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Review

Research Progress on Stress–Fracture–Seepage Characteristics for Hazard Prevention in Mine Goafs: A Review

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Abstract: Large-scale coal mining has created many goaf areas, which have become one of the most frequent sources of mine hazards. Investigations on the stress–fracture–seepage characteristics around goafs could help with identifying and controlling goaf-area hazards. Scholars have conducted theoretical analyses, similar simulation experiments, numerical simulations, and field measurements to analyze the multifield coupling development of mining stopes, including the stress variations, fracture advancement, and permeability-change characteristics. In the longwall-mining process, a stress-relief zone is formed above the goaf area, while a stress-concentration zone is formed in the adjacent coal seams. Mining-stope fracture goes through a process of stress-relief expansion, stress-recovery closure, and end-fracture expansion. The permeability of coal rock in mining stopes rises in all directions with the increase in the fracturing ratio. Further studies could concentrate on the distribution characteristics of the abutment pressure around the goaf area. A permeability model based on the coupling of the coal stress, damage, gas adsorption, and desorption is expected to be established to improve the accuracy of the permeability prediction and seepage analysis at the boundary of the goaf area. Relevant studies could provide better theoretical guidance for preventing hazards, such as gas-related incidents and coal spontaneous combustion in the goaf, as well as for the stability control of the goaf boundary.

Keywords: mining hazards; stress distribution; permeability change; goaf area

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1. Introduction

Energy is the basis and support for prosperity and sustainable economic development around the world [1]. Thus, economic development is often positively correlated with the increasing demand for energy [2]. Coal is the main energy source to ensure the healthy economic development of many countries (e.g., a total of 16.7 trillion tons of coal resources have been identified in China, accounting for about 94% of the total fossil energy) [3]. Currently, because of the "Carbon peak" and "Carbon neutralisation" policies for carbon emission reduction, energy development in China is in a stage of intensive transformation. The effects of the incremental replacement of coal by renewable energy are gradually emerging. However, the primary status of coal in economic development will remain unshakable in the near future [4].

The longwall-mining method has the advantages of high output and a high recovery rate, making it widely used in underground mining. However, for this mining method, its potential negative effects on the surface and groundwater in mining areas cannot be ignored. Because most longwall-mining methods use the full-caving technique to manage the roof, the top caving area of the roof is large. Thus, the overlying rock strata subside with serious deformation. When the coal seam is close to the water-bearing layer or the surface water body, mining fractures may penetrate the water-resistant layer, resulting in water loss and the gushing of water out into the working face [5]. In addition, the upper part of the goaf area and surrounding coal bodies are prone to destabilization and collapse, which leads to widespread damage and destruction. The permeability of damaged coal increases by hundreds or thousands of times, causing a large influx of gas from the boundary to the goaf area, and increasing the threat of gas-related incidents and coal spontaneous combustion [6,7]. Therefore, for the safe and efficient production of coal mining, scholars have investigated the stress–fracture–seepage characteristics of the goaf area by theoretical analysis, similar simulation experiments, numerical simulations, and field measurements. In this study, the existing works are reviewed and summarized. Accordingly, future research directions are proposed.

2. Research Progress Analysis

2.1. Stress-Distribution Characteristics of Goaf Area

The weight of overlying strata is evenly distributed over the coal seam before it is mined. With the advancement of the longwall working face, rock formation above the mining space breaks up due to a lack of support, and then collapses into the goaf area. This process causes the redistribution of the primary rock stresses, forming a stress-relief zone above the goaf area, and a high-stress zone in the adjacent coal seam [8]. The additional vertical stress on the adjacent coal seam due to stress transfer is called the abutment pressure, as shown in Figure 1. As the working face advances, crumbling rock in the middle of the goaf area is gradually compacted, and the vertical stress returns to the original-rock-stress level. The overlying load of the goaf boundary is still shared by the coal seam, and the vertical stress is less than that of the original rock. This region is called the stress-recovery zone [9]. According to the distribution characteristics of the mining stress, the surrounding rock of the stope is divided into the original-rock-stress zone, the coal-wall-support influence zone, the stress-recovery zone, and the recompaction zone along the horizontal direction.

Studies on the characteristics of the stress distribution during longwall mining have been intensively conducted. Yixin JI et al. [10] analyzed that the growth coefficient of the abutment pressure in front of the mining working face increases first, then decreases, and finally tends to stabilize, taking the fully mechanized mining face with a large mining height as the engineering background, and simulating a coal-seam depth of 270 m. Minggao Qian et al. [11] divided the abutment-pressure area during longwall-mining advancement into the elastic zone and plastic zone according to whether the coal-seam bearing load is greater than its ultimate bearing strength. They concluded that the abutment pressure in the plastic zone in front of the working face increases exponentially to the peak, while the abutment pressure in the elastic zone exponentially decreases to the original rock stress. To figure out the evolution law of the overburden stress, Hongyun Yang et al. [12] selected 2442, 2443, and 2444 haulage roadways in Baijiao Coal Mine, the buried depth of which was about 518 m, and carried out a physical simulation experiment of multilayer coal mining. The stress in the roadway roof experienced the relief–increase–relief process during the mining of the upper coal seam. In the process of middle-coal-seam mining, there is stress concentration between the upper and middle roadways. After the lower coal seam is mined, there is no concentrated stress. Hongpu Kang et al. [13] took the W2302 working face in Sihe Coal Mine as the engineering background (the overburden depth was between 350 and 430 m). Through a physical similarity experiment and numerical simulation, the relationship between the large-scale roof caving and abutment pressure in a longwall working face was studied. They proposed an increase in the horizontal pressure of the roof to 5 times the pre-mining original rock stress as a precursor to large-roof collapse. By using COMSOL numerical simulation software with the elastoplastic softening model, Shengjun Di et al. [14] analyzed the overburden thickness of 433~586 m on a 12,507 working face in

Tunlan Coal Mine, and found that the stress-concentration zone in the overlying strata of the working face is rounded rectangular. The inclination-direction stress at the beginning of mining is relatively small. As the working face advances, the short-edge effect disappears, and the peak stress around the working face in the goaf area is of the same magnitude. BN Whittaker and RN Singh [15] concluded that there is a yield zone at the longwall-mining face and lateral coal wall. The abutment pressure is zero, and it rapidly rises with the increasing distance from the coal wall, with a maximum abutment-pressure value of four to six times the original rock stress.

