

Article

Mechanical Characteristics of Gas Hydrate-Bearing Sediments: An Experimental Study from the South China Sea

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Abstract: Clarifying the mechanical characteristics of gas hydrate-bearing sediments (GHBS) from a mechanical perspective is crucial for ensuring the long-term, safe, and efficient extraction of natural gas hydrates. In this study, seabed soft clay from the northern South China Sea was utilized to prepare clayey silt samples, aligning with gradation curves related to hydrate extraction projects in the Shenhu area of the South China Sea. Utilizing the high-pressure low-temperature hydrate triaxial testing system (ETAS), twelve sets of triaxial shear tests were conducted. The results highlight that increases in hydrate saturation and confining pressure significantly enhance GHBS' strength and stiffness, with more pronounced volume expansion observed during shearing. These tests have elucidated the mechanical responses of GHBS. Subsequently, empirical formulas were developed to characterize their properties under varying conditions. Additionally, based on the experimental data, the micro-mechanisms of GHBS were analyzed, suggesting that hydrates notably contribute to the filling and cementing effects in GHBS, with these effects varying with changes in hydrate saturation and confining pressure. This study contributes to a deeper understanding of the fundamental mechanical properties of GHBS.

Keywords: gas hydrate-bearing sediments; triaxial shear test; mechanical properties; empirical formulas; seabed soft clay; South China Sea



Citation: Yuan, Q.; Kong, L.; Liang, Q.; Liang, J.; Yang, L.; Dong, Y.; Wang, Z.; Wu, X. Mechanical Characteristics of Gas Hydrate-Bearing Sediments: An Experimental Study from the South China Sea. *J. Mar. Sci. Eng.* **2024**, *12*, 301. <https://doi.org/10.3390/jmse12020301>

Academic Editor: George Kontakiotis

Received: 8 January 2024

Revised: 30 January 2024

Accepted: 6 February 2024

Published: 8 February 2024



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1. Introduction

Gas hydrate-bearing sediments (GHBS) are deep-sea sedimentary bodies that contain natural gas hydrates. These hydrates are cage-like crystalline compounds formed from natural gas and water under high-pressure and low-temperature conditions, predominantly comprising methane [1]. They are widely described in geological records [2], and are extensively found in terrestrial permafrost regions, along continental margins, and in the deep-sea abyssal plains [3]. The discovery of natural gas hydrate deposits in numerous countries [4,5] signifies their potential as a new energy source, especially given the declining availability of traditional hydrocarbons. However, GHBS are subject to stringent stability requirements. Environmental changes or human activities that induce minor shifts in soil pressure or temperature can destabilize these hydrates, leading to gas release. Such events can drastically alter the soil's mechanical behavior, affecting characteristics like compressibility [6], failure features [7], and the strength and stiffness of the soil [8]. These changes can precipitate extensive marine geological disasters, exacerbate the greenhouse effect [9], and harm the marine ecosystem [10], thereby posing significant risks to hydrate exploitation and environmental safety. Consequently, investigating the mechanical

properties of GHBS is vital for understanding their deformation responses to ensure the sustainable and safe extraction of natural gas hydrates.

In situ mechanical testing is deemed the most reliable approach to ensure accuracy. Winters et al. [11,12] examined the physical properties of GHBS from various locations, including the North Slope of Alaska, Mackenzie Delta, and regions off the east coast of India and the Andaman Islands, using techniques such as infrared imaging, acoustic testing, thermal conductivity, resistivity testing, and shear strength assessments. Japan's "Tokai-oki to Kumano-nada Project" in 2004 [13] involved drilling up to 250–400 m below the seabed and employed a pressure–temperature corer (PTCS) for sampling. Bondarenko et al. [14] identified the optimal conditions for natural gas hydrate deposits in the Black Sea at depths of 500–750 m (8–9 °C, 20 MPa) and summarized their characteristics. However, due to the unique conditions required for hydrate storage, deep-sea in situ mechanical testing is costly. Consequently, most current research on GHBS involves synthesizing hydrates in labs and analyzing their mechanical properties. Methods like triaxial shear tests [15,16], one-dimensional consolidation tests [17], and analogous material tests [18] simulate various hydrate saturations, particle types, and temperature and pressure conditions in studying the behavior of GHBS. These experiments yield crucial insights but also have limitations, such as difficulty in replicating natural high-pressure, low-temperature conditions and differences in microstructure and properties between synthetic and natural GHBS samples. Therefore, while lab tests offer valuable perspectives on the mechanical properties of GHBS, their results should be interpreted with caution and complemented by other research approaches for a fuller understanding.

In this study, surface soil from the northeastern South China Sea was gathered to investigate the mechanical properties of silty fine sandy GHBS using configured sandy soil. We focused on the quantitative relationships between the mechanical properties, strength, and stiffness of GHBS, leading to the development of empirical equations. Finally, we analyzed the unique mechanical characteristics of GHBS and discussed the hydrates' mechanisms of action.

2. Experimental Study of GHBS

2.1. Material and Test Equipment

In August 2017, we procured surface soil samples from a natural gas hydrate deposit in the northern region of the South China Sea. This effort was supported by the third leg of the shared voyage initiative sponsored by the National Science Foundation Committee in the northeastern South China Sea and Luzon Strait. The sampling occurred at the YD2-04 station (115°16.407' E, 19°57.056' N), located at a depth of 1077 m. The sample comprised soft clay, as depicted in Figure 1.

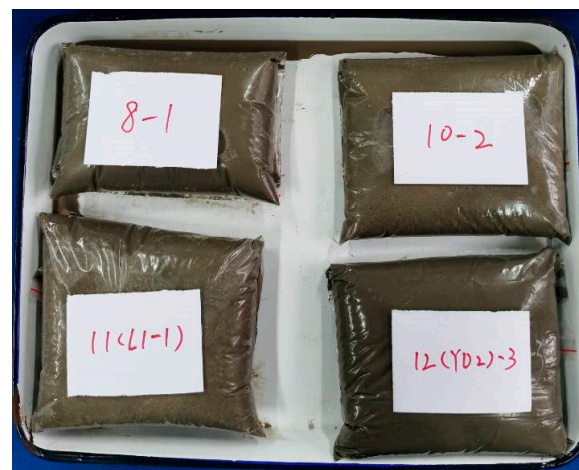


Figure 1. Preparation of argillaceous silt.

Figure 1 illustrates the natural gas hydrate deposit in the South China Sea of China [19,20]. Previously, two pilot mining projects [21] demonstrated that the primary reservoir soil in the South China Sea's hydrate deposit area is silty mud. Due to sample limitations in quantity and volume, our study primarily utilizes the particle size and mineral composition analysis data from Liu et al. [22] on sediments post-hydrate decomposition in the Shenhu area of the South China Sea. We synthesized silty mud, combining high-purity quartz sand with the obtained soft clay. Initially, we cleaned and dried the quartz sand, then separated particles into different sizes using a vibrating sieve, as shown in Figure 2a. Based on Liu et al. [22], we determined an 8% clay content and incorporated it into the residual soil sample from prior tests. The final composition of the prepared silty mud after thorough mixing is presented in Figure 2b.

