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Study on Permeability Enhancement of Seepage–Damage Coupling Model of Gas-Bearing Coal by Water Injection

Wenbin Wu [1,2], Zhen Wang [2,*], Zhuangzhuang Yao [2,3,*], Jianyun Qin [4] and Xinglan Yu [1]

[1] College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590, China; cqwenbinwu@163.com (W.W.); 202182010061@sdust.edu.cn (X.Y.)
[2] China Coal Technology Engineering Group, Chongqing Research Institute, Chongqing 400037, China
[3] China Coal Technology Engineering Group, Chinese Institute of Coal Science, Beijing 100013, China
[4] Kuche Yushuling Coal Mine Co., Ltd., Kuche 842099, China; qzzin@163.com
* Correspondence: cumtwangzhen@126.com (Z.W.); 17300238664@163.com (Z.Y.)

Abstract: The use of high-pressure water injection technology in gas-bearing coal seams is an important method for effectively addressing coalbed methane issues. To explore the mechanisms and influencing factors of water injection and permeability enhancement, a model was established based on the theories of unstable seepage and elastic damage in coal and rock mass. Additionally, a mechanical model of elastic damage-based beams was established, taking into account rheological damage, and the mechanical property variation of the surrounding rock in the working face was analyzed. The study included numerical simulations and verification with practical examples. The results suggested that high-pressure water injection could cause damage to the coal body and deformation of the roof, resulting in changes in ground stress, which was a significant contributor to the increase in coal seam permeability. The study showed positive correlations between rheological effects, injection time, injection flow rate, coal seam depth, and the influence range of water injection. Case studies indicated that the long-term influence range of water injection was approximately 60 m, which aligned with field results. The paper introduces a mechanical model for calculating variations in ground stress. This model can help assess the impact of water injection and permeability enhancement, providing valuable insights for related engineering projects.

Keywords: water injection; elastic foundation beam; time-variant damage; coupled damage model; coal seam permeability

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1. Introduction

The geological conditions of coal seams in some regions of China are very complex, characterized by soft structures, high gas content, and low permeability [1,2]. Less than 30% of coal seams have a permeability greater than 1.0×10^{-3} μm^2, and in high-gas mines, 95% of the coal seams are classified as having low permeability [3]. In recent years, due to the increase in mining depth, the occurrence conditions of coal seams have also changed, such as increased gas content, elevated gas pressure, and decreased permeability of surrounding rock. Gas disasters have gradually become one of the main factors restricting the safe and efficient mining of high-gas outburst mines. It is crucial to enhance traditional gas extraction methods to improve efficiency [4,5]. Improving the permeability of coal seams is a key measure in boosting gas extraction efficiency [6]. Therefore, to enhance the permeability of coal seams, their structure must be reformed. High-pressure water injection into coal seams is an effective way to increase the permeability of coal rock mass and to facilitate regional gas control [7–9]. In recent years, many scholars have conducted in-depth research on the seepage of coal seam water injection through theoretical calculations, experimental research, numerical simulations, and other means, achieving numerous results [10–14].

Hydraulic fracturing technology originated from the development methods for enhancing low-permeability oil and gas reservoirs. Since oil and gas reservoirs consist mainly of sandstone and other hard rock formations, hydraulic fracturing technology has led to a relatively advanced understanding of crack initiation mechanisms, crack propagation processes, and related technologies. Zhen [15] employed a radial seepage experiment system to measure the permeability of raw coal samples and subsequently numerically simulated the stress–seepage evolution patterns within the coal matrix surrounding water injection boreholes. Fu et al. [16], using a self-developed numerical program specifically designed to model the coupling between rock fracture processes and fluid flow, captured the evolution of rock cracks during seepage-induced damage. Based on the Drucker–Prager criterion, statistical strength theory, and continuous damage medium theory, Wang [17] derived the rock damage evolution equation and developed a numerical simulation program for seepage in damaged rock, utilizing the finite element software COMSOL (latest v. 6.2) and MATLAB for computational analysis. Chen et al. [18] conducted a thorough permeability test to study the evolution of damage and permeability characteristics of rock under confining pressure. They employed continuum damage mechanics theory, coupled with plastic damage evolution and seepage effects. Researchers have analyzed damage evolution and permeability, but their analyses were not based on multi-level coupled damage, and there is relatively little research about water injection scenarios. Jia et al. [19] explored the damage evolution and seepage behavior of surrounding rock during tunnel excavation, considering the combined influence of pore water pressure and damage. Wang et al. [20] used the finite difference method and discrete element method, and constructed a fluid–solid coupling model to analyze the deformation and failure patterns of coal around boreholes as well as the seepage behavior during coal seam water injection under varying lateral pressure coefficients. They used the fluid–solid coupling model to analyze seepage behavior. However, factors such as permeability and initial and rheological damage in the coal seam can all affect the results, so a comprehensive analysis is necessary.

Compared with hard oil and gas reservoirs, the mechanisms and corresponding technology of high-pressure water injection and permeability increase in coal seams, especially soft-permeability coal seams, are different [21]. Liang proposed a nonlinear pore elastic damage model considering anisotropic characteristics [22]. The fully coupled finite element method was utilized to calculate and analyze the multi-phase coupling effect of gas, liquid, and solid during the coal seam water injection process, yielding favorable results. Zhou et al. [23], combined with fractal theory, studied the pore characteristics and seepage evolution process of coal in the process of water injection by nuclear magnetic resonance, and analyzed the influence of pore connectivity and water injection pressure change on the effect of coal seam water injection. Liu et al. [24] conducted a simulation to study the impact of coal seam water injection on pressure relief and permeability enhancement on the actual working face. The study was based on porous media seepage theory and its influencing factors.

When studying the issue of water injection in coal seams and increased permeability, scholars did not consider the effects of rheological damage, as well as the deformation of the coal seam and overlying strata, on the permeability of the coal seam. In light of this, this paper establishes a mechanical model of the foundation beam to analyze the influence of roof deformation on coal permeability. By establishing coupled damage evolution equations, a comprehensive analysis is conducted on the effects of initial damage, seepage damage, and rheological damage during the water injection process. The mechanism and external influencing factors of high-pressure water injection on coal permeability are studied, and the model and calculation results are verified through practical engineering applications.

2. Establishment of a Theoretical Model of Coal Seam Water Injection

2.1. Establishment of Coupled Damage Constitutive Model

It was assumed that the strength of rock micro-elements obeys Weibull distribution [25]; as such, the expression of foundation damage variable D_0 can be obtained:

$$D_0 = 1 - \mathrm{e}^{-\frac{1}{m}\left(\frac{\varepsilon_0}{\varepsilon_c}\right)^m} \tag{1}$$

where m and a are Weibull distribution parameters, and ε_0 is the strain of the basic damage state.

Xu H. [26] conducted a uniaxial compression creep test on soft rock, and obtained the relationship between the rheological damage variable D_1 of rock with time:

$$D_1 = \frac{E_0 - E_\infty}{E_0}\left(1 - e^{-\alpha_1 t_0}\right) \tag{2}$$

where E_∞ is the final elastic modulus of rock mass, MPa; α_1 is the elastic modulus attenuation parameter, d^{-1}; and t_0 is the rheological time, d.

Considering the rheological damage under the premise of basic damage of rock, according to the strain equivalent hypothesis of Lemaitre [27] and the principle of continuous damage mechanics, the coupled damage constitutive model of rock can be obtained:

$$\sigma = E\varepsilon(1 - D_0)(1 - D_1) = E\varepsilon(1 - D) \tag{3}$$

where σ is the stress in the coupled damage state MPa; E is the elastic modulus of rock material before damage, MPa; and ε is the strain in the coupled damage state.

Then, the coupling damage variable is expressed as

$$D = D_0 + D_1 - D_0 D_1 \tag{4}$$

After the failure of the loaded rock, its strength does not immediately change to 0, but there is residual strength generated by friction. In the Lemaitre strain equivalence hypothesis, the residual strength is considered to modify Equation (3) [28] and the damage threshold of rock material [29]. The constitutive model of rock damage considering the damage threshold and residual strength can be obtained as follows:

$$\sigma = \begin{cases} E\varepsilon & \varepsilon - \varepsilon_a \le 0 \\ E\varepsilon(1 - D) + \sigma_r D & \varepsilon - \varepsilon_a > 0 \end{cases} \tag{5}$$

where σ_r is the residual strength, MPa, and ε_a is the damage strain threshold.

