The permeability properties of bedded coal and rock: Review and new insights

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Abstract
It is beneficial to understand deeply the permeability properties of coal and rock for the stability control of mining engineering, underground engineering, oil and gas engineering, nuclear waste storage engineering, and so on. Therefore, new insights for the permeability properties of bedded coal and rock are summarized and proposed. (1) “Five guarantees” coring technology is worth for vigorous promotion and application. (2) The internal spatial fabric has the significant effect on the mechanical behavior evolution law of (bedded) coal and rock, but the effect is not dominant. (3) The permeability-energy evolution models of (bedded) coal and rock should be constructed considering the idea of initial high in situ stress reduction, which is helpful for the energy visualization characterization of (bedded) coal and rock. Meanwhile, it can be combined with the structural evolution theory for in-depth characterization and disclosure. (4) Researches on the permeability properties of (bedded) coal and rock under multi-field or multi-phase or phase-field coupling conditions should be strengthened based on considering the initial damage produced and the distribution characteristics of in situ stress under the coring environment. (5) More accurate and scientific permeability evolution models of (bedded) coal and rock should be vigorously constructed based on the above insights.

KEYWORDS
“five guarantees” coring technology, bedding effect, energy-permeability evolution model, initial high in situ stress reduction, phase-field coupling, structural evolution theory

1 | INTRODUCTION

The program of "Deep Space, Deep Sea, and Deep Earth" is the primary plan of China’s new journey to become the world scientific and technological country. Among them, "Going Deep into the Earth" is a key strategic scientific issue that China needs to be solved. Meanwhile, the plan of "Deep Earth" was first proposed in the "13th Five-Year Plan for National Science and Technology Innovation," and the Deep Earth Exploration is included in the Major project plan of Science and Technology Innovation 2030. Currently, the exploitation of resources...
is constantly entering to the deep.6-10 The mining depth of coal resources has reached to 1501 m (Suncun Coal Mine in Shandong, China). The mining depth of geothermal resources has also exceeded 3000 m (Iceland). The mining depth of metal mineral resources has reached to 4350 m (Mbonge Gold Mine in South Africa). The depth of oil and gas resources exploitation has exceeded 7500 m (Xinjiang, China). Therefore, the exploitation of deep resources has become normal. However, the current theory of shallow rock mechanics cannot adapt to the rapid development of deep engineering. Therefore, it is urgent to establish the perfect and mature fundamental theory of deep rock mechanics to better provide accurate theoretical basis and optimization guidance for field practices. As shown in Figure 1, joints and natural discontinuities are all over the deep strata, and the bedding effect is significant. Therefore, the deep rock has the significant properties of heterogeneity, discontinuity, and anisotropy. Additionally, cracks in deep rock are dense and widespread with the water or gas seepage extended and unobstructed. According to relevant studies showed,11-15 the seepage pressure, the temperature, and in situ stress of surrounding rock in deep mines at a depth of 1000 m can be as high as 7–10 MPa, 30–50°C, and 25–35 MPa, respectively. Therefore, it is necessary to comprehensively expound the permeability properties of (bedded) coal and rock based on the deep environment.

Currently, domestic and foreign scholars have studied the permeability properties of bedded coal and rock and obtained abundant research results. On the one hand, many scholars have studied on the permeability properties of bedded coal and rock under true triaxial loading or unloading conditions.16-30 Yin’s team developed the multi-functional true triaxial fluid–solid coupling test system. Moreover, they analyzed the stress path effect, unloading effect, lithology effect, coal–rock combination effect, anisotropy, intermediate principal stress effect, and other factors on the permeability properties of bedded coal, shale, sandstone, and coal–rock combination.16-30 Additionally, the anisotropic permeability evolution characteristics of bedded coal, shale, sandstone, and coal–rock combination were better characterized. Meanwhile, the permeability evolution models of bedded coal and rock under X, Y, and Z direction were both constructed, which revealed the mechanical mechanism of deformation and permeability of bedded coal and rock under true triaxial condition.16-30 On the other hand, many scholars have studied on the permeability properties of bedded coal and rock under the conventional triaxial loading or unloading conditions. Li et al.31 studied the permeability properties of coal with bedding angles of 0°, 45°, and 90° under triaxial loading with different impact rates and established the corresponding permeability evolution models. Additionally, Chen et al.32 constructed the permeability evolution model of bedded coal with the change in radial strain. Meanwhile, Niu et al.33 characterized the permeability evolution characteristics of bedded coal with the change in effective stress by defining multiple parameters. Additionally, the anisotropic permeability evolution characteristics of bedded sandstone were characterized.

FIGURE 1 Factors of influencing the stability of deep underground engineering including but not limited to the bedding effect, high in situ stress, high seepage pressure, high temperature, and strong disturbance.31 Note: T—Temperature, (°C); $P_w$—Osmotic water pressure, (MPa); $H$—Buried depth, (km); $\sigma_1$—Maximum principal stress, (MPa); $\sigma_3$—Minimum principal stress, (MPa)
and the mechanical mechanism of permeability was revealed.\textsuperscript{34-37} Meanwhile, the permeability properties of bedded shale were studied, and anisotropic permeability evolution models were established from brittleness, microscopic, and multi-scale perspectives, respectively.\textsuperscript{38-40} Besides, Jin et al.\textsuperscript{41} and Meng et al.\textsuperscript{42} both deeply studied the evolution law of the P-wave velocity, compressive modulus, uniaxial compressive strength, and uniaxial tensile strength of rocks with anisotropy angle. However, scholars mentioned above mainly adopt gases such as CO\textsubscript{2}, N\textsubscript{2}, H\textsubscript{2}, He, CH\textsubscript{4}, and Ar as the seepage bodies to conduct the experimental studies. Additionally, as shown in Figure 2, the permeability evolution ranges of coal, shale, and sandstone are generally (0.001 mD, 1000 mD), (0.0000001 mD, 1 mD), and (0.0001 mD, 100 mD), respectively. Meanwhile, there are corresponding measurement methods of permeability for corresponding permeability evolution ranges.

Domestic and foreign scholars mentioned above have studied the permeability properties of bedded coal and rock from various research perspectives. However, the experimental process of water seepage is more complicated than gas seepage due to the long time-consuming and water-rock effect. Meanwhile, the water seepage test requires high tightness of the sample to avoid the occurrence of water–oil mixture phenomenon. Therefore, the research on the permeability properties of bedded coal and rock under water seepage is relatively rare. Additionally, most of the researches on the permeability properties of bedded coal and rock were only limited to bedding angles with 0° and 90°, but that under the bedding angles with interval (0°, 90°) were ignored. Additionally, most scholars focused on the permeability properties of bedded coal, bedded shale, and bedded sandstone, while that of other bedded rocks were relatively rare. Meanwhile, most scholars focused on the research on the permeability of bedded coal and rock under multiple-field coupling (seepage field, stress field, temperature field, chemical field, etc.), but that under multi-phase/phase-field coupling were ignored. Therefore, it is necessary to characterize and comprehensively expound the permeability properties of bedded coal and rock, to provide a certain of theoretical basis for the stability control of deep mines.

