STUDY ON STRENGTH OF ARTIFICIAL METHANE HYDRATE-
BEARING CLAY SEDIMENTS UNDER TRIAXIAL COMPRESSION

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ABSTRACT
To study the strength of artificial methane hydrate-bearing clay sediments, a series of triaxial constant strain rate tests were performed under various conditions with confining pressures ($P$) at 2.5, 3.75 and 5MPa, temperatures ($\theta$) at –5, –10, –15 and –20°C and strain rates ($\dot{\varepsilon}$) at 0.1, 0.5 and 1%/min. The results showed that the shear strength of methane hydrate-bearing clay sediments increased in conditions of the enhancement of confining pressure, the enhancement of strain rate and the decrease of temperature. Three regression functions were developed to describe the shear strength under the different conditions. According to Mohr Coulomb’s criterion, the shear strength of methane hydrate-bearing clay sediments was analyzed. It can be found that both of cohesion and friction angle increased with the decrease of temperature and increase of strain rate.

Keywords: Strength; Methane hydrate-bearing clay sediments; Confining pressure; Temperature; Strain rate

INTRODUCTION
Gas hydrate deposits have been considered as a huge potential resource. The resource mainly exists on land in the polar region, permafrost in the altiplano and offshore around the globe [1]. The gas hydrate deposits are stable under conditions of low temperature and high pressure. However, the stable conditions need to be perforce destroyed for the dissociation and production of natural gas from gas hydrate deposits. Any exploitation of methane hydrates offshore could lead to the seafloor slope instability and a large-scale release of CH4 under unfavorable circumstances [2]. Thus it is essential to determine mechanical properties before attempting to exploit these deposits.

The approaches for studying mechanical properties include the seismic velocity surveys and triaxial shear tests on natural and synthetic samples under conditions of stabilization, formation and dissociation. Seismic velocity may be affected by the properties of the host sediment, such as its particle size distribution and grain shape [3]. The compressional wave velocity was substantially lower in fine-grained sediment containing gas hydrate than in coarse-grained sediment [4]. Furthermore, the shear wave velocity increased with the increase of mass clay content in the gas hydrate-bearing sediment [5]. The experimental results from triaxial shear tests are used to estimate the stress strain behavior and strength of gas hydrate-bearing sediment. The strength of pure methane hydrate in high-temperature creep was far stronger than the water ice at the same conditions of temperature and strain rate [6]. Moreover, the strength of pure methane hydrate increased with the decrease of temperature and the increase of pressure [7]. However, natural gas hydrate always exists in the sediments which include soil, ice/water and air. The experimental measurements of pure hydrates from a laboratory are difficult to

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evaluate the mechanical properties of the hydrate sediment no matter some properties may be similar. The mechanical properties of gas hydrate sediment varied with the content of hydrate, sediment properties and the experimental conditions no matter a natural or synthetic sample [8]. Furthermore, the volumetric strain has dilative tendency no matter there is a decrease of the effective confining pressure or not during the hydrate dissociation in sediments without axial loading [9]. In addition, the gas hydrate can be substituted with a tetrahydrofuran hydrate in the triaxial tests because the physical chemical properties of the tetrahydrofuran hydrate are similar to the methane hydrate and the tetrahydrofuran hydrate is easier to be formed [10]. These results reflected the mechanical behavior of gas hydrate.

However, little attention has been focused on mechanical property of methane hydrate-bearing clay sediments in the previous researches. This paper conducts laboratory studies designed to systematically analyze the stress strain behavior and shear strength of methane hydrate-bearing sediments. In addition, the relationship of shear strength with confining pressure, temperature and strain rate was analyzed.

