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Laboratory testing of clayey-silty hydrate reservoir exploitation: Considering the permeability-stress coupling effect

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ABSTRACT

Elucidating the multi-field, multi-phase coupling mechanisms in submarine hydrate reservoirs is essential for releasing their energy potential. Current research gaps remain in understanding the permeability-stress coupling characteristics of hydrate reservoirs. This study conducted permeability-stress coupling tests on hydrate-bearing clayey-silty sediments (HBCS). The seepage characteristics and mechanical response of HBCS under seepage-stress coupling effects were investigated. The results indicate that under stress conditions, the seepage flow of HBCS follows a logarithmic relationship with axial strain, with its rate of increase decelerating as axial strain grows. Apparent permeability decreases rapidly at first and then more gradually with increasing axial strain. Hydrate saturation (S_h) and seepage pressure difference (P_s) exhibit a coupling effect on apparent permeability. At low- S_h levels, particle migration induced by seepage reduces permeability. At high- S_h levels, permeability is affected by two competing mechanisms (pore expansion and particle migration) driven by seepage forces. Unlike triaxial tests for HBCS, under seepage conditions, the plastic deformation capacity of HBCS is enhanced. The stress-strain curve exhibits strain hardening and plastic flow, and lacks obvious strain softening. Shear strength decreases with increasing S_h and P_s , while the secant modulus E_{50} rises with both parameters. During hydrate exploitation, production efficiency correlates with S_h . In low- S_h reservoirs, a “slow and steady” production strategy is recommended to prevent sand production and wellbore blockage. In high- S_h reservoirs, increasing P_s can promote pore expansion and fracture propagation, thereby enhancing production efficiency. This study provides a reference for engineers to understand the multi-field and multi-phase coupling characteristics during the exploitation of hydrate reservoirs.

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1. Introduction

As an important part of marine energy, accelerating the commercial development of natural gas hydrate is of great significance to building a resource-saving and environmentally sustainable production model. Nevertheless, their exploitation involves complex processes characterized by multi-physical field coupling and multi-phase fluid flow. The interaction between seepage and stress fields

may induce reservoir instability, wellbore collapse, methane leakage, and other geo-environmental challenges (Collett et al., 2019; Tan et al., 2021; Zhao et al., 2025b). Therefore, investigating the complex behaviors of hydrate-bearing sediments (HBS) under seepage-stress coupling conditions. It is essential for optimizing exploitation strategies, guiding engineering site selection, and mitigating operational risks. Such understanding will also provide a scientific basis for advancing new energy development, preventing and controlling geological disasters, and supporting marine engineering construction (Abbasi et al., 2022; Yang et al., 2023b).

As a multiphase porous medium, the permeability of natural gas hydrate reservoirs governs fluid transport behavior during exploitation (Zhang et al., 2025b; Zhao et al., 2024). Researchers have employed various methods to investigate the permeability characteristics of HBS (Hu et al., 2024; Xu and Konno, 2024). Through laboratory tests, scholars investigated the influence of

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factors such as hydrate saturation, confining pressure, and sediment type on HBS permeability. The principal conclusion is that the permeability of HBS exhibits a non-linear decrease with increasing hydrate saturation and confining pressure. This is attributable to the filling effect of hydrates on the pore structure and the compressive effect of confining pressure thereon (Gao et al., 2019; Zhang et al., 2024b). Matrix particle type also affects permeability, which is generally higher in sand-particle sediments than in clay-particle sediments (Deng et al., 2024; Konno et al., 2015). In addition, considering the complexity of hydrate reservoir structure, reservoir heterogeneity and anisotropy reduce the sensitivity of permeability to variations in hydrate saturation (Li et al., 2024f). Concurrently, the influence of reservoir hydrate saturation on gas-phase and water-phase permeability exhibits distinct variations. As hydrate saturation increases, the relative permeability of the water phase increases while that of the gas phase decreases (Wang et al., 2024b). Significant progress has also been made in understanding the seepage characteristics of HBS at the mesoscopic level. Based on CT scans and pore network models, scholars have conducted research into the seepage characteristics of HBS, focusing on its microstructure, anisotropy, and heterogeneity. Research findings indicate that the occurrence pattern of hydrates significantly influences the seepage characteristics of HBS, with the absolute permeability of the grain-coating type being higher than that of the pore-filling type (Luo et al., 2024). However, regardless of the occurrence pattern, when the pore throat radius is small and the capillary pressure is high, the relative permeability of the water phase is significantly reduced (Bao et al., 2025). Fractures, as a quintessential manifestation of reservoir heterogeneity, can significantly enhance reservoir permeability when mature. Conversely, a reduction in fracture dip angle will decrease permeability (Li et al., 2024e). This aptly illustrates the anisotropy of reservoir permeability, which intensifies with increasing hydrate saturation and stress levels (Wu et al., 2024; Zhang et al., 2024c). Moreover, concerning practical issues in hydrate extraction, robust permeability models and constitutive models facilitate production assessment and reservoir risk prediction (Zhou et al., 2024a). Permeability models evolved rapidly from early empirical models, gradually establishing formulations capable of describing changes in hydrate saturation, confining pressure, pore pressure, and particle size (Gao et al., 2019). Given the long-term nature of hydrate reservoir exploitation, creep effects have also been incorporated into permeability models and constitutive models (Lei et al., 2025; Qu et al., 2025). However, existing models remain inadequate in describing the coupling relationship between permeability and stress. This necessitates intensified exploration of the permeability-stress coupling relationship, providing extensive databases to underpin the establishment of models.

At present, advances in testing equipment and the diversification of research methods have enabled increasingly extensive and in-depth studies on the mechanical properties of natural gas hydrates (Wang et al., 2024a; Wu et al., 2026; Zhang et al., 2023; Zhong et al., 2024). Taking triaxial shear tests as an example, scholars have conducted a series of investigations focusing on factors such as hydrate saturation, sediment particle morphology and type (Guo et al., 2022; Wu et al., 2022), temperature and pressure conditions (Chen et al., 2022; Zhang et al., 2022; Zhou et al., 2021), degree of consolidation (Liu et al., 2023; Zhao et al., 2023c), and hydrate occurrence pattern (Liu et al., 2024; Zhang et al., 2024a). A general consensus has been reached regarding the influence of these factors on the mechanical behavior of HBS. For instance, increases in hydrate saturation and effective confining pressure significantly enhance the strength and stiffness of HBS; clay particles facilitate sliding and rolling among the

matrix particles, while fine sand particles help improve strength and promote dilatant behavior. Building on single-factor studies, researchers have begun to explore more complex aspects such as coupled loading conditions, multi-factor and multi-field interactions, anisotropy, and heterogeneity. These efforts are gradually revealing the intricate mechanical properties of submarine hydrate reservoirs (Li et al., 2024d; Ma et al., 2025a; Tang et al., 2024; Zhou et al., 2024b). Studies indicate that cyclic loading leads to the accumulation of plastic deformation in HBS, causing the material to approach (though never fully attain) an ideal elastic state (Liu et al., 2025a). Furthermore, reservoir fractures, as well as the sequence, dip angle, and thickness of layered hydrate zones, significantly influence the mechanical response of HBS (Du et al., 2023; Wang et al., 2025b; Ye et al., 2024). Specifically, the formation and propagation of fractures gradually reduce the strength of HBS, whereas increases in the thickness, dip angle, and saturation of hydrate layers can enhance strength to some extent.

In light of the current scarcity of research into the multi-field coupling characteristics of hydrate reservoirs, this study conducted permeability-stress coupling tests on hydrate-bearing clayey-silty sediments (HBCS). The coupled state of HBCS under the combined effects of seepage and stress fields is simulated in the laboratory. This paper investigates the influence of hydrate saturation and seepage pressure difference on the seepage characteristics and mechanical behaviour of HBCS. Based on the test results, this research analyzes the seepage-shear coupling mechanism of HBCS. Concurrently, drawing upon existing hydrate extraction experience and technology, corresponding engineering suggestions and insights are provided. This work provides essential parameters (such as permeability, shear strength, and elastic modulus) for stability analysis during hydrate production.

2. Test design

2.1. Test materials and apparatus

To accelerate the development of emerging energy sources, based on the particle size distribution of natural samples of HBCS from Well SH-2, 7 in the Shenhu area of the South China Sea, this paper uses a mixture of quartz sand and South China Sea clay as the host sediment (Liu et al., 2012). The particle size distribution of natural samples and artificially prepared clayey-silty samples is shown in Fig. 1. Among them, Fig. 1(a) and (b) are seabed clay; Fig. 1(c) is quartz sand; Fig. 1(d) is a mixed sample of clay and

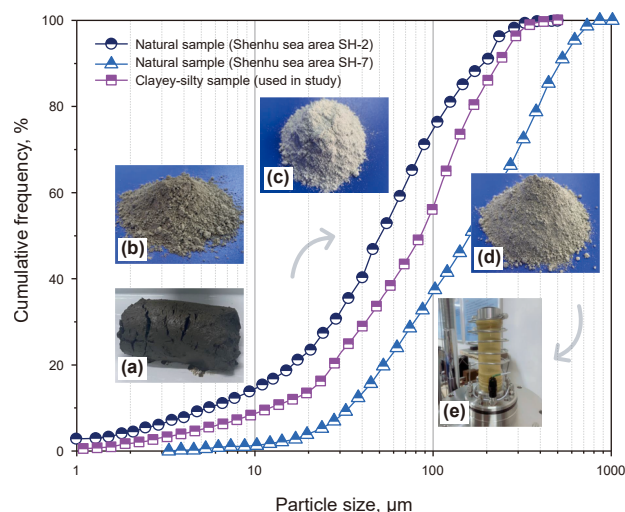


Fig. 1. Particle size distribution curves of the clayey-silty sediments.

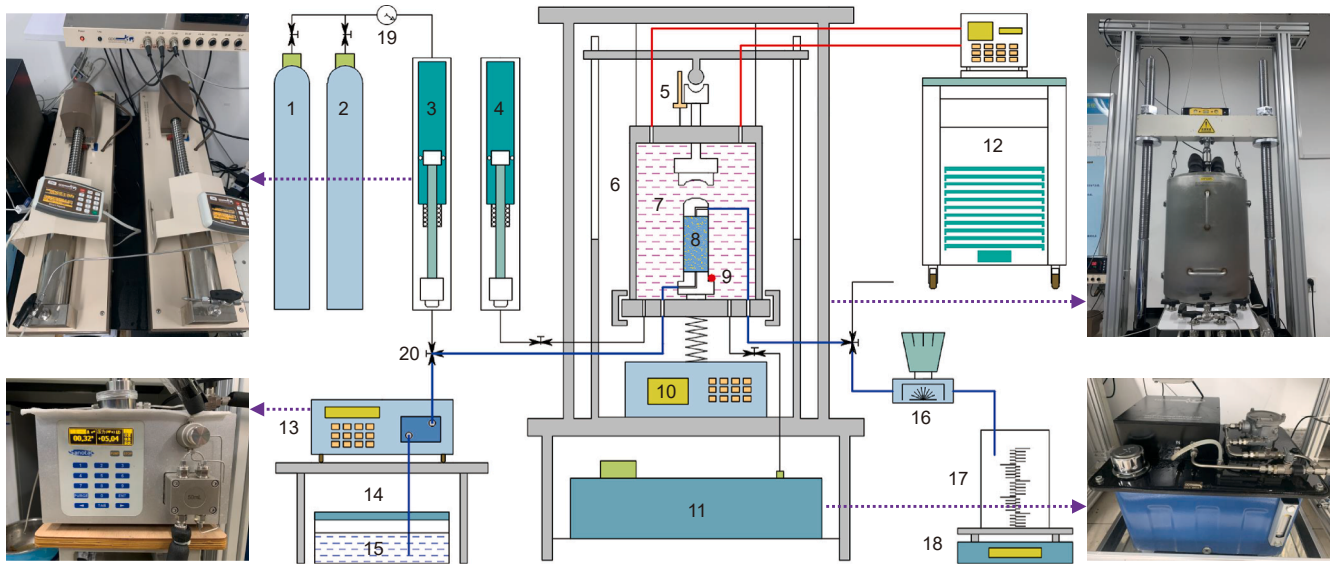


Fig. 2. Hydrate permeability-stress coupling test system. 1: Methane gas cylinder; 2: Nitrogen gas cylinder; 3: Pore pressure controller; 4: Confining pressure controller; 5: Displacement sensor; 6: Pressure chamber; 7: Silicone oil; 8: Sample; 9: Temperature sensor; 10: Axial pressure controller; 11: Oil transfer pump; 12: Water bath (temperature controller); 13: Infusion pump; 14: Incubator; 15: Low-temperature deionized water; 16: Back pressure valve; 17: Volumetric flask; 18: Electronic scale; 19: Pressure gauge; 20: Valve.

quartz sand; Fig. 1(e) is the filled sample (diameter: 50 mm, height: 100 mm).

Fig. 2 shows the schematic diagram and actual photograph of the test apparatus. The test system mainly consists of five modules: pressure loading module, temperature control module, gas supply module, seepage control module, and data acquisition module. The control range and accuracy of the test apparatus are shown in Table 1. The tests used methane gas with a purity of 99.9% to form hydrates.

It should be noted that the permeability-stress coupling test apparatus is completed by modifying the hydrate triaxial shear test apparatus (Zhao et al., 2023a). Unlike the hydrate triaxial shear test apparatus, the permeability-stress coupling test apparatus is equipped with a low-temperature seepage system (Wu et al., 2025). This enables the test to simultaneously obtain the changes of permeability, stress, and other relevant parameters of the sample. Data acquisition is automatically recorded by GDSLAB software, and the acquisition frequency is set to once every 10 s. Data are plotted using Origin software. For the stress-strain curve and seepage flow curve, display one data point for every 40 data points, with the remaining points connected automatically.

2.2. Test methods

This study employs the gas-excess method to prepare HBCS samples, indirectly controlling hydrate saturation by regulating water mass in sediments (Yan et al., 2022; Zhao et al., 2023d). The

estimation method of hydrate saturation is shown in Eq. (1) (McMullan and Jeffrey, 1965).

$$S_h = \frac{V_h}{V_p} = \frac{\frac{n \cdot M_w + M_c}{n \cdot M_w} \cdot m_w}{\rho_h \cdot \left(V - \frac{m_s}{G_s \cdot \rho_w} \right)} \quad (1)$$

where S_h is the hydrate saturation, %; V_h is the volume of the hydrate, mm^3 ; V_p is the volume of the pore space in the sample, mm^3 ; ρ_h is the density of the hydrate, g/cm^3 ; V is the volume of the sample, mm^3 ; m_s is the mass of the sample host sediments (clay and quartz sand), g; G_s is the specific gravity of host sediments; ρ_w is the density of the water, g/cm^3 ; n is the hydration number (5.75) (Ghiassian and Grozic, 2013); M_w is the molar mass of the water, g/cm^3 ; M_c is the molar mass of the methane, g/mol ; m_w is the mass of the water in the sample, g.

For the permeability-stress coupling test, this paper uses the steady-state method to measure permeability (Lin et al., 2023; Xu et al., 2024b). The seepage test controls the seepage pressure difference (P_s) by adjusting the inlet pressure (P_1) and outlet pressure (P_2). To effectively test and analyze the seepage field-stress field coupling characteristics of HBCS, the following assumptions are adopted in this study: a) The permeating fluid (low-temperature deionized water) is assumed incompressible. b) Steady-state continuous seepage occurs under constant pressure within the sample. c) The sample's cross-sectional area remains constant during the seepage field-stress field coupling effect. Therefore, the apparent permeability (K) can be obtained by calculating the seepage flow (Q) into the sample per unit time, with the calculation method shown in Eq. (2):

$$K = \frac{\mu L Q}{A P_s t} = \frac{\mu (L_i - S_r \cdot t) Q}{A (P_1 - P_2) t} \quad (2)$$

where K is the apparent permeability, mD ; μ is the viscosity of water ($1.731 \times 10^{-3} \text{ Pa}\cdot\text{s}$ for 1°C); L is the sample height, m; S_r is the shear rate, m/s ; Q is the seepage flow over some time, ml ; A is the sample cross-sectional area, m^2 ; P_s is the seepage pressure difference, Pa; P_1 , P_2 are the inlet pressure and outlet pressure of

Table 1
Technical specifications of the test.

