INTRODUCTION

China is rich in coal bed methane (CBM). CBM reserve, which is buried above the depth of 2000 m, is 36.81 trillion m$^3$, and it is almost equal to the amount of conventional natural gas resources. As an associated product of coal, CBM is not only the major hazards in coal mine, and it is also a kind of greenhouse gases; of which, the global warming potential is 25 times more than that of carbon dioxide. Additionally, CBM is a valuable clean energy, so
the United States, Russia, Canada, Australia, and many other countries begin to develop CBM resources. Therefore, how to extract gas safely and efficiently has become the demand for safety, economy, and environment of coal mine in China.9

Coal permeability is a key parameter that affects the drainage of CBM. Coal permeability is a complex function of fracture in coal. So it is not just influenced by the self-structure factors including scale, bedding direction, and other factors, but also influenced by the external factors such as stress, gas pressure, and temperature.10 Compared with other influencing factors, the change in stress may lead to the failure of the coal body11,12 and then lead to the sudden increase in permeability, which is conducive to the flow of gas in the coal seam.13 However, the original permeability of coal seams in China is only 10−4–10−3 mD,14 which is far lower than that of coal seams in other countries. Therefore, Chinese scholars pay more attention to the study of the permeability evolution after the stress-induced plastic failure of coal.15,16 According to the Mohr–Coulomb failure criterion, the loading stress path and unloading stress path both can make the coal be damaged.17,18 For the loading stress path, Yang et al,19 Wang et al,20,21 and Xue et al22-25 experimentally studied the change law of damage-induced permeability due to loading stress in the process of the complete stress–strain of coal samples. For the unloading stress path, Yin et al26-29 Xu et al,30 and Zhang et al31 carried out a large number of experiments to analyze the influencing factors such as style of loading stress path, speed of unloading stress, and cyclic unloading stress on coal permeability. What’s more, Chen et al32 and Xu et al,33 respectively, used the CT scanning technology and acoustic emission technology to quantitatively describe the stress-induced plastic deformation of coal and then obtained the corresponding relationship between plastic deformation and permeability.

To develop a damage-induced permeability model of coal, it is necessary to analyze not only the change in the original fracture, but also the evolution law of the new fracture in coal. In addition, adsorption deformation of coal matrix will be induced after adsorbs gas, which makes the permeability characteristics of coal to be more complicated than that of rock. There have been abundant research achievements on the elastic permeability model of coal body and the damage constitutive of rock, which can provide a fundamental basis for the damage-induced permeability model of coal.34,35 Zhu and Tang36 established a damage constitutive equation of rock. Take into account this equation, Zhu et al37 took the damage variable to describe the volume strain of coal. Then, the volume strain of coal, as a bridge, was applied to establish a new damage-induced permeability model. Based on the same damage constitutive equation, Yang et al38 and Zheng et al39 directly used the damage variable to modify the elastic permeability models to obtain the damage-induced permeability models, respectively. Espinoza et al40 and Hu et al41 established the damage dual-pore constitutive equations of coal, respectively. Take into account these equations, they established damage-induced dual-pore permeability model, respectively. Later, Wang et al42 further simplified the dual-pore permeability model into single-pore permeability model. Xie et al43 established another damage-induced permeability model based on the theory of fracture mechanics. Then, Zhang et al44 further enriched and modified the model by taking into consideration the strain softening characteristics of coal. Since all the above damage-induced permeability models refer to the damage variables, which are the basis of verifying permeability models, due to the lack of effective description of damage variables, all the above permeability models were not verified after they were established.