**EXPERIMENTAL PROGRAM**

**Equipment and material**

The schematic diagram of triaxial testing system used is shown in Figure 1. Confining pressure was provided up to 30MPa by a closed-loop pressure control servo-system which is able to maintain the set cell pressure. The pressure control servo-system consists of a computer control unit, a digital control servomotor and a hydraulic piston. The computer control unit compares the actual cell pressure with the target pressure directly and sends a correction signal to the servomotor. Then the servomotor controls the hydraulic piston to advance or recoil in order to drive the actual cell pressure to reach the target pressure. In temperature control-system the temperature is adjusted in a range between –30 and 25°C by using a controllable constant temperature bath and heat exchangers. The temperature of liquid coolant in the constant temperature bath always maintains a few degrees lower than the desired testing temperature. When the actual cell temperature is higher than the target temperature, the digital control circulating pump drives liquid coolant into heat exchanger to cool the cell down. The axial strain rate is controlled by an axial loading frame. This loading frame can apply a 60KN loading capacity for specimen.

One common hydrate formation approach in laboratory experiments is the flushing of methane gas through spray water, initially partially or fully saturated porous media under the condition of low temperature and high pressure. This approach requires the expensive equipments and more complicated preparation process although the high hydrate saturation can be reached. Therefore in this study the methane hydrate was obtained by using an ice-seeding method [11], which requires only a high pressure reactor. However, the formation of methane hydrate needs a longer preparation time. The methane hydrate can hardly reach a high saturation status. For this study the formation time was about 48 to 72 hours and the methane hydrate saturation was about 20–30%, which can be calculated on the basis of the amount of methane gas from hydrate dissociation in the sample.

In order to prepare the artificial samples close to the natural hydrate-bearing clay sediments, the soil used in the present study was kaolinite clay which was the most typical clay in the marine sediments. The distribution of particle size was analyzed by using a centrifugal particle size analyzer. The mean particle size and specific surface are 3.91μm and 2.60 g/cm3 respectively.

**Testing program and procedures**

Tests were carried out in the condition of temperature (T) equals to –5, –10, –15, –20°C and
confining pressure \((P)\) equals to 2.5, 3.75, 5MPa. The strain rates \(\dot{\varepsilon}\) were 0.1, 0.5 and 1%/min. The identical testing conditions were repeated at least once in order to check the validity of the experimental results.

The detailed procedure for methane hydrate-bearing sediment sample preparation was as follows. The kaolinite clay was baked to remove its moisture in advance and later cooled in the refrigerator. In addition, the ice powder was broken by the block shaving machine and was used to fill into the reactor. The high pressure methane gas was also injected into the closed reactor. Then the reactor was put in the refrigerator for forming methane hydrate in the low temperature. After the formation reaction was completed, the unsaturated methane hydrate was removed from the reactor. The drying kaolinite clay was mixed with the unsaturated methane hydrate in proportion according to the experimental requirements. The mixture of clay and unsaturated methane hydrate was put into a mold to make specimen at high pressure (10MPa) using a pressure crystal device. Finally the sediment specimens were removed from the mold, wrapped in a rubber membrane and timely put in the pressure chamber.

Prior to shearing, the cell was filled with the silicon oil. The cell pressure and temperature were adjusted to gain the desired experimental condition. The axial strain was monitored by using a displacement sensor. The loading stress was measured with a load cell. These data were recorded by the computer data acquisition system automatically. All tests including specimen preparation were carried out in a low temperature room (about \(-10^\circ\text{C}\)).

