



# Article The Effect of Salinity on the Strength Behavior of Hydrate-Bearing Sands

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**Abstract:** The first prerequisite for the efficient and safe exploitation of gas hydrate resources is to accurately analyze the primary mechanical performance of hydrate-bearing sediments (HBSs). The mechanical performance of HBSs is complex and affected by many factors, including the reservoir environment in situ (temperature, pore pressure, salinity). Several published studies have demonstrated a correlation of the mechanical behavior of hydrates with temperature and pressure (*T*-*P*<sub>P</sub>). However, the research on the effect of salinity on the mechanical properties of hydrates or HBSs is still a relatively blank field. This study found that the strength of HBSs decreased with increasing salinity. This phenomenon can be attributed to the influence of salinity on the phase equilibrium state of hydrates. NaCl changed the relationship between the phase equilibrium curve of the hydrate and the *T*-*P*<sub>P</sub> conditions. The distance between the *T*-*P*<sub>P</sub> conditions and equilibrium curve was reduced with increasing salinity, which in turn led to a decline in sample strength. Moreover, the effect of the phase equilibrium of hydrates on the mechanical performance of HBSs was further explored. NaCl was added to HBSs to regulate the phase equilibrium state of the hydrate. When the *T*-*P*<sub>P</sub> conditions were on the phase equilibrium curve, the strength behaviors of HBSs showed a high degree of consistency.

Keywords: hydrate; mechanical properties; salinity; phase equilibrium

# 1. Introduction

As potential fossil energy, natural gas hydrates (NGHs) have considerable development prospects [1,2]. Some studies estimate that gas hydrate reserves are much more abundant than conventional fossil fuels [3–5]. The commercial exploitation of natural gas hydrates is a technical highland for the world powers to strive. Many countries (including the United States, Russia, Canada, Japan, and India) have invested a lot of personnel and resources in the geological survey of marine hydrate resources and commercial exploitation of hydrate resources [6–13]. China has also invested many resources in this field in the past two decades. The China Geological Survey (CGS) confirmed the rich NGH resources in China through a large number of geological survey missions [14]. It successfully drilled and cored NGH in the Shenhu area of the South China Sea in 2007 [15–17]. In recent years, China has further increased investment and successfully conducted two exploitation trials (in 2017 and 2020) of NGH in the Shenhu area of the South China Sea [18,19]. Taking the lead in realizing the commercial exploitation of NGH will be a scientific and technological highlight for all countries in the future.

Ensuring the efficiency and safety of gas hydrate exploitation is the premise of commercial exploitation, and many funds should be invested to conduct technological breakthroughs. The traditional exploitation methods proposed by the researchers include the depressurization method, heat injection method, carbon dioxide replacement method, and chemical inhibitor method [20–23]. Moreover, some new exploitation methods have been



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**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). proposed in recent years, such as solid fluidization [24,25]. However, NGH mainly occurs in marine sediment pores in cementation, pore filling, and load bearing. The decomposition of hydrates will destroy the original skeleton cementation structure and weaken the bearing capacity of the reservoir [26–28]. Furthermore, hydrate decomposition will produce gas and water and generate many pores, changing the original stress state and leading to reservoir deformation [29–31]. A series of reservoir changes will affect the gas production rate and significantly increase the risk of submarine landslides and other severe geological disasters [32,33]. On the other hand, the leakage of methane gas produced by the massive decomposition of hydrate will aggravate the greenhouse effect and become a cause of global climate change [34,35]. Therefore, a thorough explanation of the mechanical performance of HBSs is essential for the commercial exploitation of NGH [36].

To break down the mechanical performance mechanism of hydrate reservoirs and conduct a stability analysis of hydrate resource strata, governments, research institutions, and many researchers have invested much money and energy into the laboratory [37–46]. After years of research and accumulation, the experimental study of the mechanical performance of HBSs has formed a complete system from macroscopic experiments to microscopic experiments and from laboratory experiments to field experiments on exploration ships [47–52]. After nearly 20 years of development, researchers have a clearer understanding of the mechanical mechanism of HBSs. As a kind of multiphase soil material with complex properties, their mechanical performances are influenced by a series of factors, such as reservoir environmental conditions, stress state, stress history, soil density, hydrate phase transformation, and microscopic characteristics [32,51,53].

