

Article

Long-Term Productivity Prediction for Hydraulically Fractured Deep Coalbed Methane Wells Considering Coal Creep Under Multiphysics Coupling

Zhiqiang Li *, Lei Liu *, Ruokun Zheng, Liang Wang, Yu Peng and Wei Wang

School of Petroleum and Natural Gas Engineering, Chongqing University of Science and Technology, Chongqing 401331, China

* Correspondence: 2018754@cqust.edu.cn (Z.L.); 2024201060@cqust.edu.cn (L.L.)

Abstract

The long-term productivity of hydraulically fractured deep coalbed methane (CBM) wells is jointly governed by desorption-driven gas supply from the coal matrix, the effective-stress response and time-dependent creep of natural cleats, and the progressive degradation of hydraulic-fracture conductivity. To address the difficulty of conventional models in consistently describing the time-dependent transport capacities of natural cleats and hydraulic fractures, this study develops a productivity-prediction model for hydraulically fractured deep CBM wells that couples gas storage in the coal matrix, dynamic natural-cleat permeability, and dynamic hydraulic-fracture conductivity. Based on mass conservation, the model accounts for free- and adsorbed-gas storage, single-phase gas flow, matrix-fracture mass transfer, and wellbore production. The evolution of natural-cleat permeability incorporates effective-stress-induced closure, Langmuir desorption shrinkage, and fractional-order creep, whereas the evolution of hydraulic-fracture conductivity considers fracture compaction, elastic deformation and embedment of proppants, and creep-induced closure of the coal rock. The nonlinear coupled equations are solved using a fully implicit finite-difference scheme. The field dataset comprises daily production records from six deep CBM wells and is used only to constrain physically reasonable ranges of field parameters and provide reference production characteristics. The results indicate that effective stress primarily controls the rapid closure of flow pathways during the early production stage, while the relative contribution of coal creep increases with production time. Neglecting either coal creep or stress sensitivity leads to an overestimation of cumulative gas production over the medium and long term. The proposed model provides a physically constrained analytical framework for evaluating the long-term productivity of hydraulically fractured deep CBM wells and comparing alternative production strategies.

Keywords: deep coalbed methane; coal creep; hydraulic fracturing; dynamic permeability; fracture conductivity; productivity prediction



Academic Editor: Youguo Yan

Received: 16 June 2026

Revised: 23 July 2026

Accepted: 1 August 2026

Published: 5 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Deep coalbed methane (CBM), as an important component of unconventional natural gas, is characterized by large resource potential, low-carbon attributes, and strategic replacement significance. It has therefore become an important target for increasing natural gas reserves and production and for promoting energy-structure transformation in China. Since the 14th 5-Year Plan period, CBM exploration and development in China have gradually shifted from shallow and medium-depth reservoirs to deep formations, and major

breakthroughs in deep CBM have substantially expanded the development potential of the CBM industry [1]. A recent national-scale assessment further quantified the resource potential and identified favorable exploration targets for deep CBM in China [2]. CBM development not only supplements clean energy supply but also contributes to coal-mine safety and carbon-emission reduction [3]. Compared with shallow and medium-depth CBM reservoirs, deep CBM reservoirs in China are characterized by large burial depth, high in situ stress, high reservoir pressure, poor porosity–permeability conditions, and strong heterogeneity, resulting in geological characteristics and production responses that differ markedly from those of shallow and medium-depth CBM reservoirs [4]. From the perspective of the concept and classification of coal-measure gas, deep coal-measure gas development should simultaneously consider coal reservoir properties, gas occurrence state, and engineering stimulation conditions [5]. The productivity of deep CBM is jointly controlled by reservoir gas-bearing properties, desorption capacity, pressure system, and stimulation effectiveness [6]. From an energy-strategy perspective, breakthroughs in deep coal-measure gas are of great significance for securing natural gas supply and promoting the large-scale development of unconventional gas resources [7]. Hydraulic fracturing is a key technology for improving flow capacity and enhancing single-well productivity in deep CBM reservoirs. Previous studies have shown that fracturing-fluid systems, completion methods, fracturing tools, and gas-well management practices are important factors controlling stimulation performance [8]. Field applications in the Shenfu and Linxing blocks of the Ordos Basin indicate that volumetric fracturing and large-scale volumetric fracturing can effectively improve stimulated reservoir volume, gas drainage volume, and horizontal-well productivity; however, complex fracture propagation and long-term proppant support remain key factors limiting sustained post-fracturing production [9,10]. Wide-field electromagnetic monitoring of mid-deep CBM hydraulic fracturing has further shown that fracturing-fluid migration, fracture propagation, and stimulation effectiveness exhibit pronounced spatiotemporal heterogeneity [11]. The proper integration of drilling, completion, and fracturing technologies is essential for efficient CBM development [12]. Under stress-sensitive conditions, fracturing-fluid leakoff and variations in fracture conductivity directly affect post-fracturing CBM well productivity [13]. Therefore, productivity prediction for hydraulically fractured deep CBM wells should not focus solely on initial reservoir properties but should also account for the dynamic degradation of hydraulic fracture conductivity during long-term production.

The production behavior of hydraulically fractured deep CBM wells is strongly stage dependent. Deep CBM wells commonly undergo dewatering and pressure drawdown, rapid production buildup, relatively stable production, and production decline stages, with distinct controlling factors at different stages [14]. Deep CBM well productivity is jointly controlled by coal-seam burial depth, reservoir pressure, permeability, gas content, drainage strategy, reservoir stability, flow-pathway closure, and the adaptability of existing development technologies [15,16]. Gas-content prediction and pressure-evolution analyses further show that spatial variations in adsorbed- and free-gas contents, as well as spatiotemporal pressure propagation characteristics, significantly influence fractured-well productivity and the optimization of CBM development strategies [17,18]. From the perspective of reservoir flow theory, CBM production involves multiscale mechanisms, including adsorption–desorption, matrix diffusion, natural-cleat flow, hydraulic-fracture transport, and wellbore production. CBM is mainly stored in an adsorbed state on the pore surfaces of the coal matrix, and gas production is closely related to pore structure, the cleat system, pressure evolution, gas content, permeability, adsorption characteristics, and production-performance data [19,20]. The fundamental distinction between CBM reservoirs and conventional gas reservoirs lies in adsorbed-gas storage and cleat-controlled

flow, while pressure, gas saturation, and permeability variations strongly affect CBM productivity during drainage [21,22]. Langmuir adsorption theory provides the theoretical basis for describing gas adsorption and desorption in CBM reservoirs [23]. Dual-porosity models provide important theoretical frameworks for describing gas transport in the coal matrix–cleat system [24,25].

Dynamic permeability evolution is a key factor controlling the accuracy of long-term productivity prediction for deep CBM reservoirs. Coal permeability evolution during production is governed by the combined effects of effective stress, pore pressure, matrix shrinkage, adsorption-induced strain, horizontal effective stress variation, internal structure, boundary conditions, mechanical equilibrium, and multiphysics coupling effects [26–33]. Field characterization in the Zhengzhuang area has further demonstrated that the in situ stress state directly controls coal-reservoir permeability and CBM well productivity [34]. Pressure depletion not only increases effective stress and compresses natural cleats, but it also induces matrix shrinkage and changes cleat aperture. Meanwhile, adsorption-induced swelling, stress variation, effective-stress coefficients, and sorption-induced strain are coupled and jointly influence coal permeability evolution. However, most existing permeability models emphasize instantaneous or quasi-static stress–sorption responses, whereas the time-dependent permeability decline caused by long-term coal creep remains insufficiently represented in productivity prediction. Experimental and theoretical studies have shown that coal creep can alter reservoir permeability and should not be neglected in long-term CBM productivity prediction [35–37]. Creep compression can reduce fracture volume and permeability over time, while temperature, creep, and matrix–fracture interaction can jointly affect the time-dependent permeability evolution of deep coal. Under different temperature and stress conditions, creep deformation gradually narrows flow pathways and aggravates permeability decline. In addition to permeability evolution within the coal reservoir, the long-term degradation of hydraulic fracture conductivity is another critical factor affecting stable production from deep CBM wells. Proppant distribution, proppant compaction, proppant embedment, fracture-aperture variation, coal-fines invasion, proppant-size combination, nonuniform proppant placement, fines migration, and fines retention can significantly influence fractured-well productivity and fracture flow capacity [38–41]. Therefore, if hydraulic fracture conductivity is treated as a constant, or if conductivity loss is considered only during the early post-fracturing stage, productivity-prediction models cannot accurately capture the production-decline mechanisms of deep CBM wells during the middle and late stages of production.

Data-driven methods have also been applied to CBM production forecasting. Deep-learning-based production-prediction models can improve the fitting accuracy of complex production-dynamic data [42]. In a broader subsurface-energy context, scenario-based data assimilation has demonstrated how geological uncertainty and production observations can be integrated to update reservoir scenarios and improve production estimates [43]. This approach provides a useful reference for uncertainty-aware forecasting, although its direct application to CBM requires CBM-specific storage, transport, and deformation mechanisms. However, data-driven models generally rely on large volumes of high-quality production data and often lack physical constraints and mechanistic interpretability. For new wells, data-limited blocks, and engineering problems requiring identification of long-term decline mechanisms, physically interpretable productivity-prediction models remain necessary.

To directly compare the mechanisms represented by existing models with those included in the present study, Table 1 summarizes representative model classes and the proposed model.

Table 1. Comparison of representative existing models and the proposed model.

Model Class	Effective Stress	Desorption Shrinkage	Coal Creep	Dynamic Hydraulic Fracture Conductivity/Proppant Embedment	Main Limitation or Advantage
Stress–sorption permeability models [26–33]	Yes	Yes	No	No/No	Natural-cleat permeability only; no time-dependent creep or hydraulic-fracture degradation.
Coal creep–permeability models [35–37]	Yes	Partial	Yes	No/No	Time-dependent coal permeability only; no coupled hydraulic-fracture degradation.
Propped-fracture conductivity models [38–41]	Partial	No	No	Yes/Partial	Hydraulic-fracture transport only; no coupling with coal-matrix supply or natural-cleat evolution.
Proposed model	Yes	Yes	Yes	Yes/Yes	Unified coupling of coal-matrix storage, dynamic natural-cleat permeability, and dynamic hydraulic-fracture conductivity.

As summarized in Table 1, the principal unresolved issue is not the absence of individual mechanisms, because effective-stress sensitivity, desorption shrinkage, coal creep, and propped-fracture degradation have each been investigated previously. Rather, existing models generally focus on either natural-cleat permeability evolution or hydraulic-fracture conductivity degradation and rarely distinguish their different response time scales within a unified long-term productivity framework. Consequently, the coupled evolution of coal-matrix gas supply, natural-cleat permeability, and hydraulic-fracture conductivity, as well as the stage-dependent transition of the dominant controlling mechanism, remains insufficiently characterized.

To address this gap, this study develops a productivity-prediction model for hydraulically fractured deep CBM wells that couples coal-matrix gas storage, dynamic natural-cleat permeability, and dynamic hydraulic-fracture conductivity. The novelty lies in three aspects: (1) the model distinguishes the rapid effective-stress and desorption-shrinkage responses from time-dependent coal creep; (2) coal-creep effects are transmitted simultaneously to natural-cleat permeability and hydraulic-fracture conductivity, thereby linking the evolution of the two principal transport pathways; and (3) single-mechanism and mechanism-exclusion cases are used to identify stage-dependent changes in the dominant controls on production. The natural-cleat module captures the competing effects of effective-stress-induced closure, Langmuir desorption shrinkage, and fractional-order creep, whereas the hydraulic-fracture

module describes the progressive conductivity degradation associated with fracture compaction, proppant elastic deformation and embedment, and creep-induced closure. Fully coupled, single-mechanism, and mechanism-exclusion simulations are conducted to identify the dominant controls on production behavior at different stages. Field production records from six deep CBM wells are used only to constrain physically reasonable ranges of field parameters and provide reference production characteristics; strict history matching and cross-well validation are not performed in this study. The proposed framework provides a physically interpretable tool for long-term productivity evaluation and hydraulic-fracturing performance assessment in deep CBM wells.

2. Single-Phase Gas Flow Model for the Coal Cleat System

2.1. Model Assumptions and Applicability

To define the physical scope of the proposed productivity-prediction model for hydraulically fractured CBM wells and to facilitate the formulation and numerical solution of the governing equations, the following assumptions are adopted:

(1) CBM flow is treated as isothermal, single-phase compressible gas flow. Gas flow through the equivalent coal-reservoir continuum and hydraulic fractures is assumed to obey Darcy's law.

(2) Methane adsorption and desorption in the coal matrix are assumed to satisfy local thermodynamic equilibrium and are described by the Langmuir isotherm. Gas storage in the coal matrix comprises both free gas and adsorbed gas.

(3) The coal matrix–natural cleat reservoir is represented using an equivalent-continuum approach. The anisotropy and dynamic evolution of the natural-cleat system are characterized by dynamic equivalent permeabilities in the x and y directions, whereas hydraulic fractures are represented as independent high-conductivity flow pathways.

(4) The far-field total stresses are prescribed and remain constant throughout the simulation period. Pore-pressure depletion alters natural-cleat permeability and hydraulic-fracture conductivity through the effective-stress response, while time-dependent coal deformation is described using the fractional-order creep constitutive relationship. The complete spatial displacement field and local stress redistribution are not explicitly solved.

(5) Gas–water two-phase flow, coal-fines migration, non-Darcy flow, thermal effects, and chemical interactions between the fracturing fluid and coal are neglected.

Under these assumptions, the proposed model is primarily applicable to the medium- and long-term production stages of hydraulically fractured deep CBM wells after the main dewatering and pressure-drawdown processes have been completed and gas-phase flow has become dominant.

2.2. Mass Conservation Equation

The coal matrix is the primary storage medium of deep CBM and provides sustained gas supply during long-term production from fractured wells. Considering free-gas transport in the matrix, adsorbed-gas desorption, and mass transfer from the matrix to hydraulic fractures, the gas continuity equation for the matrix system is expressed as follows:

$$\frac{\partial}{\partial x} \left(\frac{k_{mx} \rho_g}{\mu_g} \frac{\partial P_m}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{k_{my} \rho_g}{\mu_g} \frac{\partial P_m}{\partial y} \right) - W_{mf} = \frac{\partial(\phi_m \rho_g)}{\partial t} + \frac{\partial[(1 - \phi_m) q_a]}{\partial t} \quad (1)$$

where k_{mx} is the x-direction cleat permeability, mD; k_{my} is the y-direction cleat permeability, mD; P_m is the matrix pressure, MPa; μ_g is the gas viscosity, mPa·s; ϕ_m is the total matrix porosity; t is time, d; q_a is the adsorbed-gas content per unit matrix volume, kg/m³; ρ_g is the gas density, kg/m³; and W_{mf} is the mass-transfer term between the matrix and the hydraulic fracture, kg/(m³·d). Physically, Equation (1) represents the balance among spatial

gas transport, the accumulation of free and adsorbed gas, and gas exchange between the coal matrix–cleat continuum and hydraulic fractures. The pressure gradient drives gas flow, pressure depletion induces adsorbed-gas desorption, and the mass-transfer term W_{mf} couples the reservoir continuum with the hydraulic-fracture system.