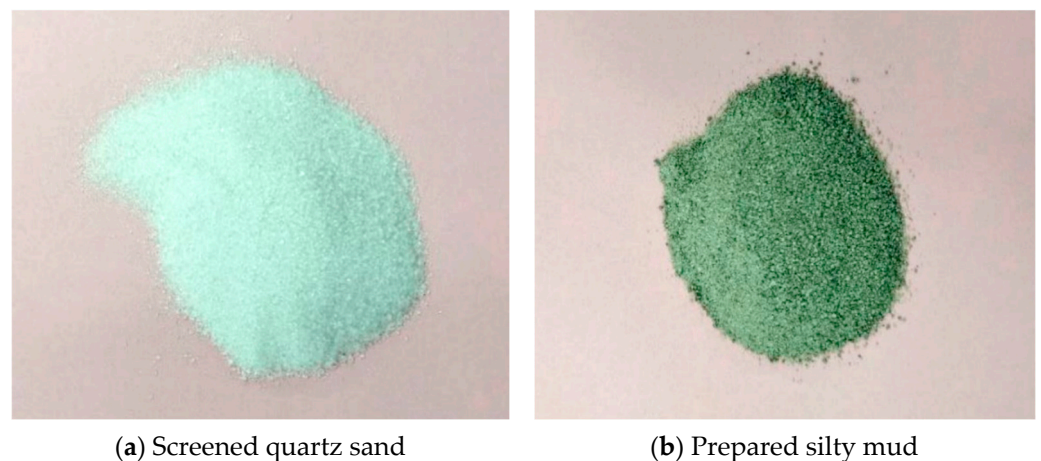


Figure 2. Details the preparation process of silty mud.

Figure 3 displays the grading curve, while Table 1 compares the grading indices of the experimental materials from Liu et al. [22] and our study. This comparison indicates a close resemblance between the prepared silty mud and the particle grading of the mining area's reservoir soil, aligning well with the grading characteristics of the South China Sea mining area's reservoir soil. Beyond the metrics listed in Table 1, the silty mud prepared in our study exhibited a specific gravity of 2.6590, with maximum and minimum porosity ratios of 1.2117 and 0.7693, respectively.

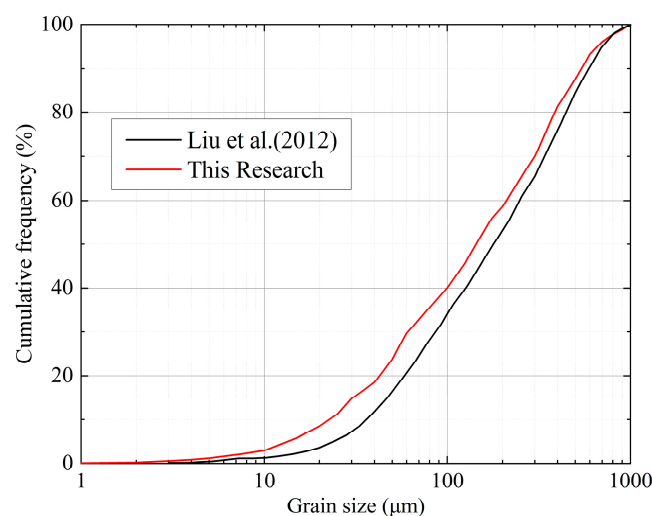


Figure 3. Experimental material grading curve [22].

Table 1. Grading index.

Material	$d_{10}/\mu\text{m}$	$d_{30}/\mu\text{m}$	$d_{50}/\mu\text{m}$	$d_{60}/\mu\text{m}$	$C_u = d_{60}/d_{10}$	$C_c = d_{30}^2/(d_{10} \cdot d_{60})$
[22]	0.0430	0.1012	0.21479	0.2932	6.8198	0.8123
This study	0.0299	0.0768	0.1737	0.2360	7.8824	0.8349

Our experimental setup utilized the high-pressure low-temperature hydrate triaxial testing system (ETAS system) produced by Europa and America Geotechnical Company. Figure 4a illustrates the physical assembly of the system, while its schematic is provided in Figure 4b. For experimental safety, the CH₄ gas tank was housed in an explosion-proof cabinet and complemented with flammable gas concentration detection and communication devices, including a handheld flammable gas concentration detector.

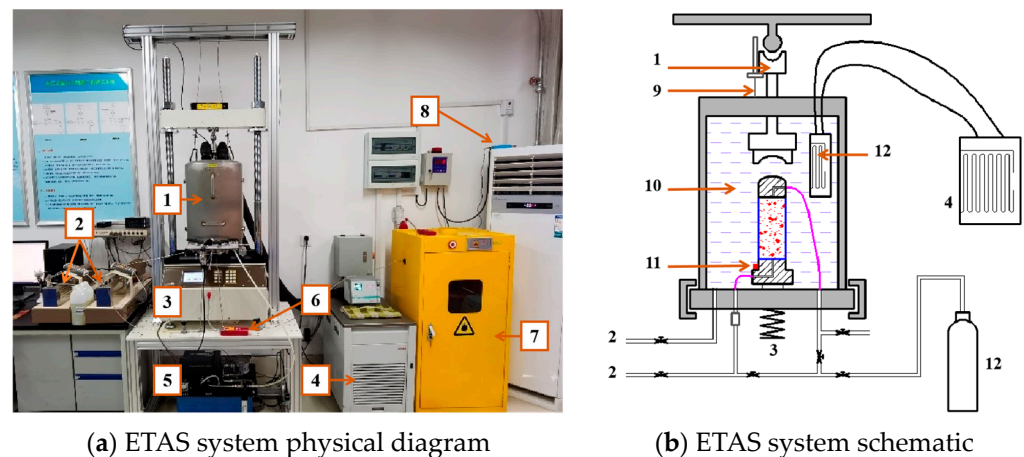


Figure 4. Physical and schematic diagrams of the ETAS system. 1—pressure chamber; 2—standard controller (32 MPa/200 mL); 3—axial loading (100 kN); 4—water bath (−20 °C~65 °C); 5—oil pump; 6—gas detector; 7—explosion-proof cabinet; 8—gas alarm communication instrument; 9—displacement sensor; 10—silicon oil; 11—temperature sensor; 12—methane gas.

The ETAS system comprises an axial loading system, a stainless steel high-pressure triaxial pressure chamber, a water bath, two standard controllers, and other essential components and spare parts. The axial loading system, motor servo-controlled with a 100 kN range and a precision of 0.1% of the full scale, facilitates pressure control either manually or via GDSLAB (v2) software. Manual operation offers speed selection, enabling easy specimen-load sensor contact. The axial load is exerted externally; the pressure chamber, crafted from high-strength stainless steel, can withstand up to 32 MPa. Silicone oil is pumped into the chamber to control the confining pressure. The water bath, maintaining the chamber's liquid medium temperature, ranges from −20 °C to 65 °C, with a temperature sensor at the sample base's interface providing real-time feedback. The two standard pressure–volume controllers operate within a 32 MPa/200 mL range with a 0.1% full range/volume accuracy. The pressure transmission mediums can be gas, liquid, or a mixture, with the confining pressure controller utilizing silicone oil and the back pressure controller using methane gas. Qingdao Ludong Gas Co., Ltd. (Qingdao, China) supplied the methane, with a factory pressure of 10 ± 0.5 MPa and a purity of 99.999%.

