic diagram of ecological carrying capacity and aquifer water loss

by the stratum is $q = \gamma h_1$, and the minimum span L of the rock beam is:

$$L = \sqrt{\frac{2R_T}{\gamma h_1}} h \tag{2}$$

where: γ is the average bulk density of the rock layer, 25 KN/m^3; and h_1 is the sum of the thicknesses of the overburden over the key impervious stratum.

Fan et al. (2016) showed in their work that after the water conducting fracture zone communicates with the aquifer during mining, the roof inflow water source is mainly composed of static reserves and dynamic reserves. The static reserves are elastic release water of the confined aquifer and gravity release water of the phreatic aquifer. The dynamic reserves are recharged by atmospheric precipitation and lateral recharge from the falling funnel. The storage capacity of each water source is calculated by the following equation:

$$Q_j = MF(\mu_s \Delta H + \mu) \tag{3}$$

$$Q_d = \int_0^t \left[K\frac{M(2H_0 - M) - H_W^2}{2L} \right] (n_1 b + n_2 vt) dt \tag{4}$$

where: Q_j is the static reserve; μ_s is the water storage coefficient; F is the area of goaf, $F = vt * L * M$; ΔH is the water level drawdown; μ is the specific yield; Q_d is the dynamic reserve; K is the hydraulic conductivity; H_0 is the initial hydraulic head; H_W is the hydraulic head in the well; n_1 and n_2 are coefficients, taking 2 for multi-side wells and 1 for one-side wells; v is the advancing speed of the working face; M is the mining thickness of the working face; and t is the mining duration.

Determination of Degree of Surface Ecological Damage of Mining

According to the mining situation of the mine in the mining area, it is known that there will be water accumulation in the surface subsidence pit, and it is inferred that the reason for the water accumulation in the collapse pit is that the water in the Quaternary pore aquifer flows into the surface subsidence pit during the subsidence of the stratum. Therefore, it is important to monitor the degree of damage that high-intensity mining has on the surface ecology. Two transects were set up in the monitoring station, one along the strike direction and another along the dip. The length of the survey transects was calculated by Eqs. (5) and (6) (Luan et al. 2020; Zhao et al. 2019). The observation station layout is shown in Fig. 4a and the cross section of the observation station is shown in Fig. 4b.

$$L_Z \geq 2\left(H_0 - h\right)\cot(\delta - \Delta\delta) + 2hcot\varphi \quad (5)$$

$$D_1 \geq \left(H_0 - h\right)\cot(\delta - \Delta\delta) + hcot\varphi \quad (6)$$

where: Lz is the length of the strike transect; H_0 is the mining depth of the working face, 318 m;δ is the strike movement angle, 63°;h is the thickness of the soil layer, 140 m;Δδ is the correction value of strike movement angle, 20°;φ is the loose layer movement angle, 45°; and D_1 is the distance from the working face open-off cut.

According to the calculation, the length of the direct observation line should not be less than 661.8 m; the distance from the inclined line to the open eye of the working face should be more than 330.9 m. After considering the accuracy of the relevant parameters and the terrain, the inclined observation line was arranged at a distance of 416.8 m from the working face eye; the length of the direction observation line was 1200 m. There were 40 observation points in the trend observation line and the interval between the observation points was 25 m. The inclination observation line had 41 observation points 25 m apart. The 15th measurement point on the trend observation line is the working face cut-eye. The observed settlement during each period was measured by GPS and a level meter.

