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Effect of Layer Spacing on Fracture Development and Seepage Evolution of Surrounding Rocks During Repeated Mining Under Insufficiently Collapsed Gob

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Abstract: Repeated mining under insufficiently collapsed gobs is a complex process in underground mining and is associated with safety hazards such as ground collapse and subsidence. The effect of layer spacing on the fracture network evolution and fluid transport mechanisms in rock strata during this process has not been systematically studied. In this work, the discrete element method was employed to analyze the fracture development and seepage evolution of surrounding rocks in the Nanliang coal mine across varying layer spacings (5, 20, 35, 50, and 65 m). A systematic evaluation of the rock mass integrity was conducted through damage coefficient quantification. The key findings revealed that an increase in the layer spacing progressively reduced the damage coefficients in both the overburden strata above the goaf and in the interlayer formations ahead of the working face, accompanied by reduced fracture propagation intensity. Shear failure mechanisms dominated throughout the mining process. Fractal characteristics of the fractures intensified with the advance of the working face, while the hydraulic conductivity and interstitial pressure in the interlayer strata exhibited declining trends with reduced attenuation rates. Our findings provide critical insights for ensuring the safety and improving the efficiency of repeated mining under insufficiently collapsed gobs.

Keywords: layer spacing; repeated mining; insufficiently collapsed gob; fracture development; seepage evolution



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1. Introduction

The progressive depletion of shallow, easily accessible coal reserves has intensified mining activities in structurally complex coal seam groups, particularly in China where multilayered coal formations dominate [1,2]. The effect of layer spacing on the fracture network evolution and fluid transport mechanisms in surrounding rocks is a concern in the mining of coal seam groups, particularly while mining under insufficiently collapsed gobs formed by interval mining. Hence, it is necessary to study the influence of layer spacing on the fracture development and seepage evolution of surrounding rocks during repeated mining under insufficiently collapsed gobs. Such research can provide theoretical support for the stability control of surrounding rocks during coal seam group mining.

Current studies on fracture propagation within coal seams have predominantly employed computational modeling and experimental approaches, supplemented by field data interpretation. For example, Lian et al. [3,4] used FLAC3D-based computational platforms to examine roadway deformation patterns during repeated mining and validated their simulations against empirical measurements. Focusing on shallow coal seams in the Ning-tiaota mine, Huang and Han [5] identified stress redistribution mechanisms and secondary crack expansion features in the overlying strata. Zhang et al. [6] adopted UDEC discrete element modeling to evaluate fracture dynamics in shallow-buried adjacent seams with varying interlayer configurations in the Shendong mine. For deep coal seams, Li et al. [7,8] integrated numerical and 3D similar simulations to reveal fracture evolution mechanisms during repeated mining. Pan et al. [9] investigated vertical crack propagation mechanics and spatial fracture patterns in the overburden strata; Huang et al. [10–12] modeled the multi-seam mining process in the Wanli mine to assess fracture mining interactions.

Physical simulation have been frequently utilized in experimental studies. Ghabraie et al. [13–15] tested diverse sand mixtures to characterize fracture development in multi-seam environments. Ning et al. [16] formulated a roof failure criterion, demonstrating that large interlayer distances prevent lower-seam mining from altering the failure patterns of the upper-seam roof, though greater mining heights intensified overlying strata damage. Cheng et al. [17] analyzed stress-induced fracture distribution under dual-layer mining in Shaqu coal mine located in Shanxi Province, China. Teng et al. [18,19] explored fracture control strategies for coal pillars under repeated mining. Liu et al. [20] correlated fracture patterns with fractal dimensions using splitting tests and field data. Guo et al. [21–23] combined physical and numerical models to examine overburden failure mechanisms, whereas Zhang and He [24] employed field-monitored simulations to identify the structural interactions between fracture networks and load-bearing strata. Whether it is laboratory experiments or numerical simulations, there are currently few studies on the development law of fractures in surrounding rocks after repeated mining of coal seam groups under insufficiently collapsed gobs.

Permeability behavior in multi-seam systems has been examined through coupled numerical and experimental methods. Zheng et al. [25] developed a multi-physics model linking permeability, mechanical damage, and gas adsorption to assess subsidence impacts on underlying layers. Shi et al. [26] simulated ventilation dynamics in multi-level goafs under fire zones, resolving coupled seepage–diffusion equations. Jia et al. [27] integrated mechanical-permeability tests with numerical simulation to quantify the permeability evolution in protective layers. Tian et al. [28] evaluated stress–displacement–gas flow interdependencies in long-distance mining seams. He et al. [29] modeled permeability variations in protected seams during the mining of the lower protective layer.

Laboratory-based permeability analyses include Yuan and Zhang's [30] cyclic stress–path experiments on coal–gas systems. Ren et al. [31] demonstrated that disturbed stress levels significantly enhance pre-failure permeability. Xue et al. [32] compared permeability distributions under protective layer mining, top coal caving mining, and no pillar mining methods. Zhang et al. [33–35] revealed time-dependent permeability alterations during repeated mining, noting reduced stress sensitivity during loading phases and amplified effects in fractured specimens. Li et al. [36,37] identified logarithmic and power-function relationships between permeability, stress, and porosity in fragmented coal under cyclic loading. Whether it is experimental approaches or computational modeling, there is currently a lack of research on the characteristics of rock seepage after repeated mining of coal seam groups under insufficiently collapsed gobs.