Technical indicators	Range	Accuracy
Axial stress	0–100 kN	$\pm 0.1\%$
Confining pressure	0–32 MPa	$\pm 0.1\%$
Pore pressure	0–32 MPa	$\pm 0.1\%$
Axial deformation	0–50 mm	$\pm 0.075\%$
Temperature control	-20 – 65°C	$\pm 0.1^\circ\text{C}$
Seepage flow	0.001–49.999 mL/min	$\pm 0.5\%$
Seepage pressure	0.01–30 MPa	$\leq 0.5\%$

the seepage, respectively, Pa; t is the seepage time, s. Compared with Darcy's law used in conventional seepage tests, shear rate is introduced into Darcy's law in this paper (Ma et al., 2025b). This reflects the influence of the triaxial shear process on permeability.

Additionally, during the permeability-stress coupling test, the pore pressure is affected by the seepage pressure difference (P_s). Therefore, the calculation method of the effective confining pressure (σ') during the test process is defined here, as described in Eq. (3):

$$\sigma' = P_c - P_p = P_c - \frac{P_1 + P_2}{2} \quad (3)$$

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

2.3. Test steps and test scheme

The main steps of the permeability-stress coupling test are as follows:

(1) HBCS sample preparation.

- Sample preparation and freeze-thaw cycles. Using the “layered filling method”, the clayey-silty samples were filled into a rubber membrane with a thickness of 2 mm. Finally, a cylindrical sample with a diameter of 50 mm and a height of 100 mm was prepared (Liu et al., 2022). The modules of the test apparatus are effectively connected, and the samples are subjected to freeze-thaw cycles using a water bath system. In Fig. 3, points A, B represent the temperature and pore pressure during freeze-thaw cycles.
- Hydrate formation. The confining pressure and pore pressure of the sample were regulated using the “pressure loading module”. Hydrate formation was carried out at a temperature of 0.5 °C and a pore pressure of 5 MPa (point D in Fig. 3). The process was maintained for over 48 h, or until the volume change rate recorded by the pore pressure controller fell below 1 mm³/min. Under these conditions, it was assumed that all the water present in the sample had reacted with methane gas to form hydrates.

- Gas displacement. After the hydrate formation is complete, excess methane is displaced with nitrogen gas. The displacement process needs to maintain the pore pressure within the hydrate phase equilibrium pressure. Meanwhile, to reduce the upper pressure limit of subsequent seepage tests, the outlet pressure was set at 4 MPa, the inlet pressure at 5 MPa, and the pore pressure at approximately 4.5 MPa during the gas displacement process.

(2) Seepage preparation.

- Low-temperature deionized water preparation. Based on the phase equilibrium curve in Fig. 3, the water temperature must be kept below 4.2 °C during seepage. Low-temperature deionized water is achieved by the ice-water mixing method. Measurements show that the temperature of deionized water in the pressure chamber ranges from 0.1 to 0.8 °C, and the water temperature at the seepage outlet is between 1.2 and 2 °C. As shown in Fig. 3, the temperature-pressure conditions during the seepage process satisfy the phase equilibrium conditions of hydrates.
- Sample water saturation and consolidation. The same displacement method was used to displace nitrogen gas with low-temperature deionized water. Afterwards, the sample consolidation was carried out at a pore pressure of 4.5 MPa. Consolidation adopts a graded consolidation method, such as when the target effective confining pressure is 3 MPa, consolidation was carried out sequentially at effective confining pressures of 1, 2, and 3 MPa. The consolidation standard is that the change of sample volume within 5 min is less than 5 mm³.
- Steady-state seepage debugging. The tests used the steady-state method to measure permeability. Therefore, it required seepage debugging to create the steady water phase seepage. According to the test scheme, the infusion pump and seepage channel are opened, and the specified seepage inlet pressure is set. Debugging is considered complete when the seepage outlet and inlet pressures are constant and the outlet water flow is smooth.

(3) Permeability-stress coupling test.

The shear test was started according to the test scheme. In this study, the shear rate was 0.1 mm/min, the effective confining pressure was controlled at 3 MPa, and the reactor temperature was 0.5 °C. During the shearing process, the confining pressure and pore pressure are kept constant, and the axial stress increases. The final sample is destroyed because the deviatoric stress reaches the critical value. The loading path for the test is identical to that of the conventional consolidated drained triaxial shear test, wherein the p - q curve is an inclined straight line. Stop the test when the axial strain reaches 20%. Afterwards, the pressure and temperature were adjusted to point E in Fig. 3 to bring the sample out of phase equilibrium. After the hydrate has decomposed, dismantle the test apparatus to complete the test.

Based on the above methods and steps, 12 samples were prepared in this study. The tests were conducted using the control variable method, which considered the effects of hydrate saturation and seepage pressure difference on HBCS. Therefore, hydrate saturation and seepage pressure difference are the independent variables of the test, and confining pressure, pore pressure, and seepage inlet pressure are the dependent variables. The conditions and parameters of the test are detailed in Table 2.

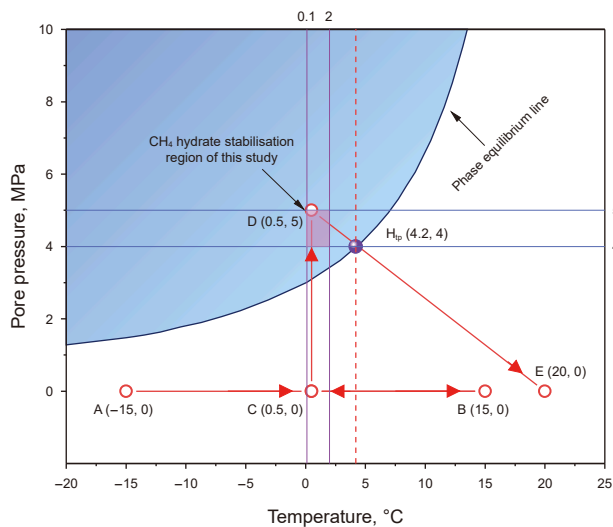


Fig. 3. Temperature and pore pressure path and phase equilibrium range of methane hydrate during the test.

Table 2
Permeability-stress coupling test scheme for HBCS.

S_h , %	σ' , MPa	P_c , MPa	P_p , MPa	P_s , MPa	P_1 , MPa	P_2 , MPa	S_r , mm/min
0							
10		7.5	4.5	1	5		
20	3	8.5	5.5	3	7	4	0.1
30		9.5	6.5	5	9		

Notes: S_h is the hydrate saturation; σ' is the effective confining pressure; P_c is the confining pressure; P_p is the pore pressure; P_s is the seepage pressure difference; P_1 is the seepage inlet pressure; P_2 is the seepage outlet pressure; S_r is the shear rate.

3. Analysis of test results

3.1. Permeability characteristics under stress

By measuring changes in seepage flow during permeability-stress coupling tests, this section primarily explores the

permeability characteristics of HBCS under stress. The relationship between seepage flow (Q), apparent permeability (K), hydrate saturation, and seepage pressure difference during stress loading is discussed.

3.1.1. Effect of stress loading on seepage flow

3.1.1.1. Variation law of Q - ε_a curve. Fig. 4 shows the Q - ε_a curves for 12 groups of tests. The results show that the Q - ε_a curve exhibits distinct nonlinearity. Meanwhile, it demonstrates approximate linearity in the early stress loading stage and nonlinearity in the middle-to-late stress loading stages. The Q - ε_a curve is similar to a logarithmic function ($y = \log_a x$, $a > 1$). As the strain ε_a (x) increases, the increment of seepage flow ΔQ (Δy) gradually decreases. Furthermore, in terms of details, as shown in the enlarged region ABC of Fig. 4, the Q - ε_a curve exhibits a smooth line (where the seepage flow remains constant as strain increases). This reflects the influence of stress on water-phase seepage. During stress

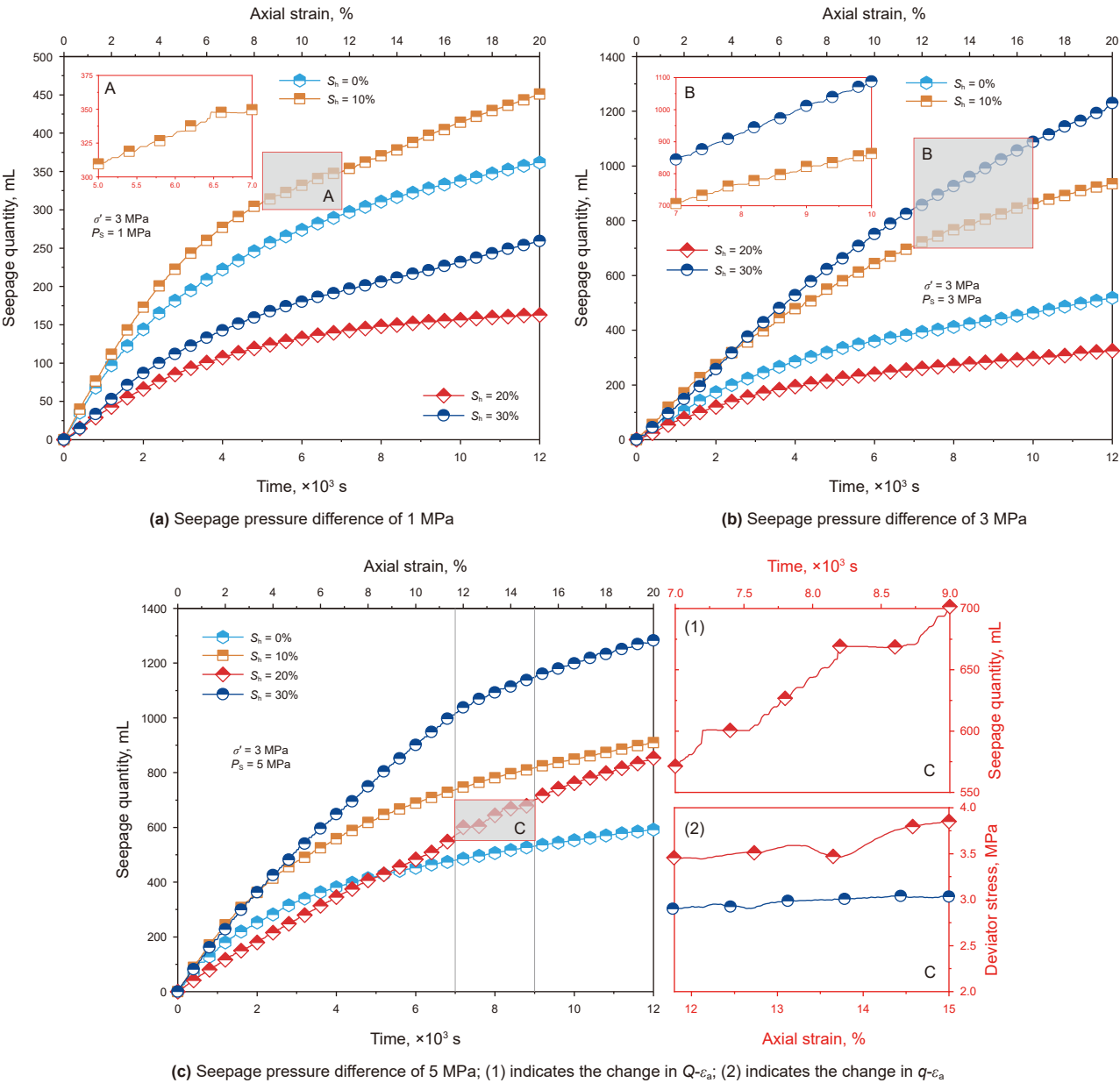


Fig. 4. Effect of hydrate saturation on seepage flow under the seepage pressure difference of 1, 3, 5 MPa.

loading, the skeletal structure of HBCS changes, and the seepage pore-throat continuously shrinks or even closes under stress compression. This leads to a temporary cessation of water-phase seepage and the seepage flow increment becomes smaller.

Fig. 4(c) enlarged region (1) and (2) describe the seepage flow and stress changes in the region C, respectively. The enlarged region (2) is taken from the stress-strain curve in Section 3.2.1. From the correspondence between (1) and (2), it can be seen that when the stress change is small, the seepage flow increases rapidly. At this point, as axial strain increases, most seepage pore throats may not be squeezed and shrunk. Therefore, the water-phase seepage velocity (the slope of the Q - ε_a curve) remains stable, while the seepage flow rate increases uniformly. Simultaneously, due to the lack of contact and support between particles, stress does not increase significantly but remains relatively stable. When stress changes significantly (at time 8.2 and strain 13.5), the seepage flow remains constant while stress increases rapidly. At this point, as axial strain increases, most seepage pore throats may be squeezed shut. This causes the water phase flow to temporarily cease. Stress increases due to particle contact and compression.

It is worth noting that not all data have such a corresponding relationship, which is determined by the complex characteristics within HBCS. However, the special case in Fig. 4(c) is sufficient to illustrate the nature of mutual correspondence and coupling between seepage field-stress field in HBCS.

3.1.1.2. Influence of hydrate saturation and seepage pressure difference on Q - ε_a curves. As shown in Fig. 4(a) and (b), under seepage pressure difference of 1, 3 and 5 MPa, the seepage flow of HBCS exhibits a trend of first increasing, then decreasing, and finally increasing again as the hydrate saturation increases. This is because hydrate changes the pore structure of sediments. When the hydrate saturation is low ($S_h = 10\%$), the presence of hydrates improves the particle skeleton of the sediment, giving it a more

favorable flow pore-throat. Subsequently, as the hydrate saturation increases ($S_h = 20\%$), the flow pore-throat is blocked by hydrates, making it more difficult for water to pass through the sample and slowing down the flow velocity. When the hydrate saturation ($S_h = 30\%$) further increases, the cementation, supporting, and filling functions of hydrates are destroyed during consolidation and stress loading processes. This leads to an increase in flow pore-throats, accelerated flow velocity, and increased seepage flow.

The above results correspond to the results of CT-shear test (Huang et al., 2024). Huang et al.'s research indicates that during the 3%–6% strain stage, pore space continues to be compressed, but the compression of some pores has reached its limit. Sand particles rotated to optimize the force chain transmission, causing an expansion of the pore space. Simultaneously, after the cementation failure, significant particle separation occurred. Therefore, as shown in Fig. 5, during the shearing process, there are phenomena of pore expansion and pore throat increase. Concurrently, in this study, if the hydrate particles are intact when $S_h = 30\%$ (Cementation has not failed), then the plugging effect of hydrate on sediment pores is higher than $S_h = 20\%$. This is consistent with the research results that hydrate saturation increases, then sediment porosity decreases (Bao et al., 2025; Li et al., 2025a). However, as shown in Fig. 4, the seepage flow curve for $S_h = 30\%$ consistently lies above that for $S_h = 20\%$. This reflects the damaging effect of consolidation on the hydrate.

As shown in Fig. 4(c), with the further increase in seepage pressure difference (5 MPa), the effect of hydrate saturation on seepage flow changed. When $S_h = 20\%$, the seepage flow begins to exceed that of the hydrate-free sediment as the axial strain increases, and approaches HBCS with $S_h = 10\%$. This may be similar to the dominant seepage channels of seepage in the field of rock mechanics (Wang et al., 2025c; Xu et al., 2024b). Under the action of relatively large seepage pressure difference, the seepage force

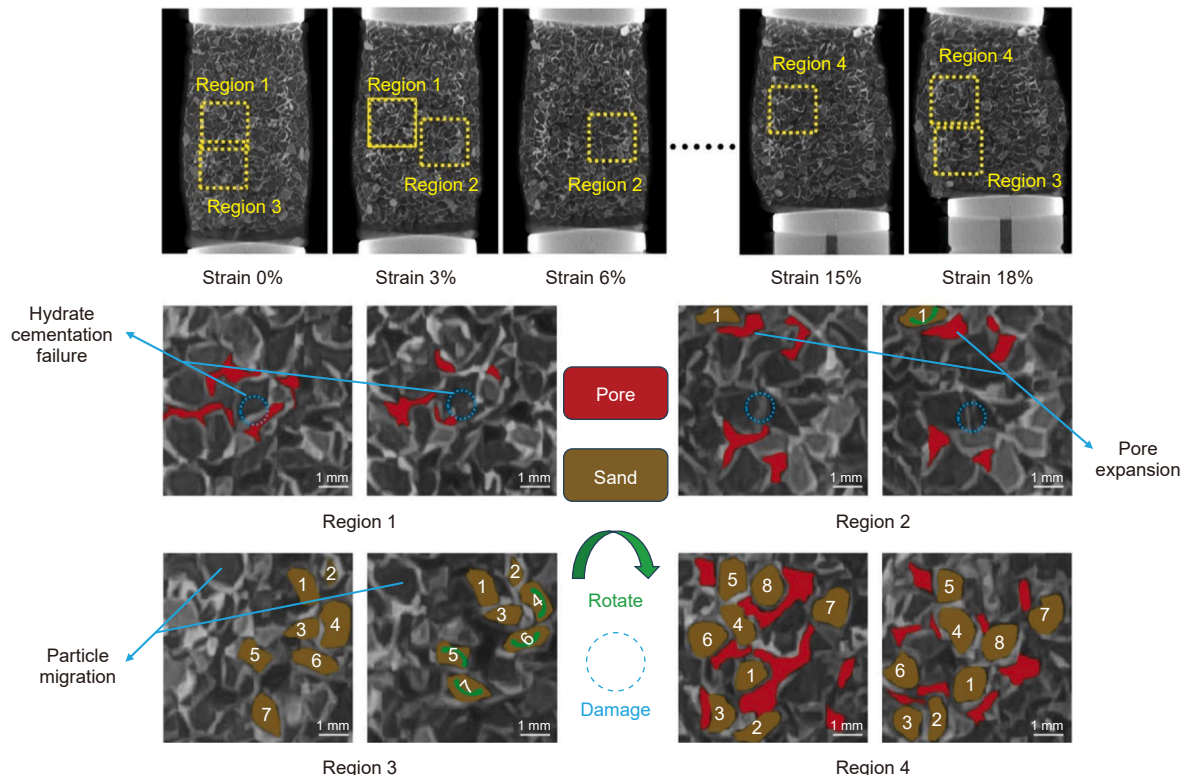


Fig. 5. CT images during the triaxial shear process (Huang et al., 2024).

expands some seepage channels, thus forming a dominant flow channel (Li et al., 2024e; Xu and Konno, 2024). Therefore, in the hydrate exploitation process, for the reservoir with high hydrate saturation, increasing the initial seepage pressure difference is conducive to forming the dominant exploitation path. Its internal mechanism is similar to hydraulic fracturing of rocks (Liu et al., 2025b).

