Marine and Petroleum Geology 66 (2015) 451–459

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Mechanical behavior of hydrate-bearing pressure-core sediments visualized under triaxial compression

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ARTICLE INFO

Article history:
Received 24 September 2014
Received in revised form
5 February 2015
Accepted 16 February 2015
Available online 28 February 2015

Keywords:
Pressure core
Hydrate-bearing sediments
Triaxial test
Hydrate saturation
Strength
Stiffness

ABSTRACT

Geomechanical and geotechnical properties are essential for evaluating the stability of deep seabed and subsea production systems for gas hydrate extraction from marine sediments. In this study, natural gas hydrate-bearing sediment was subjected to triaxial compression tests (shearing) using a newly developed triaxial testing system (TACTT) to investigate the geomechanical behavior of sediments recovered from below the seafloor in the eastern Nankai Trough, where the first Japanese offshore production test was conducted in 2013. The sediments were recovered using a hybrid pressure coring system, with pressure cores cut using onboard pressure core analysis tools. The pressure cores were subsequently transferred to our shore-based laboratory and subsampled using pressure core non-destructive analysis tools (PNATS) for the TACTT system. Pressure and temperature conditions were maintained within the hydrate stability boundary during coring and laboratory testing. An image processing technique was used to capture deformation of the sediment sample within the transparent acrylic test cell, and digital photographs were obtained for each 0.1% strain level experienced by the sample during the triaxial compression test. Analysis of the digitized images showed that sediments with 63% hydrate saturation exhibited brittle failure, whereas hydrate-free sediments exhibited ductile failure. The increase in shear strength with increasing hydrate saturation in natural gas hydrates is in agreement with previous data from sediments containing synthetic gas hydrates.

1. Introduction

In March 2013, Japan extracted methane gas from offshore methane hydrates for the first time (JOGMeC, 2013; David, 2013). Methane hydrates are ice-like solid compounds in which a large amount of methane is trapped within the crystalline structure of water (Sloan, 2003). Natural gas hydrates in marine sediments or in permafrost regions worldwide are expected to be promising sources of natural gas (Makogon, 1981, 1982; Kvenvolden, 1988; Kvenvolden et al., 1993). The objective of the 2013 gas production test was to verify a 'depressurization method', whereby solid methane hydrate in the pores within the soil is transformed into gas for collection. In the process, complex physical events, such as changes in soil structure and thermal conductivity, pore fluid and gas migration, and other phenomena, need to be considered. A combination of such phenomena could cause destabilization of the reservoir due to the dissociation of the hydrate.

Understanding the geomechanical and geotechnical properties of gas hydrate-bearing sediments is essential to developing sustainable gas production methodologies. Dissociation of gas hydrate in sediments may affect the stability of subsea structures and well borings, increase the occurrence of geohazards (e.g., subsea landslides and seafloor subsidence), and influence gas productivity (Bugge et al., 1988; Collett and Dallimore, 2002; Kleinberg, 2005; Sakamoto et al., 2009; Fulong et al., 2012). Previous laboratory tests using synthetic gas hydrate-bearing sands have included triaxial and plane strain compression tests to investigate mechanical properties (Hyodo et al., 2005, 2013; Yun et al., 2007; Miyazaki et al., 2011; Yoneda et al., 2013a). However, only a few laboratory

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http://dx.doi.org/10.1016/j.marpetgeo.2015.02.028

tests on natural gas hydrate-bearing sediments have been reported (Masui et al., 2007; Yoneda et al., 2010), because the hydrate dissociates rapidly under atmospheric pressure and at ambient temperatures. In order to retain hydrates at atmospheric pressure, the temperature of the sample has to be maintained lower than approximately −80 °C. Tests on recovered pressure core have shown that, even with only brief depressurization, exsolution of methane gas from the pore water destroys the intact structure of the sediment. In addition some of the gas hydrate might dissociate during sample preparation such that the true behavior of the intact hydrate-bearing sediment is lost (Priest et al., 2014). Hydrate concentration within discrete layers at production sites is usually greater than 50% hydrate saturation. However, hydrate saturation in previous natural samples had only less than 40% (Masui et al., 2007; Yoneda et al., 2010). Knowledge of the intact mechanical properties of hydrate-bearing sediments with high hydrate saturation is essential to evaluating the stability of the production zones.

To investigate the intact strength of natural gas hydrate-bearing sediments in the eastern Nankai Trough pressure coring using a hybrid pressure coring system (hybrid-PCS) was undertaken in June and July 2012 (Yamamoto, 2015; Inada and Yamamoto, 2015). Recovered pressure cores were subsampled using the pressure core analysis and transfer system (PCATS) (Schultheiss et al., 2011) and subsequently transported to the laboratory within hydrate stability pressure–temperature conditions to avoid dissociation of natural gas hydrates. In this study, we performed triaxial compression shear tests on natural gas hydrate-bearing sediments at *in situ* pressures without any hydrate dissociation using a newly developed transparent acrylic cell triaxial testing system (TACTT system) (Yoneda et al., 2013b) to determine a range of strength parameters.