2.2. Establishment of Mechanical Model of Elastic Damage Foundation Beam

During the process of water injection, the coal seam surrounding the borehole undergoes damage, leading to a redistribution of the surrounding stress. For the sake of research convenience, based on the theory of elastic foundation beams, the basic roof is considered as a rock beam of unit width, while the coal seam and the immediate roof are regarded as the foundation. Subsequently, the mechanical model of the foundation beam is established. As shown in Figure 1, the model uses a single width of the main roof and coal seam. The main roof has a vertical downward uniform load q; q is taken as the weight of the overlying strata, and p(x) is the basic reaction force. The foundation beam model is symmetrical around the borehole water injection hole, so half of it is taken as the research object for analysis.

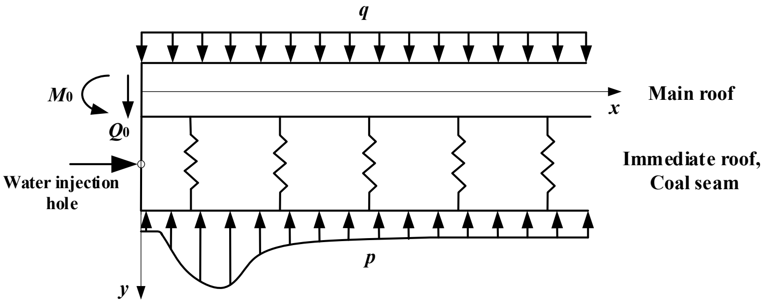


Figure 1. Schematic diagram of the mechanical model of the elastic foundation beam.

Based on the theory of beams, the differential equation of the deflection curve of the beam on any foundation is

$$E_r I \frac{\mathrm{d}^4 y}{\mathrm{d}x^4} = q - p \tag{6}$$

where E_r is the elastic modulus under plane strain conditions, MPa; $E_r = E'_r/\left(1 - v_r^2\right)$, E'_r is the elastic modulus of the main roof, MPa; v_r is the Poisson's ratio of the main roof; I is a moment of inertia, m^4; y is the deflection of the main roof, m; $p(\mathrm{x})$ is the foundation reaction force, MPa; q is the uniformly distributed overlying strata load acting on the rocking beam, $q = \gamma H$, MPa; γ is the average volume force of the overlying strata, $\mathrm{kN/m^3}$; and H is the buried depth of the coal seam, m.

Taking into account the damage sustained by the coal mass, the foundation reaction force will undergo changes. Consequently, the foundation beam ceases to satisfy the original equation, necessitating the establishment of a new differential equation for the deflection curve for pertinent analysis. It is assumed that the deformation of the coal seam along the y-axis direction is uniform, that is, $\varepsilon_\mathrm{y} = y/\mathrm{m}_0$, where m_0 denotes the thickness of the coal seam, and the foundation support reaction force p on the coal seam surface is approximately regarded as the vertical stress in the y-axis direction of the coal. The damage constitutive equation is shown in Formula (5). Combined with Formula (6), the differential equation of the deflection curve of the elastic damaged foundation beam considering the threshold and residual strength can be deduced as follows:

$$\frac{\mathrm{d}^4 y}{\mathrm{d}x^4} + \frac{k_1}{E_\mathrm{r} I} y = \frac{\gamma H}{E_\mathrm{r} I}, \quad y - y_\mathrm{a} \leq 0 \tag{7}$$

$$\frac{\mathrm{d}^4 y}{\mathrm{d}x^4} + \frac{k_1}{E_\mathrm{r} I} y(1 - D) + \frac{\sigma_\mathrm{r}}{E_\mathrm{r} I} D = \frac{\gamma H}{E_\mathrm{r} I}, \quad y - y_\mathrm{a} > 0 \tag{8}$$

where $k_1 = E_b/m_0$, with $\mathrm{E_b}$ representing the elastic modulus under plane strain condition, MPa; $E_b = E'_b/\left(1 - v_b^2\right)$, with E'_b representing the elastic modulus of the foundation, MPa; and v_b is the Poisson's ratio of the foundation.

2.3. Establishment of Seepage–Damage Model of Coal Seam Water Injection

Due to the limitation of upper and lower coal rock, models are usually simplified as a plane strain problem in the process of solving the stress field formed by seepage around the borehole [30]. Therefore, at the end of coal seam water injection, the solution process of the stress field formed by the unstable seepage around the borehole is simplified as a plane strain problem.

(1) Theoretical analysis of unstable seepage

Percolation differential equation:

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial P}{\partial r} = \frac{\phi \mu C_t}{K} \cdot \frac{\partial P}{\partial t} \tag{9}$$

Initial condition, when $t = 0$:

$$P(r, 0) = P_0 \tag{10}$$

The boundary (inner boundary) condition at $r = a$:

$$r \frac{\partial P}{\partial r}\bigg|_{r=a} = \frac{Q\mu}{2\pi K h} \tag{11}$$

Boundary (outer boundary) conditions at infinitely large strata:

$$\lim_{r \to \infty} P(r, t) = P_0 \tag{12}$$

where (r) is the distance from the center of the borehole, m; (t) is seepage time, h; (P) is pore water pressure, MPa; (P_0) is the initial pore water pressure, MPa; (Q) is flow rate, m^3/h; (K) is coal seam permeability, $\mu\mathrm{m}^2$; (h) is the thickness of coal seam, m; (μ) is fluid viscosity, Pa·s; (a) is the borehole radius, m; ($\mathrm{C_t}$) is the compression coefficient, MPa^{-1}; and (ϕ) is the porosity of coal seam.

Effective stress field distribution and stress boundary conditions formed by seepage action:

$$\frac{\mathrm{d}\sigma_r'}{\mathrm{d}r}+\frac{\sigma_r'-\sigma_\theta'}{r}+\alpha\frac{\mathrm{d}P}{\mathrm{d}r}=0 \tag{13}$$

$$\begin{cases}\sigma_r'=P_w-\alpha P_w & r=a\\ \sigma_r'=P_0-\alpha P_0 & r=c\end{cases} \tag{14}$$

where σ_r' is the effective radial stress, MPa; σ_θ' is the effective circumferential stress, MPa; c is the outer radius, m; θ is the angle; and P_w is the inner boundary water pressure of the borehole, MPa.

(2) The influence of stress on seepage

Based on Biot's effective stress, in the elastic stage, the larger the effective stress, the smaller the porosity of the rock [31]. The permeability changes with the porosity and has a cubic relationship with the porosity [32]. The relationship is

$$\overline{\sigma_v}=\left(\sigma_r'+\sigma_\theta'+\sigma_z'\right)-\alpha P \tag{15}$$

$$\phi=(\phi_0-\phi_r)\cdot\mathrm{e}^{-\alpha_\phi\overline{\sigma_v}}+\phi_r \tag{16}$$

$$K=K_0(\phi/\phi_0)^3 \tag{17}$$

where $\overline{\sigma_v}$ is the average effective stress, MPa; ϕ_0 and ϕ_r are the initial porosity under a 0 stress state and the ultimate porosity under a high-pressure state, respectively; α_ϕ is the sensitivity coefficient of porosity to stress, Pa^{-1}, which, here, is $5.0\times10^{-8}\ \mathrm{Pa}^{-1}$; and K_0 represents the initial permeability of the medium under a 0 stress state, $\mu\mathrm{m}^2$.

(3) Effect of damage on permeability

The permeability model is a constitutive equation that describes the flow of water through a rock mass. The model includes a damage variable, which accounts for changes in rock permeability when the rock is damaged by fluid intrusion. The relationship can be expressed as

$$K_D=K_0(\phi/\phi_0)^3\cdot\mathrm{e}^{\alpha_k D_2} \tag{18}$$

where K_D is the permeability after damage, $\mu\mathrm{m}^2$; D_2 is the seepage damage variable caused by seepage; and α_k is the influence coefficient of damage on permeability, which, here, is 5.0.