Assuming monolayer adsorption on the pore walls, the absolute adsorbed-gas content in the matrix is described using the Langmuir isotherm:

$$q_a = \frac{\rho_s M_g}{V_{std}} \frac{V_L P_m}{P_L + P_m} \quad (2)$$

where q_a is the adsorbed-gas content, kg/m³; M_g is the gas molar mass, g/mol; V_L is the Langmuir volume, m³/kg; P_m is the current matrix pore pressure, MPa; P_L is the Langmuir pressure, MPa; ρ_s is the coal density, kg/m³; and V_{std} is the standard gas volume, m³/mol.

2.3. Dynamic Permeability Model for the Natural Cleat System

Natural cleats are the principal flow pathways through which deep CBM migrates from the coal matrix to hydraulic fractures and the wellbore, and their aperture evolution controls reservoir permeability. Figure 1 illustrates the competitive mechanisms governing cleat aperture during production-induced pressure drawdown. Pressure depletion increases effective stress and compresses the cleat aperture from the initial value b_0 to b_1 . Meanwhile, adsorbed-gas desorption induces coal matrix shrinkage, which partially offsets cleat closure and restores the aperture toward b_2 . During long-term production, coal creep further enhances cleat closure. Accordingly, the dynamic response of natural cleats can be described as a coupled competition among stress-induced compression, creep-induced closure, and desorption shrinkage compensation, which provides the physical basis for the dynamic permeability model developed in this study.

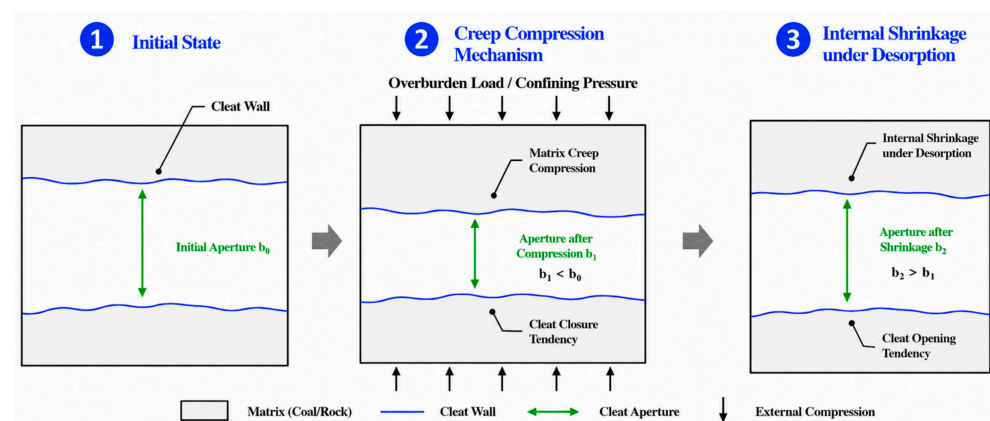


Figure 1. Conceptual model of the competitive aperture-evolution mechanisms in natural cleats during production-induced pressure drawdown.

Reservoir pressure serves as the key coupling variable linking the flow and deformation processes. As reservoir pressure decreases, the effective stress increases, causing instantaneous or quasi-instantaneous elastic closure of the natural cleats. The sustained effective stress further induces coal creep that accumulates with loading time. Meanwhile, methane desorption causes shrinkage of the coal matrix, which provides opposing compensation for cleat closure. In this study, stress sensitivity is defined as the instantaneous elastic response of the cleats to the current effective-stress state, whereas coal creep is defined as history-dependent delayed deformation under sustained loading. To avoid double counting, the instantaneous elastic component is included only in the stress-sensitivity term, while the fractional-order constitutive relation is used exclusively to describe the delayed creep component. These three

mechanisms jointly determine the equivalent strain and instantaneous aperture of the cleats, which subsequently affect natural-cleat permeability through the aperture–permeability relationship and feed back into pressure propagation, matrix–fracture gas exchange, and wellbore production. Conceptually, the total closure strain can be expressed as the sum of the stress-sensitive closure strain and the creep-induced closure strain, minus the aperture compensation caused by desorption-induced shrinkage.

During CBM production, decreasing pore pressure increases effective stress and alters cleat-system permeability. The mechanisms controlling permeability evolution include matrix compression, cleat compression, gas-desorption-induced matrix shrinkage, and coal creep [44]. The linear strain induced by matrix compression is expressed as:

$$\Delta\varepsilon_m = \frac{(1 - 2\nu)(P_m - P_{m0})}{E} \quad (3)$$

where $\Delta\varepsilon_m$ is the strain induced by matrix compression; ν is the Poisson's ratio of coal; P_{m0} is the initial reservoir pore pressure, MPa; and E is the elastic modulus of coal, MPa.

The cleat-compression-induced strain is expressed as:

$$\Delta\varepsilon_f = -\alpha_c(P_m - P_{m0}) \quad (4)$$

where $\Delta\varepsilon_f$ is the cleat-compression-induced strain; and α_c is the cleat compressibility, MPa^{-1} .

Gas desorption induces matrix shrinkage. The desorption-induced strain is expressed as:

$$\Delta\varepsilon_L = \frac{S_L P_{m0}}{P_L + P_{m0}} - \frac{S_L P_m}{P_L + P_m} = \frac{S_L P_L (P_{m0} - P_m)}{(P_L + P_{m0})(P_L + P_m)} \quad (5)$$

where $\Delta\varepsilon_L$ is the matrix shrinkage strain induced by gas desorption; S_L is the Langmuir volumetric strain constant; P_L is the Langmuir pressure, MPa; P_m is the current matrix gas pressure, MPa; and P_{m0} is the initial matrix gas pressure, MPa.

Deep coal exhibits pronounced time-dependent deformation under sustained stress, and its creep response is commonly characterized by non-exponential evolution, retardation over a broad range of time scales, and loading-history dependence [35–38,45,46]. Conventional integer-order rheological models, such as the Kelvin, Maxwell, and Burgers models, represent several discrete retardation times using a finite number of elastic and viscous elements. These models can describe typical instantaneous elastic deformation, attenuated creep, and steady viscous flow. However, when the continuous retardation behavior of deep coal over a broad time range needs to be represented, additional rheological elements are generally required, resulting in more unknown parameters and greater uncertainty in parameter identification. In contrast, fractional-order rheological models introduce a power-law memory kernel through fractional derivatives and can describe a continuous distribution of retardation times, non-exponential decay, and loading-history effects within a relatively compact parameter framework. Therefore, a fractional-order model is better suited to the medium- and long-term creep behavior considered in this study and can be conveniently coupled with pressure depletion, effective-stress evolution, and the dynamic natural-cleat permeability model. Accordingly, a fractional-order creep constitutive relation is adopted herein. When the applied stress is lower than the yield stress, the viscoelastic creep response is described by Equation (6). When the applied stress reaches or exceeds the yield stress, a viscoplastic damage term is introduced into the viscoelastic response, and the accelerated deformation is described by Equation (7).

$$\varepsilon(t) = \frac{\sigma}{E_e} + \frac{\sigma}{E_{ve}} - \frac{\sigma}{E_{ve}} E_{\gamma,1} \left[-E_e \left(\frac{t}{\eta_{ve}} \right)^\gamma \right], \quad (\sigma < \sigma_s) \quad (6)$$

where $\varepsilon(t)$ is the creep strain of coal at time t ; σ is the axial stress applied to the coal, MPa; E is the instantaneous elastic modulus, MPa; E_{ve} is the elastic modulus of the viscoelastic element, MPa; $\eta_{ve,d}$ is the viscosity coefficient of the fractional viscoelastic element expressed in the day-based time system, MPa·d $^\gamma$; γ is the fractional order; $E_{\gamma,1}(\cdot)$ is the Mittag-Leffler function; σ_s is the yield or critical stress, MPa; and t is the loading time, d.

No independent coal-creep experiments were conducted in this study. The values of the fractional order γ , viscoelastic modulus E_{ve} , and viscosity coefficient η_{ve} were selected primarily with reference to published fractional-order creep experiments and constitutive-model studies on coal [46,47], together with the long-term deformation characteristics of deep coal. In these studies, the parameters of the fractional-order model were identified through creep tests, demonstrating that the model is applicable to describing the nonlinear and history-dependent creep behavior of coal.

$$\varepsilon(t) = \frac{\sigma}{E_e} + \frac{\sigma}{E_{ve}} - \frac{\sigma}{E_{ve}} E_{\gamma,1} \left[-E_{ve} \left(\frac{t}{\eta_{ve}} \right)^\gamma \right] + \frac{\sigma - \sigma_s}{\eta_{vp}^\gamma} t^\gamma E_{1,1+\gamma}(a_0 t), \quad (\sigma \geq \sigma_s) \quad (7)$$

where $\eta_{vp,d}$ is the viscosity coefficient of the viscoplastic element expressed in the day-based time system, MPa·d $^\gamma$; a_0 is a parameter associated with viscoplastic damage; and $E_{1,1+\gamma}(\cdot)$ is the Mittag-Leffler function.

In the production calculations, the applied stress is lower than the yield stress; therefore, the sub-yield fractional creep relation shown in Equation (8) is used in the subsequent coupled calculation [48]:

$$\varepsilon(t) = \sigma \left(\frac{1}{E_e} + \frac{1}{E_{ve}} - \frac{1}{E_{ve}} E_{\gamma,1} \left[-E_{ve} \left(\frac{t}{\eta_{ve}} \right)^\gamma \right] \right), \quad \sigma < \sigma_s \quad (8)$$

In the dynamic response calculation of natural cleats, elastic/viscoelastic deformation, coal creep, Langmuir desorption shrinkage, and cleat compression jointly determine the effective strain increment. Based on the linear superposition principle, the equivalent strain increments in the x and y directions are expressed as [44]:

$$\Delta \varepsilon_x = (1 - 2\nu) \Delta \sigma_e \left(\left\{ \frac{1}{E} + \frac{1}{E_{ve}} - \frac{1}{E_{ve}} E_{\gamma,1} \left[-E_{ve} \left(\frac{t}{\eta_{ve}} \right)^\gamma \right] \right\} \right) + \omega \frac{t^\gamma E_{1,1+\gamma}(a_0 t)}{\eta_{vp}^\gamma} + \frac{(1 - \alpha_B)}{3} S_L \left(\frac{P_m}{P_L + P_m} - \frac{P_{m0}}{P_L + P_{m0}} \right) - \alpha_t (P_m - P_{m0}) \quad (9)$$

The strain increments in the x and y directions are identical. Where $\Delta \varepsilon_x$ is the total strain increment in the x direction; $\Delta \sigma_e$ is the effective stress increment, MPa; ω is the viscoplastic creep correction coefficient; α_B is the Biot coefficient; and α_t is the cleat compressibility in the (t) direction, MPa $^{-1}$.

Equations (3)–(9) convert pressure-depletion-induced stress response, desorption shrinkage, and time-dependent creep into changes in effective cleat strain. On this basis, Equations (10) and (11) further map aperture variation into dynamic permeability in the two principal directions.

Natural cleat permeability is highly sensitive to aperture variation. Based on the parallel-plate cubic law and considering anisotropy caused by differences in horizontal principal stresses, the cleat permeabilities in the x and y directions are given by:

$$k_{mx} = \frac{\phi_c w_{inx}^2 (1 - \Delta \varepsilon_x)^2}{12} \quad (10)$$

where ϕ_c is the cleat-system porosity; w_{inx} is the x-direction cleat aperture, mm, and $\Delta\epsilon_x$ is the strain increment in the x direction.

$$k_{my} = \frac{\phi_c w_{iny}^2 (1 - \Delta\epsilon_y)^2}{12} \quad (11)$$

where w_{iny} is the y-direction cleat aperture, mm; and $\Delta\epsilon_y$ is the strain increment in the y direction.

To characterize the anisotropy of initial cleat aperture caused by the difference between horizontal principal stresses, the initial aperture relationships in the x and y directions are established as follows:

$$w_{iny} = w_0 \exp[-c_f(\sigma_{\min} - P_{m0})] \quad (12)$$

where w_0 is the cleat aperture under the reference state, mm; c_f is the cleat compressibility used in the initial aperture anisotropy model, MPa^{-1} ; $\sigma_{\min}$ is the minimum horizontal principal stress, MPa; and p is the pore pressure in the cleat system, MPa.

$$w_{inx} = w_0 \exp[-c_f(\sigma_{\max} - P_{m0})] \quad (13)$$

where $\sigma_{\max}$ is the maximum horizontal principal stress, MPa.

Thus, under initial conditions, the relationship between the initial cleat apertures in the x and y directions is obtained as follows:

$$w_{inx} = w_{iny} \exp[-c_f(\sigma_{\max} - \sigma_{\min})] \quad (14)$$

Equations (12)–(14) describe the effect of initial principal-stress differences on cleat-aperture anisotropy. Together with Equations (9) and (10), these relationships constitute the natural-cleat permeability-updating module and are used in the productivity calculations to evaluate permeability evolution during production.

3. Flow Model for the Coal Reservoir Fracture-Network System

3.1. Flow Model for the Coal Reservoir Fracture Network

Because the thickness of a hydraulic fracture is much smaller than its areal extent within the reservoir plane, pressure variation across the fracture thickness is neglected, and gas transport within the fracture is treated as two-dimensional flow in the x–y plane. The mass-conservation equation for the hydraulic fracture system is:

$$\frac{\partial}{\partial x} \left(\frac{K_f \rho_g}{\mu_g} \frac{\partial P_f}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{K_f \rho_g}{\mu_g} \frac{\partial P_f}{\partial y} \right) + W_{mf} - Q_{well} = \frac{\partial (\phi_f \rho_g)}{\partial t} \quad (15)$$

where K_f is the fracture permeability, D; ϕ_f is the hydraulic fracture porosity; Q_{well} is the mass flow rate from the hydraulic fracture into the wellbore, i.e., the production term, $\text{kg}/(\text{m}^3 \cdot \text{d})$; and P_f is the pressure in the hydraulic fracture system, MPa.

For the horizontal-well production model:

$$Q_{well} = \frac{2\pi \rho_g K_f W_f}{\mu_g V_b} \frac{P_f - P_{wf}}{\ln(r_e/r_w)} \quad (16)$$

where W_f is the hydraulic fracture width, m; P_{wf} is the bottomhole flowing pressure, MPa; r_e is the equivalent well radius, m; r_w is the wellbore radius, m; and V_b is the volume of the grid block containing the well, m^3 .