Sitao Zhu et al. [16] analyzed the distribution characteristics of the abutment pressure at a longwall mining face under an extra-thick alluvial layer. Based on the load-transfer mechanism between the key layer and stratum, a theoretical-calculation model of the abutment pressure of the longwall face was established. N. E. Yasitli and B. Unver [17] conducted a simulation study on an M3 longwall comprehensive working face in Turkey. They found that the abutment pressure reached a peak value of 14.4 MPa at 7 m in front of the working face, and then gradually decreased with the increasing distance from the working face. At a distance of 70 m, the abutment pressure was reduced to the original rock stress. M. Rezaei et al. [18] regarded a longwall-mining face and its surrounding rock as an independent system. An analytical model of a coal pillar and the roadway-mining-stress distribution was established while considering the strain in the equilibrium before and after mining. Bin Yu et al. [19] monitored the mining stresses in a longwall working face by adopting borehole stress meters. They indicated that the influence range of the abutment pressure at the working face was 100 m, and the peak abutment pressure was 50 m in front of the working face. Guangxiang Xie and Lei Wang [20] concluded that the distribution of the abutment pressure is related to the thickness of the initial coal mining, and the peak value is negatively correlated to the thickness of the initial coal mining and is proportional to the distance from the coal wall.

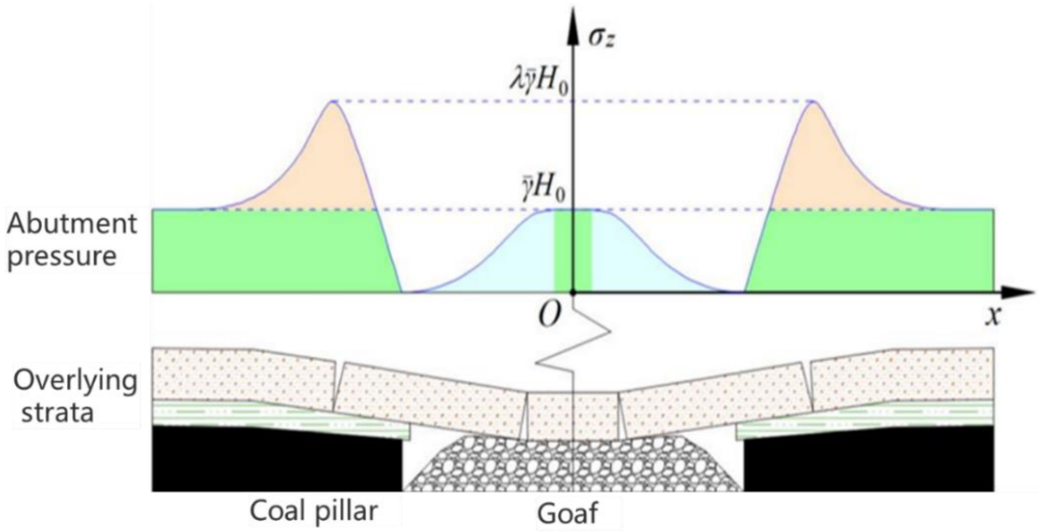
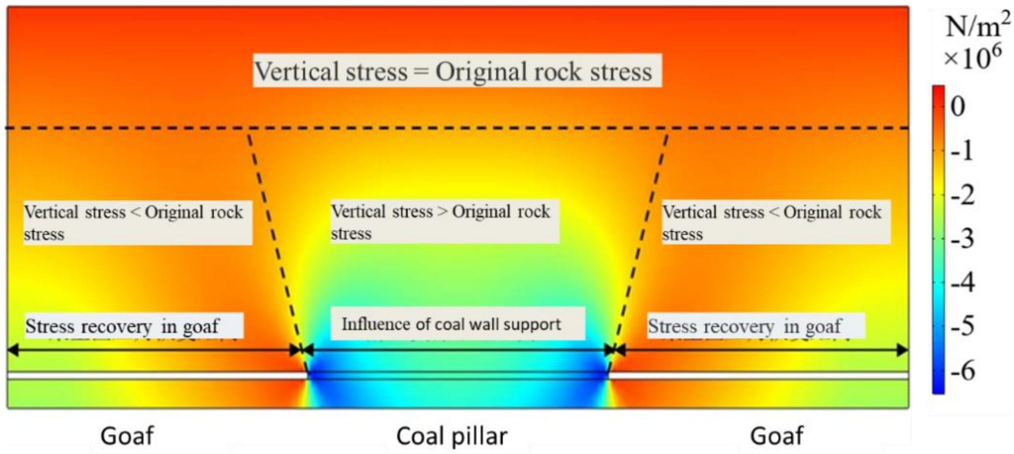
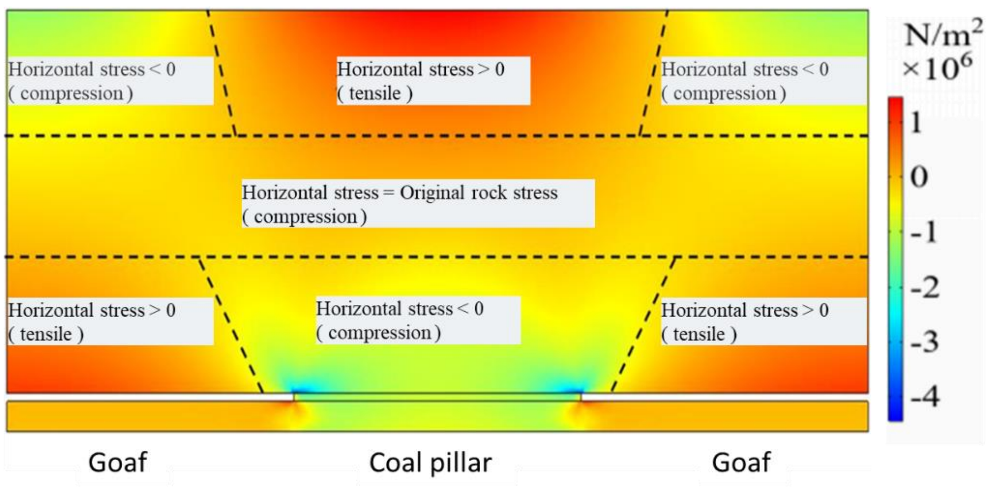


Figure 1. Distribution of abutment pressure in surrounding rock of mining stope [21].

