Introduction

When modeling the influence of deformation of porous hydrate bearing rocks on permeability, a uniform distribution of stress in the matrix is assumed, as well as the constancy of the Young's modulus under loading. This is justified by the fact that the minerals that make up the rock are weakly compressible, their volumetric compression coefficients are extremely small and can be considered constant up to loads of 200 MPa [Zimmerman et al., 1986]. The absence of significant deformations in consolidated rocks is also confirmed by experimental studies of highly porous sandstones under triaxial compression [Khimulia et al., 2024]. However, this approach is inconsistent with the findings of most experimental studies, which have observed that consolidated porous rocks exhibit marked sensitivity to initial loading. The significant reduction in permeability under applied stress can be attributed to the closure of pre-existing relaxation cracks—features that inevitably form in rock samples during the release of natural stresses (e.g., during core extraction or sample preparation). The existence of these cracks is supported by microstructural analyses of natural rock samples, confirming their role in governing stress-dependent permeability behavior.

The classical approach to determining permeability under loading is the use of a power or exponential laws, where the exponent is often cited by many authors as the coefficient of sensitivity of permeability to loading [Kozhevnikov et al., 2022]. However, the nature of this coefficient remains poorly understood. Some studies have attempted to establish a relationship between the exponent of the power equation and the porosity or permeability of rocks based on statistical dependencies. Nevertheless, these attempts have not provided a comprehensive understanding of the true nature of the law governing permeability changes. This paper presents the results of comparative modeling of the deformation of a porous medium with and without microcracks.

Method

During initial loading, rocks experience microcrack closure, leading to an increase in Young's modulus with applied stress. The nonlinear stress-dependence of Young's modulus is attributed to progressive rock compaction as microcracks gradually close. To evaluate the influence of compaction dynamics, numerical simulations were conducted under two conditions: constant Young's modulus and stress-dependent nonlinear Young's modulus for porous media (Figure 1a). This nonlinear mechanical response arises from the presence of microcracks and their closure under compressive loading. By explicitly incorporating microstructural features, including crack networks, the model deviates from the assumption of a monolithic pore structure (Figure 1b, c), thereby enabling a more accurate representation of microcrack-mediated deformation and its impact on permeability evolution under stress.

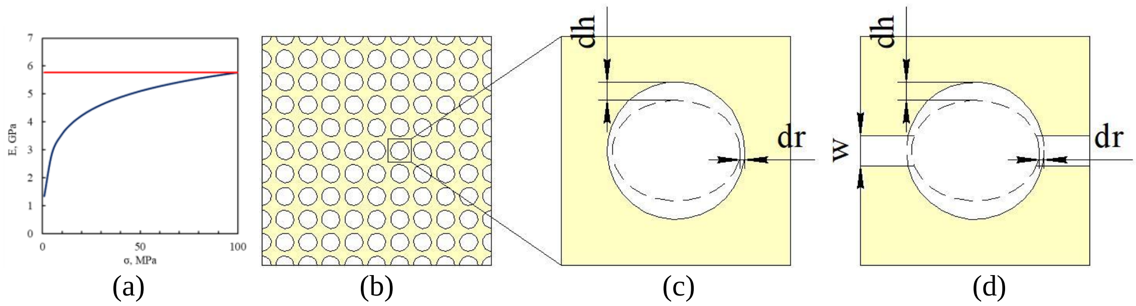

Figure 1 *(a) – Young's moduli from stress adopted in the modeling, red line – without taking into account microcracking, blue – with taking into account microcracking; (b) – calculation model of a porous medium; (c) – without taking into account microcracking; (d) – with taking into account microcracking.*