Here, r_e is the effective drainage radius, which is expressed as:

$$r_e = \begin{cases} 0.20\Delta x & \Delta x = \Delta y, K_x = K_y \\ 0.28 \frac{[(K_y/K_x)^{1/2}\Delta x^2 + (K_x/K_y)^{1/2}\Delta y^2]^{0.5}}{(K_y/K_x)^{1/4} + (K_x/K_y)^{1/4}} & \text{otherwise} \end{cases} \quad (17)$$

where Δx and Δy are the grid dimensions in the x and y directions for the grid block containing the well, respectively, m; and K_x and K_y are the effective permeabilities in the x and y directions, respectively, D. For an isotropic hydraulic fracture, $K_x = K_y = K_f$ may be used. Equations (16) and (17) couple fracture pressure, bottomhole flowing pressure, equivalent well radius, and fracture permeability, thereby providing the control relationship for wellbore-production calculation. Physically, Equation (15) describes the balance among gas transport within the hydraulic fractures, gas inflow from the coal reservoir, gas accumulation in the fractures, and gas production into the wellbore. The hydraulic-fracture system receives gas from the coal matrix–cleat continuum through the mass-transfer term W_{mf} , whereas gas is discharged into the horizontal well through the production term Q_{well} . Equations (16) and (17) further relate fracture pressure, bottomhole flowing pressure, fracture permeability, and grid-scale drainage geometry, thereby transmitting changes in fracture flow capacity to the well-production calculation.

3.2. Hydraulic-Fracture Conductivity Model

During long-term production from CBM wells, hydraulic fracture conductivity gradually decreases owing to closure stress and time-dependent deformation of coal. In this study, conductivity loss is decomposed into three components: proppant elastic deformation, proppant embedment into the coal surface, and creep-induced fracture closure.

Proppant deformation:

$$\beta = 1.04D \left(K^2 p_c \frac{1 - \nu_1^2}{E_1} \right)^{2/3} \quad (18)$$

where β is the elastic deformation of the proppant, mm; D is the initial fracture aperture, mm; K is the proppant spacing coefficient; p_c is the effective closure pressure, MPa; ν_1 is Poisson's ratio of the proppant; and E_1 is the elastic modulus of the proppant, MPa.

Proppant embedment [45]:

$$h = 1.04D_1 \left(K^2 p_c \right)^{2/3} \left[\left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_{2e}} \right)^{2/3} - \left(\frac{1 - \nu_1^2}{E_1} \right)^{2/3} \right] \quad (19)$$

where h is the proppant embedment into the coal surface, mm; D_1 is the proppant diameter, mm; ν_2 is Poisson's ratio of coal, dimensionless; and E_{2e} is the equivalent elastic modulus of coal, MPa.

Real-time fracture aperture:

$$D_w(t) = D - 2\alpha_{\text{creep}}(t) - 2h - 2\beta \quad (20)$$

where $D_w(t)$ is the real-time fracture aperture at time (t), mm; and $a_{\text{creep}}(t)$ is the fracture-aperture loss induced by coal creep at time (t), mm;

The total aperture loss is expressed as:

$$\Delta D(t) = 2\alpha_{\text{creep}}(t) + 2h + 2\beta \quad (21)$$

where $\Delta D(t)$ is the total fracture-aperture loss at time (t) , mm;

The time-dependent porosity is expressed as:

$$\phi(t) = \frac{[D - 2\alpha_{\text{creep}}(t) - h]\phi_0 - 2\beta}{D - 2\alpha_{\text{creep}}(t) - 2h - 2\beta} \quad (22)$$

where $\phi(t)$ is the porosity of the propped fracture at time (t) ; and ϕ_0 is the initial porosity of the propped fracture.

The time-dependent pore-throat radius is expressed as:

$$r(t) = r_0 \frac{D - 2\alpha_{\text{creep}}(t) - 2h - 2\beta}{D - 2\alpha_{\text{creep}}(t) - h} \quad (23)$$

The time-dependent tortuosity is expressed as:

$$\tau(t) = \sqrt{\left[\frac{D - 2\alpha_{\text{creep}}(t) - 2h - 2\beta}{D - 2\alpha_{\text{creep}}(t) - h} \right]^2 (\tau_0^2 - 1) + 1} \quad (24)$$

where $\tau(t)$ is the pore tortuosity at time (t) ; and τ_0 is the initial pore tortuosity.

The time-dependent permeability is expressed as:

$$k(t) = \frac{\{[D - 2\alpha_{\text{creep}}(t) - h]\phi_0 - 2\beta\} [D - 2\alpha_{\text{creep}}(t) - 2h - 2\beta] r_0^2}{8[D - 2\alpha_{\text{creep}}(t) - h]^2 \left\{ \left[\frac{D - 2\alpha_{\text{creep}}(t) - 2h - 2\beta}{D - 2\alpha_{\text{creep}}(t) - h} \right]^2 (\tau_0^2 - 1) + 1 \right\}} \quad (25)$$

where $k(t)$ is the fracture permeability at time (t) , μm^2 .

The time-dependent fracture conductivity is expressed as:

$$F_{\text{RCD}}(t) = \frac{\{[D - 2\alpha_{\text{creep}}(t) - h]\phi_0 - 2\beta\} [D - 2\alpha_{\text{creep}}(t) - 2h - 2\beta]^2 r_0^2}{80[D - 2\alpha_{\text{creep}}(t) - h]^2 \left\{ \left[\frac{D - 2\alpha_{\text{creep}}(t) - 2h - 2\beta}{D - 2\alpha_{\text{creep}}(t) - h} \right]^2 (\tau_0^2 - 1) + 1 \right\}} \quad (26)$$

where $F_{\text{RCD}}(t)$ is the fracture conductivity at time (t) , $\mu\text{m}^2 \cdot \text{cm}$; and r_0 is the initial pore-throat radius, μm .

Equations (18) and (19) calculate proppant deformation and embedment, respectively, whereas Equations (20) and (21) determine the real-time fracture aperture and total aperture loss. Subsequently, Equations (22)–(24) transmit aperture changes to porosity, pore-throat radius, and tortuosity, and Equations (25) and (26) finally yield time-dependent fracture permeability and conductivity. In the numerical solution, $k(t)$ obtained from Equation (25) is updated as the dynamic fracture permeability $K_f(t)$ in the hydraulic fracture flow equation and wellbore productivity coefficient, thereby feeding conductivity degradation back into gas-rate calculation.

4. Numerical Model, Solution Procedure, and Grid-Convergence Assessment

To numerically solve the proposed productivity-prediction model for hydraulically fractured deep CBM wells that couples coal-matrix gas storage, dynamic natural-cleat permeability, and dynamic hydraulic-fracture conductivity, a fully implicit finite-difference method was employed to discretize the governing equations for storage, fluid flow, inter-medium mass exchange, wellbore production, and hydraulic-fracture conductivity evolution. At each time step, the effective stress, natural-cleat permeability, and hydraulic-fracture conductivity were updated according to the current pressure, followed by iterative solution of the pressure field and calculation of daily gas production and cumulative gas

production. The physical roles and variable-transfer relationships of the equation groups are summarized as follows. Equations (1) and (2) describe free- and adsorbed-gas storage and desorption supply in the coal matrix. Equations (3)–(14) convert reservoir-pressure depletion into effective-stress variation, desorption shrinkage, creep strain, cleat-aperture change, and dynamic natural-cleat permeability. Equations (15)–(17) describe gas transfer through hydraulic fractures and production into the wellbore, whereas Equations (18)–(26) convert closure stress and time-dependent coal deformation into fracture-aperture loss and dynamic fracture conductivity. Reservoir pressure is the principal coupling variable. At each time step, the matrix and fracture pressures are used to update effective stress, natural-cleat permeability, adsorbed-gas content, and hydraulic-fracture conductivity. The pressure difference between the reservoir and hydraulic fractures determines W_{mf} , while the difference between fracture pressure and bottomhole flowing pressure determines Q_{well} .

4.1. Computational Geometry and Boundary Conditions

A two-dimensional planar model was developed to describe the production process of hydraulically fractured deep CBM wells. The computational geometry, horizontal-well/hydraulic-fracture configuration, and boundary conditions are illustrated in Figure 2. The coal matrix mainly accounts for free-gas and adsorbed-gas storage and desorption supply. The natural-cleat system is represented using dynamic equivalent permeabilities in the x and y directions, whereas hydraulic fractures are explicitly represented in the numerical model and assigned dynamic conductivity that evolves with pressure and production time.

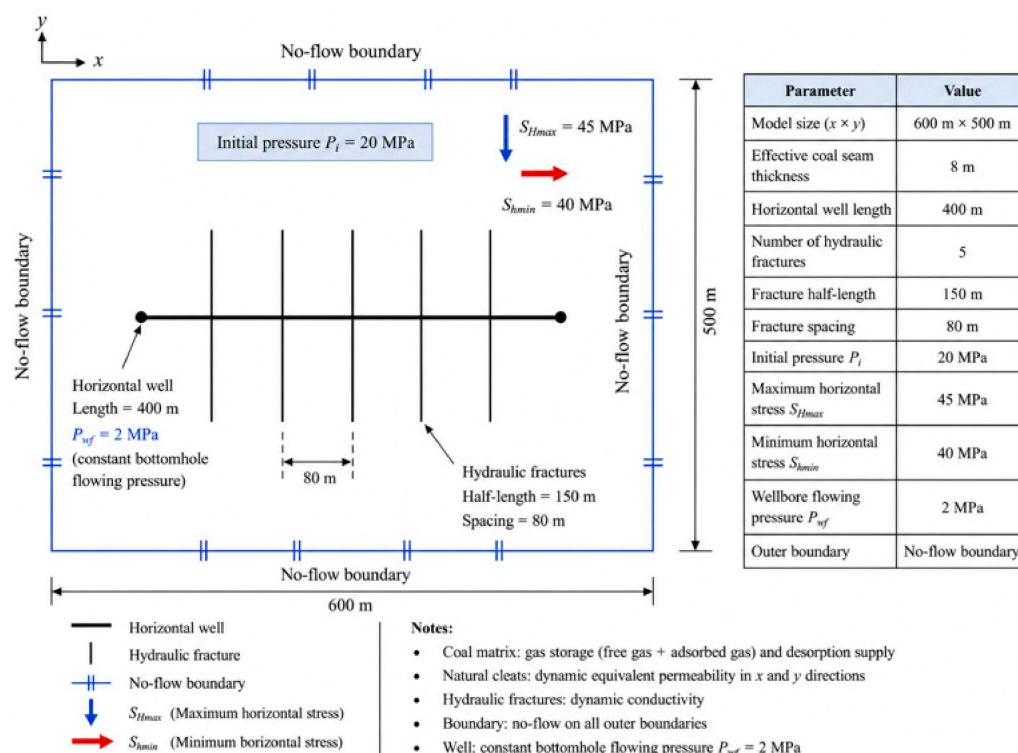


Figure 2. Computational geometry and boundary conditions of the productivity-prediction model for a hydraulically fractured deep CBM well.

The computational domain is a two-dimensional rectangular region with dimensions of 600 m × 500 m, and the effective coal-seam thickness is 8 m. A horizontal well is located along the centerline of the computational domain, with a well length of 400 m. Five hydraulic fractures approximately perpendicular to the horizontal well are included, with

a fracture half length of 150 m and a fracture spacing of 80 m. The initial pressures of both the coal reservoir and hydraulic fractures are set to 20 MPa. The maximum and minimum horizontal principal stresses are 45 MPa and 40 MPa, respectively. The outer boundaries of the computational domain are specified as no-flow boundaries, and the horizontal well is produced under a constant bottomhole flowing pressure of 2 MPa. The base spatial grid size is 2 m $\times$ 2 m, and the time step is 1 d.

4.2. Field Production Data

The field dataset consists of daily production records from six CBM wells. The dataset mainly includes daily gas production, cumulative gas production, daily water production, bottomhole flowing pressure, dynamic fluid level, and production schedules. The six-well dataset is used only to constrain physically reasonable ranges of field parameters and to provide reference production characteristics.

4.3. Grid-Independence Analysis

To evaluate the influence of spatial discretization on the simulation results, a grid-independence analysis was conducted based on the baseline case. Three uniform grid sizes of 4, 2, and 1 m were adopted, while the time step was fixed at 1 d for all cases. Except for the grid size, all simulations employed identical computational domains, fracture geometries, physical parameters, initial conditions, boundary conditions, and production schedules. The evaluation metrics included cumulative gas production at 180, 720, and 1800 d, as well as the average natural-cleat permeability and average hydraulic-fracture conductivity at 1800 d. The results obtained using the refined 1 m grid were used as the reference.

The results indicate that all evaluation metrics gradually converge as the grid size decreases from 4 m to 2 m and 1 m. Compared with the 1 m grid, the relative differences in cumulative gas production using the 2 m grid are 1.52%, 0.60%, and 0.14% at 180, 720, and 1800 d, respectively. The relative differences in the average natural-cleat permeability and average hydraulic-fracture conductivity at the end of the simulation are 0.12% and 0.14%, respectively. The maximum relative difference among all evaluation metrics is 1.52%, indicating that further refinement of the grid size from 2 m to 1 m results in limited changes in the major simulation outputs. Considering both computational accuracy and efficiency, the 2 m grid was adopted for subsequent simulations.

4.4. Governing Equations

The governing equations established in Sections 2 and 3 are directly used in the numerical model. Specifically, Equation (1) describes mass conservation in the coal matrix–natural cleat system, Equation (2) describes adsorbed-gas storage, Equation (15) governs hydraulic-fracture flow, and Equation (16) defines wellbore production. To facilitate the subsequent finite-difference discretization, the wellbore productivity coefficient and the matrix–fracture mass-transfer term are introduced below.

The wellbore productivity coefficient is defined as:

$$J_w = \frac{2\pi\rho_g K_f W_f}{\mu_g V_b \ln(r_e/r_w)} \quad (27)$$

where J_w is the wellbore productivity coefficient, kg/(m³·d·MPa).

Therefore, the well production term can be simplified as:

$$Q_{well} = J_w (P_f - P_{wf}) \quad (28)$$

The mass-transfer term between the matrix and fracture is expressed as:

$$W_{mf} = \lambda_{mf}(P_m - P_f) \quad (29)$$

where λ_{mf} is the matrix-fracture interporosity flow coefficient, $\text{kg}/(\text{m}^3 \cdot \text{d} \cdot \text{MPa})$.

The definitions in Equations (27)–(29), together with the governing equations in Equations (1), (2), (15), and (16), complete the coupled productivity formulation for the coal matrix and hydraulic fractures. In the matrix equation, W_{mf} represents a mass outflow term, whereas in the hydraulic-fracture equation, it represents a mass inflow term. Q_{well} denotes the mass output from the hydraulic fracture to the wellbore. These equations are discretized in the following subsection.

