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Mechanical and dissociation properties of methane hydrate-bearing sand in deep seabed

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Abstract

A series of triaxial tests has been carried out on the mechanical properties and dissociation characteristics of sands containing methane hydrate using an innovative high pressure apparatus which has been developed to reproduce the in-situ conditions expected during proposed methane extraction methods. It was found that the strength of MH sand increased with MH saturation due to particle bonding. Dissociation by heating caused large axial strains for samples with an initial shear stress and total collapse for samples consolidated in the metastable zone. In the case of dissociation by de-pressurization, axial strains were generated by increasing effective stress until a stable equilibrium was reached. However, re-pressurization led to the collapse in the metastable zone.

Keywords: Methane hydrate-bearing sand; Triaxial compression test; High pressure; Temperature; Back pressure; Strength; Stiffness; Stability; (IGC: B10/D6)

1. Introduction

Methane hydrate (MH) is a solid compound in which a large amount of methane is trapped within a crystalline structure of water, forming a solid similar to ice. It is known to exist in a stable condition under certain temperature and pressure conditions. Its existence has been confirmed in permafrost layers and in deep ocean floors (Kvenvolden et al., 1993). Although Japan has no permafrost zones, it is believed that MH exists in the seafloor, and development is underway for MH to be a future energy resource, replacing oil and coal (MH21 Research Consortium, 2001; Nagakubo, 2009). Recently, the existence of a large-scale MH natural gas reservoir has been investigated in the Nankai Trough (Fujii et al., 2008, 2009). Worldwide, MH is believed to exist in various forms, such as massive structures within muddy layers or at the surface of deep seabeds, or embedded within the pores of sandy layers (Waite et al., 2009). The seabed in the Nankai Trough consists of alternating layers of sand and clay, and it has been confirmed that the MH-enriched zone is buried within the voids of the sand layer (Suzuki et al., 2009).

Currently, the method proposed for abstracting methane in the Nankai Trough is by drilling a shaft into the MH-rich layer, and heating, depressurizing, or inserting hydrate inhibitors, causing the MH to become dissociated into methane and water after which the gas could be collected (Yamamoto, 2009). Using these methods, the solid MH existing in the pores within the soil is transformed into gas for collection; in the process, complex physical events, such

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as changes in the soil structure and thermal conductivity, pore fluid and gas migration, and other complicated phenomena need to be considered. It is predicted that a combination of such phenomena could cause consolidation and shear deformation of the ground due to changes in the effective stress and decrease in soil particle strength. Therefore, it is important to investigate the mechanical properties of MH-bearing sediments, for safe and economical exploitation.

Based on the author's experience of triaxial testing of sand specimens (Yasufuku et al., 1991; Hyodo et al., 2002), the investigation of the mechanical behavior of MH-bearing sediments was started using a triaxial compression test apparatus equipped with a high-pressure cell inside a freezer. Isotropic consolidated undrained triaxial compression tests were performed on specimens consisting of granulated MH and sand prepared by mixing and compacting mixture of MH powder and sand to investigate the effects of temperature and confining pressure on the strength characteristics of MH and sand mixtures (Hyodo et al., 2002, 2005). As a result, it was found that the shear strength of MH sand mixture increased with MH content increase. In addition, the shear strength of MH sand mixtures was found to increase with decrease in temperature and increase in confining pressure. The development of a testing apparatus which could more accurately reproduce the deep seabed temperature and stress conditions was initiated and a triaxial compression test machine was developed that could simulate predicted temperature changes in-situ and during the MH production process and apply high back (pore water) pressure and confining pressure corresponding to those existing in-situ. The dissociation of MH by heating and de-pressurization could be reproduced and the investigation of the deformation response of MH-bearing sands during the MH dissociation process became possible (Hyodo et al., 2007, 2008; Yoneda et al., 2007a, 2007b). Using this apparatus, methane gas could be injected into moist sand within the cell to produce MH dispersed around the soil particles similar to that occurring in deep seabed conditions. The authors performed consolidated drained triaxial compression tests on MH-bearing sediments under a similar physical environment to that found in-situ and an empirical equation for predicting strength of MH-bearing sediments associated with temperature, water pressure and MH saturation has been proposed (Yoneda et al., 2007a, 2007b). K_0 consolidated drained triaxial compression tests were also performed on undisturbed sediments from the Nankai Trough. These showed the mechanical properties of undisturbed sediments and artificially prepared sediments to be quite similar (Yoneda et al., 2010).

Miyazaki et al. (2007) performed triaxial compression tests with varying strain rates to investigate the shear strength characteristics and shear rate dependency for medium and large-strain ranges. They performed triaxial compression tests on dense specimens with varying confining pressures, and an empirical equation for predicting shear strength of MH-bearing sediments related to confining pressure was proposed. In addition, employing a comparatively low pressure to generate hydrate from THF (tetrahydratefuran), Yun et al. (2007) formed hydrate within sand, silt and kaolinite using THF-saturated water and carried out compression tests on hydrate-bearing sand with 0% to 100% of hydrate saturation. The results indicated that the increase in shear strength was small for THF-hydrate saturation ratios less than 40% but a marked increase in shear strength was observed when the saturation ratios exceeded 40%.

For the consideration of deformation due to MH production, a one-dimensional cylinder type experiment is commonly used. Sakamoto et al. (2008) used the depressurization method to dissociate the hydrate in MH-bearing sand and based on the observed one-dimensional compression behavior, they examined the changes in the seepage characteristics. Lee et al. (2010) also investigated settlement by hydrate formation and dissociation within sand, silt and kaolinite using THF under various confining pressures. These results are valuable for predicting settlement simply due to de-pressurization. However, in the case of there being some initial shear stress, the deformation caused by de-pressurization with dissociation of MH is still not clear.

A series of triaxial tests has been carried out in this study in order to investigate the mechanical properties and dissociation characteristics of methane hydrate bearing sand using an innovative high pressure apparatus which has been developed to reproduce the in-situ conditions.

2. Testing equipment and sample preparation

2.1. Triaxial testing apparatus

To reproduce the stress and temperature conditions in the deep seabed and to examine the mechanical behavior of MH-bearing sand specimens under such conditions and when MH is produced, a temperature-controlled high pressure triaxial testing apparatus was developed where the pore pressure and confining pressure could be controlled under various temperature and high pressure conditions. Fig. 1(a) shows the physical appearance of the device, while Fig. 1(b) shows a schematic diagram of the testing system. A detailed description of each part shown in Figure is presented below.

(a) *Test specimen*
A cylindrical frozen specimen measuring 30 mm in diameter × 50 mm high, or 50 mm in diameter × 100 mm high was used.

(b) *Pedestal*
To prevent the dissociation of natural MH samples, test specimens had to be set-up rapidly. For this purpose, the pedestal in the present apparatus was