Determining How Flow Cracks Evolve During High-Intensity Mining

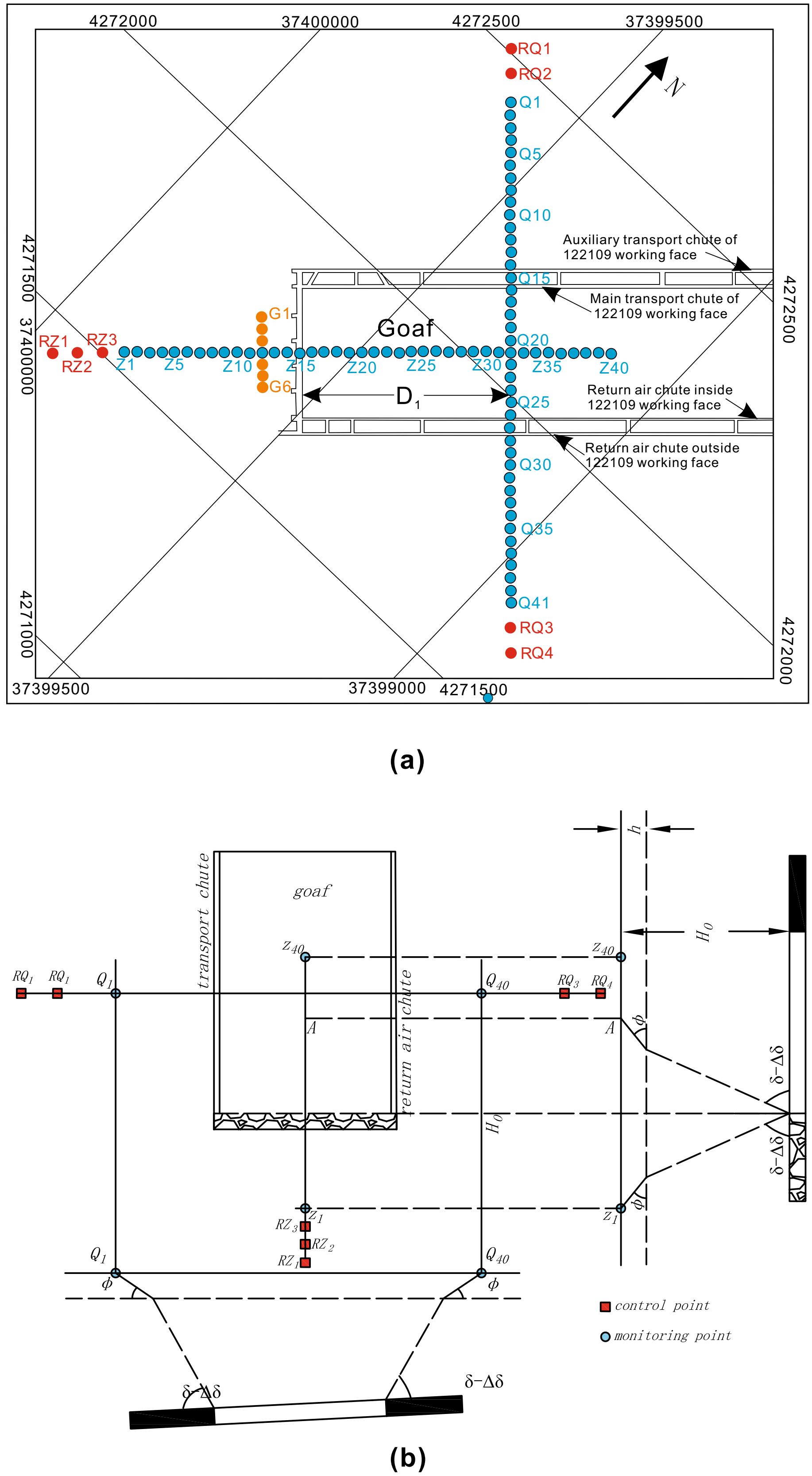
Studying how hydraulic fractures develop in the overburden under specific geological conditions provide a theoretical basis for the formulation of reasonable coordinated mining measures. A ground drilling method was used to measure the height of the overburden hydraulic fracture development after the 122,109 working face was mined. According to our previous analysis of overburden fissure evolution (Yang et al. 2014; Ning et al. 2019; Fang et al. 2021; He et al. 2021), the overburden damage pattern of the first mining face is saddle shaped, with the middle line of the mining area as the axis of symmetry. The highest point of this damage pattern is mainly distributed along the edge of the down-slot and the lowest point is mainly distributed in the middle of the mining area. Therefore, the center line of the mining area was used as the symmetry axis for observation hole arrangement. Observation holes LD-1, LD-2, and LD-3 were mainly used to observe the height of the inclined hydraulic fracture zone of the working face, while LD-2 and LD-4 observation holes were mainly used to observe the height of the hydraulic fracture zone of the working face. LD-1 was drilled in the middle of the mining area, 132 m from the middle of the transport chute. LD-2 and LD-3 were arranged on both sides of the transport chute and were mainly used to observe the height of the hydraulic fracture zone of the working face. LD-3 was located in the middle of the coal column, 10 m from the middle of the transport chute. Observation holes and LD-2 and LD-4 were in the same profile, and LD-4 was also 20 m from the middle of the transport chute. The arrangement of monitoring holes is shown in Fig. 5.

Results

Analysis of the Degree of Surface Ecological Damage in the Mining Area

Field observations were conducted 18 times over one year. The dynamic settlement curve of the 122,109 working face is shown in Fig. 6 and the degree of surface ecological damage is shown in Fig. 7. As shown in Fig. 6a, the degree of ground surface damage continued to increase as the working face advanced, and finally stabilized with a maximum settlement value of 5.6 m. Figure 6b reflects the same subsidence characteristics in each period as those of Fig. 6a. The maximum sinking position of the dip survey line was the same as the maximum sinking position of the strike survey line. Note that the field measurements were not carried out at all measurement points because some were submerged in ponded water during mining. To further illustrate the disturbance of the surface ecology, the surface damage during each period was recorded through images (supplemental Fig. S-2). The observation maps of the first and sixteenth periods at the same location are shown in Fig. 7. The surface ecology experienced different degrees of disturbance and destruction including accumulation of water in low-lying land, plant depletion and death, and destruction of cultivated land. This field monitoring and analysis indicate that the fragile ecological landform over the working face was severely damaged by the high-intensity mining. Therefore, when coal mining takes place in ecologically fragile areas, coordinated development of the "coal resources-ecological water environment" must be considered to avoid great damage to the ecological environment.

Fig. 4 (a) The drawing of layout of observation station, (b) The cross section of the observation station



Analysis of How the Water-Flowing Fractured Zone Evolved in the Mining Area

The water-flowing fractured zone was measured by drilling fluid filtration loss measurement (Fang et al. 2019); the variation of water level with drilling depth in the four monitoring holes is shown in supplemental Fig. S-3. The water level in each borehole decreased with the drilling depth until it intercepted the top interface of the water diversion fracture. All the water in the hole leaked, so the water level could not be detected. The comprehensive detection results at the four monitoring boreholes are summarized in Table 1.

- The depth to water at LD-1 borehole was 91.5 m where the circulation fluid completely lost. The buried depth of the coal seam roof at LD-1 was 301.5 m. Therefore, the height of the water flowing fracture zone at LD-1 borehole was 210.1 m.
- The water level at LD-2 borehole was observed from 72.8 m, and the circulation fluid was completely lost at 86.7 m. The buried depth of the coal seam roof of LD-2 was 300.1 m, and the mining thickness of the coal seam at LD-2 working face was 10.5 m. As a result, the height of the water flowing fracture zone at LD-2 was 213.4 m.
- The water level change at LD-3 borehole started from 75 m, and the circulation fluid in the borehole completely lost at 168.6 m. The buried depth of the coal seam roof at LD-3 was 309.1 m, and the mining thickness of the coal seam at LD-3 working face was 11.5 m. The height of the water flowing fracture zone at LD-3 borehole was calculated to be 140.5 m.
- The water level observation at LD-4 borehole started from 77.8 m, and the water level could not be measured in the borehole at 84.1 m. The buried depth of the coal seam roof at LD-4 was 299.1 m, and the mining thickness of the coal seam was 10.5 m. Therefore, the height of the water flowing fracture zone observed in LD-4 borehole was 215 m.

