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Comparative analysis of coal permeability models accounting for the stress-strain state of the rock mass

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Abstract

Coal seam permeability is a key parameter controlling degassing efficiency, the intensity of methane emission, and the safety of mining operations. As permeability decreases with depth and is critically dependent on the stress-strain state, its reliable prediction requires models capable of adequately describing the interaction between sorption-induced deformation, poroelastic effects, and fracture aperture closure mechanisms. Owing to the absence of a unified approach for permeability assessment under complex stress-strain conditions, the objective of this study was to systematize and compare the principal empirical and analytical models describing this dependence. To this end, an analytical review of models accounting for sorption-elastic deformation, porosity evolution, effective stress effects, thermoelastic behavior, and cleat system parameters was conducted. Model comparison was performed through numerical simulations of permeability variation over an effective stress range of 0–50 MPa and at depths of up to 1500 m. The models incorporated parameters such as the Biot coefficient, deformation modulus, sorption compressibility, initial permeability, and geometric characteristics of fractures. The results of the parametric calculations demonstrate that, despite conceptual differences, all models exhibit a common trend of nonlinear permeability reduction with increasing effective stress. This behavior reflects the physical processes of pore space compression and fracture aperture reduction. It was established that the most intensive permeability decline occurs within the effective stress range of 5–15 MPa, corresponding to active cleat closure, whereas at depths exceeding 1000 m permeability changes tend to stabilize due to exhaustion of the deformation potential of the fracture structure. Overall, the analysis revealed differing model sensitivities to geomechanical parameters, with the influence of sorption-induced deformation being comparable to that of poroelastic effects. Model selection is shown to be condition-dependent: the Seidle (1992) model is most suitable for accounting for sorption-induced deformation, the Palmer & Mansoori (1998) model for deep coal seams with variable porosity, and the Karkashadze & Hautiev (2015) model for describing elastic deformation effects. The derived relationships can be applied to assess the natural permeability of coal seams in undisturbed rock masses.

Keywords

coal seam, permeability, stress-strain state, sorption-induced deformation, effective stress, permeability models, degassing

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СВОЙСТВА ГОРНЫХ ПОРОД. ГЕОМЕХАНИКА И ГЕОФИЗИКА

Научная статья

Сравнительный анализ моделей зависимости фильтрационных свойств угля от напряженно-деформированного состояния массива

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Аннотация

Проницаемость угольных пластов – ключевой параметр, определяющий эффективность дегазации, интенсивность метановыделения и безопасность горных работ. Поскольку проницаемость снижается с глубиной и критически зависит от напряжённо-деформированного состояния, для её прогноза необходимы модели, способные адекватно описывать взаимодействие сорбционных деформаций, пороупругих эффектов и механизма закрытия трещин. В связи с отсутствием унифицированного подхода к оценке проницаемости в условиях сложного НДС целью данной работы стали систематизация и сопоставление основных эмпирических и аналитических моделей этой зависимости. Для этого был выполнен аналитический обзор моделей, учитывающих сорбционно-упругие деформации, изменение пористости, влияние эффективного давления, термоупругие эффекты и параметры кливажа. Сопоставление моделей проведено путём численного моделирования изменения проницаемости в диапазоне эффективных напряжений 0–50 МПа и на глубинах до 1500 м. В модели были включены такие параметры, как коэффициент Био, модуль деформации, сорбционная сжимаемость, начальная проницаемость и геометрические характеристики трещин. Результаты вариационных расчётов показали, что несмотря на различия все модели демонстрируют общую тенденцию к нелинейному уменьшению проницаемости с ростом эффективного напряжения. Это отражает физические процессы сжатия порового пространства и закрытия трещин. Установлено, что наиболее интенсивное снижение проницаемости происходит в интервале 5–15 МПа, соответствующем активному закрытию трещин кливажа, тогда как на глубинах свыше 1000 м изменение проницаемости стабилизируется из-за исчерпания потенциала деформации трещинной структуры. Таким образом, анализ выявил различную чувствительность моделей к геомеханическим параметрам, причём влияние сорбционных деформаций оказалось сопоставимым с пороупругими эффектами. Выбор конкретной модели зависит от условий: для учёта сорбционных деформаций оптимальна модель Seidle (1992), для глубоких пластов с изменчивой пористостью – модель Palmer (1998), а для описания упругих деформаций – модель Каркашадзе и Хаутиева (2015). Полученные зависимости применимы для оценки природной проницаемости угольных пластов в ненарушенном массиве.

Ключевые слова

угольный пласт, проницаемость, напряжённо-деформированное состояние, сорбционные деформации, эффективное давление, модели проницаемости, дегазация

Финансирование

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Для цитирования

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Introduction

Accurate prediction of coal seam permeability directly affects the assessment of methane abundance in mine workings and the efficiency of pre-drainage operations. Unsubstantiated estimates of these parameters may, on the one hand, lead to reduced longwall production rates (and, consequently, lower coal output) and, on the other hand, to the manifestation of hazardous gas-dynamic processes in underground mines, posing risks to miner safety and the stability of mine workings [1].