2 | CORING AND PROCESSING

As shown in Figure 3, bedded coal and rock samples are mainly obtained by coring or drilling with different angles in large blocks of bedded coal and rock from underground mines. However, many studies have shown that the environment before sampling has the significant effect on the permeability properties and mechanical behavior of bedded coal and rock samples. Therefore, Academician Xie\textsuperscript{43} proposed the idea and concept of “five guarantees” coring. Meanwhile, the corresponding “five guarantees” coring device was designed and developed (see Figure 4). The idea and concept proposed can make the research conclusions become more consistent with the application and promotion of field engineering practice.

Additionally, it is easy to lead to the uncertainty and randomness in the coring process of bedded coal and rock due to the complexity of the geological situation in the coring strata. Meanwhile, the influence of the environment on the initial mechanical properties of the coring samples is also ignored, which easily leads to a certain of deviation in the conclusions obtained from the laboratory test. Therefore, the author suggests that the coring of bedded coal and rock should be conducted based on the idea of “five guarantees” coring. Then, high-precision CT scanning technology and 3D printing technology should be adopted to conduct the 3D reconstruction and 3D printing. Therefore, the coring normal state of bedded coal and rock specimens will be breakthrough, and the coring predicament of bedded coal and rock specimens will be relieved.

3 | FABRIC RESPONSE CHARACTERISTICS AND FUNDAMENTAL PHYSICAL PARAMETER

After the coring and processing of bedded coal and rock specimens are completed, a lot of preparatory work should be done before conducting the tests. They include

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Permeability evolution ranges of different rock types and different measurement permeability methods.\textsuperscript{34,35} Note: GRI is the Gas Research Institute method.}
\end{figure}
the identification of the spatial fabric, the determination of the fundamental physical parameters, and the acquisition of the fundamental mechanical parameters. It can lay the theoretical basis and parameter reference for the later test results and inverse verification analysis.

3.1 Fabric response characteristics

Relevant study results show that the internal fabric composition of coal and rock can significantly affect the evolution law of the fundamental mechanical and physical parameters. Figure 5 shows the evolution characteristics of elastic modulus of typical coal and rock as its internal fabric composition changes. It can be found that the effect of the internal fabric composition on fundamental physical and mechanical parameters has a certain of limits, and the effect is not unlimited, but the effect has nothing to do with lithology effect. It indicates that the internal fabric of coal and rock can significantly affect the mechanical behavior, but its effect is not dominant, including the bedded coal and rock.

Therefore, it is necessary for the accurate characterization of the spatial fabric characteristics of bedded coal and rock before the tests. Moreover, the authors suggest that a multidisciplinary approach should be adopted integrating quantum mechanics, molecular dynamics, intelligent mechanics and even statistical mechanics with rock mechanics, fracture mechanics, damage mechanics, rheology mechanics, and other disciplines. Meanwhile, 3D (Three Dimensions) printing, CT (Computerized Tomography) scanning, SEM (scanning electron microscopy), and other means can be also comprehensively adopted. The spatial fabric of bedded coal and rock will be characterized quantitatively and qualitatively with high precision in this way.

3.2 Fundamental physical parameters

Generally, the fundamental physical parameters of coal and rock specimens mainly include the wave velocity, porosity and density. The fluctuation of wave velocity can indirectly reflect the homogeneity of coal and rock with the same bedding angle, while the density and porosity can indirectly explain the discontinuity of coal and rock with the same bedding angle. Relevant study results show that the wave velocity of bedded coal and rock presents various evolution characteristics with the increasing of the bedding angle (see Figure 6). For example, the wave velocity decreases with the increasing of the bedding angle, but the change rate of the wave velocity increases with the increasing of the bedding angle as example 1. Additionally,
the wave velocity increases with the increasing of the bedding angle, but the change rate of the wave velocity decreases with the increasing of the bedding angle as example II. Additionally, the wave velocity increases with the increasing of the bedding angle, but the change rate of the wave velocity first increases slowly, then sharply increases, and finally decreases slowly with the increasing of the bedding angle as example III. The difference of the evolution characteristics of wave velocity with the bedding angle changes is mainly contributed to lithology effect.

Additionally, the porosity shows a W-shaped evolution law with the increasing of the bedding angle. Among them, when the bedding angle is 45°, the porosity is the minimum. When the bedding angle is 60°, the porosity is maximum. Moreover, the density shows the evolution characteristics with first increasing, then decreasing, and finally increasing with the increasing of the bedding angle. Among them, when the bedding angle is 30°, the density is the maximum. When the bedding angle is 45°, the density is minimum.

However, most scholars tend to ignore the role and status of the fundamental physical parameters of coal and rock, resulting in the "useless" illusion of them. In fact, it is a very effective nondestructively auxiliary means adopting the wave velocity to monitor the mechanical behavior characteristics of coal and rock. Additionally, the
Porosity is an indispensable fundamental parameter in permeability theoretical derivation and numerical simulation verification. Additionally, the density is an important parameter of material definition in estimation of the stress state and numerical simulation verification. Therefore, the acquisition and the characterization of its evolution.
characteristics of fundamental physical parameters of coal and rock can lay a certain of theoretical foundation for results analysis and field engineering application.

4 | FUNDAMENTAL MECHANICAL PARAMETERS

Generally, there are many forms of laboratory mechanical tests to obtain the fundamental mechanical parameters of coal and rock. The main forms of laboratory mechanical tests are shown in Figure 7. Additionally, the fundamental mechanical parameters mainly include the elastic modulus, Poisson’s ratio, uniaxial compressive strength, uniaxial tensile strength, and strength parameters: cohesion and internal friction angle. Generally, most of the above fundamental mechanical parameters are obtained by conducting the uniaxial compression (tensile) tests of coal and rock. However, additionally, the elastic modulus can also be obtained by nano-indentation tests of coal and rock, while the cohesion and internal friction angle are generally obtained by the conventional triaxial test or shear test of coal and rock. Among them, the fundamental mechanical parameters of bedded coal and rock are obtained in the same way.