As shown in Fig. 6, the effect of seepage pressure difference on HBCS seepage flow is relatively simple: seepage flow increases as seepage pressure difference increases. Notably, apart from the formation of dominant seepage channels under the conditions of ($P_s = 5$, $S_h = 20$) in Fig. 6(c), which leads to a larger seepage flow. The total seepage flows at seepage pressure difference of 3 and 5 MPa are quite close under other conditions, especially in Fig. 6(b) and (d).

This indicates that seepage flow does not increase linearly with increasing seepage pressure difference. The greater the

seepage pressure difference, the smaller the positive effect on seepage flow. The reason is that as the seepage pressure difference increases, the seepage force continues to increase, and the sediment-carrying capacity of water-phase seepage is enhanced. Smaller host particles and hydrate particles move with the water flow, which will eventually block the seepage channels. This results in a reduction in the overall seepage velocity and seepage flow rate of the sample. Fig. 6(b) illustrates this point: the seepage flow at $P_s = 3$ MPa ultimately exceeds the seepage flow at $P_s = 5$ MPa.

In summary, an increase in seepage pressure difference promotes the formation of dominant seepage pathways. Simultaneously, greater seepage forces enhance the sediment-carrying capacity of water flow. This reminds engineers that the problem of sand production in hydrate mining may be related to the excessive seepage pressure difference and seepage velocity. Appropriately reducing the exploitation rate (thereby decreasing the seepage

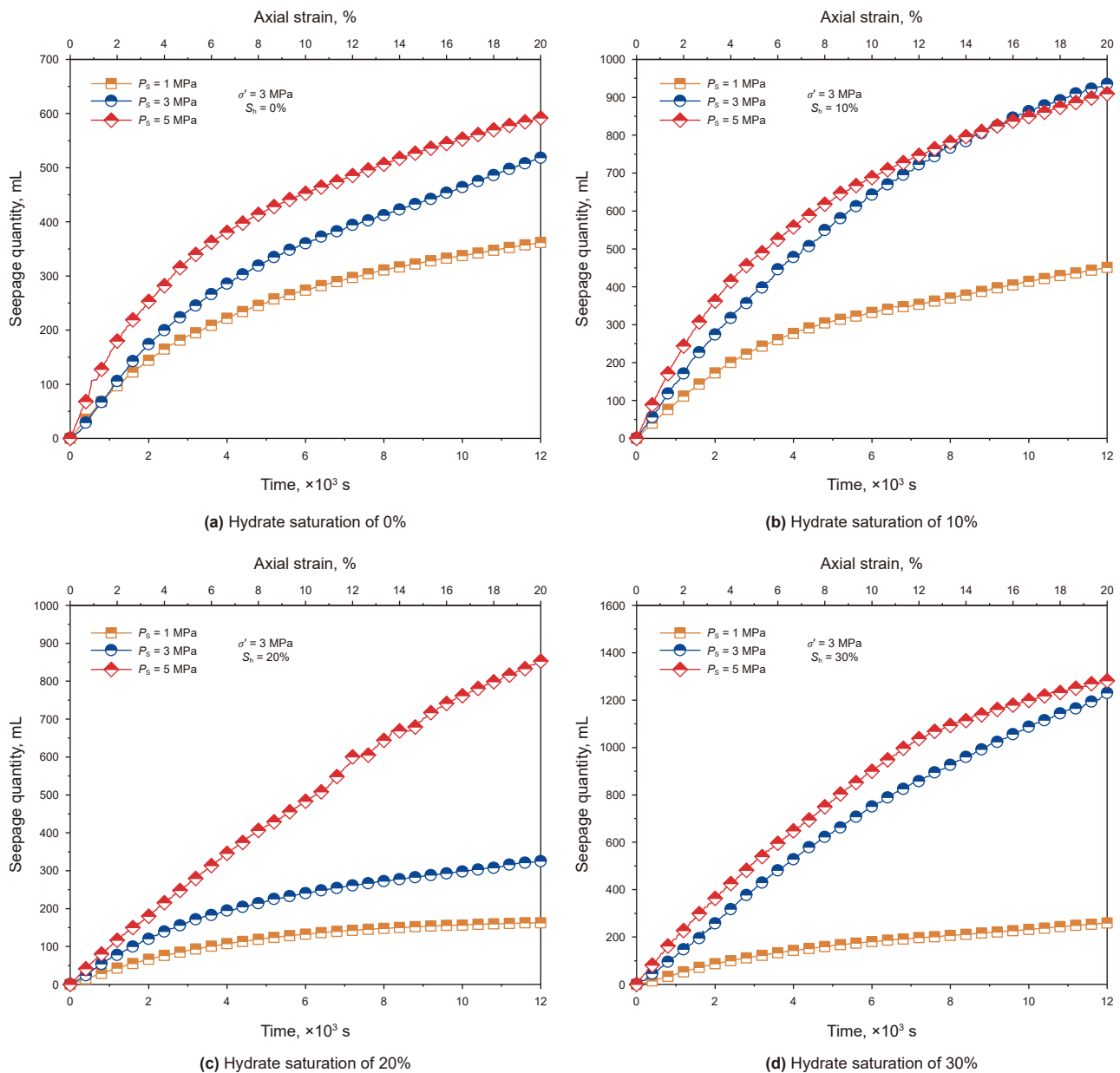


Fig. 6. Effect of seepage pressure difference on seepage flow under the hydrate saturation of 0%, 10%, 20%, 30%.

pressure difference) may be more conducive to sand production control.

3.1.2. Effect of stress loading on apparent permeability

3.1.2.1. Variation law of K - ε_a curve. Based on the calculation method of apparent permeability (K) in Section 2.3, the variation of apparent permeability was derived as shown in Figs. 7 and 8. The K - ε_a curve shape is similar to a negative exponential function ($y = a \cdot e^{-bx}$). With axial strain increases, the apparent permeability first decreases rapidly and then gradually (Lei et al., 2022b; Zhao et al., 2023b). Additionally, the K - ε_a curve exhibits significant fluctuations in the early stress loading stage, while becoming relatively stable in the late stress loading stage. Meanwhile, in the early stress loading stage, the apparent permeability exhibits a transient increase or decrease. To better explain the causes of fluctuations, the first point of the K - ε_a curve (apparent permeability at 10 s of water-

phase seepage) is defined as the initial permeability, as shown in Fig. 7(a).

In the first 10 s of the permeability-stress coupling test, it was considered that the stress loading did not affect the internal structure of the sample. Thus, the first point of the K - ε_a curve can describe the initial permeability of the sample without loading. There are two main reasons for the fluctuation of the K - ε_a curve at the early stress loading stage: a) When stress acts on the sample, the compressive stress causes pore water within the sample to extrude. Under the double promotion of seepage force and stress, the apparent permeability of HBCS suddenly increases, making it higher than the initial permeability. b) Additionally, the compressive stress in the early stress loading stage may also cause rapid reduction or closure of seepage pore-throats at the seepage outlet, leading to a decrease in apparent permeability below the initial value. Based on these two points, the rise and fall of

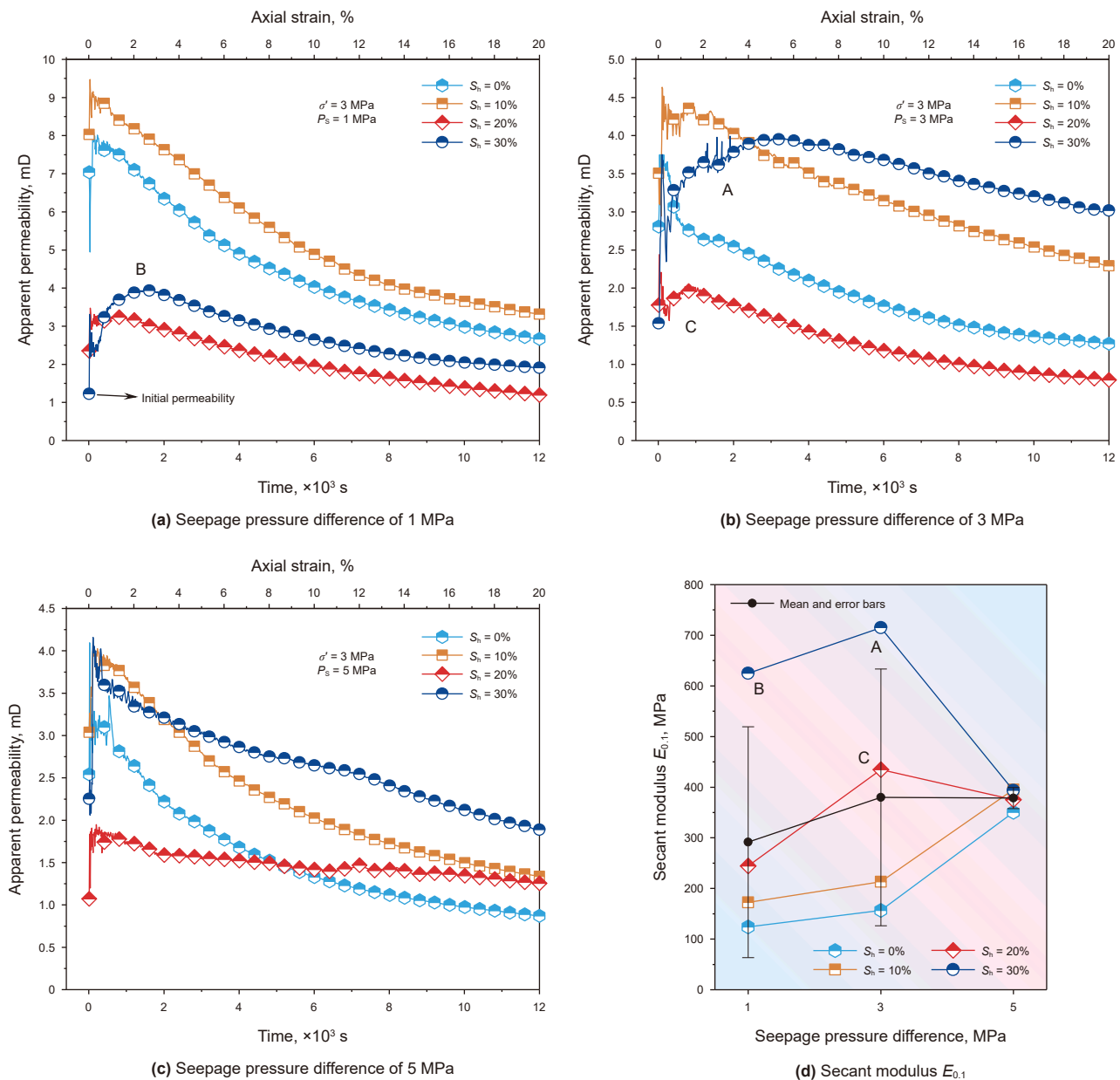


Fig. 7. Effect of hydrate saturation on apparent permeability under the seepage pressure difference of 1, 3, 5 MPa.

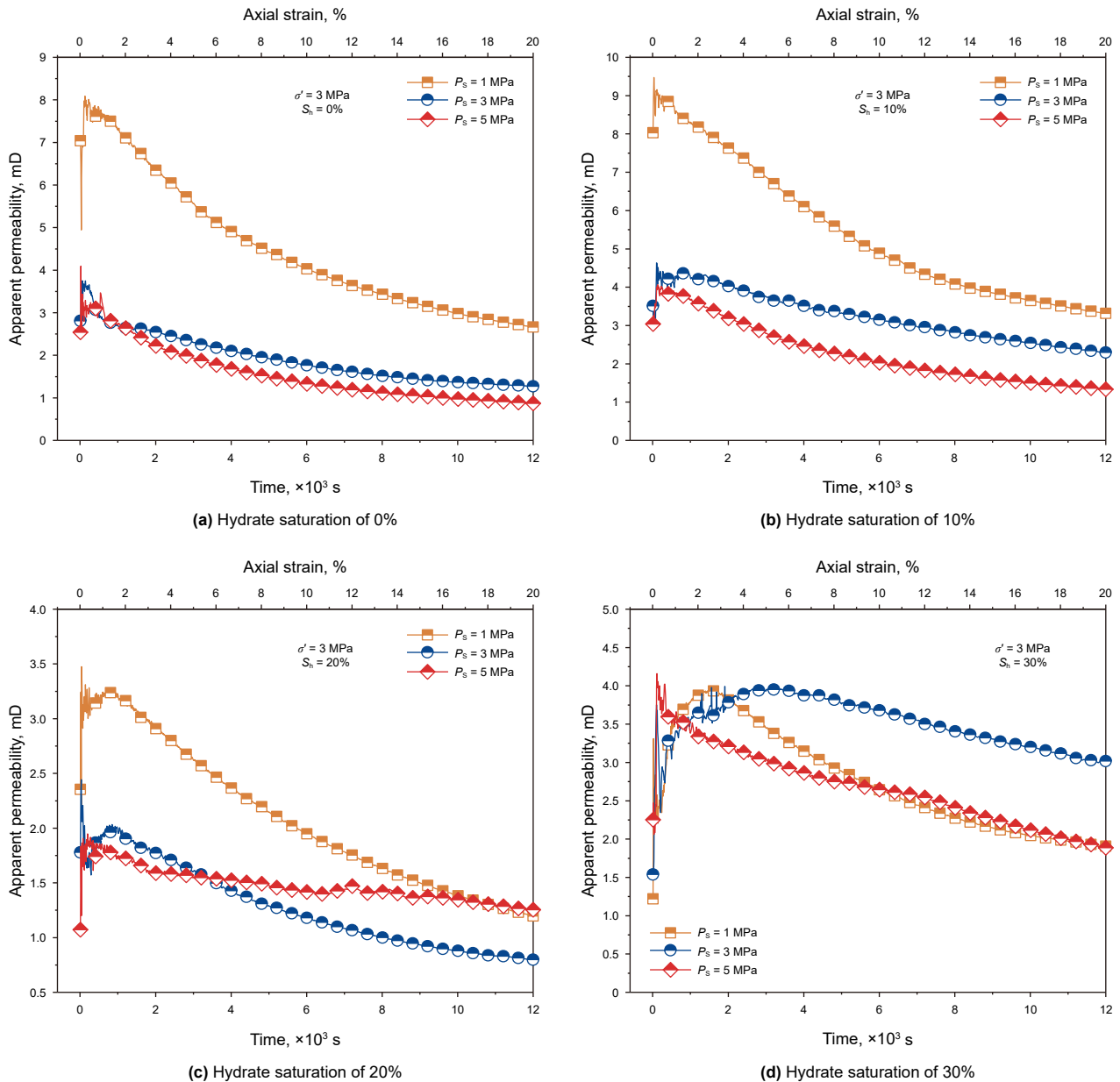


Fig. 8. Effect of seepage pressure difference on apparent permeability under the hydrate saturation of 0%, 10%, 20%, and 30%.

apparent permeability in the early stress loading stage result from the coupling effects of both mechanisms.