In summary, while existing studies have focused on addressing the fracture and permeability behavior of coal seam groups, limited attention has been given to the effect of

layer spacing during repeated mining under insufficiently collapsed gobs. To address this issue, this study employed discrete element modeling to quantify how varying interlayer distances govern fracture propagation and permeability evolution in the repeated mining of the Nanliang mine under insufficiently collapsed gob.

2. Methodology

2.1. Numerical Modeling of Repeated Mining Under Insufficiently Collapsed Gob

Focusing on repeated mining in the interval goaf of the Nanliang coal mine, this study utilized the Universal Distinct Element Code (UDEC 7.0) modeling platform to simulate mining processes under insufficiently collapsed gobs. The geo-mechanical properties of the numerical model were calibrated based on the field data, shown in Figure 1 and Table 1, to ensure accuracy. Figure 1 illustrates the comprehensive histogram of the 30105 working face and the location of Nanliang coal mine. Table 1 details the mechanical parameters of distinct geological layers. All the data listed are from the coal mine site. The ratio of the horizontal stress to the vertical stress in the shallow coal seams was 1.25.

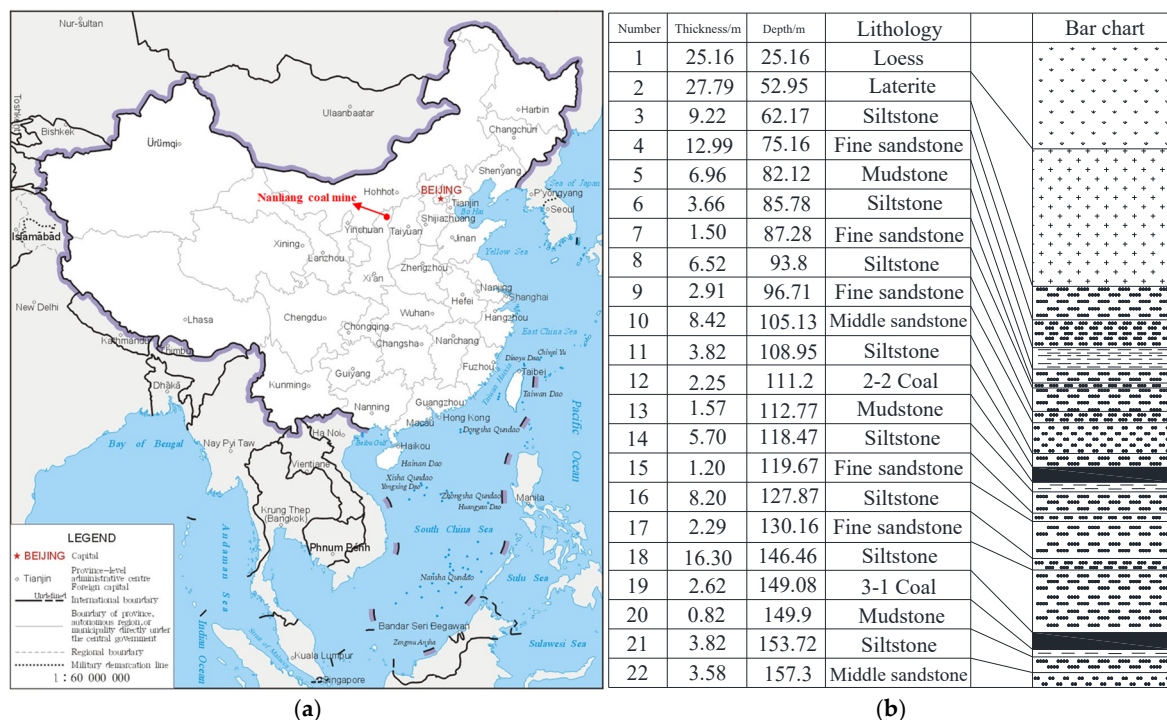


Figure 1. Location diagram of the Nanliang coal mine (a) and a comprehensive histogram of the 30105 working face (b).

Table 1. Mechanical parameters of the coal and rocks in different strata around the Nanliang coal mine.

Lithology	Density (kg/m ³)	Poisson's Ratio	Elastic Modulus (GPa)	Bulk Modulus (GPa)	Shear Modulus (GPa)	Compressive Strength (MPa)	Tensile Strength (MPa)	Cohesion (MPa)	Internal Friction Angle (°)
Loess	1800	0.44	0.07	0.19	0.02	0.18	0.10	0.15	10
Mudstone	2033	0.36	3.0	3.57	1.10	25.20	1.90	2.2	30
Fine sandstone	2268	0.24	4.1	4.19	1.56	37.80	2.83	2.91	43
Middle sandstone	2182	0.32	3.9	3.61	1.48	35.20	2.50	2.8	35
Siltstone	2293	0.31	4.9	4.30	1.87	47.22	3.73	5.37	36
2-2 coal seam	1251	0.29	2.6	2.06	1.01	20.43	1.45	2.98	44
3-1 coal seam	1251	0.31	2.8	2.46	1.07	22.50	1.24	2.97	37

Based on the comprehensive histogram shown in Figure 1 and the mechanical parameters listed in Table 1, a 200 m × 158 m discrete element model of the Nanliang coal

mine was constructed, as shown in Figure 2, using the Mohr–Coulomb constitutive model. For the 2-2 coal seam, the interval mining method (for every 50 m of the working face advancement, a 10 m coal pillar was left) was implemented, whereas longwall mining was employed for the 3-1 coal seam (the advance distance of the working face typically reaches hundreds of meters or even several kilometers). The excavated zones in the 2-2 seam were sequentially designated as Goaf 1#, 2#, and 3#, whereas the mined-out region of the 3-1 seam was labeled Goaf 4#, with its active face advancing beneath Goaf 2#. Two critical zones were monitored: the overlying rock mass of the 2-2 coal seam and interlayer rock mass in front of the 3-1 coal seam working face, termed research areas A and B, respectively. By monitoring the damage contact area, the damage coefficients of the overlying rock and interlayer rock mass caused by repeated mining were analyzed.