The environmental conditions of hydrate reservoirs are complex and changeable. Hydrate exploitation will lead to further changes in the reservoir environment. The existence of NGH follows the phase equilibrium condition. The extreme (high pressure and low temperature) marine stratum environment provides guaranteed conditions for the growth, accumulation, and occurrence of NGH, as shown in Figure 1. The prediction of NGH resources is mainly based on the T- $P_P$  environment of the seabed stratum obtained from the geological survey [16,54]. The growth of hydrate crystals, the density of hydrate solids, the ratio of the cage, and the dislocation movement of crystal defects are all influenced by temperature and pressure conditions [39,55–58], and might further influence the mechanical performance of HBSs.



**Figure 1.** A diagram showing the effects of water depth, seafloor temperature, and geothermal gradient on the gas hydrate stability zone (modified from Li et al. [59]).

Previous studies have shown that with decreasing temperature and increasing pore pressure, HBSs will exhibit higher strength and tend to exhibit strain-softening properties and dilatancy [60–62]. Moreover, there is a certain correlation between the equilibrium state

of the hydrate phase and the mechanical performance of HBSs [39,60,63]. It is worth noting that the marine hydrate reservoir is in a saline environment. As one of the most common thermodynamic inhibitors, NaCl can inhibit the gas hydrate's phase balance, shifting the phase equilibrium curve toward high  $P_P$  and low T directions. Considering the correlation between the mechanical performance of NGH and the hydrate phase equilibrium, salinity is likely to impact the mechanical performance of NGH. Researchers have analyzed the effect of salinity on the mechanical performance of HBSs through DEM simulation [64]. They concluded that increasing salinity would reduce the strength of NGH. However, this potential relationship has yet to be addressed, and there are still few experimental studies on the mechanism of salinity on the mechanical performance of HBSs. Since marine hydrates are always in a saline environment, the effect of salinity on their mechanical performance will be an essential and unavoidable research topic. Moreover, studies have shown that salinity can also impact exploitation processes, such as CO<sub>2</sub>-CH<sub>4</sub> replacement. Therefore, it is necessary to consider the influence of salinity in the research of marine hydrate exploitation and other related fields [65,66].

In this work, saline methane hydrate-bearing samples (MHBSs) were prepared by mixing brine or injecting brine for saturation. The relationship between salinity and mechanical performance of MHBSs was investigated by consolidation drainage (CD) triaxial tests. The relationship between the samples' mechanical performance and the hydrate's phase equilibrium was further explored by comprehensively regulating the three experimental variables: temperature, pore pressure, and salinity. Furthermore, this study will provide new ideas for subsequent research in this field and promote the development of exploitation on the mechanical performance of hydrates.

#### 2. Experiment

#### 2.1. Experimental Apparatus

An MHBS triaxial test apparatus was used, which has good performance in the high  $P_P$  and low *T* triaxial tests [67]. The highly accurate control of effective confining pressure was achieved by three ISCO pumps (500D series, Teledyne, Lincoln, NE, USA). The axial loading of the test sample is provided by a hydraulic power source (with a capacity of 600 kN). Moreover, temperature control is one of the most important technical parameters of the MHBS triaxial apparatus. Ample cold storage preliminarily controlled the overall temperature of the experimental system, and the sample temperature was further regulated by the constant temperature water bathing (with an accuracy of  $\pm 0.1$  K). Furthermore, an in situ hydrate formation and sample water saturation system were designed, which were mainly responsible for two plunger pumps. It is worth noting that these two plunger pumps are also part of the apparatus pressure control system mentioned above. The pressure control range is 0~25 MPa.

A linear variable differential transformer (LVDT) measured the samples' shear deformation. The axial loading was picked up by a force transducer mounted on the triaxial loading rod. Moreover, because soil particles do not have compressibility, the change in sample volume can be measured by pore drainage.

### 2.2. Sample Remolding

The soil particles of the triaxial test samples were sifted silica sand (mean diameter = 224  $\mu$ m, the particle size range is from 125  $\mu$ m to 380  $\mu$ m), and the particle size distribution curve is shown in previous studies [63]. Based on the target size (diameter = 61.8 mm, height = 125 mm), porosity (*n* = 40%), and initial water saturation (*S*<sub>iw</sub>), the amount of sand and water required for sample preparation can be calculated:

$$m_{\rm s} = \rho_{\rm s} \cdot V \cdot (1 - n) \tag{1}$$

$$V_{\rm w} = S_{\rm iw} \cdot V \cdot n \tag{2}$$

where  $m_s$  is the mass of the sample;  $\rho_s$  is sand density; *V* is sample volume; and  $V_w$  is water volume.