4.5. Finite-Difference Discretization

The computational domain is divided into $N_x \times N_y$ rectangular grids, with grid sizes Δx and Δy . The time levels are denoted by n and $n + 1$, and the time step is Δt . The flow coefficients of the matrix and fracture systems are defined as:

$$M_m = \frac{K_m \rho_g}{\mu_g} \quad (30)$$

where M_m is the matrix flow coefficient, $\text{kg}/(\text{m} \cdot \text{d} \cdot \text{MPa})$.

$$M_f = \frac{K_f \rho_g}{\mu_g} \quad (31)$$

where M_f is the fracture flow coefficient, $\text{kg}/(\text{m} \cdot \text{d} \cdot \text{MPa})$.

The transmissibility coefficients of the matrix system are defined as:

$$T_{m,E} = \frac{M_{m,i+1/2,j}}{\Delta x^2}, \quad T_{m,W} = \frac{M_{m,i-1/2,j}}{\Delta x^2} \quad (32)$$

where $T_{m,E}$ and $T_{m,W}$ are the transmissibility coefficients of the matrix system in the east and west directions, respectively, $\text{kg}/(\text{m}^3 \cdot \text{d} \cdot \text{MPa})$; $M_{m,i+1/2,j}$ and $M_{m,i-1/2,j}$ are the matrix flow coefficients at the east and west interfaces of grid i,j , respectively, $\text{kg}/(\text{m} \cdot \text{d} \cdot \text{MPa})$; and Δx is the grid spacing in the x direction.

$$T_{m,N} = \frac{M_{m,i,j+1/2}}{\Delta y^2}, \quad T_{m,S} = \frac{M_{m,i,j-1/2}}{\Delta y^2} \quad (33)$$

where $T_{m,N}$ and $T_{m,S}$ are the transmissibility coefficients of the matrix system in the north and south directions, respectively, $\text{kg}/(\text{m}^3 \cdot \text{d} \cdot \text{MPa})$; $M_{m,i,j+1/2}$ and $M_{m,i,j-1/2}$ are the matrix flow coefficients at the north and south interfaces of grid i,j , respectively, $\text{kg}/(\text{m} \cdot \text{d} \cdot \text{MPa})$; and Δy is the grid spacing in the y direction.

The accumulation term of the matrix system is linearized as:

$$A_m = \frac{C_m}{\Delta t} \quad (34)$$

where A_m is the accumulation coefficient of the matrix system, $\text{kg}/(\text{m}^3 \cdot \text{d} \cdot \text{MPa})$; C_m is the storage coefficient of the matrix system, $\text{kg}/(\text{m}^3 \cdot \text{MPa})$; and Δt is the time step, d .

$$C_m = \frac{\partial}{\partial P_m} [\phi_m \rho_g + (1 - \phi_m) q_a] \quad (35)$$

If the matrix porosity is approximated as constant, then:

$$C_m = \phi_m \frac{d\rho_g}{dP_m} + (1 - \phi_m) \frac{dq_a}{dP_m} \quad (36)$$

where q_a is the adsorbed-gas content, kg/m³.

From the Langmuir equation:

$$\frac{dq_a}{dP_m} = \frac{\rho_s M_g}{V_{std}} \frac{V_L P_L}{(P_L + P_m)^2} \quad (37)$$

The accumulation term of the fracture system is linearized as:

$$A_f = \frac{C_f}{\Delta t} \quad (38)$$

where A_f is the accumulation coefficient of the fracture system, kg/(m³·d·MPa); and C_f is the storage coefficient of the fracture system, kg/(m³·MPa).

$$C_f = \frac{\partial(\phi_f \rho_g)}{\partial P_f} \quad (39)$$

where C_f is the storage coefficient of the fracture system, kg/(m³·MPa).

Compared with the matrix system, the hydraulic fracture storage term does not include an adsorbed-gas accumulation contribution. Its effect on productivity is mainly reflected in pressure-transfer capacity and the dynamic conductivity variation controlled by $K_f(t)$.

4.6. Numerical Model

Using a fully implicit finite-difference scheme, the discrete equation for the matrix system in grid i,j is:

$$(A_m + \sum T_{m,f} + \lambda_{mf})P_{m,i,j}^{n+1} - T_{m,E}P_{m,i+1,j}^{n+1} - T_{m,W}P_{m,i-1,j}^{n+1} - T_{m,N}P_{m,i,j+1}^{n+1} - T_{m,S}P_{m,i,j-1}^{n+1} - \lambda_{mf}P_{f,i,j}^{n+1} = A_m P_{m,i,j}^n \quad (40)$$

where $\sum T_m$ is the sum of the transmissibility coefficients in all directions of the matrix system, kg/(m³·d·MPa); $P_{m,i,j}^{n+1}$ is the matrix pressure in grid i,j at time level $n + 1$, MPa; $P_{m,i+1,j}^{n+1}$, $P_{m,i-1,j}^{n+1}$, $P_{m,i,j+1}^{n+1}$ and $P_{m,i,j-1}^{n+1}$ at $n + 1$ are the matrix pressures in the adjacent grids at time level $n + 1$, MPa; $T_{m,E}$, $T_{m,W}$, $T_{m,N}$, and $T_{m,S}$ are the matrix transmissibility coefficients in the east, west, north, and south directions, kg/(m³·d·MPa); $P_{f,i,j}^{n+1}$ is the fracture pressure in grid i,j at time level $n + 1$, MPa; and $P_{m,i,j}^n$ is the matrix pressure in grid i,j at time level n , MPa.

Where the sum of the transmissibility coefficients in all directions of the matrix system is given by:

$$\sum T_m = T_{m,E} + T_{m,W} + T_{m,N} + T_{m,S} \quad (41)$$

The discrete equation for the hydraulic fracture system is:

$$(A_f + \sum T_f + \lambda_{mf} + J_w)P_{f,i,j}^{n+1} - T_{f,E}P_{f,i+1,j}^{n+1} - T_{f,W}P_{f,i-1,j}^{n+1} - T_{f,N}P_{f,i,j+1}^{n+1} - T_{f,S}P_{f,i,j-1}^{n+1} - \lambda_{mf}P_{m,i,j}^{n+1} = A_f P_{f,i,j}^n + J_w P_{wf}^{n+1} \quad (42)$$

where $\sum T_f$ is the sum of the fracture-system transmissibility coefficients in all directions, kg/(m³·d·MPa); $P_{f,i,j}^{n+1}$ is the fracture pressure in grid i,j at time level $n + 1$, MPa; $P_{f,i+1,j}^{n+1}$, $P_{f,i-1,j}^{n+1}$, $P_{f,i,j+1}^{n+1}$ and $P_{f,i,j-1}^{n+1}$ at $n + 1$ are the fracture pressures in adjacent grids at time level $n + 1$, MPa; $T_{f,E}$, $T_{f,W}$, $T_{f,N}$, and $T_{f,S}$ are the fracture transmissibility coefficients in the east, west, north, and south directions, kg/(m³·d·MPa); $P_{m,i,j}^{n+1}$ is the matrix pressure in grid i,j at

time level $n + 1$, MPa; $P_{f,i,j}^n$ is the fracture pressure in grid i,j at time level n , MPa; and P_{wf}^{n+1} is the bottomhole flowing pressure at time level $n + 1$, MPa.

Where the sum of the transmissibility coefficients in all directions of the fracture system is given by:

$$\sum T_f = T_{f,E} + T_{f,W} + T_{f,N} + T_{f,S} \quad (43)$$

Equations (40) and (42) provide the fully implicit finite-difference discretization of the governing equations for the coal matrix and hydraulic fracture systems. Gas exchange between the matrix and fracture is represented by the interporosity-flow term $\lambda_{mf}(P_m - P_f)$, whereas well production is controlled by the wellbore productivity coefficient J_w and the pressure difference between fracture pressure and bottomhole flowing pressure.

4.7. Matrix Solution and Production Calculation

Taking the matrix and fracture pressures in all grid blocks as unknowns, the discrete equation system can be written in matrix form as:

$$AP^{n+1} = b \quad (44)$$

where A is the coefficient matrix; P^{n+1} is the pressure vector at time level $n + 1$; and b is the right-hand-side vector.

$$P^{n+1} = \begin{bmatrix} P_m^{n+1} \\ P_f^{n+1} \end{bmatrix} \quad (45)$$

where P^{n+1} is the pressure vector at time level $n + 1$; P_m^{n+1} is the matrix pressure vector at time level $n + 1$; and P_f^{n+1} is the fracture pressure vector at time level $n + 1$.

$$\begin{bmatrix} A_{mm} & A_{mf} \\ A_{fm} & A_{ff} \end{bmatrix} \begin{bmatrix} P_m^{n+1} \\ P_f^{n+1} \end{bmatrix} = \begin{bmatrix} b_m \\ b_f \end{bmatrix} \quad (46)$$

where A_{mm} is the matrix-system coefficient submatrix; A_{mf} is the coupling submatrix representing the effect of fracture pressure on the matrix equation; A_{fm} is the coupling submatrix representing the effect of matrix pressure on the fracture equation; A_{ff} is the fracture-system coefficient submatrix; P_m^{n+1} is the matrix pressure vector; P_f^{n+1} is the fracture pressure vector; b_m is the right-hand-side vector of the matrix system; and b_f is the right-hand-side vector of the fracture system.

Because gas density, gas viscosity, and adsorbed-gas content are all pressure dependent, the model is nonlinear. Therefore, at each time step, the fluid and rock properties are updated iteratively, and the pressure field is solved. The convergence criterion is:

$$\max \left| \frac{P^{l+1} - P^l}{P^{l+1}} \right| < \varepsilon_{tol} \quad (47)$$

where P^{l+1} is the pressure at iteration $l + 1$, P^l is the pressure at iteration l , and ε_{tol} is the convergence tolerance.

After the fracture pressure is obtained, the instantaneous wellbore gas production rate is:

$$Q_g^{n+1} = J_w (P_{f,well}^{n+1} - P_{wf}^{n+1}) \quad (48)$$

where Q_g^{n+1} is the gas production rate at time level $n + 1$; J_w is the wellbore productivity coefficient; $P_{f,well}^{n+1}$ is the fracture pressure in the grid containing the well at time level $n + 1$; and P_{wf}^{n+1} is the bottomhole flowing pressure at time level $n + 1$.

The cumulative gas production is:

$$G_p^{n+1} = G_p^n + Q_g^{n+1} \Delta t \quad (49)$$

where G_p^{n+1} is the cumulative gas production at time level $n + 1$, m^3 ; G_p^n is the cumulative gas production at time level n , m^3 ; Q_g^{n+1} is the gas production rate at time level $n + 1$, m^3/d ; and Δt is the time step.

In summary, Equations (40) and (42) constitute the core discrete formulation for coupled flow in the coal matrix and hydraulic fracture systems, whereas Equation (26) dynamically feeds hydraulic fracture conductivity degradation back into fracture flow coefficients and well production calculation. This numerical framework can be used to analyze the effects of coal creep, matrix desorption shrinkage, and stress sensitivity on long-term gas-production behavior.

5. Results and Discussion

Table 2 summarizes the fixed values and parameter ranges used in the coupled coal matrix–natural cleat–hydraulic fracture model. The parameters include reservoir properties, natural-cleat properties, hydraulic-fracture properties, proppant-related parameters, and numerical settings for the finite-difference simulation.

Table 2. Basic parameters for calculation.

Parameter	Symbol	Range	Unit	Reference or Basis
Simulation time	t	0–1800	d	—
Initial cleat aperture	w_{c0}	100	μm	[32,33]
Initial cleat permeability	k_{c0}	1.15	mD	[26]
Proppant diameter	D_1	0.6	mm	[38,41]
Initial fracture conductivity	F_{RCD0}	7.4	$\mu\text{m}^2 \cdot \text{cm}$	[13]
Matrix porosity	ϕ_m	0.01–0.09	—	[19,22]
Langmuir volume	V_L	0.025	m^3/kg	[20]
Langmuir pressure	P_L	2	MPa	[20]
Fractional creep order	γ	0.1–0.9	—	[46,47]
Viscoelastic modulus	E_{ve}	0.5–2	GPa	[46,47]
Viscosity parameter	η_{ve}	1–10	$\text{MPa} \cdot \text{d}^\gamma$	[46,47]
Elastic modulus	E	2	GPa	[35,37]
Poisson's ratio	ν	0.2–0.35	—	[35,37]
Hydraulic fracture width	W_f	0.003	m	—
Bottomhole flowing pressure	P_{wf}	2	MPa	—
Grid spacing	$\Delta x, \Delta y$	2	m	—
Time step	Δt	1	d	—
Nonlinear iteration tolerance	ε_{tol}	1×10^{-5}	—	—
Coal density	ρ_s	1400	kg/m^3	[19,20]
The initial reservoir pore pressure	P_{m0}	20	MPa	—
Maximum horizontal principal stress	σ_{max}	45	MPa	[4,34]
Minimum horizontal principal stress	σ_{min}	40	MPa	[4,34]
Proppant elastic modulus	E_1	50	GPa	[38,41]
Gas viscosity	μ_g	0.02	$\text{mPa} \cdot \text{s}$	[22]
Initial pore tortuosity	τ_0	1.2–3.0	—	[38,41]
Wellbore radius	r_w	0.1	m	—
Initial porosity of propped fracture	ϕ_0	0.25–0.45	—	[38,41]
Initial pore-throat radius	r_0	30–100	μm	[38,41]
Initial fracture aperture	D	3	mm	—

Based on the coupled coal matrix-natural cleat-hydraulic fracture model developed above, this section presents numerical analyses of porosity-permeability evolution, hydraulic fracture conductivity degradation, and cumulative gas production during long-term production from a hydraulically fractured deep CBM well. In the natural cleat system, the model simultaneously considers stress sensitivity caused by increasing effective stress, matrix shrinkage induced by methane desorption, and creep deformation under long-term loading. In the hydraulic fracture system, the model further incorporates conductivity degradation caused by fracture compaction, proppant embedment, and creep-induced closure of coal. Comparisons between single-mechanism cases and the fully coupled case are used to identify the direction, stage dependence, and relative importance of different mechanisms in long-term productivity response.

The simulated production period is set to 1800 d. The initial natural cleat aperture, initial cleat permeability, and initial hydraulic fracture conductivity are 100 μm , 1.15 mD, and 7.4 $\mu\text{m}^2\cdot\text{cm}$, respectively. Four cases are considered for natural cleat evolution: coal creep only, matrix desorption shrinkage only, stress sensitivity only, and triple coupling. Five cases are considered for hydraulic fracture conductivity: an ideal no-degradation case, fracture compaction only, proppant embedment only, coal creep only, and three-mechanism coupling. For cumulative gas production, the fully coupled model is used as the base case and is compared with simplified cases that neglect coal creep, matrix desorption shrinkage, and stress sensitivity, respectively. These simulations are mainly used to reveal long-term response patterns under multimechanism coupling; the field-prediction capability of the model should be further assessed by history matching against actual production data.