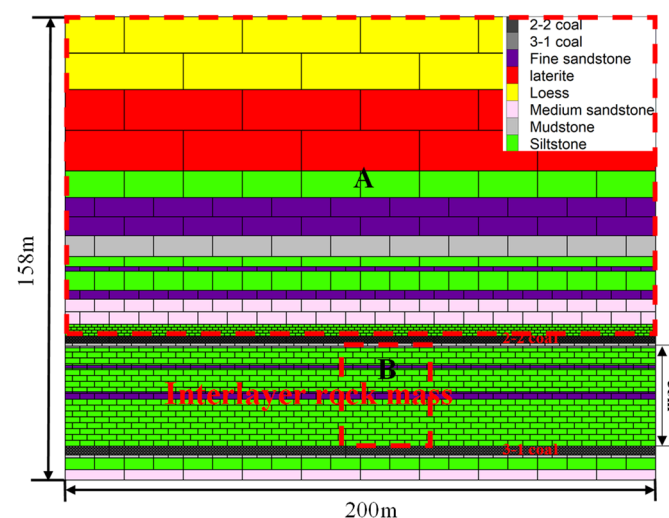


Figure 2. UDEC numerical model of the Nanliang coal mine.

2.2. Seepage Simulation of Repeated Mining Under Insufficiently Collapsed Gob

Based on the above numerical model of the repeated mining under insufficiently collapsed gob, a fluid–solid coupling model was re-established for the numerical simulation. Due to the mining of a shallow-buried coal seam, the surface subsidence and soil dislocation can lead to large cracks in the loose layer as well as water seepage. Therefore, slightly different from the above model, the seepage model is without the soil layer on the surface and assumes that there is a rainwater accumulation area above the 2# goaf. An initial water pressure of 3.0 MPa was applied to the overlying rock mass of the 2# goaf, and a seepage model of the surrounding rock during repeated mining under the insufficiently collapsed gob was constructed, as shown in Figure 3. As the measurement points, two points were selected in research area A and five points in research area B, to monitor the changes in the pore pressure before and after repeated mining (as shown in Figure 3). Laboratory tests conducted based on the actual situation on site, have found that the fragmented coal and rock mixture with a grading index of 0.8 and a mass ratio of 1:10 between the fragmented coal and rock most closely represents the actual situation of the fragmented coal and rock mass in insufficiently collapsed gobs. This study adopted the stress–pore–water seepage coupling model of the fragmented coal and rock mixture obtained through water seepage experiments on saturated, fragmented coal and rock mass, as expressed in Equation (1), which is the permeability evolution model of the fragmented coal and rock mass before and after repeated mining in insufficiently collapsed gobs. Moreover, the axial stress–gas permeability evolution law of the fractured rock mass (expressed as in Equation (2)) was taken as a reference for the water permeability evolution law of the interlayer fractured rock mass before and after repeated mining [38]. A fluid–structure coupling simulation of

the repeated mining process under insufficiently collapsed gob was performed. Figure 4 shows the specific simulation process.

$$\begin{cases} \varphi = m_1 + u_1 e^{\frac{-\sigma_a}{v_1}} \\ k_w = \frac{u_2 - v_2}{1 + e^{(\sigma_a - m_2)/n_2}} + v_2 \end{cases} \quad (1)$$

Here, φ and k_w are the porosity and water permeability of the fragmented coal and rock mass, respectively, and σ_a is the axial stress of the saturated fragmented coal and rock mass; m_1 , m_2 , u_1 , u_2 , v_1 , v_2 , and n_2 are the fitting parameters.

$$k_{fg} = m_4 + n_4 \sigma_{ta} \quad (2)$$

Here, k_{fg} is the gas permeability of the fractured rock mass, σ_{ta} is the axial stress of the fractured rock mass under triaxial compression, and m_4 and n_4 are the fitting parameters.

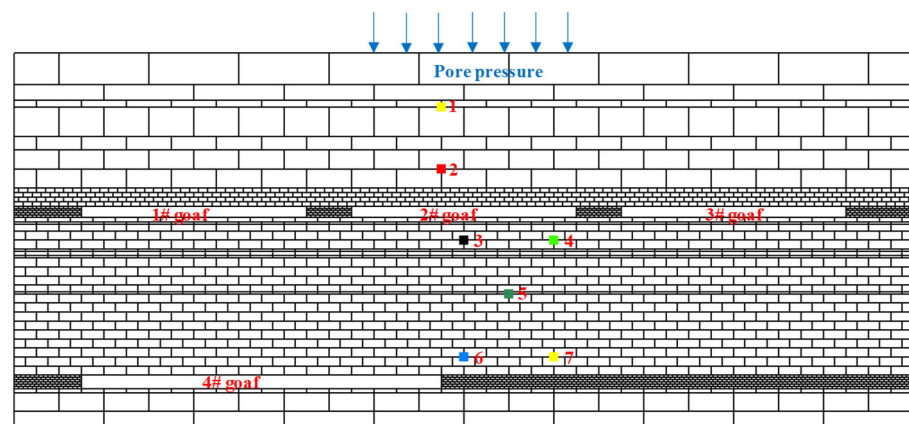


Figure 3. Seepage model of repeated mining under insufficiently collapsed gob.

