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Permeability evolution and model of methane hydrate-bearing sediments under coupled shear strain, effective confining pressure, and hydrate saturation

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ABSTRACT

The permeability of methane hydrate-bearing sediments (MHBS) is a key parameter for evaluating reservoir exploitation potential and formulating efficient production strategies. In actual field development, MHBS exists in a complex environment characterized by stress-seepage coupling. Research on the permeability model of methane hydrate-bearing sediments under multi-factor coupling conditions remains scarce, limiting the assessment of methane hydrate (MH) reservoir hydrocarbon production potential and efficient development. This study used quartz sand and deep-sea clay from the South China Sea as matrix materials to generate MH, simulating MHBS. Systematic triaxial seepage experiments were conducted to assess the influence of multiple factors, including triaxial shear process, effective confining pressure, and hydrate saturation, on the permeability characteristics of MHBS. The results demonstrate the following: (1) During triaxial compression, permeability exhibits a nonlinear variation—first decreasing and then stabilizing or rebounding—with increasing shear strain, reflecting stress-induced pore structure evolution; (2) the permeability of MHBS decreases nonlinearly with increasing effective confining pressure, showing higher sensitivity in the low-pressure range. Effective confining pressure reduces sample permeability by compressing seepage channels, and this effect is more significant at the initial stages of stress growth; (3) hydrate saturation is negatively correlated with permeability, with the cementing effect of hydrates being the primary cause for the decrease in permeability of MHBS, also reducing the impact of effective confining pressure; (4) effective confining pressure, hydrate saturation, and shear strain have a coupled effect, jointly influencing the permeability of MHBS, but their relative weights vary and require specific consideration; (5) based on experimental data, a permeability prediction model considering the coupling effects of shear strain, effective confining pressure, and hydrate saturation was established. This model demonstrates excellent predictive accuracy and can be applied to forecast the hydrocarbon yield potential of MHBS under varying geological and engineering conditions, providing quantitative basis for reservoir evaluation and gas production prediction. This study bridges the gap between laboratory permeability characterization and field production capacity forecasting, offering critical theoretical and technical support for the sustainable development of marine gas hydrate resources.

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1. Introduction

Methane hydrate (MH) resources are widely distributed in deep-water regions along continental margins. Their global carbon reserves are more than twice those of natural gas, making MH one of the most promising “next-generation” clean energy resources (Zhao YP et al., 2025). As the global

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economy and population continue to grow, the International Energy Agency (IEA) forecasts that global natural gas demand will increase by an average of 1.4% per year through 2040, while conventional reserves continue to decline at an accelerated rate (Chong ZR et al., 2016). The economic and large-scale development of hydrate resources can provide emerging economies with reliable low-carbon energy support without increasing carbon emissions, meeting humanity's growing resource demands, driving infrastructure upgrades, and fostering blue economic development in coastal nations, thus becoming a new engine for sustainable global economic growth (Evro S et al., 2024).

The seepage behavior of methane hydrate-bearing sediments (MHBS) is fundamental for evaluating reservoir exploitation potential and formulating efficient exploitation strategies (Zhang YC et al., 2024). In terms of artificially generating hydrate samples, Mahabadi N et al. (2016) used tetrahydrofuran (THF) as a substitute for methane, measured the permeability of soils containing THF hydrates, and analyzed the relationship between capillary suction and gas intake as a function of hydrate saturation; Xiao CW et al. (2022) used glass sand, whereas Li G et al. (2019) used quartz sand as the primary matrix material to generate MH for permeability tests; Jin JK et al. (2024) further proposed a combination of quartz sand and deep-sea clay to prepare samples that better simulate the realism of marine sediments. In terms of experimental methods, most existing studies have focused on the influence of one or two variables on the permeability of MHBS. For example, Zhang Z et al. (2022) used a hydrate permeability testing system to investigate the effects of stress on the permeability of clayey silt cores containing THF hydrates, and found that pore compression and throat blockage induced by small particle fragmentation are important factors leading to permeability reduction; Zhao YP et al. (2023) employed a triaxial shear-seepage coupling integrated testing system to examine the combined effect of effective stress and hydrate saturation on the permeability of hydrate-bearing sediments (HBS); however, their work mainly addressed the coupling between consolidation pressure and seepage and did not involve triaxial shear. Shen PF et al. (2020) used a high-pressure reactor to investigate the coupled effects of porosity and hydrate saturation on MHBS permeability, and reported that when the porosity of the porous medium ranged from 39.68% to 49.94%, the influence of the packing structure on relative permeability was negligible. Overall, relatively few studies have considered the influence of multi-factor coupling on the flow behavior of MHBS. In reality, MH production is a complex process involving the interaction of fluid flow, *in situ* stress, and reservoir deformation, among other factors. During MH dissociation, reservoir mechanical properties, permeability characteristics, and physical properties evolve dynamically. Investigating these evolutionary processes and the coupled effects of multiple factors is essential for addressing engineering problems such as wellbore instability and collapse, and for providing key parameters for the design

efficient and safe MH production strategies (Zeng J et al., 2023; Dong L et al., 2026).

In recent years, many researchers have focused on permeability models for MHBS and have proposed a series of models, such as those developed by Kleinberg, Katagiri, Wang and co-workers (Kleinberg RL et al., 2003; Katagiri J et al., 2017; Cui LY et al., 2025; Wang YH et al., 2025). Research on hydrate permeability models has evolved from early single-factor (saturation models) models to two-factor (saturation-effective stress models) coupled models, and is gradually advancing toward multi-factor coupled models. However, only a few studies have incorporated all three key factors simultaneously. The development of multi-factor coupling models can help explain the evolution of hydrate permeability under complex production conditions and provide new methodologies and experimental data support for pre-production resource evaluation, prediction of hydrocarbon prediction potential, and recovery of free gas (Xu JC et al., 2022).

In this study, the high-pressure and low-temperature conditions of MH reservoirs in the South China Sea were accurately reproduced. Based on geological information such as clay content, grain size, and particle size distribution of reservoir sediments, high-fidelity sediment samples were constructed to ensure the reliability of the experimental data. Unlike previous studies that typically examined the influence of only one or two factors on MHBS flow behavior, this work systematically investigates, for the first time, the coupled effects of effective confining pressure, hydrate saturation, and triaxial shear on permeability. The evolution of MHBS permeability under multi-factor coupled conditions is revealed, and a new permeability prediction model that incorporates these coupled effects is established. The proposed model exhibits a higher predictive accuracy and broader applicability than existing models, and provides a theoretical foundation for evaluating hydrocarbon potential and assessing the commercial development prospects of MH reservoirs.