From the initial damage variable expression (1), the expression of the seepage damage variable is

$$D_2=1-\mathrm{e}^{-\frac{1}{m}\left(\frac{\overline{\varepsilon_2}}{\varepsilon_\mathrm{c}}\right)^m} \tag{19}$$

where $\overline{\varepsilon_2}$ is the equivalent strain.

For in-plane strain problems,

$$\overline{\varepsilon_2}=\frac{\sqrt{2}}{3}\sqrt{(\varepsilon_r-\varepsilon_\theta)^2+\varepsilon_r^2+\varepsilon_\theta^2} \tag{20}$$

3. Analysis of Initial Damage and Influencing Factors of Surrounding Rock of Coal Seam Water Injection Hole

During the initial stage of injecting water into the coal seam, drilling boreholes and injecting high-pressure water causes changes in the stress of the surrounding rock which in turn affects the permeability of the rock. The stress and seepage fields are both important in the mechanical environment of the surrounding rock of water injection boreholes, and they influence each other. As a result of this process, coal and rock inevitably undergo damage, leading to a damaged area with reduced mechanical properties. Therefore, it is vital to analyze the evolution of damage and stress distribution in the surrounding rock after drilling and seepage to assess rock stability.

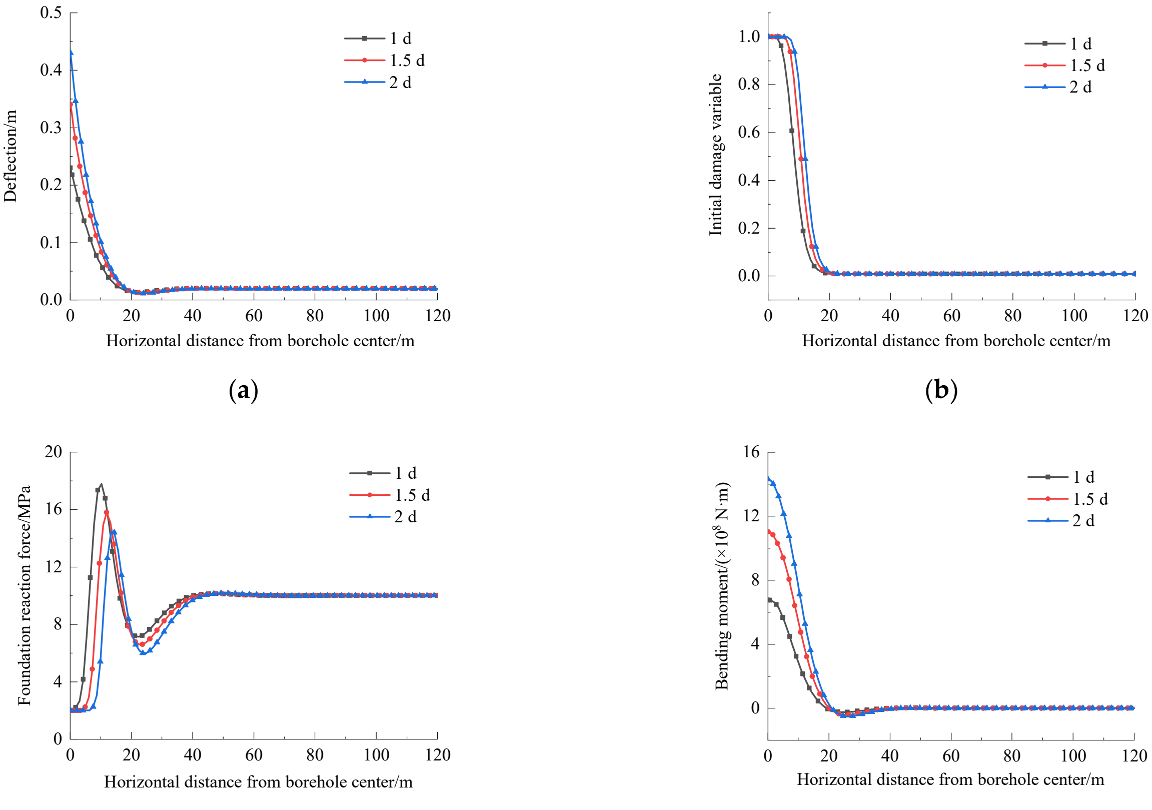
The basic mechanical parameters required for calculation are shown in Table 1. The data in Table 1 are from the technical service report of Hemei No.6 Coal Mine. The data in Table 1 are substituted into the mechanical model of an elastic damage foundation beam, considering the foundation damage and seepage damage generated in the process of coal seam water injection, and the total damage variable formed by the combination of the two is defined as the initial damage. The deflection curve of the coal seam roof is numerically calculated using Matlab to solve the differential equation. On this basis, the coal seam reaction force and the initial damage are further obtained to reveal the variation law of the permeability of the coal seam, as well as the variation law of the bending moment of the roof, and the influence of the roof deformation on the permeability enhancement effect of the coal seam water injection is studied. The influence of water injection time, water injection flow rate, and buried depth of coal seam on the deflection, initial damage, foundation reaction force, and bending moment curve of the foundation beam is analyzed under the condition that other parameters remain unchanged.

Table 1. Basic mechanical parameters.

Parameter Name	Unit	Numerical Value
Initial pore water pressure (P_0)	MPa	2
Gas pressure (P_s)	MPa	1
Flow rate (Q)	m^3/h	8
Water injection time (t)	d	2
Initial permeability (K_0)	μm^2	3.7×10^{-5}
Thickness of stratum (h)	m	10
Fluid viscosity (μ)	Pa·s	1×10^{-3}
Coefficient of compressibility (C_t)	MPa^{-1}	0.06
Original porosity (ϕ_0)		0.039
Ultimate porosity (ϕ_r)		0.009
Radius of drill hole (a)	m	0.05
Poisson ratio (v)		0.5
Average volume force of overlying strata (γ)	kN/m^3	25
Burial depth of coal seam (H)	m	400
Rock beam stiffness (E_rI)	$N \cdot m^2$	0.5
Coal seam thickness (m_0)	m	3
Plane strain elastic modulus of coal seam (E_b)	GPa	1.5
Peak stress (σ_c)	MPa	20.91
Peak strain (ε_c)		0.207
Residual strength (σ_r)	MPa	2

3.1. The Influence of Different Water Injection Time

In the case of other parameters being unchanged, the influence of the change in water injection time on the deflection, initial damage, foundation reaction force, and bending moment of the foundation beam is shown in Figure 2.



(**a**) (**b**) (**c**) (**d**)

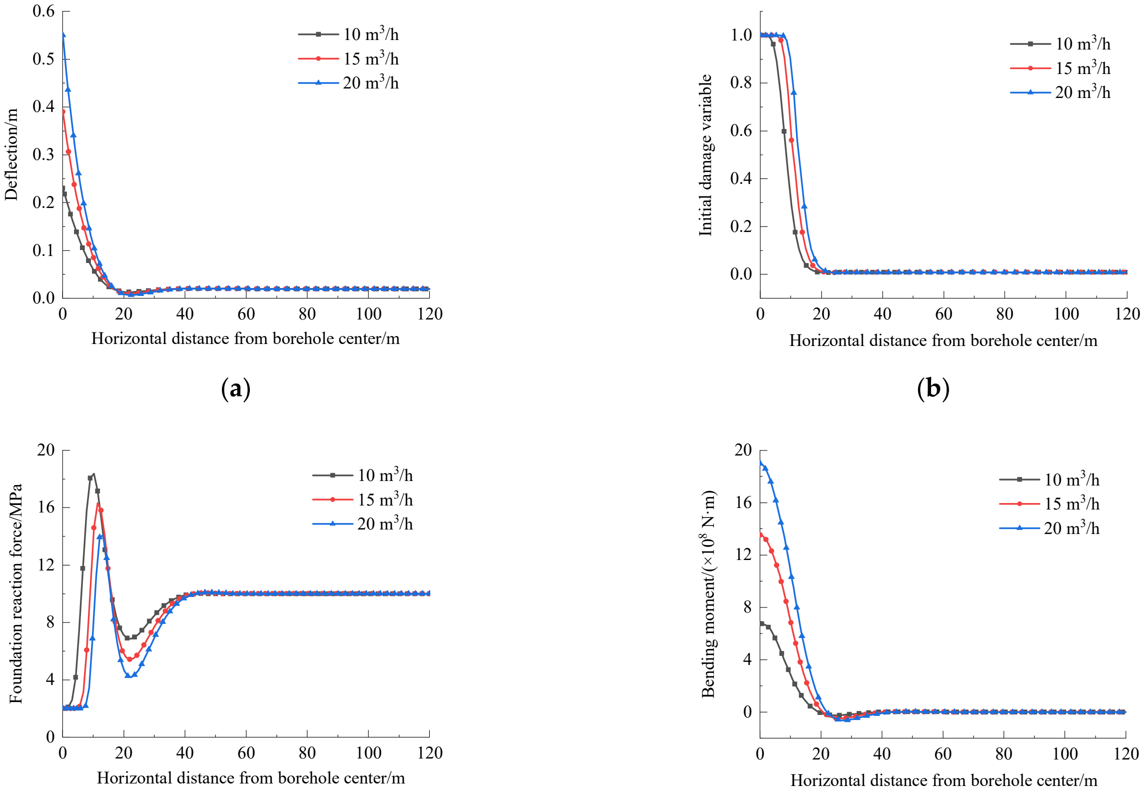
Figure 2. Effect of different water injection time on damaged foundation beam. (**a**) Deflection. (**b**) Initial damage variable. (**c**) Foundation reaction force. (**d**) Bending moment.