4.1 | \((E), (\mu), (\sigma_{UCS}),\) and \((\sigma_t)\)

Related study results show that there is a certain of differences in the evolution law of the fundamental mechanical parameters of bedded coal and rock with the change in the bedding angle, and the difference is mainly attributed to the lithology effect. The elastic modulus and the uniaxial compressive strength of bedded coal and rock mainly exhibit V-shaped evolution law with the change in the bedding angle, and the reason for different evolution types lies in the different positions of minimum values (see Figure 8A,C). However, the elastic modulus and the uniaxial compressive strength of bedded coal and rock also have other evolution laws with the change in the bedding angle, which both increase with the increasing of the bedding angle (see Figure 8A-II and D-III).

Additionally, the uniaxial compressive strength of bedded coal and rock shows a W-shaped evolution law with the increasing of the bedding angle, and the reason for the different evolution types lies in the different location of “valley bottom” (see Figure 8B). Additionally, the uniaxial tensile strength of bedded coal and rock shows the evolution characteristics of inverted “S” and inverted “V” with the increasing of the bedding angle (see Figure 8D-I and D-II).

Currently, the researches on the fundamental mechanical parameters of bedded coal and rock are only qualitative. The main reason lies in the complex geological situation of deep engineering, and the underground environment (in situ stress state, temperature, water, gas, and other factors) has a significant effect on deep bedded coal and rock. Additionally, the test samples are mainly obtained by sampling drilling and coring. The evolution law of the fundamental mechanical parameters of bedded coal and rock and its precision acquisition for the numerical simulation verification and the field practice of underground engineering can provide important parameter and reliable theoretical basis. However, the cost is too large, the workload is too heavy, and it is not realistic in the
actual operation for the fundamental mechanical parameters of bedded coal and rock quantified accurately widely obtained.

Therefore, the authors suggest that first grasp accurately the geological characteristics of underground engineering and their fundamental properties of deep bedded coal and rock, rational to adopt advanced scientific methods (such as 3S accurate orientation detection system, laser trans-lamellar fluoroscope, electro-magnetic radiation scanner, ground sound monitoring system, and unmanned aerial vehicle infrared detector) for precise exploration and capture. Therefore, using the super computer and other high-precision instruments for image display and high-speed operation calculation to implement the underground engineering gradually transfer to transparency, intelligence, and modernization.

4.2 | (C) and (φ)

Additionally, the cohesion and internal friction angle are also the fundamental mechanical parameters of coal and rock, which are mainly obtained by the envelope of Mohr stress circle or the equation of strength criterion under different confining pressures or by the VAST. Additionally, the cohesion and internal friction angle of bedded coal and rock basically show the synchronous and cooperative V-shaped evolution characteristics with the increasing of the bedding angle (see Figure 9). Among them, the evolution characteristics of the cohesion and the internal friction angle can also be characterized by parameters: the plastic shear strain and dilatancy angle. However, the stress path of laboratory conventional triaxial tests adopted ignores the initial damage of coal and rock samples caused by the environment before coring. It is easy to make a certain of errors in the conclusions obtained by the laboratory tests. Moreover, it is easy to provide differential theoretical reference for the actual practice in underground engineering.

Therefore, the authors suggest that the stress path adopted in laboratory mechanical tests should fully conform to the evolution characteristics of the surrounding rock in actual underground engineering. For example, using the "Five Guarantees" coring technology to drill deep bedded coal and rock specimens firstly. Then, the "three-stage" stress path was adopted for laboratory mechanical tests based on the mechanical behavior evolution characteristics of the surrounding rock of deep mines roadway before excavation, excavation, and after excavation (see Figure 12). It can obtain more accurate strength parameters for the stability control of the deep mines in the way.52,53

5 | PERMEABILITY PROPERTIES

The research on the permeability characteristics of bedded coal or rock is on the right track only after the coring of coal and rock specimens, the fundamental physical and mechanical parameters of coal and rock obtained. Meanwhile, the permeability measurement method and seepage body should be selected comprehensively according to the time-consuming period and the dense degree of coal and rock specimens before conducting the seepage test to improve the success rate of seepage tests. Similarly, it is also necessary before conducting the seepage test of bedded coal and rock.

5.1 | Permeability measurement method and seepage body

5.1.1 | Pulse decay method (PDM), Pressure oscillation method (POM), and Steady state method (SSM)

Generally, the permeability measurement methods of coal and rock are mainly divided into PDM and SSM.

Among them, according to different forms of osmotic pressure set, PDM can be divided into four types, namely PDM-1, PDM-2, PDM-3, and PDM-4. Corresponding schematic diagram of PDM is shown in Figure 10A–D, while that of SSM is shown in Figure 10E.

As shown in Figure 10C, in the experimental process of using PDM to measure the permeability of coal and rock, the confining pressure and axial stress should be loaded to the initial value at a certain of rate firstly. Then, keeping the confining pressure constant, vacuum saturation was conducted on the heat-shrinkage-sealed coal or rock specimens in the triaxial compression chamber that of the air was discharged from the lower outlet. Additionally, the coal and rock specimens in the triaxial compression chamber need to be fully seeped until the upper and lower pressures of coal or rock specimens reach to the equilibrium (Psp). At the time, it can be considered that the pressure distribution in the coal and rock specimens under this condition is uniform and balanced (Pup=Pdn). Finally, stress increment (dp) is applied to the coal and rock specimens of the upper inlet and through the coal and rock specimens discharged to the lower outlet. When the time required the atmospheric pressure reduced in the upper inlet and the time required the atmospheric pressure raised in the lower outlet for reaching a new equilibrium line again (Pup = Pdn), the permeability can begin be measured. The calculation expression of the corresponding permeability is54:
FIGURE 9 Evolution law of strength parameters with β: (a) C; (b) φ. Note: C—Cohesion, (MPa); φ—Internal friction angle, (°); β—Bedding angle, (°); I and II represent the evolution curves of C and φ with β, respectively.

\[ k = \chi \beta V \left( \frac{\ln \left( \frac{\Delta p}{\Delta t} \right)}{2 \Delta t \frac{4}{L}} \right) \]  

Where \( \chi \) is the gas viscosity coefficient (MPa·s), \( \beta \) is the gas compression coefficient, \( V \) is the volume of the stabilized vessel \((m^3)\), and \( A \) is the cross-sectional area \((m^2)\). Additionally, \( L \) is the height of the coal and rock sample \((m)\), \( \Delta r \) is the time during which the pore pressure difference is changed \((s)\), and \( \Delta P_i \) and \( \Delta P_f \) are the initial and final pore pressure differences \((MPa)\), respectively, in the \( \Delta t \) period.