2.2. Specimen Preparation

The formation of hydrates necessitates specific thermobaric conditions, requiring both the temperature and pressure to be situated within the confines of the phase equilibrium curve. This curve is mathematically represented as:

$$\ln(1000p_{\text{eq}}) = 38.98 - 8533.8/T_{\text{eq}} \quad (1)$$

where p_{eq} denotes the critical equilibrium pressure for the stability of natural hydrates (in Pascals), and T_{eq} represents the critical equilibrium temperature for the stability of natural hydrates (in Kelvins).

Converting p_{eq} and T_{eq} from Equation (1) into MPa and °C, respectively, yields the phase equilibrium curve for natural gas hydrates, depicted in Figure 5. The point (T_{eq} , p_{eq}) must reside within the shaded region of this curve. The lines and arrows in the figure trace the hydrate formation pathway utilized in this study. Figure 6 illustrates a schematic of the gas channel structure, facilitating the preparation of geotechnical samples infused with energy sources through controlled valve and pipeline manipulation.

For sample preparation using the excess gas method, a matrix sample with pre-determined water content was initially prepared, followed by the introduction of an excess of methane. The required mass of water was calculated based on the chemical equation governing the formation of natural gas hydrates, represented as:



Here, n is the reaction stoichiometry, typically ranging between 5 and 6 [23], and can be approximated as 5.75 [24,25].

Assuming a sample volume of V , with a matrix sample porosity of n , hydrate saturation denoted as S_h , and a hydrate density (ρ_h) of 0.91 g/cm^3 , the mass of water required can be derived as:

$$m_{\text{H}_2\text{O}} = \frac{207}{239} n V S_h \rho_h \quad (3)$$

To prepare GHBS samples, dried clayey silt was placed in a tray. The water mass, exclusive of gas, was computed using Equation (3). This water was then added to a sprayer and carefully sprayed into the material while simultaneously mixing with a spoon. The mixture was then wrapped in cling film and left to rest for 24 h, ensuring uniform water distribution, before proceeding with GHBS sample preparation.

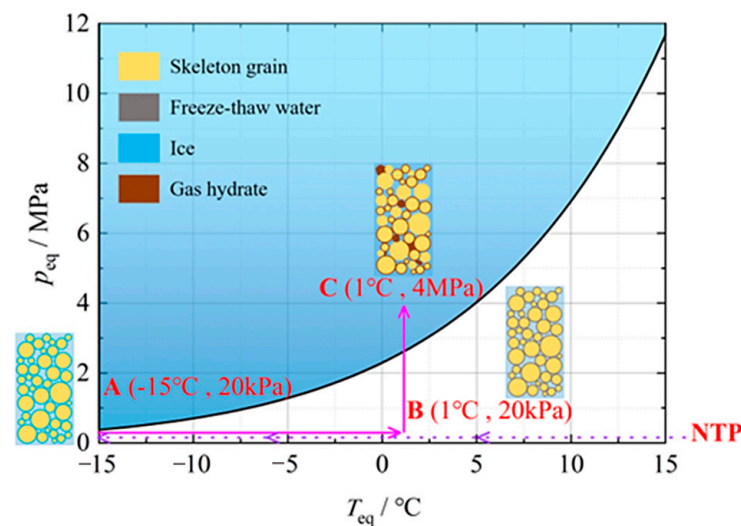


Figure 5. Phase equilibrium curve and hydrate formation path.

Utilizing ice meltwater as the water source for hydrate sediments, a method proven to expedite hydrate formation, has been validated by multiple studies. For instance, Takeya et al. [26] and Chen et al. [27] observed that freeze–thaw cycles considerably reduce the hydrate formation induction period. Hyodo et al. [28] and Khlebnikov et al. [29] employed meltwater from ice as the water source in energy layers, significantly enhancing the rate of natural gas hydrate formation. This study adopts similar methodologies, employing controlled temperature and valve adjustments to generate meltwater from ice and manage the direction of methane gas flow, thereby facilitating rapid and stable hydrate synthesis. The specific experimental procedures are as follows:

(1) Initiate the oil pump to fill the pressure chamber with silicone oil, applying a confining pressure of 200 kPa. Connect the water bath to the pressure chamber and activate it, achieving the conditions at point A in Figure 5 ($-15\text{ }^{\circ}\text{C}$, 20 kPa). Commence sample freezing, maintaining this state for 6 h.

(2) Upon completion of freezing, open the gas tank and channels L_A and L_0 (Figure 6), where L_0 is attached to a 2 L gasbag. Monitor the pore pressure readings and adjust the gas tank's pressure relief valve to maintain pore pressure around 20 kPa, ensuring the gas flow rate is controlled to prevent sample disturbance. This process allows methane to thoroughly flush the sample, displacing the internal air. When the volume of the gasbag is maximized, indicating complete displacement, close the L_0 channel.

(3) Proceed with thawing by heating, aligning with point B in Figure 5 ($1\text{ }^{\circ}\text{C}$, 20 kPa). Keep channels L_A and L_B open to ensure the even distribution of meltwater and gas pressure within the sample.

(4) Induce hydrate formation by adjusting the temperature and pressure to match point C in Figure 5 ($1\text{ }^{\circ}\text{C}$, 4 MPa), while concurrently raising the confining pressure to 5 MPa. To maintain steady back pressure, open the L_C channel connected to the back pressure controller, keeping channels L_A and L_B open to maintain a consistent 4 MPa pressure at both the top and bottom of the sample. Continue this process for a minimum of 48 h, ensuring adequate hydrate formation time and sufficient gas volume during the formation phase. After 48 h, close the gas tank, keep only the L_C channel open, and use the back pressure controller to continue stabilizing the pressure for over 10 h. Once the back pressure controller volume remains largely unchanged, it can be concluded that no further hydrate formation will occur, signifying the completion of GHBS sample preparation.

(5) Follow the experimental plan for subsequent procedures, including consolidation, shearing, and other test stages.

(6) Post experiment, close all channels, attach a flowmeter to the L_0 channel, and gradually open the L_0 valve. The gas released by the decomposition of hydrates within the GHBS is collected in the gasbag through the flowmeter.

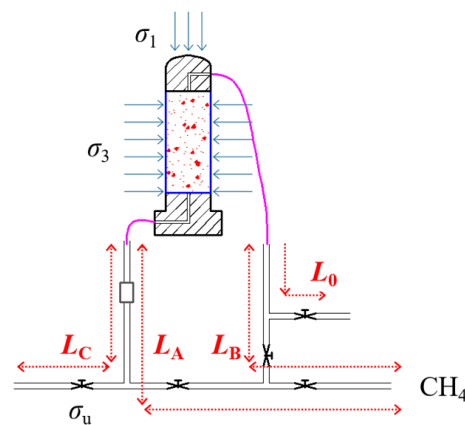


Figure 6. Schematic of pipeline channels during GHBS sample preparation.