The above results show how mining damaged the porous fractured confined aquifers of the weathered rock and Middle Jurassic Zhiluo Formation and the 2–2 coal water-bearing rock segment of the Middle Jurassic Yan'an Formation. The top interface of the water-flowing fracture reached the bottom of the laterite layer. However, the thickness of the Baode Formation laterite is very variable, which means that mine water disaster accidents can occur very easily in areas where the laterite is thin or missing.

Water-Controlled Coal Mining in an Ecologically Fragile Mining Area

The surface above the 122,109 working face sank 5.6 m, which caused a large amount of water to accumulate in the surface collapse area. At the same time, the water level in the

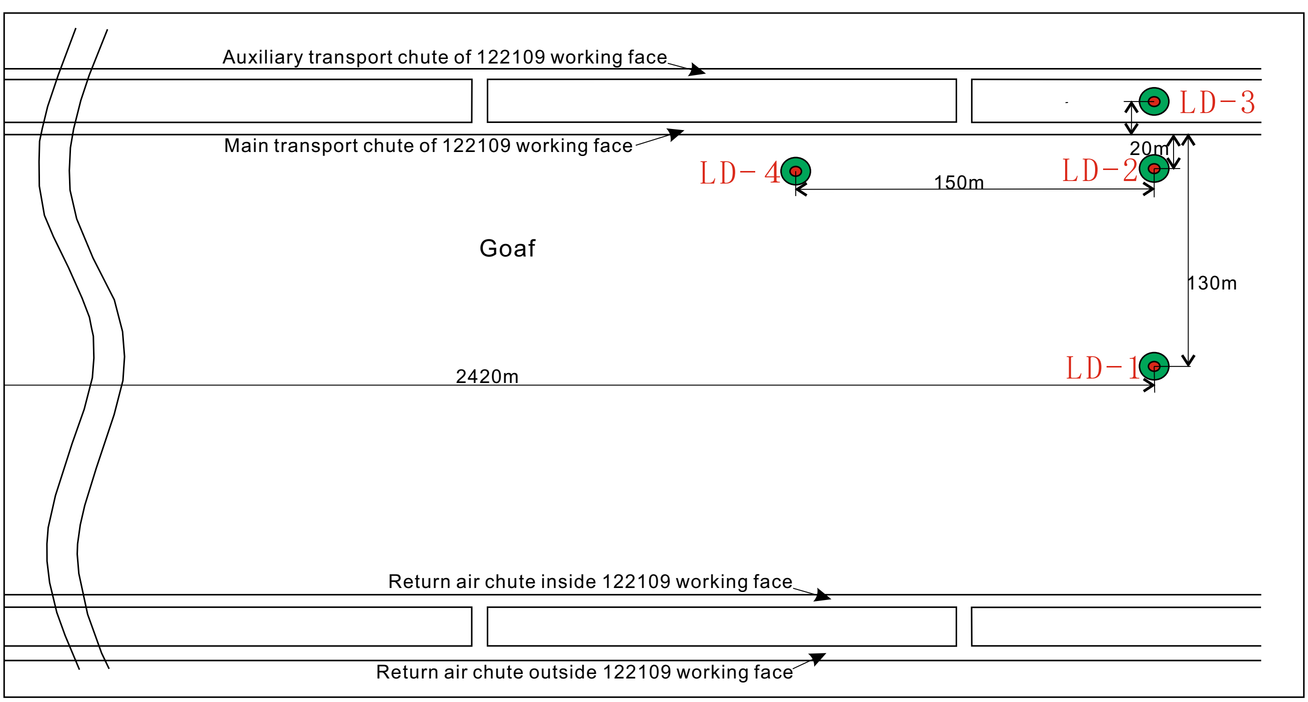


Fig. 5 Layout of monitoring boreholes

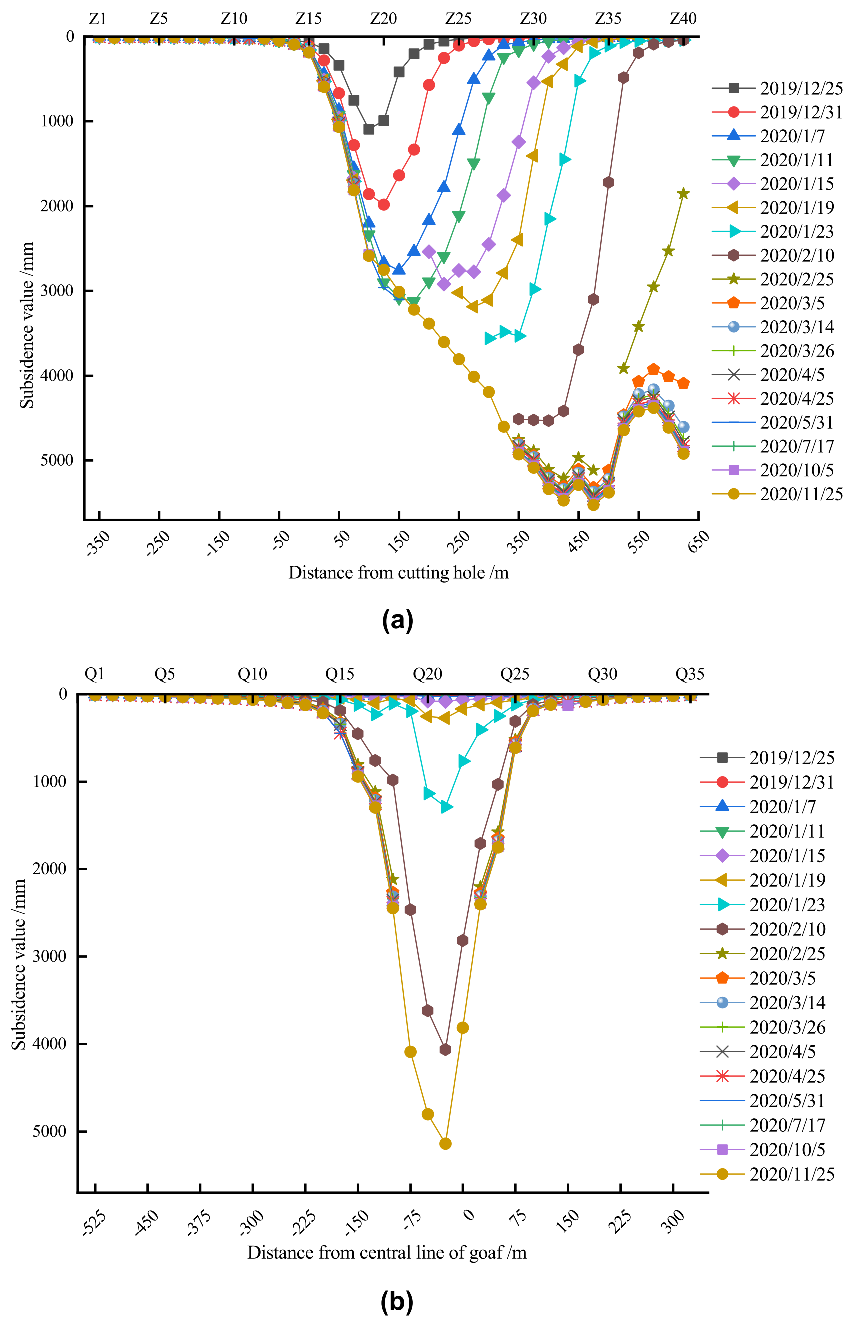


Fig. 6 Dynamic subsidence curve of 122,109 working face in different observation periods **a** Strike observation line and **b** Dip observation line

Quaternary Upper Pleistocene Salawusu Formation aquifer, supplies the surface ecological vegetation, also decreased, and the runoff field of the Quaternary Upper Pleistocene Salawusu Formation aquifer also changed due to the breaking and subsidence of the rock layer (Liu et al. 2019a, b; Wang et al. 2013; Xu et al. 2020a, b). The area's surface vegetation was extensively depleted by the decline of the water table. In addition, cultivated land in the collapse site was severely damaged and the standing water prevented the growth of the cultivated vegetation. This paper refines a generalized model of rock damage after high-intensity mining to provide theoretical support for the realization of "coal resources-ecological environment" in ecologically fragile mining areas (Fig. 8).

When the top of the water-flowing fractured zone communicates with the aquifer of the Salawusu Formation, the water will percolate from the water channel into the mine. If water flow exceeds the mine's drainage capacity, a water inrush will occur (Yin et al. 2019). Meanwhile, the aquifer's water level decline and accumulation in the subsidence zone will cause the vegetation to die. Therefore, when carrying out high-intensity recovery mining in ecologically fragile areas, the contradiction between the fragile

