Development of high-pressure low-temperature plane strain testing apparatus for methane hydrate-bearing sand

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Abstract

A high-pressure low-temperature plane strain testing apparatus was developed for visualizing the deformation of methane hydrate-bearing sand due to methane hydrate production. Using this testing apparatus, plane strain compression tests were performed on pure Toyoura sand and methane hydrate-bearing sand with localized deformation measurements. From the results, it was observed that the methane hydrate-free specimens, despite their relatively high density, showed changes in compressive volume. Marked increases in the initial stiffness and strength of the methane hydrate-bearing sand were observed (methane hydrate saturation of $S_{MH}=60\%$). Moreover, the volumetric strain changed from compressive to dilative. For the specimens with methane hydrate, a dilative behavior above $S_{MH}=0\%$ was observed. An image analysis showed that the shear bands of the methane hydrate-bearing sand were thinner and steeper than those of the host sand. In addition, the dilative volumetric strain in the shear band increased markedly when methane hydrate existed in the pore spaces.

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1. Introduction

Recent investigations have shown that methane hydrate (hereafter referred to as MH) is a potential future energy resource. Both thermal recovery methods and depressurization methods have been suggested and developed for extracting methane gas from MH-bearing sediment reservoirs in deep ocean floors, for example, the Nankai Trough (Yamamoto, 2009; Fujii et al., 2008; Nagakubo, 2009). Using both methods, MH in the ground is dissociated to release methane gas. Hydrates in the pore spaces of sand can be classified into three types: pore-filling, load-bearing and cementing (Waite et al., 2009). These three types of hydrate-bearing sediment can be prepared in the laboratory by three different methods, namely, using hydrate grains and ice seeding (Hyodo et al., 2005; Ebinuma et al., 2005), applying partial water saturation (Kneafsey et al., 2005; Waite et al., 2004), and employing dissolved gas (Katsuki et al., 2006; Tohidi et al., 2001). In the case of pore-filling, the hydrate exists in the pore spaces with no bridging between soil particles and affects the pore fluid bulk stiffness and fluid conduction properties (Helgerud et al., 1999). In the case of load-bearing, the hydrate bridges the soil particles and confers the mechanical stability to the granular skeleton by becoming part of the load-bearing framework. Pore-filling
hydrate naturally becomes of the load-bearing type when the pore space hydrate saturation exceeds $S_h = 25\% - 40\%$ (Yun et al., 2005, 2007). In this case, shear stiffness and peak strength increase with increasing hydrate saturation and significant dilative behavior is observed when hydrate saturation $S_h$ exceeds 40% (Yun et al., 2005, 2007; Masui et al., 2005). In the third case, cementing, the hydrate cements the intergranular contacts. If the host sand is dense, even a small amount of hydrate can markedly increase sediment shear and bulk stiffness by bonding the adjacent grains together. For this type of MH-bearing sediment, experiments under various conditions have shown that its mechanical properties are dependent on hydrate saturation, confining pressure, soil density, particle distribution, temperature, and water pressure (Berge et al., 1999; Yun et al., 2005, 2007; Hyodo et al., 2007, 2008a, 2008b; Yoneda et al., 2010; Miyazaki et al., 2010, 2011). Researchers have discussed the obtained relationships of dilatancy with mobilized shear strength and stiffness; in particular, Yun et al. (2005) and Waite et al. (2009) proposed a possible micro-mechanical model for hydrate-bearing sediment. Then, several constitutive models (e.g., Hyodo et al., 2008a, 2008b; Uchida et al., 2012) have been proposed on the basis of their idea, and seabed deformation due to MH exploitation was predicted (Kimoto et al., 2007; Klar et al., 2010; Yoneda et al., 2011).

For any soil sediments consisting of discrete particles and associated voids, a mechanical examination of the localized shear band deformation is significant for evaluating and modeling the mechanical properties of these sediments from a micro-mechanical viewpoint (e.g., Newland and Allely, 1957; Rowe, 1962). Different types of elemental tests, for example, plane strain and box shear tests, have been performed to investigate the angle (Tatsuoka et al., 1990; Ueno et al., 2000; Ikeda et al., 2003) under low and medium confining pressures. In addition, model tests such as bearing capacity tests (White et al., 2003), have been carried out to clarify the micro-mechanical deformation properties of foundations. Recently, research studies using X-ray CT have been widely used, and the behavior of soil particles on shearing is becoming clear (Otani et al., 2000; Hall et al., 2010; Ando et al., 2011; Higo et al., 2011, 2013). Thus far, tests must be performed at high pore water pressures and low temperatures with high confining pressures to examine the MH reservoirs. Hence, failure patterns of MH-bearing sand have not yet been observed. The realization of deformation is significant from the gas production point of view, because there are concerns about gas leakage and/or channel formation in alignment with localized deformation like shear bands. In the present study, a plane strain testing apparatus that can simulate the predicted high pore water pressure, low temperature, and confining pressure corresponding to those existing in situ, and that can be applied in compression shear tests, is developed to investigate the effect of hydrate bearing under high confining pressure on the constitutive behavior of sand materials. In addition, the localized deformation of MH-bearing sand was observed visually.