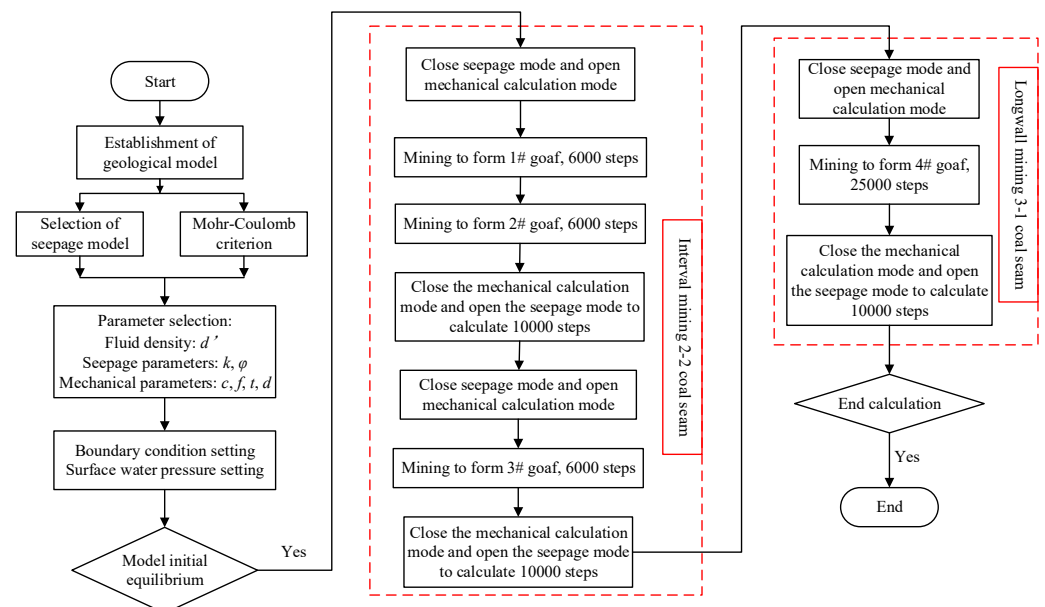


Figure 4. Seepage simulation process of repeated mining under insufficiently collapsed gob.

3. Results and Discussion

3.1. Effect of Layer Spacing on Strata Collapse

As shown in Figure 1, the interlayer rock mass between the 2-2 and 3-1 coal seams of the Nanliang coal mine is mainly composed of siltstone, fine sandstone, and mudstone. The modeling was simplified by only considering siltstone as the interlayer rock mass during the modeling process; its simulation results were unaffected. Therefore, models with layer spacings of 5, 20, 35, 50, and 65 m were constructed to simulate the effect of layer spacing on the fracture development of surrounding rocks during repeated mining.

Variations in interlayer distances do not significantly influence collapse patterns and fracture propagation within overlying rock mass [6]; thus, these were omitted from detailed analysis. Figure 5 shows the post-mining collapse morphologies across various differing layer spacings. The observations reveal that as the spacing increases, both the interlayer rock mass and insufficiently collapsed gob exhibit progressively reduced collapse magnitudes following repeated mining. This indicates that as the layer spacing increases, the stress transmission between the rock mass gradually decreases, and the energy dissipation increases, resulting in a gradual decrease in the degree of rock collapse and a more gradual movement of the rock layers.