Coal is formed in sedimentary basins where the accumulation of organic matter occurs under a wide range of tectonic settings, from stable platform regions to actively deforming fold-and-thrust belts [2]. Tectonic movements cause redistribution of sedimentary material and changes in pressure and temperature conditions. As a result, coal seams acquire complex structural features, including folding, faulting, and zones of tectonic mélange [2]. These processes are accompanied by the development of tectonic fracture systems, which may either enhance or reduce rock mass permeability depending on their orientation and scale [3, 4]. Fault zones are typically associated with increased fracturing and alterations in the filtration-storage properties of coal. In addition, faults induce stress redistribution within the rock mass, creating specific geomechanical conditions that significantly influence the permeability of the coal-bearing strata [5]. The surrounding host rocks also affect the mechanical behavior of the coal-bearing rock mass, albeit more locally. For example, strong and brittle rocks such as sandstones and limestones may form zones of elevated stress concentration, whereas weaker and more ductile layers (e.g., clay-rich rocks) facilitate stress redistribution [4, 6].

Coal permeability is primarily governed by its fracture density and porosity. A spatially variable stress field involving compression, tension, and shear promotes the formation of faults and microfractures, thereby increasing the volume of void space [4]. However, the influence of the stress-strain state of the coal-bearing rock mass on methane emission from coal seams is not unambiguous. An increase in stress may lead to a reduction in fracture permeability due to cleat closure, whereas stress relief is commonly associated with an increase in fracture aperture and enhanced permeability [5]. At the same time, structural changes in the mineral skeleton of the coal-bearing rock mass may intensify methane desorption from coal micropores [3, 4].

The aim of this study is to perform a comparative analysis of existing empirical and analytical models describing the dependence of coal permeability on the stress-strain state. To achieve this aim, the following objectives were addressed: (1) analysis of the mathematical framework of coal permeability models accounting for the stress-strain state of the coal-bearing rock mass; (2) a systematic analytical review of existing models of this type; (3) numerical simulation of permeability variations over an effective stress range of 0–50 MPa and depths of 0–1500 m to compare model behavior; (4) assessment of model sensitivity to their intrinsic hyperparameters and determination of applicability limits; and (5) development of practical recommendations for selecting permeability models for filtration modeling of coal-bearing rock masses.

Data and methods

The coal matrix exhibits a unique ability to swell during gas adsorption and to contract during desorption. During methane desorption, gas diffuses through the coal matrix into the natural fracture network of coal, commonly referred to as the coal cleat system [3]. Within the matrix of hard coal, fractures of endogenous and exogenous cleat are distinguished, while fracture transmissivity depends on their density, aperture, orientation, persistence, and other parameters [3, 7]. Endogenous cleat forms during coalification and is controlled by internal processes associated with changes in coal composition during its genesis [8]. It is typically represented by two mutually orthogonal cleat sets – the face cleat and the butt cleat [9] (Fig. 1, *a*).

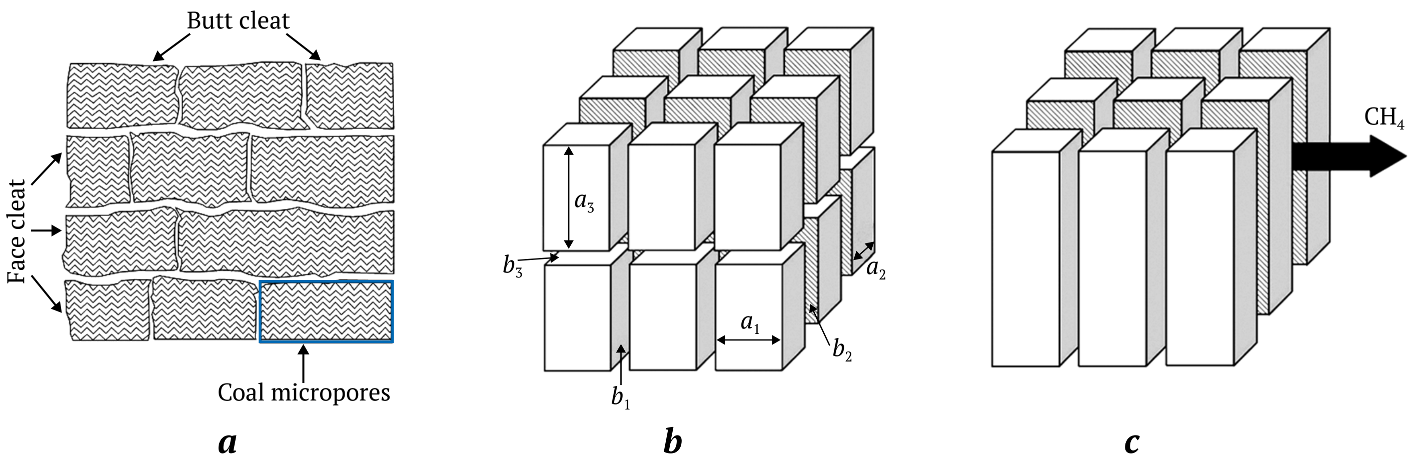

Fig. 1. Coal matrix model [9] and cellular (cubic) permeability model of the coal matrix [10, 14]:
a – coal matrix model; *b* – anisotropic model: a_1, a_2, a_3 – the edge lengths of the cubic cells (intact coal matrix blocks), b_1, b_2, b_3 – the effective fracture apertures associated with the cleat systems; *c* – isotropic model