It is worth noting that the climb path of apparent permeability at different hydrate saturations is not uniform during the early stress loading stage. Combined with the mechanical parameter analysis in Section 3.2.2 below. It is found that the climb path of apparent permeability is related to the initial secant modulus $E_{0.1}$ of HBCS. When the initial secant modulus $E_{0.1}$ is low, the apparent permeability peaks very quickly in the early stress loading stages (axial strain $<1\%$). When the initial secant modulus $E_{0.1}$ is high (e.g., points A, B, and C in Fig. 7(d)), there exists a slow growth phase of the apparent permeability in the early stress loading stage. The peak of the apparent permeability occurs after the axial strain $>1\%$, as shown in Fig. 7(a) and (b).

The above phenomena illustrate the influence of the initial stiffness of HBCS on apparent permeability: the greater the initial stiffness, the higher the density of the particle skeleton, and the

greater the obstruction to seepage flow. As shear deformation increases, the particle skeleton of HBCS is gradually destroyed, and apparent permeability begins to gradually increase. When the apparent permeability reaches its maximum value, further increases in axial strain will narrow or close the seepage pore-throat. This results in a decrease in apparent permeability. Thus, there is a corresponding relationship between the initial stiffness and the variation in apparent permeability during the early stress loading stage. This reflects the impact of structural changes within HBCS on its seepage characteristics, illustrating the mechanism by which stress influences the apparent permeability of HBCS (Lei et al., 2022a).

3.1.2.2. Influence of hydrate saturation and seepage pressure difference on K - ε_a curves. As shown in Fig. 7, under seepage pressure difference of 1 and 3 MPa, the apparent permeability exhibits a trend of first increasing, then decreasing, and then increasing

again as hydrate saturation increases. This result is consistent with the effect of hydrate saturation on the Q - ε_a curve. Therefore, the internal mechanism of change is also similar.

It should be noted that the effect of seepage pressure difference on apparent permeability is different from its effect on seepage flow. As shown in Fig. 8(a) and (b), under conditions of $S_h = 0\%$ and 10%, the apparent permeability decreases as the seepage pressure difference increases. The reduction in apparent permeability is primarily attributed to two factors. First, the most direct factor is that the calculation of apparent permeability is inversely proportional to the seepage pressure difference. Second, an increase in seepage pressure difference enhances the sediment-carrying capacity of water, leading to blockage of seepage pore-throats (Johnson et al., 2011).

As the hydrate saturation increases, the effect of seepage pressure difference on apparent permeability begins to change. As shown in Fig. 8(c) and (d), with increasing hydrate saturation, the K - ε_a curves under different seepage pressure differences begin to intersect and overlap. This result of the coupling effect of hydrate saturation and seepage pressure difference. At low saturations, hydrates impose less restriction on sediment matrix particles. As the sediment-carrying capacity of water flow increases, matrix particles are carried by the flow to block the seepage pore-throat. At high saturations, the restriction of hydrates on matrix particles is enhanced, weakening the sediment-carrying capacity of water under the same seepage pressure difference.

In addition, under the same hydrate saturation, the effect of seepage pressure difference on the apparent permeability is also different. As shown in Fig. 8(c), under the condition of $S_h = 20\%$, the K - ε_a curves exhibit convergence and overlap when the seepage pressure difference is 1 and 5 MPa. In contrast, under conditions of $S_h = 30\%$, the K - ε_a curve of 3 MPa lies below the K - ε_a curve of 1 and 5 MPa during the initial stage of stress loading. However, during the middle and late stress loading stages, it is higher than both curves.

This phenomenon demonstrates the different effects of increasing the seepage pressure difference: a) A low seepage pressure difference ($P_s = 1$ MPa) is insufficient to actively destroy the skeletal structure of HBCS. b) A higher seepage pressure

difference ($P_s = 3$ MPa) possesses the ability to actively destroy the skeletal structure of sediments, but its sediment-carrying capacity is weak, resulting in a higher apparent permeability. c) High seepage pressure difference ($P_s = 5$ MPa) exhibits strong capabilities for both destroying sediment skeletal structures and sediment transport. As a result, high seepage pressure difference simultaneously creates new seepage pores and blocks existing ones. This causes their apparent permeability to gradually approach that of low seepage pressure difference.

In summary, under low saturation conditions, an increase in seepage pressure difference reduces the apparent permeability of HBCS. Under high saturation conditions, the situation is more complex. An increase in seepage pressure difference, on the one hand, facilitates the formation of new seepage pore-throat. But on the other hand, it enhances the sediment-carrying capacity of the water flow, leading to the blockage of seepage pore-throats. Therefore, when conducting hydrate production, determining the optimal exploitation rate (optimal seepage pressure difference) for reservoirs with different hydrate saturations is key to improving hydrate production efficiency.

3.1.2.3. Initial permeability and shear permeability. The initial permeability of HBCS determines the hydrate production efficiency (Qin et al., 2020; Zhao et al., 2025a). Figs. 9 and 10 show the initial permeability and shear permeability of HBCS, respectively. The definition of initial permeability is given in Section 3.1.2.1, while shear permeability refers to the apparent permeability of HBCS when it reaches shear strength.

As shown in Fig. 9(a), under seepage pressure differences of 1 and 3 MPa, the initial permeability first increases and then decreases with the increase in hydrate saturation. By contrast, under the seepage pressure difference of 5 MPa, the initial permeability shows a pattern of first increasing, then decreasing, and then increasing again with hydrate saturation increasing. Meanwhile, as shown in Fig. 9(b), the seepage pressure difference only promotes permeability when the hydrate saturation reaches 30%. In contrast, at the hydrate saturation of 0%, 10%, and 20%, the initial permeability decreases with the increase in seepage pressure difference.

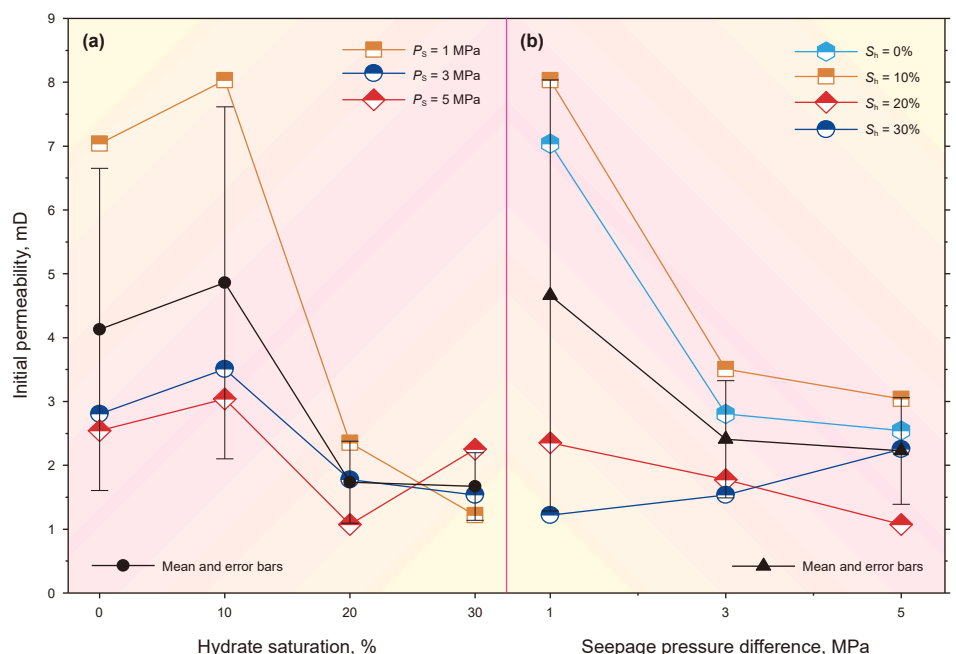


Fig. 9. Initial permeability of HBCS under seepage-stress coupling conditions.

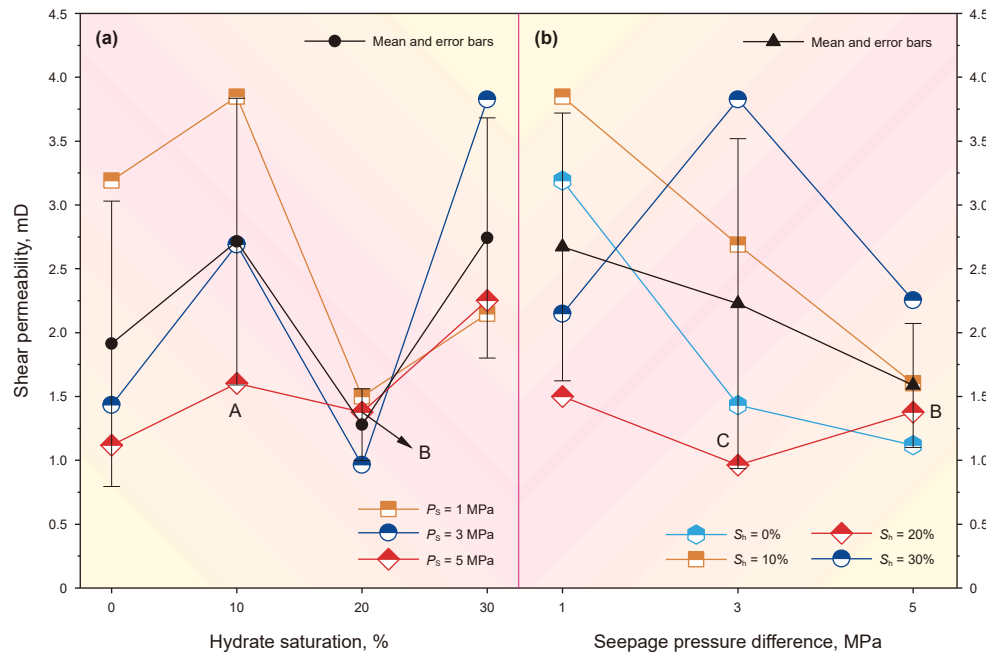


Fig. 10. Shear permeability of HBS under seepage-stress coupling conditions.

The above results reflect the effect of consolidation on the seepage characteristics of the samples. At low hydrate saturations, the cementation, supporting, and filling effects of hydrates on sediment particles are not destroyed by consolidation stress. The seepage pore-throat decreases with increasing hydrate saturation. At high hydrate saturation, consolidation stress causes the cluster body formed between hydrates and sediment particles to be destroyed, creating new seepage pore-throat and leading to initial permeability increase.

Unlike the initial permeability, under the action of stress, the effects of hydrate saturation and seepage pressure difference on shear permeability undergo significant changes. As shown in Fig. 10(a), under the same seepage pressure difference, the shear permeability exhibits a trend of first increasing, then decreasing, and then increasing again with the increase in hydrate saturation. Meanwhile, as shown in Fig. 10(b), when hydrate saturation is low ($S_h = 0\%$, 10%), shear permeability decreases with the seepage pressure difference increasing. When hydrate saturation is high ($S_h = 30\%$), shear permeability first increases and then decreases as the seepage pressure difference increases.

It is worth noting that when the hydrate saturation of 20%, the shear permeability first decreases and then increases as the seepage pressure difference increases. This is caused by special point B ($P_s = 5$, $S_h = 20$). As mentioned in Section 3.1.1.1 above, it has formed the dominant seepage channel. Under normal conditions, the permeability at point B should be lower than that at point C ($P_s = 3$, $S_h = 20$). This is also the reason for the reduced difference between points A and B in Fig. 10(a) (under other seepage pressure difference conditions, the difference in shear permeability between $S_h = 10\%$ and $S_h = 20\%$ is significant).

3.1.3. Comparison and discussion

The permeability characteristics of HBS are crucial for assessing the exploitation potential of hydrate reservoirs and predicting gas production efficiency. It not only affects the transport efficiency of gas and liquid but is also closely related to reservoir stability and potential geological hazards (Wang et al., 2024). In recent years, with the in-depth research on the exploration and trial production

of natural gas hydrates. A series of advances have been made in the permeability characteristics of HBS, and some common conclusions have been reached:

- The permeability of HBS has a power function relationship with hydrate saturation. Reservoir permeability decreases non-linearly with the increase of hydrate saturation (Bao et al., 2025; Gao et al., 2019; Ma et al., 2024; Wang et al., 2024a; Zhao et al., 2023d).
- The content of clay particles and fine particles significantly affects the permeability characteristics. The permeability of reservoirs decreases with increasing clay content and fine particle content (Chen et al., 2018; Deng et al., 2024; Lei et al., 2022b; Ma et al., 2024; Wu et al., 2018).
- Permeability exhibits a power-law relationship with effective stress. As the effective stress increases, permeability gradually decreases and tends to stabilize. Therefore, the influence of stress on HBS is more significant in the initial stage of the test (Li et al., 2024f; Wu et al., 2022; Xu et al., 2024a; Zhang et al., 2024b; Zhao et al., 2023d).

The above conclusions are mostly based on single-phase fluid permeability tests, which consider the impact of a single factor on HBS permeability. After analyzing the influence mechanism of various factors, it is found that the hydrate formation fills sediment pores and blocks flow pathways. The clay exhibits significant water sensitivity and expansion properties, while fine particles have filling and densifying effects. Increased confining pressure and effective stress compress seepage channels. Therefore, whether it is the changes in the internal factors (such as hydrate saturation and the type and content of matrix particles) of HBS, or the influences from external factors (such as confining pressure and effective stress), the essence of changes in the permeability characteristics of HBS is the expansion and contraction of seepage channels.

However, the hydrate exploration process is a multi-phase fluid flow and multi-physical field coupling process. Therefore, some scholars have conducted multi-phase flow permeability tests and

multi-physical field coupling permeability tests focusing on the permeability characteristics of hydrate reservoirs. These studies further consider the changes of gas phase and water phase permeability under the conditions of hydrate steady state and dissociation (Wang et al. 2024a, 2024b). The influence of effective stress (confining pressure) on reservoir permeability and the influence of seepage field on reservoir strength and stiffness are investigated (Zhao et al., 2023b).

Therefore, as shown in Fig. 11, the research on the permeability characteristics of HBS has undergone a transition from basic research (single-phase flow permeability tests) to advanced research (multi-field coupling permeability tests). The theoretical basis for permeability characteristics is Darcy's law, which is measured using the constant pressure method or constant flow method. In future applied research, the unsteady-state method more closely approximates the actual conditions of hydrate production. However, applied research demands higher technical capabilities and faces greater challenges in implementation. Therefore, in future research work, scholars should balance basic research and advanced research while also iteratively upgrading pressure-holding core sampling technology and transient pulse methods.

At present, there is still a long way to go in researching the permeability characteristics of HBS. For example, research on the dynamic changes in reservoir permeability characteristics under multi-physical field coupling remains limited. The seepage mechanism under multi-factor coupling has not yet been clarified. At the same time, shear deformation generated by hydrate reservoirs under seawater pressure will destroy the pore structure of sediments, promoting fluid exchange and heat transfer. Studying the coupling relationship between fluid and stress loading can

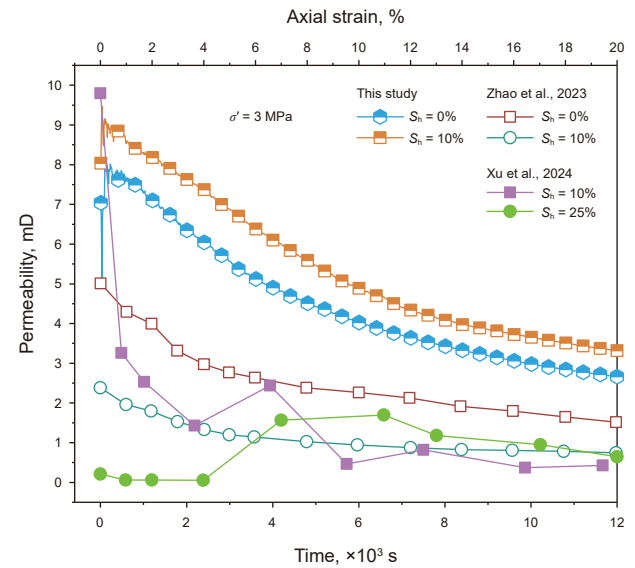


Fig. 12. The effect of stress loading on permeability (Xu et al., 2024a; Zhao et al., 2023b).

quantify the dynamic processes during hydrate exploitation and improve the accuracy of hydrate exploitation models.