From Figure 2, it is evident that the deflection and bending moments of the basic roof reach their maximum values at the top of the borehole. As the water injection time increases, both the deflection and bending moments of the basic roof exhibit an increase within a specific horizontal distance from the borehole center. Furthermore, with prolonged water injection, the extent of damage expands under the same degree of damage, and the initial damage intensifies at the same horizontal distance from the borehole center. At water injection times of 1 day, 1.5 days, and 2 days, the peak values of the basic reaction force are, respectively, 17.78 MPa, 15.78 MPa, and 14.43 MPa, with peak positions at 10.3 m, 12 m, and 13.3 m. Notably, as the time for water injection increases, the maximum value of the basic reaction force decreases, and the position of this maximum gradually shifts away from the borehole. The influence ranges of the foundation reaction force are 34 m, 36 m, and 39 m, respectively, indicating an expansion of the influence range with increased water injection time. This suggests that continuous water injection enables water to reach positions further away from the injection hole, thereby enhancing the influence range of water injection and permeability.

3.2. The Influence of Different Water Injection Flow

Under the condition that other parameters remain unchanged, the influence of the change in water injection flow on the deflection, initial damage, foundation reaction force, and bending moment of the foundation beam is shown in Figure 3.

It is evident from Figure 3 that the maximum deflection and bending moments of the main roof occur at the top of the borehole. As the water injection flow increases, there is a corresponding increase in the deflection and bending moments of the main roof within a specific range of horizontal distance from the borehole center. Additionally, the range of damage and initial damage also increase proportionally with the distance from the borehole center. When the water injection flow rates are 10 m^3/h, 15 m^3/h, and 20 m^3/h, the peak values of the basic reaction force are 18.36 MPa, 16.33 MPa, and 14.08 MPa, respectively, with peak positions at 10.3 m, 11.4 m, and 13.3 m. As the water injection flow rate increases, the maximum value of the basic reaction force decreases, and the maximum position gradually moves away from the borehole. The influence range of the foundation reaction force is 35 m, 37 m, and 38.5 m, respectively, and is also increasing. It is evident that the influence range of water injection also increases with the water injection flow rate.



(**a**) (**b**)

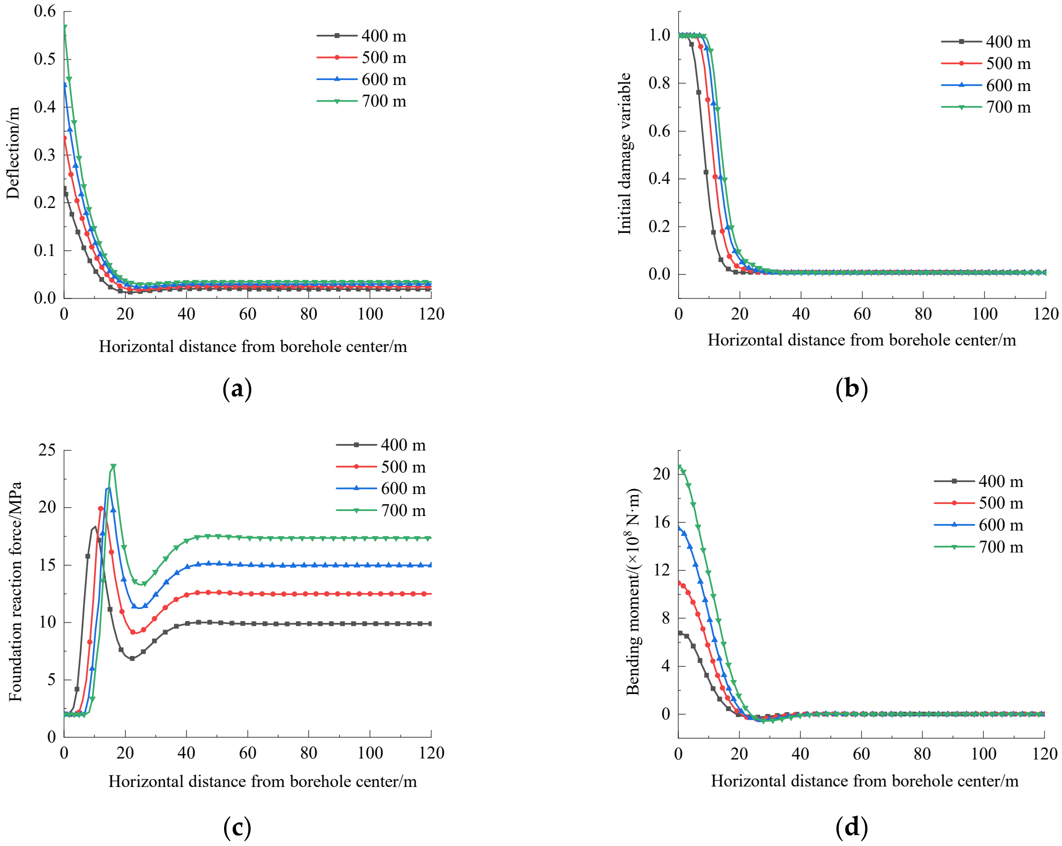
(**c**) (**d**)

Figure 3. Effect of different water injection flow on damaged foundation beam. (**a**) Deflection. (**b**) Initial damage variable. (**c**) Foundation reaction force. (**d**) Bending moment.

3.3. The Influence of Different Coal Seam Buried Depth

Under the condition that all other parameters remain constant, Figure 4 illustrates how changes in coal seam depth affect the deflection, initial damage, foundation reaction force, and bending moment of the foundation beam.

As seen in Figure 4, the deflection and bending moments of the primary roof are greatest at the top of the borehole. The greater the burial depth is, the larger the maximum bending moment is. The deflection of the beam at the borehole and away from the center of the borehole also increases. That is to say, when the burial depth of the coal seam increases, the relative deformation also increases, which is relatively close to the engineering practice. When the burial depths are 400 m, 500 m, 600 m, and 700 m, the peak values of the foundation reaction force are 18.36 MPa, 19.9 MPa, 21.74 MPa, and 23.64 MPa, and the peak positions are 10.3 m, 12 m, 15 m, and 16.2 m, respectively. As the buried depth increases, the maximum value of the foundation reaction force also increases, and the position of this maximum value moves farther away from the borehole. It is important to remember that before reaching the maximum value of the foundation reaction force, a greater depth of burial results in a smaller force. The range of influence of the foundation reaction force is 35 m, 36 m, 36.8 m, and 38 m, respectively. With an increase in buried depth, the influence range of the foundation reaction force also expands. It is clear that as the depth of the buried coal seam increases, the area of influence of water injection and permeability enhancement also expands.



(**a**) (**b**)

(**c**) (**d**)

Figure 4. The influence of different buried depth of coal seam on damaged foundation beam. (**a**) Deflection. (**b**) Initial damage variable. (**c**) Foundation reaction force. (**d**) Bending moment.