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In general, absolute permeability can be derived from the Navier–Stokes equations for viscous fluid flow. In practice, however, due to limited availability of detailed information, Darcy's law is commonly applied [10]. It is generally assumed that Darcy flow in coal is governed by flow within the cleat system, while the contribution of flow through matrix pores is negligible. Fracture permeability typically ranges from 0.001 to 100 mD, whereas the permeability of coal microblocks is on the order of microdarcies or nanodarcies [9, 11, 12]. Consequently, coal seam permeability is primarily controlled by the cleat system [8]. The presence of cleat results in pronounced permeability anisotropy. Experimental studies indicate that the ratio of permeability along the face cleat to that along the butt cleat varies from 2:1 to 17:1 [11, 13]. In this case, the components of the absolute permeability tensor of coal can be described using a model of a homogeneous impermeable medium intersected by two mutually orthogonal fracture systems [10]:

$$q = -\frac{b_i^3}{12a_i}\frac{1}{\mu}\Delta P, \tag{1}$$

where b_i is the fracture aperture, m, and a_i is the edge length of the cubic cell, m.

Equation (1) is applied to a single cleat system i contributing to the overall flow. Considering the roughness of the fracture-pore space, the parameter b_i is referred to as the effective hydraulic aperture and is typically smaller than the corresponding cell edge a_i. The absolute permeability of the cleat system is determined according to Scheidegger [15]:

$$k_{abs} = -\frac{b_i^3}{12a_i}, \tag{2}$$

or, in ratio form,

$$\frac{k_i}{k_{i_0}} = \left(\frac{b_i}{b_{i_0}}\right)^3, \tag{3}$$

where b_i is the effective fracture aperture, m; k_i is the effective phase absolute permeability of the medium, m^2; b_{i_0} is the initial fracture aperture, m; and k_{i_0} is the initial absolute permeability, m^2.

The stress-strain state of a mined coal seam is primarily controlled by the lateral stress coefficient, mining depth, physico-mechanical properties of the rocks, structural heterogeneities, and sorption-kinetic properties of the rock mass.

Vertical stresses acting within the rock mass give rise to lateral confinement stresses. Several approaches exist for estimating lateral stress [16]: according to A. Heim, lateral stress in the rock mass equals lithostatic pressure, analogous to hydrostatic conditions; according to A.N. Dinnik, lateral stress is defined by the lateral stress coefficient characterizing elastic horizontal response to the weight of overlying strata; according to N. Hast, lateral stress includes, in addition to the Dinnik component, tectonic stresses induced by the regional tectonic stress field. In some parts of the Earth's crust, horizontal tectonic stresses may even exceed lithostatic values, as confirmed by instrumental measurements [16, 17].

Mechanical or thermal loading of coal induces a range of sorption-related effects that result in expansion or contraction of the rock material [6, 9]. As a consequence, an additional and distinct component of the stress-strain state – sorption-induced stress – develops within the coal mass. The magnitude of sorption-induced deformation (and, consequently, stress) depends on gas saturation, gas pressure, temperature, as well as structural and textural characteristics of coal. Coal with high microporosity exhibits greater gas adsorption capacity, which enhances swelling effects. The relationship between stress and sorption-induced deformation in coal can be described using a generalized elasticity law modified to include sorption effects analogous to thermal expansion [18–20]. For a linear elastic medium, this relationship can be expressed as:

$$\sigma_{ij} = C_{ijkl} \times \varepsilon_{ij} + K_s \varepsilon_s \delta_{ij}, \tag{4}$$

where K_s is the sorption modulus characterizing the influence of gas sorption-induced deformation; ε_s is the sorption strain caused by gas adsorption or desorption; δ_{ij} is the Kronecker delta ($\delta_{ij} = 1$ if $i = j$, and $\delta_{ij} = 0$ if $i \neq j$).

In coal permeability models, the dependence of permeability on the stress state is commonly expressed in terms of effective stress. The effective stress tensor is defined as:

$$\sigma_{eff,\,ij} = \sigma_{ij} - \omega P_f \delta_{ij}, \tag{5}$$

where σ_{ij} are the components of the total stress tensor; ω is the Biot coefficient (dimensionless); P_f is the pore fluid pressure, Pa; and δ_{ij} is the Kronecker delta ($\delta_{ij} = 1$ if $i = j$, and $\delta_{ij} = 0$ if $i \neq j$).

Thus, the generalized stress model for a coal-bearing rock mass comprises several principal components: lithostatic stress σ_g, lateral confinement stress σ_r, tectonic stress σ_{tect}, thermal stress σ_{th}, and sorption-induced stress σ_s.