2. Plane strain testing apparatus

A high-pressure low-temperature plane strain testing apparatus has been developed to examine and visualize the deformation of MH-bearing sand. Fig. 1(a) shows an overview of the temperature-controlled room where the equipment, shown in Fig. 1(b) and (c), was installed to generate MH at a given temperature.

The experiments were controlled using a PC set up outside the room. Fig. 2 shows a schematic diagram of the apparatus. A detailed description of each part shown in this figure is presented below.

(a) **Test specimen**

The sample was 80 mm (length) × 60 mm (width) × 160 mm (height).

(b) **Pressure cell**

The pressure cell had thick acrylic observation windows (c) installed in the front and the back of the specimen through which pictures could be taken.

(c) **Observation window**

The thickness of the observation window was 70 mm. The window is capable of tightening a confining plate. The observing direction is the same as that of applied intermediate stress $\sigma_2$ in the plane strain.

(d) **Confining plate**

A confining plate was used to maintain plane strain conditions during the testing with an acryl block 70 mm in thickness. LEDs on the left, the right, the top, the center,

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![Fig. 1. (a) Exterior view of refrigeration room; (b) setting of specimen; (c) exterior view of homeothermic high-pressure plane strain device.](image-url)
The temperature in the tank could be controlled within the range of ±0.1 °C.

(n) Confining pressure amplifier

Cell pressures of up to 20 MPa, controllable within the range of ±0.1 MPa, were supplied by oil pressure.

(o), (p) Heating tank

This device consisted of a system for adjusting the temperature from 0 °C to +50 °C within the syringe pump. The temperature of the tank could be controlled within the range of ±0.1 °C.

(q) Cell liquid pump

The cell liquid pump circulates water into the pressure cell.

(r) Displacement transducer

This device is for measuring the vertical displacement of the specimen.

(s) Load cell

To eliminate the effect of piston friction, a cylindrical loading cell, which is not affected by temperature or pressure, was set up in the cell. The maximum permissible load was 200 kN, and it was possible to measure it with an accuracy of 1/1000 for the full-scale load.

(t) Loading equipment

To apply high compression stress, a piston designed to resist up to 200 kN was installed; loading was performed via a pulse-controlled method using a stepping motor.

(u) Pressure gage

The pressure gage measures the pore pressure and the cell pressure up to 20 MPa.

(v) Camera & lens

A 25-million-pixel digital single-lens reflex camera was used. A fisheye lens (15 mm F2.8) was used for observing the whole specimen from the window.
A thermometer was installed inside the specimen, and the temperature in the triaxial room was measured. The temperature of the cell was controlled on the basis of the value indicated by the thermometer.

3. Generation of MH and experimental procedure

MH-bearing sand was artificially produced on the basis of the observation that MH existed within the pores of the sediment bridging the particles of the undisturbed core samples taken from the Nankai Trough (Suzuki et al., 2006). Toyoura sand was chosen as the host sand with a mean particle size of 0.162 mm. A given amount of water, calculated from the MH saturation target, was mixed with sand whose volume was determined to correspond to the target density. Moist soil was arranged in 12 layers in a silicon membrane and each layer was molded by compaction using a tamper 40 times.