To better realize the verification of the damage-induced permeability model, some scholars used different methods to describe the damage variables or avoid using the damage variables in the permeability model. Xue et al23 and Zhang et al45 used acoustic emission technology to describe the damage variables, and then, their damage-induced permeability models were verified by experimental data, respectively. Xie et al46 mainly studied the evolution law of damage-induced permeability caused by gas pressure in the process of gas drainage, so they used the changes of gas pressure to describe the damage variables in coal. Then, they carried out experimental verification on their damage-induced permeability model. Zhang et al47 used the change in radius of the microfracture to describe the damage variables and then achieved their model validation. In order to avoid the description of damage variables, Chen et al48 believed that the damage-induced permeability should be modified by a coefficient, which was exponential to the deviatoric stress. Then, a damage-induced permeability model including modified coefficient was established and verified by experimental data. Cheng et al49 took volume expansion point of coal as the demarcation point of original fracture and new fracture, and adopted expansion volume after the demarcation point to describe the new fractures. Then, a mining-enhanced permeability model was established, and it was verified by field permeability data and expansion deformation data of coal seam. All in all, all the above permeability models were verified, but most of them still need to use the complex method to describe the damage variable. An et al50 provided us with a good idea to describe the damage of coal, and they used the equivalent plastic strain instead of the damage variable. Then, they modified the PM model51 to establish a damage-induced permeability model. However, their permeability model was established under the conditions of uniaxial strain with constant vertical external stress, and it was not validated. Therefore, it was hard to describe the change in permeability under complicated stress states.
The damage-induced permeability model was often used to study the gas drainage in coal with plastic failure caused by roadway excavation and stress unloading. However, in the process of gas predrainage, only the elastic permeability model is used to study the gas predrainage. For example, Liu et al.,52 Dong et al.,53 and Si et al.54 did not use the damage-induced permeability model in the study of gas predrainage. In the process of gas predrainage, the excavation of borehole will also cause the damage of coal and sudden increase in permeability surrounding the borehole, which may affect the gas predrainage. In addition, the method of gas predrainage is one of the main regional prevention and control measures for coal and gas outburst, and it is directly related to the judgment of the risk of gas outburst. Therefore, whether the sudden increase in permeability caused by plastic failure should be considered in the predrainage still needs to be further analyzed.

The purposes of this paper are to improve the theory of damage-induced permeability and discuss whether the sudden increase in permeability caused by plastic failure should be considered in the predrainage. Firstly, the permeability evolution experiments during the complete stress-strain process of coal were carried out firstly. On the basis of permeability evolution laws and equivalent plastic strain, a new damage-induced permeability model, which includes the effect of interaction between matrix and fracture, was developed and validated. Then, solid–gas coupling models of coal were developed based on the new permeability model, and the numerical simulation of gas predrainage in combination of soft coal and hard coal under different cases were carried out. In addition, the necessity of applying damage-induced permeability model to gas predrainage was analyzed. Finally, the results of numerical simulation were used to further optimize the borehole layout of gas predrainage in the field.

2 DAMAGE-INDUCED PERMEABILITY EVOLUTION EXPERIMENTS

2.1 Experimental facilities and method

The permeability of coal specimen was tested by the experimental facility of adsorption-seepage-mechanics coupling characteristics system, which mainly includes mechanics and temperature control module, test module, and seepage control module. The range of loaded axial stress is 0–600 kN by the mechanics control module, and that of loaded confining stress is 0–60 MPa. The temperature can be applied from room temperature to 90°C by the temperature control module. For the seepage control module, the high-precision measuring pump is mainly used to inject gas into the gas pipe, with the maximum injection pressure up to 40 MPa. The principle of the system is illustrated in Figure 1.

Based on Darcy’s law, many methods for testing the permeability of porous media have been developed in the laboratory. The methods for testing the permeability of coal can be classified as two kinds, the steady-state method and transient state method. In this paper, the transient pressure pulse method was chosen, and the testing gas was methane.
The procedures of coal permeability evolution experiments during the complete stress–strain process can be mainly divided into the six stages, as follows:

1. Measuring the geometric size stage: The height and diameter of the coal sample were measured.
2. Installation of coal specimen stage: First, the coal specimen and top base were put on the bottom, and the silica gel was smeared outside the coal specimen. Second, the coal sample was wrapped in a length of heat-shrinkable tube, and a hot air gun was used to make the heat-shrinkable tube close contact with the coal sample. Then, the sealing tape was wrapped around the two ends of the heat-shrinkable tube. Finally, the axial and radial strain gauges are installed outside the coal sample, and the gas pipes were connected with the top base and bottom. The Installation of coal specimen is shown in Figure 2A.
3. Applying hydrostatic pressure stage: The hydraulic oil was injected into the measuring chamber by the confining stress pump, and the mechanics control system was used to apply the hydrostatic pressure to the predetermined value (2 MPa or 4 MPa in this paper). Then, the temperature control system was set at 30°C.
4. Vacuum pumping stage: The coal specimen was vacu-umed by the vacuum pump for at least 24 hours.
5. Gas injection and adsorption equilibrium stage: Methane was injected into the coal specimen by the measuring pump, and the gas pressure was kept at 1 MPa. When there was no change of the gas volume in the measuring pump and the strain values of coal, the coal reached the methane adsorption equilibrium state.
6. Permeability measurement stage: The axial stress was applied according to the predetermined mechanical path (as shown in Figure 2B) to determine the permeability at elastic strain stage and plastic damage strain stage.