Dependence of coal permeability on the stress-strain state and practical implications

In empirical models describing the dependence of permeability on the stress-strain state, the mean stress within the rock mass is commonly used. Factors related to sorption-induced deformation and pore pressure are typically incorporated at the macroscale.

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Below, the principal empirical models are reviewed; for consistency and comparability, they are recast into a unified analytical form.

One of the earliest models of this type was proposed in [21] as an empirical relationship between permeability and mean stress, based on laboratory data obtained from coal samples collected from the Pittsburgh and Virginia coalfields (USA). The distinguishing feature of this model is that it accounts solely for stress-induced changes in fracture aperture resulting from mechanical loading:

$$k_\sigma = k_0\left[e^{(-3\cdot 10^{-3}\cdot\sigma\cdot k_0^{-0,1})} + 2\cdot 10^{-4}\cdot\sigma^{\frac{1}{3}}\cdot k_0^{\frac{1}{3}}\right], \quad (6)$$

where k_σ is stress-dependent permeability, mD; k_0 is permeability at zero stress, mD; and σ is the mean normal stress, Pa.

In [22], an empirical relationship between permeability and effective stress was proposed for coals from the Leigh Creek Basin (Australia):

$$k_\sigma = 1.013\cdot 10^{-0.031\cdot\sigma_{eff}}. \quad (7)$$

This relationship was subsequently generalized into an exponential form that serves as a basis for more advanced permeability models:

$$k_\sigma = k_0\exp(-C_p\cdot\sigma_{eff}), \quad (8)$$

where k_σ is the current coal seam permeability under effective stress, m^2; k_0 is the natural (initial) permeability of the coal seam in the absence of applied stresses, m^2; C_p is the permeability sensitivity coefficient with respect to effective stress, Pa^{-1} (typically ranging from 0.01 to 0.1 Pa^{-1} depending on fracture structure); and σ_{eff} is the effective stress, Pa.

Model [23] accounts for the influence of sorption-induced deformation on fracture aperture variations. In contrast to the previous models, it employs changes in stress and strain rather than their absolute values:

$$k_\sigma = k_0\exp(-3C_p\Delta\sigma_{eff}\cdot S\Delta\varepsilon_s), \quad (9)$$

where $\Delta\sigma_{eff}$ is the change in effective stress, Pa; $\Delta\varepsilon_s$ is the change in sorption strain caused by variations in the amount of adsorbed gas; and S is the permeability sensitivity coefficient with respect to sorption-induced deformation. The parameter S typically varies in the range 0.1–1.0 (other parameters are identical to those in model [22]).

Model [24] also incorporates the effect of sorption-induced deformation on fracture behavior; however, unlike model [23], it uses absolute values of stress and strain:

$$k_\sigma = k_0\exp(-C_p\cdot\sigma_{eff} + (1-\gamma)\Delta\varepsilon_s), \quad (10)$$

where γ is the sorption deformation compensation coefficient, varying between 0 and 1 (other parameters are consistent with models [22, 23]).

Models [25, 26], which further develop model [23], explicitly include coal porosity and sorption-induced deformation within a Darcy-flow framework. These models are based on changes in deformation and stress within the rock mass:

$$k_\sigma = k_0\left(\frac{\varphi}{\varphi_0}\right)^n\exp(-3C_p\Delta\sigma_{eff} + S\Delta\varepsilon_s), \quad (11)$$

where φ is the current coal seam porosity under effective stress (fraction); φ_0 is the initial porosity in the absence of applied stresses (fraction); and n is an empirical exponent typically ranging from 1 to 3 (other parameters correspond to those in model [23]).

Model [27] proposes an alternative formulation to model [22] by explicitly accounting for the deformation properties of the rock. Its distinguishing feature is the use of mean stress and Young's modulus in explicit form:

$$k_\sigma = k_0\cdot 10^{-0.31\cdot 10^{-6}\cdot(\sigma_0-\sigma)\cdot\frac{E}{E_0}}. \quad (12)$$

In a generalized form, the model can be expressed as:

$$k_\sigma = k_0\cdot 10^{-C_p\cdot 10^{-6}\cdot(\sigma_0-\sigma)\cdot\frac{E}{E_0}}, \quad (13)$$

where σ is the current mean normal stress, Pa; σ_0 is the initial mean normal stress, Pa; E is the current Young's modulus of the rock under mean stress, Pa; E_0 is the initial Young's modulus in the absence of applied stresses, Pa; C_p is the permeability sensitivity coefficient with respect to effective stress, Pa^{-1}. The coefficient C_p typically ranges from 0.01 to 0.1 Pa^{-1}, depending on fracture structure.

The mean normal stress is defined as:

$$\sigma = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3}. \quad (14)$$

Using a lithostatic stress model combined with lateral stress estimated following the Dinnik approach enables evaluation of depth-dependent variations in mean and effective stress:

$$\sigma_z = \rho\cdot g\cdot H,$$
$$\sigma_{x,y} = \sigma_z\cdot\frac{\mu}{1-\mu}, \quad (15)$$

Fig. 2, *a* presents the calculated permeability-effective stress relationships for five models: Gray (1987) [22], Seidle (1992) [23], Palmer & Mansoori (1998) [24], Shi & Durucan (2004) [25, 26], and Karkashadze & Hautiev (2015) [27]. Using the same data, permeability-depth relationships can be derived (Fig. 2, *b*). All models exhibit a common trend of nonlinear permeability reduction with increasing effective stress, reflecting the physical processes of pore space compression and fracture closure within coal seams under external loading.