2.3. Test Scheme

This study examines two variables across 12 sets of consolidation and drained tests: effective confining stress and hydrate saturation, detailed in Table 2. The effective confining stresses (σ_3') were set at three levels: 1 MPa, 3 MPa, and 5 MPa. For each level of effective confining stress, three different hydrate saturations were established: 10%, 20%, and 30%.

In the course of the experiment, the pore pressure was consistently maintained at 4 MPa, as indicated in Figure 5. Consequently, the total confining pressures were established at 5 MPa, 7 MPa, and 9 MPa, respectively.

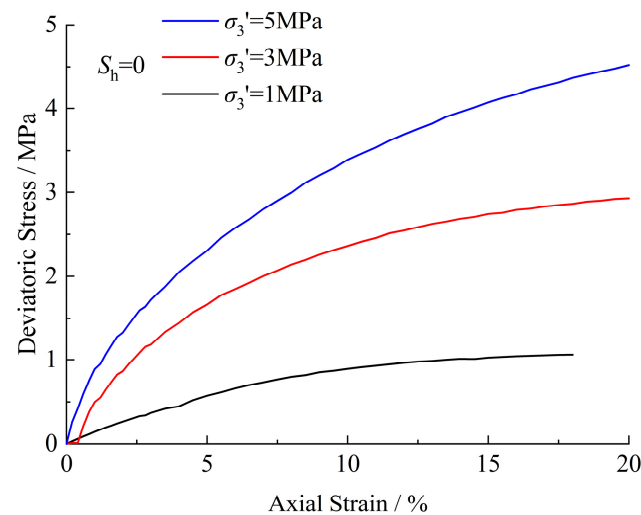
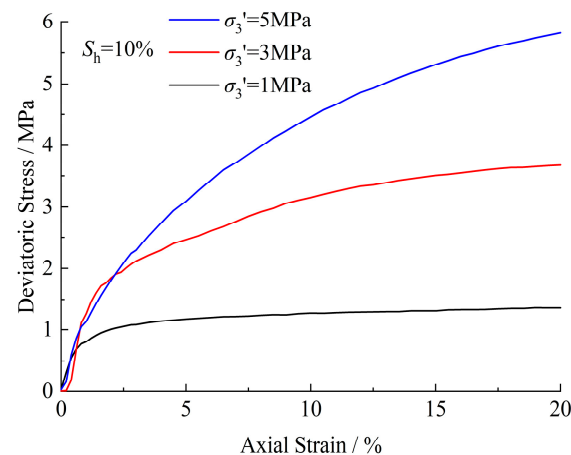
Table 2. Test Scheme.

Number	Hydrate Saturation (S_h , %)	Effective Confining Stress (σ_3' , MPa)
GHBS01	0, 10, 20, 30	1
GHBS03	0, 10, 20, 30	3
GHBS05	0, 10, 20, 30	5

3. Results and Interpretation

3.1. Stress–Strain Relationship

Figure 7 presents the stress–strain curve at $S_h = 0$, where samples devoid of hydrates demonstrate characteristics akin to loose or medium dense sand, uniformly exhibiting strain hardening without noticeable peak strength. This suggests that GHBS, in the absence of hydrates, share similarities with typical soil types. However, hydrate saturation markedly influences the mechanical properties of GHBS. Figure 8, representing $S_h = 10\%$, continues to display strain hardening. Under identical axial strains, the deviatoric stress is notably higher than that in Figure 7, especially under the confining pressures of 3 MPa and 5 MPa. It was observed that at a confining pressure of 1 MPa and $S_h = 10\%$, the GHBS maintained stable deviatoric stress at an axial strain of 8%, attributable to hydrates enhancing the compactness of the GHBS, which in turn strengthens particle frictional interactions and facilitates the earlier attainment of peak strength.

**Figure 7.** Stress–strain curve ($S_h = 0$).**Figure 8.** Stress–strain curve ($S_h = 10\%$).

In Figure 9, at $S_h = 20\%$, under a 1 MPa confining pressure, it can be seen that peak strength is achieved at an axial strain of 3%, and at a 3 MPa confining pressure, the curve nears peak strength at an axial strain of 15%. This behavior is attributed to hydrates enhancing the frictional properties within GHBS particles, while increased confining pressure additionally boosts GHBS compactness. This indicates the dual contribution of hydrate saturation and confining pressure to GHBS strength.

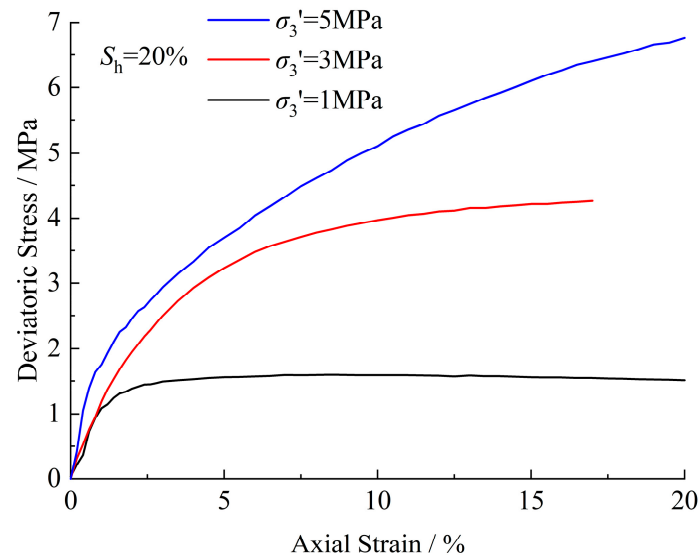


Figure 9. Stress–strain curve ($S_h = 20\%$).

Figure 10, corresponding to $S_h = 30\%$, aligns with Figures 7–9 in that increased confining pressure leads to higher deviatoric stress. Notably, the curve shape differs: the initial stiffness of the sample sets is more pronounced, and at 1 MPa confining pressure, the curve exhibits strain softening. Moreover, hydrates contribute additional strength to GHBS, but this strength diminishes more swiftly under lower confining pressures (1 MPa), resulting in strain softening. This elucidates two impacts of hydrates: the filling effect, where greater S_h enhances initial stiffness and shear strength, and the cementing effect, where hydrates alter a GHBS's internal structure, boosting its additional strength.