2. Experimental methods

2.1. Laboratory equipment

This study employed a high-pressure, low-temperature triaxial seepage experimental system capable of both generation and measuring methane hydrate. The system comprises four functional modules: (1) A confining pressure control module, (2) a pore pressure control module, (3) a hydrate reactor, and (4) a data acquisition system (Wang HJ et al., 2021).

The hydrate reactor is cooled by a constant-temperature water bath, which controls the temperature of the triaxial unit and, consequently, the specimen. A thermocouple installed inside the reactor continuously monitors the specimen temperature in real time. The sediment sample in the reactor is a cylinder with dimensions of 50 mm × 100 mm, wrapped in a 1 mm thick black rubber membrane, and mounted between

the base and the upper pressure head, thereby forming a sealed space isolated from the pressure chamber. Gas pressure in the system is regulated by a high-precision ISCO (Isco Precision Syringe) pump, which can provide a maximum pore pressure of 30 MPa with a precision of 0.01 MPa. The GDS (Global Digital Systems) pump applies and maintains confining pressure by pressurizing silicone oil between the inner wall of the reactor and the rubber membrane. The maximum pressure is 16 MPa, with a precision of 0.01 MPa, providing the required environmental pressure for *in situ* hydrate formation (Liu T et al., 2025). A gas mass flow meter and a pressure gauge are installed at the outlet of the reactor to measure the gas flow rate and outlet pressure during the seepage test. The outlet pressure is controlled by a backpressure valve, and the pressure difference between the upstream and downstream ends is measured by a pressure sensor. Throughout the experiment, temperature and pressure data are recorded by an A/D module and transmitted to a computer terminal.

2.2. Sample preparation

The marine soil used in this study was collected from the Shenhua area in the South China Sea. High-fidelity sediment samples and marine soil were obtained using a marine sediment insulation and pressure-retaining corer independently designed and developed by the research team, as shown in Fig. 1 (Fu CH et al., 2025; Xu M et al., 2026). Geophysical and chemical investigations in this region indicate that the clay content of gas hydrate-bearing strata ranges from 15% to 35%, hydrate saturation ranges from 10% to 40%, and hydrates occur at depths of approximately 1000 m below the seabed (Li Y et al., 2024; Ren JJ et al., 2024). Ye JL et al. (2020) extracted MH reservoir cores from depths of 203 m to 277 m below sea level during the second MH production test in the South China Sea. Based on the geological conditions at the test site, the effective confining pressure in the MH reservoir is estimated to be 0.5–3.5 MPa, the pore pressure is approximately 4.5 MPa, and the ambient temperature during the production is about 1.5°C. The corresponding experimental design conditions are summarized in Table 1.

In this study, cylindrical sediment samples with dimensions of 50 mm × 100 mm were reconstructed. According to XRD and SEM analyses of SH-W02-B

sediments by Ren JJ et al. (2024), quartz is the dominant mineral, with a total clay content of 31% and an average mineral grain size of 20 μm. In addition, based on the full-well data provided by Ye JL et al. (2020), the average porosity of the MH reservoir is approximately 40%, with the pores filled with liquid water. Therefore, following the sample preparation procedure proposed by Huang L et al. (2025), the sample porosity was set to 45%. Assuming the sediment was in an unsaturated soil state with an initial water saturation of 0.5, dry quartz sand and marine soil were first mixed thoroughly. A specific volume of deionized water was then added. After ensuring homogeneous mixing, the mixture was compacted in five layers using a three-part mold. Subsequently, the compacted sample was frozen at −10°C for 4 hours. The mold was then opened, and the sample was removed and enclosed in a black rubber membrane. The relevant physical parameters of the sample are shown in Table 2.

In previous hydrate formation studies, the excess-gas method has been widely adopted owing to its simplicity and controllability (Yang YK et al., 2024). Accordingly, the excess-gas method was also employed in this study to generate MH. The specific operation is as follows: The sample wrapped in the black rubber membrane is installed between the upper and lower pressure heads inside the reactor, with permeable stones and gaskets placed at both ends. The sample is then sealed using O-rings and metal clamps to ensure isolation from the pressure chamber. The water bath system is installed, the water bath temperature is initially set to 15°C, and the pressure chamber is filled with oil. The pressure control program is then operated to reach the prescribed values of confining pressure and pore pressure. Subsequently, the ambient temperature is lowered to 1.5°C, during which hydrate formation occurs. Once gas consumption ceases, hydrate formation is considered complete. After a consolidation period of 6 hours, the triaxial shear–seepage test is conducted.

2.3. Triaxial shear-seepage experiments and related calculations

The method used to calculate MH saturation generated by

Table 1. Experimental design conditions.

Sample number	$S_h/\%$	σ_c/MPa	P_p/MPa	$C_c/\%$	Osmotic pressure/MPa	Experimental temperature/°C
1–4	0	5, 6, 7.5	4.5	20	2	1.5
5–8	10					
9–12	20					
13–16	30					

Table 2. Sample material parameters.

Project	Value	Sample
Size/mm ²	50 × 100	
Total volume of sample/cm ³	196.35	
Porosity	0.45	
Initial water saturation	0.50	
Deep-sea clay density/(g/cm ³)	2.72	

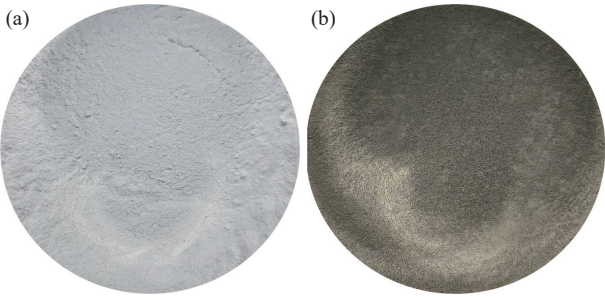


Fig. 1. Triaxial shear–seepage test materials. a–Quartz sand; b–deep-sea clay.