According to the overlying stratum tangential-stress curve of a working face, Jiangong Zhang [22] concentrated on a 12,507 fully mechanized mining face in the Tunlan Mine. He found that the advanced abutment pressure varied greatly with noncomplete mining, and it gradually stabilized with complete mining. Wenxue Wang et al. [23] theoretically investigated the spatial evolution of an underground mining space based on the decay law of the average bulking coefficient of fractured rock that satisfies a logarithmic function with the height, and the functional relationship between the stress recovery of the collapsed and fractured rock in the goaf area and land subsidence was derived. Yihe Yu [21] adopted the finite element analysis software COMSOL Multiphysics (including the Solid Mechanics module with the elastoplastic softening model) to simulate the distribution of the vertical stress, horizontal stress, and shear stress in the overlying strata of longwall mining areas, as shown in Figure 2. He found that, for the vertical-stress distribution of the overlying strata, mining leads to a redistribution of the load in the overlying strata. Part of the load is transferred to the coal pillar, thus making the vertical stress in a certain range above the goaf area smaller than the original rock stress and forming a stress-recovery zone. In contrast, the vertical stress above a certain range of the coal pillar is greater than the original rock stress, resulting in a support zone of the coal wall. Meanwhile, as rock formation is farther from the mining area, the effect of the mining on the vertical stress of the overlying strata decreases. In the part of rock formation near the surface, the vertical stress is nearly equal to the original stress. For the horizontal-stress distribution of the overlying strata, the overlying rock strata of the goaf area are supported by a coal pillar at the end, and they are bent down toward the mining area in the middle, thus forming horizontal tensile stresses in the roof strata of the mined area, and horizontal compressive stresses in the rock strata near the surface. On the contrary, the horizontal compressive stress in the roof strata of the coal pillar and the horizontal tensile stress near the corresponding surface are formed. Regarding the shear-stress distribution in the overlying strata, it is mainly distributed at the junction of the coal pillar and goaf area. Meanwhile, with the increasing distance to the mined area, the shear-stress distribution expands to both sides of the coal pillar and goaf area.

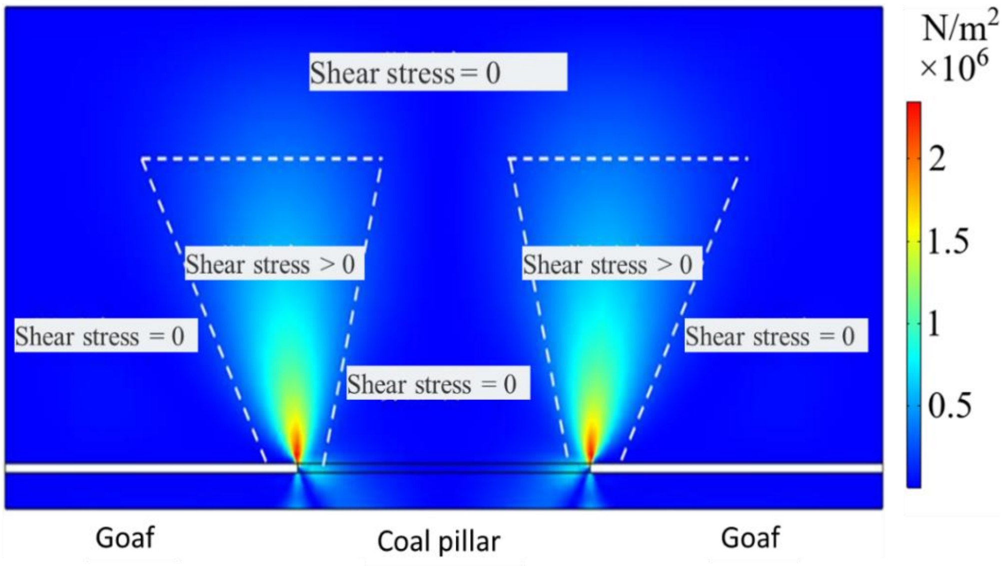


(**a**) Vertical stress in overlying strata.



(**b**) Horizontal stress in overlying strata.

Figure 2. *Cont.*



(**c**) Shear stress in overlying strata.

Figure 2. Mining-induced-stress distributions in overlying strata [21].

Zixin Gao [24] used FLAC3D numerical simulation software (particularly, the elasto-plastic constitutive model and Mohr–Coulomb model) to analyze the deformation and damage in the overlying strata of the goaf area under different mining depths (100 m and 130 m) in Zhangbaya Coal Mine. Under the influence of mining, vertical stresses are unevenly developed in rock mass. Compressive- and tensile-stress zones are developed within the overlying strata. The tensile-stress zone is located within the overlying strata directly above the goaf zone. This area lies within a downward-opening parabola, which is generally where the collapse and fracture zone develop. For compressive stress, its value is large above the coal wall on both sides of the working face, and the value gradually becomes smaller from the bottom to the top, as shown in Figure 3.