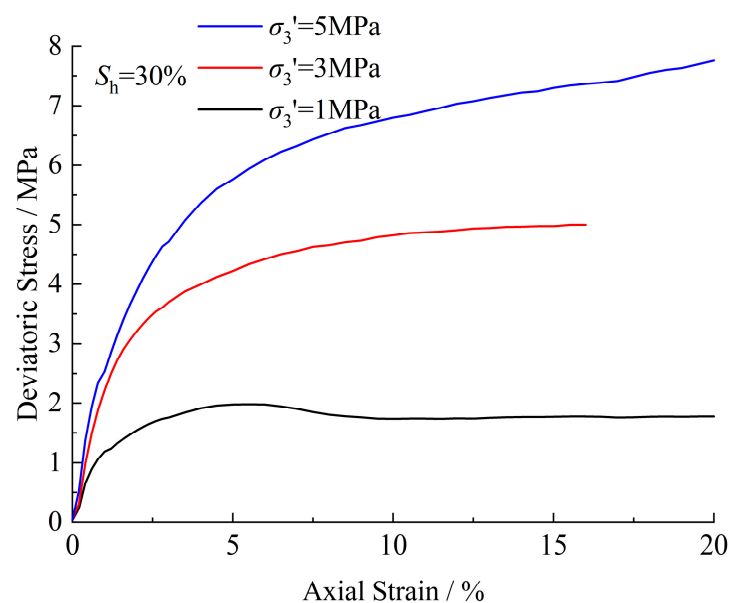


Figure 10. Stress–strain curve ($S_h = 30\%$).

3.2. Volumetric Strain

Figure 11 illustrates the volumetric strain curve of silty fine sand without hydrates, where under various σ_3' conditions, a consistent pattern of shear shrinkage is observed. As σ_3' intensifies, the restraint imposed on the sample strengthens. This enhanced confining pressure tightens particle contacts, demanding greater frictional resistance to facilitate particle rotation and sliding, thus leading to increased volume shrinkage during shearing.

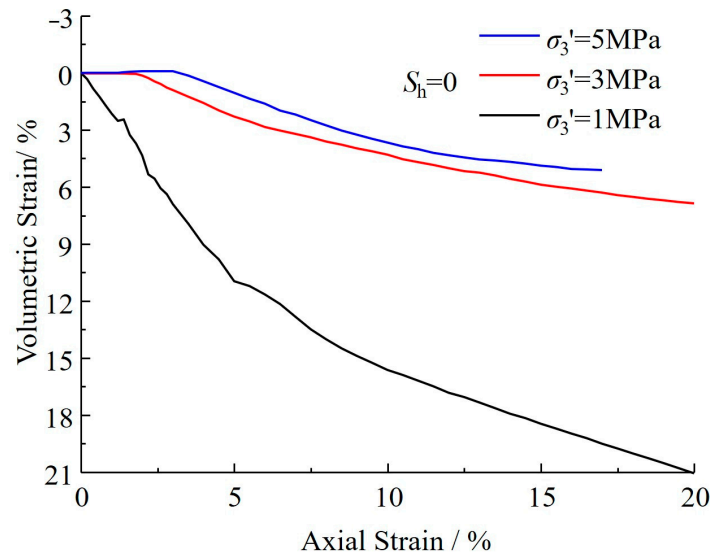


Figure 11. Volumetric Strain Curve ($S_h = 0$).

For GHBS at $S_h = 10\%$, the volumetric strain curve shown in Figure 9 markedly contrasts with Figure 12. At $\sigma_3' = 5$ MPa, the shear shrinkage in GHBS is considerably lower than in non-hydrate-bearing silty fine sand. At σ_3' values of 1 MPa and 3 MPa, GHBS exhibits behavior akin to dense sand, where shear dilation escalates with decreasing σ_3' .

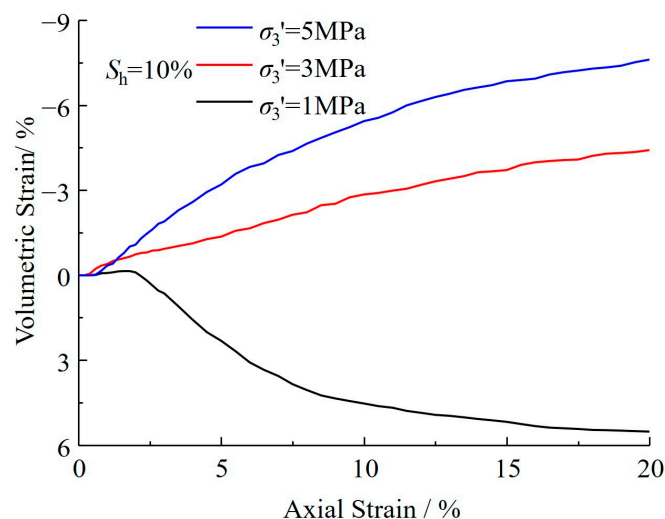


Figure 12. Volumetric strain curve ($S_h = 10\%$).

Figure 13 depicts the volumetric strain curve for GHBS at $S_h = 20\%$. A comparison with Figure 8 ($S_h = 0$) and Figure 9 ($S_h = 10\%$) reveals that with increasing S_h , GHBS exhibits reduced shear shrinkage and augmented shear dilation, indicating that hydrates enhance the shear dilation characteristics of GHBS. The presence of hydrates in GHBS increases soil compactness, effectively altering GHBS grading. This grading shift impacts

the internal structure of the particles and their spatial arrangement, leading to varied volumetric responses under identical stress paths.

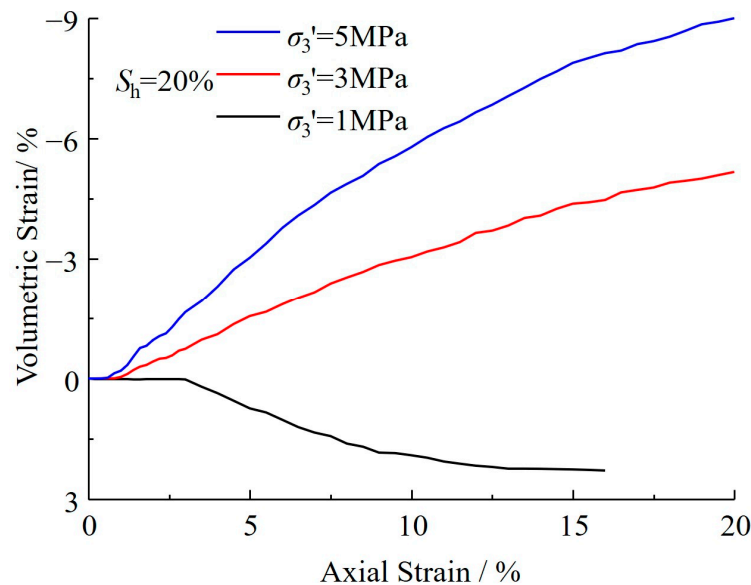


Figure 13. Volumetric strain curve ($S_h = 20\%$).

Additionally, the shear dilation observed in Figures 12 and 13 predominantly occurred under the lower confining pressures of $\sigma_3' = 1$ MPa and 3 MPa. This is attributed to the reduced constraining effect of confining pressure on GHBS. Under shear stress, internal soil particles within GHBS undergo rotation and flipping, resulting in shear dilation deformation. This phenomenon is more pronounced under conditions of lower confining pressure and higher hydrate particle content. Concurrently, the relative motion among particles weakens the additional strength of GHBS, leading to a softening effect. This is corroborated by the experimental data shown in Figure 8 ($\sigma_3' = 1$ MPa, $S_h = 30\%$), which indicate that GHBS shear dilation becomes more pronounced with increasing σ_3' and S_h .