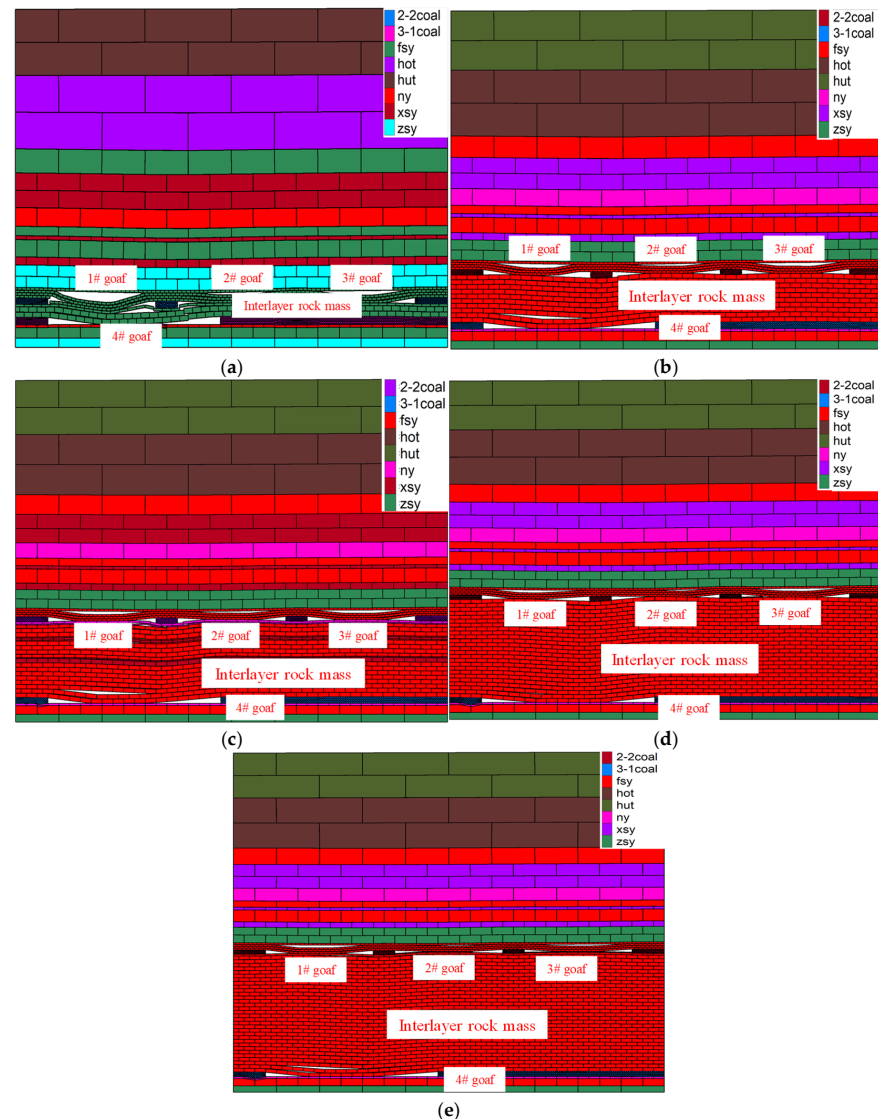


Figure 5. Strata collapse state after repeated mining with different layer spacings: (a) 5 m, (b) 20 m, (c) 35 m, (d) 50 m, and (e) 65 m.

3.2. Effect of Layer Spacing on the Fracture Development of Surrounding Rocks

Figure 6 illustrates fracture propagation patterns under different layer spacings following repeated mining. Observations indicate that in research area A, overlying the insufficiently collapsed gob, the total contact length remains unchanged despite an increase in spacing, while research area B exhibits progressive expansion in terms of both spatial extent and total contact length with increasing spacing. To quantify the impact of interlayer distance on fracture evolution, long-term monitoring of the contact failure length was conducted in both zones.