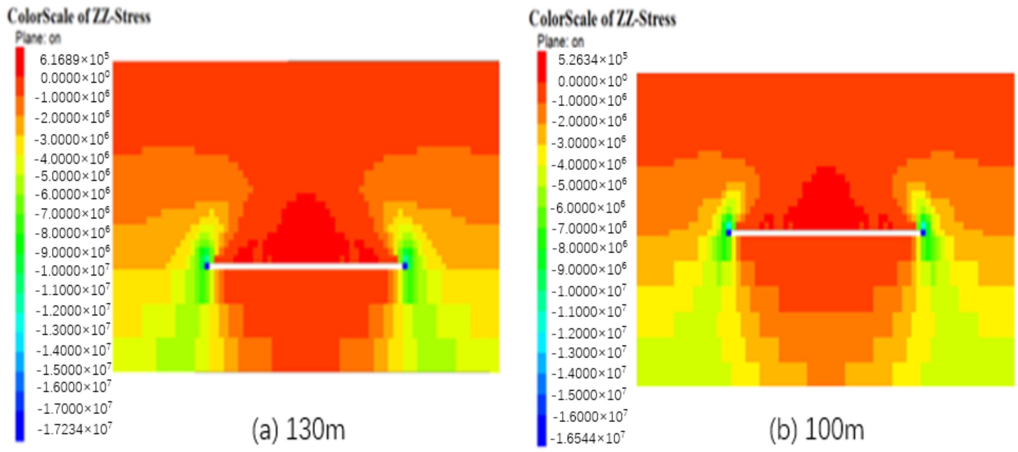


Figure 3. Vertical-stress distribution around goaf area under different mining depths [24].

Meanwhile, shear stress appears in the coal wall on both sides of the goaf area and in the overlying strata of rock. The distribution of the shear-stress area on both sides is approximately symmetrical, with approximately equal stress values and opposite stress directions. Shear-stress concentration also occurs, where the absolute value of the shear stress is the largest, and the shear-stress damage to the rock is the most serious. As the mining depth decreases, the maximum stress value of the shear-stress concentration at the coal wall of the goaf area gradually increases, as shown in Figure 4.

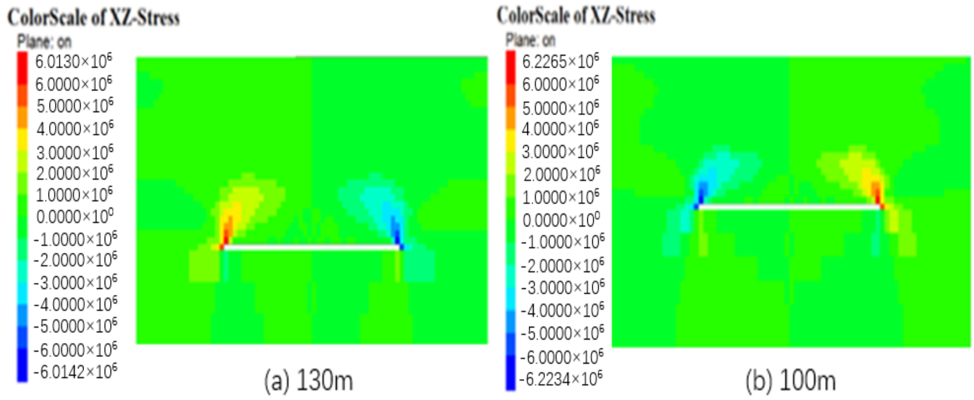


Figure 4. Shear-stress distribution around goaf area under different mining depths [24].

2.2. *Development Law of Fractures in Mining Stopes*

Regarding the characteristics of the overlying-strata fracture development under different mining conditions of a coal-seam group, Jian-hua LI et al. [25] conducted similar-material simulation tests on the overlying-strata changes in a single-level 31,114 mining working face in Lijiahao Coal Mine. The influencing mechanisms of the underlying mining on the development of overlying fractures were revealed. Jie Zhang et al. [26] investigated the fracture-development pattern of a shallowly buried coal seam (buried depth less than 150 m) overlying strata based on the average buried depth (68.21 m) of the coal seam in a 30,100 working face of Nanliang Coal Mine. The influence of the shallow-burial-depth conditions on the fracture-development process and its effect on the wind-leakage pattern in a goaf were analyzed. Jing Zhao et al. [27] took the 20,102 working face of Shennan'ao Coal Mine as the background, with the buried depth of the coal seam being 555~631 m, and the average buried depth of the coal seam being 598 m. They conducted an empirical study on the evolution patterns of the overlying fractures under large-mining-height conditions in composite roofs. Through numerical simulation, it was found that the roof and floor fractures in the goaf area experienced stress-relief expansion, stress-recovery closure, and end-fracture expansion, as shown in Figure 5. Taking the 8201 comprehensive mining face of the Caochanggou mine as the research subject, Yixin Zhao et al. [28] investigated the rock integrity and bearing capacity of the floor strata under the influence of repetitive mining between the close coal seams through theoretical analysis, numerical simulation, and borehole probing. The damage to the rock formation at the bottom of the 8201 comprehensive mining working face was dynamically evolving, as shown in Figure 6. At the same time, corresponding prevention and control measures were proposed for the potential safety hazards at the mining working face. Jie Zhang et al. [29] considered that, in the structure of a "goaf area-working face" or "goaf area-goaf area-working face", the overlying strata fractures go through six dynamic cyclic variation stages, including generation, expansion, closure, regeneration, penetration, and reclosure.

During coal mining, the overlying strata move and break in a certain area, forming the corresponding mining fractures. The distribution of mining fractures significantly influences engineering practices, such as gas-drainage, gas-leakage, and coal-combustion prevention, underwater coal mining, and coal-seam filling. The fractures in the overlying strata of the goaf area include separated fractures and broken fractures. Separated fractures are fissures that form along the seam when the overlying coal seam sinks during the mining process. It could cause the expansion and deformation of the overlying coal seam, resulting in gas-pressure relief. Broken fractures are formed by the sink and rupture of the overlying strata, which connect the gas between the upper and lower coal seams. During the movement of the overlying strata, separated fractures mainly appear in the lower part of the key stratum, which controls the generation, development, and spatial and temporal distributions of the broken fractures. In the direction of the working-face advancement, as the advancement continues, separated fractures keep enlarging before the initial breaking of the key stratum, and the largest separation between the strata is in the middle of the goaf area. After the breaking of the key stratum, it is gradually compacted in the middle of the goaf area. The fractures in the middle of the goaf area gradually close. However, there are still obvious separated fractures on both sides of the goaf zone [30].