the excess-gas method is outlined below. The change in gas volume, V_T , caused by the decrease in temperature is first considered and is calculated using Eq. 1:

$$V_T = \left(1 - \frac{Z_2 T_2}{Z_1 T_1}\right) V_n \quad (1)$$

where V_n represents the pore volume; Z_1 represents the initial gas compression factor; T_1 represents the initial ambient temperature; Z_2 represents the final gas compression factor; T_2 represents the final ambient temperature. The volume of methane gas consumed during hydrate formation, V_2 , is defined as Eq. 2:

$$V_2 = V_1 - V_T \quad (2)$$

where V_1 is the total gas consumption volume, monitored by the data acquisition system. The hydrate saturation S_h is then calculated according to the Eq. 3 (Li YH et al., 2024b):

$$S_h = \frac{V_h}{V_n} = \frac{P_p V_2 (M_{CH_4} + n \cdot M_{H_2O})}{\rho_m \cdot R Z_2 T_2 \cdot V_n} \quad (3)$$

where P_p is the pore pressure, MPa; M_{CH_4} and M_{H_2O} are the molar masses of methane and deionized water, g/mol; n is the hydrate reaction constant, with a value of 5.75; ρ_m is the density of MH, with a value of 0.916 g/cm³; R is the gas constant, with a value of 8.314 J/(mol·K).

After completing the MH saturation calculation and consolidation process, the triaxial shear-seepage test is initiated. Prior to shearing, the initial gas-phase permeability of the sample is measured. The outlet valve is opened, and the backpressure valve is adjusted to maintain a pressure difference of 2 MPa between the upstream and downstream ends. The test duration is 5 minutes. Once the gas flow stabilizes, the data are recorded, the outlet valve is closed, and the backpressure setting is maintained. Subsequently, axial loading is applied at a constant displacement rate of 0.1 mm/min. The gas-phase permeability of the sediment is measured each time the axial strain increases by 2.5%, and loading is terminated once the cumulative strain reaches 15%. Finally, the water bath temperature is increased to 15°C. When the volume of the pore pressure pump remains unchanged, hydrate is considered to have fully decomposed, and the gas-phase permeability of the sediment at this stage is measured.

Methane is a compressible gas. According to Darcy's law, the gas-phase permeability of the specimen is calculated using Eq. 4 (Li YH et al., 2024a):

$$K = \frac{2P_0 \mu Q L}{A(P_1^2 - P_2^2)} \quad (4)$$

where the unit of permeability K is millidarcy (mD); P_0 is the average of the upstream and downstream pressures, which is equivalent to the pore pressure P_p , MPa; μ is the gas viscosity, mPa·s; Q is the gas flow rate through the cross-sectional area of the sample, ml/s; L is the sample length, cm; A is the cross-sectional area of the sample, cm²; P_1 and P_2 are

the upstream and downstream pressures, MPa. The effective confining pressure σ_E of the sample is calculated by Eq. 5:

$$\sigma_E = \sigma_c - P_p \quad (5)$$

where σ_c is the confining pressure, MPa; P_p is the pore pressure, MPa.

3. Results and discussion

3.1. Effect of the triaxial shear process on permeability

This triaxial shear tests were conducted under displacement-controlled loading. The stress-strain curves are shown in Fig. 2. Both increasing effective confining pressure and hydrate saturation lead to enhanced strength and stiffness of the sediments. After shearing, the specimens exhibited varying degrees of dilation or contraction, depending on their initial conditions. These findings are consistent with previous studies.

The relationship between axial strain and permeability under different effective confining pressures are shown in Fig. 3. The reduction in permeability occurs primarily during the early stage of strain development. By comparing the stress-strain and permeability-strain curves, it is evident that permeability decreases markedly during the strain hardening phase. During this phase, rapid reductions in porosity and the progressive closure of microfractures and pore channels lead to significant narrowing of flow pathways and, consequently, to a pronounced loss of permeability (Wang YH et al., 2025). With further shear deformation, the permeability of specimens under low effective confining pressure and low saturation remains essentially stable, whereas specimens under high effective confining pressure exhibit a continuous decline. Specimens with high saturation exhibit a rebound in permeability at larger strains. This behavior can be attributed to the fact that, under low effective confining pressure and high saturation, shear-induced dilation or shear band formation promotes localized increases in pore connectivity. Conversely, under high confining pressure, stronger compressive forces result in denser particle packing. Particle breakage during shear may generate fine debris that fills pore spaces, further reducing permeability. When hydrate saturation is high, the cementation effect of hydrates restrains particle rearrangement, thereby helping preserve part of the original pore structure (Yoneda J et al., 2015). Consequently, under high effective stress, the permeability of hydrate-bearing samples tends to stabilize or slightly increase rather than decline monotonically.

Under a confining pressure of 6 MPa and a hydrate saturation of 20%, computed tomography (CT) images of the specimen before and after compression are shown in Fig. 4. In these images, white represents sediment particles, dark gray denotes pores and fractures, and blue highlights pore spaces. In the initial state, the pore distribution within the sediment sample is relatively uniform. After the triaxial shear-seepage process, the pore structure exhibits a predominantly