Figure 14 presents the volumetric strain at $S_h = 30\%$, where the GHBS consistently demonstrate shear dilation. Higher hydrate content increases the likelihood and extent of particle inter-rotation and movement, thereby accentuating the shear dilation properties.

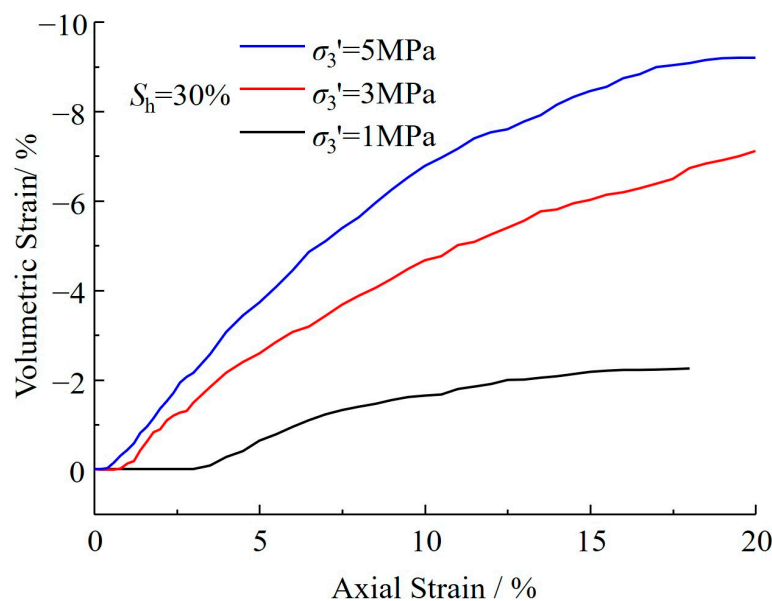


Figure 14. Volumetric strain curve ($S_h = 30\%$).

4. Discussion

4.1. Shear Strength and Peak Strength

We analyzed the strength of clayey silt GHBS based on the previous test data. The so-called strength is the shear strength of materials. The function that characterizes the failure conditions of materials is called the strength criterion. Among many strength criteria, the Mohr–Coulomb criterion (M-C criterion) is the most widely applied in engineering practice because of its simplicity, practicality, and simple parameter acquisition [30]. The M-C criterion states that when the ratio of shear stress to normal stress on the shear plane of a material reaches the maximum, the material will yield and collapse. The M-C criterion can be expressed as:

$$\tau = c + \sigma' \tan(\varphi) \quad (4)$$

where τ is the shear strength, that is, the shear stress on the failure surface; σ' is the normal stress on the failure surface; c is the cohesion; and φ is the friction angle.

Taking the value corresponding to the axial strain $\varepsilon_a = 15\%$ as the failure strength value, according to the data shown in Figures 7–10, we drew the corresponding Mohr circle to obtain the common tangent; that is, the strength envelope, the slope, and intercept of the envelope. The shear strength index of GHBS under the M-C criterion can be obtained by applying Equation (4), as shown in Figure 15.

According to the data in Figure 15, the quantitative relationship between c and φ can be obtained as shown in Figure 16. The expression can be recorded as:

$$\begin{cases} c = (-3.72S_h^2 + 167.10S_h)p_a \\ \varphi = (17.20 + 0.22S_h)^\circ \end{cases} \quad (5)$$

where p_a is atmospheric pressure, which can be simply taken as 0.1 MPa.

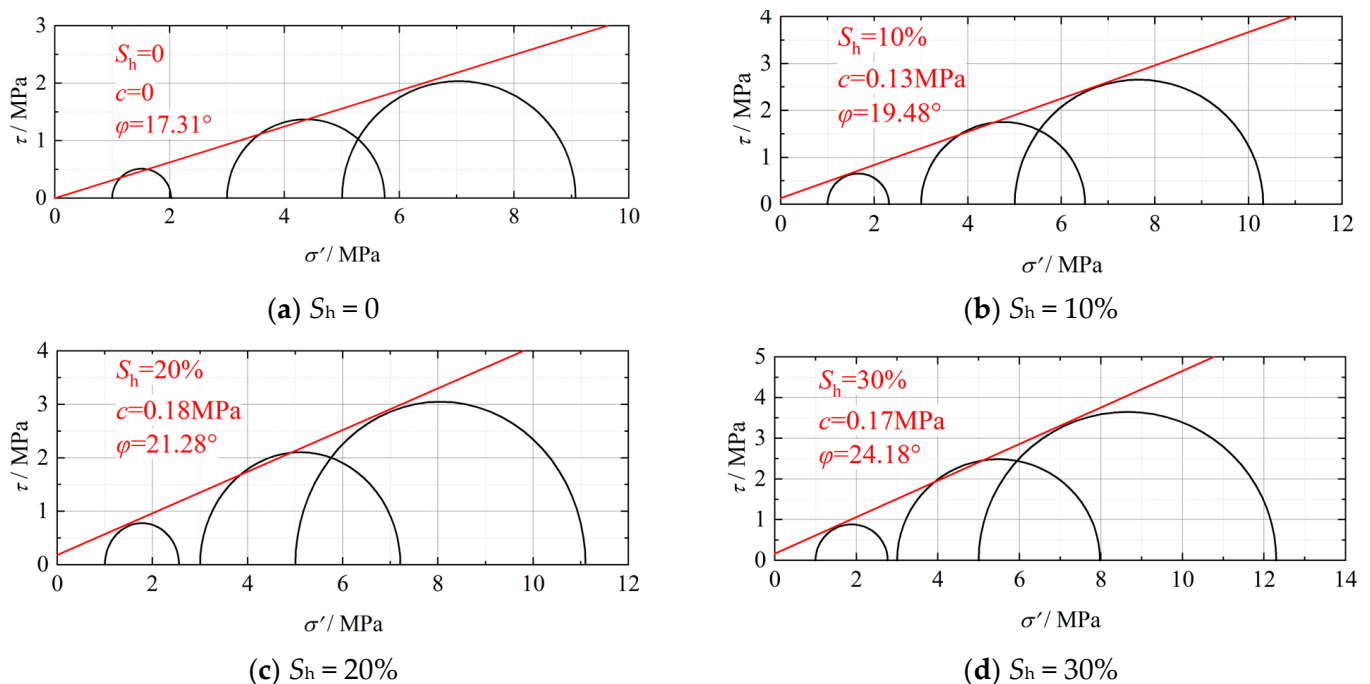


Figure 15. Mohr circle of GHBS.

When substituting Equation (5) into Equation (4) to obtain the strength of GHBS described by the M-C criterion, it can be seen that the friction angle φ rises continuously with the increase in S_h , but the increase is small. The cohesion c has a parabolic relationship with S_h , and when S_h is small, c rises gradually. However, when S_h increases to a certain extent, c begins to decrease.