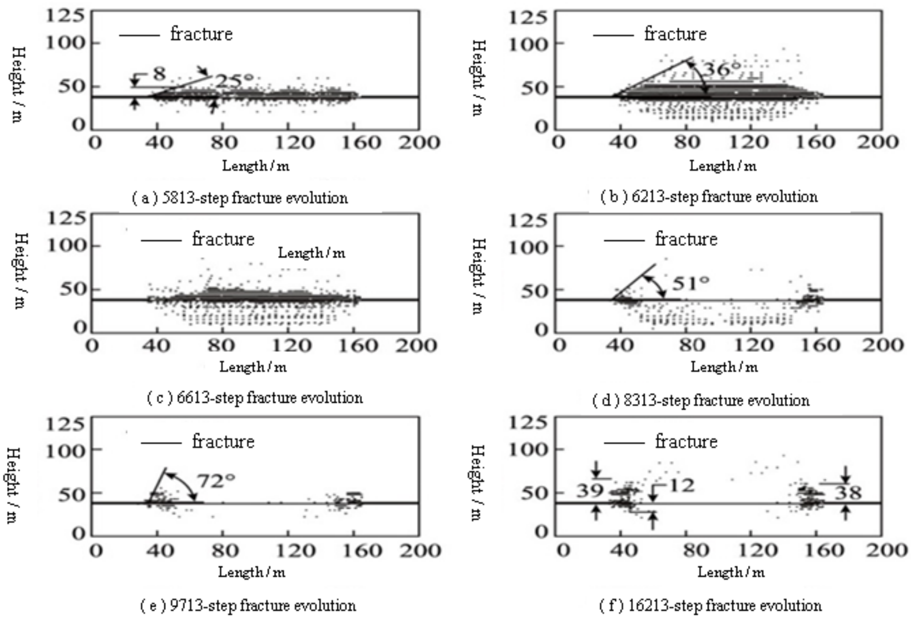


Figure 5. Fracture evolution process in different mining steps [27].

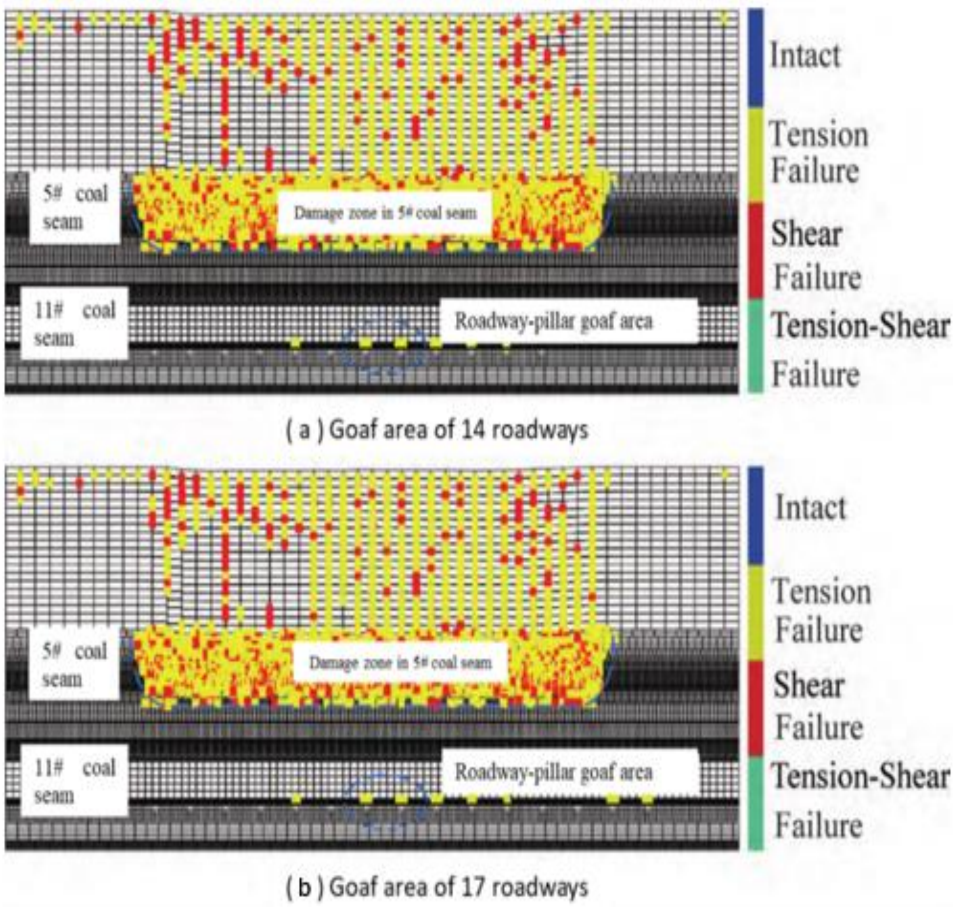


Figure 6. Evolution of mining fractures in mining stope [28].

A vertical-penetrating fracture is the channel for gas and other substances to emit into the mining working face, and it is called a gas-conducting fracture. At the early stage of mining, gas-conducting fractures develop unevenly from the bottom to the top. The fractures in the lower key stratum play a controlling role in its dynamic development process. When the mining working face is advanced at a certain distance, the distribution of the gas-conducting-fracture zone also shows the characteristics of an "O"-type distribution. The goaf area provides the main access, and the height of the gas-conducting-fracture zone depends mainly on the location of the main key stratum. When the main key stratum is close to the mined seam (less than a certain critical value), the main key stratum could generate blocks when it fractures. Extensive subsidence and gyration cause the fractures in the key stratum to expand and extend to the top of the bedrock [30]. Under the conditions of roof excavation and roadway construction, the roof part under the overlying strata affected by roof excavation could be easily broken. This phenomenon leads to a significant increase in gas-conducting fractures. However, the rupture of collapsed roofs provides good support to the overlying strata, making it more difficult to break the roof above the overlying strata, and reduces the gas-conducting fractures [31]. By using PFC3D numerical simulation software specialized in the particle flow model, Wei Li [32] focused on the Qinglongshan coal mine, and it was found that the overlying strata could cause impact due to stress concentration and stratum collapse. More fractures were generated, accumulated, and developed in the floor strata of the working face, forming fracture channels until the depth of the fracture area reached 15 m.