As shown in Figure 10E, the steps of the initial value set and vacuum saturation of SSM are consistent with those of the PDM in the experimental measuring process of the permeability of coal and rock. Then, the coal or rock specimens in the triaxial compression chamber need to be fully seeped until the upper and lower pressures of coal and rock specimens reach to the equilibrium \((P_{up})\). At the time, it can be considered that the pressure distribution in the coal and rock specimens under this condition is uniform and balanced \((P_{up}=P_{dn})\). Finally, stress increment \((\Delta P)\) is applied to the coal and rock specimens of the upper inlet. Meanwhile, the pressure of lower outlet is consistent with the initial conditions. At the time, the permeability of coal and rock can be measured. Finally, the permeability of coal and rock can be calculated according to Darcy’s law:\n
\[ k = \frac{2Q \chi LP_{up}}{A(P_{up}^2 - P_{dn}^2)} \]  

Among them, where \( k \) is the permeability of coal or rock, \( \chi \) is the gas viscosity coefficient \((MPa·s)\), \( Q \) is the flow velocity of seepage body \((m^3·s^{-1})\), and \( A \) is the cross-sectional area \((m^2)\). Additionally, \( L \) is the height of the coal and rock sample \((m)\), \( P_0 \) is the reference pressure \((MPa)\), and \( P_{up} \) and \( P_{dn} \) are the pressures of upper inlet and lower outlet, respectively, \((MPa), (MPa)\).

With the continuous breakthrough and innovation of national science and technology development, laboratory test methods have become more superior, and the accuracy has become more accurate. Similarly, the permeability test methods and accuracy of coal and rock are constantly innovating and breaking through, including that of bedded coal and rock. However, coal and rock will inevitably be accompanied by a series of evolution processes such as compaction, deformation, damage, and failure under stress-seepage coupling. According to the law of energy conservation, coal and rock are bound to accumulate and dissipate energy during the entire process. Although there are some models of coal and rock based on the energy accumulation and depletion in previous studies, they both neglected the initial accumulate and dissipate energy of coal and rock under the sampling environment before the tests. Therefore, it is suggested that based on fully relying on the continuous improvement advantages of the accuracy for the permeability test of (bedded) coal and rock, the permeability-energy evolution model need to be established considering the initial high in situ stress reduction (see Figure 11), to indirectly quantify the energy accumulation and dissipation of coal and rock in the entire process. Meanwhile, it can be combined with the structural evolution theory for in-depth characterization and disclosure. Furthermore, it can provide more accurate theoretical basis for the early warning and prediction of rock burst and other disasters in deep engineering.

5.1.2 | Seepage body

As shown in Table 1, the seepage body used by domestic and foreign scholars for the research on the permeability properties of coal and rock is mainly gas, which mainly includes N₂, CO₂, H₂, H₂O, Ar, and CH₄. Among them, the Klinkenberg effect exists in the gas flow process of tight rock. The denser the rock is, the more significant the Klinkenberg effect is. Additionally, the influence of Klinkenberg effect on permeability was first studied by Klinkenberg in 1941. If the Klinkenberg effect occurs, Darcy’s law will no longer be applied. Additionally, the seepage behavior shows the nonlinear characteristics in the tight rock, and the smaller the permeability of the medium, the more obvious the nonlinear characteristics. Meanwhile, most scholars are limited to focus on the permeability properties under the bedding angles of
$0^\circ$ and $90^\circ$ of coal and rock, but ignore that under other bedding angles of coal and rock.

Additionally, the bedding effect of coal and rock corresponds to its own anisotropy property. However, is are a certain of issues such as the non-extreme bedding effect of rock mechanics for the deep engineering practice, and these key scientific issues are accompanied by the water effect.

Therefore, it is urgent to conduct the research on the permeability properties of coal and rock under solid–liquid or solid–liquid–gas multi-phase coupling, to provide a more reasonable theoretical basis and practical reference for field engineering. Additionally, the authors suggest that the initial damage characteristics of bedded coal and rock caused by the high initial in situ stress should be fully considered in the research on the permeability properties of bedded.

**FIGURE 10** Diagram of permeability test methods: (A) PDM-1; (B) PDM-2; (C) PDM-3; (D) POM; (E) SSM$^{50,92}$
coal and rock under solid–liquid or solid–liquid–gas multi-phase coupling. Namely, the coring work of bedded coal and rock specimens should be conducted according to the idea of "five guarantees" coring. Then, the permeability properties of bedded coal and rock under multi-phase coupling are studied to obtain more accurate conclusions.

5.2 | Permeability evolution law

Currently, the permeability evolution law of coal and rock under conventional triaxial condition have been obtained (see Figure 12A). Additionally, the permeability evolution characteristics of coal and rock under conventional triaxial condition and its stress–strain curve show the significant stage-corresponding characteristics, although the peak permeability obviously lags the peak strength behind. In the compaction stage (OA), the original pores and cracks in the coal and rock are compressed. Therefore, the opening of the seepage channel becomes smaller, the permeability of coal and rock at stage (OA) is reduced to \( k_{\text{min}} \) (corresponding to stage OA of permeability evolution curve). In the linear elastic deformation stage (AB), coal and rock can produce the linear elastic deformation at stage (AB), and the pores or cracks compacted by stage (OA) are basically constant, and the opening of seepage channel is basically constant. Therefore, the permeability of coal and rock at stage (AB) is basically constant (corresponding to stage AB of permeability evolution curve). In the stable crack growth stage (BC), new cracks are derived and spread stably in the coal and rock. Therefore, the number of seepage channels increases, and the permeability increases slowly (corresponding to stage BC of permeability evolution curve). In the unstable crack growth stage (CD), the coal and rock gradually reach to the peak strength from the yield point, and the new cracks develop and extend rapidly. Therefore, the surface of macroscopic failure is formed. As a result, the crack opening in the coal and rock increases sharply again, namely, the opening of seepage channels increases sharply again. Therefore, the permeability at stage (CD) has a dramatically increased evolution characteristic (corresponding to stage CD of permeability evolution curve). In the post-peak strain softening stage (DE), the surface of macroscopic failure of coal and rock has been formed, namely the dominant seepage channel has been formed. Therefore, the permeability of coal and rock at stage (DE) basically remains \( k_{\text{max}} \) constant (corresponding to stage DE of permeability evolution curve).