4. Study on the Influence Scope of Water Injection for Enhancing Permeability in Coal Seams

Improving the permeability of a coal seam is essential for enhancing the efficiency of gas extraction. However, this water injection process can lead to initial damage near the borehole and subsequent rheological damage over time. These types of damage can alter the stress and permeability of the coal. For example, in December 2011, Hemei No. 6 Coal Mine carried out multiple water injections to increase the permeability of the 3002 lower heading face of the II1 coal seam, leading to a coal and gas outburst in June 2021. However, the mine did not investigate the extent of its influence. Therefore, it is necessary to determine the range and degree of initial and rheological damage of the coal based on relevant theories.

4.1. Project

To enhance the permeability of the II1 coal seam in Hemei No.6 Coal Mine, water injection was performed in the lower section of the mine, specifically targeting the 3002 working face. This working face is situated within the 30 mining area of the third level of the mine. It is bordered by 585 North Lane and an unmined area to the east, the goaf of the 2146 working face to the west, solid coal to the south, and the three-level boundary return air lane (north) and another unmined area to the north. The coal seam in the working face is stable and the structure is simple. The buried depth of the coal seam is 130~950 m, the average thickness of the coal seam is 7.48 m, the dip angle of the coal seam is 10~30°, and the average dip angle is 20°. The pseudo-roof of II1 coal is not developed, and the immediate roof is grayish-brown sandy mudstone, mainly quartz feldspar, with an average thickness of 3.90 m. The main roof consists of grayish-brown medium-grained sandstone, primarily composed of quartz feldspar. It has a thickness ranging from 4.80 m to 13.3 m, with an average thickness of 6.95 m.

The drilling parameters are designed according to the geological conditions. The borehole diameter is 94 mm, the sealing length is 12~20 m, and the drilling is based on a 0.5 m coal seam. Among them, 3002 bottom pumping lane 1~30 # drilling field drilling is designed, 31~37 # drilling field drilling is designed, 58~80 # drilling field drilling is designed, and 81~110 # drilling field drilling is designed; the drilling hole of 8~36 # drilling field in 3002 bottom drainage roadway is designed, the drilling hole of 37~59 # drilling field is designed, and the drilling hole of 60~89 # drilling field is designed. The specific layout is shown in Figure 5.

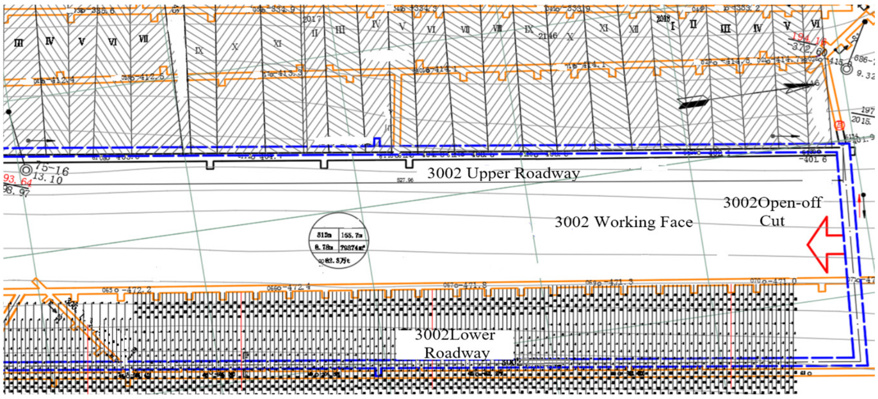


Figure 5. General map of regional outburst prevention measures in 3002 working face.

To further improve the extraction effect, two rounds of crosslayer boreholes were designed for the 3002 lower crossheading in No.6 Coal Mine of Hemei Coal Industry Co., Ltd., Weinan, Shannxi, and hydraulic punching and anti-reflection measures were taken in each round of construction. The first round of supplementary drilling is shown in Figure 6. A total of 101 groups of drilling fields are designed for the construction of a 3002 bottom drainage roadway. The spacing of the drilling fields is 5 m. There are 5 boreholes in each drilling field, with a total of 505 boreholes, and the boreholes penetrate the coal seam to reach 0.5 m. The construction of this round of boreholes commenced in March 2021. By 3 June 2021, a total of 203 boreholes with a sealing length of 12–20 m were completed.

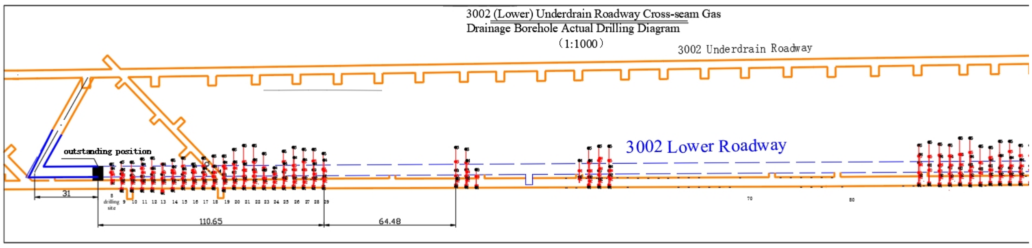


Figure 6. Construction plan of the first round of supplementary drilling.

For the construction of the second round of supplementary drilling for the lower bottom drainage roadway, 101 drilling fields were designed with a spacing of 5 m. Each drilling field consisted of 3 boreholes, totaling 303 boreholes. The boreholes penetrated the coal seam to a depth of 0.5 m from the top, and the sealing length ranged from 12 to 20 m.

4.2. Long-Term Influence Scope of Water Injection for Enhancing Permeability

(1) The influence range of water injection in the initial stage of increasing permeability

The basic mechanical parameters of the 3002 working face in Hemei No.6 Coal Mine are shown in Table 2.

Table 2. Basic mechanical parameters of 3002 working face.

Parameter Name	Unit	Numerical Value
Initial pore water pressure (P_0)	MPa	2
Gas pressure (P_s)	MPa	1.2
Flow rate (Q)	m^3/h	12
Water injection time (t)	d	2
Initial permeability (K_0)	μm^2	3.7×10^{-5}
Thickness of stratum (h)	m	10
Fluid viscosity (μ)	Pa·s	1×10^{-3}
Coefficient of compressibility (C_t)	MPa^{-1}	0.06
Original porosity (ϕ_0)		0.039
Ultimate porosity (ϕ_r)		0.009
Radius of drill hole (a)	m	0.047
Poisson ratio (v)		0.5
Average volume force of overlying strata (γ)	kN/m^3	25
Burial depth of coal seam (H)	m	700
Rock beam stiffness (E_rI)	$N \cdot m^2$	0.5
Coal seam thickness (m_0)	m	10
Plane strain elastic modulus of coal seam (E_b)	GPa	1.5
Peak stress (σ_c)	MPa	20.91
Peak strain (ε_c)		0.207
Residual strength (σ_r)	MPa	2
Elastic modulus attenuation parameter (α_1)		0.1

The data from Table 2 are substituted into the established mechanical model of the elastic damage foundation beam. Together with the initial damage evolution equation derived after coal seam water injection, the differential equation of the deflection curve is numerically solved using Matlab, and the theoretical curve is plotted, as depicted in Figure 7. To investigate the impact of the initial damage induced by water injection on the deflection, foundation reaction force, and bending moment curve of the foundation beam under coal elasticity conditions, the initial influence range of water injection is determined.

Figure 7 reveals that when considering foundation damage caused by drilling excavation during water injection and seepage damage resulting from unstable seepage post-high-pressure water injection—collectively termed as the initial damage during water injection and infiltration—the application of the elastic damage foundation beam model reveals a complete damage zone proximate to the water injection hole, characterized by a damage variable of 1. In this area, the foundation reaction force remains constant despite any increase in deformation, indicating residual strength. This reaction force peaks within the damage zone. As the horizontal distance from the borehole center increases, the deflection and bending moments gradually decrease. In horizontal directions further from the borehole center, beam deflection stabilizes, indicating that coal deformation tends towards stability at low values, not reaching the deformation threshold for damage. In this state, the coal remains elastic, with a damage value of 0, and the foundation reaction force numerically equates to the overburden load. The damage influence range extends approximately 45 m from the center of the borehole horizontally, and there is minimal variation in these parameters beyond 45 m in the deep section. It can be seen that after considering the initial damage, the influence range of 3002 working faces in the initial stage of water injection is about 45 m.