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At the same time, each model incorporates different physical and geomechanical mechanisms, resulting in distinct curve shapes.

The results of the comparative analysis demonstrate significant practical relevance for the coal mining industry. The derived relationships (Fig. 2) can be applied in the development of three-dimensional geomechanical and filtration models of coal-bearing rock masses used to assess degassing efficiency, gas-dynamic behavior of coal seams, and methane abundance in mine workings. Appropriate selection of a permeability model reduces uncertainty in the design of degassing systems, optimizes the placement and parameters of drainage boreholes, decreases the number of ineffective drilling operations, and mitigates the risk of gas-dynamic hazards. The expected economic benefits are associated with increased longwall productivity and reduced costs of degassing operations.

Sensitivity analysis of permeability-stress relationships and discussion of results

Analytical permeability models require data on the microstructural characteristics of coal, reservoir pressure parameters, fluid distribution within the coal-bearing rock mass, and the stress state governing coal deformation. However, at the scale of coal seam permeability modeling, acquiring such detailed information is practically infeasible. In this context, empirical relationships are more appropriate, as they enable coal seam permeability to be described through stress-state parameters. This simplifies the modeling procedure and makes it feasible in practice; however, reliable application of such relationships requires an assessment of model sensitivity and applicability limits.

Based on the analysis performed, the following criteria are proposed for model selection:

– the dominant deformation mechanisms in the seam (sorption-induced, thermoelastic, poroelastic, and structural porosity changes);

– coal seam depth and the expected range of effective stress, which control the shape of the permeability reduction curve;

– microstructural characteristics of the reservoir (presence of a well-developed cleat system and porosity sensitivity to pressure);

– approximate gas saturation and the intensity of sorption processes;

– contrasts in elastic properties among different coal ranks.

To evaluate model sensitivity to stress terms in their governing equations, a set of parametric (variation) calculations was performed by varying the stress values. Model sensitivity is defined as the derivative of permeability with respect to effective stress [28]. It characterizes the rate at which permeability changes as stress increases and is expressed as the following gradient:

$$Sens = \frac{\partial k}{\partial \sigma_{eff}}. \qquad (16)$$

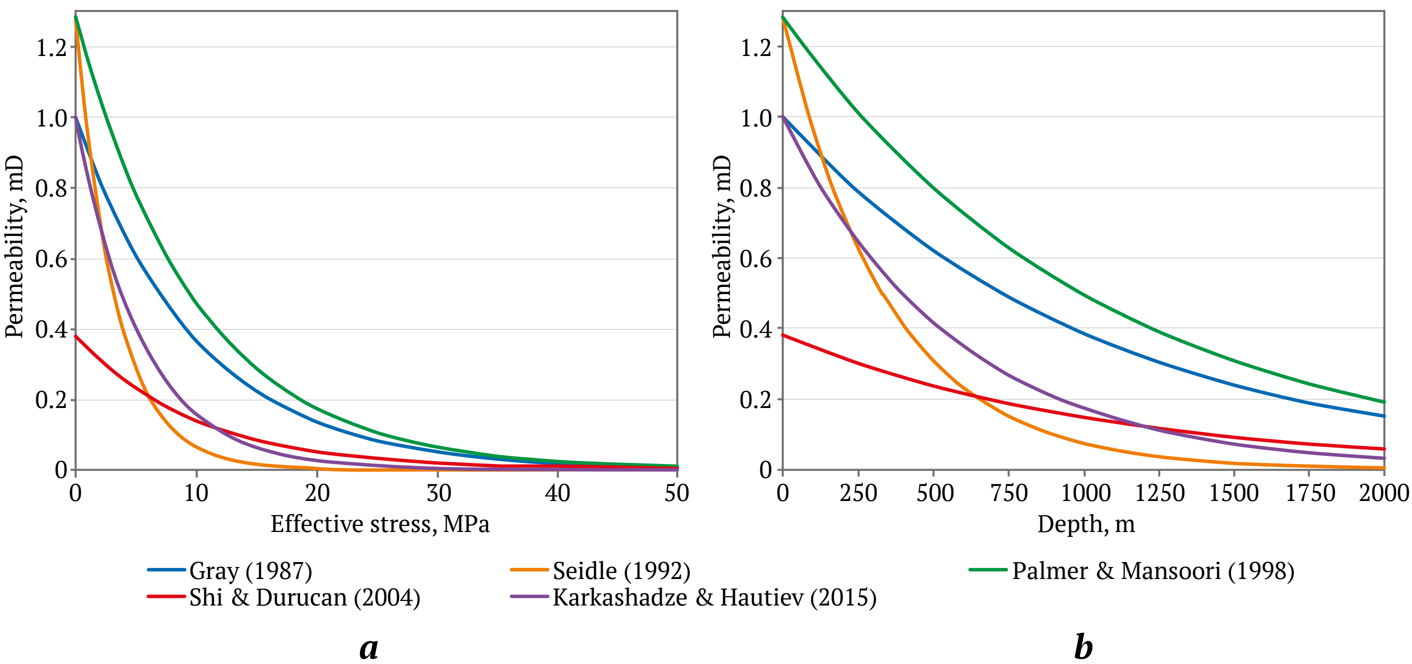

Fig. 2. Permeability as a function of effective stress (*a*) and coal seam depth (*b*) for different model (calculations performed using the following constants: $C_p = 0.1$ Pa^{-1}; $k_0 = 1 \cdot 10^{-12}$ m^2 (1 mD); $\Delta\varepsilon_s = 0.5$; $S = 0.5$; $\gamma = 0.5$; $\varphi_0 = 0.03$; $\varphi = 0.02$; $E_0 = 5 \cdot 10^9$; $E = 3 \cdot 10^9$)

Sensitivity reflects the rate of permeability change in response to stress variations. High (absolute) sensitivity implies a more rapid reduction in permeability with increasing stress, whereas low sensitivity indicates a more gradual change. To determine applicability limits, the sensitivity analysis was carried out for the stress-dependent terms in each model using the parametric calculations described above. The calculation parameters are summarized in Table 1. The full set of results for all models is available as a dataset in the Zenodo repository: https://zenodo.org/records/18441537.

Table 1

Model parameters

No.	Model parameters	Parameter ranges
1	Variable parameters	C_p = 0.01; 0.05; 0.1 Pa^{-1} σ_{eff} = 0–50 MPa $\Delta\sigma_{eff}$ = 0–50 MPa $\Delta\varepsilon_s$ = 0.005; 0.05; 0.5 S = 0.1; 0.5; 1.0 $E = 3\cdot10^9; 4\cdot10^9; 5\cdot10^9$ Pa γ = 0.1; 0.5; 1.0 φ = 0.025; 0.035; 0.045 n = 1, 2, 3
2	Constants	$k_0 = 1\cdot10^{-12}$ m^2 (1 mD) C_p = 0.1 $\Delta\varepsilon_s$ = 0.5 Σ = 0.5 γ = 0.5 φ_0 = 0.03 $E_0 = 5\cdot10^9$ σ_0 = 0 MPa

The Gray (1987) model [22] describes permeability as a simple exponential function of effective stress (Fig. 3). This is a baseline model that accounts solely for compression of the pore space as stress increases. Permeability decreases rapidly at low stress levels and gradually stabilizes at higher stresses. The model exhibits moderate sensitivity and is commonly used as a reference for comparison with more advanced formulations. Owing to the absence of additional parameters, it is less suitable for site-specific conditions where sorption-related, thermal, or mechanical deformation effects must be considered.

The Seidle (1992) model [23] predicts a more pronounced reduction in permeability at low effective stress values, which is attributed to the influence of sorption-induced deformation. The model introduces an additional parameter, ε_s, representing sorption strain caused by gas adsorption or desorption (methane or carbon dioxide), as well as the parameter S, which characterizes the sensitivity of the sorption contribution. As a result, permeability decreases more rapidly within the effective stress range of 0–5 MPa. This model is particularly suitable for evaluating in situ coal masses where sorption effects are expected to play a significant role.

The Palmer & Mansoori (1998) model [24] exhibits a smoother permeability decline compared with models [22, 23], owing to its consideration of the combined effects of sorption-induced and thermal deformation. The parameter γ allows the influence of deformation associated with temperature variations and gas sorption to be represented. At low stress levels, the model behavior is similar to that of the Gray