However, the authors believe that due to the neglect of the initial damage characteristics caused by the environment of coal and rock before the tests, it is easy to make a certain of magnitude errors in the permeability evolution law of coal and rock under the conventional triaxial condition. Furthermore, it cannot fully provide accurate theoretical basis and reference for the field practice in deep
| Year | References | Seepage body | Rock types | Method | Effective stress/MPa | Temperature/°C | Permeability/mD | Sample size |
|------|------------|--------------|------------|--------|---------------------|----------------|----------------|-------------|
| 1968 | Brace et al. | Ar | Granite | PDPM−3 | 9–405 | 9–25 | 0.0000042–0.000023 | A: 5 cm², L: 1.61 cm |
| 1980 | Sutherland & Cave | Ar | Salt rock | PDPM−3 | 0.9–25.7 | 22.8 | 0.00005–0.000851 | A: 15.68 cm², L: 6.294 cm |
| 1986 | Li et al. | Ar | Sandstone | PDPM−3 | 1.5–2 | N/A | 0.00402–0.0234 | A: 15.68 cm², L: 1.61 cm |
| 1989 | Harpalani & Zhao | CH$_4$; He | Coal | SSM | 5.52–10.92 | N/A | 0.00047–0.01104 | D: 38.1 mm, L: 76.2 mm |
| 1989 | Harpalani & Schraufnagel | CH$_4$ | Coal | SSM | 7.51–13.55 | N/A | 0.0002–0.011 | D: 38.1 mm, L: 76.2 mm |
| 1990 | Harpalani & Schraufnagel | CH$_4$ | Coal | SSM | 3.47–9.92 | N/A | 0.001–0.0063 | D: 38.1 mm, L: 76.2 mm |
| 1990 | Harpalani & Schraufnagel | CH$_4$; He | Coal | SSM | 5.54–10.05 | N/A | 0.00053–0.00204 | D: 38.1 mm, L: 76.2 mm |
| 1997 | Harpalani & Chen | He | Coal | PDPM−3 | 5.4 | 44.4 | 0.02–0.4 | D: 89 mm |
| 1999 | Al-hawaree | CO$_2$ | Coal | SSM | 6, 10, 16 | 52 | 1.1–143.2 | D: 25.4 mm, L: 38.1–63.5 mm |
| 2005 | Robertson & Christiansen | N$_2$; CH$_4$; CO$_2$ | Coal | SSM | 1.315–6.415 | 26.7 | 57–292 | D: 50.8 mm |
| 2007 | Guo et al. | CO$_2$ | Coal | SSM | 4.9–8.3 | 23 | 0.03–0.05 | D: 33.75 mm, L: 85.5 mm |
| 2008 | Lin et al. | N$_2$; CH$_4$; CO$_2$ | Coal | SSM | 2.76 | 22 | 0.19–19.78 | D: 28 mm, L: 70 mm |
| 2008 | Billiotte et al. | N$_2$; He | Mudstone | PDPM−3 | 4.5–21.5 | 30 | 0.0000001–0.000008 | D: 24 mm, L: 30–50mm |
| 2008 | Fedor et al. | N$_2$ | Claystone | PDPM−3 | 6–7 | 35 | 0.0000001–0.001 | D: 36 mm, L: 10 mm |
| 2009 | Pini et al. | N$_2$; CH$_4$; CO$_2$ | Coal | PDPM−3 | 5.52–13.52 | 45 | 50–12070 | D: 25.4 mm, L: 36 mm |
| 2010 | Han et al. | N$_2$; He; CO$_2$ | Coal | SSM | 5.8–39.8 | 45 | 0.0000021–0.001102 | D: 28.5 mm, L: 21.2 mm |
| 2010 | Pan et al. | CH$_4$; He; CO$_2$ | Coal | PDPM−3 | 2–6 | 45 | 0.1–1 | D: 45 mm, L: 105.5 mm |
| 2010 | Cui et al. | He | Sediment | PDPM−3 | 0–45 | 19.6 | 0.0002–0.1 | N/A |
| 2011 | Chen et al. | CH$_4$; He; CO$_2$ | Coal | PDPM−3 | 2–6 | 35, 45 | 0.01–0.97 | D: 45–45.5 mm, L: 101–105.5 mm |
| 2011 | Wang et al. | CH$_4$; He; CO$_2$ | Coal | PDPM−3 | 0.4–11 | N/A | 0.00000067–1.65 | D: 25 mm, L: 25–50 mm |
| 2011 | Metwally & Sondergeld | N$_2$ | Tight gas reservoir, Shale | PDPM−2 | 5.52 | 25.6 | 0.0000079–0.00014591 | D: 25.4 mm, L: 50.8 mm |
| 2012 | Tinni et al. | N$_2$ | Shale | PDPM−2 | 6.9–34.5 | N/A | 0.000001–0.000095 | N/A |
| 2012 | Chalmers et al. | CH$_4$ | Shale | PDPM−3 | 9.6–23 | N/A | 0.0000071–0.075 | D: 25.4 mm, L: 25.4 mm |
| 2012 | Kumar et al. | CH$_4$; He; CO$_2$ | Coal | PDPM−3 | 4.3–8.4 | N/A | 0.01–6.63 | D: 25 mm, L: 50 mm |
| Year  | References          | Seepage body | Rock types | Method   | Effective stress/MPa | Temperature/°C | Permeability/mD | Sample size       |
|-------|---------------------|--------------|------------|----------|-----------------------|----------------|-----------------|------------------|
| 2013  | Li et al.           | CO₂          | Coal       | SSM      | 2.2–4                  | 26             | 0.00007–0.01359 | D: 25.3 mm, L: 25.41–42.18 mm |
| 2013  | Xu et al.           | CH₄; CO₂     | Coal       | SSM      | 1–5                   | N/A            | 0.06–0.99       | D: 50 mm, L: 100 mm |
| 2013  | Vishal et al.       | CO₂          | Coal       | SSM      | 4.8                    | 26             | 0.04–31         | D: 39 mm         |
| 2013  | Kim & Lee           | N₂           | Sediment   | PDM–3    | 3.45                   | N/A            | 0.0004–0.007    | D: 38.1 mm, L: 45.7 mm |
| 2013  | Alnoaimi & Kovscek  | CH₄; He; CO₂ | Shale      | PDM–3    | 3.45                   | 21.5           | 0.01–0.04       | D: 25 mm, L: 46 mm |
| 2014  | Niu et al.          | N₂           | Coal       | SSM      | 7–8                    | 25, 50         | 13.8–33.3       | D: 50 mm, L: 100 mm |
| 2014  | Gensterblum et al.  | Ar; He       | Coal       | SSM      | 7.39–18.1              | 35             | 0.59–4.95       | D: 38 mm, L: 18.68–24.9 mm |
| 2014  | Rananthunga et al.  | CO₂; N₂      | Coal       | SSM      | 2–5                    | 25, 40         | 0.00018–0.00035 | D: 25 mm, L: 50 mm |
| 2014  | Lin & Kovscek       | N₂; He; CO₂  | Coal       | SSM & PDM–3 | 3                  | 22             | 0.6–18         | D: 25.4 mm, L: 25–75 mm |
| 2015  | Wang et al.         | He; CO₂      | Coal       | PDM–3    | 0.9–6.7                | 23             | 0.00002–0.01046 | D: 25.4 mm, L: 50.8 mm |
| 2015  | Yang et al.         | He           | Tight gas reservoir | PDM–3 | 2                    | 30             | 0.000000621–0.0000063 | D: 25 mm, L: 30 mm |
| 2015  | Meng et al.         | He; CH₄; CO₂ | Coal       | SSM      | 1.5–3.2                | 11.5           | 0.000047–0.000837 | D: 50 mm, L: 100 mm |
| 2015  | Kumar et al.        | He; CO₂      | Coal       | PDM–3    | 3.2–9                  | 20             | 1.4–38         | D: 25 mm, L: 50 mm |
| 2015  | Seomoon et al.      | CH₄; CO₂     | Coal       | SSM      | 2.07                   | 15             | 1.6–5.3        | D: 38.1 mm, L: 108.3 mm |
| 2015  | Li et al.           | CO₂          | Coal       | SSM      | 2.2–4                  | 26             | 0.00434–0.02013 | D: 25.4 mm, L: 35.4 mm |
| 2016  | Anggara et al.      | He; CH₄; CO₂ | Coal       | SSM      | 2–4                    | N/A            | 0.015–0.229    | D: 50 mm, L: 100 mm |
| 2016  | Gao et al.          | CH₄          | Shale & sandstone | PDM–3 | 3.45                   | 21.5           | 0.00000179–0.000485 | D: 38 mm, L: 25 mm |
| 2016  | Ma et al.           | He; CH₄      | Shale      | PDM–3    | 1.5                   | 55             | 0.000004–0.003042 | Cubes with each side–20 mm |
| 2017  | Meng & Li           | N₂; CH₄; CO₂ | Coal       | PDM–3    | 3.5                    | 20             | 1.0–23.1       | D: 25 mm, L: 46 mm |
| 2017  | Danesh et al.       | CH₄          | Coal       | SSM      | 0.5–2.5                | 35             | 4.14–5.6       | D: 61 mm, L: 95 mm |
| 2017  | Feng et al.         | CO₂          | Coal       | PDM–3    | 15.10–19.93            | 40.5           | 0.000004–0.0035 | D: 5.1 mm, L: 7.6 mm |
| 2019  | Sato et al.         | NaCl         | Sandstone  | N/A      | N/A                    | 25             | 0.0103–34.9    | D: 50 mm, L: 100 mm |
| 2019  | Wang et al.         | CH₄          | Coal       | PDM–3    | 3.5–7.5                | 30             | 0.073–0.797    | D: 50 mm, L: 100 mm |
| 2020  | Zhang et al.        | H₂           | Salt rock  | PDM–3    | 1–20                   | N/A            | 0.00000000849–0.0000014 | D: 63.8–66.85 mm, L: 52.03–83.18 mm |
| 2021  | Xiao et al.         | CO₂          | Sandstone  | PDM–1    | 6                      | 25             | N/A            | D: 50 mm, L: 100 mm |