2.2 Permeability evolution results

Permeability evolution results during the complete stress–strain process were measured under the condition of fixing the gas pressure and confining stress, and then, the axial stress increased until the residual stress point. The gas pressure is 1 MPa, and the confining stress was 2 and 4 MPa, respectively. Permeability evolution results during the complete stress–strain process of coal are shown in Figure 3.

According to the permeability evolution results during the complete stress–strain process of coal shown in Figure 3, the following laws can be obtained:

1. With the increase in axial strain, the coal permeability decreases slowly at first, then increases rapidly, and finally increases slowly or even remains unchanged. This is primarily because that the coal body is in the elastic strain stage, in which the coal permeability is mainly controlled by the original fractures, so the coal permeability decreases with the increase in axial strain in this stage. Then, with the increase in axial strain, the coal body will be strongly damaged. A number of new fractures will appear in the coal, and the connectedness of coal will improve gradually. So the permeability slowly increases before the peak stress point.
and suddenly increases after the peak stress point. At the residual stress stage, the coal body will still be slightly damaged, which leads to a slow increase in permeability, but the change in permeability is little compared with the previous explosive increase.

2. After the volume expansion point, the permeability does not increase immediately. With the increase in deviatoric stress, the permeability still tends to decrease. Permeability begins slightly increases before the peak stress point, so the extreme point of permeability locates between the volume expansion point and peak stress point. As a result, the extreme point of permeability lags behind the volume expansion point. This phenomenon is because that some new fractures appear in the coal due to the damage of deviatoric stress after the volume expansion point, but these new fractures appear in the local area of coal, and they are not interconnected between each other. So the new fractures have not been really involved in the gas seepage. However, the increase in deviatoric stress will further close the original fractures, so the coal permeability does not immediately increase after the volume expansion point, but continues to decrease. Until the peak stress point, the connectivity between these new fractures is improved. Then, after the peak stress point, there is a sudden increase in permeability. This phenomenon of permeability lagging behind volume expansion point also exists in the data of literature.22

3. Coal permeability explosively increases after the peak stress, which is much higher than the initial hydrostatic permeability. If the ratio of the coal permeability after the peak stress to the initial permeability under hydrostatic pressure is defined as the increasing coefficient of permeability, thus the increasing coefficient of permeability is 200-300 in Figure 3. This is primarily because that the failure mode of coal is mainly the obvious vertical penetrating fractures or shear fractures, which can increase the coal permeability very well.

In the process of the complete stress–strain of coal, the confining stress is fixed, and the gas pressure in coal can also be considered as a constant value. In this case, only the axial deviatoric stress changes, so the change in axial deviatoric stress is equivalent to the change in bulk stress. The coal permeability is mainly controlled by the fracture structure of coal, and the stress environment of coal determines the development of the fracture structure of coal. Therefore, in order to further understand the evolution relationship of permeability in the process of the complete stress–strain of coal, the relation between permeability and deviatoric stress was obtained, as shown in Figure 4.

According to Figure 4, with the change in deviatoric stress, the permeability evolution law can be roughly divided into four stages. With the increase in deviatoric stress, the permeability decreases first and then increases slowly. With the decrease in deviatoric stress, the permeability increases rapidly and finally increases slowly or even remains unchanged. The initial decrease is due to the closure of the
original fractures under the compression of stress, and the slow increase is the generation of new fractures, in which stage there are not many penetrating fractures and it lasts for a short time in the whole process. Then, the rapid increase in permeability is due to the macroscopic fractures. At last, coal will still be slightly damaged, which results in a slow increase in permeability.

3 | DAMAGE-INDUCED PERMEABILITY MODEL

In this paper, based on the permeability evolution law obtained from the experiments and elastic permeability model, a new damage-induced permeability model was developed from the form of stress.