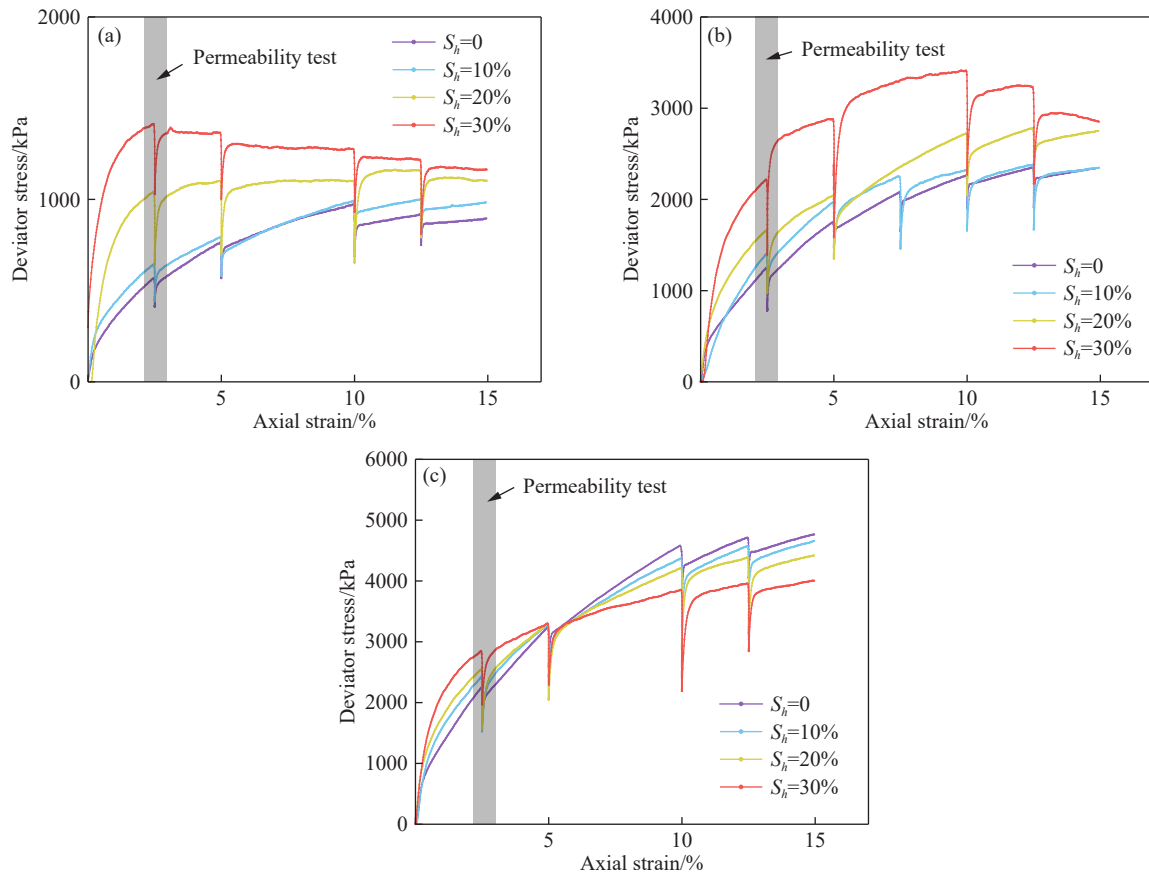


Fig. 2. Stress-strain relationship curves at different saturation levels. a—Effective confining pressure of 0.5 MPa; b—effective confining pressure of 1.5 MPa; c—effective confining pressure of 3.0 MPa.

clustered pattern, with pores concentrated mainly in zones where fractures develop. This behavior arises from the strong capillary adsorption capacity of fine particles, which exerts a repulsive effect on hydrates during their formation phase causing localized aggregation and heterogeneous spatial distribution (Li YH et al., 2023). Liu ZC et al. (2019) suggested that these locally highly saturated regions exhibited lower resistance to migration and rearrangement of hydrate colloids, leading to volumetric shrinkage and strain hardening of the sediment during triaxial shear. The resulting volumetric contraction reduces porosity and decreases permeability. In highly saturated specimens, these regions predominantly contribute to an increase in brittleness (Hu QB et al., 2023). With continued axial deformation, numerous microcracks and fractures are generated, providing preferential pathways for gas flow and thereby increasing the overall permeability of the specimen.

3.2. Effect of effective confining pressure on the permeability

The results shown in Fig. 5 illustrate the evolution of permeability with effective confining pressure for hydrate saturation of 0, 10%, 20%, and 30%. Permeability decreases nonlinearly with increasing effective confining pressure. Under elevated effective confining pressure, circumferential compression reduces pore volume and forces sediment particles into a denser arrangement, thereby constricting flow

channels and reducing initial permeability. These findings align with the near-well permeability evolution observed by Li SJ et al. (2025) in production experiments at hydrate field. In Fig. 5a, the slope of the permeability–pressure curve decreases with increasing effective confining pressure, indicating the presence of a threshold effect. This reflects the fact that pore structures cannot be compressed indefinitely and that smaller pores exhibit higher resistance to compaction. Fig. 5b shows permeability after shear deformation, where the curve slope becomes more complex due to the combined effects of confining pressure and shear-induced changes in pore structure. To further quantify the influence of effective confining pressure and its interaction with shear deformation, the permeability stress-sensitivity coefficient and permeability damage rate are introduced, defined as Eqs. 6, 7 (Wang HJ et al., 2021):

$$\eta_K = -\frac{1}{K_i} \frac{\partial K}{\partial F} \quad (6)$$

where K_i is the initial permeability under a certain condition, mD; ∂K and ∂F are the changes in permeability and influencing factors.