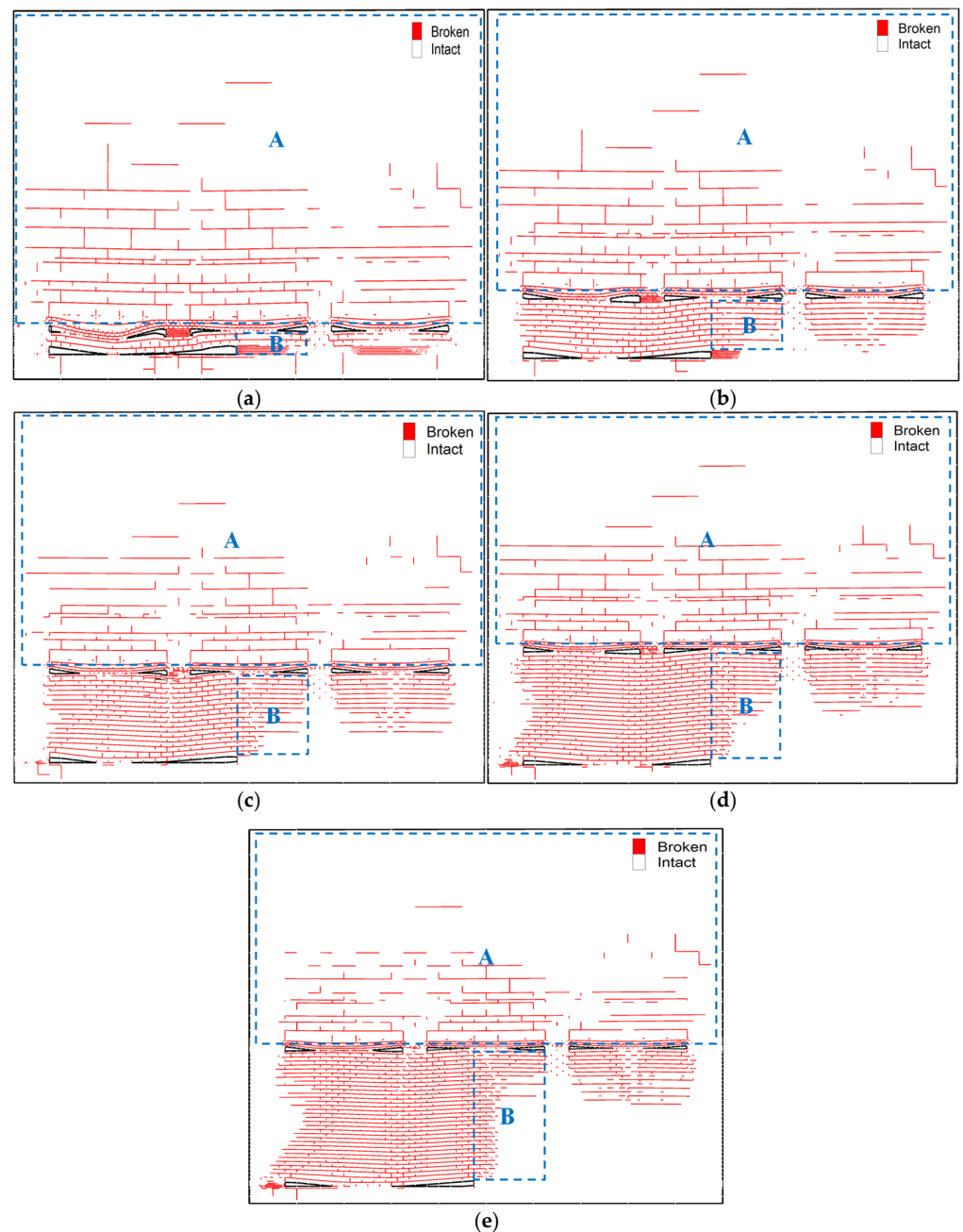


Figure 6. Fracture development state under different intervals after repeated mining: (a) 5 m, (b) 20 m, (c) 35 m, (d) 50 m, and (e) 65 m.

Building upon Bai et al.'s [39,40] analysis on tension-shear fracture evolution during roof failure, this study proposes a rock mass damage coefficient to quantify the fracture development intensity. The total damage coefficient of the rock mass is defined as the

cumulative length of tension and shear failures relative to the total contact length within a monitored zone (Equation (3)). The tension and shear damage coefficients of the rock mass were calculated by dividing their respective contact failure lengths by the total contact length within the monitored zone (as Equations (4) and (5)). The total, tension, and shear contact failure lengths can be calculated using UDEC 7.0 software.

$$K_d = \frac{c_t + c_s}{c_0} \times 100\% \quad (3)$$

$$K_t = \frac{c_t}{c_0} \times 100\% \quad (4)$$

$$K_s = \frac{c_s}{c_0} \times 100\% \quad (5)$$

where K_d , K_t , and K_s are the total, tension, and shear damage coefficients of the rock mass, respectively. c_0 , c_t , and c_s are the lengths of the total contact, tension, and shear contact failures in the rock mass, respectively.

Figure 7 illustrates the impact of layer spacing on fracture propagation within the overburden strata and pre-face interlayer rock mass during repeated mining under insufficiently collapsed gobs. The observations reveal that as the spacing increases, both these regions exhibit a declining damage coefficient, indicating a reduction in both the fracture development intensity and fracture density, and the damage mechanism is dominated by shear. This is consistent with the conclusion presented by Huang et al. [5] in that the overlying rock fractures are mainly composed of shear-tension composite fractures. Notably, at minimal interlayer distances (5 m), shear–tension damage disparities in these zones become apparent. For example, because the goaf in the 2-2 coal seam is insufficiently collapsed gob, that is, the upper rock mass is not fully collapsed, the damage coefficient of the overlying rock mass of the 2-2 coal seam is generally lower than that of the interlayer rock mass. This is consistent with the conclusion drawn by Zhang et al. [6]. Moreover, the reduction extent of the damage coefficient in the overlying rock mass is smaller than that in the interlayer rock mass. This shows that with an increase in the layer spacing, the stress transfer gradually weakens, the stress concentration decreases, and the energy dissipation gradually increases. The residual energy is not sufficient to drive the generation and expansion of new fractures. The disturbance range of repeated mining and the overlap area of the primary mining damage gradually decrease, and the generation of new fractures is suppressed.

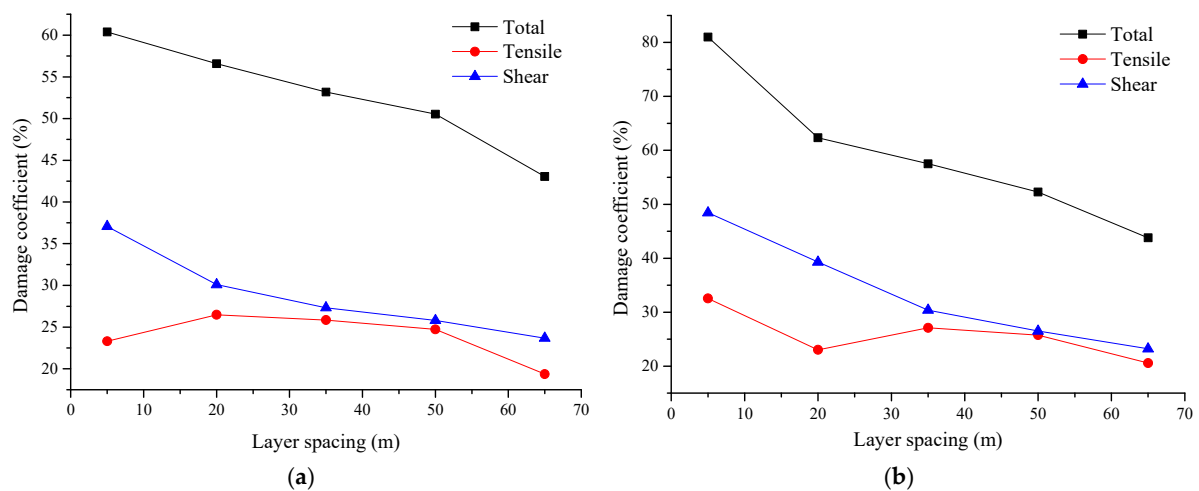


Figure 7. Impact of different layer spacings on the damage coefficient of the rock mass in different research areas: (a) A and (b) B.