Therefore, this study conducted permeability-stress coupling tests. As shown in Fig. 12, compared with previous research, this study provides the dynamic variations of permeability and flow rate of HBS throughout the entire process from stress loading to

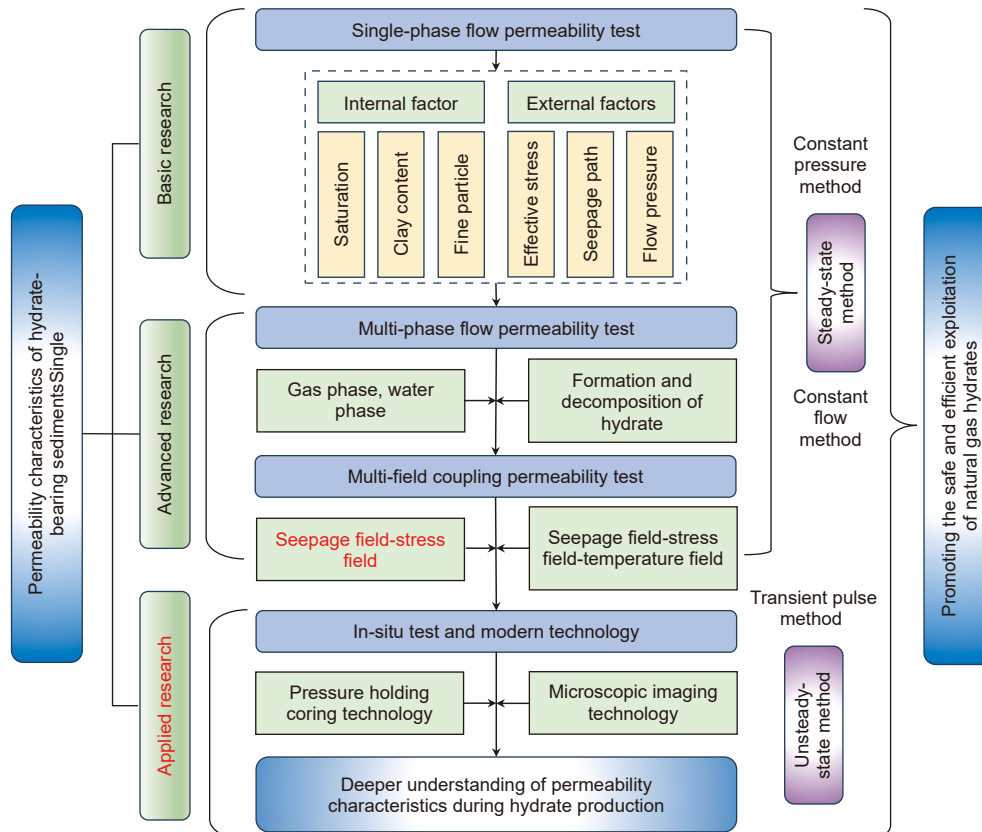


Fig. 11. Research progress on the permeability characteristics of HBS.

deformation and failure. The research results will not only help improve natural gas hydrate exploitation methods but also provide solid data support for many fields, such as ocean engineering construction and geological disaster prediction.

3.2. Mechanical properties under seepage

This section mainly analyses the stress-strain relationship, strength, and secant modulus variation rules of HBCS under different seepage pressure difference conditions. Exploring the effect of hydrate saturation on the mechanical properties of HBCS under water-phase seepage.

3.2.1. Stress-strain relationship

3.2.1.1. Variation law of stress-strain curve. Figs. 13 and 14 show the stress-strain relationship curves of 12 groups of permeability-stress coupling tests. Analysis of the curves reveals that, consistent with conventional triaxial shear tests, the stress-strain curves under seepage conditions still exhibit distinct nonlinear (elasto-plastic) behavior (Yan et al., 2017). What differs is that under the influence of water-phase seepage, the stress-strain curves exhibit

more small-range fluctuations, thereby reducing the smoothness of the curves.

As shown in the enlarged region ABC of Fig. 13, the curve is smoother in region A than in B and C. Meanwhile, this phenomenon becomes more obvious with the increase of seepage pressure difference, hydrate saturation, and axial strain. This may stem from seepage conditions, hydrate saturation, and axial loading affecting both sediment pore structure and particle skeleton stability (Chen et al., 2025b; Yan et al., 2023).

Firstly, the filling, supporting, and cementation of hydrate improve the pore structure of sediments and enhance the particle skeleton. Therefore, the water-phase seepage through HBCS is smoother and more stable. During the stress loading process, the influence of water-phase seepage on the stress-strain curve is also smaller. This is well demonstrated by the smoother stress-strain curves at $S_h = 10\%$ compared to those at $S_h = 0\%$ in Fig. 13. At the same time, the smoothness of the stress-strain curve does not continue to increase with increasing hydrate saturation. As shown in Fig. 13(b) and (c), the smoothness of the stress-strain curve decreases instead when $S_h = 20\%, 30\%$. This is because the increase in hydrate particles makes it more difficult for water to pass

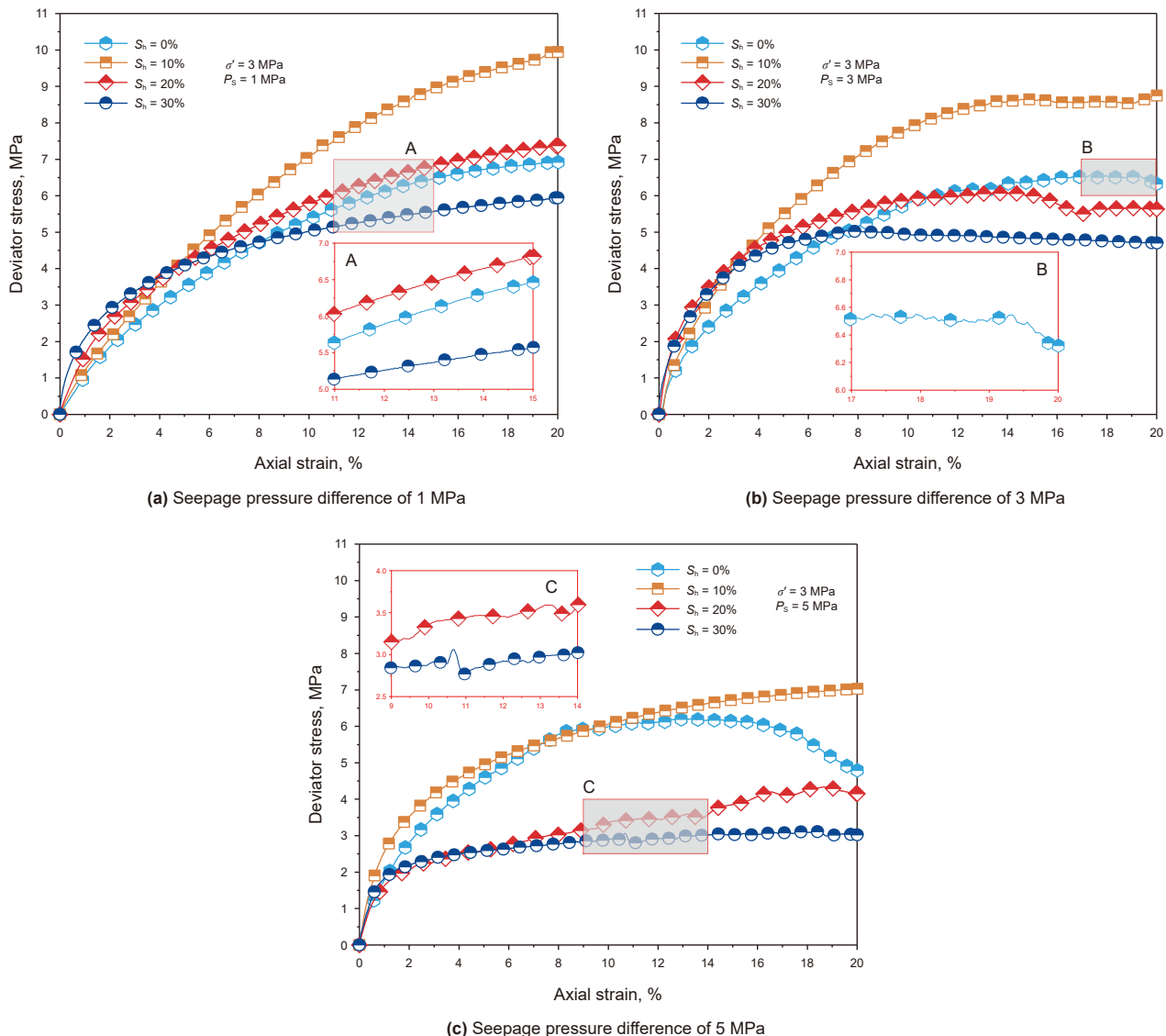


Fig. 13. Stress-strain relationships for different hydrate saturations at seepage pressure difference of 1, 3, 5 MPa.

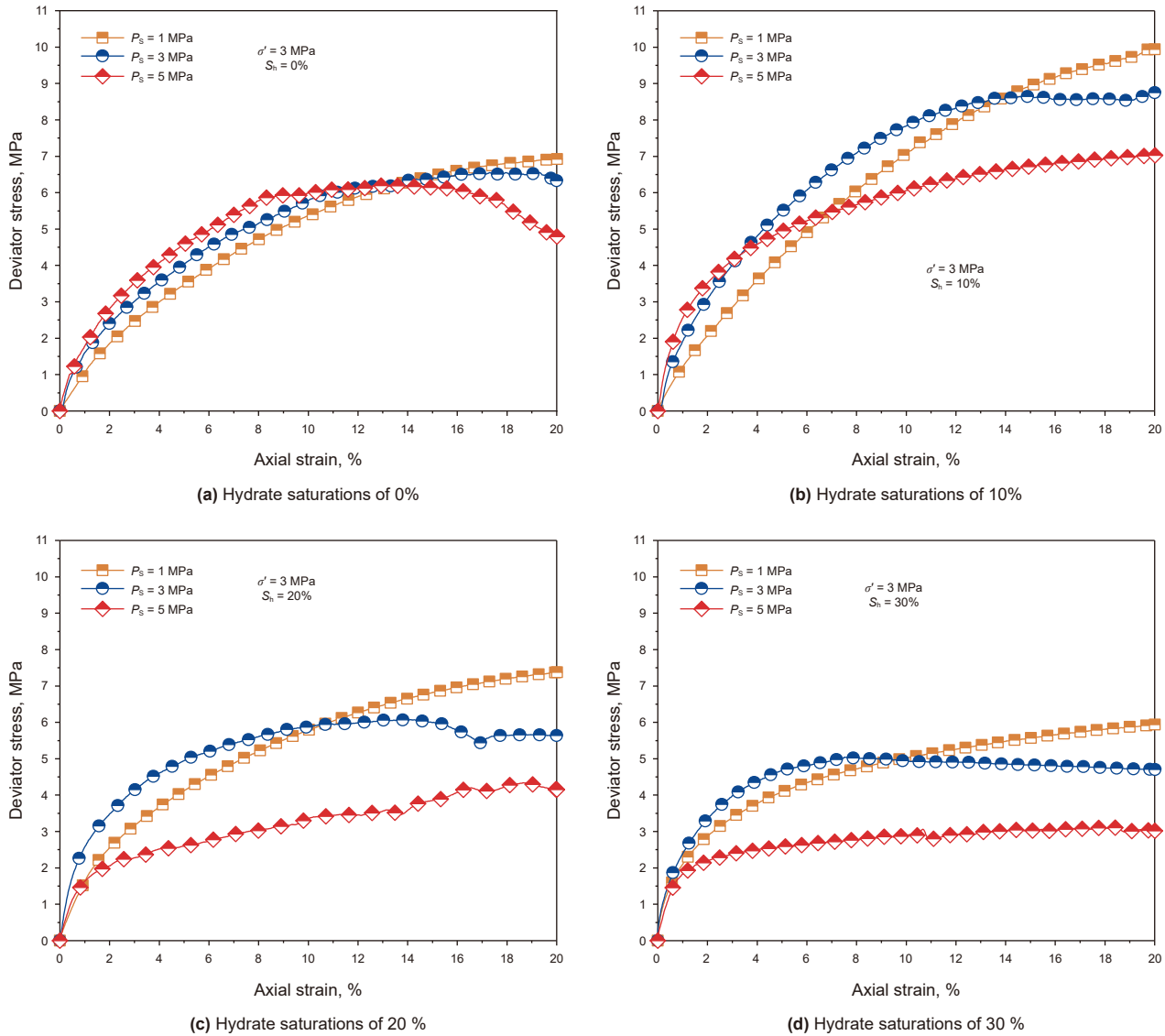


Fig. 14. Stress-strain relationships for different seepage pressure difference at hydrate saturations of 0%, 10%, 20%, 30%.

through the HBCS. Consequently, the seepage force generated by the water-phase seepage increases its impact on the stress loading process, which leads to a decrease in the stress-strain curve smoothness. This result reflects the blockage effect of hydrates on the pore structure of sediments.

Secondly, the increase in seepage pressure difference also reduces the stress-strain curve smoothness. In geotechnics, the magnitude of seepage force is positively correlated with the seepage pressure difference and the hydraulic gradient. Therefore, the seepage pressure difference increase leads to the seepage force increase, which in turn increases the influence of the water-phase fluid on the internal pore structure of the HBCS. During the interaction between the seepage field and the stress field, matrix particles are simultaneously subjected to seepage forces and deviatoric stress. Concurrently, this leads to a greater degree of fluctuation in the stress-strain curve during the stress-loading process.

Finally, axial strain has a more direct effect on the stress-strain curve. This is because with the increase of axial strain, the pore structure and skeleton structure in the sample are constantly damaged. The pore system becomes complex under the stress effect (Li et al., 2021b). Pore shrinkage and plugging continue to

increase, and the seepage channels inside the sample become progressively more complex. The interaction between seepage forces and stress gradually increases with increasing axial strain, leading to an increase in the effect of water-phase seepage on the stress-strain curve.

These results clearly demonstrate the influence of water-phase seepage on HBCS mechanical behavior, while revealing the complexity of actual submarine hydrate reservoir properties under multi-field and multi-phase conditions.

3.2.1.2. Influence of hydrate saturation and seepage pressure difference on stress-strain curves. From Figs. 13 and 14, it can be observed that the majority of the stress-strain curves exhibit strain-hardening and plastic-flow types. Only three curves ($P_s = 3$, $S_h = 20$), ($P_s = 3$, $S_h = 30$), ($P_s = 5$, $S_h = 0$) showed strain-softening. Among them, the softening phenomenon of the curve ($P_s = 3$, $S_h = 30$) is not obvious, which is closer to plastic flow; On the other hand, the curves ($P_s = 3$, $S_h = 20$), ($P_s = 5$, $S_h = 0$) show significant softening only after the axial strain reaches 14%. Meanwhile, in Fig. 13(a)–(c), the stress-strain curve for $S_h = 10\%$ is more obvious than the hardening trend for $S_h = 0\%$.

The above results show that, compared with the conventional triaxial test, the stress-strain curve of HBCS under the condition of water seepage shows a more obvious strain-hardening trend (Choi et al., 2018; Sang et al., 2025). Meanwhile, water-phase seepage weakens the softening effect of hydrate on the stress-strain curve (You et al., 2023; Zhao et al., 2023c). However, the hydrate saturation increase still has the effect of promoting “strain-softening”. As shown in Fig. 13, with the hydrate saturation increasing, the stress-strain curves gradually transform from strain-hardening to plastic-flow type.

As shown in Fig. 14, the stress-strain curve for hydrate-free sediments exhibits an increased tendency towards strain softening as the seepage pressure difference increases. However, the stress-strain curves did not show significant softening as the seepage pressure difference increased. It is only that the hardening tendency decreases and the plastic-flow tendency increases. Overall, the increase in seepage pressure difference reduces the strain-hardening and promotes plastic-flow tendency of the stress-strain curve.

3.2.2. Mechanical parameter analysis

Shear strength and elastic modulus are crucial parameters for analysing sample stability (Li et al., 2025b; Wang et al., 2025a). This section will discuss the influence of the seepage field on mechanical parameters.

3.2.2.1. Shear strength. Fig. 15 shows the variation of shear strength of HBCS under different hydrate saturation and seepage pressure difference conditions. There are two methods for determining the shear strength in this study: when the stress-strain curve exhibits a peak (strain softening type), the deviatoric stress corresponding to the peak is taken as the failure deviatoric stress, i.e., the peak deviatoric stress is the shear strength of HBCS. When the stress-strain curve of the strain-hardening type, the deviatoric stress corresponding to an axial strain value of 15% is taken as the shear strength of HBCS (Li et al., 2019; Shen et al., 2021; Wang et al., 2021).