$$\mu_K = \frac{K_i - K_s}{K_i} \quad (7)$$

where K_i is the initial permeability under certain conditions,

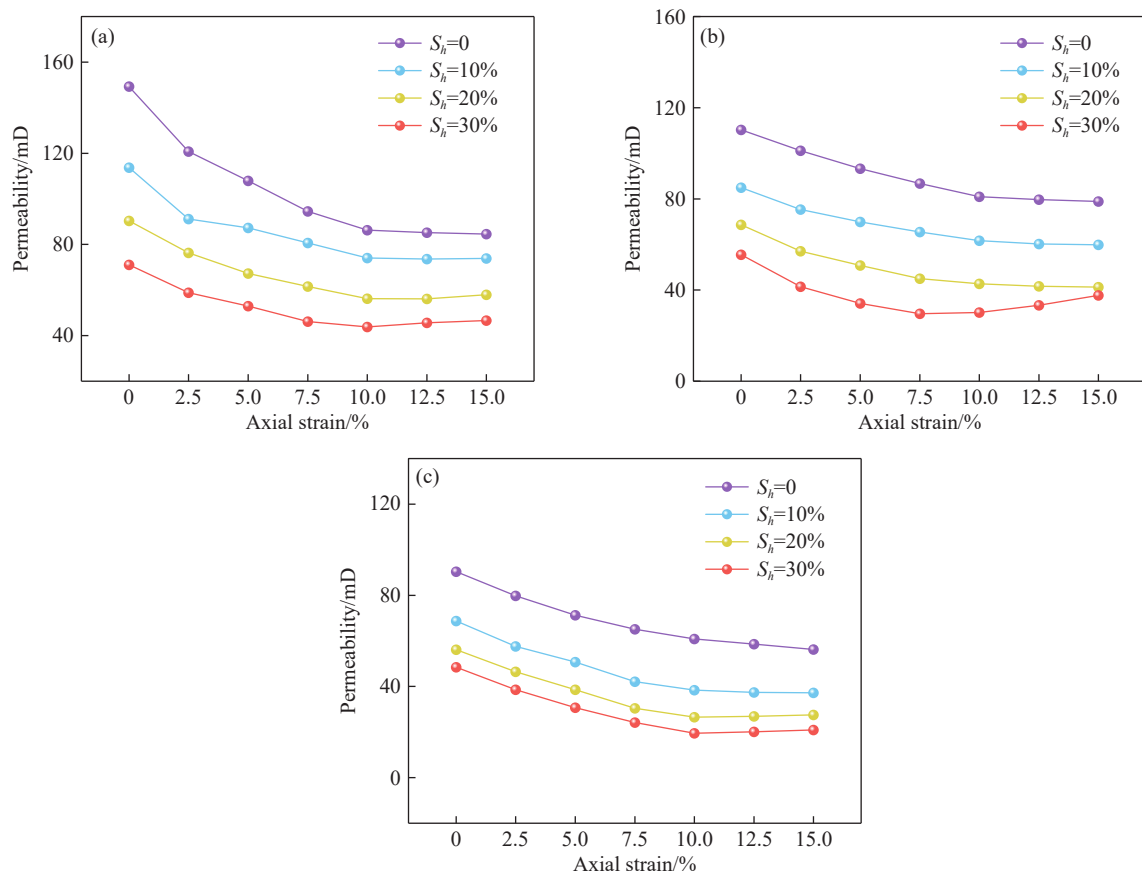


Fig. 3. Permeability-strain relationship curves for different saturation levels. a—Effective confining pressure of 0.5 MPa; b—effective confining pressure of 1.5 MPa; c—effective confining pressure of 3.0 MPa.

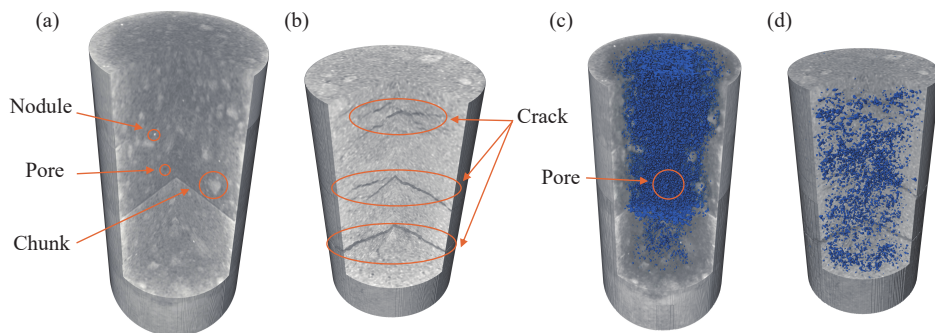


Fig. 4. CT scan image of specimen at 6 MPa and 20% saturation. a, c—Specimen before triaxial shearing; b, d—specimen after triaxial shearing.

mD; K_s is the permeability after an increase in effective confining pressure and shear deformation, mD.

The permeability stress-sensitivity coefficient and the permeability damage rate under varying hydrate saturations are shown in Fig. 6. The stress-sensitivity coefficient decreases with increasing effective confining pressure, indicating that deformation transitions from pore compression to grain-supported behavior. Hydrate cementation slightly weakens this compression effect (Yoneda J et al., 2019). The coupling of effective confining pressure and shear strain increases the permeability damage rate due to enhanced pore collapse and blockage. Under high effective confining pressure, the permeability damage rate increases with hydrate saturation, highlighting the combined influence of stress and

hydrate cementation. These results demonstrate that permeability evolution results from the integrated effects of multiple interacting factors.

3.3. Effect of hydrate saturation on sample permeability

The effect of MH saturation on sediment permeability under different effective confining pressures is shown in Fig. 7. Both before and after shearing, permeability decreases monotonically with increasing hydrate saturation. In Fig. 7a, the curve becomes steeper under low effective confining pressure as limited particle contact area enhances the likelihood of hydrate clustering on grain surfaces. These clusters hinder gas flow, whereas increasing confining

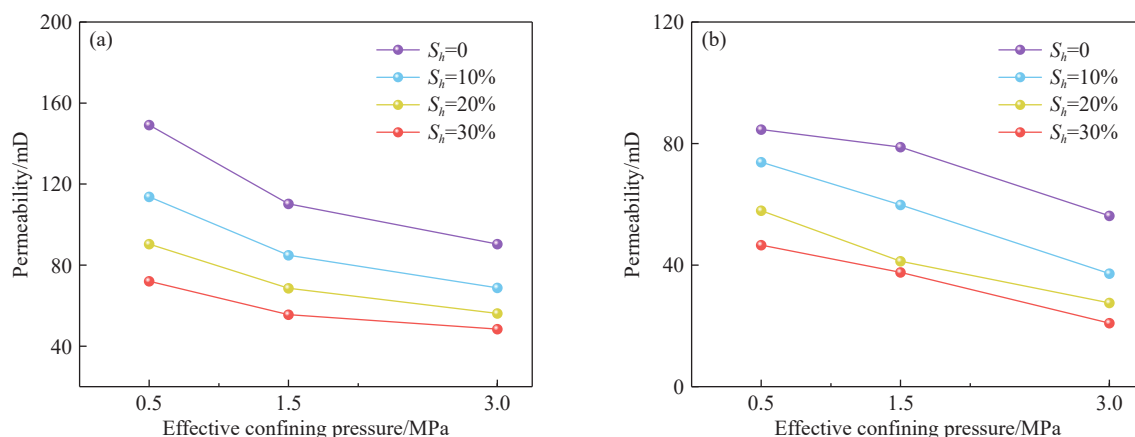


Fig. 5. Relationship curves between effective confining pressure and permeability at different saturation levels. a—Before triaxial shearing; b—after triaxial shearing.

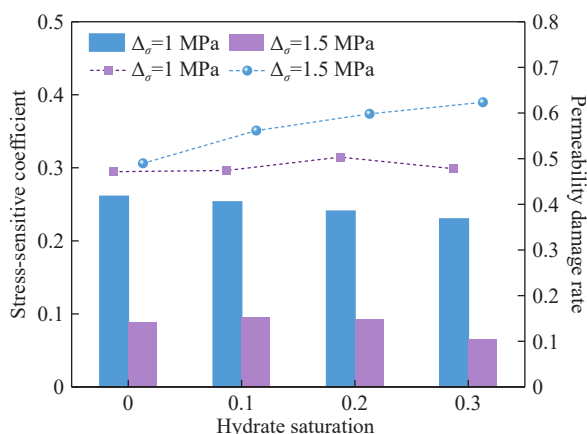


Fig. 6. Relationship between stress-sensitivity coefficient and damage rate in different saturation permeability values. Column chart corresponds to left Y-axis permeability sensitive coefficient, and point-line diagram corresponds to right Y-axis permeability damage rate.

pressure suppresses cluster formation (Ao TX et al., 2025). After shearing (Fig. 7b), permeability decreases overall, and although the monotonic trend persists, the slope no longer follows an evident pattern, indicating the need for further quantitative analysis. On average, a 10% increase in hydrate saturation reduces permeability by more than 20%.