The sand and water (pure or saline water) were mixed evenly in a sealed bag. The sample remodeling process was conducted by using the moist tamping method. The quantified amount of deionized water was evenly mixed with sand and layered into the mold (hammered 15 times per layer). Ensure that all the measured water–sand mixtures were compacted into the mold, and the height reached 125 mm. Next, the mold-containing sample was carefully sealed and placed in the freezer (253.15 K). After being frozen for at least 4 h, the remodeled sample was installed in the triaxial chamber. Silicone oil and methane gas are injected into the pressure chamber and sample pore, respectively. Then, all the preparations before the hydrate in situ formation have been completed.

#### 2.3. Triaxial Tests (Water-Saturated Samples)

The process was shown as follows for the triaxial tests of the water-saturated samples. The sand and pure water mixture were used for sample remolding. The initial effective confining pressure ( $\sigma_c$ ) was set at 0.2 MPa by controlling pore pressure ( $P_P$ ) and confining pressure ( $\sigma_c$ ) at 5 MPa and 5.2 MPa, respectively. Moreover, the sample temperature (T) was set at 276.15 K. The *T*- $P_P$  conditions of the samples were already in the stable zone, and the in situ hydrate formation began. It will take about two days to fully hydrate the synthesis, at which point the samples no longer consume methane gas. Based on the methane gas consumption of the samples logged by the plunger pump, the hydrate saturation of the samples ( $S_h$ ) can be calculated [68]:

$$S_{\rm h} = \frac{V_{\rm h}}{V_{\rm pore}} = \frac{\frac{P_{\rm h}V_{\rm g}}{ZRT_{\rm h}} \cdot M_{\rm h}}{\rho_{\rm h} \cdot V \cdot n}$$
(3)

where  $V_{\text{pore}}$  is sample pore volume, which is equal to  $V \cdot n$ ;  $T_{\text{h}}$  and  $P_{\text{h}}$  are temperature and pressure conditions for hydrate formation, respectively; Z is the compression factor of methane gas under the current temperature pressure conditions (0.8834);  $\rho_{\text{h}}$  (0.91 g/cm<sup>3</sup>) is hydrate density [1]; and  $M_{\text{h}}$  (124 g/mol) is the molar mass of the hydrate.

The saline water saturation process was conducted. Firstly, to suppress the decomposition of the hydrate, the  $P_P$  and  $\sigma_c$  were raised to 9 MPa and 9.2 MPa, respectively. Then, the sample was infiltrated by saline water, and the static differential pressure between the top and bottom of the sample (0.2 MPa) was maintained by adjusting the backpressure valve at the top outlet of the samples. The samples will gradually be infiltrated by saline water until fully saturated. In Table 1, the parameters of the water-saturated samples were listed.

Table 1. Parameters of the water-saturated samples.

Case Number	The Salinity of Pore Water $\omega_{pore water}$ (wt%)	Hydrate Saturation S <sub>h</sub> (%)	
1-1	0	60.6	
1-2	4	59.9	
1-3	8	60.1	

The T- $P_P$  was raised to the experimental conditions (278.15 K and 15 MPa) in this paper. Then, the  $\sigma'_c$  was raised to 2 MPa, and the samples were consolidated for over 24 h. The drained triaxial test was conducted on the samples when the above preparation was completed. The samples were sheared at a fixed strain rate by controlling the axial loading system, and the test data were obtained (stress–strain and volumetric strain curves).

#### 2.4. Triaxial Tests (Gas-Saturated Samples)

In this work, several gas-saturated samples were also prepared for triaxial tests. Sand and saline water mixtures were used for sample remolding. It should be noted that this part of the test did not adopt fixed T- $P_P$  conditions for all cases. The T- $P_P$ 

conditions of hydrate formation are different for each gas-saturated sample. Moreover, the formation of hydrate will lead to the precipitation of salt, leading to the gradual increase in salinity in the remaining pore water, which will eventually lead to the macroscopic halt of hydrate formation. Due to the above phenomenon, it is necessary to appropriately increase the initial water saturation ( $S_{iw}$ ) to prepare samples with 60%  $S_h$ . After the hydrate synthesis process, the triaxial consolidation drainage experiment was conducted directly under the current temperature and pore pressure conditions without water saturation. All experimental parameters in this part of the triaxial tests are shown in Table 2.