3.1 | Model development

It is useful to pointing out that the range from volume expansion point to the peak stress point in the process of the complete stress–strain of coal and the difference of permeability between the two points cannot even be distinguished. Moreover, permeability in elastic strain stage is much less than that in plastic damage strain stage, so the difference in permeability between the two points is ignored when we research the relationship between stress and permeability. An et al.50 ignored the slow increase stage of permeability before the peak stress point, and they thought the permeability evolution with the stress before the peak stress point could be described by the model of elastic permeability model. So we chose the lowest permeability point is corresponding to the peak stress point in this paper. After the peak stress point, the permeability increases explosively and some scholars believe that this increase can be approximately regarded as linear in the plastic damage strain stage.55 In residual stress stage, the permeability measured in this paper increases slowly, some scholars believe that the permeability in this stage can be approximately considered unchanged.56,57 In this paper, the simplified permeability evolution law during the complete stress–strain process is as shown in Figure 5.

According to Figure 5, the permeability can be roughly classified into three stages in the complete stress–strain process. The first stage is before the peak stress point. In this stage, the deformation of coal body is mainly elastic, and the permeability can be characterized by the elastic model. The second stage is plastic damage strain stage. In this stage, the deformation of coal body is strongly plastic, and various macro-fractures appear which make the permeability change abruptly. The third stage is the residual stress stage, and the plastic deformation of the coal body is slow, and the permeability is basically unchanged.

In the first stage, the permeability can be characterized by the elastic permeability model. Based on the pore-elasticity principle and coal matrix–fracture interactions, an elastic permeability model, which includes the effective stress and matrix sorption deformation under triaxial stress conditions, has been developed by us in a published paper.58 The elastic permeability model can be expressed as

$$\frac{k}{k_0} = \exp \left\{ -3C_f \left[ \Delta \sigma - \Delta p + \frac{E}{3(1-2v)} \Delta \varepsilon^m \right] \right\}$$

where $k$ and $k_0$ are the instantaneous permeability and initial permeability, respectively, mD. $C_f$ is the fracture compressibility, MPa$^{-1}$. $E$ is Young’s modulus, MPa; and $v$ is Poisson’s ratio. $\sigma$ is the bulk stress, MPa, and it can be calculated by this equation $\sigma = (\sigma_1 + \sigma_2 + \sigma_3) / 3$, $\sigma_1$, $\sigma_2$, $\sigma_3$ are the stress in i, j, k directions. $\rho$ is the gas pressure, MPa. $f_m$ is the internal swelling ratio of matrix adsorption deformation, and $\varepsilon^S_m$ is the adsorption strain of matrix, $\varepsilon^S_m = \frac{e^S_{b} - e^S_{b \max}}{p + p_0}$. $\varepsilon^S_{b \max}$ is the maximum adsorption

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4}
\caption{Relation between permeability and deviatoric stress}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5}
\caption{Simplified permeability evolution law during the complete stress–strain process}
\end{figure}
strain of coal body, \( p_s \) is the Langmuir-type adsorption pressure of coal body, MPa.

In the second stage, the permeability and the plastic strain of coal both increase, so the permeability is approximately regarded as linear increase with the plastic strain. The permeability at this stage can be described as

\[
\frac{k}{k_0} = (1 + \frac{\gamma^p}{\gamma^{ps}}) \exp \left\{ -3C_f \left[ \Delta \sigma - \Delta p + f_m \frac{E}{3(1-2v)} \Delta \varepsilon^S_m \right] \right\} \tag{2}
\]

where \( \xi \) is the sudden increase coefficient of permeability. \( \gamma^p \) and \( \gamma^{ps} \) are the instantaneous equivalent plastic strain and initial equivalent plastic strain, respectively, \%. \( \gamma^p = \sqrt{2/\left[3(e_1^p e_1^p + e_2^p e_2^p + e_3^p e_3^p)\right]} \), \( e_1^p \), \( e_2^p \), \( e_3^p \) are the plastic strain in \( i, j, k \) directions, \%, \(^{60}\)

In the third stage, coal permeability increases slowly or even remains basically unchanged. The permeability at this stage can be expressed as

\[
\frac{k}{k_0} = (1 + \xi) \exp \left\{ -3C_f \left[ \Delta \sigma - \Delta p + f_m \frac{E}{3(1-2v)} \Delta \varepsilon^S_m \right] \right\} \tag{3}
\]