2.3. Distribution Characteristics of Permeability in Mining Stopes

Coal mining causes breakage in the overlying strata of the mining area, resulting in the development of rock fractures, increasing fracture rates, and enhancing the fracture connectivity. Thus, the stratigraphic seepage characteristics are improved. Due to the different supporting conditions of the coal-pillar goaf area to the overlying strata, the mining stress is redistributed in the influenced area of the mining-stope boundary. Meanwhile, fractures are highly developed, and compaction and closure are difficult. As a result, the permeability of the overlying strata increases. Therefore, this area has become a high-risk area for the vertical water seepage of the overlying strata, the lateral seepage of the accumulated water from adjacent mining areas, and gas gushing out. The current studies on the permeability characteristics of fractured formations mainly focus on the permeability variation in the single-fracture and regular multiple-fracture models. Few studies have investigated the permeability characteristics of complex multiple-fractured rock formations in overlying strata. Yong Zhang et al. [33] classified the macroscopic gas channels in a roof according to the deformation and force characteristics of the roof, fracture development pattern, and channel-conduction characteristics during mining. The channel classification is listed as follows: the gas-turbulence channel, gas-transition channel, and gas-seepage channel. Xiangbin Xiong et al. [34] studied the single-fracture flow from three aspects: the fluid-motion pattern, factors influencing the flux capacity of the fracture, and numerical simulation methods of the single-fracture seepage. The analysis revealed that the fracture-seepage-flow pattern is complex. At the same time, the simulation of seepage test devices under complex stresses is still a bottleneck for the research. Section-roughness evaluation is a complex problem, and the reasonable choice of a numerical method is very important. By using FLAC3D simulation analysis, Zhaoping Meng et al. [35] selected the working face of the Yuecheng Minefield in the Jincheng mining area, and the buried depth of the coal seam was 432 m. It was found that the permeability distribution of the rock in the goaf area was consistent with its stress–strain and damage patterns. The distributions of the vertical and horizontal permeability-coefficient ratios of the rocks in the goaf area are shown in Figure 7.

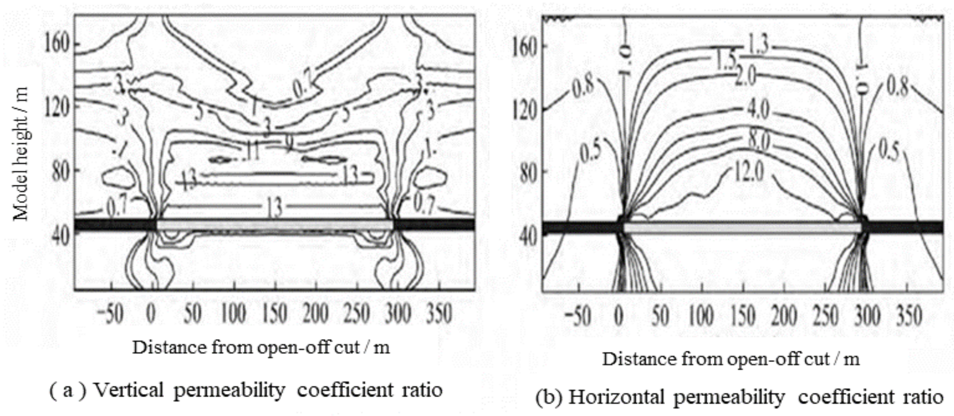


Figure 7. Permeability-coefficient ratios of rock mass in goaf [35].

Yonglei Wang [36] took the 3116 working face of the first panel and the 3308 working face of the third panel in Bofang Coal Mine as the research objects, and the average buried depth of the coal seam was 288 m. Based on the cubic law, the fracture–stress–seepage equation was derived. The pore-water-pressure and seepage-velocity parameters in FLAC 3D simulation software were used to analyze the evolution law of the overburden permeability. In addition, the effects of the rock elastic modulus, coal-seam mining height, and burial depth on the permeability of the overlying strata at the mining-stope boundary were analyzed. The developed numerical model and pore-water-pressure diagram are shown in Figures 8 and 9, respectively. Dongming Zhang et al. [37] took the 2461 working face of Baijiao Coal Mine of the Chuanmei company as the research object, and the buried depth of the coal seam was 476.3~582.5 m. The ZLGH vibrating string borehole stress meter, gas-pressure test table, and CXK6-Z mine intrinsically safe borehole imaging system were adopted to measure the stress, gas pressure, and mining-fracture characteristics. According to the coupling mechanism of mining-induced stress, the mining-induced fracture and gas flow in a fractured coal mass, which is a model that reflects the relationship between the mining stress and the permeability of fractured coal rock, was established. The permeability of fractured coal rocks under the influence of mining is related to the fracture width, fracture connectivity, fracture unevenness, fracture spacing, normal fracture stiffness, and mining stress. Furthermore, the goaf permeability is positively correlated with the fracture width and negatively correlated with the fracture distance. The influence factors of the permeability include the following five aspects: the coal-pillar width, coal-pillar height, coal-pillar shape, coal-pillar strength, and coal-pillar stiffness. The accuracy of permeability models is of significance to the prediction of the permeability in goaf areas. Some permeability models have been established for permeability evaluation, either including the stress effect or gas-desorption effect [38] (e.g., the Cui and Bustin model [39], and Gu and Chalaturnyk model, respectively [40]).