Case Number	Initial Water Saturation S <sub>iw</sub> (%)	Initial Salinity $\omega_{ m initial}$ (wt%)	Hydrate Saturation S <sub>h</sub> (%)	Temperature T (K)	Pore Pressure P <sub>P</sub> (MPa)
2-1 2-2 2-3	50 54.5 54.5	0 0 2.00	58.5 58.9 59.5	278.15	9
2-4 2-5	54.5 54.5	1.60 2.86	59.4 60.0	274.15 274.15	5 9

Table 2. Experimental parameters of the gas-saturated samples.

For cases 2-3, the pore water's initial salinity ( $\omega_{initial}$ ), target hydrate saturation ( $S_h \approx 60\%$ ), temperature (T), and pore pressure ( $P_P$ ) were set as known conditions. Due to salt precipitation, the initial water saturation ( $S_{iw}$ ) needs to be calculated in order to generate MHBSs of 60% hydrate saturation. Using the GMsem software of the Colorado School of Mines, the salinity limit under current temperature and pressure conditions was calculated ( $\omega_{limit} = 14.0 \text{ wt\%}$ ). The mass of consumed water ( $m_{w-c}$ ) is then calculated according to a hydrate saturation of 60%. Furthermore, according to the conservation of salt mass, the initial water saturation ( $S_{iw}$ ) could be calculated according to the following equations:

$$(m_{\rm w} - m_{\rm w-c}) \cdot \omega_{\rm limit} = m_{\rm w} \cdot \omega_{\rm initial} \tag{4}$$

$$S_{\rm iw} = \frac{V_{\rm w}}{V_{\rm pore}} = \frac{m_{\rm w} \cdot (1 - \omega_{\rm initial}) / \rho_{\rm w}}{V_{\rm pore}}$$
(5)

where  $m_w$  is the mass of pore water and  $\rho_w$  the density of pure water.

Moreover, in order to control experimental variables and exclude the influence of initial water saturation, case 2-2 was conducted. For cases 2-4 and 2-5, the initial water saturation ( $S_{iw}$ ) was the known variable, while the initial salinity ( $\omega_{initial}$ ) needed to be calculated by using Equations (4) and (5).

For gas-saturated MHBSs, triaxial tests were conducted without a water-saturation process. When the samples no longer consumed methane gas (the hydrate saturation reached the target value), MHBSs were consolidated, and deviatoric stress was applied to the samples for shearing.

# 3. Results and Discussion

### 3.1. The Effect of Salinity under Water-Saturated Conditions

For the water-saturated samples, the salinity of the pore water ( $\omega_{pore water}$ ) was the unique variable. By processing the experimental data, the stress–strain and the volumetric strain curves were plotted as the preliminary test results, as shown in Figure 2. Through the visual observation of test curves, all the test curves showed strain-softening behaviors. The samples' strength increased with decreasing  $\omega_{pore water}$ . Moreover, by analyzing the volumetric strain curves, all samples showed dilatancy behaviors. The increasing salinity weakened the dilatancy to some extent.



Figure 2. Triaxial test curves of MHBSs under different pore salinities.

According to previous studies, the T- $P_P$  conditions would act on the mechanical performance of MHBSs. The strength and dilatancy of MHBSs increased with increasing distance "L" between T- $P_P$  condition points and the hydrate phase equilibrium curve [60]. In this section, there was no difference in the preparation process of the three groups of samples, except for the difference in injected brine concentration in the process of water saturation. As a thermodynamic inhibitor, salt will enhance the phase equilibrium pressure and reduce the phase equilibrium temperature. Figure 3 shows the phase equilibrium curves under different salinities calculated by CSMGem (Hydrate Research Center, Colorado School of Mines). Although the T- $P_P$  conditions of these water-saturated tests remain unchanged, the pore water salinity will change the distance "L" mentioned above. Under the experimental conditions of this paper, with increasing pore water salinity, the distance "L" will be shortened and eventually lead to a decrease in the strength of MHBSs. A more detailed analysis of the influence of salinity on the mechanical performance of MHBSs will be conducted in the subsequent section.



Figure 3. Phase equilibrium curves of methane hydrate under different salinity conditions.

# 3.2. The Effect of Salinity under Unsaturated Conditions

The triaxial tests in Section 3.1 studied the relationship between the salinity and the strength of MHBSs under the water-saturated condition. It is preliminarily concluded that the samples' strength showed a negative correlation with pore water salinity. However, there is an interference factor in the study of the influence of salinity on the water-saturated sample strength. During the water saturation process, injecting salt water into the pores of samples will lead to a small amount of hydrate decomposition due to the methane fraction depression in the water. The injection of saline with different concentrations may lead to the difference in the decomposition amount of hydrate, which in turn may slightly reduce the hydrate saturation of MHBSs. Therefore, triaxial tests of the unsaturated samples were conducted in this paper to verify the correlation between salinity and sample strength of MHBSs.