In the developed model, the natural rock is replaced by a medium consisting of tubes (Figure 1b) with a critical radius r. The model is based on the dependence of the rock permeability on the porosity and the critical radius of the pore channel in the form $k = 8.5 \cdot (\phi \cdot r^2)^{1.3}$ [Nishiyama and Yokoyama, 2017]. A comparison of two models was made: monolithic (Figure 1c) and with microcracks (Figure 1d). The following patterns were used in the model:

$$k = 8.5 \cdot (\phi \cdot r^2)^{1.3}$$
$$\mu = \frac{\varepsilon_l}{\varepsilon_h}$$
$$\varepsilon_l = \frac{dr}{r}$$
$$dr = \mu \cdot \varepsilon_h \cdot r$$
$$\varepsilon_h = \frac{dh}{h} = \frac{\sigma_m}{E} = \frac{\sigma_b}{E \cdot (1 - \phi)}$$
$$dh = \frac{\sigma_b \cdot h}{E \cdot (1 - \phi)}$$
$$E = 964.5 \cdot Ln(\sigma) + 1330.6$$
$$\sigma_b = \sigma_m - P_p$$
$$P_p = 0$$
$$\varepsilon_l = \mu_m \cdot \varepsilon_h$$
$$dr = \varepsilon_l \cdot r = \mu_m \cdot \varepsilon_h \cdot r$$
$$\phi = \frac{V_p}{V} = \frac{l_t \cdot S_p}{V} = \frac{l_t \cdot \pi \cdot r^2}{V}$$
$$\phi_\sigma = \frac{l_t \cdot \pi \cdot (r - dh) \cdot (r - dr)}{V_\sigma} = \frac{l_t \cdot \pi \cdot (r - dh) \cdot (r - dr)}{l_t \cdot H_\sigma \cdot L_\sigma}$$
$$H_\sigma = H - \varepsilon_h$$
$$D_h = \frac{2 \cdot \sqrt{2 \cdot (r - dh) \cdot (r - dr)}}{\sqrt{(r - dh)^2 + (r - dr)^2}}$$
$$r_\sigma = \frac{D_h}{2}$$
$$k_\sigma = 8.5 \cdot (\phi_\sigma \cdot r_\sigma^2)^{1.3}$$

where k is the permeability; f is the porosity; r is the average pore radius; h is the average pore diameter; dr is the change in the pore radius due to transverse deformation; μ is the Poisson's ratio; dh is the change in the pore radius due to longitudinal deformation; ε_l and ε_h are the longitudinal and transverse deformation; σ, σ_m are the effective and rock stress; P_p is the pore pressure; E is the Young's modulus; V_p, V are the volume of pores and rock; S is the cross-sectional area of the bed face; H is the bed thickness; l_t is the length of the pore channels; D_h is the diameter of the deformed pore.

Results and discussion

The results of numerical simulations for digital porous media models are presented in Figure 2. In these plots, the red line represents permeability evolution under pressure without incorporating microfractures, while the blue line corresponds to simulations accounting for microfracture dynamics. The numerical model was validated by comparing its outputs with experimental core study data (Figure 3). Analysis of the simulation results (Figure 2) reveals that omitting microfractures produces a linear stress-permeability relationship, which contradicts experimental observations (Figure 3). In contrast, simulations incorporating microfractures yield exponential stress-dependent permeability trends, enabling predictions of permeability changes through the exponent derived from exponential approximation equations. A comparison of modeled and experimental results demonstrates that the exponents characterizing rock stress sensitivity share the same order of magnitude, thereby validating the proposed model's ability to replicate experimentally observed nonlinear behavior.

