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Experimental research on the mechanical properties of methane hydrate-bearing sediments during hydrate dissociation

Yongchen Song, Yiming Zhu, Weiguo Liu*, Jiafei Zhao, Yanghui Li, Yunfei Chen, Zhitao Shen, Yan Lu, Chongming Ji

Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, School of Energy and Power Engineering, Dalian University of Technology, Dalian 116024, PR China

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ABSTRACT

This paper describes studies of the effect of hydrate dissociation on the safety and stability of methane hydrate-bearing sediments. Methane hydrates within the sediments were dissociating under the conditions of a confining pressure of 0.5 MPa, 1 MPa, 2 MPa and a temperature of −5 °C. After 6 h, 24 h, or 48 h, a series of triaxial compression tests on methane hydrate-bearing sediments were performed. The tests of ice-clay and sediments without hydrate dissociation were performed for comparison. Focusing on the mechanical properties of the sediments, the experimental results indicated that the shear strength of the ice-clay mixtures was lower than that of the methane hydrate-bearing sediments. The strength of the sediments was reduced by hydrate dissociation, and the strength tended to decrease further at the lower confining pressures. The secant modulus E_S of the sediments dropped by 42.6% in the case of the dissociation time of the hydrate of 48 h at the confining pressure of 1 MPa; however, the decline of the initial yield modulus E_0 was only 9.34%. The slower hydrate dissociation rate contributed to reducing the failure strength at a declining pace. Based on the Mohr–Coulomb strength theory, it was concluded that the decrease in strength was mainly affected by the cohesive reduction. Moreover, the mathematical expression of the M–C criterion related to the hydrate dissociation time was proposed. This research could be valuable for the safety and stability of hydrate deposits in a permafrost region.

1. Introduction

The largest accumulations of natural gas on Earth are in the form of gas hydrate, which occur worldwide on continental and insular slopes and rises of active and passive margins, on continental shelves of polar regions, and in deep-water environments of inland lakes and seas; and recently, 3D seismic data and high-resolution seismic reflection data have provided information about the existence of gas hydrate around these regions (Kvenvolden, 1995; Kvenvolden et al., 1993; Rajan et al., 2013; Simonetti et al., 2013). The extensive applications of nature gas hydrates in engineering include preconditioning of the fuel gas mixture before combustion (Ponnivalavan et al., 2013), natural gas transport and storage materials (Nam-Jin et al., 2010) and mechanical separation of CO_2 from combustion effluent (Theunissen et al., 2011). Methane hydrates, the solids composed of rigid cages of water molecules that enclose methane, represent an important possible future energy source (Darvish, 2004; Kvenvolden, 1988). Although the exploitation of methane hydrate can efficiently satisfy the increasing energy demand (Collet, 2002), there are still important difficult-to-solve issues, such as the natural disasters of submarine landslides and tsunamis and the increase of the greenhouse effect caused by the dissociation of hydrate (Kayen and Lee, 1991; Brown et al., 2006; Blumier, 2000; Glasby, 2003; Kim et al., 2013). Therefore, it is essential to study the mechanical properties of methane hydrate-bearing sediments during hydrate dissociation to guarantee the safety and stability of hydrate deposits.

The mechanical properties of hydrate-bearing sediments have been studied in recent years, along with the development of technology and the maturation of testing equipment. Durham et al. (2003) studied the creep characteristics of pure artificial methane hydrate, and the studies indicated that the strength of these methane hydrates were much stronger than ice under the same conditions. Winters et al. (2004, 2007) indicated that the strength was enhanced in the case of the sediments containing hydrate under the triaxial compression tests on artificial and undisturbed samples of hydrate-bearing sediments, and a further study was

* Corresponding author. Tel.: +86 411 84706795; fax: +86 411 84708015.
E-mail addresses: zymhunter@aliyun.com (Y. Zhu), liuwg@dlut.edu.cn (W. Liu).

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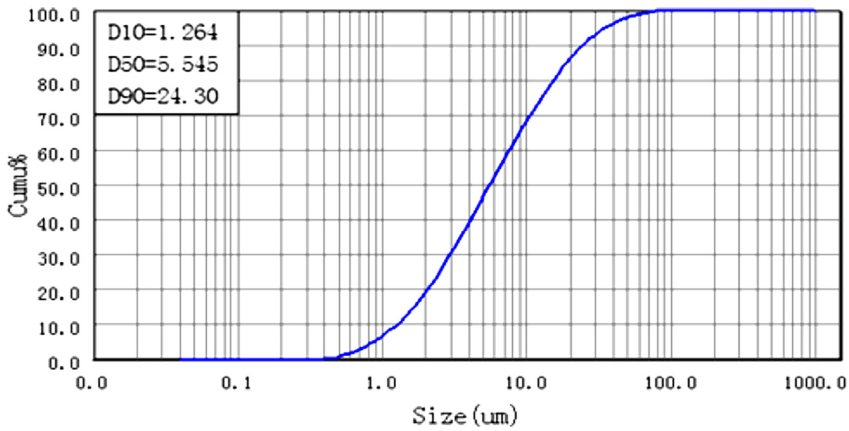