After forming the specimen, it was subjected to a series of processes under specified temperatures and pressures, as depicted in Fig. 3. Firstly, the specimen was set up inside the pressure cell (a) and subjected to 0.2 MPa of confining pressure for self-withstanding. Then, the pore pressure and the confining pressure were gradually increased to 5 MPa and 5.2 MPa, respectively, while methane was being injected into the specimen and the specimen was kept at the temperature and pressure where stable MH could exist (b). At this stage, the gas pressure was increased gradually with 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 the hydrate was judged to be complete when there were no marked changes in the amount of gas. After the hydrate was generated for 3 days, the gas in the pipe was then substituted with water under constant pressure, and water was allowed to infiltrate the specimen for 2 days. Then, pore-water pressure was applied (c) and the temperature was adjusted to follow the prescribed test conditions (d). While keeping the pressure constant, consolidation was carried out until the specified mean effective stress was reached. After a compression shear test, pore pressure was released, the temperature of the specimen increased, and MH dissociated. The amount of gas was measured using the gas flow meter shown in Fig. 1(b). The amount of gas measured allowed the estimation of the MH saturation, assuming the density of MH to be 0.913 g/cm³ (Sloan, 1998).

4. Plane strain compression tests for MH-bearing sand

Specimens were prepared without MH (pure Toyoura sand/ MH saturation of $S_{MH}=0\%$) and with MH (MH saturation of $S_{MH}=60\%$) with an effective confining pressure of 3.5 MPa and a porosity of 40%. In previous results (Masui et al., 2005; Hyodo et al., 2007, 2013; Miyazaki et al., 2011) of triaxial tests on Toyoura sand containing a synthetic gas hydrate, it has been confirmed that an increase in hydrate saturation tends to stimulate strain softening. Therefore, specimens were prepared to generate high MH saturation in this research. 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 both cases, with and without MH specimens, show an initially compressive volume change and strain softening after hardening. Volumetric strain without MH specimens increased all along, notwithstanding the high relative density. This behavior might be due to the effect of grain crushing because of the high confining pressure (Miura et al., 1977). Marked increases in the initial stiffness and strength are observed in the case with MH. Changes in volumetric strain from compressive to dilative are seen for the specimen with $S_{MH}=60\%$ instead of compressive behavior only for the specimen with $S_{MH}=0\%$. This is believed to be due to the hardening action induced by MH on the sand particles.
5. Localized deformation

Several analytical methods have already been proposed for evaluating localized deformation. For example, (1) tracking intersections on the sealing sleeve (Tatsuoka et al., 1990), (2) gamma-rays (Desrues et al., 1985), (3) stereophotogrammetry (Desrues and Viggiani, 2004), (4) X-ray computed tomography (Desrues et al., 1996; Hall et al., 2010), and (5) Particle image
Fig. 7. Volumetric strains during compression tests: (a) $S_{\text{MH}}=0\%$ and (b) $S_{\text{MH}}=60\%$.

Fig. 8. Incremental maximum shear strains during compression tests: (a) $S_{\text{MH}}=0\%$ and (b) $S_{\text{MH}}=60\%$. 
velocimetry (White et al., 2003). Here, the simplest method, (1), is used. Digital photos were taken at each axial strain level. Geometric correction was performed on the photographs to cancel the distortion of the lens by polynomial reduction methods. Localized shear strain and volumetric strain were monitored during the compression tests. Figs. 6–8 show the contours of the maximum shear strain and the volumetric strain at each strain level, seen on the sigma-2 plane of each specimen, defined for the initial dimensions of each specimen. These were constructed from the strain increments defined for the elements on the lateral plane, as shown in Fig. 5. The strain increments were obtained from the incremental displacements measured at four nodes of each element, assuming linear changes in the strain increments for each element. Strain was calculated from the deformation gradient tensor and the Lagrange strain tensor defined by the shape function matrix and the deformation matrix of the four nodes as with finite element method analyses. The contours were depicted on the basis of this strain. The incremental displacement was determined by measuring the coordinates of every node of the grid, which was provided by the distinct center of the intersection point.