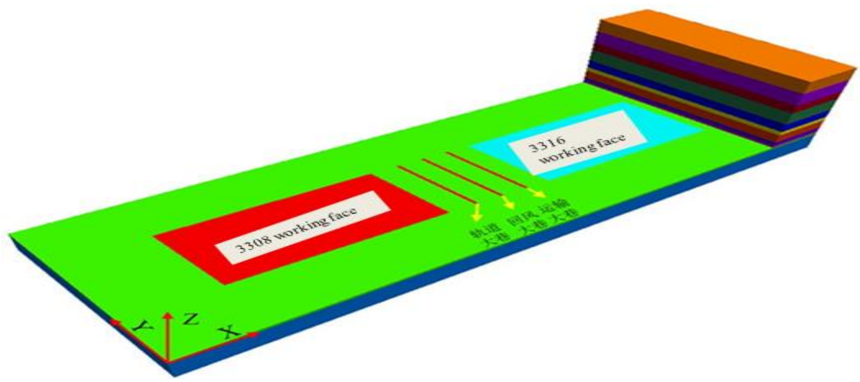
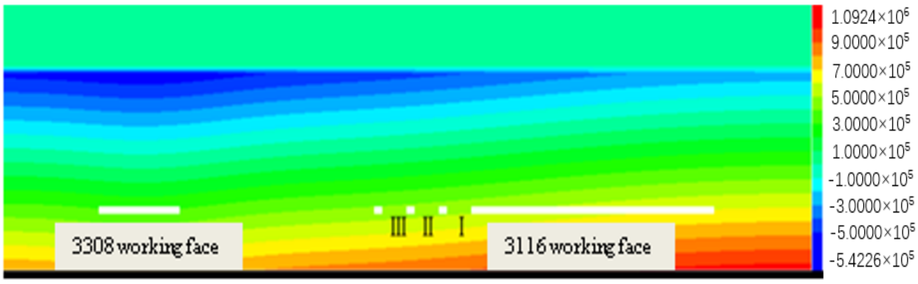
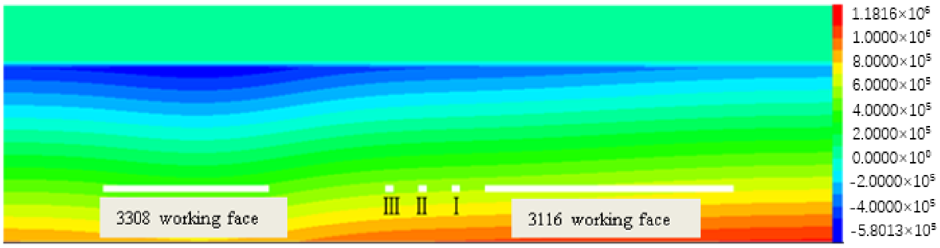


Figure 8. Numerical calculation model of mining of Yonglei Wang [36].



(**a**) 100 m of mining



(**b**) 200 m of mining

Figure 9. Pore-water-pressure distribution in 3308 mining working face [36].

3. Summary and Discussions

Related researchers have analyzed the stress variations, fracture advancement, and permeability-change characteristics in mining stopes by adopting theoretical analysis, similarity experiments, numerical simulations, and field tests, as shown in Table 1. The main conclusions of these studies are as follows:

(1) Stress variation: The weight of the overlying strata is evenly distributed over the coal seam before it is mined. With the advancement of longwall mining, a stress-relief zone is formed above the goaf area, while a stress-concentration zone is generated in the adjacent coal seams. The larger loading stress of the goaf area corresponds to the smaller loading stress of the surrounding rocks, and vice versa. After mining, the stress in the roof of the roadway goes through the process of stress relief, stress increase, and re-decompression [41]. The roof cutting of the roadway in the middle coal seam creates a stress-increase zone in the overlying strata between the upper and middle roadways. In addition, the roof cutting of the roadway in the lower coal seam causes serious damage to the surrounding rocks, leading to no concentrated stress;

(2) Fracture development: For the multilayer-coal-seam group, the development pattern of the fractures in the overlying strata during upper-coal-seam (first-mined seam) mining is the same as for single-coal-seam mining. However, if the lower coal seam is subsequently mined, the superimposed mining destroys the equilibrium caused by the upper-coal-seam mining, resulting in a large development of fractures. The fractures in the overlying strata and floor strata of the mining area experience the process of stress-relief expansion, stress-recovery closure, and end-fracture expansion. The fracture closure in the middle of the mining area is accompanied by fracture expansion at the ends. Meanwhile, the fracture closure in the roof strata is faster than that in the floor strata;

(3) Permeability changes: Affected by mining activities and external loads, microfractures inside coal and rock occurs, expands, and connects, which could result in an exponential increase in the permeability. The fracture ratio in the overlying strata has an obvious influence on the seepage characteristics. Whether it is vertical seepage or horizontal seepage, the permeability coefficient in the fractured zone of the goaf area increases with the growth in the fracture ratio, showing a power-curve relationship.

Table 1. Summary of studies on stress–fracture–seepage characteristics of goaf areas.