Note: “N/A” represents the data are not available; D, L, and A are the diameter, length, and area of sample.
(A) Conventional triaxial loading

(B) "Three-stage" triaxial loading and unloading
engineering. Therefore, according to the stress distribution characteristics corresponding to the roadway of deep mines before excavation, excavation, after excavation (see Figure 12C), the authors designed the “three stage” loading and unloading stress path. Additionally, the stress path was adopted to conduct stress-seepage coupling test of coal and rock, and the permeability evolution characteristics were obtained (see Figure 12B). It can be seen that the coal or rock under the stress path underwent a complex process of loading, unloading and re-loading (see Figure 12B). In general, compared with the permeability evolution characteristics of coal and rock under the conventional triaxial condition, that under the “three-stage” loading and unloading condition is wider. Namely, adopting the “three-stage” stress path to conduct stress-seepage coupling test considering the original damage characteristics of coal and rock specimens produced by high initial stress can make the conclusion and law more accurate and reliable. Furthermore, avoiding the magnitude difference of permeability of coal and rock, which can gradually realize the effect of transfer from qualitative research to semi-quantitative, even quantitative research.

As shown in Figure 12B, in the initial high in situ stress state reduction stage I (O1O1), due to the three-dimensional high stress compression in coal and rock, the compaction degree of original pores or cracks in the coal and rock are greatly improved, which can make the coal and rock almost close to “rigid body” [64]. Therefore, the opening of seepage channel of coal and rock decreases to the minimum at stage I (corresponding to stage 001 of the permeability evolution curve). In the constant axial pressure—unloading confining pressure stage II (O2O2), the high confining pressure of coal and rock is unloaded at stage II, which easily leads to producing a large number of tensile micro-cracks in the radial direction of coal and rock. Therefore, the number of radial seepage channels increases sharply, which leads to the permeability sharply increases at stage II (corresponding to stage 002 of the permeability evolution curve). Additionally, according to Griffith strength theory, a large number of new radial tensile micro-cracks tips will produce the concentration phenomenon of tensile stresses, which leads to the illusion of axial compression deformation of coal and rock at stage II. In axial loading stage III (O3E), this stage can be divided into five sub-stages, which are secondary compaction stage III(AB), linear elastic deformation stage III(BC), unstable crack growth stage growth III(BC), and post-peak strain softening stage III(BC), respectively. The corresponding permeability evolution stages are 00a, ab, bc, cd, and de, respectively. Additionally, in the stage III(0), the new radial tensile micro-cracks of coal and rock are secondary compacted. Therefore, the opening of seepage channel becomes secondary smaller, and the permeability further decreases. In the stage III(0), coal or rock produces the linear elastic deformation. Therefore, the opening and the number of seepage channels basic remains constant. However, compared to the test results under the conventional triaxial stress-seepage condition, the rate of linear elastic deformation stage under the “three stage” loading and unloading stress path increases obviously. It can also indicate that the fundamental mechanical parameters, the elastic modulus and Poisson’s ratio under the “three stage” loading and unloading stress path, will be more accurate. In the stage III(0), secondary new cracks are derived in the coal and rock, which are stably extended with the axial loading. Therefore, the number of seepage channels increases and leads to the permeability increases slowly. In the stage III(0), coal and rock gradually reach to the peak strength from the yield point, and the secondary new cracks in coal and rock develop and extend rapidly, and then form the surface of macroscopic failure. As a result, the opening degree of the secondary new cracks in coal and rock increases sharply again. Therefore, the opening degree of the seepage channels increases sharply again, which leads to the permeability increases sharply. In stage III(0), the surface of macroscopic failure of coal and rock has been formed. Therefore, the dominant seepage channel has been formed, which leads to the permeability of coal and rock in stage III(0) basically remains constant.
Additionally, the safety and stability of deep engineering cannot avoid the influence of joints and natural discontinuities. Therefore, the authors also believe that it is urgent to conduct the research on the permeability properties of the bedded coal and rock under the “three stage” loading and unloading stress path. Meanwhile, they should be promoted and expanded gradually from the stress-seepage coupling test under the conventional triaxial condition to that under the true triaxial condition. For example, from the scale perspective, the true triaxial stress-seepage coupling tests of (bedded) coal and rock need to be conducted with “three stage” loading and unloading stress path. Meanwhile, equipped with the real-time auxiliary implementation of the true triaxial scanning CT scanner, the permeability properties of (bedded) coal and rock can be obtained. Therefore, the time-dependent failure mechanism of (bedded) coal and rock can be revealed from the mesoscopic perspective; Additionally, from the perspective of phase-field coupling, the true triaxial solid-liquid-gas multi-phase coupling tests of (bedded) coal and rock need to be conducted to further reveal the interaction effect mechanism between phase-field. Of course, the true triaxial stress-seepage coupling tests of (bedded) coal and rock also need to be conducted based on the “five guarantees” coring technology, and the permeability evolution law obtained can also be more accurate.