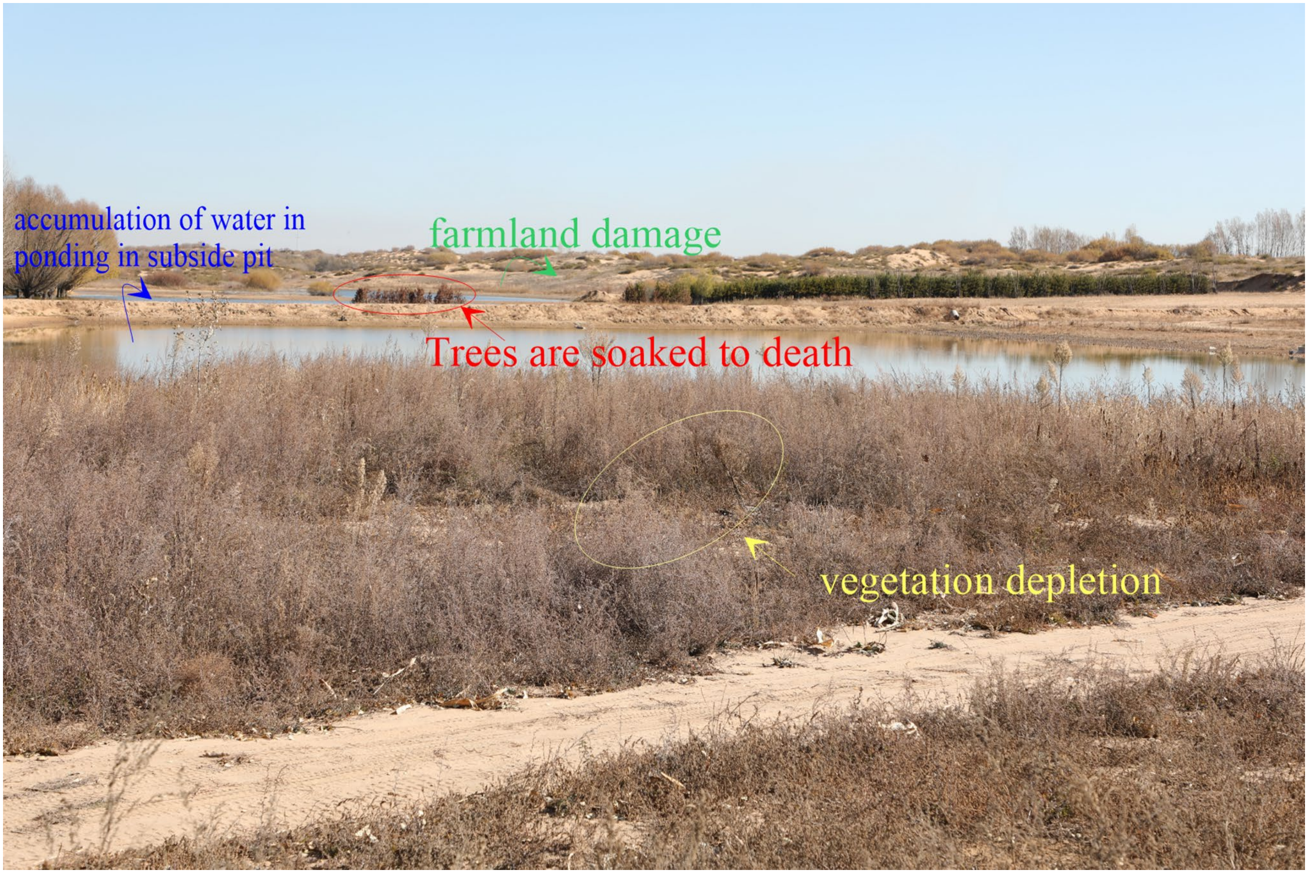


Fig. 7 The observation map of the 16th period

Table 1 Monitoring borehole test results

Borehole identification	Mining thickness (m)	Water flowing fracture zone	
		Height (m)	Ratio of fracture height to mining thickness
LD-1	11	210.1	19.1
LD-2	10.5	213.4	20.3
LD-3	11.5	140.5	12.2
LD-4	10.5	215.0	20.5

ecological environment and high-intensity coal mining must be resolved by the development of water-controlled coal mining methods.

Water-Controlled Coal Mining Architecture in Fragile Mining Areas

A collaborative mining framework for water-controlled coal mining in ecologically fragile areas was designed (Fig. 9). The framework has four components. First, the ecological landform, hydrogeological conditions, and height of the water-flowing fractures of the mining area must be investigated, which we summarize as "three studies". Next, the coal mining method and process parameters used when mining the coal seam must be determined, which we refer to as "one determination". Then, analog and numerical models are used to determine and verify the most rational coal mining and recovery methods. If the result indicates that the methods being evaluated will not meet the requirements for water-controlled coal mining, then you go back to the previous step. Because the research methods consist of both physical and numerical simulations, we refer to it as "two verifications". The final component is to track and analyze the selected coal mining method and process parameters to validate whether the degree of surface damage and the water level change of the aquifer meet the requirements of water-controlled mining. This involves evaluating the degree of surface ecological damage after mining and the change of the water level in observation wells, which we briefly refer to as "two tracking".

In summary, the collaborative framework for water-controlled coal mining in the ecologically fragile area can

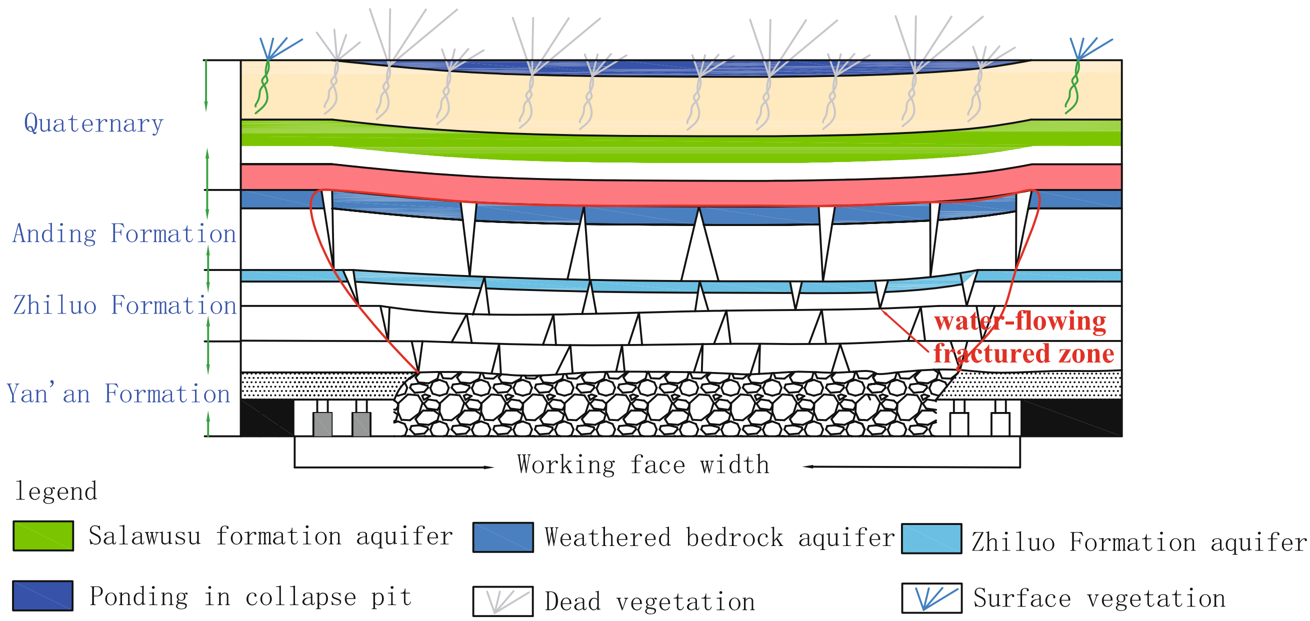


Fig. 8 Geological generalization model

be briefly described as “three studies, one determination, two verifications, and two tracking”. The four parts of the collaborative mining framework complement and interact with each other, as opposed to independently studying the mine geology, mining methods, and ecological environment. Therefore, using this architecture should maximize the utilization of coal resources and ecological landform protection while minimizing water loss in the aquifer.