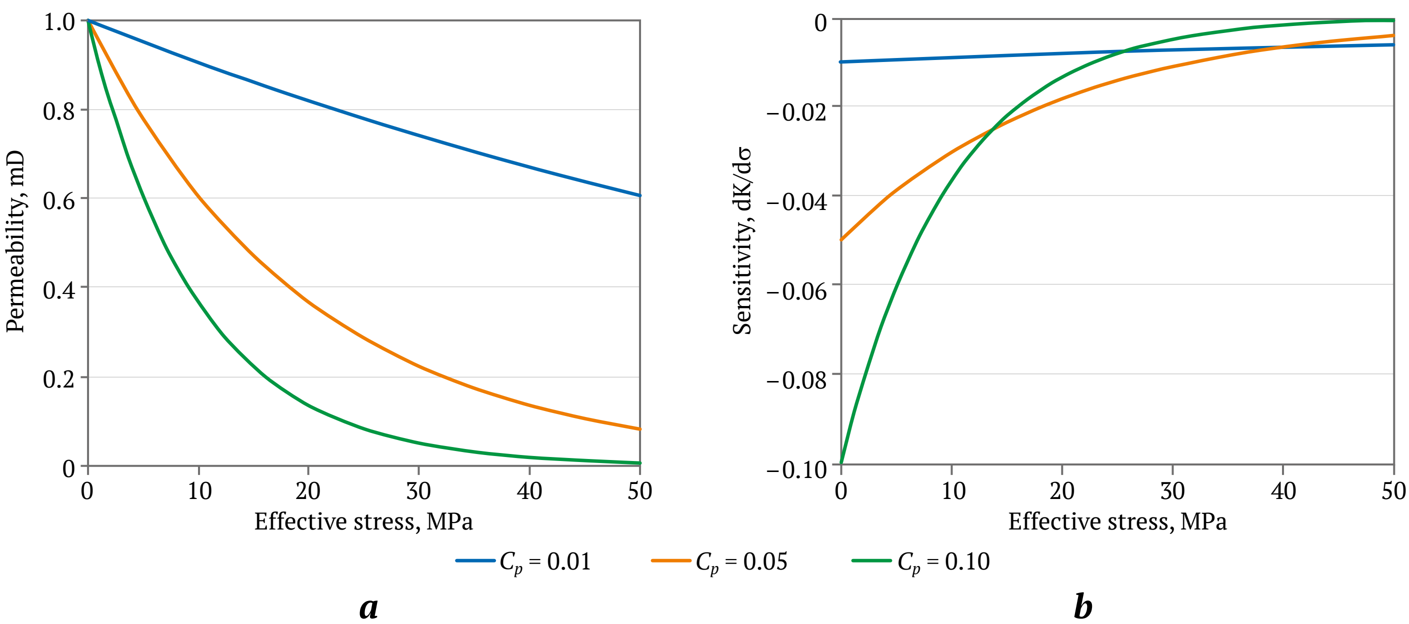

Fig. 3. Sensitivity analysis of the Gray (1987) model [22]. Permeability (*a*) and sensitivity (*b*) as functions of effective stress for different values of the coefficient C_p

model [22]; however, as stress increases, the permeability reduction becomes more gradual. This model is well suited for assessing the natural permeability of coal-bearing rock masses at greater depths, where variations in the geothermal gradient become increasingly important.

The Shi & Durucan (2004) model [25, 26] explicitly incorporates the effect of porosity on permeability. Permeability is expressed as a power-law function of porosity φ, normalized to its initial value φ_0. The model includes the exponent n, which controls the degree of porosity influence, as well as the sorption strain parameter ε_s. Among the models considered, it demonstrates the most uniform permeability reduction, particularly at effective stress levels exceeding 10 MPa. This behavior reflects its dependence on porosity and its comparatively lower stress sensitivity. The model is therefore appropriate for evaluating the natural permeability of rock masses characterized by potentially variable pore structure within the mineral skeleton.

The Karkashadze & Hautiev (2015) model [27] exhibits intermediate behavior between models [22] and [24] (Fig. 4). Its distinguishing feature is the explicit consideration of Young's modulus E, normalized by its initial value E_0 which enables permeability changes induced by elastic deformation of the coal seam to be described. Permeability decreases moderately with increasing effective stress, while the parameter C_p smooths the permeability curve within the intermediate stress range. The model is more sensitive to the mechanical properties of the coal mass, making it suitable for conditions where variations in physico-mechanical properties are significant, particularly in settings where elastic and tectonic stresses contribute substantially to the formation of the stress field.