5.3 Permeability evolution models

Due to the non-replicability and difference of coal and rock specimens (although 3D printing technology can be adopted, the difference of materials is difficult to eliminate), it is far from enough to obtain the permeability evolution law of bedded coal and rock. Because the unified permeability criterion about cannot be established for prediction and early warning. Therefore, it is necessary to establish a reasonable permeability evolution model based on a lot of experimental data and results. Furthermore, a permeability evolution equation with strong universality need to be built to provide a certain of theoretical guidance and reference for field engineering.

Domestic and foreign scholars have done a lot of work on the construction of the permeability evolution models of coal and rock, and obtained relatively abundant research results. The details of permeability evolution model of coal and rock under various conditions are shown in Table 2.

Additionally, due to the complexity and uncertainty of the spatial structure of coal and rock system, domestic and foreign scholars have adopted multiple systems such as fluid mechanics, damage mechanics and fractal theory to study the permeability properties of coal and rock. Meanwhile, they have made a certain of ideal assumptions and simplified treatments for the seepage system of coal and rock. Therefore, the homogenized seepage model of crack matrix, seepage model of crack matrix considering the circuitous degree of cracks and fractal seepage model considering homogeneity and circuitous degree of internal cracks are established, respectively. The corresponding seepage models of coal and rock are shown in Figures 13-15, respectively.

Among them, the homogenized seepage model of crack matrix in rock and coal is suitable for numerical simulation to verify the scientific and rationality of mechanical test results, but the application scope of this model is narrow. Comparatively, the seepage model of crack matrix considering the circuitous degree of cracks in rock and coal is more applicable. The seepage models of crack matrix considering the circuitous degree of cracks in rock and coal are often adopted to simulate the flow and transport characteristics of porous media. The most significant characteristic of the method is that the diameter and circuitous degree of spatial cracks in coal and rock system are considered. The research idea of establishing the fractal seepage model considering homogeneity and circuitous degree of internal cracks in rock and coal mainly comes from the Sierpinski carpet current flow model with the electrical conduction characteristics of porous media. This model is widely used in the seepage properties of coal or rock. Mainly because it can not only take into account the fractal characteristics of system structure, but also consider the circuitous degree and the length and diameter of spatial cracks.

The above mentioned domestic and foreign scholars have built permeability evolution models of coal and rock under various conditions, but they ignored the damage of coal or rock caused by the environment before the tests, and naturally ignored the authenticity and accuracy of the initial permeability of coal and rock. Therefore, the authors believe that when considering the construction of permeability evolution model of coal and rock, “five guarantees” coring technology should be adopted or the “three-stage” loading and unloading path proposed should be adopted considering the engineering evolution history of coal or rock before the tests. Namely, the accuracy and authenticity of initial damage (initial permeability) of coal and rock before the tests are fully considered. And then achieve the effect of quantitative or semi-quantitative construction of permeability evolution models of coal and rock, so that the established permeability evolution models of coal and rock are more universal, more extensive, and more scientific and reasonable. Of course, the permeability evolution models of bedded coal and rock should be established in the same way.
TABLE 2 Details about permeability evolution models of coal and rock