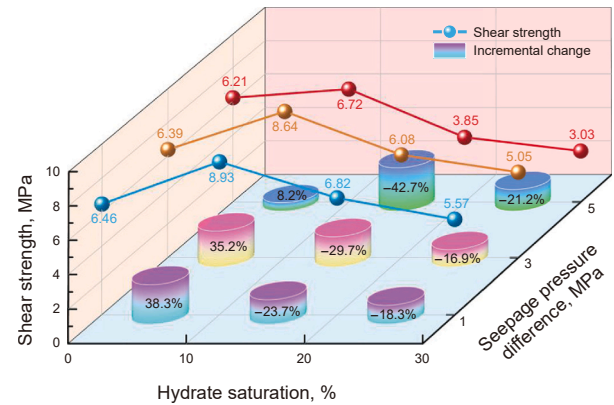


Fig. 16. Percentage change in shear strength increment for HBCS.

Fig. 16 shows the increment change of shear strength under seepage field-stress field coupling conditions. Combined with Fig. 15(a) and 16, it can be seen that under the same seepage pressure difference condition, the shear strength exhibits a trend of initially increasing and subsequently decreasing as hydrate saturation rises. In detail, the shear strength of hydrate-free sediments under different seepage pressure difference conditions is approximately the same (in the range of 6.2 to 6.5 MPa). The presence of hydrates enhances the strength of sediments. Meanwhile, the strengthening effect of hydrates on the shear strength decreases with increasing seepage pressure difference. As shown in Fig. 16, when the seepage pressure difference of 1, 3, and 5 MPa, the shear strength increases with $S_h = 10\%$ compared to hydrate-free sediments are 38.3%, 35.2%, and 8.2%, respectively. Hence, the presence of hydrate enhances the shear strength under the action of seepage, which is the same as the results of conventional triaxial shear tests (Xu et al., 2022; Yang et al., 2023a).

However, as the hydrate saturation continues to increase ($S_h = 10\% \sim 30\%$), the shear strength decreases. From Figs. 15 and 16, it can be seen that the reduction degree of shear strength

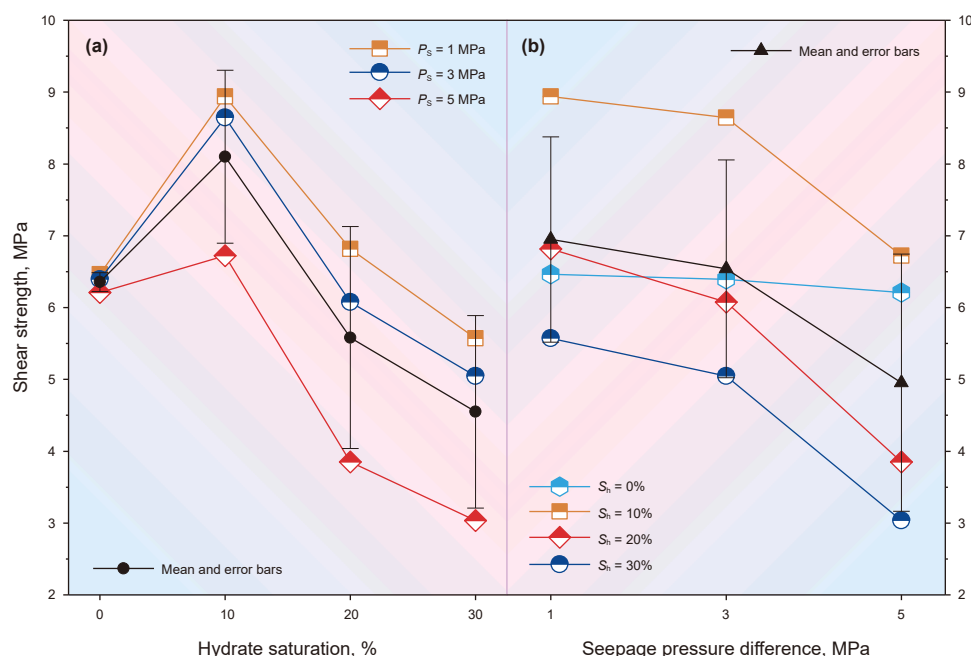


Fig. 15. Shear strength of HBCS under seepage-stress coupling conditions.

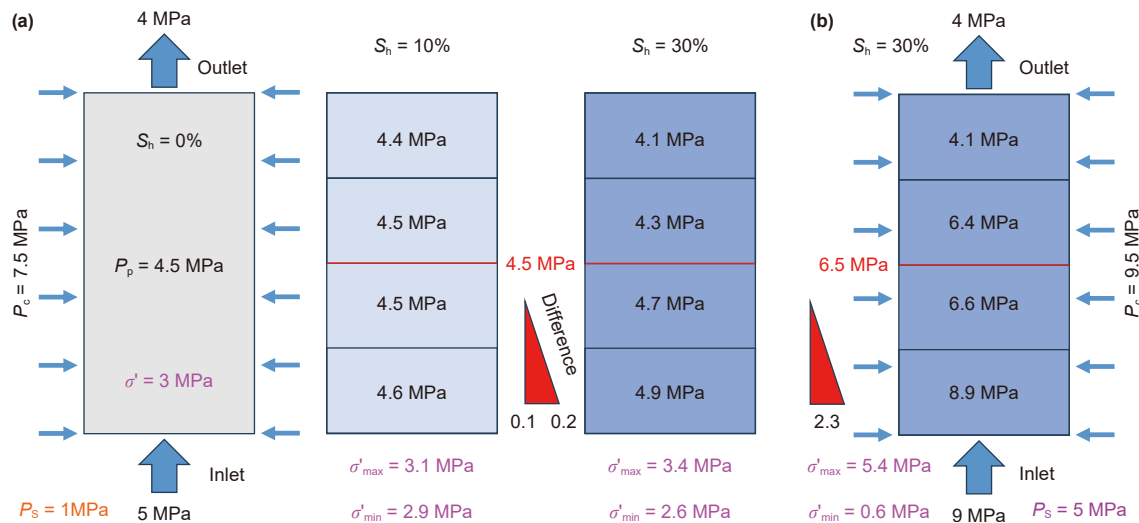


Fig. 17. Variation of pore pressure distribution inside the sample during the seepage process.

decreases with increasing hydrate saturation. But it increases with rising seepage pressure differential. In general, under water-phase seepage conditions, the shear strength of hydrate-free sediments is less affected by seepage. The shear strength decreases slowly with increasing seepage pressure difference. Small amounts of hydrate (low saturation) are beneficial to improve the shear strength. When hydrates are more abundant (high saturation), the presence of hydrates weakens the shear strength (Wu et al., 2025; Zhang et al., 2025a).

The above results are significantly different from those of conventional triaxial tests. In the conventional triaxial test results, the shear strength increases with increasing hydrate saturation (Kong et al., 2023; Luo et al., 2022; Yan et al., 2024). However, in this study, the shear strength decreases with increasing hydrate saturation. Uneven effective stress distribution under seepage conditions drives this phenomenon (Luo et al., 2020; Zhang and Wang, 2023).

Firstly, the biggest difference between the conventional triaxial shear test and the permeability-stress coupling test is the seepage condition. In conventional triaxial tests, the pore pressure is controlled by the gas or water phase at constant pressure, and measurements are generally monitored in real time. In the permeability-stress coupling test, the pore pressure is controlled by the dynamic water phase, which is less stable.

Secondly, the pore pressure in this study is calculated as the average of inlet pressure and outlet pressure, which itself is an estimate. Thus, the monitoring error of pore pressure in the permeability-stress coupling test is larger compared to the conventional triaxial shear test. This results in a difference between the actual pore pressure and the monitored pore pressure, which affects the conversion of effective stresses.

Finally (and more importantly), the seepage process in the permeability-stress coupling test represents a dissipation process of pore water pressure (Bao et al., 2025; Lei et al., 2025). Under ideal conditions with intact pore structures and smooth pore-throat channels, flowing water exerts minimal influence on the sample. While pore pressure equals the arithmetic mean of inlet and outlet pressures. In practice, the seepage pressure difference causes a disparity in pore pressure between the two ends of the sample. This results in an uneven distribution of effective stress within the sample.

In summary, based on Terzaghi's effective stress principle (effective stress is equal to the difference between total stress and

pore water pressure). Combined with the previous experimental results, the shear strength of hydrate-free sediments is close under different seepage pressure differences. It is assumed that water-phase seepage has a small effect on the pore pressure of hydrate-free sediments. That is, when $S_h = 0\%$, the pore pressure inside the sample is uniformly distributed, as shown in Fig. 17. Therefore, under the condition of seepage inlet pressure of 5 MPa and outlet pressure of 4 MPa, the pore pressure (4.5 MPa) of the sample with $S_h = 0\%$ is uniformly distributed, which corresponds to an effective stress of 3 MPa.

Subsequently, the random generation of hydrates fills part of pores in sediments, causing partial blockage of seepage pore-throat and thus hindering the dissipation of pore water pressure. This will cause an uneven distribution of pore pressure within the sample. Taking Fig. 17(a) as an example, when $S_h = 10\%$, there is little blockage of the pore-throat channels. The maximum and minimum values of the effective stresses inside the sample are closer to each other. At this point, the effective stress reduction due to water-phase seepage is negligible. Moreover, the cementation and support of hydrates improve the skeletal structure of the sediments (Li et al., 2021a; Ouyang et al., 2023; Ramamoorthy et al., 2022). Therefore, the shear strength of the sample with $S_h = 10\%$ is greater than that with $S_h = 0\%$.

When $S_h = 30\%$, the seepage pore-throat is blocked more seriously. It is more difficult to dissipate the pore water pressure. This results in a high pore pressure at the seepage inlet and a low pore pressure at the outlet. The effective stress at the seepage inlet of the sample decreases, leading to a decrease in the overall shear strength of the sample. When the seepage pressure difference ($P_s = 5$ MPa) is further increased, the pressure difference between the seepage inlet and seepage outlet will be further widened, as shown in Fig. 17(b). Therefore, the difficulty of dissipating the pore water pressure is further enhanced by the combined effect of seepage pressure difference and hydrate, leading to a smaller minimum effective stress and a further reduction in the shear strength.

Overall, the HBCS shear strength decreases with increasing hydrate saturation under seepage conditions. The mechanism is that the hydrate blocks the seepage pore-throat, the effective stress inside the sample is reduced, which in turn reduces the overall shear strength. In addition, the nature of seepage changes is the pore space change of sediment particles. In addition to hydrate saturation, seepage pressure difference, and shear

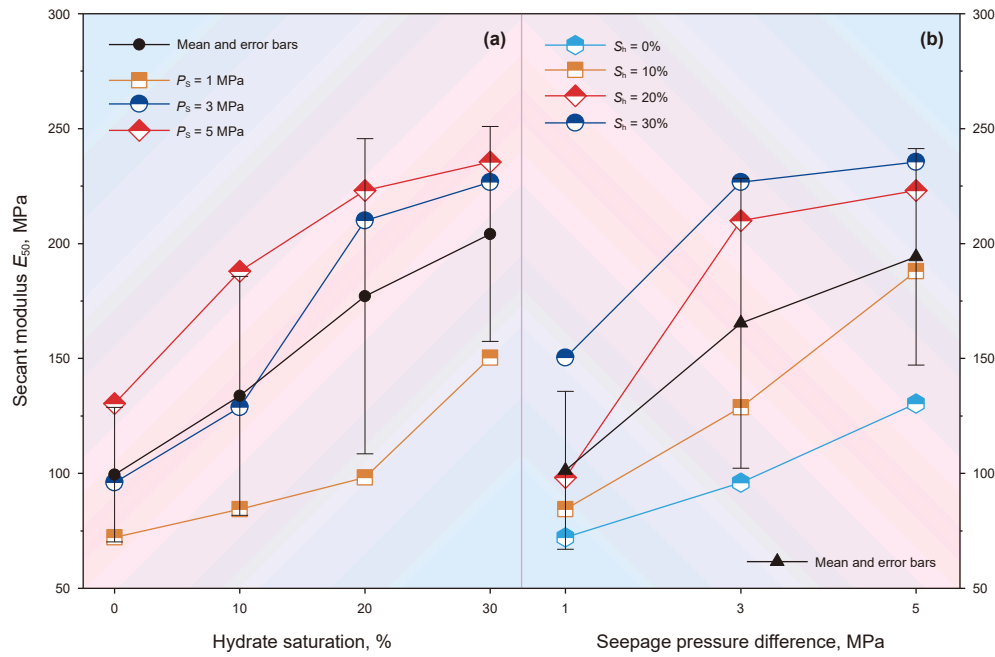


Fig. 18. HBCS's secant modulus E_{50} under seepage-stress coupling conditions.

deformation discussed above, particle size distribution, degree of consolidation, and effective confining pressure all cause changes in particle porosity. There is a coupling relationship between the various influencing factors (Hyodo et al. 2014, 2017; Li et al., 2024c).

3.2.2.2. Secant modulus. This study uses the secant modulus (E_{50}) to describe the stiffness changes of HBCS. Fig. 18 shows the variation of E_{50} with hydrate saturation and seepage pressure difference. The definition of E_{50} is: the slope of the straight line passing through two points (the point where the deviatoric stress reaches 50% of the shear strength and the origin) on the stress-strain curve.

As shown in Fig. 18, the E_{50} of HBCS increases with the increase in both hydrate saturation and seepage pressure difference.

However, the above results differ from the initial stiffness of the stress-strain curve in Section 3.2.1. As shown in Fig. 13(c), under the seepage pressure difference of 5 MPa, the initial stiffness of the stress-strain curves for different hydrate saturations does not differ significantly. Therefore, the initial secant modulus ($E_{0.1}$) is defined here (Slope of the straight line passing through the point with 0.1% axial strain and the origin) to reflect the initial stiffness of HBCS.

Figs. 19 and 20 show the changes in the $E_{0.1}$ with the hydrate saturation and seepage pressure difference. At lower seepage

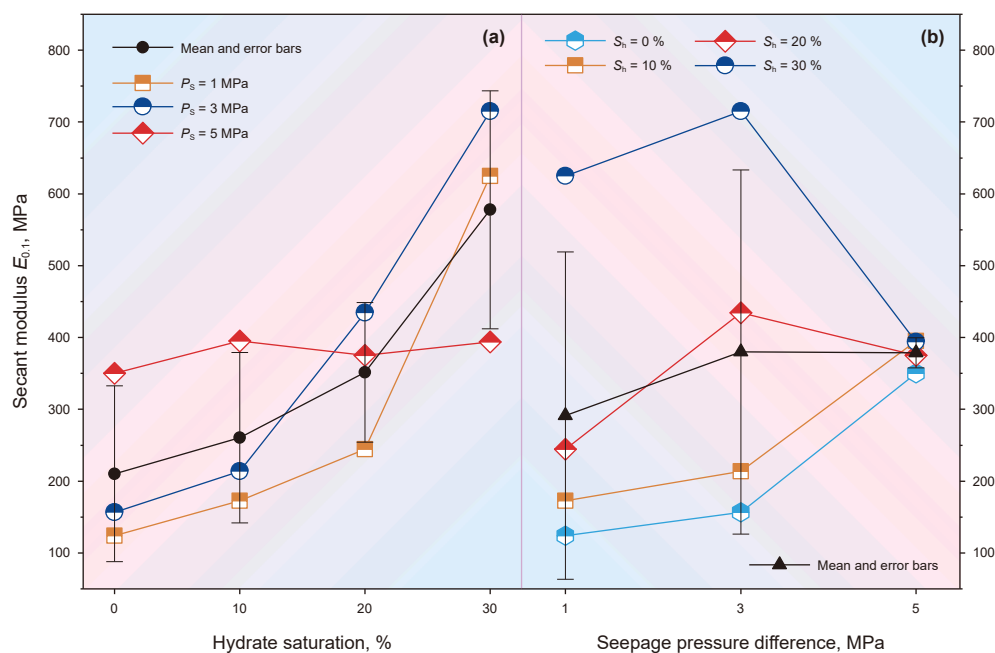


Fig. 19. HBCS's initial secant modulus $E_{0.1}$ under seepage-stress coupling conditions.

