LOCALIZED DEFORMATION OF METHANE HYDRATE-BEARING SAND BY PLANE STRAIN SHEAR TESTS

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ABSTRACT
High pressure and low temperature plane strain testing apparatus was developed for visualizing deformation of methane hydrate bearing sand due to methane hydrate production. Using this testing apparatus, plane strain compression tests and methane hydrate dissociation test by depressurization method were performed. Both global and local deformations were successfully measured during MH dissociation. From the results, it was noted that the compressive deformation by depressurization increases with increase in initial shear strain. Moreover, it was observed during water pressure recovery that the failure mode of methane hydrate bearing sand was the same as in compression test.

Keywords: methane hydrate, deformation, compression, plane strain

INTRODUCTION
Due to recent investigations, methane hydrate is expected to become a possible future energy resource. Both thermal recovery methods and depressurization methods have been suggested and developed for exploiting the methane hydrates from reservoirs that exist in deep ocean floors [1,2]. Using both methods, methane hydrates in the ground are dissociated to release the methane gas. During this process, the mechanical strength of the sediments may change as temperature and pore water pressure in the ground change in the vicinity of the production well. In addition, rebound of the ground and possible landslides caused by the reduction in effective stress accompanying the water pressure recovery after

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the end of production are also important issues. Mechanical properties of methane hydrate-bearing sediments were investigated through laboratory tests using high pressure and low temperature triaxial compression test [3-7]. These results are valuable as material parameters were obtained for predicting deformation simply due to depressurization. However, localized deformation as shear bands form by compression and depressurization resulting from dissociation of MH is still not clear.

In this study, high pressure and low temperature plane strain testing apparatus is developed for visualizing deformation of methane hydrate bearing sand due to methane hydrate production.

**EXPERIMENT AND SAMPLE**

**Plane strain testing apparatus**

In this research, a high pressure - low temperature plane strain testing device through which the local deformation in MH-bearing sediment was developed. Fig. 1(a) shows the overview of the temperature-controlled room where the equipment shown in (b) was installed. To generate MH at a given temperature, it was necessary to set up the test in the room. The experiments were controlled by PC set up outside the room. Figure 2 shows the schematic diagram of this testing apparatus. The size of sample (a) is 80(L) x 60(W) x 160(H) mm. The pressure cell (b) has thick acrylic observation windows (c) installed in front and back of specimen through which pictures can be taken. To keep the plane strain condition during test, the confining plate (d) is set up. Furthermore, to take a photo of the specimen, LED is set up on the left, right, top and center and bottom of the confining plate. The specimen was observed by the camera which was remotely controlled with a timer. Two syringe pumps are connected to the top and the bottom of the specimen, respectively which not only controls pressure of water and methane gas but also measure the volume change of specimen. The gas flow meter (j) is applied to measure the amount of methane gas after the test.

Based on the observation of the undisturbed core samples sampled from Nankai Trough [6], MH in-situ exists within the pores of sediments to bond each particle. Based on this, MH-bearing sand was artificially produced. Toyoura sand was chosen as the host sand. Firstly, the amount of water calculated from MH saturation of target was mixed with sand whose volume was determined to correspond to a target density. The moist soil was placed in 12 layers in a mould with each layer compacted 40 times by a tamper.

**Generation of MH and Experimental Procedure**

After formation the specimen was subjected to a series of processes under specified temperatures and pressures, as depicted in Figure 3. First of all, the specimen was set up inside the pressure cell (a). Then, the pore pressure was gradually increased to 5 MPa while methane was injected into the specimen and the specimen environment was kept at a temperature and pressure condition where stable MH could exist (b). At this stage, the gas
Pressure was increased gradually over a period of time so that the specimen's moisture content would not become non-uniform as a result of the pressurized injection. By keeping the gas pressure constant in the connection between the specimen and the syringe pump and by observing the amount of gas flowing at various times, the transformation of water within the pores into hydrate was judged to be complete if there was no marked change in the amount of gas. After the hydrate was generated, the gas in the pipe was then substituted with water under constant pressure and water was allowed to infiltrate the specimen. Then, the pore water pressure was applied (c) and the temperature was adjusted to the prescribed test condition (d). While keeping the pressure constant, consolidation was carried out until the specified effective stress was reached. After shear or dissociation test, the temperature in the specimen was increased and MH dissociated; the amount of gas was measured using the gas flow meter shown in Figure 1(b). The amount of gas measured allowed the estimation of MH saturation, assuming the density of MH to be 0.912 g/cm³.

Figure 3. Paths of pressure and temperature followed in producing MH-bearing sand.