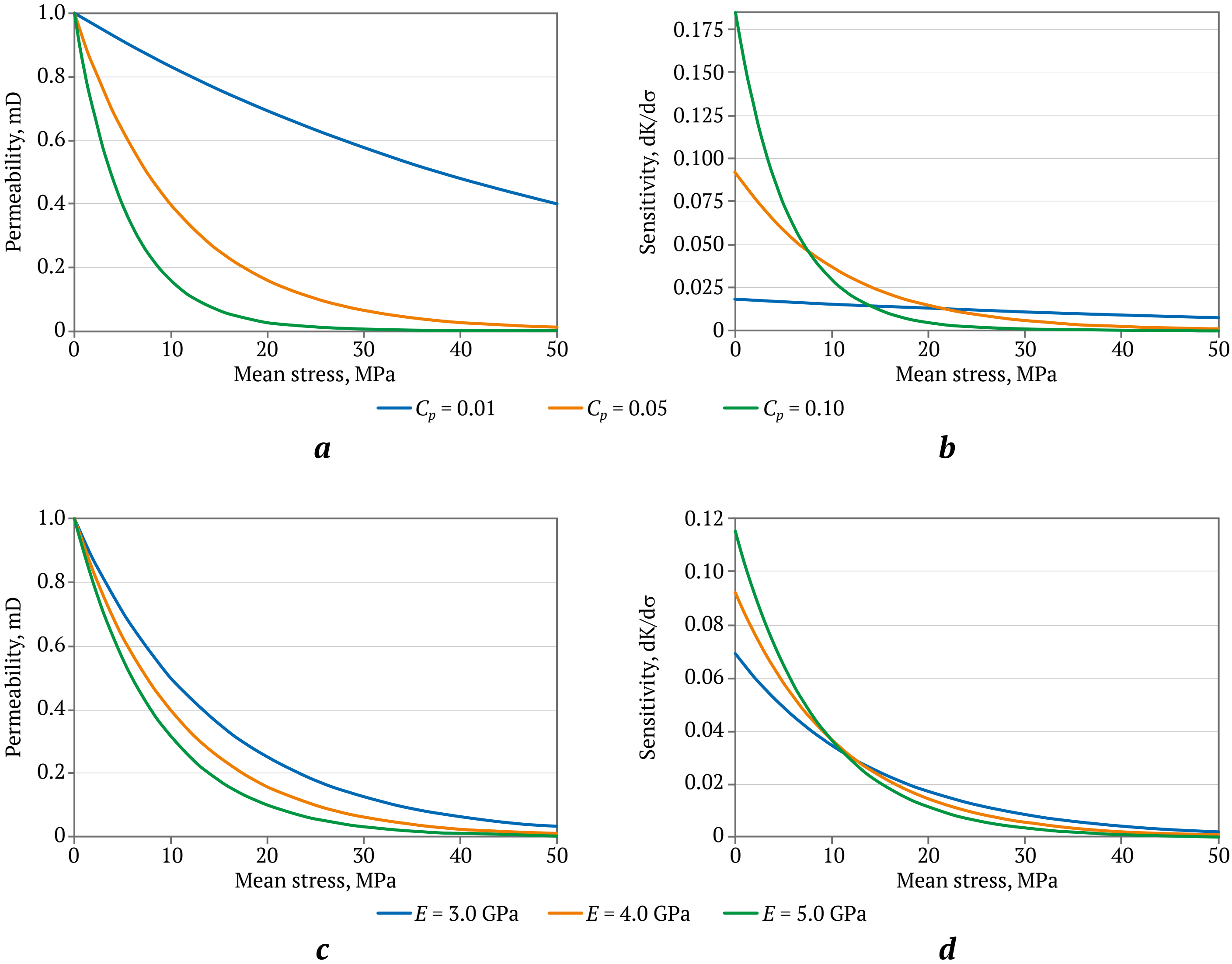

Fig. 4. Sensitivity analysis of the Karkashadze & Hautiev (2015) model [27]. Permeability (*a*) and sensitivity (*b*) as functions of effective stress for different values of the coefficient C_p; permeability (*c*) and sensitivity (*d*) as functions of effective stress for different values of Young's modulus of the rock mass, E

Conclusions

Analytical models of geological medium permeability require consideration of coal microstructural characteristics, reservoir pressure parameters, fluid distribution within the coal-bearing rock mass, and factors governing the stress-strain state. However, under coal seam-scale permeability modeling conditions, acquiring such detailed data is practically infeasible. In this context, a systematic analytical review and analysis of the mathematical frameworks of existing models were conducted, making it possible to identify the parameters that play a decisive role in shaping permeability-stress-strain relationships.

The study demonstrates that a wide range of stress–strain factors influence coal permeability. In accordance with the stated objectives, numerical experiments and sensitivity analyses of the principal empirical models with respect to variations in effective stress were performed. The parametric calculations revealed a common trend across all models: a nonlinear decrease in permeability with increasing effective stress. This behavior reflects the physical processes of pore space compression and fracture closure in coal seams under external loading. At the same time, each model is based on distinct physical and geomechanical assumptions, resulting in differences in curve shape and in the degree of sensitivity to key parameters. A comparative sensitivity analysis of the main empirical and analytical permeability models to changes in the stress-strain state of the coal-bearing rock mass was carried out.

The principal scientific contribution of this study lies in identifying differences in the sensitivity of existing permeability models to the geomechanical parameters of coal-bearing rock masses, as well as in delineating stress-strain ranges in which these models either diverge most strongly or, conversely, converge in their behavior. The following criteria are proposed for model comparison and selection: the nature of dominant deformation mechanisms within the seam; depth of occurrence and the expected range of effective stress; microstructural characteristics of the reservoir; approximate gas saturation and the intensity of sorption processes; and the presence of contrasting elastic properties among different coal ranks.

Within a unified problem formulation, the behavior of the models was examined for variations in effective stress over the range 0–50 MPa and depths up to 1500 m. This approach enabled comparison of their responses to intrinsic geomechanical parameters, including deformation modulus, sorption-induced strain, porosity, and elastic properties. Although the study does not aim to develop a new permeability model, it yields a methodological outcome: zones of increased and reduced sensitivity were identified for each relationship, facilitating informed selection of an appropriate permeability model for specific geomechanical conditions. Model choice should therefore depend on the dominant stress-field formation mechanisms within the coal seam: sorption-induced deformation is best captured by model [23]; deep seams with variable porosity are more adequately described by model [24]; and elastic deformation effects are most effectively represented by model [27]. These relationships can be applied to assess the natural permeability of coal seams in undisturbed rock masses.

Overall, the study provides a comprehensive comparative analysis of permeability models within a unified computational framework. Key zones of model divergence and convergence as functions of geomechanical parameters have been established, forming a scientific basis for their justified selection. The proposed criteria and specific recommendations constitute a practical toolkit for improving the reliability of filtration modeling of coal-bearing rock masses within defined stress and depth ranges.

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