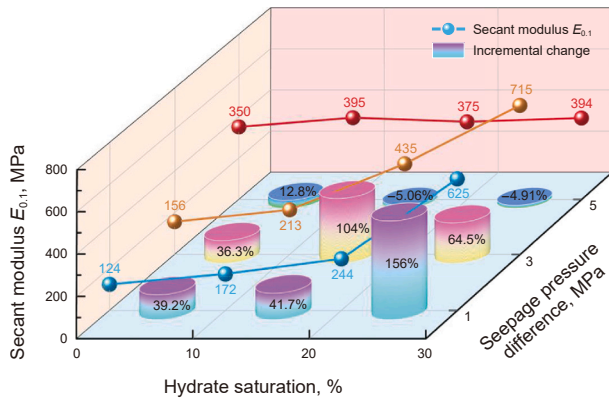


Fig. 20. Incremental changes in initial tangent modulus $E_{0.1}$ under seepage-stress coupling conditions in HBCS.

pressure difference (1, 3 MPa), the $E_{0.1}$ increases with increasing hydrate saturation. At the higher seepage pressure difference (5 MPa), the $E_{0.1}$ changes little with increasing hydrate saturation, with an average fluctuation of around 10%. At lower hydrate saturation (0%, 10%), the $E_{0.1}$ increases with increasing seepage pressure difference. At higher hydrate saturation (20%, 30%), $E_{0.1}$ first increases and then decreases with increasing seepage pressure difference.

To sum up, the initial stiffness (initial secant modulus $E_{0.1}$) is influenced by the coupling effect of hydrate saturation and seepage pressure difference. When the seepage pressure difference is low, the hydrate saturation dominates the change in initial stiffness, and $E_{0.1}$ increases with increasing hydrate saturation. When the seepage pressure difference is large, the effect of hydrates on the initial stiffness of sediments decreases significantly, and $E_{0.1}$ changes little with increasing hydrate saturation, as shown in Fig. 20.

Combined with the findings of conventional triaxial tests (Kou et al., 2022; Sang et al., 2024), the primary reasons for the above test results are as follows: a) At low hydrate saturations, the cementation, support, and filling effects of hydrates on sediment matrix particles improve the skeletal structure. b) At high hydrate saturations, the cementation, support, and filling effects fail prematurely during the consolidation process, damaging the skeletal structure (Han et al., 2018; Hauge et al., 2016; Yoneda et al., 2016).

Additionally, due to the effect of water-phase seepage in the permeability-stress coupling test, the greater the seepage pressure difference, the more significant the influence of seepage force on the internal structure of HBCS. Therefore, the mechanism by which water-phase seepage affects the initial stiffness of HBCS is as follows: a) Under low seepage pressure difference, the seepage force induced by seepage is small, leading to rapid dissipation of pore water pressure. Seepage has minimal influence on hydrate particles and sediment matrix particles (Zhang et al., 2024c). b) Under high seepage pressure difference, the seepage force is large, resulting in slow dissipation of pore water pressure. The large seepage force causes the migration of hydrate particles and matrix particles, as well as damage to cementation and support effects. c) An increase in seepage pressure difference enhances the pore pressure and confining pressure during consolidation and seepage processes, and the increased pressure improves the consolidation effect (Cameron et al., 1990; Dong et al., 2020; Gajanayake et al., 2022; Yoneda et al., 2019).

In summary, the variation in stiffness of HBCS is influenced by multiple factors. Firstly, hydrate formation enhances the skeletal structure of sediments. Secondly, in the consolidation stage, the consolidation effect of sediments with different hydrate saturation

is different. When hydrate saturation is high, the enhancing effect of hydrates on the particle framework may be destroyed. Moreover, during the initial stages of shear, seepage force may have a destructive effect on sediments.

4. Analysis of seepage field-stress field coupling mechanism

Based on the permeability-stress coupling test results, this section starts from the internal structural changes of HBCS. It discusses the seepage mechanism under shear action and the shear mechanism under seepage action.

4.1. Seepage mechanism under stress

The seepage characteristics of geotechnical materials are fundamentally determined by variations in the seepage pore-throat (Jang et al., 2019). Fig. 21 shows the seepage mechanism of HBCS in the permeability-stress coupling test. For hydrate-free sediments, the presence of clay particles promotes the sliding and rolling of sediment particles. This helps to improve the compactness of the sample during the consolidation process. Meanwhile, due to the water absorption and expansion characteristics of clay particles, they will block the seepage channels (Roscoe et al., 1963; Wu et al., 2018).

For HBCS, the presence of hydrates limits the action of clay, which leads to a decrease in compression and blockage of seepage pores during consolidation. Therefore, a small amount of hydration can improve the pore structure and increase its apparent permeability. However, as hydrate saturation continues to increase, hydrates start to occupy excess pores and form the cluster body with sediment matrix particles (Yoneda et al., 2016). The integrity of HBCS increases, but its porosity decreases. This leads to a reduction in water-phase seepage channels and a decrease in pore-throat diameters, thus reducing the apparent permeability.

During the stress loading stage, the seepage characteristics of HBCS begin to be affected by stress. In the initial stress loading stage, stress has a significant effect on the apparent permeability. Firstly, stress loading compresses the pore space inside the sample, causing pore water to be squeezed out. Secondly, stress destroys the particle skeleton structure of HBCS, forming new seepage channels. Thus, the expulsion of pore water and the formation of seepage pathways promote an increase in permeability, whereas the compression of pore spaces leads to a decrease in permeability. The antagonistic effect of these two factors results in the fluctuating behavior of apparent permeability at the initial stress loading stage.

During the middle stress loading stage, axial loading stabilizes the pore structure of HBCS. At this stage, the seepage pore throat has begun to form, and the stress-induced expulsion of pore water consequently diminishes. As axial strain increases, the number of seepage pore-throat channels decreases, and the pore-throat diameter shrinks (Cai et al., 2020). The permeability exhibits a stable decreasing trend as the seepage pore-throats decrease. In the late stress loading stage, internal pores of the sample are gradually compressed to the limit, and the permeability gradually tends to stabilize.

4.2. Shear mechanism under seepage

Figs. 22 and 23 illustrate the shear mechanism of HBCS under the action of water-phase seepage. By analysing the changes in sediment particles and hydrates during the test process. The shear mechanism of HBCS under water-phase seepage conditions is further revealed.

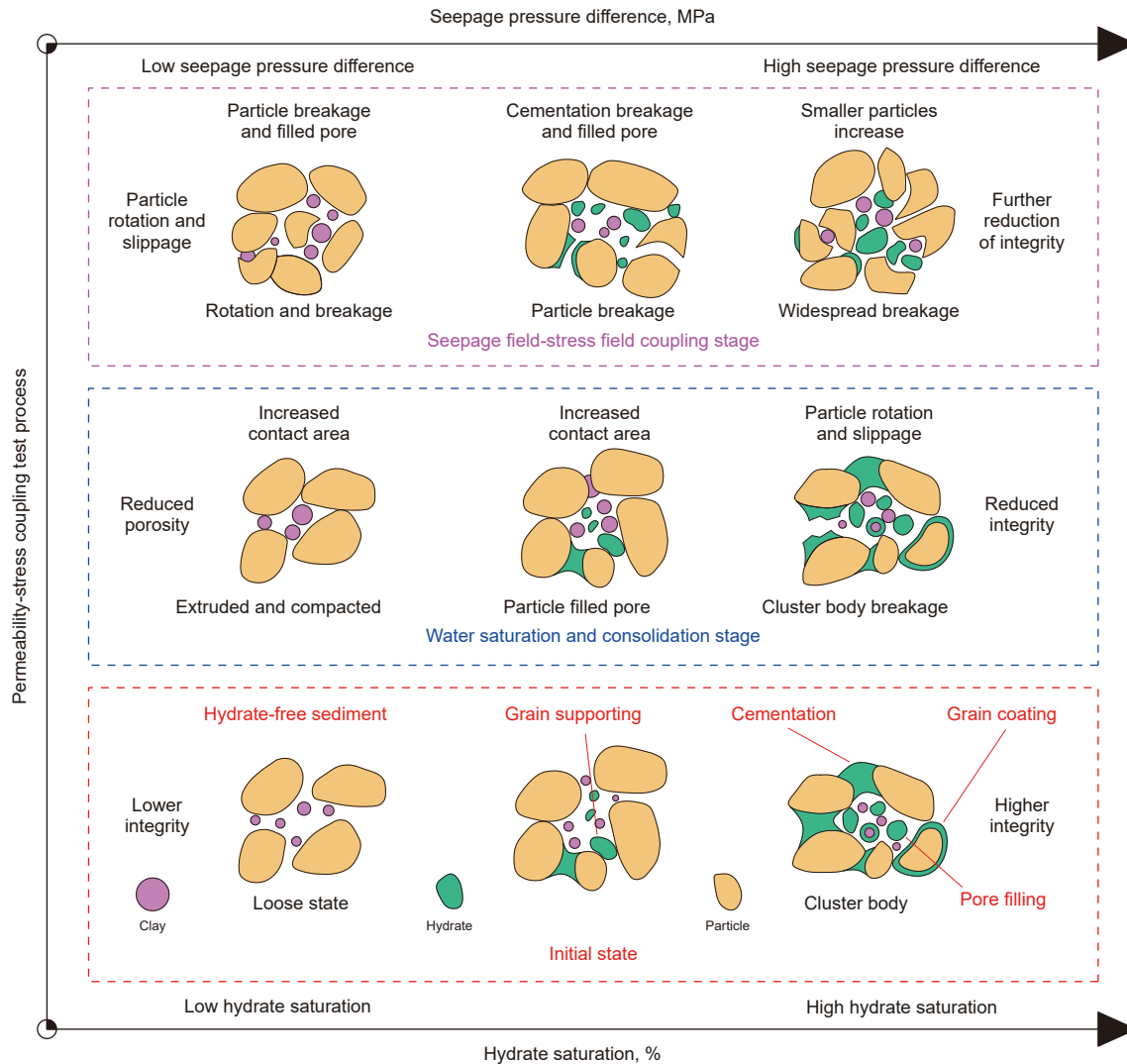


Fig. 21. Mechanism of seepage characteristics of HBCS under shear action.

(1) Mechanism analysis of shear strength

Regarding shear strength, water-phase seepage primarily functions to transport particles and expand pores. While the role of hydrates is opposite, restricting particle migration and blocking seepage pores. As shown in Fig. 22, in the hydrate-free sediments, the addition of low-temperature deionized water causes the clay in the sample to absorb water and expand. Although clay particles fill the pores of sediments, they cannot serve as skeletal particles to bear stress due to their low strength. Additionally, clay particles also have a lubricating effect, promoting the sliding and rolling of skeleton particles, which further reduces the shear strength of the sediment.

With the hydrate formation, the pores within HBCS will be filled. The cementation effect of hydrates strengthens the particle skeleton (Bian et al., 2022; Ramamoorthy et al., 2022). Meanwhile, hydrates restrict some clay particles, weakening their role in promoting particle sliding and rotation. Therefore, the presence of hydrates enhances the shear strength of HBCS.

However, as shown in Fig. 23, as the hydrate saturation increases, the hydrate's blocking effect on the seepage channel becomes more obvious. Although stress may cause fracturing of hydrates and matrix particles during consolidation and stress

loading, thereby forming new seepage channels. The fragmented particles will eventually block seepage pores under the action of seepage forces. The blockage of seepage channels leads to an increase in pore water pressure, thereby reducing the effective stress of the HBCS. Under stress loading, the regions with higher pore pressure are more prone to deformation (Jiang et al., 2019). Consequently, the shear strength of the HBCS decreases as the hydrate saturation and seepage pressure difference increase.

(2) Mechanism analysis of secant modulus

The water-phase seepage exerts a significant influence on the secant modulus of HBCS. As shown in Fig. 22, during the water saturation process, clay particles absorb water and undergo expansion. Although the particles are compacted during consolidation, the effect of clay promoting the sliding and rotation of skeletal particles still exists. This results in the secant modulus of hydrate-free sediments remaining at a relatively low level. For HBCS, the cementation, support, and filling effects of hydrates facilitate the formation of the cluster body. Meanwhile, hydrates also limit the lubricating effect of clay particles, which greatly improves the deformation resistance of HBCS.

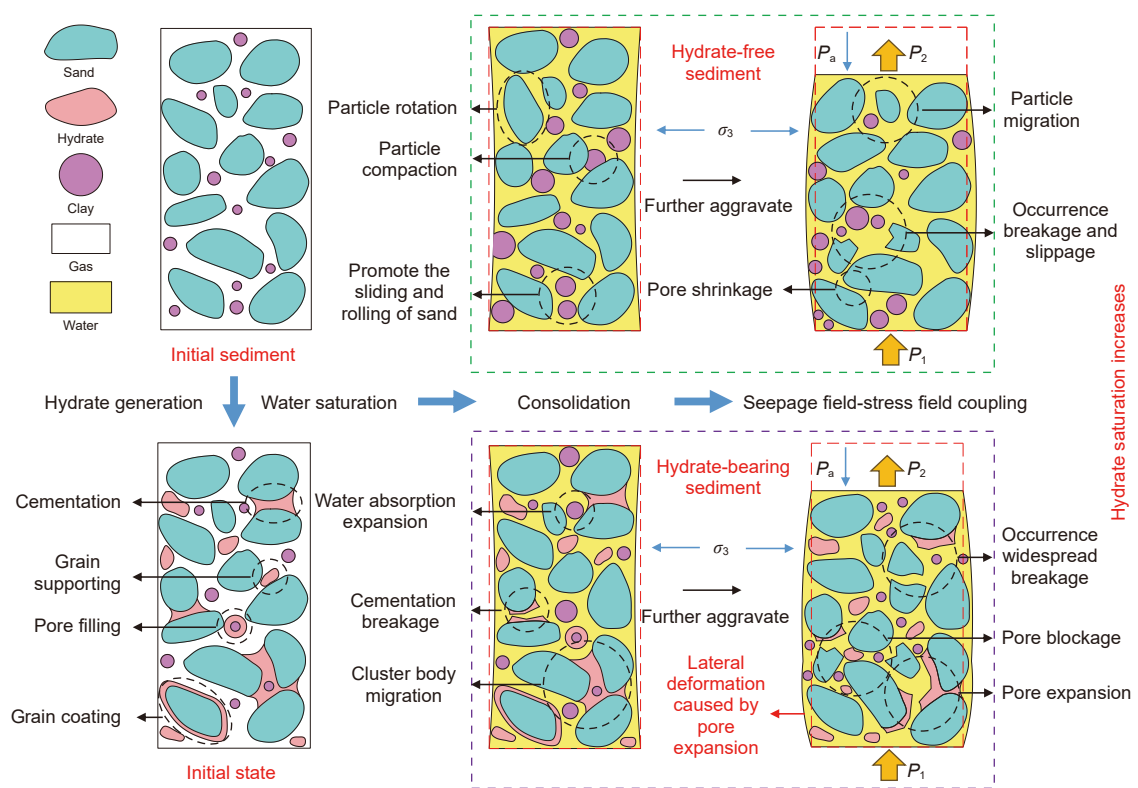


Fig. 22. Consolidation shear mechanism of HBCS under seepage action.

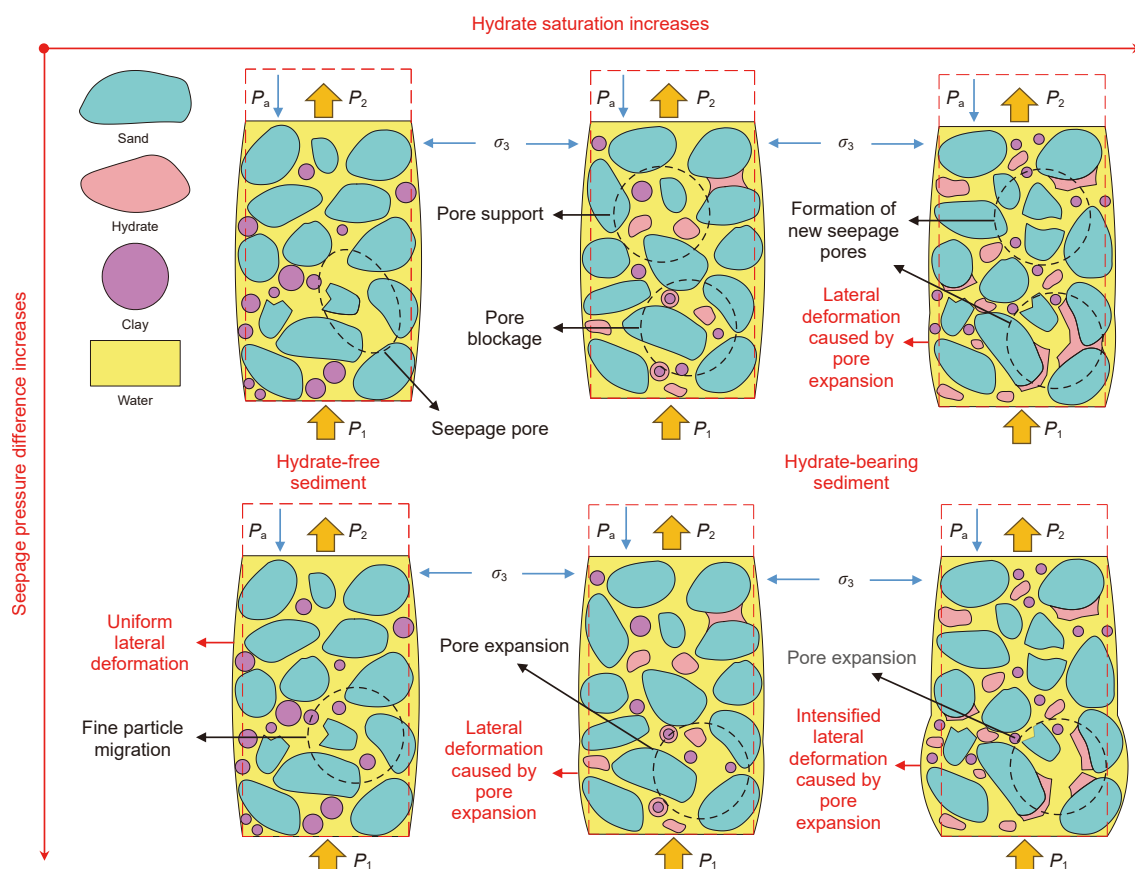


Fig. 23. Effect of seepage pressure difference and hydrate saturation on the shear mechanism of HBCS.