3.2 Model validation

In the underground coal mine, the change in stress caused by mining is instantaneous, so more attention should be given to the influence of mining stress on the damage and permeability of the coal body. Therefore, the permeability data in Figure 3A were selected to validate the model. On this condition, both the confining pressure (2 MPa) and gas pressure (1 MPa) can be seen as invariants, so the Equation (4) can be further rewritten as

\[
\frac{k}{k_0} = \begin{cases} 
(1 + \frac{\gamma^p}{\gamma^{ps}}) \exp \left\{ -3C_f \left[ \Delta \sigma - \Delta p + f_m \frac{E}{3(1-2v)} \Delta \varepsilon^S_m \right] \right\} & 0 \leq \gamma^p \leq \gamma^{ps} \\
(1 + \xi) \exp \left\{ -3C_f \left[ \Delta \sigma - \Delta p + f_m \frac{E}{3(1-2v)} \Delta \varepsilon^S_m \right] \right\} & \gamma^p > \gamma^{ps} \end{cases} \tag{5}
\]

During the process of model validation, fracture compressibility, sudden increase coefficient, and initial equivalent plastic strain will be used. Then, we will explain the three required parameters:

1. Before the damage-induced permeability experiments, the permeability experiments under hydrostatic pressure stage were performed. Base on the permeability data under hydrostatic pressure stage, the fracture compressibility of 0.1395 MPa\(^{-1}\) was calculated.
2. The initial equivalent plastic strain is calculated based on the curve of complete stress–strain process, and the calculated initial equivalent plastic strain is 0.0101.
3. The ratio of the permeability in the residual stress stage and that at the initial hydrostatic pressure point is obtained, and then, the ratio is corrected by considering the influence of the difference of bulk stress. Then, the sudden increase coefficient (\( \xi \)) is 2305.

Substituting the above three parameters into the damage-induced permeability model Equation (5), the modeled data
of permeability could be obtained. Then, the modeled data of permeability and experimental data were drawn to compare with each other. The relationships between permeability data, axial strain, and deviatoric stress were made, as shown in Figure 6.

In the second stage, coal permeability will increase explosively after the peak stress point, and this process is extremely complicated. In this paper, parameters of sudden increase coefficient and equivalent plastic strain were used to simplify permeability model. Although the permeability model has been simplified to some extent, the damage-induced permeability model can match the experimental data of permeability very well (as shown in Figure 6), which indicates that the damage-induced permeability model is reasonable.

4 | NUMERICAL SIMULATION OF PERMEABILITY MODEL’S APPLICATION TO GAS PREDRAINAGE

4.1 | Solid–gas coupling models of coal

4.1.1 | Mechanical constitutive equation

As a kind of porous medium, coal is composed of matrix and fractures. There are fractures between the matrices and a large number of pores in the matrix. Therefore, coal is a porous medium with dual-pore characteristics. If the gas adsorption deformation is treated as thermal expansion deformation, the mechanical constitutive equation of isotropic coal containing gas can be expressed as

$$G u_{i j} + \frac{G}{1-2\nu} u_{i j} - \alpha_J p_{f j} - \alpha_m p_{m j} - K e_{b d} \delta_j f_i = 0 \quad (6)$$

where $G$ is the shear modulus of coal body, MPa, and $K$ is the bulk modulus of coal body, MPa. $f$ is the body force, MPa. $p_f$ and $p_m$ are the gas pressure of fracture and gas pressure of pore, MPa, respectively. $\alpha_J$ and $\beta_m$ are the effective stress coefficients of fracture and effective stress coefficient of pore, respectively. $\alpha_J = 1 - \frac{K}{K_m}$, $\alpha_m = \frac{K}{K_s}$, $K_m$, $K_s$ are the bulk modulus of coal matrix and bulk modulus of coal skeleton MPa, respectively.

4.1.2 | Failure criterion equation

In this paper, the Drucker–Prager equation is selected as the failure criterion of coal containing gas. Under the condition of plane strain, the Drucker–Prager criterion can match the Mohr–Coulomb criterion as

$$F = \frac{\sin \phi}{\sqrt{3}} \frac{3}{\sqrt{3}} l_1 + \frac{3}{\sqrt{3}} \frac{3}{\sqrt{3}} \frac{\sin^2 \phi}{\sqrt{3}} l_2 - \sqrt{J_2}$$

where $C$ is the cohesive force, MPa, and $\phi$ is the internal friction angle. $J_2$ is the second invariant of the stress deflection, and $\alpha_J$ is the first invariant and second invariant of the stress tensor. $C = C_0 - (C_0 - C_f) \sin^\varphi \frac{p}{p}$. where $p_0$ is the initial cohesive force before the peak stress point, MPa, and $C$ is the residual cohesive force during the residual stress stage, MPa.