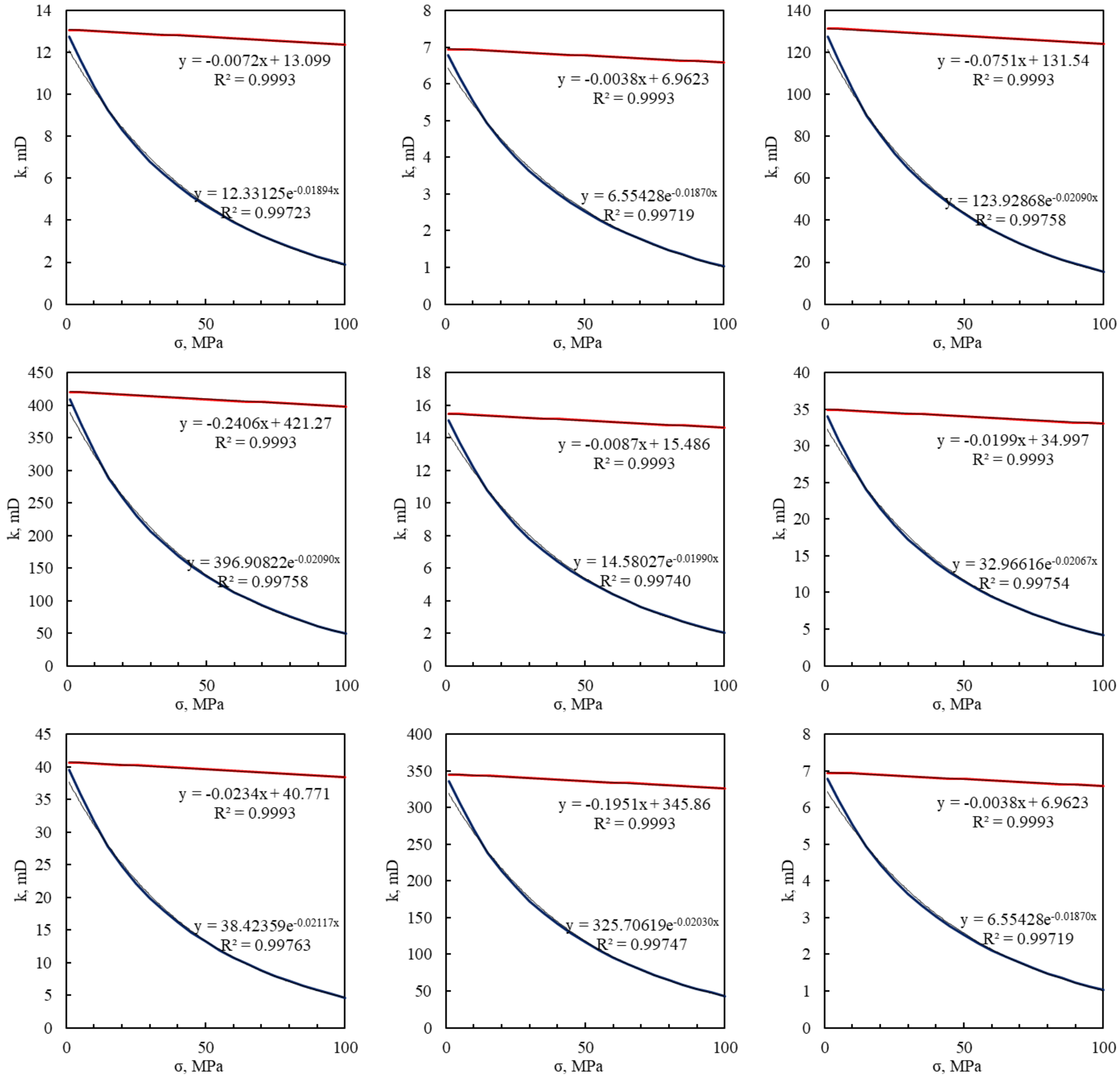

Figure 2 *Permeability values of porous rock samples calculated using the model. Red line – without taking into account microfractures, blue – taking into account microfractures.*

Conclusions

The numerical modeling results demonstrate that accounting for microfractures in porous media leads to exponential dependencies of permeability on stress, which align well with experimental observations, while models without microfractures show unrealistic linear relationships. The validation of the model through comparison with experimental core studies confirms that the exponents of the equations characterizing rock sensitivity to stress are of the same order of magnitude, establishing the model's reliability. These findings emphasize the crucial role of microfractures in determining permeability changes under stress and provide a more accurate approach to predicting permeability variations in porous hydrate-bearing rocks, moving beyond the limitations of traditional uniform stress distribution assumptions.