**PLANE STRAIN COMPRESSION TEST**

**Testing results**

In the experiments, the specimens were subjected to different methane hydrate saturation (SMH=0, 60%) with effective confining pressure 3.5 MPa and porosity 40%. Shearing was conducted at a strain rate of 0.1%/min. Fig. 4 shows the deviator stress, axial strain and volumetric strain relations. From the figure, it is observed that the specimens show compressive volume change and softening after strain hardening. Moreover, a marked increase in the initial stiffness and strength is observed as the MH saturation increases. The volumetric strain changes from compressive to dilative, and for specimens with SMH=60%, significant dilative behavior was observed. This is believed to be due to the hardening action induced by MH on the sand particles.

Figure 4. Stress strain curves for host sand and MH-bearing sand.

**Localized deformation**

Figure 5 shows (a) SMH=0 % (pure sand) and (b) SMH=60% specimen during compression test at each strain level. In (a) SMH=0%, shear band was observed at εa=9% and the second shear band was initiated at εa=15%. These shear bands appear when strain softening occurred as indicated in Fig. 4. Then, it seems that the stress concentrated inside the shear band. Next, (b) SMH=60%, shear band appeared at εa=6% and it was observed clearly at εa=9%. Secondary shear band occurred at εa=12%. These shear bands appear during strain softening in Fig. 4 in the same manner as in pure sand. The thickness of the shear bands both (a) =1.8mm and (b) =1.0mm was measured from the photograph where the first shear band was generated. The shear band thickness was measured at interval of parallel lines which were drawn where the grid lines are most dramatically curved. The thickness of the shear band in the low confining pressure which was done by Tatsuoka[8] is about 20 times the mean particle size. It is about 3.2mm for Toyoura sand with 0.162mm mean
particle size. However, the thickness of shear band in the present study is about ten times the mean particle size. It seems that this is due to the high confining stress. In addition, the thickness of the shear band of (b) SMH=60% is thinner than that of (a) SMH=0% which was caused by cementation of MH. The distribution of maximum shear strain $\gamma_{\text{max}}$ of SMH=0% and 60% in each axial strain level analyzed by Particle Tracking Velocimetry (PTV) method is illustrated in Fig. 6. For the MH-bearing sand specimen [SMH=50%] tested under high confining pressure (3 MPa), the first shear band was not initiated at about 6% overall axial strain followed by softening in the nominal stress response. The second shear band initiated after additional shearing (overall 12%) along the first shear band. Shearing then continued along the two bands until the completion of the test. Localization of deformations of MH-bearing sand is greater than pure sand.

The distribution of volumetric strain $\varepsilon_v$ in each strain level was illustrated in Fig. 7. Here, compression is defined to be positive and the expansion is to be negative. In both (a) SMH=0% (pure sand) and (b) SMH=50%, the shear bands observed in Fig. 5 have dilated with axial strain increase. In the same strain level, the volumetric strain of (b) SMH=50% is greater than (a) SMH=0%.

DEPRESSURIZED METHANE HYDRATE-BEARING SAND

After consolidation at an effective stress equivalent to in-situ conditions, MH dissociation was performed by decreasing the pressure. The experimental conditions and the corresponding experimental results are summarized in Table 1. Fig. 8 shows the stress paths followed at two different cases. In Case 1, initial shear stress was $K_0$ condition and the mean principal effective stress was increased from (a) to (a') to simulate depressurization. In the case of depressurization, the pore water pressure was allowed to increase again after dissociation to represent post-production equilibrium conditions being restored. In Case 2 the stress path was taken into the metastable zone between the failure envelopes for pure sand and MH-bearing sand. The purpose of this test was to study the effect of dissociation and consequent loss of particle bonding in the zone where failure could occur for an unbonded sand.
Table 1. Testing condition for MH dissociation tests

<table>
<thead>
<tr>
<th>Test name</th>
<th>Vertical stress $\sigma_1$ (MPa)</th>
<th>Horizontal stress $\sigma_3$ (MPa)</th>
<th>Initial pore pressure $P$ (MPa)</th>
<th>Depressurization (0.5MPa/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>15.0</td>
<td>13.5</td>
<td>12.0</td>
<td>12.0→3.5</td>
</tr>
<tr>
<td>Case2</td>
<td>24.4</td>
<td>13.0</td>
<td>10.0</td>
<td>10.0→3.0</td>
</tr>
</tbody>
</table>