**EXPERIMENTAL RESULTS AND PRELIMINARY ANALYSIS**

Figure 2 shows the axial strain-dependence curves of deviator stress. It can be seen that the deformation processes of methane hydrate-bearing clay sediments varied with experimental conditions although the stress strain curves all showed the shape of hyperbola. The stress strain behavior all presented the weak strain hardening at each condition. After the peak deviator stress was rapidly reached at small strains, the deviator stress decreased with increasing strain and then increased again. The lower the temperature was or the higher the pressure was, the larger the peak deviator stress became. This mechanical property of methane hydrate clay sediments is similar with that of the soil. Consequently, according to the research method on the soil stress-strain behavior and structure the stress-strain curves of methane hydrate can be divided into two stages: the rapid structural damage stage and the complete structural damage stage. At the rapid structural damage stage the deviator stress rapidly increased with the increasing axial deformation from initial strain up to about 2\%, and the structure of methane hydrate also rapidly was damaged. When the specimens reached the complete structural damage stage at the large strains beyond about 2\%, the axial deformation presented an overwhelming increase with the continuous load. However, the deviator stress had almost no increase. In fact, the structure of specimen had already been damaged completely and the specimen had approached or reached failure state.
It is difficult to develop a model comprising all relevant factors. Thus the models containing some main factors were established under given conditions [12]. In this paper, the relationship of maximum deviator stress with confining pressure, temperature, and strain rate were investigated, and three formulas are suggested to predict the peak shear strength of methane hydrate-bearing clay sediments.

**Relationship among shear strength, confining pressure and temperature**

Figure 3 shows the confining pressure-dependence trend lines of maximum deviator stress at strain rate 1%/min and temperature −5, −10, −15 and −20°C. It can be seen that the peak strength of methane hydrate-bearing clay sediments increases with increasing confining pressure. The effect of confining pressure on peak shear strength of methane hydrate-bearing sediments was consistent with the previous studies [8, 9, 13].

In addition, when the strain rate remained constant all the curves presented a good linear relationship with the confining pressure regardless of temperature. Thus the linear relationship between the peak strength and confining pressure can be given by:

$$ (\sigma'_3 - \sigma''_3)_{\text{max}} = A_0 + A_1 \sigma'_3 $$  \hspace{1cm} (1)

In which, $A_0$ and $A_1$ are the intercept and slope of the curve under each temperature. The linear relationship was similar to the behavior observed in the study of frozen soil [14]. By regression analysis, it was found that the value of curve slope
$A_0$ is a function of two order of absolute value of temperature.

$$A_0 = 0.51 + 0.295|\theta| - 0.006|\theta|^2$$  (2)

Where, $\theta$ is the temperature. In addition, the values of $A_1$ varied linearly with temperature. The expression of $A_1$ is given by:

$$A_1 = 0.216 + 0.011|\theta|$$  (3)

Substituting (2) and (3) into (1),

$$(\sigma_1 - \sigma_3)_{\text{max}} = 0.51 + 0.295|\theta| - 0.006|\theta|^2 + (0.216 + 0.011|\theta|)\sigma_3$$  (4)

Eq. (4) describes a linear relationship between the peak strength, confining pressure and temperature for methane hydrate-bearing sediments at strain rate 1%/min. On the basis of experimental data, $A_0$ and $A_1$ corresponding to other strain rate can be obtained using the method above.

Figure 4 shows the temperature-dependence trend lines of maximum deviator stress at strain rate 1%/min and confining pressure 2.5, 3.75 and 5MPa. It can be seen that the peak strength increased with the decrease of temperature. The results also coincide with the previous researches[8, 9]. The curve tendency is almost consistent with the decrease of temperature under different confining pressure although the curves were nonlinear. However, by logarithmic transformation of the temperature and peak strength, a linear relationship can be obtained in Figure 5. For frozen soil Arenson et al. proposed the following relationship [15]:

$$(\sigma_1 - \sigma_3)_{\text{max}} = K|\theta|^m$$  (5)

In which, $K$ and $m$ are experimental coefficients.

From Figure 5 $\log K$ and $m$ represent the intercept and slope of the $\log (\sigma_1 - \sigma_3)_{\text{max}}$ ~ $\log |\theta|$ curve respectively. It was found that the curve intercept $K$ increased with the increase of confining pressure. Moreover, the intercept of $K$ linearly correlates with confining pressure:

$$K = 0.779 + 0.136\sigma_3$$  (6)

In addition, the value of $m$ is obtained via regression analysis. It can be found that the value of $m$ changes slightly with the increase of absolute value of temperature. Thus the average of the value of $m$ was taken, which is equal to 0.5. Substituting (6) into (5),

$$(\sigma_1 - \sigma_3)_{\text{max}} = (0.779 + 0.136\sigma_3)|\theta|^{0.5}$$  (7)

Eq. (7) indicates that the peak shear strength follows a power law against absolute value of temperature.