Fig. 8 shows the saturation-sensitivity coefficient and damage rate of the permeability of MHBS specimens. The sensitivity of permeability to hydrate saturation is significantly greater than its sensitivity to stress, confirming that hydrate saturation is the dominant factor influencing MHBS permeability. As saturation increases, the saturation-sensitivity decreases, indicating fewer remaining flow channels. The permeability damage rate, influenced by the combined effects of hydrate saturation and shear strain, exceeds the stress-induced damage alone, thereby further confirming the primary role of hydrate saturation in governing permeability reduction. The permeability damage rate increases with rising hydrate saturation, reflecting the blocking effect of hydrate-induced cementation on gas flow. Moreover, the damage rate exhibits a V-shaped dependence on effective confining pressure—initially decreasing and

subsequently increasing—indicating that effective confining pressure suppresses hydrate cluster formation and thus weakens hydrate-induced pore cementation (Mahabadi N et al., 2019).

4. Sediment seepage model considering multiple factors

4.1. Permeability model

From the analysis of the experimental results, it can be concluded that shear deformation, effective confining pressure, and hydrate saturation are all negatively correlated with permeability. To further investigate the coupled effects of these three factors, a feasible analytical approach is to employ empirical parameters combined with data-fitting techniques. First, a permeability model is established for the dominant factor, namely hydrate saturation. This model is selected from widely recognized hydrate-saturation-permeability models that exhibit good theoretical consistency, strong agreement with experimental observations, and high curve-fitting accuracy. Subsequently, the empirical parameters in the hydrate-saturation-permeability model are treated as the dependent variable, while the other two influencing factors are taken as independent variables. By fitting functional relationships using the experimental data, a sediment permeability model is derived that accounts for the combined effects of all three factors.

Currently, numerous hydrate-saturation-permeability models have been proposed, including the Tokyo model proposed by Masuda in 1997, which is purely empirical; the Parallel Capillary model proposed by Kleinberg RL et al. (2003), which is based on capillary flow theory; the HBS permeability model proposed derived from the Kozeny-Carman equation, such as the Kozeny-Katagiri model; and various hybrid models (Singh H et al., 2019). As shown in Table 3, the Parallel Capillary model is most consistent with the modeling framework adopted in this study. It is based on an idealized hydrate morphology characterized by a pore filling habit, in which hydrates occupy the interparticle pore space. The porous medium is idealized as a bundle of straight, parallel cylindrical capillaries, with spherical hydrate bodies suspended at the centers of the cylindrical pores. The model

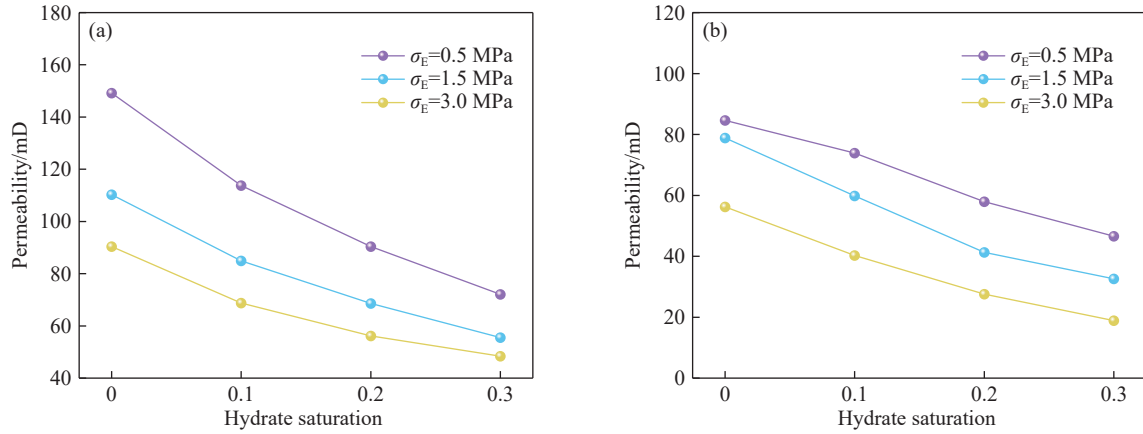


Fig. 7. Saturation and permeability relationship curves for different effective confining pressures. a–Before triaxial shearing; b–after triaxial shearing.

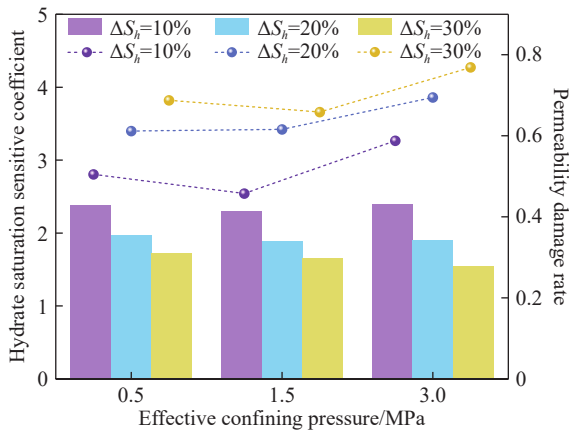


Fig. 8. Relationship between saturation–sensitivity coefficient and damage rate for different effective confining pressure permeability values. Column chart corresponds to left Y-axis hydrate saturation sensitive coefficient, and point-line diagram corresponds to right Y-axis permeability damage rate.

Table 3. Correlation coefficients for different permeability models.

Model type	Calculation formula	Fitting conditions	Correlation coefficient R^2
Tokyo model	$K_r = (1 - S_h)^n$		0.92
Kozeny-Katagiri model	$K_r = \frac{(1 - S_h)^{n+2}}{\left(1 + \sqrt{\frac{(4 - \pi)S_h}{\pi}}\right)^2}$	$\sigma_E = 0.5 \text{ MPa}$	0.98
Parallel Capillary model	$K_r = \frac{(1 - S_h)^{n+2}}{(1 + \sqrt{S_h})^2}$	$\varepsilon = 0$	0.99

assumes a uniform pore-size distribution and homogeneous hydrate suspension. For heterogeneous sediments, model predictions exhibit only minor deviations in high-permeability layers, but tend to overestimate productivity in low-permeability layers.