5.1. Dynamic Evolution of Natural Cleat Aperture

Natural cleats constitute the principal internal flow pathways through which gas released from the coal matrix is transported toward hydraulic fractures. Changes in cleat aperture alter the available flow space and therefore affect the gas-supply capacity of the coal reservoir. Figure 3 compares the evolution of natural-cleat aperture under coal creep, matrix desorption shrinkage, stress sensitivity, and their coupled effects. The initial cleat aperture is set to 100 μm in all cases. In this study, stress sensitivity denotes the instantaneous or quasi-instantaneous elastic response of natural cleats to changes in effective stress, coal creep denotes delayed and loading-history-dependent deformation under sustained stress, and matrix desorption shrinkage denotes contraction of the coal matrix caused by methane desorption. Because these mechanisms act in different directions and over different characteristic time scales, they produce distinct aperture-evolution paths.

When only matrix desorption shrinkage is considered, the natural-cleat aperture increases gradually and reaches approximately 101.94 μm at 1800 d, corresponding to an increase of approximately 1.94% relative to the initial value. As reservoir pressure decreases, adsorbed methane is progressively released from the internal surfaces of the coal matrix. The reduction in adsorption-induced swelling causes the matrix blocks to contract, which tends to increase the separation between opposing cleat surfaces and enlarge the available flow space. The aperture increase is concentrated mainly during active pressure depletion and subsequently weakens because the Langmuir-type desorption strain approaches a finite limiting value. Matrix desorption shrinkage therefore provides a positive but bounded compensation for cleat closure. When only stress sensitivity is considered, the natural-cleat aperture decreases rapidly during the early production stage and subsequently approaches a relatively stable value. At 1800 d, the aperture is approximately 88.47 μm , representing a reduction of approximately 11.53% relative to the initial value. Under the prescribed far-field total stress, reservoir-pressure depletion increases the effective normal stress acting on the cleat surfaces and causes elastic compression of the cleat system. Because the pressure

decline is most pronounced during the early production stage, the increase in effective stress and the associated aperture loss are concentrated in this period. As the pressure-decline rate decreases, the additional effective-stress increment becomes smaller, which explains the gradual stabilization of the stress-sensitivity curve. When only coal creep is considered, the natural-cleat aperture decreases continuously throughout production and reaches approximately 94.64 μm at 1800 d, corresponding to a reduction of approximately 5.36%. Unlike the predominantly instantaneous elastic response represented by stress sensitivity, coal creep is a delayed deformation process governed by both loading duration and stress history. Under sustained effective loading, the coal skeleton continues to deform even after the rate of reservoir-pressure decline has decreased, resulting in progressive compression of the cleat space. The relatively rapid early change followed by a slower long-term decline reflects the retardation and memory characteristics represented by the fractional-order creep model. Although the creep-induced aperture loss is smaller than that caused by stress sensitivity under the present parameter conditions, creep produces a persistent long-term closure effect that cannot be represented by an instantaneous stress–strain relationship. Under the triple coupling of stress sensitivity, matrix desorption shrinkage, and coal creep, the natural-cleat aperture exhibits a rapid initial decrease followed by a slower long-term decline. At 1800 d, the coupled aperture decreases to approximately 85.04 μm , about 14.96% lower than the initial value. The rapid early-stage decline is mainly associated with effective-stress-induced elastic closure, whereas the continued reduction during the middle and late stages reflects the accumulation of time-dependent creep deformation. Matrix desorption shrinkage acts in the opposite direction and partially offsets the two closure mechanisms. However, under the present parameter conditions, the opening compensation provided by matrix shrinkage is insufficient to counterbalance the combined effects of stress sensitivity and coal creep. Consequently, the coupled aperture is lower than those obtained in all three single-mechanism cases at the end of the simulation.

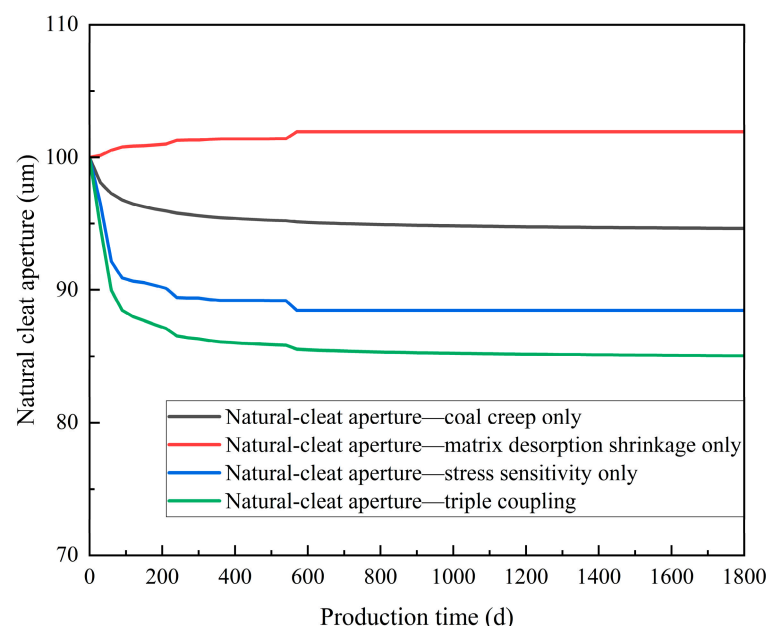


Figure 3. Evolution of natural cleat aperture with production time under different mechanisms.

Overall, the contrasting aperture responses reflect the different action modes and temporal characteristics of the three mechanisms. Stress sensitivity is most pronounced during the early pressure-depletion stage, when the increase in effective stress induces rapid elastic closure of the natural cleats. Coal creep contributes a slower but cumulative reduction in aperture under sustained loading, whereas desorption-induced matrix shrinkage acts in the

opposite direction and partially compensates for cleat closure. The superposition of these mechanisms results in a coupled response characterized by a rapid initial decrease followed by a gradual long-term decline. Under the present parameter conditions, the compensating effect of matrix shrinkage is insufficient to offset the combined closure caused by stress sensitivity and coal creep.

5.2. Evolution of Natural Cleat Permeability and Competition Among Triple Effects

The evolution of natural cleat aperture directly affects the gas-transmission capacity of the coal reservoir. Figure 4 shows the evolution of natural-cleat permeability under different physical mechanisms. The initial natural-cleat permeability is set to 1.15 mD in all cases. The same pressure path and strain responses used for Figure 3 are adopted, and permeability is updated through the aperture–permeability relationship in Equations (10) and (11). All other reservoirs and numerical parameters are kept unchanged to ensure comparability among the different mechanisms. Compared with cleat aperture, permeability provides a more direct measure of internal gas-flow capacity and is therefore a key indicator for evaluating the long-term productivity response of deep CBM wells.

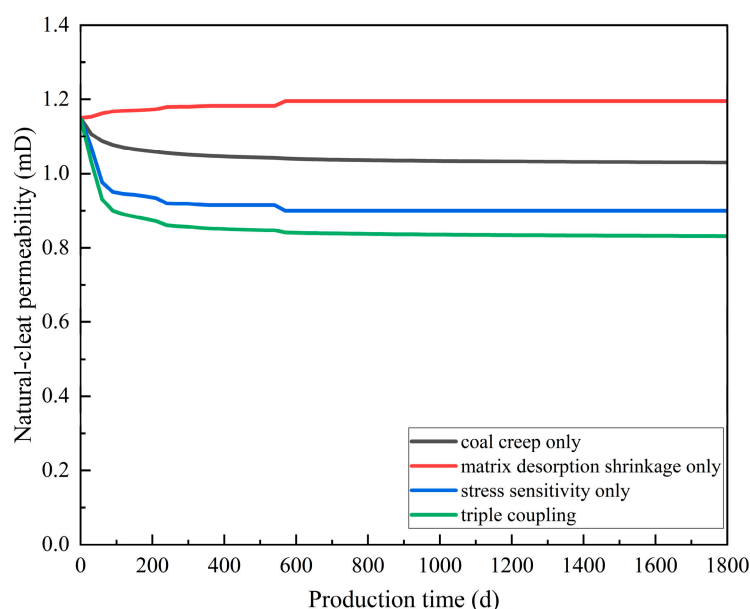


Figure 4. Evolution of natural cleat permeability with production time under different mechanisms.

As shown in Figure 4, the effects of the different mechanisms on natural-cleat permeability differ substantially in both direction and magnitude. When only matrix desorption shrinkage is considered, permeability increases gradually and reaches approximately 1.195 mD at 1800 d, about 3.91% higher than the initial value. The corresponding aperture increase is relatively small, but the aperture–permeability relationship converts this geometric change into a measurable improvement in flow capacity. When only coal creep is considered, permeability decreases continuously to approximately 1.030 mD at 1800 d, corresponding to a reduction of approximately 10.43%. This decline reflects the persistent compression of natural cleats caused by delayed coal deformation under sustained loading. Stress sensitivity produces the strongest individual permeability reduction: permeability decreases rapidly during the initial pressure-depletion stage and then approaches approximately 0.900 mD, about 21.74% below the initial value. The rapid early decrease is consistent with the quasi-instantaneous increase in effective normal stress, while the subsequent stabilization follows the reduced rate of additional pressure depletion.

Under the triple coupling of stress sensitivity, matrix desorption shrinkage, and coal creep, natural-cleat permeability exhibits the greatest overall decline. During early production, rapid reservoir-pressure depletion increases effective stress and sharply reduces permeability. During the middle and late stages, the pressure-decline rate becomes smaller, but creep deformation continues to accumulate and maintains a slow downward trend. At 1800 d, the coupled permeability decreases to approximately 0.832 mD, about 27.68% below the initial value. Matrix desorption shrinkage partially compensates for permeability reduction, but its positive contribution is insufficient to offset the combined permeability loss caused by stress sensitivity and coal creep. Because permeability varies nonlinearly with aperture, the relative permeability changes are greater than the corresponding aperture changes, making permeability more sensitive to closure of the natural-cleat system.

These permeability-evolution trends are qualitatively consistent with previous experimental and numerical studies. Experimental observations have shown that increasing effective stress reduces coal permeability and that sorption-induced deformation modifies the permeability response [30,31]. Studies considering coal creep and matrix–fracture interaction have also reported progressive permeability reduction under sustained loading [35–37]. Owing to differences in coal rank, moisture content, confining stress, and boundary conditions, the comparison is limited to the governing mechanisms and normalized trends rather than absolute numerical agreement.

Figure 5 compares the normalized stage-averaged aperture-effect indices of coal creep, matrix desorption shrinkage, and stress sensitivity. For each single-mechanism case, the absolute deviation of natural-cleat aperture from its initial value was calculated at each time step and then averaged over the corresponding production stage (0–180 d, 181–720 d, and 721–1800 d). The three stage-averaged values were subsequently normalized by their sum so that the indices within each stage add up to 100%.

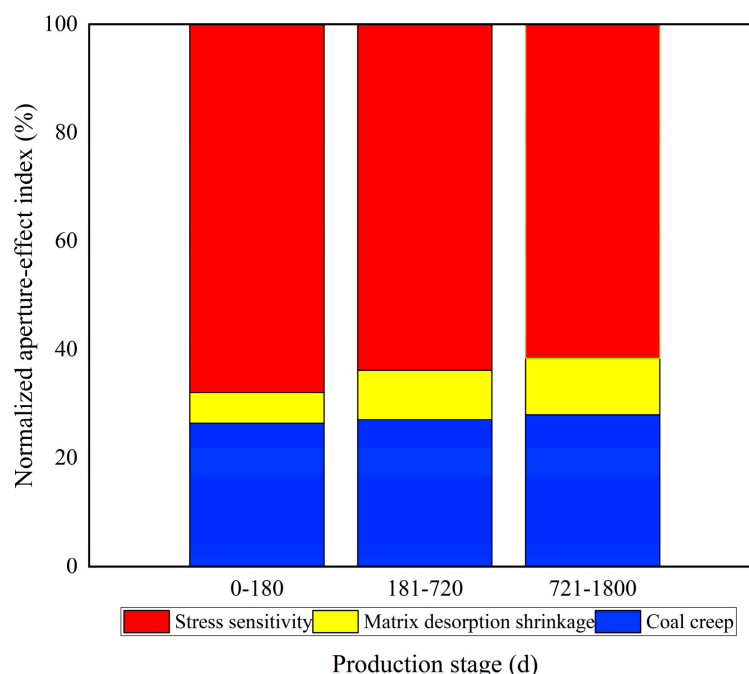


Figure 5. Normalized stage-averaged aperture-effect indices of coal creep, matrix desorption shrinkage, and stress sensitivity during different production stages.

During the early production stage of 0–180 d, stress sensitivity accounts for approximately 68.1% of the total aperture effect, whereas coal creep and matrix desorption shrinkage account for approximately 26.4% and 5.6%, respectively. During the middle stage of 181–720 d, the corresponding indices are approximately 64.0%, 27.1%, and 8.9%. During

the late stage of 721–1800 d, stress sensitivity remains dominant at approximately 61.7%, while the indices of coal creep and matrix desorption shrinkage increase slightly to approximately 28.0% and 10.4%, respectively. These results indicate that stress sensitivity remains the principal mechanism controlling natural-cleat geometry throughout production. Coal creep provides a persistent secondary contribution, whereas the compensating effect of matrix desorption shrinkage becomes more evident with pressure depletion but remains comparatively limited.

To avoid interpretive bias caused by the opposite directions of the positive and negative effects, Figure 6 compares the normalized stage-averaged permeability-effect indices of the three mechanisms. For each single-mechanism case, the absolute relative deviation of natural-cleat permeability from its initial value was calculated at each time step and then averaged over the corresponding production stage. The stage-averaged values of coal creep, matrix desorption shrinkage, and stress sensitivity were subsequently normalized by their sum so that the three indices add up to 100% within each stage. During the 0–180 d, 181–720 d, and 721–1800 d stages, the permeability-effect index of stress sensitivity is approximately 67.4%, 63.0%, and 60.7%, respectively, and therefore remains dominant throughout production. The corresponding index of coal creep is approximately 26.8%, 27.6%, and 28.4%, indicating a persistent and slightly increasing time-dependent influence. The matrix-desorption-shrinkage index increases from approximately 5.8% in the early stage to 9.4% in the middle stage and 10.9% in the late stage. These results demonstrate that stress sensitivity is the primary mechanism causing natural-cleat permeability to deviate from its initial state. Coal creep provides a persistent secondary contribution to flow-capacity loss, whereas matrix desorption shrinkage provides an increasingly evident but comparatively limited positive compensation.