Testing results during depressurization

Fig. 9 (a) ~ (d) shows the variation of pore pressure, cumulative gas production, temperature and axial strains during the de-pressurization stages. In Fig. 9 (a), pore pressure decrease from 12.0MPa to 3.5MPa for Case 1 and decrease from 10MPa to 3.0MPa for Case 2 with depressurization rate 0.5MPa/min. Both Case 1 and Case 2 exceed MH stability boundary after 20min. Methane gas productions start at these points in Fig. 9(b). Gas production continued for approximately 5 hours in Case 1 and 12 hours in Case 2 from initiation. The temperatures decrease dramatically as gas production started in Fig. 9(c). The temperature in Case 1 decreases to 3.1°C and in Case 2 to 1.6°C. These temperatures are the stable condition at 3.0MPa and 3.5MPa of MH. During gas production, the temperature decreases because of the endothermic reaction according to the dissociation of MH. After gas production started the temperature remained constant for 2 to 3 hours in Case 1 and 8 to 10 hours in Case 2. This is because of dissociation and re-generation of MH. It means that MH still exist during the time the temperature was constant. Then, average gas production rate was calculated when the tempera-
(3.0MPa) is three times larger than Case 1 (3.5MPa) at early stage of MH production. After the temperature became constant for both cases, it was increased up to the initial state with energy added from the outside through the membrane. In Fig. 9(d), axial strains increase gradually afterwards and settle. This behavior is because of MH dissociation and consolidation of sand with decrease in pore pressure and increase in effective stress. Axial strain of Case 2 is greater than in Case 1 after testing due to initial shear stress.

Testing results during pressure recovery
After dissociation the pore water pressure was ramped back up to initial condition with repressurization speed 0.5MPa/min to represent a restoration of post-dissociation equilibrium conditions being restored in-situ. Fig. 10 (a) and (b) shows the variation of pore pressure and axial strains during the re-pressurization stages. In Case 1, there was an elastic recovery of axial and volumetric strains due to a decrease in effective stress. However in Case 2, collapse occurred as the now unbonded soil moved outside the failure envelope.

Localized deformation
Figure 11 shows the stress paths followed in Case 1 and Case 2. Firstly, Point (A) shows the state before depressurization, (B) the middle state for depressurization range, (C) the state after depressurization, (D) after MH dissociates completely and (E) the state of after pressure recovery. Figures 12 and 13 show the results of image analysis. Figures 12 (a) and (b) show maximum shear strain for Case 1 and Case 2, respectively. Shear strain did not occur during depressurization and MH dissociation (A) to (D) in both Case 1 and Case 2. The specimen deformed uniformly. However, in Case 2 from (D) to (E), shear band occurred and localized shear strain was observed. Next, Figure 13 shows the volumetric strain. In both cases, the specimen was compressed uniformly during (A) to (D). The shear band which was observed during pressure recovery (D) to (E) had dilated in Case 2.

Figure 11. The variation of pore pressure with elapsed time during depressurization.

COMPARISON OF SHEAR BANDS
The deformation inside and outside the shear band was compared to understand the difference in mechanical properties caused by compression or pressure recovery. Figure 14 shows the maximum shear strain for each axial strain level. The maximum shear strain of inside shear band increases dramatically at $\varepsilon_a=8\%$ for both compression test and pressure recovery test where shear band occurs. Next, Figure 15 shows the volumetric strain for each axial strain level with stress strain curves. Volumetric strains were different at $\varepsilon_a=8\%$ between compression test and pressure recovery test because of the initial shear
stress applied in the latter. Therefore, volumetric strain during depressurization dilated more than during compression test. During depressurization, volumetric strain increases with increase in effective stress and MH dissociation. After shear band occurred, the inside part of shear band dilated in both of tests. From $\varepsilon_a=8\%$ to $12\%$, the tendency of increment of volumetric strain is the same even though the absolute value is different. Thus, it is clear that the deformation of methane hydrate-bearing sand is the same when sheared by compression or pressure recovery.

![Figure 12. Maximum shear strain during compression test.](image12)

![Figure 13. Volumetric strain during compression test.](image13)

**CONCLUSIONS**

In this study, using high pressure - temperature controlled plane strain testing apparatus, plane strain compression tests and methane hydrate dissociation test by depressurization method were performed. It succeeded in the measurement of the localized deformation. From the compression test results, it was observed that the specimens showed compressive volume change at 3MPa of confining pressure, notwithstanding the high relative density. Moreover, a marked increase in the initial stiffness and strength was observed as the MH saturation of MH bearing specimens increased. The volumetric strain changed from compressive to dilative, and for specimens with $S_{MH}=50\%$, significant dilative behavior was observed. By using image analysis, shear band of methane hydrate bearing sand was thinner than that of host sand. In addition, in the
shear band, dilative volumetric strain increases remarkably with increase in methane hydrate saturation. From the methane hydrate dissociation tests, compressive deformation by depressurization increased with initial shear strain increase. It was observed during water pressure recovery that the failure mode of methane hydrate bearing sand was the same as in compression test.

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REFERENCES