2. Sample preparation and experimental setup

The coring hole (AT1-C) drilling operation was conducted after the Japan Agency for Marine-Earth Science and Technology's Expedition 906 using the deep water drilling vessel D/V *Chikyu* (Yamamoto, 2015). AT1-C was located 40 m northeast of the production well AT1-P in 998.7 m water depth. The coring operation was carried out from a depth of 260 m below the seafloor (mbsf) in a silty zone above the methane hydrate concentration zone. The sample used in this study was recovered from a depth of 278 mbsf. During coring, the inner barrel of the hybrid-PCS is lowered down from the drilling vessel to the borehole. Then up to 3 m of deep-sea sediments is cored and retrieved under *in-situ* pressures. Once on deck, the pressurized autoclave of the inner barrel of the drilling tool, which contains the sediment core, is removed and cooled in an ice bath to prevent hydrate dissociation. Once cooled, the autoclave is connected to the PCATS, and the sediment core is retrieved within its plastic liner. The core is subjected to non-destructive testing, including P-wave velocities measurements, and X-ray images of the core (Suzuki et al., 2015). From this data a detailed cutting plan was developed for subsequent sub-sampling of these cores. Based on the cutting plan, each pressure core was initially subsampled into 1.2 m or 0.35 m lengths at pressure and placed into storage chambers. These sections of core were subsequently transported to the onshore laboratory and subsampled under pressure into smaller sections of core for testing using pressure-core non-destructive analysis tools (PNATs), which we developed on the basis of pressure core characterization tools (Santamarina et al., 2012).

Figure 1 shows an exterior photograph of the PNATs and a conceptual diagram of the pressure core transfer procedures. The PNATs apparatus comprises the transported pressure chamber holding the long core section (Schultheiss et al., 2011), a cutting tool, an observation window, the temporary storage chamber, a manipulator for retrieving and placing sub-sectioned cores, and a pressure chamber for the TACTT system. First, the storage chamber that was used during transport of the pressure core was connected to the PNATs. The plastic liner holding the sediment core was grabbed by the manipulator and retrieved into a temporary storage chamber under 10 MPa of fluid pressure. The ball valve was closed to allow the exchange of the transportation storage chamber with the TACTT pressure chamber. Previously the testing section of the pressure core had been identified by comparison with an X-ray CT image obtained by PCATS and viewing from the observation window. The pressure core including the plastic liner, was cut to a length of 85 mm using a diamond saw and stored in the pressure chamber for the TACTT system. Figure 2 shows a schematic diagram of the TACTT system. The pressure core sub-section was installed in the TACTT system conveyance chamber and transferred into the sealing sleeve with a target marker within the transparent acrylic triaxial cell.

The pressure and temperature conditions from the beginning of pressure core recovery (within the seafloor) to the placing of the core in the TACTT system are shown in Figure 3a. The conditions were maintained within the hydrate stability boundary throughout the entire process of core handling, sub-sectioning and laboratory testing. Figure 3b shows gamma-ray density (ρ_i) and P-wave velocity (V_p) measured by PCATS onboard ship for the section of core tested; measurements were acquired at 1 cm spacing down the core; ρ_i ranged from 1.75 to 1.96 g/cm^3, with an average value of 1.91 g/cm^3. The top (0–20 mm from the top of the sample) and middle (40–60 mm from the top of the sample) parts of the sample exhibit low-density, i.e., with measured density less than 1.9 g/cm^3. Subsequent analysis of the sediment mineralogy revealed layers containing mica in these low density regions. Figure 3c shows an X-ray CT image of the sample, also obtained by PCATS. The pressure chambers previously used were typically made of stainless steel, which prevented visual observations of a core sample during subsequent testing and made it difficult to investigate specimen behavior during testing and to evaluate the validity of tests. Figure 3d shows an optical image of natural gas hydrate-bearing sediments under 10 MPa water pressure captured through the observation window of the TACTT-system which is shown in Figure 2; this is the first time that such an image has been obtained. It can be observed that the sample has a dipping layer, which is due to sediment deposition.

The testing procedure followed that of Yoneda et al. (2013b). A confining pressure of 11.5 MPa, simulating 1.5 MPa of mean effective stress at *in situ* hydrostatic pressure, was applied through the sealing sleeve for consolidation. Axial loading was applied at a strain rate of 0.1%/min under drained conditions while maintaining the pore pressure at 10 MPa and temperature at 5 °C. This strain rate is an adequately slow speed for maintaining drainage conditions during testing for this sample. An image processing technique (Yoneda et al., 2013b) was used to capture deformation of the sediment sample within the transparent acrylic test cell, and digital photographs were obtained for each 0.1% strain level experienced by the sample during compression. After axial loading, the methane gas hydrate present in the sample was dissociated by reducing the pore pressure (depressurization), and the volume of released gas was measured using a gas flow meter. From the gas volume measured during hydrate dissociation, the initial fraction of gas hydrate present within the pore space of the sample, S_h, could be quantified. After the test, the sample was reconstituted by tamping at 2 cm intervals, and the triaxial compression test was repeated to enable comparison between the behavior of the sample with and without hydrate. The soil particle density ($\rho_s = 2.63$ g/cm^3) and mean particle size ($D_{50} = 113$ μm) were also measured.