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Effects of dissociation on the shear strength and deformation behavior of methane hydrate-bearing sediments

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ABSTRACT

A series of tests were conducted in order to investigate the shear strength and deformation behavior of methane hydrate-bearing sediments during dissociation using the thermal recovery method or depressurization method. An innovative temperature-controlled high pressure triaxial apparatus which can reproduce the *in situ* conditions of hydrate reservoirs was used. The results indicate that: (1) the failure strength of isotropically consolidated methane hydrate-bearing sediments which dissociated completely using the thermal recovery method is less than that of pure Toyoura sand. However, the initial stiffness and volumetric strain are higher than that of pure Toyoura sand. (2) The thermal recovery method will cause the failure of methane hydrate-bearing sediments when the axial load is higher than the strength of methane hydrate-bearing sediments after dissociation. (3) The depressurization method will not cause collapse of methane hydrate-bearing sediments during depressurization. However, water pressure recovery will lead to failure when the axial load is larger than the strength of the methane hydrate-bearing sediments after dissociation. (4) The depressurization rate shows little effect on the ultimate deformation of methane hydrate-bearing sediments, while the initial deformation rate increases with increasing depressurization rate. (5) The larger the reduction of pore pressure, the larger axial strain and volumetric strain.

1. Introduction

Methane hydrate is a solid clathrate compound in which a large amount of methane is trapped within a crystal structure of water, forming a solid similar to ice (Ripmeester et al., 1987; Sloan, 1998). It generally exists in the permafrost layers and submarine continental margins where there is a stable phase equilibrium condition for hydrate (Dawe and Thomas, 2007; Milkov, 2004). It is believed to form by migration of natural gas from depth along geological faults, followed by precipitation, or crystallization, on contact of the rising gas stream with cold sea water (Taylora et al., 2000). Also, it always acts as a cap for trapping the oil and natural gas reservoirs (Macdonald et al., 1994; Rutqvist et al., 2009). The worldwide amount of carbon bound in methane hydrate is conservatively estimated to total twice the amount of carbon to be found in all known fossil fuels on Earth (Lee and Holder, 2001). Methane hydrate has attracted global attention due to its widespread occurrence, potential as an energy source for replacing traditional fossil fuels, association with climate change and geological disasters (Brown et al., 2006; Dawe and Thomas, 2007; Glasby, 2003; Lee and Holder, 2001).

Recovery of methane from hydrates requires the dissociation of methane hydrates due to its immobile and low permeability which can be accomplished in at least four ways: the thermal recovery method, depressurization method, chemical injection method and CO_2 displacement recovery method (Kamath et al., 1991). However, there are many uncertainties in the production process, especially related to the deformation of the ground caused by dissociation. It is considered that instability will be induced when the hydrate is dissociated (Ning et al., 2012). The gas trapped in the hydrates can be released abruptly and fiercely which can lead to well-control problems (Brown et al., 2006; Cameron et al., 1990; Glasby, 2003; Vanoudheusden et al., 2004). The changes of effective stress and decrease of cementation between soil particles could cause consolidation and shear deformation of the ground and in turn

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produce geological disasters. As a result, it is important to study the deformation properties of hydrate-bearing sediments during dissociation in order to assess the long-term stability of the hydrate layers.

In order to meet the requirements of engineering activities, a series of numerical and experimental studies on the deformation properties of hydrate-bearing sediments during dissociation have been conducted. Kimoto et al. (2007) developed a chemo-thermo-mechanically coupled simulation method to predict the deformation of the ground during the hydrate dissociation process by the thermal recovery and depressurization method. However, it still needs to be verified against experimental results. Aoki et al. (2007) used a specially designed pressure vessel to clarify the compaction behavior of methane hydrate-bearing sediment during dissociation by the depressurization method. The relationships among vertical displacement of reservoir sand, pore pressure and temperature were obtained. Rutqvist et al. (2009) analyzed the geomechanical response during depressurization production from hydrate-bearing permafrost deposits by using a simulation method. The simulation results showed that the depressurization results in an increased shear stress within the body of the receding hydrate and causes a vertical compaction of the reservoir. The increased shear stress may lead to shear failure which depends on the initial stress state as well as on the geomechanical properties of the reservoir. Lee et al. (2010) studied the volume change associated with formation and dissociation of tetrahydrofuran hydrate in sediment. The results indicated that hydrate dissociation under drained, zero lateral strain conditions is always associated with some contraction, regardless of effective stress level, or hydrate saturation. The volumetric strain during dissociation under zero lateral strain scales with hydrate saturation and sediment compressibility. Hyodo et al. (2007, 2009) and Yoneda et al. (2010) performed triaxial compression tests on methane hydrate-bearing sediments under a similar condition to that *in situ*, and the relationships among shear strength, temperature, pore pressure and hydrate saturation were obtained. The deformation behavior of isotropically consolidated methane hydrate-bearing sand which dissociated by heating and depressurizing was also studied (Hyodo et al., 2011, 2013b). Li et al. (2011, 2012a, 2012b) primarily studied the effect of temperature, confining pressure, strain rate and porosity on the mechanical properties of laboratory-formed methane hydrate and methane hydrate-bearing sediment using kaolin clay as a host. A constitutive model describing the stress-strain behavior and a strength criterion for methane hydrate-bearing sediment were established (Li et al., 2012c, 2013). These studies are valuable; however, the deformation behaviors of methane hydrate-bearing sediments during dissociation are still not well understood. Further investigations are required in order to safely and economically extract of methane from methane hydrate reservoirs.