Figure 5. The logarithmic temperature-dependence trendlines of logarithmic maximum deviator stress

**Relationship among shear strength, confining pressure and strain rate**

Figure 6 shows the strain rate-dependence trend lines of maximum deviator stress at temperature –10°C and confining pressure 2.5, 3.75 and 5MPa. It shows that the strain rate is proportional to the maximum deviator stress. The peak strength increased with the increase of strain rate, which is confirmed by previous researches [8, 9]. Moreover, the peak strength was linearly correlated to strain rate when the confining pressure remains constant. At the temperature of –
10°C the expression of the mathematical relationship between \((\sigma_1 - \sigma_3)_{\text{max}}\) and \(\dot{\varepsilon}\) can be written:

\[
(\sigma_1 - \sigma_3)_{\text{max}} = B_0 + B_1 \dot{\varepsilon}
\]

In which, \(B_0\) and \(B_1\) are the intercept and slope of curve under each confining pressure. The linear relationship is similar with that of frozen soil [14].

In which, \(B_0\) and \(B_1\) are the intercept and slope of curve under each confining pressure. The linear relationship is similar with that of frozen soil [14].

\[
\sigma = c + \sigma \tan \phi
\]

where \(\tau\) is shear strength (MPa), \(\sigma\) is normal stress (MPa), \(c\) is cohesion (MPa), \(\phi\) is angle of internal friction (°).

The Mohr-Coulomb failure criterion is always used to evaluate the shear strength of soil. The cohesion and internal friction angle are two key factors in the failure criterion. The cohesive force is determined by the synthesis action of repulsive and attractive force between particles. The internal friction strength represents the sliding and interlocking friction between particles. For methane hydrate-bearing clay sediments the shear strength can be considered as a combination of the cohesion between the methane hydrate, ice and soils and the friction between the soils particles. The Mohr’s envelopes all accord with the Mohr Coulomb’s criterion within the range of confining pressure in tests.

The relationship between the strength, confining pressure and strain rate for methane hydrate-bearing sediments can be determined by Eq. (11).

Comparison between experimental and calculated results

Figure 3, 4 and 6 also show the comparison between the experimental measurements and the calculated results. The relatively error between the experimental and calculated strengths was less than 5% under each condition. The experimental results are in close agreement with the simulation.

SHEAR STRENGTH BASED ON MOHR-COULOMB CRITERION

Figure 6. The strain rate-dependence trendlines of maximum deviator stress at temperature –10°C and confining pressure 2.5, 3.75, 5MPa.

With the analysis of the linear regression, both of curve slope and intercept are dependent on confining pressure. The expressions of \(B_0\) and \(B_1\) are therefore given by:

\[
B_0 = 1.819 + 0.236\sigma_3
\]

\[
B_1 = 1.209 + 0.061\sigma_3
\]

Substituting (9) and (10) into (8),

\[
(\sigma_1 - \sigma_3)_{\text{max}} = 1.819 + 0.236\sigma_3 + 1.209\dot{\varepsilon} + 0.061\sigma_3\dot{\varepsilon}
\]

The relationship between the strength, confining pressure and strain rate for methane hydrate-bearing sediments can be determined by Eq. (11).