To evaluate the effect of the interlayer distance on the fracture network complexity during repeated mining under insufficiently collapsed gob, a fractal analysis was performed using the crack image analysis system (CIAS 1.0) developed by Tang et al. [41]. Fractal dimensions of numerically simulated fracture networks—generated under varying interlayer distances—were computed with CIAS parameters (threshold: 90; noise attenuation: 5). The threshold and noise attenuation values were set to pre-process the image such as gray scaling, binarization, and denoising, facilitating the comparison and fractal analysis of fracture development images with different layer spacings. As depicted in Figure 8, the fractal dimensions exhibit a positive correlation with the layer spacing, indicating enhanced fracture branching and interconnectivity at wider spacings. At wider intervals, a higher fractal dimension is observed within a certain area, indicating that the fracture network is more branched but sparser.

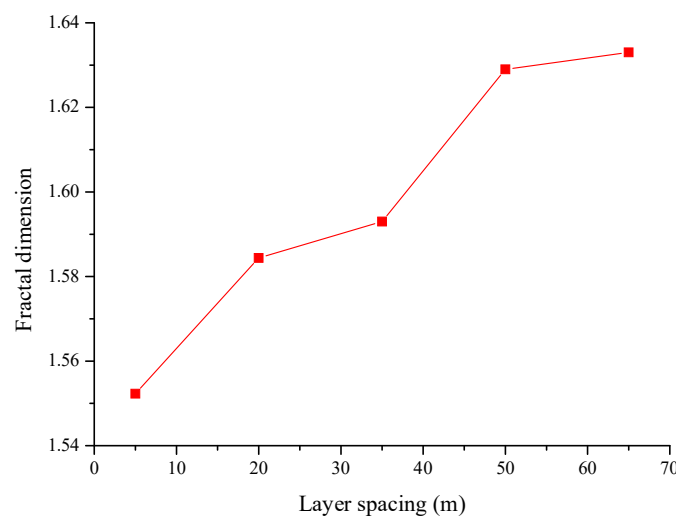


Figure 8. Impact of layer spacing on the fractal dimension of fractures developed in the surrounding rock.

3.3. Effect of Layer Spacing on the Seepage Evolution of Surrounding Rocks

Before repeated mining of the coal seam, because roof caving is insufficient in the insufficiently collapsed gob, the fractures in the overlying rock mass are mostly horizontal tensile fractures and cannot be connected to form a fracture network. After repeated mining, the overlying rock mass and interlayer rock body of the insufficiently collapsed gob are fully caved, resulting in a large number of shear cracks, which connect to the fluid channels. This study mainly simulated and analyzed the seepage flow after repeated mining under the insufficiently collapsed gob and analyzed the flow direction of water in the rock mass by observing the pore pressure in the rock mass fractures. Taking layer spacings of 5, 20, 35, 50, and 65 m, this study compared the seepage characteristics after repeated mining under different layer spacing conditions.

As shown in Figure 9, the pore pressure distribution of the rock formation under different layer spacings is constrained by the color scale range, which is indicated by the boundary of the 0.1 MPa pore pressure. Clearly, with increasing layer spacing, the areas with pore pressure in the interlayer rock mass in front of the working surface in the lower group coal seams gradually decrease, that is, areas with water flowing through gradually decrease. This indicates that an increase in the layer spacing brings about a gradual decrease in both the degree of fracture development as well as the permeability of the interlayer rock body.