As shown in Fig. 9, the mean correlation coefficient R^2 of the fitted curves is 0.99, therefore, this model is adopted as the permeability framework in the present study. Its mathematical expression is given in Eq. 8 (Kleinberg RL et al., 2003):

$$K_r = \frac{K_i}{K_0} = \frac{(1 - S_h)^{n+2}}{(1 + \sqrt{S_h})^2} \quad (8)$$

where K_r is the relative permeability, defined as the ratio of the effective gas-phase permeability K_i to the absolute permeability K_0 of the medium under single-phase saturation conditions; n is a fitting parameter, defined herein as a damage index influenced jointly by effective confining pressure and shear strain; S_h is the hydrate saturation.

As shown in Fig. 10, numerical fitting was performed to obtain a nonlinear surface describing the relationship between n , effective confining pressure σ_E , and shear strain ε . After optimization, the correlation coefficient $R^2 = 0.99$. The specific relationship is expressed in Eq. 9:

$$n = 0.01\sigma_E^3 + 0.44\sigma_E - 81.8\varepsilon^3 - 7.92\varepsilon - 2.01\sigma_E^2\varepsilon + 18.41\sigma_E\varepsilon^2 + 10.05\sigma_E\varepsilon - 0.54 \quad (9)$$

where σ_E is the effective confining pressure, MPa; ε is the shear strain (expressed as a percentage and rounded to two decimal places). Substituting Eq. 9 into Eq. 8 yields Eq. 10:

$$K_r = \frac{(1 - S_h)^{0.01\sigma_E^3 + 0.44\sigma_E - 81.8\varepsilon^3 - 7.92\varepsilon - 2.01\sigma_E^2\varepsilon + 18.41\sigma_E\varepsilon^2 + 10.05\sigma_E\varepsilon + 1.46}}{(1 + \sqrt{S_h})^2} \quad (10)$$

Eq. 10 represents a permeability model that incorporates the coupled effects of multiple factors and is consistent with the experimental results presented in this study. Compared with existing predictive models, this coupled model is constructed on the basis of the Parallel Capillary model and achieves multi-factor integration through parameter fitting. Quantitative analysis was performed for deformation and stress evolution stages induced by drilling in MH reservoirs and the MH thermal-stimulation–depressurization extraction process. The coupled effects of these processes on normalized permeability were subsequently characterized.

4.2. Model validation and engineering significance

The coefficients in Eq. 9 were obtained through software-based nonlinear fitting, and the resulting values fall within a certain fluctuation range. To quantify this variation and

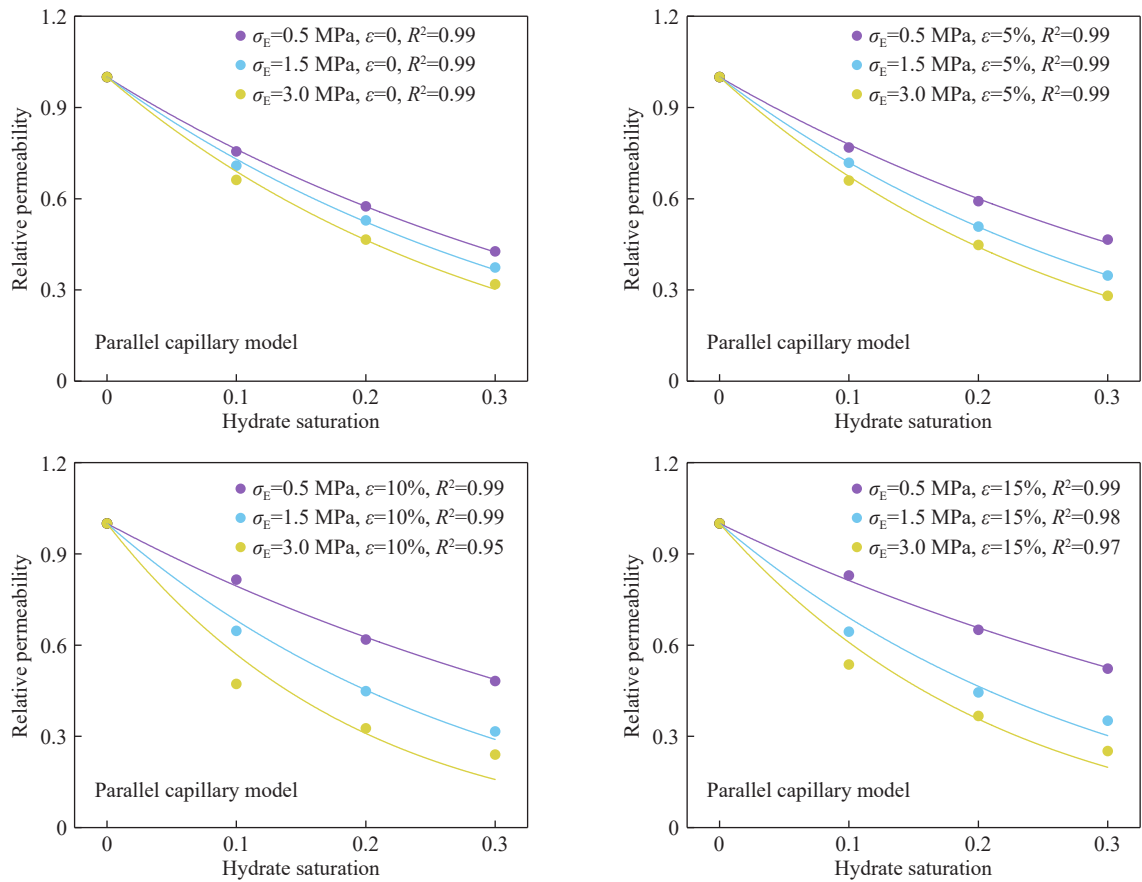


Fig. 9. Fitting curves of saturation and relative permeability at different strain stages. a–Shear strain of 0; b–shear strain of 5%; c–shear strain of 10%; d–shear strain of 15%.