| Year | References       | Seepage body | Rock types                  | Permeability evolution models                                                                                   |
|------|-----------------|--------------|-----------------------------|------------------------------------------------------------------------------------------------------------------|
| 1994 | David et al.²⁷  | Water        | Porous sandstone rock       | \( k = k_0 \exp \{ -\gamma (P_{eff} - P_L) \} \); \( k = k_0 (\phi/\phi_0)^n \)                                     |
| 1997 | Zhu & Wong²⁸    | N/a          | Berea sandstone             | \( k = k_0 e^{\gamma \phi} \)                                                                                   |
| 2003 | Morris et al.²⁹ | N/a          | Berea sandstone             | \( k = k_0 \exp \{ K (\phi (\sigma_{eff} D) - D \ min (D, D^{max}) \) \}                                            |
| 2008 | Zhang et al.³⁰  | Gas          | Coal seams                  | \( Gu_{ijkl} + \frac{G}{1 - 2\nu} u_{ijkl} - \frac{1}{2} p_i - \frac{k_{ijkl}}{\mu (\frac{1}{1 + \nu} p_i + \frac{1}{1 + \nu} p_j)} = 0 \) |
|      |                 |              |                             | \( \left[ \phi + \frac{\nu}{(\frac{1}{1 + \nu} p_i + \frac{1}{1 + \nu} p_j)} + \frac{1}{(\frac{1}{1 + \nu} p_i + \frac{1}{1 + \nu} p_j)} \right] \left[ \phi - \frac{1}{(\frac{1}{1 + \nu} p_i + \frac{1}{1 + \nu} p_j)} \right] \nabla (\frac{1}{2} | p \nabla p | ) = Q, \Delta = \frac{1}{1 + \nu} \frac{\partial \Delta}{\partial t} \)                      |
| 2009 | Ghabezloo et al.³¹ | Water        | Oolitic limestone           | \( a = a (\sigma - n_x p_x) \)                                                                                   |
| 2010 | Wu et al.³²     | Gas          | Coalbed methane             | \( k = k_0 \exp \{ -3C (\sigma - \sigma_0) \} \)                                                                  |
| 2011 | Ma et al.³³     | Gas          | Coalbed methane reservoirs  | \( k = k_0 \left( \frac{(\frac{\sigma + \nu \sigma_0}{\sigma_0})^n}{1 - \nu \phi} \right) \)                                                                  |
| 2011 | Liu et al.³⁴    | Gas          | Swelling                    | \( k = k_0 \left[ \frac{\sigma_0}{\sigma} \left( -\Delta \epsilon \frac{1}{\nu} + \frac{\Delta \epsilon}{\nu} \right) \right] : p \leq P_c \) |
|      |                 |              |                             | \( k_0 \left[ \left( 1 + \frac{\phi_0 (\phi - \phi_0)}{\phi_0 (\phi - \phi_0) + \phi_0 \phi_0)} \right] \left[ 1 + \frac{\phi_0 (\phi - \phi_0)}{\phi_0 (\phi - \phi_0) + \phi_0 \phi_0)} \right] : p > P_c \) |
| 2012 | Mitra et al.³⁵  | Gas          | Coal                        | \( \log k_0 = -3C (\sigma - \sigma_0) \)                                                                     |
| 2015 | Zheng et al.³⁶  | Gas          | Sedimentary rock            | \( k = k_0 \exp \{ \beta (\phi_r - \phi_{eq}) \} \)                                                            |
| 2017 | Zang & Wang³⁷   | Gas          | Coal                        | \( k = k_0 \left[ \frac{1}{\phi_{eq} (1 - \nu)} \left( \frac{\phi_{eq} - \epsilon_{eq} - \phi_{eq} \epsilon_{eq}}{\epsilon_{eq}} - \frac{\phi_{eq} \epsilon_{eq}}{\epsilon_{eq}} \right) \right] \) |
| 2018 | Li et al.³⁸     | GAS          | Microcracked porous rocks   | \( k = k_0 \exp \{ -m \frac{\Delta p}{\epsilon_{eq}} \} + k_{sol} \left( 1 - \frac{\epsilon_{eq}}{\epsilon_{eq}} \right) + k_{por} \exp \{ \gamma - \frac{1}{\sqrt{\epsilon_{eq}}} \left( \frac{\epsilon_{eq}}{\epsilon_{eq}} \right) \epsilon_{eq} \} \) |
| 2019 | Tian et al.³⁹   | Water        | Combined rock mass          | \( k = \frac{p_{eff}}{12 \mu} \exp \left\{ -2 \left[ \frac{\Delta \epsilon}{\epsilon_{eq}} - \frac{1}{\epsilon_{eq}} \right] \left( 1 - \mu \Delta \sigma_{con} \right) \right\} \) |
| 2019 | Zhao et al.⁴⁰   | Helium       | Fractured shale rock        | \( k = k_0 \left[ 1 + \frac{1}{\phi_0} \left( \frac{1 - 2\nu(1 + \alpha)}{1 - \nu} \right) \Delta p \right] - \frac{1}{3} \left( \frac{1 - 2\nu}{1 - \nu} \right) (\epsilon_3 - \epsilon_{eq}) \) |
| 2021 | Song & Zhang⁴¹  | Water        | Sandstone                   | \( k_{eq} = a + b (\sigma_1 - \sigma_3)_{eq} + c \sigma_3 e + d (\sigma_1 - \sigma_3)_{eq} e + e \sigma_3 e \) |
|      |                 |              |                             | \( k_{sol} = a + b (\sigma_1 - \sigma_3)_{sol} + c \sigma_3 e + d (\sigma_1 - \sigma_3)_{sol} e + e \sigma_3 e \) |
|      |                 |              |                             | \( k_{ad} = a + b (\sigma_1 - \sigma_3)_{ad} + c \sigma_3 e + d (\sigma_1 - \sigma_3)_{ad} e + e \sigma_3 e \) |
|      |                 |              |                             | \( k_{cf} = a + b (\sigma_1 - \sigma_3)_{cf} + c \sigma_3 e + d (\sigma_1 - \sigma_3)_{cf} e + e \sigma_3 e \) |

FIGURE 13 Homogenized seepage model of crack matrix in rock and coal³³¹

- Matrix homogenization;
- Cracks homogenization;
- Seepage exchange model of matrix-crack system
SUMMARY AND NEW INSIGHTS

1. The coring technology of (bedded) coal or rock should be reformed and innovated, "five guarantees" coring technology should be accelerated research and application.

2. The multidisciplinary approach should be fully adopted integrating quantum mechanics, molecular dynamics, intelligent mechanics and even statistical mechanics with rock mechanics. Meanwhile, 3D printing, CT scanning, SEM and other means can be comprehensively adopted.44 The spatial fabric of bedded coal and rock can be characterized quantitatively and qualitatively with high precision in this way.

3. The permeability and energy of coal and rock are dynamic evolution under the action of multi-field or multi-phase or field-phase coupling. How to accurately quantify the "black box" issue: energy evolution is a key scientific issue. The permeability-energy evolution model needs to be established with the initial high in situ stress reduction, to indirectly quantify the energy accumulation and dissipation of coal and rock during the entire deformation process. Meanwhile, it can be combined with the structural evolution theory for in-depth characterization and disclosure.56 Furthermore, it can provide more accurate theoretical basis for the early warning and prediction of rock burst disasters in deep engineering.

4. The permeability evolution characteristics of coal and rock under the "three-stage" loading and unloading condition is wider compared with that under the conventional triaxial condition. Namely, adopting the "three-stage" stress path to conduct stress-seepage coupling test considering the original damage characteristics of coal and rock specimens produced by high initial stress before the tests can make the conclusion and law more accurate and reliable. Furthermore, avoiding the magnitude difference of permeability of coal and rock, which can gradually realize the effect of transfer from qualitative research to semi-quantitative, even quantitative research.

5. From the scale perspective, the true triaxial stress-seepage coupling tests of (bedded) coal and rock need to conducted based on "three stage" loading and unloading stress path. Meanwhile, equipped with the real-time auxiliary implementation of the true triaxial scanning CT scanner, and the permeability properties of (bedded) coal and rock can be obtained. Therefore, the time-dependent failure mechanism of (bedded) coal and rock can be revealed from the mesoscopic perspective; Furthermore, from the perspective of phase-field coupling, true triaxial solid–liquid–gas multi-phase coupling tests of (bedded) coal and rock need to be conducted to reveal the interaction effect mechanism between phase-field.

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CONFLICT OF INTEREST
The authors declare that they have no conflict of interest.
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