Table 1. The internal friction angle and cohesive strength of methane hydrate-bearing sediments at temperature –5, –10, –15 and –20°C

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>c (MPa)</th>
<th>(\phi) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>–5</td>
<td>0.89</td>
<td>6.9</td>
</tr>
<tr>
<td>–10</td>
<td>1.25</td>
<td>8.27</td>
</tr>
<tr>
<td>–15</td>
<td>1.47</td>
<td>9.62</td>
</tr>
<tr>
<td>–20</td>
<td>1.61</td>
<td>10.56</td>
</tr>
</tbody>
</table>

Figure 7 shows the Mohr’s envelopes of methane hydrate-bearing sediments at strain rate 1%/min and temperature –5, –10, –15 and –20°C. Table 1 shows the internal friction angle and the cohesive strength of methane hydrate-bearing sediments.
It can be seen that both of cohesion and friction angle increased as the temperature decreased, which is contrary to the findings of Santamarina et al. [16]. In this study, the temperature had great impact on friction angle. However, it can be found that the variations in the shear strength of methane hydrate-bearing sediments with temperature primarily come from the variations of cohesion according to Mohr-Coulomb failure criterion. Yun et al. confirmed that the strength of soils with 100% THF-hydrate-filled porosity was determined by the cementing strength [10]. The difference of friction angle $\phi$ between the different temperature had little effect on the failure strength $(\sigma_1-\sigma_3)f$. According to the data in Table 1, the relationship between cohesion $c$ and temperature $\theta$ can be obtained in the form below:

$$c = 0.233 + 0.130|\theta| - 0.003|\theta|^3$$  \hspace{1cm} (13)

Moreover, the linear relationship between friction angle and temperature $\theta$ can be obtained in the form below:

$$\phi = 5.756 + 0.246|\theta|$$  \hspace{1cm} (14)

Figure 8 shows the Mohr’s envelopes of methane hydrate-bearing sediments at temperature $-10^\circ$C and strain rate 0.1, 0.5 and 1%/min. Table 2 shows the internal friction angle and the cohesive strength of methane hydrate-bearing sediments.

![Figure 8. Mohr’s envelopes of methane hydrate-bearing sediments at strain rate 0.1, 0.5 and 1%/min](image)

<table>
<thead>
<tr>
<th>strain rate (%/min)</th>
<th>$c$ (MPa)</th>
<th>$\phi$ ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.9</td>
<td>6.15</td>
</tr>
<tr>
<td>0.5</td>
<td>1.02</td>
<td>6.91</td>
</tr>
<tr>
<td>1</td>
<td>1.35</td>
<td>7.41</td>
</tr>
</tbody>
</table>

It can be seen that both of cohesion and friction angle increased with the increase of strain rate. The strain rate had great impact on cohesion and friction angle. However, it also can be found that the variations in the shear strength of methane hydrate-bearing sediments with stain rate come primarily from the variations of cohesion. According to the data in Table 2, the linear relationship on cohesion $c$ and strain rate can be obtained in the form below:

$$c = 0.816 + 0.51\dot{\varepsilon}$$  \hspace{1cm} (15)

Moreover, the linear relationship on friction angle and strain rate can be obtained in the form below:

$$\phi = 6.087 + 1.38\dot{\varepsilon}$$  \hspace{1cm} (16)

CONCLUSION
Triaxial compression tests on clay sediments containing methane hydrate were conducted under various conditions with confining pressures at 2.5, 3.75 and 5 MPa, temperatures at $-5$, $-10$, $-15$ and $-20^\circ$C and strain-rates at 0.1, 0.5 and 1%/min. The stress strain behavior of samples all belonged to the weak strain hardening type. The shear strength of methane hydrate-bearing sediments increased in conditions of the enhancement of confining pressure, the enhancement of strain rate and the decrease of temperature. Based on the trends of the peak shear strength, the shear strength was regarded as there functions of confining pressure, temperature and strain rate under the different conditions. By analyzing the Mohr’s envelopes, it can be found the Mohr Coulomb’s criterion is the appropriate criterion suitable for clay sediments containing methane hydrate. Both of cohesion and friction angle increased with the decrease of temperature and increase of strain rate.

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