Fig. 5 shows the (a) $S_{MH}=0\%$ (pure sand) and (b) $S_{MH}=60\%$ specimens during compression testing at various strains. At (a) $S_{MH}=0\%$, two shear bands were observed. These shear bands appeared when strain softening occurred, as indicated in Fig. 4. Thus, it seems that the stresses are concentrated inside the shear band. Next, at (b) $S_{MH}=60\%$, two shear bands were also observed. These shear bands appeared during strain softening in Fig. 4 in the same manner as those observed in pure sand. The distribution of the cumulative maximum shear strain $\gamma_{\text{max}}$ for $S_{MH}=0\%$ and $60\%$ at various axial strains is shown in Fig. 6. The shear band of $S_{MH}=60\%$ appeared earlier than that of $S_{MH}=0\%$. The cumulative maximum shear strain $\gamma_{\text{max}}$ of $S_{MH}=0\%$ is $160\%$ and that of $S_{MH}=60\%$ is $280\%$. In addition, the strain field of $S_{MH}=0\%$ spread along the shear band wider than that of $S_{MH}=60\%$. The distribution of cumulative volumetric strain $\varepsilon_v$ for each strain is shown in Fig. 7. Here, compression is defined as both positive and expansion-negative. At both (a) $S_{MH}=0\%$ (pure sand) and (b) $S_{MH}=60\%$, the shear bands observed in Fig. 5 dilated with increasing axial strain. At a given strain level, the volumetric strain of (b) $S_{MH}=60\%$ is greater than that of (a) $S_{MH}=0\%$. The distribution of the incremental maximum shear strain $\gamma_{\text{max}}$ for each section from a/A to e/E in Fig. 4, is shown in Fig. 8. In both cases with and without the MH specimen, shear bands were not observed in 0 to a/A sections. The first shear band initiated in the sections form the a/A to b/B overall axial strains followed by softening in the nominal stress response. Shear strain increased in b/B to c/C. The second shear band was initiated in d/D to e/E after additional shearing along the first shear band. Shearing then continued along the two bands until the completion of the test.

The thicknesses of the shear bands, i.e., (a) 1.8 mm and (b) 1.0 mm, were measured from Fig. 9. The shear band thickness was measured from the parallel lines drawn where the curvature of the grid lines was at a maximum. The thickness of the shear band at low confining pressures was measured by Tatsuoka et al., 1986 to be about 20 times the mean particle size. This is about 3.2 mm for Toyoura sand with a mean particle size. However, the thickness of the shear band

![Fig. 9. Thicknesses and failure angles of shear bands. (a) $S_{MH}=0\%$ and (b) $S_{MH}=60\%$.](image-url)

![Fig. 10. Assumed shear band. (a) Center of shear band and (b) assumed shear band.](image-url)
in this study was about 10 times the mean particle size. This is due to the high confining pressure. A decrease in the thickness of the shear band with an increase in the confining pressure was observed in the plane strain compression tests under low confining pressures (Yoshida et al., 1994; Pradhan, 1997). Moreover, Tejchman et al. (2012) reported that the thickness of the shear band decreases with grain crushing because of an increase in confining pressure, as determined by the FE analysis. Toyoura sand might be crushed under high confining pressures in this study. In addition, the thickness of the shear band of (b) $S_{MH}=60\%$ is thinner than that of (a) $S_{MH}=0\%$ due to the MH cementation. Next, to evaluate the volumetric strain quantitatively, the shear band was extracted at each axial strain level. The shear band that appears in the specimen is not completely or necessarily a straight line. Therefore, a process for extracting the element of a shear band is proposed (Kikkawa et al., 2007). Fig. 10 shows the process for establishing elements containing a shear band. In Fig. 10(a), the centers of the shear band are extracted by connecting the points where the displacement increment vector diverged right and left from the perpendicular direction. Next, the shear band was described in Fig. 10(b) by the elements through which the line passed. Fig. 11(a) and (b) shows the volumetric strain for each element at each axial strain level during the compression tests. In the case of a hydrate saturation of $S_{MH}=0\%$, each shear band element shows dilative behavior, although the global volumetric strain was kept compressive. It was observed that the average volumetric strain of the shear band elements decreased from an axial strain of 8%. Next, for a hydrate saturation of $S_{MH}=60\%$, most of the shear band elements dilated markedly, although some elements showed compressive behavior. The average volumetric strain of the shear band elements was dilative from an axial strain of 6%.

6. Conclusions

Plane strain compression shear tests, with the measurement of localized deformation, were performed using a high-pressure low-temperature plane strain testing apparatus. From the results, it was observed that the specimens showed a change in the compressive volume at a confining pressure of 3.5 MPa. Moreover, for MH-bearing sand, marked increases in the initial stiffness and strength were observed. The volumetric strain changed from compressive to dilative, and for specimens with $S_{MH}=60\%$, a significant dilative behavior was observed. Using an image analysis, the shear band of the MH-bearing sand was found to be thinner than that of the host sand. In addition, the dilative volumetric strain in the shear band increased markedly when MH existed in the pore spaces.

There are still many characteristics that remain unclear, such as the dependence of the degree of MH saturation and variations in the effective confining pressure, shear strain rate, and stress-anisotropy. This high-pressure low-temperature plane strain testing equipment will contribute to investigations of the shearing mechanism of MH-bearing sand. Such systematic experiments are expected to further the understanding of the general and local mechanical properties of MH-bearing sand.

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