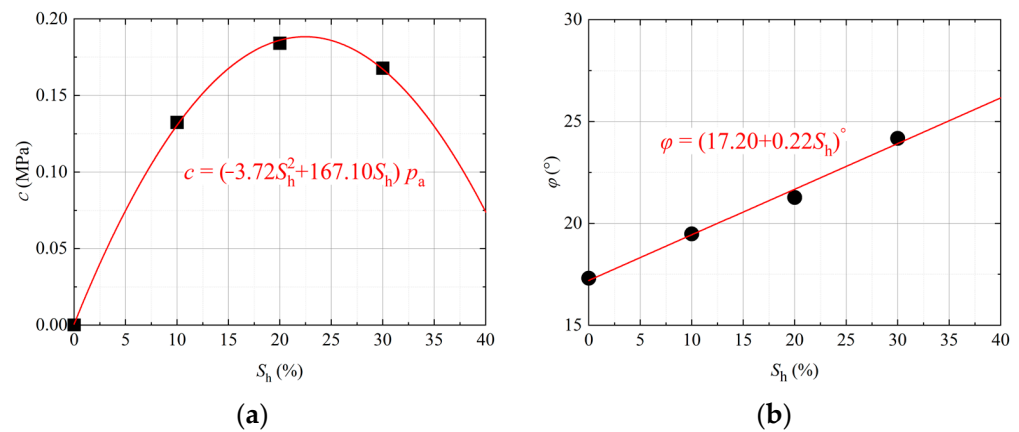


Figure 16. Relationship curve between shear strength and hydrate saturation. (a) Cohesion and S_h ; (b) friction angle and S_h .

Figure 17 shows the peak strength of the 12 sets of trials, plotted in three dimensions. It is apparent that the peak intensity σ_p exhibits a monotonically rising relationship with both S_h and σ_3' , and the slope rises with increasing S_h and σ_3' . This means that both S_h and σ_3' contribute to the peak strength.

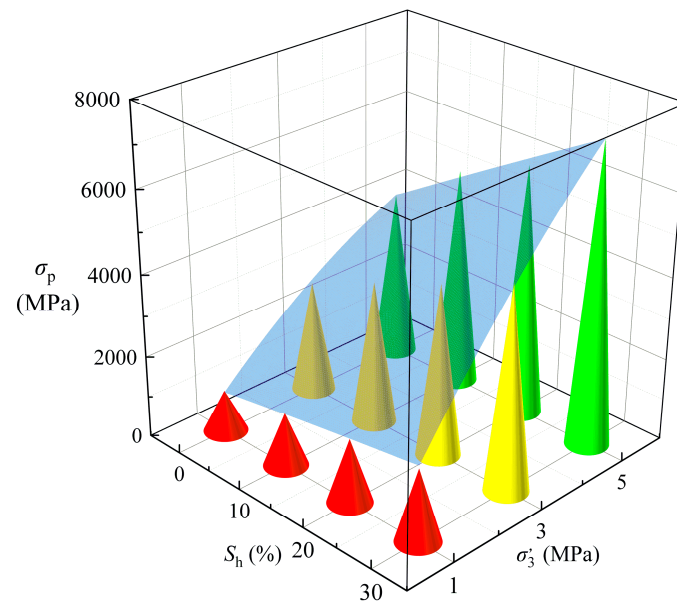


Figure 17. Initial tangent modulus of GHBS and effective confining stress.

The empirical equation used for fitting to obtain the peak strength is as follows:

$$\sigma_p = S_h p_a \left(78.78 + 19.13 \frac{\sigma_3'}{p_a} \right) + 28.56 \sigma_3' + \sigma_{p0} \quad (6)$$

where σ_{p0} is the peak strength of the specimen without hydrate.

4.2. Initial Stiffness

In order to describe the mechanical properties of GHBS quantitatively, it was observed that GHBS exhibited strain hardening, and the Duncan–Chang model (D-C model) was used to describe this type of soil. The D-C model notates the stress–strain curve as:

$$q = \frac{\varepsilon_a}{a + b\varepsilon_a} \quad (7)$$

in which

$$\begin{cases} a = 1/E_i \\ b = R_f/q_f \end{cases} \quad (8)$$

where q is the deviator stress, MPa; a and b are the fitting parameters; E_i is the initial tangent modulus, MPa; R_f is the damage ratio; and q_f is the shear stress at failure, MPa.

Using Equations (7) and (8) to fit the experimental data, the damage ratio R_f of 0.85 was obtained. The initial tangential stiffness E_i of GHBS under different initial conditions is shown in Table 3 and Figure 18. From Figure 18, it can be seen that E_i has a good linear relationship with S_h and σ_3' has basically no effect on the slope, but σ_3' determines the intercept of the curve, i.e., E_{i0} . This can be uniformly notated as:

$$E_i = 851.62S_h p_a + E_{i0} \quad (9)$$

where 851.62 is the proportional coefficient and E_{i0} is the initial stiffness of the sample without hydrate, MPa, as shown in Table 3.

Table 3. Initial tangent modulus E_i (MPa) of GHBS.

S_h	$\sigma_3' = 1 \text{ MPa}$	$\sigma_3' = 3 \text{ MPa}$	$\sigma_3' = 5 \text{ MPa}$
0	262	773	1100
10%	1241	1442	1483
20%	2087	1771	1878
30%	2599	3181	3497

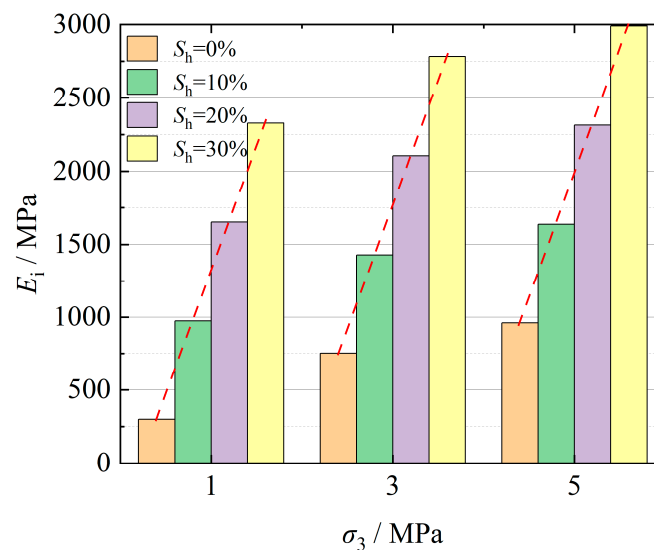


Figure 18. Initial tangent modulus of GHBS and effective confining stress.