The unsaturated samples of hydrate-bearing sediments did not undergo the process of saline water saturation and were prepared by directly mixing sand and saline water. The formation of the hydrate will result in the precipitation of salt, which leads to higher salinity in the remaining saline pore water and makes the  $T-P_{\rm P}$  condition of hydrate formation close to the phase equilibrium curve, resulting in the inability of the further generation of hydrate. Therefore, under the effect of the above factors, salt-containing samples cannot generate MHBSs with hydrate saturation close to 60% under the original condition of 50% initial water saturation. It is necessary to slightly increase the initial water saturation (54.5%) of saline samples. Figure 4 shows the effect of salinity on the mechanical performance of unsaturated MHBSs. All samples exhibit the behaviors of cemented sand (strain-softening and dilatancy). As can be seen in Figure 4, salinity significantly impacts the mechanical performance of hydrate-bearing sand, and the strength decreased as the salinity increased. The presence of salinity weakens the dilatancy of the samples. In addition, salinity significantly reduced the strength of the unsaturated samples in comparison to the water-saturated tests. The above phenomenon may be caused by the peculiarity of the sample preparation method. The unsaturated samples were remolded by mixing sand and saline water. Salt would precipitate during hydrate formation, and the salinity of the remaining pore water would gradually increase. Finally, the temperature pressure conditions of hydrate formation are gradually close to the phase equilibrium curve during the triaxial tests.



Figure 4. The effect of salinity on the mechanical performance of the unsaturated samples.

In addition, to exclude the effect of pore water on sample strength, tests were conducted on the samples with various initial pore water saturation, as shown in Figure 4 (the blue and yellow curves). According to the results, the axial strain value at peak deviatoric stress will increase with increasing initial water saturation. However, slight differences in initial water saturation have little effect on sample strength.

Salinity influences the mechanical performance of MHBSs, and the existence of salinity will weaken the strength and dilatancy of samples. Interestingly, using the tests in this section, the triaxial tests under the T- $P_P$  condition on the phase equilibrium curve were realized in a disguised way.

# 3.3. Variation Law of MHBS Strength under Saline Conditions

It has been confirmed in previous studies that the strength of MHBSs will decrease as the distance between the test condition points  $(T-P_P)$  and the phase equilibrium curve decreases. In this work, it can be seen that the mechanical performance of the test samples will be under the control of salinity. The strength and dilatancy of MHBSs decreased with increasing salinity. The above phenomenon might be caused by the effect of salinity on the hydrate phase equilibrium state. In Figure 3, with increasing salinity, the hydrate phase equilibrium curve shifts upward to the upper left (high  $P_P$  and low T direction) as salinity increases, thus narrowing the distance between test conditions  $(T-P_P)$  and the phase equilibrium curve.

Although previous studies have attempted to establish and explain the correlation between the strength and hydrate phase equilibrium state, experiments still need to be conducted directly at the T- $P_P$  points on the hydrate phase equilibrium line. These experiments can directly prove the effect and rule of hydrate phase equilibrium on the strength of MHBSs. Although T and  $P_P$  cannot be directly controlled precisely to keep the hydrate in dynamic equilibrium, it can be realized by adding salt. In Section 3.2, the salt precipitation during hydrate formation will increase the salinity of the remaining pore water and shift the hydrate phase equilibrium curve to the upper left (high  $P_P$  and low T direction). Finally, when hydrate synthesis stops (from a macro perspective), the experimental T- $P_P$  points of the unsaturated MHBSs containing salt were close to the hydrate phase equilibrium curve.

Three unsaturated MHBSs containing salt were conducted (cases 2-3, 2-4, 2-5). The initial water saturation of three groups of samples was 54.5%, and the experimental variables were salinity, temperature, and pore pressure. The calculation of the hydrate phase equilibrium curve under different salinity conditions has been performed with CSMGem software. By controlling initial salinity, *T*-*P*<sub>P</sub>, the final saturation of the hydrate can be roughly controlled at about 60%, which takes about 3 to 4 days. The experimental condition setting and the above experimental design mechanism are shown in Figure 5. The purpose of conducting experiments under the *T*-*P*<sub>P</sub> condition on the phase equilibrium curve is achieved. The experimental data curves are shown in Figure 6. All samples showed strain-softening and dilatancy behaviors.