Research Areas	Authors	Research Descriptions
Stress distribution characteristics of mining area	Yang et al. [12]	A physical simulation experiment of multilayer coal mining was conducted. The stress in the roadway roof experienced the relief–increase–relief process during the mining of the coal seam.
	Whittaker and Singh [15]	There is a yield zone at the longwall-mining face and lateral coal wall. The abutment pressure is zero, and it increases rapidly with the increasing distance from the coal wall.
	Rezaei [18]	The longwall-mining face and its surrounding rock are regarded as an independent system. On this basis, an analytical model of the coal pillar and roadway-mining-stress distribution was established.
	Ji et al. [10]	The abutment-stress growth coefficient in front of a mining working face experiences the increase–decrease–stabilization process.
	Zhu et al. [16]	The distribution characteristics of the abutment pressure at a longwall-mining face under an extra-thick alluvial layer was analyzed. The theoretical-calculation model of the abutment pressure was established.
	Kang et al. [13]	Physical similarity experiments and numerical simulations were adopted to investigate the relationship between large-roof collapse and the abutment pressure in longwall-mining faces. An increase in the horizontal pressure of the roof to 5 times the original stress is a precursor to large-roof collapse.
	Di et al. [14]	By adopting COMSOL numerical simulation software, it was found that the stress-concentration zone in the overlying strata of a working face was rounded rectangular.
	Xie et al. [20]	The distribution of the abutment pressure is related to the thickness of the initial coal seam. Its peak value is negatively correlated to the thickness of the initial coal mining, and it is proportional to the distance from the coal wall.
	Qian et al. [42], Yu et al. [43]	A coal pillar could be divided into the ultimate equilibrium zone and elastic zone under the abutment pressure. As the distance to the coal-pillar boundary increases, the abutment pressure increases in the limit-equilibrium zone and decreases in the elastic zone.
	Wang et al. [44]	The fracture angle has an important influence on the stress distribution in the mining area. With larger fracture angles, the bearing capacity of the goaf area is larger. On the contrary, smaller fracture angles lead to a smaller bearing capacity, a reduced stress-recovery area in the coal seam, and the vertical stress increases.
	Yasitli and Unver [17]	A simulation study on an M3 longwall-comprehensive-mining face in Turkey was conducted. The abutment pressure reached a peak value of 14.4 MPa at 7 m in front of the working face.
	Yu [21]	By using the software COMSOL Multiphysics, and based on the theory of ultimate equilibrium and the conservation of the overlying load, a calculation method of the range and stress of the coal-wall-support influence zone and stress-recovery zone is proposed.
	Gao [24]	The stress distribution within the overlying strata of the goaf area under different mining depths was explored by FLAC3D numerical simulation. It was concluded that there are compressive- and tensile-stress zones within the overlying strata.
	Wang et al. [23]	Based on the decay law of the average bulking coefficient of fractured rock, a model of underground-coal-mining goaf evolution was established.

Table 1. *Cont.*

Research Areas	Authors	Research Descriptions
Development pattern of fractures in mining area	Zhang et al. [26]	The fractures in the overlying strata of a shallowly buried coal seam were studied. The effects of the shallow burial depth on the evolution of the fracture development and gas-seepage pattern were analyzed.
	Zhao et al. [27]	The evolution pattern of the overlying fractures under the large-mining-height conditions of composite roofs was tested by field measurement.
	Li et al. [25]	A similar-material simulation test and theoretical analysis were adopted to reveal the influencing mechanism of multiple mining on the development of fractures in overlying strata.
	Qian et al. [30]	Model experiments, image analysis, and discrete element simulation were conducted to reveal the two-stage development pattern and "O" circle distribution characteristics of the overlying mining fissures of a longwall mining face.
	Zhao et al. [28]	Taking the 8201 mining face of the Caochanggou mine as the target, the rock integrity and bearing capacity of the floor strata affected by repetitive mining between the close coal seams were investigated through numerical simulation and borehole probing.
	Liu et al. [31]	Affected by roof excavation, there is a significant increase in gas-conducting fractures. However, the rupture of collapsed roofs provides good support to the overlying strata, making it more difficult to break the roof above the overlying strata, and thus reducing the gas-conducting fractures there.
Permeability distribution characteristics in mining stope	Zhang et al. [33]	According to the deformation and force characteristics in roof strata, and the fracture-development patterns and channel-conduction characteristics during mining, the macroscopic gas channels in the roof were classified into the gas-turbulence channel, transition channel, and seepage channel.
	Xiong et al. [34]	The single-fracture-flow characteristics were studied from three aspects: the fluid-motion pattern, fracture-flow influencing factors, and numerical simulation methods of single-fracture seepage. It was revealed that the fracture-seepage-flow pattern is complex.
	Zhang et al. [45]	With the premise of fixed-fracture laminar flow, physical-model tests have an irreplaceable role in studying the fractured-rock-seepage characteristics, and more tests are needed to simulate the actual mining of rock fractures.
	Meng et al. [35]	A FLAC3D simulation analysis showed that the permeability distribution of the goaf zone is consistent with its stress, strain, and damage characteristics.
	Wang et al. [36]	Based on the cubic law, the fracture–stress–seepage equation is derived. The coal pore-water-pressure and seepage-velocity parameters were analyzed by FLAC 3D numerical simulation, as well as the permeability variation in the overlying strata at the boundary of a mining stope.

Based on the above analysis, future research on the stress–fracture–seepage characteristics of coal-mining goafs is expected to be conducted with regard to the following aspects:

(1) Due to the different research focuses and methods on the abutment pressure of longwall-mining faces, some differences exist in the research results. Therefore, further investigations are needed to characterize the distribution of the abutment pressure;

(2) The two-dimensional mechanical model that describes the mining process should be extended to three-dimensional ones to more accurately reveal the mechanism of the fracture development in overlying strata. Meanwhile, more tests are needed to simulate the actual rock-fracturing processes, and the physical-model tests that reflect the effects of the shear stress or three-dimensional stress need to be enhanced;

(3) A large number of studies on the development pattern of fractures in overlying strata show that overlying fractures at the goaf boundary are difficult to self-close after mining. These fractures are the main seepage channels of water and gas, and they need to be comprehensively investigated. On the premise of fixed-fracture laminar

flow, the physical-similarity simulation test plays a good role in studying the seepage characteristics of fractured rocks. Meanwhile, research on fracture-filled seepage is more practical and worth further investigation;

(4) In the process of longwall mining, damage to the overlying strata at the mining-stope boundary is serious [46]. The fractures are highly developed, and compaction and closure are difficult [41]. The permeability of the damaged coal could increase by hundreds or thousands of times. In previous studies, few permeability models have considered the effects of the damage. Thus, the accuracy of coupled gas-seepage studies at the goaf boundary is expected to be improved. It is necessary to establish a multifactor coupled permeability model that integrates the coal damage, stress, and gas desorption. Through this model, changes in the permeability at the goaf boundary and the dynamic evolution of the multifield gas coupling seepage characteristics could be accurately analyzed, and the gas-rich areas could be identified. As a result, the gas-extraction performance at the goaf boundary could be enhanced. The amount of gas emissions from the goaf-boundary area and from the roof and floor rock strata to the goaf would be reduced, ensuring safe and efficient mining.

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