4.3. Discussion of Mechanism

Using the interactions between the microscopic particles of GHBS, the patterns of variation in their macroscopic mechanical properties can be better described. Many scholars have investigated the microstructure of GHBS using techniques such as CT and SEM. CT can observe the process of hydrate formation and decomposition in GHBS and identify the pore structure of the sediment [31,32]; the current observations show that hydrates are not uniformly distributed in GHBS and are usually concentrated in the center of the particle pores. The mode of assignment changes during formation, and hydrates may appear in various states, such as filling and connection, at the same moment. The filling mode dominates in the early phase of formation, where hydrates are suspended in the pore space, multiple modes coexist in the middle phase of generation; and the connection and cementation modes dominate in the late phase of generation [33]. Observations made using

a Scanning Electron Microscope (SEM) revealed that at temperatures as low as $-180\text{ }^{\circ}\text{C}$, hydrates initially begin to adhere to soil particles. As the concentration of hydrates increases, they progressively envelop the soil particles, a process illustrated in Figure 19 [34]. During the generation of GHBS in this study, the temperature was meticulously maintained at $1\text{ }^{\circ}\text{C}$. This ensured the absence of ice grains, thereby isolating hydrates as the sole influencer on the structural integrity of the GHBS.

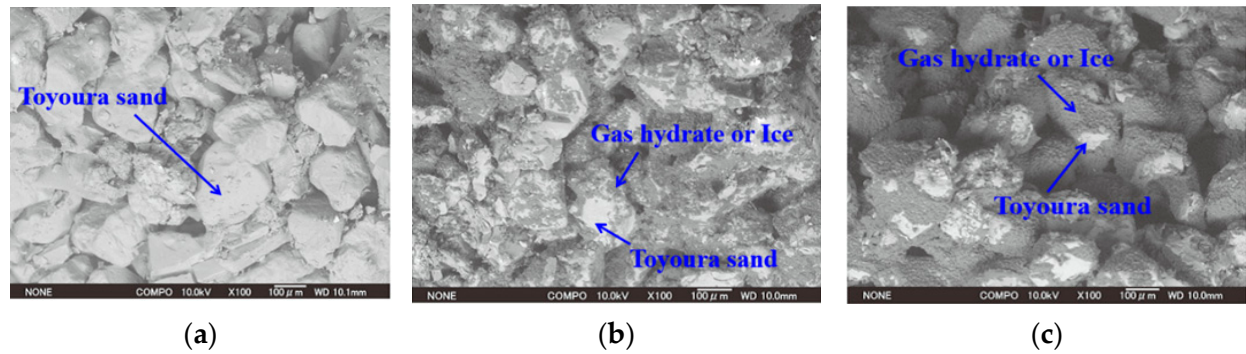


Figure 19. SEM images of GHBS [34]. (a) $S_h = 0$; (b) $S_h = 30\%$; (c) $S_h = 50\%$.

Based on these observation results and the empirical formula given in this paper, our analysis shows that:

(1) The internal friction angle reflects the frictional resistance between microscopic particles, while cohesion indicates their cementation capability. An increase in S_h leads to an initial rise and subsequent fall in cohesion, with a continuous increase in the internal friction angle, suggesting an enhancement in particle cementation and friction capabilities during early hydrate formation.

(2) The formation of hydrates densifies the soil skeleton of GHBS, leading to a tighter particle arrangement and increased resistance to particle rotation and dislocation, as shown in Figure 20a. This results in an overall increase in stiffness and strength.

(3) As the hydrate content increases, as seen in Figure 20b, the formation of a cementation structure envelops soil particles, as depicted in Figure 20c, restricting their deformation and sliding, and providing additional strength. This process enhances the rigidity and strength of GHBS. At higher S_h levels, the formation and accumulation of hydrates can expel soil particles, leading to an uneven distribution of the cementation structure, which may initially be damaged during shearing, causing a decrease in cohesion as illustrated in Figure 20d.

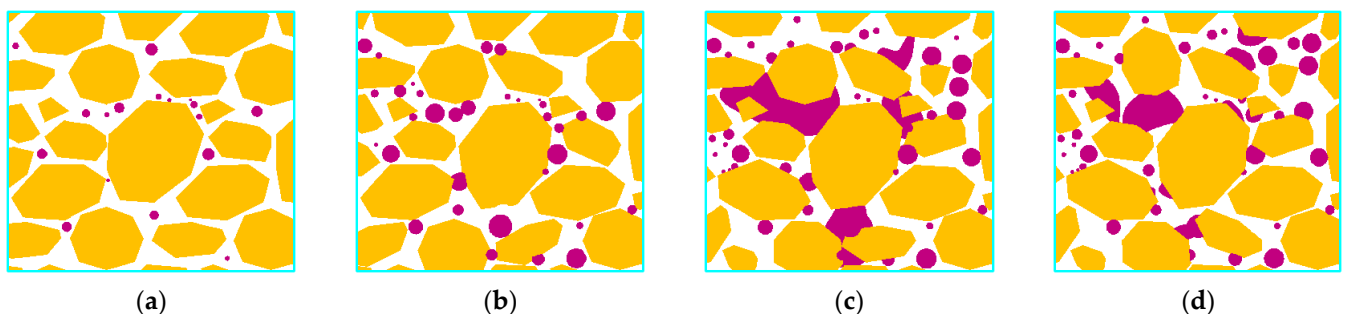


Figure 20. Microscopic mechanism of the mechanical properties of GHBS. (a) The initial phase of hydrate formation; (b) the filling of hydrate in pores; (c) the formation of the cemented structure; (d) the shearing of GHBS.

To sum up, hydrate has two effects on GHBS: filling and cementing. These two effects together lead to changes in the density, stiffness, and strength of GHBS.

5. Conclusions

This study conducted detailed experimental tests and analyses on clayey silt-type gas hydrate-bearing sediments (GHBS), thoroughly investigating the role of hydrates in GHBS. We discovered that the filling and cementing effects of hydrates not only alter the density and structure of GHBS but also significantly enhance its stiffness and strength. With increasing hydrate saturation, GHBS exhibits a marked trend towards densification and mechanical property improvement, especially in the early stages of formation, where these effects substantially boost inter-particle friction and cementation capabilities. Our findings offer new insights into the mechanisms by which hydrates influence GHBS' mechanical properties, which is crucial for future research in related fields. Additionally, the developed experimental methods and empirical formulas provide essential quantitative tools for analyzing GHBS' mechanical characteristics, laying a solid foundation for engineering applications and further studies.

Author Contributions: Conceptualization, Q.Y., Q.L., L.K. and J.L.; methodology, Q.L. and L.K.; writing—original draft preparation, Q.Y., L.K., L.Y., Y.D., Z.W. and X.W.; writing—review and editing, Q.L., L.K., J.L., L.Y., Y.D., Z.W. and X.W.; project administration, L.K., Q.L. and J.L.; funding acquisition, L.K., Q.L. and J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No. 12172187 and 11572165), the Marine Geological Survey Program of China Geological Survey (No. DD20221706), the Science and Technology Program of Guangzhou (No. 202103040003), the Guangdong Basic and Applied Basic Research Foundation (No. 2019B030302004), and the Director's research fund of the Guangzhou Marine Geological Survey (No. 2023GMGSJZJJ00002).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors wish to thank Xuhui Zhang from the Chinese Academy of Sciences for fruitful discussions and for helping to revise the manuscript, and Rui Xu, Yapeng Zhao, and Jiaqi Liu from Qingdao University of Technology for helping with the laboratory operation.

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

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