4.1.3 | Gas storage equation

Based on the state equation of ideal gas, the free gas quantity in fractures of coal per unit volume can be obtained by Equation (9) as

$$m_f = \phi_f \frac{M}{RT} p_f \quad (9)$$

where $M$ is the molecular weight of CH₄, $\phi_f$ is the fracture ratio of coal, %. $T$ is the gas temperature in coal, K. $R$ is the ideal gas constant, 8.314 J/(mol-K).

There are both free gas and adsorbed gas in coal matrix. Free gas in the pore of matrix can be described by the state equation of ideal gas, and the adsorbed gas can be described by the Langmuir adsorption model. The gas quantity in matrix of coal per unit volume.

$$m_m = \frac{M}{RT} \phi_m + \frac{a b p_m}{1 + b p_m} V_{std} \rho_b \quad (10)$$

where $\phi_m$ is the pore ratio of coal, %. $a$ is the maximum adsorption volume of coal, m³/t, and $b$ is the constant of Langmuir adsorption model, MPa⁻¹. $V_{std}$ is the molar gas constant, 0.0224 m³/mol, and $\rho_b$ is the apparent density of coal, t/m³.

4.1.4 | Gas diffusion equation

The gas migration in pore in matrix of coal can be simplified into quasi-steady-state of Fick’s diffusion. The exchanged gas quantity between the matrix and fracture of coal per unit volume can be calculated as
where $D$ is the diffusion coefficient, $m^2/s$, and $\theta$ is the shape factor of matrix, $m^{-2}$. $\tau$ is the matrix absorption time, $s$, $C_m = \frac{M}{RT}$ and $C_f = \frac{M}{RT}$.

The change of gas quantity in matrix is mainly controlled by the exchanged gas quantity between the matrix and fracture, so the Law of conservation of quantity in matrix can be described as

$$\frac{\partial m_m}{\partial t} + \frac{M}{\tau RT} (p_m - p_f) = 0 \quad (12)$$

Substituting Equation (10) into Equation (12), the relationship of matrix gas pressure and time can be calculated as

$$\frac{\partial p_m}{\partial t} = -\frac{p_m - p_f}{\tau} \left( V_m p_0 (1 + b p_m)^2 - \rho_f R T a b p_0 + R T \rho_m (1 + b p_m)^2 \right) \quad (13)$$

### 4.2.1 Geometric models and parameters

In this paper, the solid mechanics module and PDE module in COMSOL Multiphysics software, which is on the basis of finite element method, were used to solve the partial differential equations. Considering the time factor, the transient solver was used to calculate the gas pressure. The geometry model and boundary conditions are presented in Figure 7.

#### 4.2.2 Geometry size

The length and width of the model are 100 and 24.5 m, respectively. The upper and lower parts of the model are rock with a thickness of 10 m, respectively, and the middle part of the geometry model is coal seam with a thickness of 4.5 m. Seven boreholes for gas predrainage are arranged in the middle of the coal seam, and the space of boreholes is 5 m.
to the buried depth of 400 m. The lower boundary is fixed displacement boundary, and the left and right boundaries are rolled displacement boundary.

Seepage module: All the boundaries of the coal seam are zero-flow boundary. The boundary of borehole is gas pressure boundary, and the absolute gas pressure is 0.075 MPa.

4.2.3 Different cases

In Daning coal mine, China, No. 3 coal seam is a coal and gas outburst coal seam. Its average thickness is 4.73 m, and its gas content is 10-24 m³/t. There is generally a thickness of 0.2-0.5 m soft coal layer in the middle and lower part of No. 3 coal seam, which can be up to 1.5 m at local areas, and the remaining parts of No. 3 coal seam are hard coal layers. In this paper, hard coal is the coal with an original structure, and the firmness coefficient of hard coal is >0.5. Soft coal is the coal with a damaged structure, and the firmness coefficient of soft coal is <0.5. Soft coal is mainly located at the lower part of the coal seam, and four cases of the thickness of soft coal layer are set as 0, 0.2, 0.5, and 1.5 m, respectively, as shown in Figure 8.