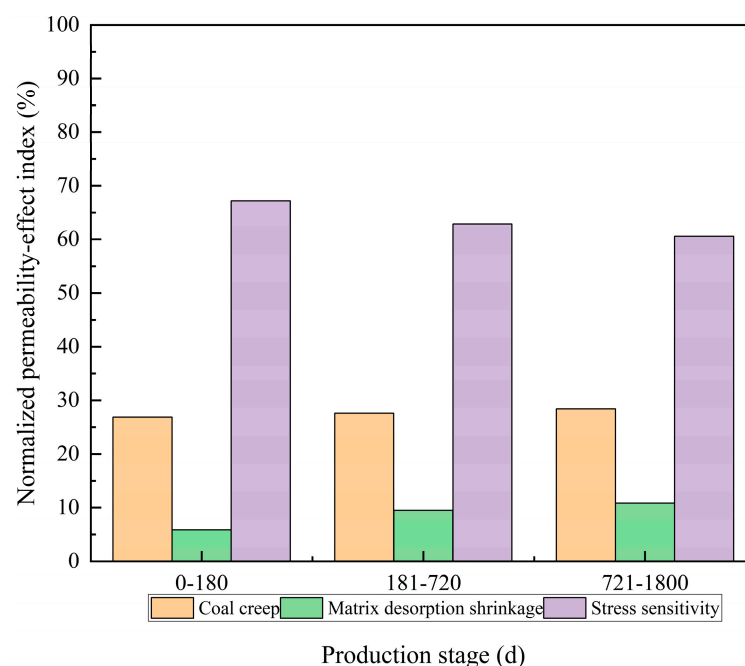


Figure 6. Normalized stage-averaged permeability-effect indices of coal creep, matrix desorption shrinkage, and stress sensitivity during different production stages.

The integrated results in Figures 3–6 indicate that stress sensitivity is the dominant mechanism controlling natural-cleat aperture and permeability throughout the production period, particularly during the rapid pressure-depletion stage. Coal creep produces a smaller but persistent time-dependent reduction in cleat aperture and permeability, and its relative influence increases slightly with production time. Matrix desorption shrinkage

provides an increasingly evident positive compensation, but its magnitude remains insufficient to reverse the coupled decline in natural-cleat flow capacity. The similar ordering of the aperture- and permeability-effect indices reflects the monotonic aperture–permeability relationship, whereas the larger relative permeability changes arise from its nonlinear dependence on aperture. Therefore, the coupled effects of stress sensitivity, matrix desorption shrinkage, and coal creep must be considered in long-term productivity evaluation for hydraulically fractured deep CBM wells.

5.3. Time-Dependent Degradation of Hydraulic Fracture Conductivity

Hydraulic fractures are the main high-conductivity pathways connecting the reservoir to the wellbore in fractured wells. Whether their conductivity can be maintained during long-term production directly affects fracturing performance and ultimate productivity. In the model developed above, hydraulic fracture conductivity evolves dynamically with fracture compaction, proppant embedment, and creep-induced closure. Figure 7 shows the evolution of hydraulic fracture conductivity with production time under different degradation mechanisms.

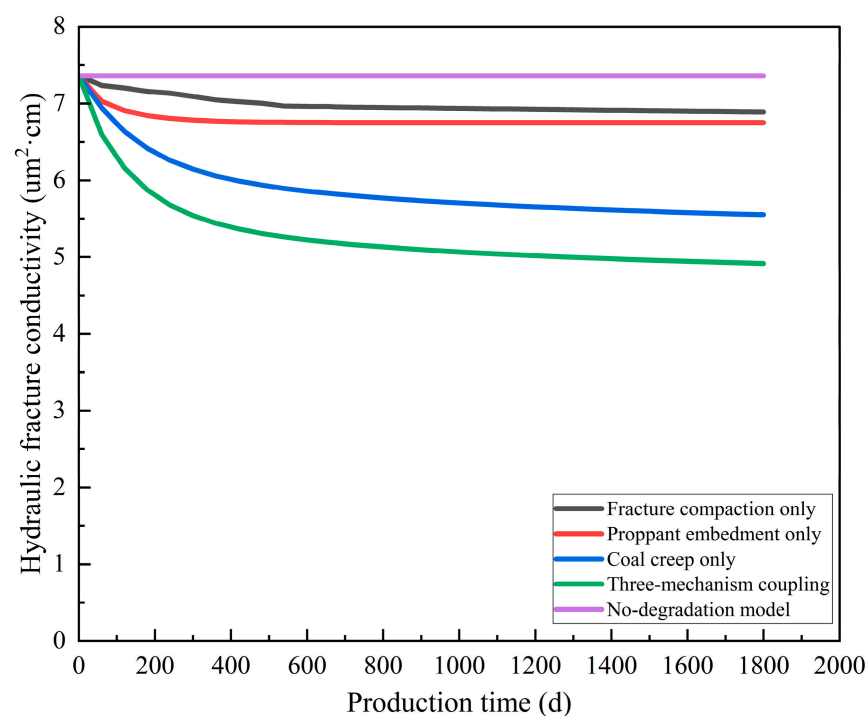


Figure 7. Time-dependent evolution of hydraulic-fracture conductivity under the no-degradation, fracture-compaction-only, proppant-embedment-only, coal-creep-only, and fully coupled degradation cases.

In the ideal no-degradation case, hydraulic fracture conductivity remains approximately $7.4 \mu\text{m}^2\cdot\text{cm}$ throughout the production period. This case serves as a reference for evaluating the strength of different degradation mechanisms. When only fracture compaction is considered, conductivity decreases mainly during early production, after which the decline rate decreases significantly; at 1800 d, the conductivity is approximately $6.9 \mu\text{m}^2\cdot\text{cm}$, about 6.8% lower than the ideal value. This result indicates that fracture compaction is mainly affected by the rapid increase in effective closure stress during early production, and its adverse effect is concentrated in the early stage. When only proppant embedment is considered, hydraulic fracture conductivity also decreases rapidly at the beginning of production and reaches approximately $6.8 \mu\text{m}^2\cdot\text{cm}$ at 1800 d, about 8% lower than the ideal value. Proppant embedment reduces the effective fracture width; however, under the current parameter conditions, the long-term conductivity loss caused by this

mechanism alone is relatively limited. When only coal creep is considered, hydraulic fracture conductivity decreases continuously throughout the production period and remains in a noticeable decline in the middle and late stages. At 1800 d, the conductivity is approximately $5.6 \mu\text{m}^2\cdot\text{cm}$, about 24.3% lower than the ideal value. Compared with fracture compaction and proppant embedment, coal creep causes substantially greater long-term conductivity loss, indicating that time-dependent closure under deep coal confining stress continuously compresses the propped fracture space and is an important mechanism controlling long-term transmissibility in fractured wells. When fracture compaction, proppant embedment, and coal creep act simultaneously, hydraulic fracture conductivity exhibits the most pronounced degradation. In the three-mechanism coupled case, conductivity decreases from approximately $7.4 \mu\text{m}^2\cdot\text{cm}$ initially to approximately $4.9 \mu\text{m}^2\cdot\text{cm}$ at 1800 d, representing a cumulative reduction of approximately 33.8%. This result indicates that hydraulic fracture conductivity loss is not a simple instantaneous superposition of different degradation mechanisms; rather, it has a clear long-term cumulative character. In particular, during middle and late production stages, coal creep further aggravates fracture transmissibility decline on the basis of aperture loss already caused by fracture compaction and proppant embedment.

Figure 8 shows the contribution shares of the degradation mechanisms of hydraulic fracture conductivity at different production stages. In the 0–180 d stage, fracture compaction contributes approximately 63%, coal creep approximately 34%, and proppant embedment approximately 4%. Fracture compaction dominates during this stage, indicating that rapid effective-closure-stress increase during early production is the primary cause of conductivity loss. In the 181–7720 d stage, the contribution of coal creep increases to approximately 69%, whereas that of fracture compaction decreases to approximately 29% and that of proppant embedment is approximately 2%. In the 72–11,800 d stage, the contribution of coal creep further increases to approximately 83%, whereas the contributions of fracture compaction and proppant embedment decrease to approximately 16% and 1%, respectively.

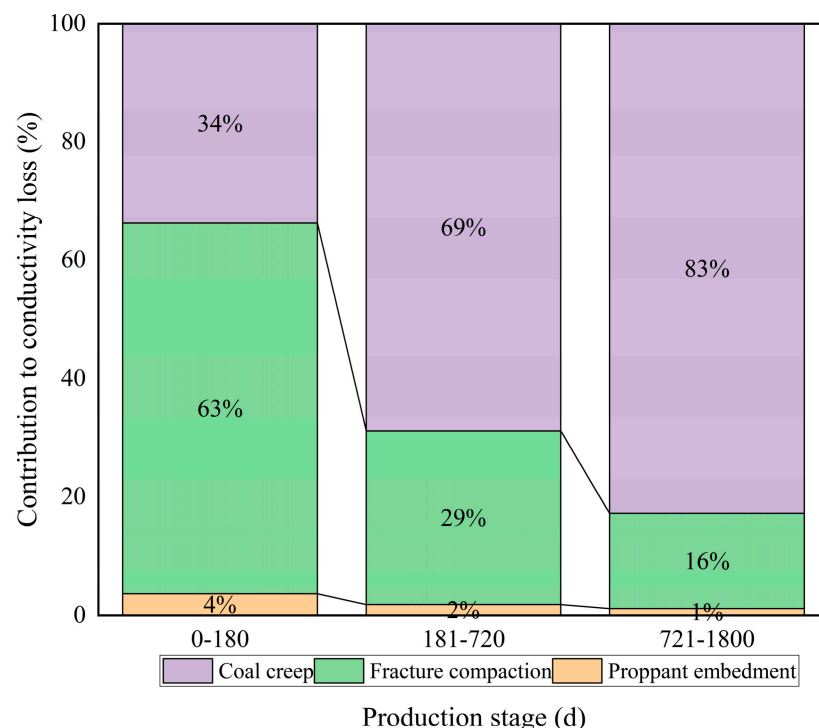


Figure 8. Contribution shares of hydraulic fracture conductivity degradation mechanisms at different production stages.

These results reveal a clear stage-dependent transition in hydraulic fracture conductivity degradation. The early stage is mainly controlled by fracture compaction, whereas the middle and late stages gradually become dominated by coal creep. This pattern is consistent with the time-dependent degradation observed in the natural cleat system: coal creep continuously weakens both natural flow pathways in the reservoir and artificial high-conductivity pathways created by fracturing. Therefore, treating hydraulic fracture conductivity as constant, or considering only early-stage closure-related loss, may lead to overprediction of middle and late-stage productivity in hydraulically fractured deep CBM wells. Published laboratory studies on propped coal fractures have shown that fracture conductivity generally decreases with increasing effective closure stress because fracture compaction, proppant deformation and embedment, and the resulting reduction in effective fracture aperture weaken the fracture flow capacity [36–39]. These experimental observations are qualitatively consistent with the present simulation, which shows a relatively rapid conductivity decline during early production, followed by continued degradation during the middle and late stages. In the fully coupled case, hydraulic fracture conductivity decreases from approximately $7.4 \mu\text{m}^2 \cdot \text{cm}$ to $4.9 \mu\text{m}^2 \cdot \text{cm}$ over 1800 d, corresponding to a reduction of approximately 33.8%. The simulated early-stage decline is mainly controlled by fracture compaction, while proppant embedment makes a comparatively limited contribution under the present parameter conditions. Creep-induced fracture closure becomes increasingly important during prolonged production.

To further evaluate the influence of different physical mechanisms on long-term productivity prediction, Figure 9 compares cumulative gas production curves for the fully coupled model and simplified models that neglect coal creep, matrix desorption shrinkage, and stress sensitivity, respectively. Overall, the differences among the cases are relatively small in the early production stage, but prediction deviations caused by model simplification gradually increase with production time, indicating that multimechanism effects have a strong cumulative influence on long-term productivity.

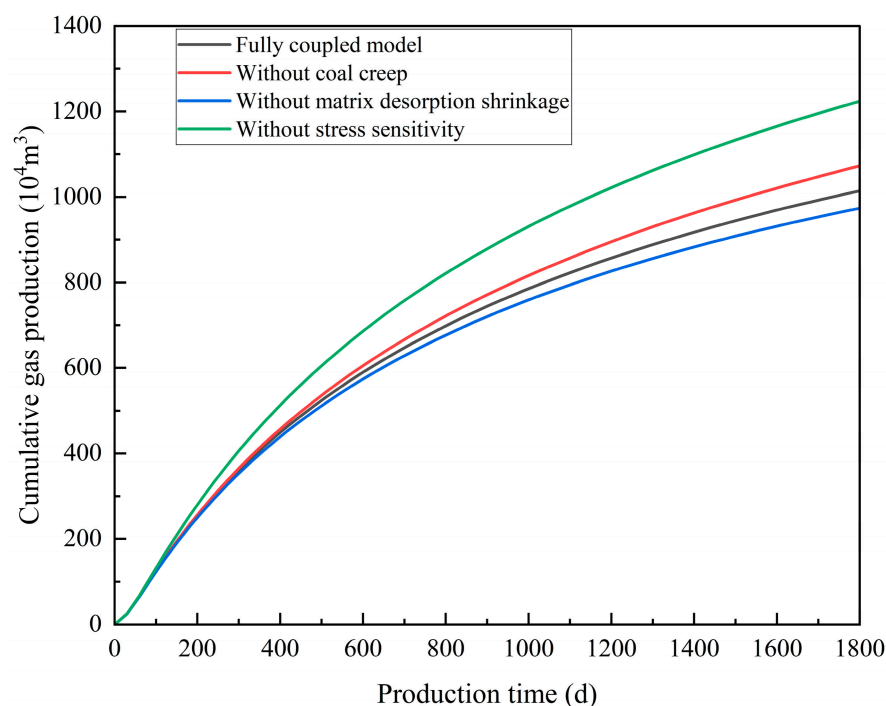


Figure 9. Evolution of cumulative gas production with production time under simplified mechanism cases.

Under the fully coupled model, the cumulative gas production at 1800 d is approximately $1010 \times 10^4 \text{ m}^3$. When coal creep is neglected, cumulative gas production increases to approximately $1070 \times 10^4 \text{ m}^3$, which is about 5.9% higher than that of the fully coupled model. This deviation indicates that coal creep suppresses long-term gas productivity by reducing natural cleat aperture and by accelerating the time-dependent degradation of hydraulic fracture conductivity. Therefore, neglecting coal creep leads to overestimation of middle- and late-stage gas transmissibility and cumulative production.

When matrix desorption shrinkage is neglected, cumulative gas production decreases to approximately $975 \times 10^4 \text{ m}^3$, about 3.5% lower than that of the fully coupled model. This result indicates that matrix desorption shrinkage provides a positive compensation effect during pressure depletion. As adsorbed gas is gradually desorbed, matrix shrinkage partly enlarges natural cleat space and offsets a portion of the closure caused by stress sensitivity and coal creep. In contrast, when stress sensitivity is neglected, cumulative gas production reaches approximately $1220 \times 10^4 \text{ m}^3$, about 20.8% higher than that of the fully coupled model. This is the largest deviation among the simplified cases, indicating that early effective-stress-induced closure has a persistent influence on long-term production.