Discussion

The establishment of a water-controlled coal mining framework in ecologically fragile areas is affected by many factors. Understanding the influence of various factors is essential to tailor a collaborative mining framework to site-specific conditions and fully exploit the positive effects of all parameters of the mining process. The mine’s location determines the ecological environment and hydrological characteristics. The mining methods and process parameters must be optimized to coordinate both protection of the fragile ecological environment and production of high-intensity coal mining (Zhang et al. 2020; Liu et al. 2019a, b). In this paper, a fluid–solid coupling numerical simulation model was used to analyze how different mining parameters affected the ecological environment (Li and Wu 2019).

Analysis of Factors Influencing the Mining Structure of Water-Controlled Coal Mining

The Influence of Working Face Length on Water-Controlled Coal Mining

To analyze the impact of working face length on surface ecological water environment, we simulated and analyzed the development of the fracture zone and the seepage evolution of the Salawusu Formation aquifer when the working face length was 80, 200, and 260 m, respectively (Fig. 10).

When the working face length was 80 m, the maximum height of model overburden damage was 46.8 m; As the working face lengthened, the overburden failure height continued to develop upward. When the working face length was 260 m, the overburden failure height peaked at 172.3 m. At the same time, the seepage field of the same cross section changed, because the height of the water diversion channel was different at different working face lengths, which caused the seepage field to change. However, when the working face length is 200 and 260 m, it affected the Zhiluo Formation aquifer, as the water flowed into the funnel formed by mining. The working face length is positively correlated with the flow vector of seepage field; for the same coal seam mining thickness, the overburden failure height and aquifer water loss both increase with the working face length.

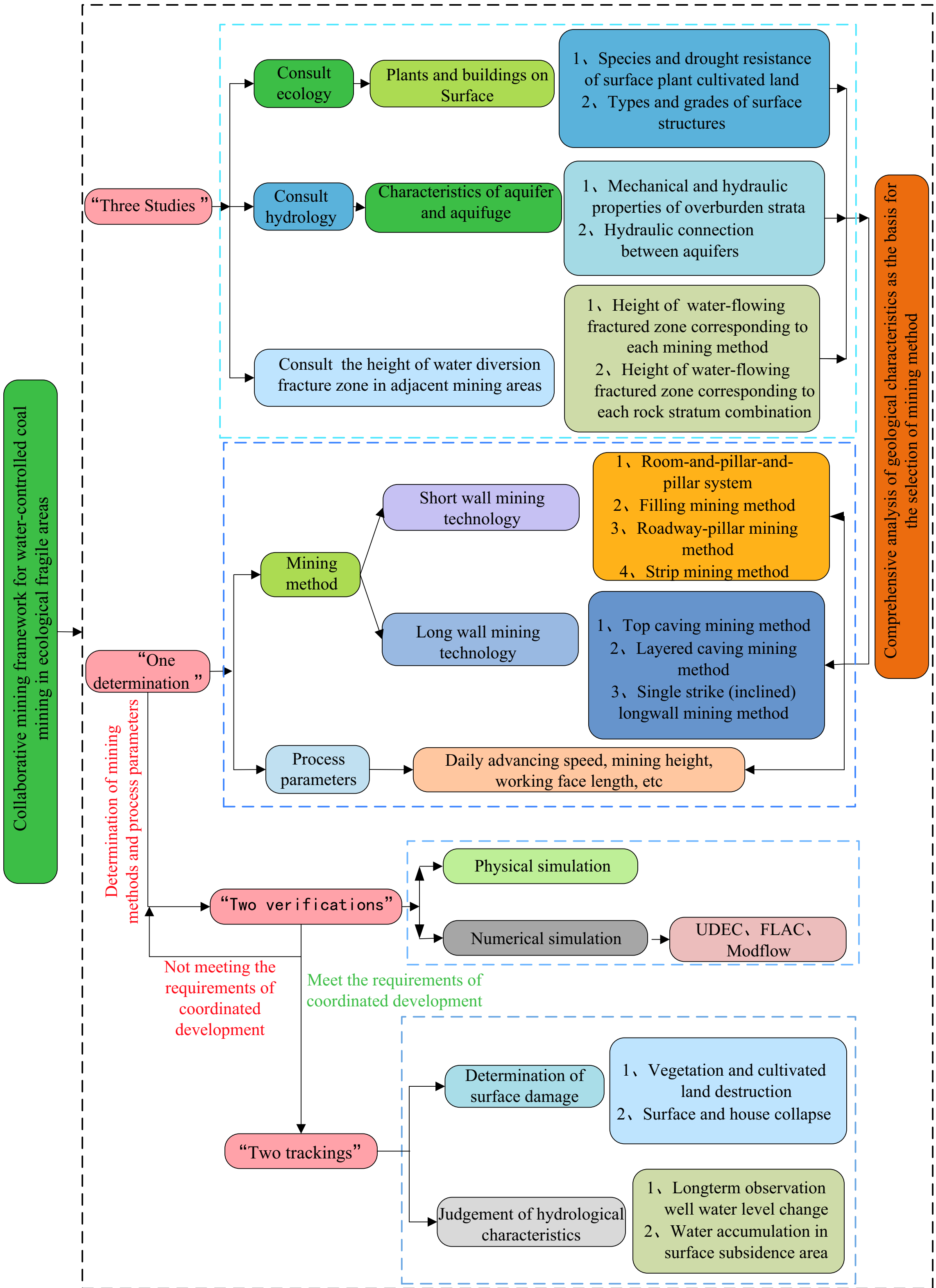


Fig. 9 Collaborative mining framework of water-controlled coal mining in ecologically fragile area

The Influence of Coal Seam Mining Thickness on Water-Controlled Coal Mining

To analyze the impact of coal seam mining thickness on the surface ecological water environment, coal seam mining thicknesses of 4, 7, and 12 m were selected for simulation, and the corresponding development of the diversion fracture zone and seepage evolution were extracted.