(2) Long-term influence range of water injection for increasing permeability

The data in Table 2 are substituted into the established mechanical model of elastic damage foundation beam. The differential equation for the deflection curve is calculated using Matlab, taking into account the evolution equation of the total damage variable, including initial damage and rheological damage. The theoretical curve is then plotted as shown in Figure 8. This study investigates the impact of water injection on the deflection, foundation reaction force, and bending moment curve of the foundation beam over 9 years, focusing on the influence of initial damage and later rheological damage caused by water injection to determine the long-term effects.

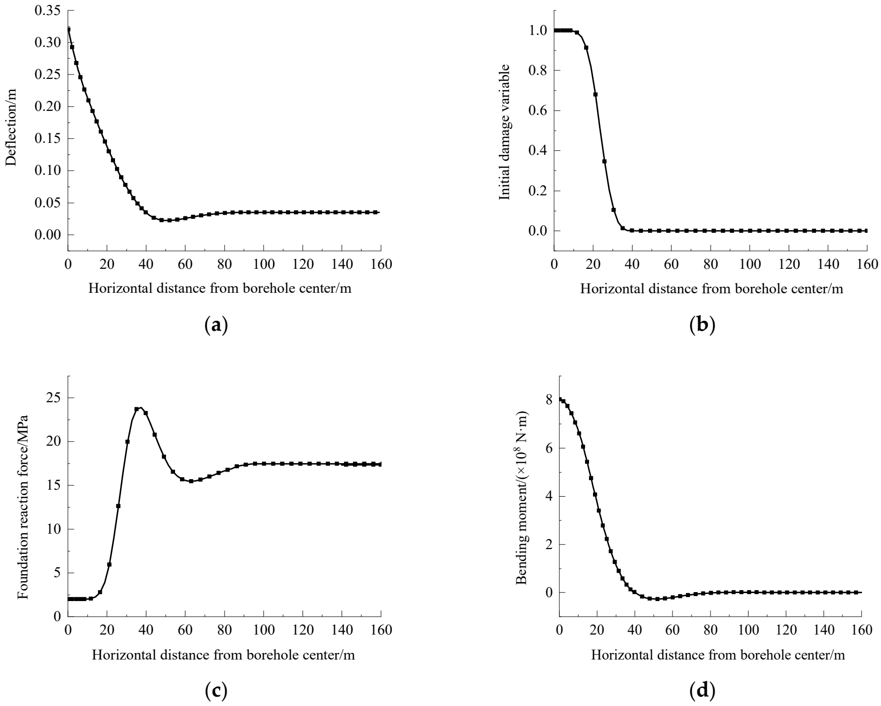


Figure 7. The influence of initial damage on the foundation beam at the initial stage of water injection and permeability enhancement. (**a**) Deflection. (**b**) Initial damage variable. (**c**) Foundation reaction force. (**d**) Bending moment.

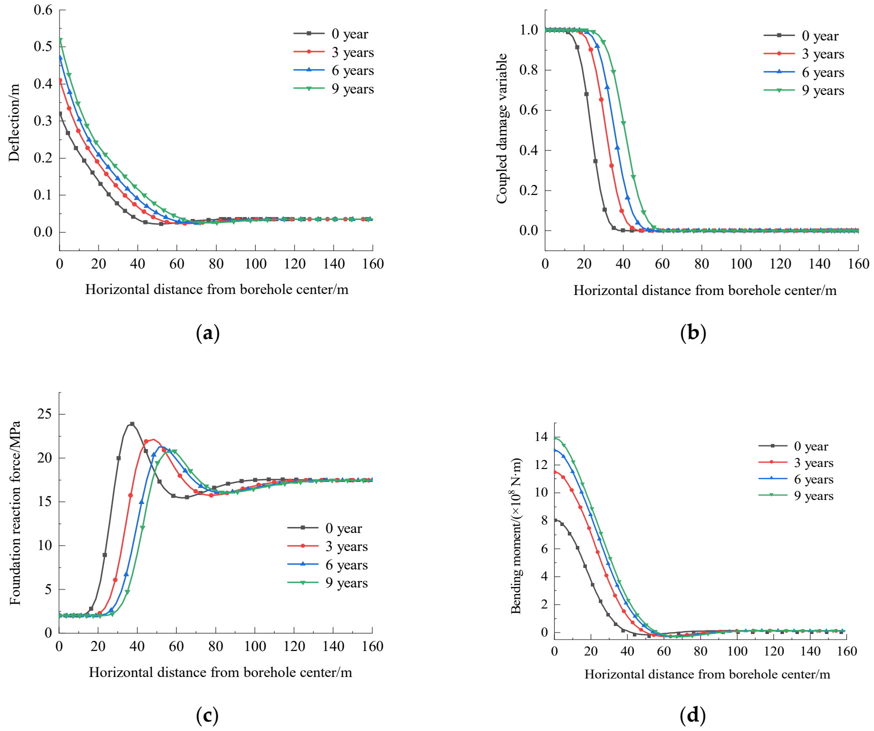


Figure 8. Influence of long-term coupling damage of water injection and permeability enhancement on foundation beam. (**a**) Deflection. (**b**) Damage variable. (**c**) Foundation reaction force. (**d**) Bending moment.

Taking into account the initial damage to the coal seam caused by water injection and permeability enhancement, and considering the subsequent rheological damage, it can be inferred from Figure 8 that as rheological time increases, the deflection and bending moments of the foundation beam gradually escalates, particularly in the vicinity of the borehole. The basic reaction force exhibits significant variation, with its maximum position shifting deeper into the coal over time, and its influence range is expanding. With the prolongation of creep time, both the failure zone and the damage zone expand. Within the damage zone, at a constant horizontal distance from the borehole center, the severity of coal damage intensifies with the prolongation of creep time. In the engineering example presented in this paper, it is evident that after 9 years, the horizontal influence range of damage extends approximately 60 m from the borehole center, while the variations in these variables beyond the 60 m depth are minimal. This indicates that, after accounting for the coupling of initial and rheological damage, the long-term influence range of water injection and permeability enhancement in the 3002 working face is approximately 60 m.

4.3. Mechanism Analysis of Coal Seam Water Injection Permeability Increasing

In the oil and gas industry, the main purpose of hydraulic fracturing technology is to produce penetrating cracks in relatively hard reservoirs, while in the coal industry, high-pressure water injection into soft low-permeability coal seams will lead to changes in the original equilibrium state of the coal within a certain range, resulting in damage and deformation of the coal seam roof, thereby changing the permeability of the coal seam. The drainage measures are adjusted based on the permeability of the coal seam and the gas occurrence. This includes drilling for further bottom drainage. It can be seen that when analyzing and studying the mechanism of coal seam water injection and permeability increase, the coupling effect of solid deformation of coal and roof and fluid flow must be considered to make the results conform to the engineering practice.

The coal damage caused by water injection in coal seam is composed of three parts. The first part is mainly seepage damage. In the process of water injection and pressure holding, the pore pressure changes, which causes the effective stress change in gas-bearing coal, and the erosion of the coal skeleton, resulting in the occurrence and development of pores and fissures, and the seepage damage of coal. The second part is the basic damage. After the drainage process at the end of the drainage, the stress state of the coal and rock mass changes again, and the roof of the coal seam sinks, resulting in the basic damage of the coal, and the permeability changes again. The third part is the rheological damage. For the coal seam that has not been mined for a long time after the drainage, the coal will be further damaged due to the rheology, resulting in the deformation of the coal seam and the roof. The closure and opening degree of pores and cracks in the coal seam also change, and the permeability of the coal seam further changes.

In the process of injecting water into coal seams to increase permeability, the area near the borehole where permeability increases can be called the effective range of permeability increase. The permeability of the area far away from the borehole remains unchanged. Between these two areas, due to roof subsidence and increased vertical stress on the coal seam, there is a transition area where permeability does not change much or may even decrease.

To prevent gas disasters and control gas occurrences, the spacing between boreholes should be arranged reasonably based on the coal seam's permeability and the state of gas occurrences. This is important when implementing drainage measures such as drilling further bottom drainage roadways in coal seams with water injection and permeability increase.