Overall, neglecting coal creep or stress sensitivity results in overprediction of cumulative gas production, whereas neglecting matrix desorption shrinkage results in underprediction. These opposite deviation directions reflect the competing effects of different mechanisms: stress sensitivity and coal creep reduce reservoir-fracture transmissibility, while matrix desorption shrinkage partially improves natural cleat flow capacity. Therefore, long-term productivity of hydraulically fractured deep CBM wells cannot be represented by a constant-permeability model or by a single stress-sensitivity relationship. Instead, it should be evaluated by simultaneously considering dynamic natural-cleat permeability, time-dependent hydraulic-fracture conductivity degradation, and matrix desorption gas supply.

5.4. Input-Parameter Uncertainty and Model Limitations

Input-parameter uncertainty should be carefully considered when interpreting the long-term productivity predictions. Reservoir and mechanical parameters, including the initial natural-cleat permeability, Langmuir pressure, fractional-order creep parameters, in situ stresses, and initial hydraulic-fracture conductivity, may vary because of reservoir heterogeneity, measurement errors, scale effects, and differences between laboratory and field conditions. Uncertainty in the fractional-order creep parameters primarily affects the magnitude and accumulation rate of time-dependent closure of natural cleats and hydraulic fractures. Uncertainty in the Langmuir pressure mainly influences gas desorption and the compensating effect of matrix shrinkage on cleat closure. The initial natural-cleat permeability and initial hydraulic-fracture conductivity primarily control gas transport from the coal reservoir to the hydraulic fractures and from the hydraulic fractures to the wellbore, respectively. Therefore, the results presented in this study should be interpreted as deterministic predictions for the specified parameter set rather than as probabilistic confidence intervals. Future studies should combine field-production history matching with Monte Carlo or Bayesian methods to quantify joint parameter uncertainty and productivity-prediction intervals.

In addition, the present model assumes isothermal single-phase gas flow and represents the coal reservoir using an equivalent-continuum approach. Gas–water two-phase flow, coal-fines migration, non-Darcy flow, thermo-chemical effects, complex fracture networks, and complete spatial stress redistribution are not explicitly considered. The fractional-order creep parameters are also assumed to remain constant throughout the simulation period. Future studies should incorporate long-term production data from multiple wells, coal-creep experiments, and propped-fracture conductivity tests to further

constrain the key model parameters and evaluate the applicability of the model under different geological conditions and in different development blocks.

6. Conclusions

To characterize time-dependent porosity–permeability evolution, hydraulic fracture conductivity degradation, and coal creep in long-term productivity prediction for hydraulically fractured deep CBM wells, this study developed a coupled single-phase gas flow–deformation model for the coal matrix, natural cleats, and hydraulic fractures. The model does not consider water flow or gas–water two-phase flow; instead, it focuses on the effects of adsorbed-gas desorption, free-gas transport, dynamic natural-cleat permeability evolution, and hydraulic fracture conductivity degradation on long-term productivity. The following conclusions are obtained by comparing the fully coupled model with simplified models representing different physical mechanisms.

(1) The long-term productivity of hydraulically fractured deep CBM wells is jointly controlled by natural cleats, the coal matrix, and hydraulic fractures, and it cannot be explained solely by initial permeability or constant fracture conductivity. During production-induced pressure drawdown, gas supply from matrix desorption, natural-cleat permeability evolution, and hydraulic fracture conductivity degradation occur simultaneously, resulting in stage-dependent production behavior. Therefore, treating reservoir permeability or fracture conductivity as constant reduces the ability of the model to explain middle- and late-stage production decline.

(2) Natural-cleat aperture and permeability evolution are governed by the competition among effective-stress sensitivity, coal creep, and matrix desorption shrinkage. Effective-stress sensitivity induces rapid elastic closure of the natural cleats during the early pressure-depletion stage and exerts the largest individual effect on natural-cleat flow capacity under the present parameter conditions. Coal creep produces a smaller but persistent and history-dependent closure that accumulates throughout production, whereas desorption-induced matrix shrinkage acts in the opposite direction and partially compensates for cleat closure. Under the fully coupled condition, the natural-cleat aperture and permeability exhibit a rapid initial decrease followed by a slower long-term decline, because the compensating effect of matrix shrinkage is insufficient to offset the combined closure caused by effective-stress sensitivity and coal creep.

(3) Hydraulic fracture conductivity exhibits significant time-dependent degradation. During early production, fracture compaction and proppant embedment are the primary causes of rapid conductivity loss. During the middle and late production stages, creep-induced continuous fracture closure further reduces fracture transmissibility. This indicates that hydraulic fracture conductivity does not remain constant after fracturing but progressively degrades with the stress state and time-dependent deformation. Neglecting this process in productivity prediction may overestimate the stable-production capacity of fractured wells during the middle and late stages.

(4) Simplifying different mechanisms affects cumulative gas production in distinct directions. Neglecting effective stress sensitivity or coal creep leads to overprediction of cumulative gas production, whereas neglecting matrix desorption shrinkage leads to underestimation of gas supply from the coal matrix to the cleat system. The fully coupled model simultaneously represents early-stage stress-sensitive response, middle- and late-stage creep-related decline, and desorption shrinkage compensation, and it is therefore more suitable for long-term productivity prediction of hydraulically fractured deep CBM wells.

(5) From an engineering perspective, the model can distinguish between flow-path closure caused by the rapid increase in effective stress during the early production stage and the sustained productivity loss associated with coal creep and fracture-conductivity

degradation during the middle and late production stages. For strongly stress-sensitive reservoirs, excessively rapid pressure drawdown should be avoided because it may induce excessive closure of both natural cleats and hydraulic fractures. For deep coal reservoirs with pronounced creep behavior, long-term fracture-conductivity retention should be considered a key criterion for evaluating proppant selection and hydraulic-fracturing design. The proposed model can provide a basis for comparing production strategies, but it cannot yet replace field-scale optimization tests.

(6) Although the present model was developed primarily for hydraulically fractured deep CBM reservoirs with high in situ stress, pronounced stress sensitivity, and significant coal-creep effects, its governing equations and coupling framework are not strictly limited by burial depth. By recalibrating the initial pressure and stress conditions, adsorption parameters, natural-cleat properties, creep parameters, and hydraulic-fracture parameters, the model can, in principle, be extended to shallow CBM reservoirs. However, water flow and gas–water two-phase transport may be more significant in shallow water-bearing reservoirs. Therefore, these processes should be incorporated into the model, and the extended model should be validated against corresponding field-production data.

These conclusions are primarily applicable to isothermal, gas-dominated production conditions within the equivalent-continuum framework adopted in this study, whereas the effects of gas–water two-phase flow, coal-fines migration, complex fracture networks, and spatial stress redistribution require further investigation.

Author Contributions: Conceptualization, Z.L. and L.L.; Methodology, Z.L. and L.L.; Software, Z.L. and L.L.; Validation, L.W., R.Z., and W.W.; Formal analysis, Z.L. and L.L.; Investigation, Z.L., L.L., Y.P., and R.Z.; Resources, L.L. and W.W.; Data curation, Z.L. and R.Z.; Writing—original draft preparation, Z.L.; Writing—review and editing, L.L., L.W., and W.W.; Visualization, Y.P. and R.Z.; Funding acquisition, Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge support from the Chongqing Natural Science Foundation (CSTB2024NSCQ-MSX0636), the Scientific and Technological Research Program of Chongqing Municipal Education Commission (KJQN202401515), and the Major National Science and Technology Program for Oil and Gas (2025ZD1405400).

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

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

Abbreviations

Table Sums up the nomenclature used in this paper:

Symbol	Definition	Unit
A	Coefficient matrix of the coupled discrete equation system.	—
A_m	Accumulation coefficient of the matrix system.	kg/(m ³ ·d·MPa)
A_f	Accumulation coefficient of the hydraulic-fracture system.	kg/(m ³ ·d·MPa)
A_{mm}	Matrix-system coefficient submatrix.	—
A_{mf}	Coupling submatrix representing the effect of fracture pressure on the matrix equation.	—
A_{fm}	Coupling submatrix representing the effect of matrix pressure on the fracture equation.	—
A_{ff}	Hydraulic-fracture-system coefficient submatrix.	—

a_0	Parameter associated with viscoplastic damage.	—
$a_{creep}(t)$	Fracture-aperture loss induced by coal creep at time t .	mm
b	Right-hand-side vector of the coupled discrete equation system.	—
b_0, b_1, b_2	Cleat apertures in the initial, effective-stress-compressed, and desorption-shrinkage-compensated states, respectively.	mm
b_m, b_f	Right-hand-side vectors of the matrix and hydraulic-fracture systems, respectively.	—
C_m	Storage coefficient of the matrix system.	kg/(m ³ ·MPa)
C_f	Storage coefficient of the hydraulic-fracture system.	kg/(m ³ ·MPa)
c_f	Cleat compressibility used in the initial-aperture anisotropy model.	MPa ^{−1}
D	Initial hydraulic-fracture aperture.	mm
D_1	Proppant diameter.	mm
$D_w(t)$	Real-time hydraulic-fracture aperture at time t .	mm
E	Elastic modulus of coal/instantaneous elastic modulus.	MPa
E_1	Elastic modulus of the proppant.	MPa
E_{2e}	Equivalent elastic modulus of coal in the proppant-embedment model.	MPa
E_{ve}	Elastic modulus of the viscoelastic element.	MPa
$E_{\gamma,1}(\cdot)$	Mittag-Leffler function used in the fractional viscoelastic relation.	—
$E_{1,1+\gamma}(\cdot)$	Mittag-Leffler function used in the viscoplastic damage relation.	—
$FRCD(t)$	Hydraulic-fracture conductivity at time t .	μm ² ·cm
$FRCD_0$	Initial hydraulic-fracture conductivity.	μm ² ·cm
G_p^n	Cumulative gas production at time level n .	m ³
h	Proppant embedment into the coal surface.	mm
J_w	Wellbore productivity coefficient.	kg/(m ³ ·d·MPa)
K	Proppant spacing coefficient.	—
k_{c0}	Initial natural-cleat permeability.	mD
K_f	Hydraulic-fracture permeability.	D
K_x, K_y	Effective permeabilities in the x and y directions, respectively.	D
k_{mx}, k_{my}	Natural-cleat permeabilities in the x and y directions, respectively.	mD
$k(t)$	Time-dependent hydraulic-fracture permeability.	μm ²
M_g	Gas molar mass.	g/mol
M_m	Matrix-system flow coefficient.	kg/(m·d·MPa)
M_f	Hydraulic-fracture-system flow coefficient.	kg/(m·d·MPa)
N_x, N_y	Numbers of rectangular grid blocks in the x and y directions.	—
p	Pore pressure in the natural-cleat system.	MPa
p_c	Effective closure pressure acting on the propped fracture.	MPa
p_m	Matrix pressure/current matrix pore pressure.	MPa
p_{m0}	Initial matrix or reservoir pore pressure.	MPa
P_L	Langmuir pressure.	MPa
P_f	Hydraulic-fracture pressure.	MPa
P_{wf}	Bottomhole flowing pressure.	MPa
p^{n+1}	Pressure vector at time level $n+1$.	MPa
p_m^{n+1}, p_f^{n+1}	Matrix- and hydraulic-fracture-pressure vectors at time level $n + 1$.	MPa
$p_{m,ij}^n, p_{f,ij}^n$	Matrix and hydraulic-fracture pressures in grid (i,j) at time level n .	MPa
$p_{f,well}^{n+1}$	Hydraulic-fracture pressure in the grid containing the well at time level $n + 1$.	MPa
p^l, p^{l+1}	Pressure vectors at nonlinear iterations l and $l + 1$.	MPa
q_a	Adsorbed-gas content per unit matrix volume.	kg/m ³
Q_{well}	Mass-production term from the hydraulic fracture into the wellbore.	kg/(m ³ ·d)
Q_g^{n+1}	Gas production rate at time level $n + 1$.	m ³ /d
r_e	Equivalent well drainage radius.	m
r_w	Wellbore radius.	m
$r(t)$	Time-dependent pore-throat radius of the propped fracture.	μm

r_0	Initial pore-throat radius.	μm
S_L	Langmuir volumetric strain constant.	—
t	Time/loading time/production time.	d
$T_{m,E}, T_{m,W},$ $T_{m,N}, T_{m,S}$	Matrix-system transmissibility coefficients in the east, west, north, and south directions.	$\text{kg}/(\text{m}^3 \cdot \text{d} \cdot \text{MPa})$
$T_{f,E}, T_{f,W},$ $T_{f,N}, T_{f,S}$	Hydraulic-fracture-system transmissibility coefficients in the east, west, north, and south directions.	$\text{kg}/(\text{m}^3 \cdot \text{d} \cdot \text{MPa})$
V_b	Volume of the grid block containing the well.	m^3
V_L	Langmuir volume.	m^3/kg
V_{std}	Standard gas volume/standard molar gas volume.	m^3/mol
W_f	Hydraulic-fracture width.	m
W_{mf}	Matrix-to-hydraulic-fracture mass-transfer term.	$\text{kg}/(\text{m}^3 \cdot \text{d})$
w_0	Cleat aperture under the reference state.	mm
w_{c0}	Initial natural-cleat aperture used in the calculation-parameter table.	μm
w_{inx}, w_{iny}	Natural-cleat apertures in the x and y directions, respectively.	mm
x, y	Spatial coordinates.	m
α_B	Biot coefficient.	—
α_c	Cleat compressibility.	MPa^{-1}
α_t	Cleat compressibility in direction t.	MPa^{-1}
β	Elastic deformation of the proppant.	mm
γ	Fractional creep order.	—
$\Delta D(t)$	Total hydraulic-fracture-aperture loss at time t.	mm
$\Delta \varepsilon_m$	Strain induced by matrix compression.	—
$\Delta \varepsilon_f$	Cleat-compression-induced strain.	—
$\Delta \varepsilon_L$	Matrix-shrinkage strain induced by gas desorption.	—
$\Delta \varepsilon_x, \Delta \varepsilon_y$	Total strain increments in the x and y directions.	—
$\Delta \sigma_e$	Effective-stress increment.	MPa
$\Delta x, \Delta y$	Grid spacings in the x and y directions.	m
Δt	Time step.	d
$\varepsilon(t)$	Coal creep strain at time t.	—
ε_v	Langmuir volumetric strain constant used in the equivalent-strain equation.	—
ε_{tol}	Nonlinear iteration convergence tolerance.	—
$\eta_{ve,d}$	Viscosity coefficient of the fractional viscoelastic element in the day-based time system.	$\text{MPa} \cdot \text{d}^\gamma$
$\eta_{vp,d}$	Viscosity coefficient of the viscoplastic element in the day-based time system.	$\text{MPa} \cdot \text{d}^\gamma$
λ_{mf}	Matrix-fracture interporosity flow coefficient.	$\text{kg}/(\text{m}^3 \cdot \text{d} \cdot \text{MPa})$
μ_g	Gas viscosity.	$\text{mPa} \cdot \text{s}$
ν	Poisson's ratio of coal.	—
ν_1	Poisson's ratio of the proppant.	—
ν_2	Poisson's ratio of coal in the proppant-embedment model.	—
φ_m	Matrix porosity.	—
φ_f	Hydraulic-fracture porosity.	—
φ_c	Natural-cleat-system porosity.	—
$\phi(t)$	Time-dependent porosity of the propped fracture.	—
ϕ_0	Initial porosity of the propped fracture.	—
ρ_g	Gas density.	kg/m^3
ρ_s	Coal density.	kg/m^3
σ	Axial stress applied to coal.	MPa
σ_s	Yield or critical stress.	MPa
$\sigma_{min}, \sigma_{max}$	Minimum and maximum horizontal principal stresses.	MPa
$\Sigma T_m, \Sigma T_f$	Sums of transmissibility coefficients in all directions for the matrix and hydraulic-fracture systems.	$\text{kg}/(\text{m}^3 \cdot \text{d} \cdot \text{MPa})$
$\tau(t)$	Time-dependent pore tortuosity of the propped fracture.	—
τ_0	Initial pore tortuosity.	—