Figure 1. Grain size distribution curve of kaolin clay.

made to investigate the shear strength characteristics of hydrate and ice and the dependence of the shear strength of hydrate-bearing sediment on the pore space contents. Hyodo et al. (2005, 2007) found that the strength of artificial hydrate-bearing sediments was affected by temperature, confining pressure, saturation of the hydrate and strain rate. Masui et al. (2005) and Miyazaki et al. (2009, 2010) reported that the shear strength and secant modulus of hydrate-bearing sediments increased with the increasing saturation of the hydrate, and that the shear strength increased with the decrease of the porosity at the same degree of saturation. Subsequently, Masui et al. (2007) observed the mechanical properties of gas hydrate samples from eastern Nankai Through and the synthetic samples. They determined that the two specimens have the same compressive strength, while there is a significant difference between the two samples in the elastic modulus. Yu et al. (2011a,b) presented a constitutive model of the stress–strain for methane hydrate and methane hydrate-bearing sediment based on the nonlinear elastic Duncan–Chang model. Li et al. (2012) noted that the cohesion decreases while the internal friction angle increases with the increasing hydrate content under a series of triaxial compression tests on artificial methane hydrate-ice mixtures. Liu et al. (2013) analyzed the strength difference between the CO_2 and CH_4 hydrate-bearing sediments to evaluate the safety of the CH_4–CO_2 replacement method.

Although there has been much research on the mechanical properties of hydrate-bearing sediments, the effect of hydrate dissociation on the safety and stability of methane hydrate-bearing sediments has rarely been studied. To clarify the dependence of the strength of hydrate-bearing sediment on the dissociation time, a series of triaxial compression tests on artificial methane hydrate-bearing sediments with 40% porosity were performed under different confining pressure and the differences between the sediments and ice-clay mixtures was studied.

2. Experimental methods

2.1. Specimen preparation

Ice powder and kaolin clay were used to produce the specimens in this study. The methane hydrate for this study was manufactured in a high-pressure chamber using methane and ice powder (Stern and Kirby, 1998). First, ice powder was manufactured by using an ice crusher to break the prepared freezing distilled water. Then, a standard 60-mesh sieve was used to obtain the suitable ice powder, which had a mean particle size of 250 μm. After that, the ice powder was put into a pressure reactor, and then the reactor was filled with methane gas of 99.99% purity until the pressure of the chamber reached to 8 MPa. Next, the reactor was put into the cold storage at the constant temperature of −10 °C for 72 h, during which the methane gas and ice powder had been reacted completely to form methane hydrate. According to the difference of the mass of the methane hydrate-ice mixture before and after hydrate dissociation, the calculated results of methane hydrate saturation were in the range of 25%–30%. Finally, the methane hydrate-bearing sediments were manufactured using the methane hydrate-ice mixture and kaolin clay, which was cooled in the cold storage as materials. The grain size distribution curve of kaolin, shown in Figure 1, was analyzed by a laser particle size analyzer. To obtain the cylindrical methane hydrate-bearing sediment with 40% porosity whose size was 61.8 mm diameter × 125 mm height, 553 g of kaolin and 147 g of methane hydrate-ice mixture were evenly mixed, and then the final mixture was placed into a pressure moulding device to form the specimen at a controlled axial load of 30 kN. Because of the nearly identical density between ice powder and the methane hydrate-ice mixture, kaolin clay and pure ice powder were mixed in the same proportion, that is, 553 g of kaolin and 147 g of pure ice powder, for making the ice-clay mixture samples. All the above processes were performed in the conditions of cold storage (−10 °C).

2.2. Triaxial testing apparatus

A DDW-600 triaxial testing device was used to conduct all the tests. The schematic diagram of the device is shown in Figure 2. This device consists of an axial loading system, a servo-control system, a confining pressure control system, a temperature control system and a computer control system, which can conduct strength tests, creep tests, stress relaxation tests and permeability experiments of hydrate with various confining pressure, temperature, strain rate and saturation. Two pressure chambers have been originally used to avoid the leakage of hydraulic oil due to the difference between inner and outer pressure in the structure of one pressure chamber. The technical indicators of the device are listed in Table 1.

The test sample is jacketed in the inside pressure chamber, which is covered by the outside pressure chamber. Then the two respective pressure chambers are filled with hydraulic oil, which comes from the storage tank. The axial loading system is used to lift the entire device to the proper height. Next, the high-precision servo motors drive the plunger pumps forward or backward to maintain the confining pressure of the two chambers required in experiments. Meanwhile, a constant temperature bath provides the circulating coolant liquid to cool the specimen down through the