4.4. Numerical Simulation of Influence Range of Water Injection Increasing Permeability

(1) Finite element model

Considering the initial damage and rheological damage of the coal near the water injection hole in the II1 coal seam of Hemei No.6 Coal Mine, based on the basic mechanical parameters of the 3002 working face in Table 1, ANSYS software (latest v. R2) is used to carry out numerical simulation, and the finite element model of the surrounding rock near the water injection hole in the gas-bearing coal seam is established, as shown in Figures 9 and 10. In Figure 10, A1, A3, and A9 are coal seams, A1 and A3 are elastic zones at the end of water injection, A9 is the damage zone at the end of water injection, A4 is the direct roof, A5 is the old roof, A6 is the direct bottom, and A7 is the old bottom.

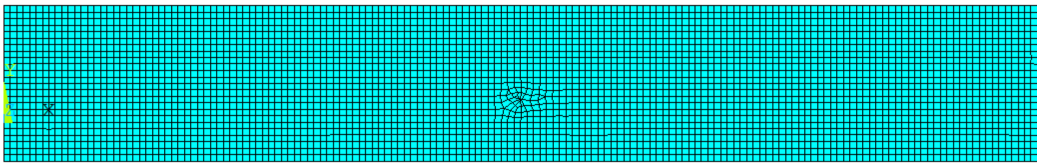


Figure 9. Mesh division of two-dimensional geometric model of initial and rheological damage of coal rock water injection and permeability increase.

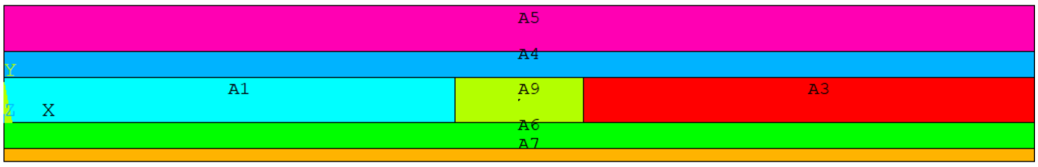
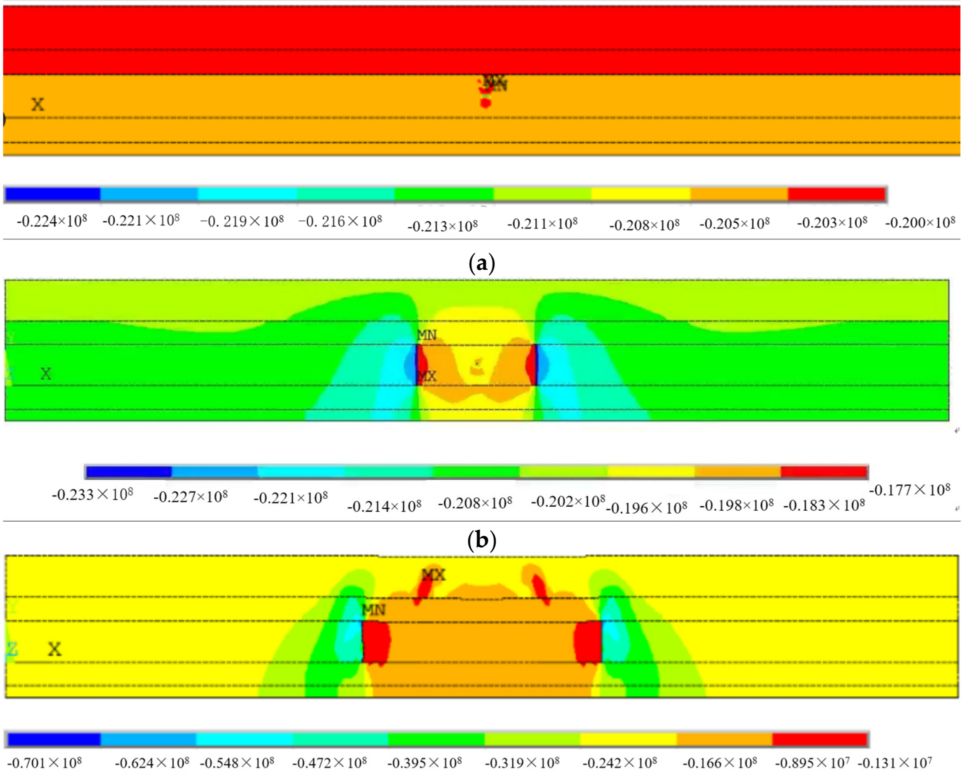


Figure 10. Two-dimensional geometric model of coal rock water injection permeability damage.

(2) Result analysis

The above finite element model is simulated and analyzed. The variation law of vertical stress in gas-bearing coal seams after considering initial damage and rheological damage is studied within 9 years, and the results are compared with those obtained by numerical calculation. The vertical stress program obtained by numerical simulation is shown in Figure 11.

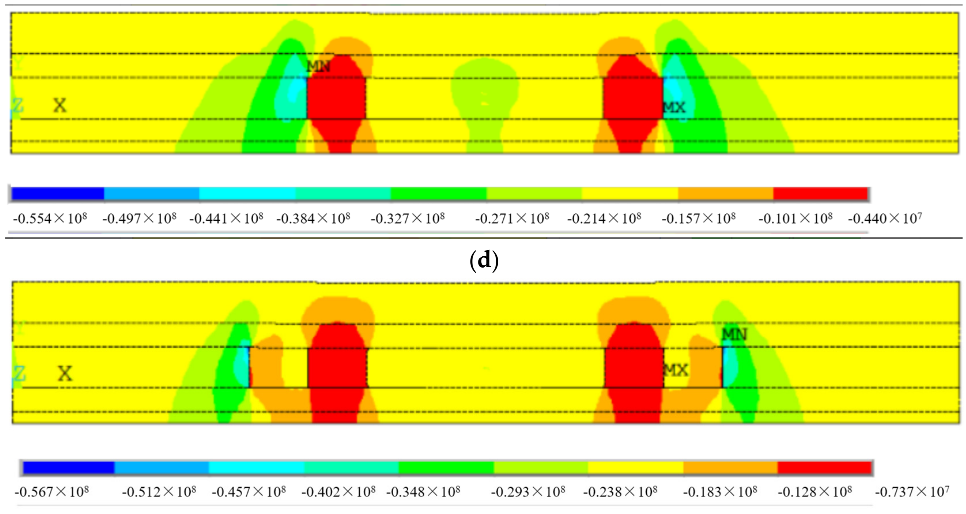


(**a**)

(**b**)

(**c**)

Figure 11. *Cont.*



(**d**)

(**e**)

Figure 11. Model vertical stress cloud diagram. (**a**) Original rock stress state. (**b**) Under the action of initial damage. (**c**) Under the action of initial damage and rheological damage after 3 years. (**d**) Under the action of initial damage and rheological damage after 6 years. (**e**) Under the action of initial damage and rheological damage after 9 years.

Examining the calculation results presented in Figure 11, it is evident that the vertical stress change area of the coal expands as rheological time progresses. Figure 11a illustrates that, before coal seam construction, the coal remains in its original rock stress state, with no alteration in vertical stress. Conversely, Figure 11b reveals that, following water injection, the vertical stress of the coal undergoes changes due to the coupling effect of seepage and damage. Even in the failure zone of the borehole's rock, residual strength still exists after failure. In the damage zone of the borehole surrounding rock, the vertical stress reaches the maximum near the borehole due to the influence of stress concentration. With the increase in distance from the center of the borehole, the vertical stress gradually decreases. In the elastic zone of the surrounding rock of the borehole, the vertical stress gradually decreases to the original rock stress with the increase in the distance from the center of the borehole. It can be seen from Figure 11c–e that after considering the rheological damage, the overall change trend in the vertical stress is the same as that when only the initial damage is considered, and it finally tends to the original ground stress. With the extension of time, the distance between the peak position of vertical stress and the drilling hole increases, and the influence range increases.

From the analysis above, we observe that injecting water into the coal seam causes seepage, leading to changes in the mechanical state and properties of the coal rock. At the same time, the seepage–damage coupling effect changes the vertical stress distribution. After considering the rheological damage, with the continuation of time, the stress concentration area shifts to the deep part of the coal seam, and the influence range of water injection and permeability increase gradually increases. It can be seen that the vertical stress variation law obtained by numerical simulation under the coupling action of initial and rheological damage of coal and rock water injection is consistent with the variation law of basic reaction force obtained by numerical calculation under the coupling action of initial and rheological damage of coal and rock water injection. The numerical calculation and numerical simulation results are compared and verified with each other.