ω	Viscoplastic creep correction coefficient.	—
CBM	Coalbed methane	—

References

- Wu, Y.G.; Men, X.Y.; Lou, Y. New progress and prospect of coalbed methane exploration and development in China during the 14th Five-Year Plan period. *China Pet. Explor.* **2024**, *29*, 1–13.
- Wang, J.; Zhao, C.; Cao, Y.; Zhan, L.; Liu, Z.X.; Lin, A.; Hu, X. Prospects and exploration directions of deep coalbed methane resources in China. *Energy Geosci.* **2026**, *7*, 100586. [\[CrossRef\]](#)
- Xu, F.Y.; Hou, W.; Xiong, X.Y.; Xu, B.R.; Wu, P.; Wang, H.Y.; Feng, K.; Yun, J.; Li, S.G.; Zhang, L.; et al. The status and development strategy of coalbed methane industry in China. *Pet. Explor. Dev.* **2023**, *50*, 765–783. [\[CrossRef\]](#)
- Guo, X.S.; Zhao, P.R.; Shen, B.J.; Liu, J.; Luo, B.; Zhao, S.; Zhang, J.; He, J.; Fu, W.; Wei, H.; et al. Geological features and exploration practices of deep coalbed methane in China. *Oil Gas Geol.* **2024**, *45*, 1511–1523. [\[CrossRef\]](#)
- Li, G.X.; Zhang, S.C.; He, H.Q.; Zhao, Z.; Niu, X.; Xiong, X.; Zhao, Q.; Guo, X.; Hou, Y.; Zhang, L.; et al. Coal-rock gas: Concept, connotation and classification criteria. *Pet. Explor. Dev.* **2024**, *51*, 783–795. [\[CrossRef\]](#)
- Xiong, X.Y.; Yan, X.; Xu, F.Y.; Li, S.; Nie, S.; Feng, Y.; Liu, Y.; Chen, M.; Sun, J.; Zhou, K.; et al. Analysis of multi-factor coupling control mechanism, desorption law and development effect of deep coalbed methane. *Acta Pet. Sin.* **2023**, *44*, 1812–1826, 1853. [\[CrossRef\]](#)
- Zhou, L.H.; He, X.X.; Xiong, X.Y.; Li, S.; Ding, R.; Yan, D.; Fu, H.; Li, Y. Scientific significance and energy strategic impact of deep coalbed methane breakthrough. *China Pet. Explor.* **2025**, *30*, 18–26.
- Zhang, S.A.; Liu, X.J.; Wen, Q.Z.; Zhang, X.; Zhao, W.; Yuan, Y. Development situation and trend of stimulation and reforming technology of coalbed methane. *Acta Pet. Sin.* **2021**, *42*, 105–118. [\[CrossRef\]](#)
- An, Q.; Yang, F.; Yang, R.Y.; Huang, Z.; Li, G.; Gong, Y.; Yu, W. Practice and understanding of deep coalbed methane massive hydraulic fracturing in Shenfu Block, Ordos Basin. *J. China Coal Soc.* **2024**, *49*, 2376–2393. [\[CrossRef\]](#)
- Yang, F.; Li, B.; Wang, K.J.; Wen, H.; Yang, R.Y.; Huang, Z.W. Extreme massive hydraulic fracturing in deep coalbed methane horizontal wells: A case study of the Linxing Block, eastern Ordos Basin, NW China. *Pet. Explor. Dev.* **2024**, *51*, 389–398. [\[CrossRef\]](#)
- Xu, Q.; Wang, D.; He, Z.; Li, C.; Guo, H.; Yang, H.; Zhang, Z.; Bai, X.; Li, Y.; Ren, S.; et al. Dynamic monitoring and effectiveness evaluation of mid-deep coalbed methane hydraulic fracturing via the wide-field electromagnetic method. *Energy Geosci.* **2026**, *7*, 100609. [\[CrossRef\]](#)
- Ma, T.; Liu, J.; Fu, J.; Wu, B. Drilling and completion technologies of coalbed methane exploitation: An overview. *Int. J. Coal Sci. Technol.* **2022**, *9*, 68. [\[CrossRef\]](#)
- Meng, Y.; Li, Z.; Lai, F. Evaluating the filtration property of fracturing fluid and fracture conductivity of coalbed methane wells considering the stress-sensitivity effects. *J. Nat. Gas Sci. Eng.* **2020**, *80*, 103379. [\[CrossRef\]](#)
- Zhang, X.R.; Lai, F.P.; Meng, Y.; Xu, X.T.; Li, H.; Liu, K. Dynamic production characteristics of deep coalbed methane: A case study of Daning-Jixian Block. *Energy Fuels* **2024**, *38*, 8700–8711. [\[CrossRef\]](#)
- Nie, Z.H.; Chao, H.Y.; Liu, Y.; Huang, H.; Yu, L. Development strategy and production characteristics of deep coalbed methane in the east Ordos Basin: Taking Daning-Jixian block for example. *J. China Coal Soc.* **2018**, *43*, 1737–1746. [\[CrossRef\]](#)
- Lu, Y.; Zhao, G.; Ge, Z.; Jia, Y.; Tang, J.; Gong, T.; Huang, S.; Li, Z.; Fu, W.; Mi, J. Challenges and development direction of deep fragmented soft coalbed methane in China. *Earth Energy Sci.* **2025**, *1*, 38–64. [\[CrossRef\]](#)
- Ouyang, Z.; Wang, H.; Sun, B.; Liu, Y.; Fu, X.; Dou, W.; Du, L.; Zhang, B.; Luo, B.; Yang, M.; et al. Quantitative prediction of deep coalbed methane content in Daning-Jixian Block, Ordos Basin, China. *Processes* **2023**, *11*, 3093. [\[CrossRef\]](#)
- Dong, Y.; Zhang, X.; Zhang, J.; Wu, K.; Liu, S. A novel surrogate model with deep learning for predicting spacial-temporal pressure in coalbed methane reservoirs. *Nat. Gas Ind. B* **2025**, *12*, 219–233. [\[CrossRef\]](#)
- Moore, T.A. Coalbed methane: A review. *Int. J. Coal Geol.* **2012**, *101*, 36–81. [\[CrossRef\]](#)
- Clarkson, C.R.; Bustin, R.M. Coalbed methane: Current field-based evaluation methods. *SPE Reserv. Eval. Eng.* **2011**, *14*, 60–75. [\[CrossRef\]](#)
- Gray, I. Reservoir engineering in coal seams: Part 1—The physical process of gas storage and movement in coal seams. *SPE Reserv. Eng.* **1987**, *2*, 28–34. [\[CrossRef\]](#)
- Seidle, J. *Fundamentals of Coalbed Methane Reservoir Engineering*; PennWell Books: Tulsa, OK, USA, 2011.
- Langmuir, I. The adsorption of gases on plane surfaces of glass, mica and platinum. *J. Am. Chem. Soc.* **1918**, *40*, 1361–1403. [\[CrossRef\]](#)
- Warren, J.E.; Root, P.J. The behavior of naturally fractured reservoirs. *SPE J.* **1963**, *3*, 245–255. [\[CrossRef\]](#)
- Barenblatt, G.I.; Zheltov, I.P.; Kochina, I.N. Basic concepts in the theory of seepage of homogeneous liquids in fissured rocks. *J. Appl. Math. Mech.* **1960**, *24*, 1286–1303. [\[CrossRef\]](#)
- Palmer, I.; Mansoori, J. How permeability depends on stress and pore pressure in coalbeds: A new model. *SPE Reserv. Eval. Eng.* **1998**, *1*, 539–544. [\[CrossRef\]](#)

27. Shi, J.Q.; Durucan, S. Drawdown induced changes in permeability of coalbeds: A new interpretation of the reservoir response to primary recovery. *Transp. Porous Media* **2004**, *56*, 1–16. [[CrossRef](#)]
28. Cui, X.; Bustin, R.M. Volumetric strain associated with methane desorption and its impact on coalbed gas production from deep coal seams. *AAPG Bull.* **2005**, *89*, 1181–1202. [[CrossRef](#)]
29. Cui, X.; Bustin, R.M.; Chikatamarla, L. Adsorption-induced coal swelling and stress: Implications for methane production and acid gas sequestration into coal seams. *J. Geophys. Res. Solid Earth* **2007**, *112*, B10202. [[CrossRef](#)]
30. Liu, J.; Chen, Z.; Elsworth, D.; Miao, X.; Mao, X. Evolution of coal permeability from stress-controlled to displacement-controlled swelling conditions. *Fuel* **2011**, *90*, 2987–2997. [[CrossRef](#)]
31. Chen, Z.; Pan, Z.; Liu, J.; Connell, L.D.; Elsworth, D. Effect of the effective stress coefficient and sorption-induced strain on the evolution of coal permeability: Experimental observations. *Int. J. Greenh. Gas Control* **2011**, *5*, 1284–1293. [[CrossRef](#)]
32. Pan, Z.; Connell, L.D. Modelling permeability for coal reservoirs: A review of analytical models and testing data. *Int. J. Coal Geol.* **2012**, *92*, 1–44. [[CrossRef](#)]
33. Gao, Q.; Liu, J.; Huang, Y.; Li, W.; Shi, R.; Leong, Y.K.; Elsworth, D. A critical review of coal permeability models. *Fuel* **2022**, *326*, 125124. [[CrossRef](#)]
34. Zhang, P.; Meng, Y.; Liu, C.; Guo, Y.; Yan, X.; Cai, L.; Cheng, Z. In-situ stress of coal reservoirs in the Zhengzhuang area of the southern Qinshui Basin and its effects on coalbed methane development. *Energy Geosci.* **2023**, *4*, 100144. [[CrossRef](#)]
35. Zhang, L.; Zhou, H.W.; Wang, X.Y.; Zhao, J.W.; Ju, Y.; Deng, T.F. On permeability evolution of coal induced by temperature, creep, and matrix–fracture interaction. *Energy Fuels* **2022**, *36*, 1470–1481. [[CrossRef](#)]
36. Zhou, H.W.; Zhang, L.; Wang, X.Y.; Rong, T.L.; Wang, L.J. Effects of matrix-fracture interaction and creep deformation on permeability evolution of deep coal. *Int. J. Rock Mech. Min. Sci.* **2020**, *127*, 104236. [[CrossRef](#)]
37. Cai, T.; Xia, J.; Feng, Z.; Su, X.; Jiang, Y. Impact of coal creep on permeability evolution under different temperatures and stresses. *Sci. Rep.* **2025**, *15*, 13335. [[CrossRef](#)] [[PubMed](#)]
38. Li, H.; Huang, B.; Zheng, W.; Zhao, X.; Tannant, D. Effect of proppant distribution in hydraulic fractures on coalbed methane extraction. *Results Eng.* **2023**, *20*, 101550. [[CrossRef](#)]
39. Chen, Q.; Huang, Z.; Huang, H.; Chen, Q.; Ling, X.; Xin, F.; Kong, X. An experimental study on the impact of the particle size and proportion of composite proppant on the conductivity of propped fractures in coalbed methane reservoirs following pulverized coal fines infiltration. *Processes* **2023**, *11*, 2205. [[CrossRef](#)]
40. Xu, J.; Zhao, Y.; Wang, M.; Dong, D.; Liu, Z.; Yang, J.; Tian, F. Permeability of large-scale fractures with ununiform proppant distributions in coalbed methane development. *Energy Sci. Eng.* **2024**, *12*, 3157–3170. [[CrossRef](#)]
41. Huang, F.; Liu, S.; Wang, G.; Cheng, W. Effects of proppant wettability and size on transport and retention of coal fines in proppant packs during the dewatering stage. *Energy Fuels* **2021**, *35*, 11510–11520. [[CrossRef](#)]
42. Li, X.; Li, X.; Xie, H.; Feng, C.; Cai, J.; He, Y. Enhanced coalbed methane well production prediction framework utilizing the CNN-BL-MHA approach. *Sci. Rep.* **2024**, *14*, 15303. [[CrossRef](#)] [[PubMed](#)]
43. Song, G.; Geiger, S.; Voskov, D.; Abels, H.A.; Vardon, P.J. Scenario-based data assimilation framework to improve production estimates for geologically complex geothermal reservoirs. *Geoenergy Sci. Eng.* **2026**, *263*, 214490. [[CrossRef](#)]
44. Guo, J.; Zhang, T.; Wu, X.; Zhao, Z.; Li, Z.; Zeng, J. Production analysis and permeability evolution of fractured horizontal wells of coalbed methane reservoir. *J. China Coal Soc.* **2025**, *50*, 516–531. [[CrossRef](#)]
45. Li, K.; Gao, Y.; Lyu, Y.; Wang, M. New mathematical models for calculating proppant embedment and fracture conductivity. *SPE J.* **2015**, *20*, 496–508. [[CrossRef](#)]
46. Huang, P.; Zhang, J.; Damascene, N.J.; Dong, C.; Wang, Z. A fractional order viscoelastic-plastic creep model for coal sample considering initial damage accumulation. *Alex. Eng. J.* **2021**, *60*, 3921–3930. [[CrossRef](#)]
47. Yang, Y.; Huang, G.; Zhang, Y.; Yuan, L. An improved Burgers creep model of coal based on fractional-order. *Front. Earth Sci.* **2023**, *11*, 1277147. [[CrossRef](#)]
48. Zhou, H.W.; Wang, C.P.; Han, B.B.; Duan, Z.Q. A creep constitutive model for salt rock based on fractional derivatives. *Int. J. Rock Mech. Min. Sci.* **2011**, *48*, 116–121. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.