The influence of coal mining thickness on water-controlled mining is shown in Fig. 11. When the length of the working face was 280 m, the height of overburden failure reached the bottom interface of the Zhiluo Formation aquifer under various coal seam mining thickness conditions. However, the height of the overburden failure linearly increased as the coal seam mining thickness increased. The height of overburden failure was 139.4 m when the coal seam was mined at a thickness of 4 m, and 147.1 m when it was mined at a thickness of 7 m. Seepage also increased accordingly. In summary, under the same hydrogeological conditions, the loss of water due to overburden failure is related to the mining process parameters of the working face.

The Influence of the Coal Mining Method on Water-Controlled Coal Mining

Supplemental Fig, S-4 shows the simulation results in response to two mining methods. When the thick coal seam was mined by backfill mining, the height of overburden failure was much less than that induced by mining the entire thickness at one time, whereas the direction of aquifer runoff was changed. The main reason for this phenomenon is that when backfill mining was used for backstoping, the downward movement of the overburden was restricted, and the overburden did not break. On-site investigations confirmed that there was little surface subsidence using the backfill mining and there was negligible impact to the ground surface.

Uncertainty Analysis

Many parameters are involved in identifying the mining framework for water-controlled coal mining. The hydraulic conductivity of the aquifer, mining thickness of the coal seam, width of the working face, and mining speed are some of the parameters. These parameters tend to vary over wide ranges (Li et al. 2018; Liu et al. 2019a, b). For example, lithology, tectonic activity, and sedimentary characteristics affect hydraulic conductivity, resulting in spatial heterogeneity of the aquifer. However, the heterogeneity of the strata was not considered while establishing the fluid–solid coupling model; instead, the strata were considered to be isotropic and homogeneous. No quantitative relationship between changes in the aquifer's hydraulic conductivity and mining intensity has been reported in the literature, and due to limited borehole data, the hydrological zoning characteristics of the mining area were not quantitatively evaluated. In

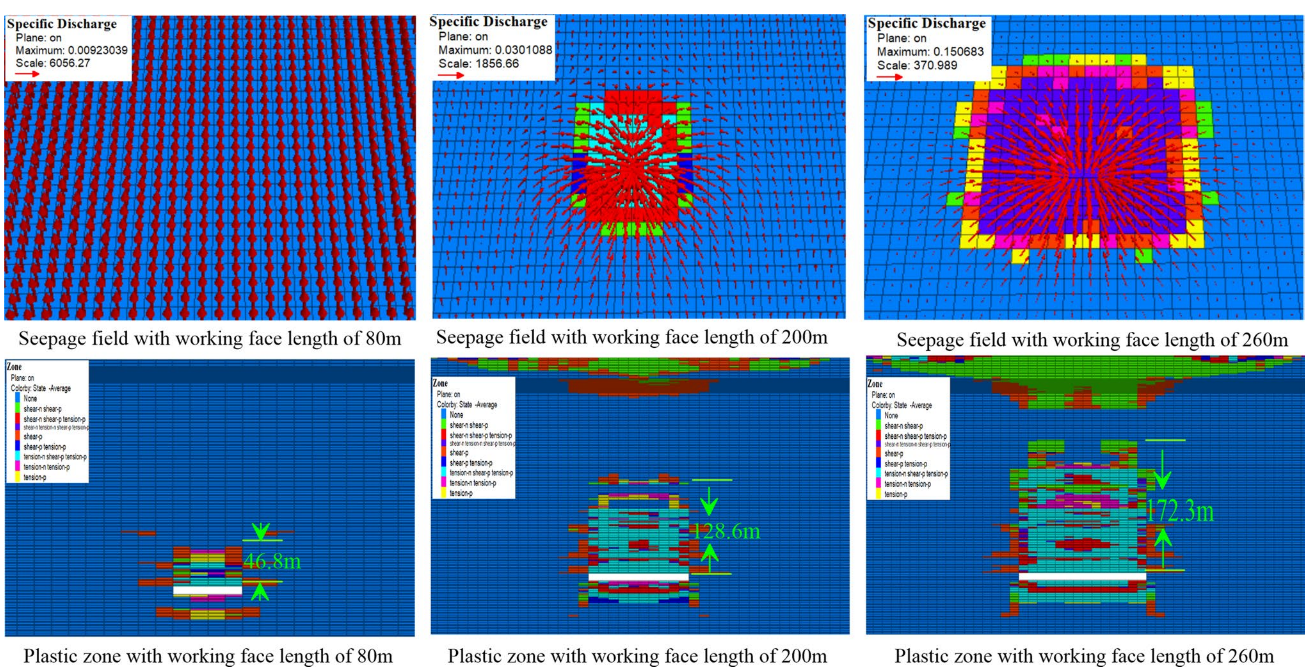


Fig. 10 Characteristics of overburden failure and seepage evolution under different working face lengths