4.5. The Gas Parameter Test and Effect Analysis of the II1 Coal Seam in the Affected Area of Water Injection and Permeability Increase

Based on the above research results, according to Equation (18), Matlab software (2017) is used for numerical calculation, and the coal seam damage distribution map and permeability distribution map of the 3002 working face of Hemei No.6 Coal Mine at the initial stage of water injection and the 9th year of rheology are obtained, as shown in Figures 12 and 13.

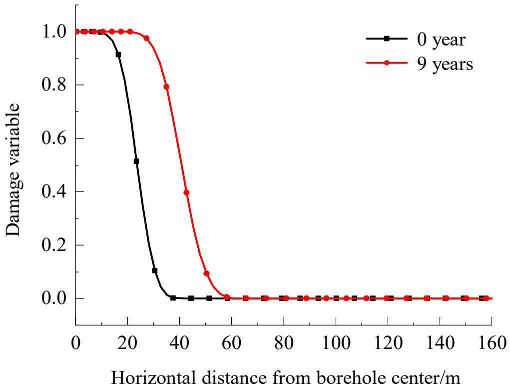


Figure 12. The damage distribution map of a coal seam in the initial stage and the ninth year of rheology.

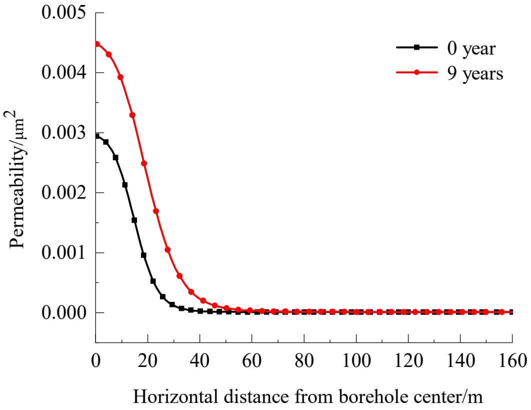


Figure 13. Initial and rheological ninth-year coal seam permeability distribution map.

It is evident from Figures 12 and 13 that the permeability of coal gradually increases with the rise in the damage variable. Additionally, the extent of permeability increase also grows gradually with increasing rheological time. Combined with Figures 7c and 8c, it can be found that in the process of coal seam water injection and permeability increase, the stress in the damaged area around the borehole is small and the permeability is large. Far away from the borehole, the coal seam is in an elastic state, the original rock stress state does not change, and the coal permeability is small; it can also be seen from the distribution law of permeability that the initial influence range of water injection and permeability increase in the 3002 working face is about 45 m, and the long-term influence range is about 60 m.

The gas parameters of the No.21 coal seam in the affected area of water injection and permeability increase in the 3002 working face were tested on site. Based on the relationship between coal permeability and damage, the effect of gas extraction was analyzed to verify the accuracy of the long-term influence range of coal seam water injection and permeability increase obtained by the above coupling damage foundation beam mechanical model. The gas parameter test of the II1 coal seam in the affected area of water injection and permeability increase in the 3002 working face is shown in Figure 14.

Meng [33] conducted an analysis of how coal permeability changes before and after water injection by examining the relationship between confining pressure, axial pressure, and permeability. However, the study did not take into account the impact of rheological damage. Figures 12 and 13 compare scenarios with and without rheological damage, demonstrating that coal seam damage expands over time, leading to changes in permeability. The study suggests that coal permeability during water injection is significantly influenced by vertical stress. The established coupled damage evolution equation and foundation beam model enable a more accurate analysis of vertical stress in the surrounding rock, considering rheological effects. Figure 14 illustrates that the coal seam near the water injection borehole has high permeability, low residual gas content, and efficient gas extraction, while the original state area far from the borehole maintains low coal permeability and high gas content. The numerical simulation and calculation results align with the trend in residual gas content changes observed in field tests. These observations indicate that the stressed zone after water injection of the coal seam should be less than 65 m. The test conclusion supports the numerical calculation conclusion.

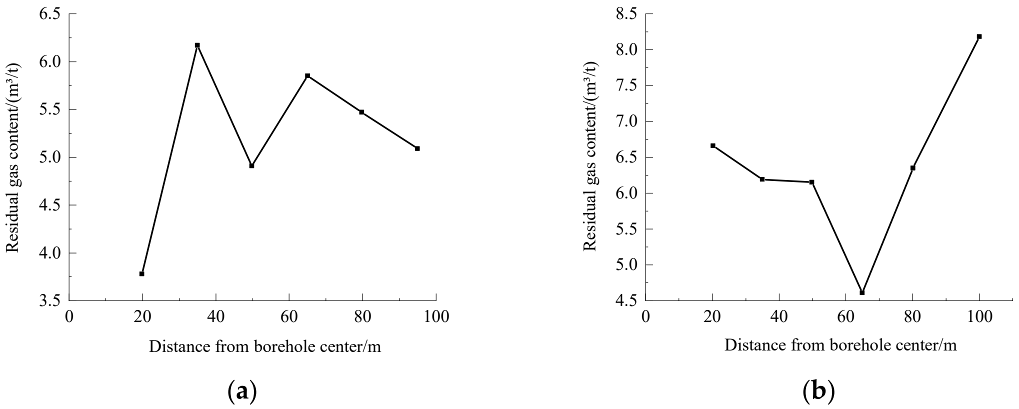


Figure 14. Gas parameter test. (**a**) Upper side of the water injection hole. (**b**) Lower side of the water injection hole.

5. Conclusions

(1) The complexity of enhancing coal seam permeability through water injection involves intricate interactions between coal and the roof, as well as fluid flow. The coupling between rheological damage and permeation damage is evident in the fact that fluid permeation may accelerate the rheological process of the rock mass, increase the effective stress state within the rock mass, and subsequently affect its rheological properties. Additionally, the coupling between rheological damage and fracture damage is evident as micro-cracks within the rock mass gradually expand and connect during long-term rheological processes, providing more favorable conditions for external fracturing. Simultaneously, external fracturing may also accelerate the rheological damage process of the rock mass. To establish a connection between theoretical analysis and engineering practice, we thoroughly consider coal seepage damage, foundation damage, and rheological damage. By establishing a mechanical model of an elastic damage foundation beam that accounts for the deformation of both the coal seam and the roof, a theoretical foundation is provided for studying the effects of coal seam water injection and permeability enhancement.

(2) Injecting high-pressure water into a coal seam causes varying degrees of deformation in the coal and the roof near the borehole, which in turn changes the permeability in those areas of the coal seam. The affected areas can be classified into three zones: the effective infiltration range, the transition zone, and the original state zone. Research has given us insights into how the time of water injection, flow rate, and depth of the coal seam affect the deformation patterns of the roof rock and the effectiveness of water injection. When the water injection time, flow rate, and coal seam depth increase, the deflection and bending moments of the basic roof also increase within a certain horizontal distance from the borehole center. This causes the damage range within the coal seam to expand and the influence range of water injection and permeability to enlarge. Studies have shown that the model created in this paper can quantitatively analyze the deformation of the coal seam roof and the progression of coal seam damage

based on water injection time, flow rate, and coal seam depth, thereby determining the influence range of permeability in the coal seam.

To summarize, by calculating the variation patterns of mechanical properties of the coal seam and surrounding rock using the mechanical model established in this paper, the influence range of external factors on permeability can be determined, providing a theoretical basis for underground engineering.

(3) Numerical simulation software was utilized to validate the results of numerical calculations. This provided the vertical stress distribution, taking into account initial damage and rheological damage in the coal near the water injection borehole. The variation pattern of vertical stress obtained from numerical simulation aligns with the variation pattern of basic reaction force derived from numerical calculations.

(4) The long-term influence range of water injection and permeability increase in the 3002 working face of Hemei No.6 Coal Mine is 60 m. The conclusion of the field test of gas parameters of the II1 coal seam in the affected area is consistent with the conclusion of numerical calculation. Therefore, when studying the effect of water injection and permeability enhancement in gas-bearing coal seams, the influence of initial damage and rheological damage should be considered comprehensively.

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Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding authors.

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