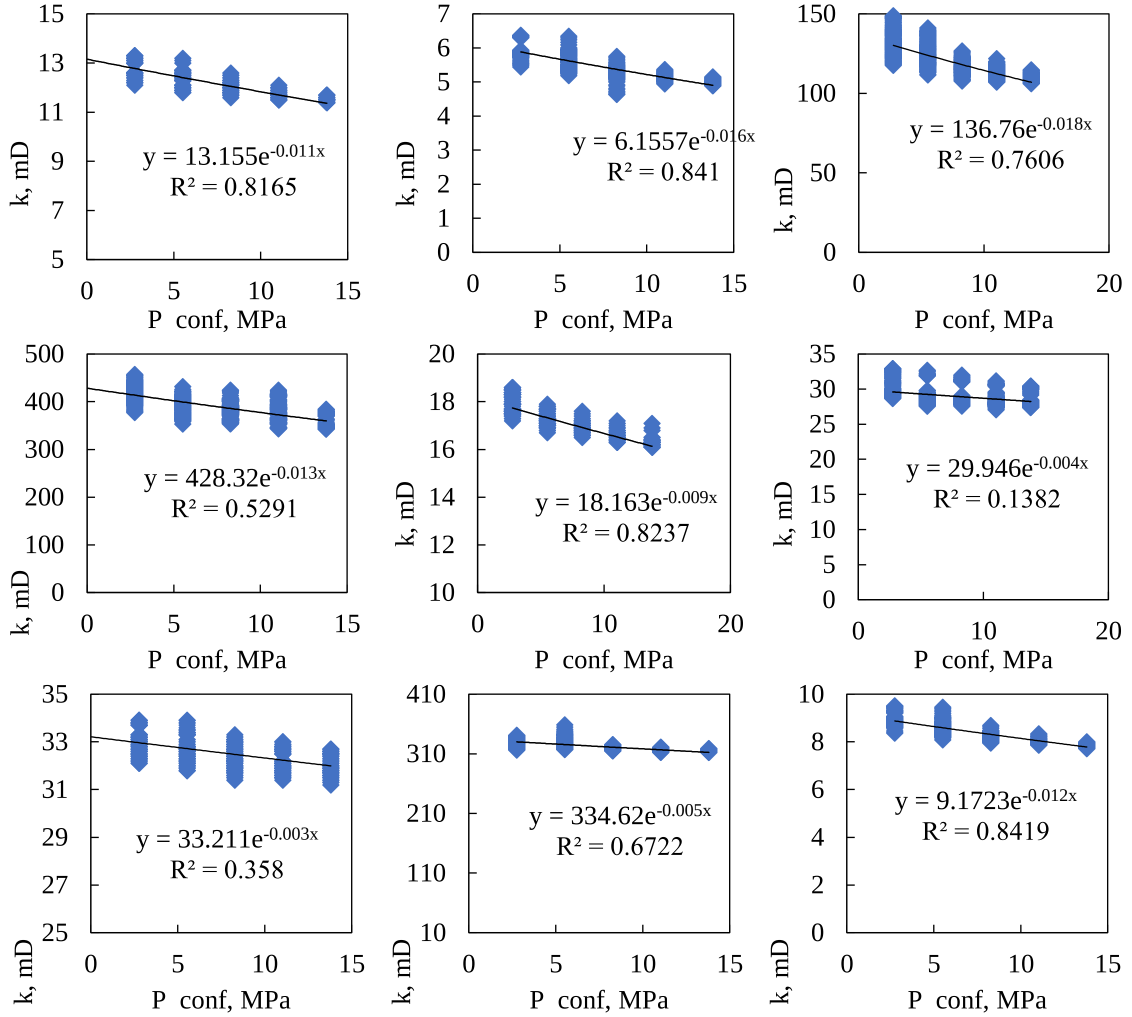

***Figure 3** The influence of confining pressure on the porous rock's permeability.*

Acknowledgements: This research was funded by the Ministry of science and higher education of the Russian Federation (Project № FSNM-2024-0008)

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