4.2.4 Initial conditions

The initial relative gas pressure in the coal seam is 1.4 MPa, and the initial stress in the coal seam is calculated according to the simulation model.

4.2.5 Model parameters

This simulation mainly involves the mechanical parameters, gas adsorption, and seepage parameters. The main parameters are given in Tables 1 and 2.

In order to improve the efficiency of solving the models, the first step of this numerical simulation was to solve the initial stress field of rock and coal. Then, the first step was to solve the stress field caused by the excavation of boreholes. Finally, the final step was to solve the stress field and seepage field caused by gas predrainage.

4.3 Numerical simulation results

In the study of the process of gas predrainage in combination of soft coal and hard coal, the influence of the damage-induced permeability evolution was considered in this paper. To make us distinguish more plastic failure and permeability distribution clearly, we only captured a certain range around the borehole shown in Figure 9. Plastic failure and permeability distribution around the borehole were figured in Figure 9.

Depending on Figure 9, after the excavation of boreholes, the stress field around the borehole will be redistributed. Then, a certain zone of plastic failure will appear around the borehole, as shown in Figure 9A, when the stress of coal is larger than the strength of coal. According to the
damage-induced permeability model Equation (4), the permeability of coal can increase suddenly after plastic failure. It can also be found that there is a region of sudden increase in permeability around the borehole where plastic failure occurs in the coal seam in Figure 9B. If only the elastic permeability model is used instead of the damage‐induced permeability model in the process of solving the model, the predicted results of gas predrainage will be inaccurate.

Xue et al.35 and Liu et al.65 thought that there are usually three zones around the borehole after excavation. The three zones, which include elastic strain zone, plastic damage strain zone, and residual stress zone, are corresponding to the strain softening model. \(R_o\), \(R_b\), and \(R_p\) represent the radius of borehole, radius of residual stress zone, and radius of plastic damage strain zone, respectively, as shown in Figure 10. However, due to the greater mechanical parameters of hard coal, there are no radius of residual stress zone around the borehole, which is different from the ideal case. There are only the elastic strain zone and plastic damage strain zone, and the radius of plastic damage strain zone is 0.2 m, as shown in Figure 9A.

There are fracture gas pressure and matrix gas pressure in the coal seam with dual‐pore structure. The matrix gas pressure should be taken as the benchmark in the study of gas predrainage. Therefore, the variations of matrix gas pressure during gas predrainage in four cases were obtained, as shown in Figure 11.
As shown in Figure 11, the matrix gas pressure in the coal seam under different cases shows a trend of decline with the increase in gas predrainage time. Compared with the Case 1 with Case 2, Case 3, and Case 4, it can be found that the existence of soft coal can make the methane be difficult to extract from the coal seam, which makes the decline of matrix gas pressure become more gradual with the increase in the thickness of the soft coal. When there is hard coal layer under the soft coal layer as shown in Figure 11A,B, the existence of soft coal not only makes the decline of matrix gas pressure become more gradual, but also hinders the flow of matrix gas in the hard coal layer to the borehole, which makes the methane be difficult to extract from all the layers in the whole coal seam. Therefore, the existence of soft coal will hinder the gas predrainage in the whole coal seam, and the increase in the thickness of soft coal layer will stretch negatively affects levels of gas predrainage.

The regional predicted indexes for coal and gas outburst include gas pressure and gas content. In this paper, gas content index of 8 m³/t is chosen. The soft coal is the key to prevention and control coal and gas outburst. According to Equation (9), Equation (10), and gas content index of 8 m³/t, the gas pressure index of soft coal can be calculated. The absolute gas pressure index of 0.55 MPa and relative gas pressure of 0.45 MPa are chosen as the critical indexes in gas predrainage. In order to better understand the influence of soft coal on gas predrainage, we have made the matrix gas pressure of the most unfavorable location during gas predrainage, as shown in Figure 12.