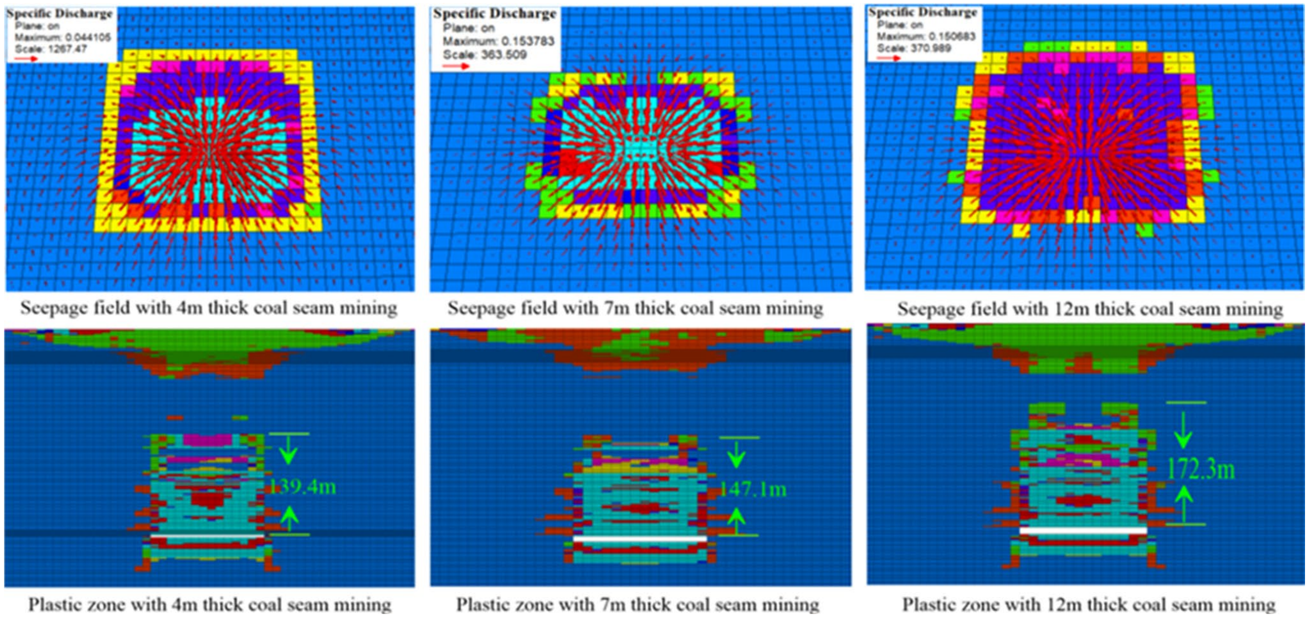


Fig. 11 Characteristics of overburden failure and seepage evolution under different coal seam mining thickness

addition, the standards for post-mining land use and restoration of any ecological destructions were undefined.

Prospect

In this study, a coordinated framework for water-controlled coal mining was established and applied to the Yushen mining area in northern Shaanxi, China. The results can be used for reference in other mining areas with similar conditions. However, additional studies are needed to improve the proposed framework, particularly with respect to the following points:

(1) The mining areas of western China that exercise high-intensity backstoping uphold the concept of water-controlled coal mining. However, high intensity mining could still have a great impact on the surface ecology, such as sharp drops in the ecological water level, drying up of springs, and formation of subsidence pits on the surface (He et al. 2016). The cost of induced disasters by high-intensity mining, such as restoration of ecological landforms or treatment and compensation of subsided land, is not included in calculating the cost per ton of coal. The traditional method of calculating the cost per ton of coal based only the cost related to production is still used, which greatly reduces the mining cost. Therefore, when carrying out water-controlled coal mining in western mining areas, we should consider both the coal seam recovery coefficient and the overall cost/benefit to the area.

(2) The water-controlled coal mining framework for ecologically fragile mining areas proposed in this paper was obtained by analysis, numerical simulation, and empirical data collected in the Yushen mining area. Further research is needed to apply this mining framework to other mining areas with different geological and ecological conditions.

(3) Coal mining enterprises have been using their experience to protect water and ecology. For example, an empirical formula derived in the last century is still used to predict the height of the water flowing fractured zone in mining areas of western China. However, the geological conditions of mining in the last century are significantly different from the geological conditions of the mines in western China. The use of these empirical formulas in the western mining areas will produce great errors and misleading results. At the same time, technical specifications have not been developed for ecological restoration in mines, and currently, technical specifications are only at the theoretical stage, and reasonable measures should be formulated according to the characteristics of different mining areas. When a mine carries out ecological restoration work, the damaged ecological landforms are not classified and prioritized; instead, the damaged areas are treated uniformly.

Conclusion

A coordinated mining framework for ecologically fragile areas was established based on both protecting the ecological water environment and extracting coal resources. Its core contents are identifying the bearing capacity of the ecological environment of the mining area, identifying the degree of surface ecological damage with coal seam mining, and identifying how the water-flowing fractured zone evolves and develops in the overburden. The following conclusions are drawn from the theoretical analysis and on-site monitoring data:

(1) Beam theory analysis suggests that the total amount of water loss from the aquifer is affected by the advancing speed of the working face, the length of the working face, the mining thickness of the working face, the thickness and ultimate tensile strength of the key impervious strata, and the hydrological coefficient of each aquifer.
(2) By monitoring the degree of surface ecological damage after high-intensity backstoping of the 122,109 working face, it was found that the maximum surface subsidence was 5.6 m. At the same time, irreversible "induced disasters" such as massive accumulation of water, depletion of vegetation, and destruction of arable land occurred in the surface subsidence area, which aggravated the original fragile landform of the mining area.
(3) Based on an analysis of the water-flowing fractured zone over the 122,109 working face, the height of overburden failure after mining reached the aquiclude, the Neogene Baode Formation laterite layer. The height of the water-flowing fractured zone is $\approx$ 21 times the mining height. The areas where the laterite layer is thin or missing are prone to water hazards.
(4) The proposed framework for water-controlled coal mining in ecologically fragile areas not only maximizes the extraction of coal resources in the mine area but also minimizes the irreversible induced disasters that often occur in mines that pursues high-intensity mining. The components included in the coordinated mining framework are complementary and mutually constraining. The fluid–solid coupling simulations were used to verify how coal seam mining thickness and face lengths affect collaborative water-controlled coal mining. The degree of deterioration of the ecological environment is positively correlated with mining process parameters when mining coal seams in an ecologically fragile environment.
(5) The proposed mining framework lays a solid foundation to determine and calculate the cost caused by environmental damage after mining and balance high benefit and high efficiency. The overall approach can be tailored to each specific mining area to formulate technical specifications for ecological restoration. Adoption of water-controlled coal mining reflects improvements in mining that coordinate production of coal resources and protection of the ecological water environment. The research results obtained in this paper are of great reference value and significance for the further refinement of water-controlled coal mining.

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