**Figure 5.** A schematic diagram of the hydrate phase equilibrium curve change during hydrate in situ synthesis (unsaturated—sample).



**Figure 6.** Changes of the mechanical performance of MHBSs under the combined effects of salinity, T- $P_{\rm P}$ .

The experimental conditions of salinity, *T*, and  $P_P$  are different. However, the experimental data curves of the three groups of samples show surprising consistency, and there is little difference between the volumetric strain curves of each. Even though the experimental variables differed, the three groups of samples were unified from the perspective of sample mechanical performance. Based on analyzing the results presented in this section, the following conjecture can be put forward on the premise that the hydrate types in sediment pores remain unchanged and the temperature is higher than the freezing point. When the *T*-*P*<sub>P</sub> conditions of MHBSs are on the phase equilibrium curve and other experimental conditions are unchanged, the mechanical performance of MHBSs will show high levels of consistency. The hydrate phase equilibrium curve is the starting point of the change in the mechanical performance of hydrate sediments with *T* and *P*<sub>P</sub>. The strength of MHBSs is affected by *T*-*P*<sub>P</sub> conditions and salinity. The relationship between the three parameters (*T*-*P*<sub>P</sub> conditions and salinity) can be established by the hydrate phase equilibrium state. The strength of MHBSs is expressed by the following formula:

$$q_{\rm S} = f(T', P_{\rm P}') \tag{6}$$

where  $q_S$  is the strength of MHBSs; T' is the difference between the current T and the equilibrium temperature at the current pore pressure  $P_P$ ;  $P'_P$  is the difference between the current  $P_P$  and the equilibrium pressure at the current T; and T' and  $P'_P$  are both affected by salinity.

Many previous studies have proved that the strength (MHBSs) is controlled by T- $P_P$  conditions. Furthermore, it has been speculated that the samples' mechanical performance may be affected by the phase equilibrium relationship [39,60,63,69]. This paper further demonstrates the relationship between the mechanical performance of MHBSs and phase equilibrium from another angle by adding salinity variables. To support the above idea, however, more experimental studies are needed. Since the mechanical performance of pure sand samples is basically not affected by temperature and pore pressure, research should be conducted from the perspective of hydrate crystals. The presence of hydrate crystals in the samples' pore space will bring cementation to the sediments and hinder the displacement torsion of sediment particles. Hydrate crystal mechanical performance is influenced by a number of environmental factors (T,  $P_P$ , salinity). Investigating the effects of environmental factors on the mechanical performance of hydrate crystals is of great

importance. Furthermore, the growth of hydrate crystals will undergo Oswald ripening [55] and other effects, which will further influence the mechanical performance of hydrates [70].

Due to the difficulty of the experiment, the basic mechanical performance of pure hydrate crystals (or pure structure hydrate) still needs to be tested. However, it is still necessary to conduct research in the above directions. Jung et al. [71] synthesized hydrate cement between the two substrates and tested the adhesion and tension of hydrates. These methods provide a reference for studying the mechanical performance of hydrate crystals. Testing the adhesion, tension, torsion, and shearing behaviors (at different  $T-P_P$  conditions and salinities) of hydrates and establishing the constitutive model can provide further exploration directions for the research content in this paper. Furthermore, by combining the constitutive model with the discrete element method (DEM), The mechanical performance of MHBSs will be further investigated from a microscopic point of view.

# 4. Conclusions

In this paper, triaxial tests were performed on methane hydrate-bearing sediments (MHBSs) containing NaCl. By analyzing the strength behaviors of MHBSs during compression, the following conclusions were drawn:

- 1. When the T- $P_P$  conditions are in the stable zone of the hydrate, the strength of watersaturated MHBSs decreases with the increasing pore water salinity. Meanwhile, with increasing pore water salinity, the dilatancy of samples will be weakened.
- 2. The strength of unsaturated MHBSs is also negatively correlated with salinity. However, unsaturated samples are more significantly influenced by salinity than watersaturated samples.
- 3. The difference in salinity sensitivity between gas-saturated sample strength and watersaturated sample strength is caused by the change in residual pore water salinity during hydrate synthesis (salt precipitation during hydrate synthesis).
- 4. For triaxial tests of unsaturated samples, the *T*-*P*<sub>P</sub> can be close to the hydrate phase equilibrium curve by adding NaCl. Furthermore, when the *T* and *P*<sub>P</sub> conditions of sandy MHBSs are on the hydrate phase equilibrium curve, the mechanical performance of the samples will show a high degree of consistency.

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