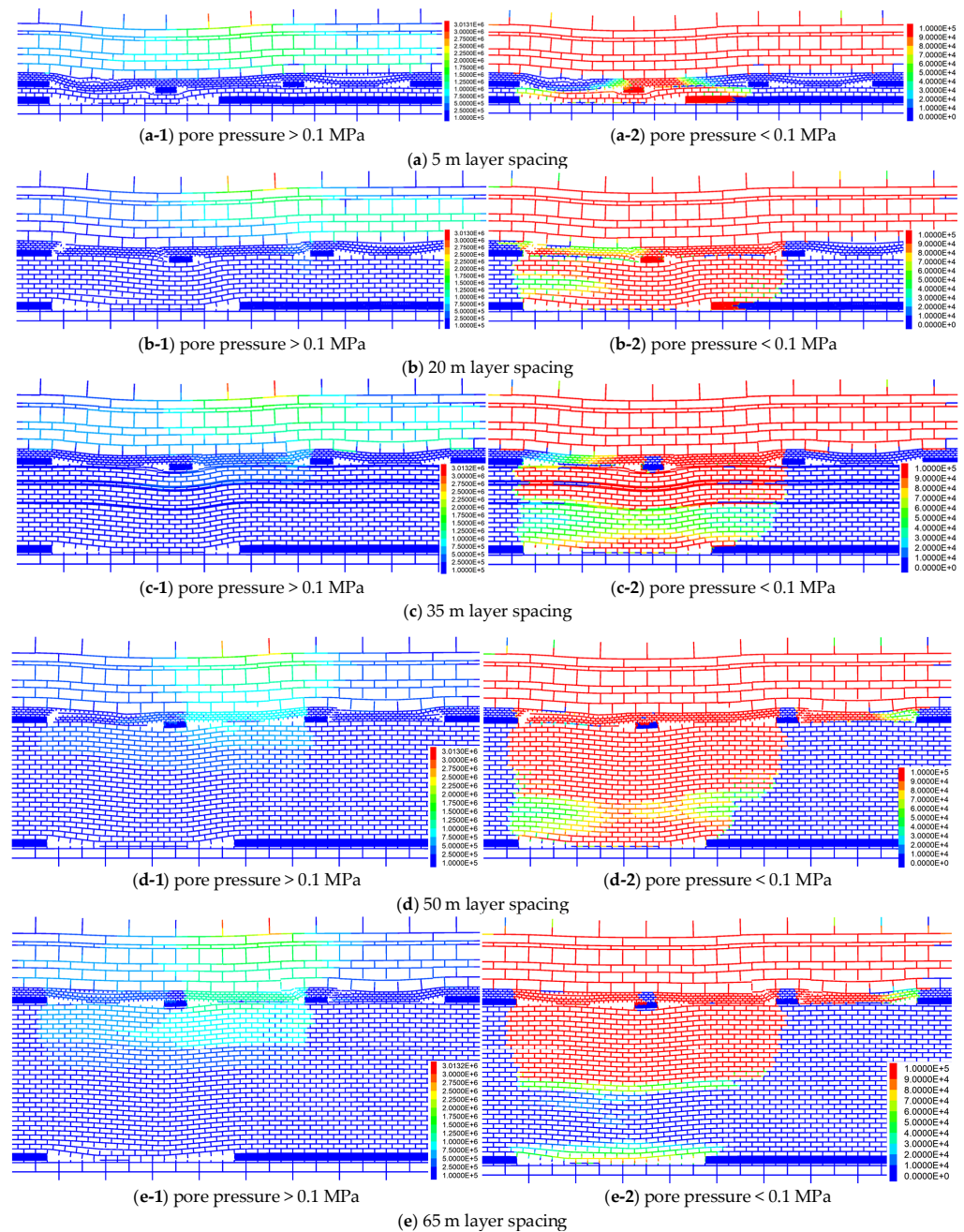


Figure 9. Pore pressure distribution in the rock formation under different layer spacings.

To quantitatively characterize the effect of layer spacing on the seepage characteristics after repeated mining, the pore pressure at measuring point 5, located in the middle of the interlayer rock mass, under different layer spacing conditions was monitored and compared, as shown in Figure 10. The figure shows the pore pressure curves under different layer spacings. With the advancement of the 3-1 coal seam working face, the permeability of the interlayer rock gradually increases, which is consistent with the conclusions drawn by He et al. and Tian et al. [28,29]. With the increase in layer spacing, the pore pressure of the interlayer rock mass gradually decreases, and the rate of decrease becomes smaller.

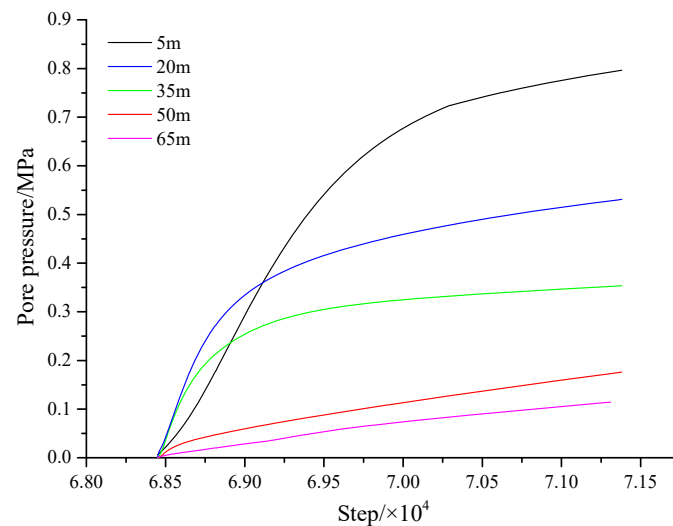


Figure 10. Pore pressure curves for the interlayer rock under different layer spacings.

4. Conclusions

This study evaluated the effect of layer spacing on fracture propagation and seepage behavior during repeated mining under the insufficiently collapsed gob in the Nanliang mine, and compared the fracture network and permeability trends at five interlayer distances (5, 20, 35, 50, and 65 m). The specific results of the study are as follows:

- (1) An increase in the layer spacing was found to be related to a decrease in the collapse magnitude of the interlayer rock. The proposed damage coefficient—the ratio of the tension and shear failure lengths to the total structural contact—helped confirm the progressive decline in the fracture development intensity within the overburden and pre-face zones. Fractal analysis revealed enhanced fracture complexity at wider spacings, although shear failure dominated across all interlayer configurations. Notably, minimal spacing (5 m) amplified shear–tension disparities.
- (2) Layer spacing inversely influenced the pore pressure and permeability in the strata ahead of the advancing face. Wider spacings diminished the pore pressure zones and attenuated permeability–stress coupling, with reduction rates decelerating progressively. This trend suggests a decrease in the number of fluid channels and stress concentrations with increasing layer spacing, consistent with the observed decrease in the damage coefficients. These results are in good agreement with field expectations, emphasizing the role of layer spacing as a critical parameter controlling post-mining hydromechanical behavior.

Our findings provide theoretical support for the safe and efficient mining of repeatedly mined coal seams under insufficiently collapsed gob.

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Conflicts of Interest: The authors declare no conflicts of interest.

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