In addition, there is an antagonistic relationship between hydrate saturation and seepage pressure difference. As shown in Fig. 23, when hydrate saturation is high, hydrates severely block the water-phase seepage channels. At this point, an increase in seepage pressure difference no longer increases the compactness of the HBCS, but instead promotes pore expansion. Water-phase seepage dissipates pore water pressure by forming new seepage throats. However, the deformation caused by pore expansion not only reduces the density of HBCS but also damages the integrity of the particle skeleton. Therefore, when both hydrate saturation and seepage pressure difference are at high levels, the enhancement effect of their increase on the secant modulus of HBCS weakens, or even evolves into a weakening effect.

At the microscopic level, scholars have reached similar conclusions through CT scans and numerical simulations (Li et al., 2024e). Under the action of seepage pressure difference, the distribution of pore pressure exhibits non-uniformity. Seepage pressure gradually decreases along the flow path: Pore pressure is greater at the inlet end and less at the outlet end. Moreover, the presence of cracks facilitates the dissipation of pore pressure. By observing the cracks in Fig. 24(b) and (c), it can be seen that the pore pressure is higher in the shorter cracks. Therefore, under the action of pressure difference, the higher pore pressure provides the driving force for crack propagation and pore expansion. Concurrently, within the HBCS composed of sediment particles and hydrate particles, crack propagation and pore expansion may induce particle migration and rotation.

In summary, the seepage field-stress field coupling mechanism of HBCS can be summarized as follows: a) The cementation, support, and other effects formed by hydrates and matrix particles, which bring about two effects: the enhancement of sediment skeleton particles and the blockage of seepage channels. b) The particle migration caused by water-phase seepage, which has two roles: Skeleton compaction and Pore expansion. c) The compaction, fragmentation, and migration of matrix particles (clay particles, quartz sand particles,

hydrate particles) caused by increasing stress, which has two functions: pore shrinkage and fracture formation. These three mechanisms collectively constitute the complex seepage and mechanical characteristics of HBCS during the seepage-stress coupling process.

5. Engineering suggestions and insights

In light of actual hydrate production conditions, this study investigates the coupled seepage-stress behaviour of HBCS. The test results show that the coupling effect of the seepage field and stress field not only affects the basic properties of HBCS, such as strength, deformation, and permeability, but also affects the safe and efficient exploitation of natural gas hydrate. Therefore, based on the test results, combined with the engineering practices and technological advances, the following suggestions and insights are proposed:

- (1) There is a nonlinear relationship between seepage pressure difference and permeability of HBCS, and a greater seepage pressure difference does not necessarily yield higher exploitation efficiency. The greater the seepage pressure difference, the stronger the sediment carrying capacity of water flow. Therefore, sand production issues in the reservoir may be caused by excessive production rates (Li et al., 2024b). This corresponds with the AT1-MC test drilling incident in Japan's Nankai Trough (Yamamoto et al., 2017). The project quickly reduced the bottomhole seepage pressure from 13.5 to 5 MPa. Although short-term gas production increased rapidly, the sand body of 30 m³ flooded into the wellbore with the fluid. Moreover, for low hydrate saturation reservoir, its permeability is more sensitive to the change of pressure difference. Therefore, it is suggested that low-saturation reservoirs adopt a “slow and steady” approach to production. This facilitates the prevention of sand production and enables long-term stable production.

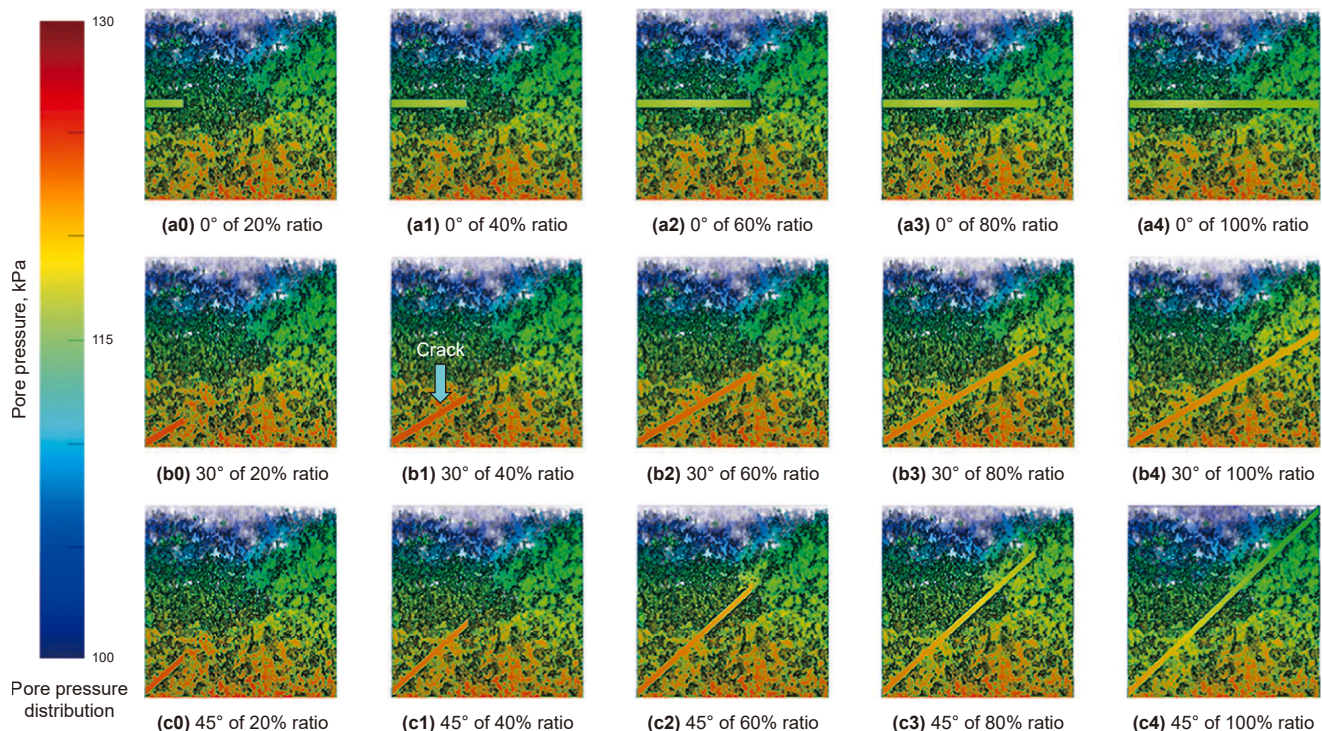


Fig. 24. Distribution of seepage pressure field in HBCs with a 0.2 mm opening crack (Li et al., 2024e).

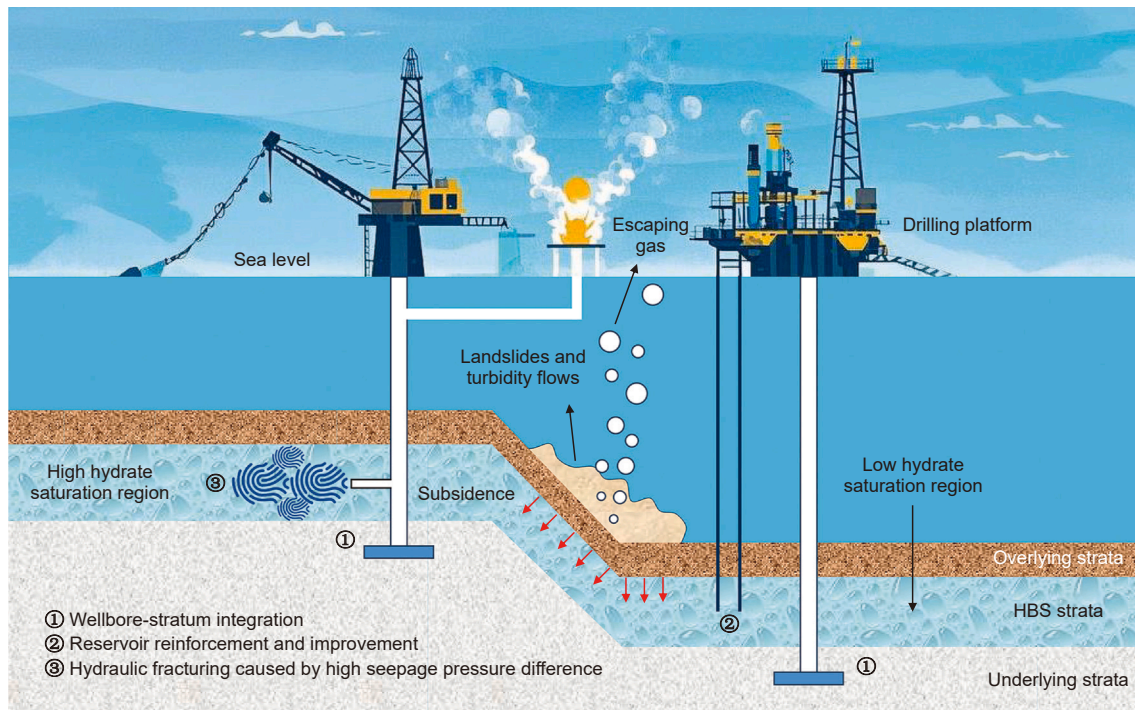


Fig. 25. Exploitation risks and suggestion for submarine natural gas hydrates.

- (2) For reservoirs with high hydrate saturation, enhancing exploitation efficiency may be achieved by increasing the seepage pressure difference. Drawing upon hydraulic fracturing techniques, implement stepwise pressure-boosted production in high saturation reservoirs (Chen et al., 2025a; Wang et al., 2018). Initial production will be at a pressure difference of 1–2 MPa. Once gas production stabilizes, the production pressure difference will be gradually increased to 3–5 MPa. High seepage force makes primary micro-cracks expand, forming high seepage channels. It is suggested to equip the high-power submersible electric pump or high-efficiency gas lift system to establish the required pressure difference. Meanwhile, a downhole microseismic monitoring array is deployed to conduct real-time tracking of the propagation morphology and scope of fractures. Ensure that the fracture modification process remains in a controllable state, and avoid the connection of large fractures from causing reservoir integrity damage.
- (3) The presence of the stress field reduces the permeability of HBCS. During the hydrate production process, the action of the stress field and stress redistribution will lead to a decrease in reservoir permeability (Luo et al., 2025). This phenomenon has been verified in the trial production in the Gulf of Mexico area. After hydrate decomposition, the formation compaction rate increases, which leads to the pore water pressure dissipation time extending from 3 days to 14 days and significantly increasing the risk of secondary collapse (Li et al. 2022, 2024a). Therefore, it is suggested to draw on the “fracturing grouting technology” and develop low-temperature early-strength drilling fluids suitable for hydrate reservoirs. Meanwhile, by means of drill pipes equipped with packers and directional injection valves, fluids are precisely pumped into the key bearing zones around the wellbore. By precisely controlling the injection pressure through a precision booster pump, the fluid is

ensured to fracture the reservoir's micro-pores and cement the particles.

- (4) The presence of seepage fields reduces the shear strength of HBCS. Under seepage-stress action, it was found in the trial production in the Shenhu Area of the South China Sea that uncemented reservoirs are prone to wellbore collapse during drilling fluid circulation. Stability must be maintained by enhancing the drilling fluid support pressure (Ye et al., 2020). Meanwhile, COMSOL multi-field coupling simulations reveal that dynamic fluid seepage reduces the shear strength of HBCS (Jiang et al., 2022; Sun et al., 2018). Therefore, engineers need to include fluid weakening effects when assessing reservoir stability. Concurrently, promote the “Wellbore-stratum integration” design and develop an anti-collapse drilling system suitable for hydrate reservoirs. By optimizing drilling fluid viscosity and pressure transmission efficiency, the wellbore shrinkage rate was effectively controlled below 5%.

Based on the above suggestions and insights, the risks and suggestions for hydrate reservoir exploitation are summarized in Fig. 25.

6. Conclusions

Investigating the seepage-stress coupling behavior of hydrate-bearing clayey-silty sediments (HBCS) is essential for the safe and efficient exploitation of natural gas hydrates. Through a series of permeability-stress coupling tests, this study systematically examines the influence of hydrate saturation (S_h) and seepage pressure difference (P_s) on the multi-field and multi-phase coupling properties of HBCS. Based on the test results, the underlying coupling mechanism between seepage and stress fields is elucidated, and practical engineering suggestions are proposed from the perspective of hydrate production. The main conclusions are as follows:

- (1) Under stress field conditions, the seepage flow of HBCS exhibits a logarithmic correlation with axial strain, where its increment decreases as axial strain increases. Meanwhile, seepage flow is positively correlated with P_s . The relationship between seepage flow and S_h is relatively complex. At low- S_h levels, seepage flow is reduced due to the pore-filling effect of hydrates. At high- S_h levels, stress-induced damage to the sediment skeleton results in increased seepage flow.
- (2) Under stress field conditions, the apparent permeability of HBCS decreases with axial strain. The apparent permeability is influenced by the coupling effect of S_h and P_s . At low- S_h levels, the apparent permeability decreases with increasing P_s . At high- S_h levels, increasing the P_s promotes both pore expansion and particle migration, and the apparent permeability is influenced by these two antagonistic effects.
- (3) Under seepage field conditions, the smoothness of the stress-strain curve diminishes, with an increase in small-scale fluctuations. Additionally, water-phase seepage weakens the softening effect of hydrates, resulting in stress-strain curve that are predominantly characterized by strain hardening and plastic flow. The stiffness characteristics of HBCS are governed by the coupling effects of S_h and P_s . The secant modulus E_{50} increases with increasing S_h and P_s .
- (4) Under seepage field conditions, the shear strength of HBCS decreases with increasing S_h and P_s . The shear strength of hydrate-free sediments decreases slowly with increasing P_s . The cementation and pore-filling effects of hydrates hinder the dissipation of pore water pressure in HBCS. As described by Terzaghi's effective stress principle, this leads to a localized reduction in effective stress, which directly diminishes the shear strength of the HBCS.
- (5) The production strategy for natural gas hydrates should be tailored according to reservoir characteristics. For reservoirs with low- S_h levels, a "slow and steady" exploitation approach is recommended to prevent excessive P_s from causing sand production and wellbore blockages. In contrast, for reservoirs with high- S_h levels, where hydrates impose stronger constraints on sediment particles, increasing the P_s can facilitate pore expansion and fracture propagation, thereby enhancing exploitation efficiency.

As a significant energy resource, the safety and stability of natural gas hydrate production are of critical importance. The findings of this study offer valuable insights for engineers to understand and analyze the multi-field, multi-phase coupling behavior of hydrate-bearing reservoirs.

CRedit authorship contribution statement

Jia-Qi Liu: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Ya-Peng Zhao:** Writing – review & editing, Project administration, Funding acquisition. **Xin-Rui Wang:** Writing – review & editing, Project administration. **Liang Kong:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Song-Kui Sang:** Writing – review & editing. **Zhi-Yuan Wang:** Writing – review & editing. **Xue-Wei Wu:** Writing – review & editing. **Gao-Wei Hu:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Data availability

All data, models, and code generated or used during the study appear in the submitted article. For any questions or need more detailed data, please contact the corresponding author of this article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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