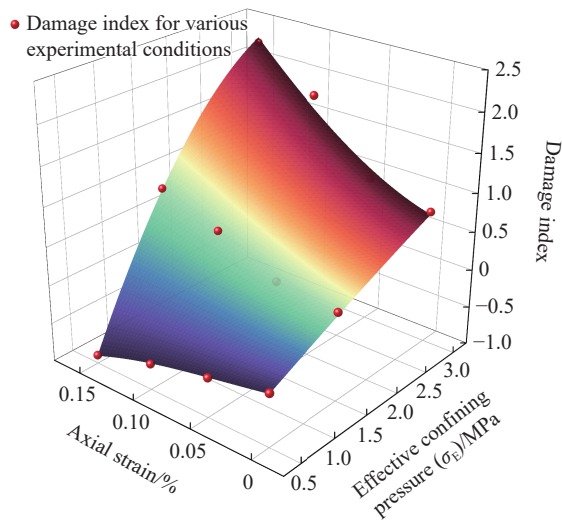


Fig. 10. Effective confining pressure-shear strain and damage index fitting surface.

perform error analysis, the ratio of the fluctuation range to the absolute value of each coefficient is defined as the fluctuation coefficient λ . The calculated values of λ are shown in Table 4, all of which are less than 0.5, indicating that the fitted coefficients exhibit limited variability and demonstrate good overall stability.

Due to the uncontrollable variability in pore structure

Table 4. Fluctuation coefficients of each coefficient.

Coefficient term	Fluctuation coefficient (λ)
σ_E^3	0.44
σ_E	0.40
ε^3	0.38
ε	0.24
$\sigma_E^2\varepsilon$	0.30
$\sigma_E\varepsilon^2$	0.40
$\sigma_E\varepsilon$	0.43
Constant term	0.19

among the reconstructed samples, systematic errors are present in the experimental results. To further validate the reliability of the model, three independent repeated experiments were conducted under conditions of 6 MPa confining pressure and 20% hydrate saturation. The corresponding shear strain values of 2.5%, 7.5% and 12.5% obtained from these experiments were substituted into Eq. 10. The absolute difference between the model-predicted permeability K' and the experimentally measured permeability K , normalized by K , was calculated as the error. The fluctuation amplitude A_K represents the maximum difference in permeability among data points obtained under identical testing conditions. The results, summarized in Table 5, show that all errors are below 10%, demonstrating the reliability of the proposed prediction model. Furthermore, the

Table 5. Error between the permeability model and laboratory experiments.

Shear strain $\varepsilon/\%$	Experimental permeability K/mD	Estimated permeability K'/mD	Experimental error/%	Fluctuation amplitude A_K/mD
Control group 1=2.5	54.41	57.52	5.4	4.95
Control group 2=2.5	59.36	57.52	3.2	4.95
Control group 1=7.5	48.51	44.96	7.9	5.75
Control group 2=7.5	42.76	44.96	4.9	5.75
Control group 1=12.5	38.07	41.61	8.5	6.53
Control group 2=12.5	44.61	41.61	7.2	6.53

accuracy improves as specimen deformation decreases, which is consistent with the expectation that larger deformations amplify heterogeneity and structural damage, leading to increased deviations between predicted and measured permeability.

Since the volume and difficulty of gas extraction are closely related to reservoir permeability, risks associated with natural gas hydrate exploitation include uncontrolled gas leakage from the seabed following hydrate dissociation, uneven seabed subsidence, and submarine landslides (Chong ZR et al., 2016). Addressing these challenges requires an improved understanding of geological structures and marine environmental conditions, particularly the evolutionary behavior of MH reservoir permeability. This, in turn, necessitates the development of appropriate mathematical models to predict reservoir hydrocarbon production potential and to evaluate environmental impacts both before and after hydrate extraction. Therefore, the primary application value of the proposed permeability model can be summarized as follows.

(i) Analyzing the evolutionary patterns of permeability in methane hydrate reservoirs at different burial depths.

(ii) Assessing extraction difficulty and predicting hydrocarbon potential under varying geological conditions of MH reservoirs.

(iii) Providing data support for establishing conditions favorable for the exploitation of hydrate-bearing strata and deeper underlying free-gas layers.

(iv) Offering a scientific basis for enhancing environmental impact assessments and improving environmental management strategies related to hydrate development.

5. Conclusions

The permeability characteristics of methane hydrate-bearing sediment (MHBS) are crucial for predicting hydrocarbon generation potential of MH reservoirs, assessing production difficulty, and formulating effective development strategies. To more accurately characterize MHBS permeability, this study conducted triaxial shear-seepage experiments incorporating multiple influencing factors and subsequently developed a permeability prediction model that accounts for their coupled effects. The main conclusions are as follows.

(i) During triaxial shear, permeability exhibits a nonlinear evolution, initially decreasing and subsequently stabilizing or increasing. In the strain-hardening stage, pore compression

leads to a rapid decline in permeability. Thereafter, high confining pressure intensifies particle breakage and pore filling, whereas specimens under low confining pressure or with high hydrate saturation may exhibit permeability increases due to shear-induced dilation or shear band formation.

(ii) Permeability decreases nonlinearly with increasing effective confining pressure, with the stress-sensitivity coefficient reaching its maximum in the low-pressure range. Effective confining pressure reduces permeability by compressing flow channels, and this effect is most pronounced during the early stages of stress application.

(iii) Hydrate saturation is negatively correlated with permeability, and for every 10% increase in hydrate saturation, gas-phase permeability decreases by more than 20% on average. Hydrate saturation is therefore the dominant factor governing MHBS permeability. Hydrate cementation substantially mitigates the compressive influence of effective confining pressure on pore structure.

(iv) Effective confining pressure, hydrate saturation, and shear strain act in a coupled manner, with each factor exerting different levels of influence on permeability. Their relative contributions vary depending on specific operational conditions and must therefore be considered collectively in engineering applications.

(v) A three-factor coupled permeability model ($R^2=0.99$, validation error $<10\%$) is established, providing a quantitative tool for production capacity forecasting and environmental impact assessment of hydrate reservoirs.

CRedit authorship contribution statement

Tian-Xiang Ao wrote the entire paper. Tian-Xiang Ao and Le Zhao conducted analyses and the figures. Ming-Zhong Gao and Ming-Zhu Qi contributed to the conceptualization of the paper. Tian-Xiang Ao, Meng Xu and Yi-Kun Yang carried out the experiment. All authors were involved in revising the manuscript and approved the submitted version.

Declaration of competing interest

The authors declare no conflicts of interest.

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