**FIGURE 10** Ideal three zones distribution around the borehole

**FIGURE 11** Matrix gas pressure during gas predrainage
When the coal seam is composed of the same kind of coal layer, the most unfavorable points for gas predrainage should be located at the intersection of the circles drawn by the radius of gas predrainage. In this case, there are two intersections for the most unfavorable point. However, considering that the soft coal layer is mainly located at the lower part of the coal seam, the most unfavorable point at the lower part of the coal seam was chosen as the monitoring point. According to Figure 12, when all the coal seam is made up of hard coal (in Case 1), the required time for the matrix gas pressure reaching the critical value is 36 days. When there is a thickness of 0.2 m soft coal layer in the middle and lower part of the coal seam (in Case 2), the required time for the matrix gas pressure reaching the critical value is 96 days. When the thickness of soft coal layer is 0.5 and 1.5 m, the required time is 158 and 412 days, respectively. Therefore, the existence of soft coal can greatly increase the required time for the matrix gas pressure reaching the critical value of the whole coal seam. In particular, the location of thickening of soft coal should be the key point of gas control, and more boreholes should be arranged to decrease the time of gas predrainage in this place.

4.4 | Results of gas predrainage in coal minefield

In view of the existence of soft coal in Daning coal mine, the directional long boreholes were applied for the gas predrainage.
According to the result of numerical simulation, when the space of boreholes for gas predrainage is 5 m, the required time of the different cases is 36, 96, 158, and 412 days. The length of the main holes is 200-700 m, and the space of main holes for gas predrainage is 5-10 m. The required time for gas predrainage is 6-18 months. In the process of drilling of main holes in the hard coal layer, some branch holes will be drilled to the roof and floor of the coal seam and the space of the branch holes is about 50 m when the thickness of soft coal layer is <0.5 m. When the thickness of soft coal layer is greater than 0.5 m, more branch holes will be added. The profile of borehole layout is shown in Figure 13A.

In this paper, the Longwall Panel 105 and 106 were selected as examples. The plan of borehole layout is shown in Figure 13B, and gas predrainage results of coalfaces are shown in Table 3.

After 12-18 months of gas predrainage in Longwall Panel 105 and 106, the volume of gas predrainage for the two Longwall Panels are $5.531 \times 10^7$ and $5.894 \times 10^7$ m$^3$, respectively, and the rate of gas predrainage is above 70%. Then, the residual gas content is <8 m$^3$/t, which implies that the risk of gas outburst of the coal seam has been eliminated. So it verifies the reliability of the arrangement of boreholes for gas predrainage.

## 5 CONCLUSIONS

In this paper, a new damage-induced permeability model of coal was developed and validated. Based on it, solid-gas coupling models of coal were established to study the gas predrainage in combination of soft coal and hard coal under different cases. The main conclusions are as follows:

1. The experimental results of permeability show that with the increase of axial strain, the coal permeability decreases slowly at first, then increases rapidly, and finally increases slowly or even remains unchanged. With the increase in deviatoric stress, the permeability decreases first, then increases slowly, later increases rapidly, and finally increases slowly or even remains unchanged. Coal permeability explosively increases after the peak stress, so the peak stress point can be regarded as the extreme point of permeability.

2. The equivalent plastic strain was used to describe the damage of coal. Then, on the basis of simplified permeability evolution law, a new damage-induced permeability model, which considers the effect of interaction between matrix and fracture, was developed and validated. The damage-induced permeability model can match the experimental data of permeability very well, so it indicates that the damage-induced permeability model is reasonable.

3. Solid-gas coupling models of coal were developed based on the new permeability model, and the numerical results show that there is a region of sudden increase in permeability around the borehole where plastic failure occurs, so the damage-induced permeability model is more appropriate to study the predrainage.

4. When the thickness of soft coal layer are 0, 0.2, 0.5, and 1.5 m with the borehole space of 5 m, the required time for the matrix gas pressure reaching the critical value is 36, 96, 58, and 412 days, respectively. Therefore, more boreholes should be arranged to decrease the time of gas predrainage in the location of thickening of soft coal. Finally, the risk of gas outburst of the coal seam has been eliminated after the gas predrainage of boreholes, which are arranged according to the numerical results.

These research results cannot only guide us to optimize the borehole layout of gas predrainage in the field, but also further enrich the theory of gas flow in coal seam.

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### TABLE 3 Gas predrainage results of coalfaces

| Longwall panel | Original gas content (m$^3$/t) | Volume of gas predrainage (m$^3$) | Rate of gas predrainage (%) | Residual gas content (m$^3$/t) |
|----------------|---------------------------------|----------------------------------|-----------------------------|-------------------------------|
| No. 105        | 15                              | $5.531 \times 10^7$             | 70.37                       | 4.44                          |
| No. 106        | 14                              | $5.894 \times 10^7$             | 72.71                       | 3.82                          |
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