In this paper, a series of tests were conducted in order to investigate the shear strength and deformation behavior of methane hydrate-bearing sediments during dissociation using the thermal recovery method or depressurization method. An innovative temperature-controlled high pressure triaxial apparatus which can reproduce the *in situ* conditions of hydrate reservoir was used.

2. Experiment

2.1. Experimental apparatus

In order to represent the formation and dissociation of methane hydrate in the deep seabed, a temperature-controlled high pressure triaxial testing apparatus was developed. The schematic diagram of the apparatus is shown in Fig.1. A description of this testing apparatus also can be found in our earlier research (Hyodo et al., 2013b).

It can simulate the *in situ* conditions in a cylindrical sediment sample (30 mm in diameter and 60 mm in height). Triaxial tests can be carried out in a temperature range from −35 °C to 50 °C with axial load capacity of 200 kN, cell pressure capacity of 30 MPa and back pressure capacity of 20 MPa. The cell pressure is controlled by the cell pressure generation device with an accuracy of ±0.1 MPa. The back pressure was controlled by two syringe pumps with an accuracy of ±0.5 MPa. The accuracy of the axial load is up to 1/1000 of the full scale load. The temperature of the sample can be adjusted within a range of ±0.1 °C by circulating the cell fluid in the triaxial testing device from the thermal control tank. It can be measured using a thermocouple which was installed near the side of the sample in the triaxial pressure chamber. A gas mass flow meter was used to calculate the methane hydrate saturation. When methane hydrate was dissociated, the amount of gas can be measured while adjusting the valve in the pipe equipped with the gas flow meter and connected to the sample. In order to measure the volume change of an unsaturated sample, a double cell was adopted. The volume change can be calculated by measuring the volume difference of the syringe pump for the inner cell and the displacement of the piston. In order to reduce the dissociation of natural methane hydrate samples, a one-touch removable socket-type pedestal was used in the present apparatus.

2.2. Experimental procedure and test conditions

The mechanical properties of synthetic methane hydrate-bearing sediments are similar to those of natural hydrate-bearing sediments (Masui et al., 2008; Winters et al., 2004, 2007). Based on the observation of the undisturbed core samples obtained from Nankai Trough (Masui et al., 2008; Suzuki et al., 2009), Toyoura sand was chosen as the host material in this study. The grain size distributions of the natural cores and Toyoura sand are shown in Fig.2.

First, the water was well mixed with the dried sand to give the determined saturation and density. Then, the moist sand was inserted into the mold (30 mm in diameter and 60 mm in height) in 15 layers and each layer was compacted with a tamper 40 times. In order to make the sample stand by itself, the mold filled with moist sand was placed in a freezer. Next, the frozen specimen was taken out from the mold and then placed on the pedestal covered with butyl rubber membrane.

For the isotropic consolidation tests, methane hydrate was formed before consolidation. The methane gas was injected into the specimen and gradually increased to 4 MPa while the confining pressure increased to 4.2 MPa and temperature turned to 1 °C. Such conditions were kept constant for 24 h to generate methane hydrate. The back pressure was increased over a period of time so that the distribution of the moisture in the specimen would not become non-uniform due to the pressurized injection. It indicated that the moisture and methane gas fully reacted when there was no obvious volume change of the upper and lower syringe pumps. After the hydrate was generated, pure water under constant pressure was allowed to infiltrate into the specimen. The residual methane gas in the pores would be replaced by water and the specimen was saturated. The degree of MH saturation was measured after the test by collecting the dissociated methane gas. Then, back pressure was applied and the temperature was adjusted to the determined condition. While keeping the pressure constant, isotropically consolidation was carried out until the specified effective stress was reached, and then dissociation or shear would be conducted.

For the K_0 consolidation tests, methane hydrate was formed after consolidation. The methane gas was injected into the