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The effects of methane hydrate dissociation at different temperatures on the stability of porous sediments

Yongchen Song, Yiming Zhu, Weiguo Liu *,[1], Yanghui Li *,[1], Yan Lu, Zhitao Shen

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

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ABSTRACT

Based on a series of triaxial compression tests on methane hydrate-bearing sediments after a hydrate dissociation time of 0 h, 1 h, 6 h, 12 h, or 24 h, the mechanical properties of the sediments were studied during hydrate dissociation at different temperatures. The results showed that strain softening behavior appeared at higher temperatures in our work. The failure strength and initial yield strength both decreased with an increase in the methane hydrate dissociation time, and the rate of decline of failure strength was faster at higher temperatures. Mathematical expressions for the failure strength and the initial yield strength in terms of the dissociation time and the temperature were also proposed. Moreover, the Duncan-Chang constitutive model of methane hydrate-bearing sediments considering the influence of temperature and hydrate dissociation time was developed, and the validity of most of the calculated results was verified by experiment.

1. Introduction

Natural gas hydrates are crystalline solids, non-stoichiometric compounds of small gas molecules and water, which form when the constituents come into contact at low temperature and high pressure (Kvenvolden, 1999; Sloan, 2003). Because gas hydrates represent a large amount of methane within 2000 m of the Earth's surface, they are considered to be an unconventional, unproven source of fossil fuel (Kvenvolden, 1993). At present, more and more scientists have become interested in the exploitation technology for gas hydrate. A variety of methods have been proposed for the recovery the natural gas from gas hydrate: depressurization, thermal injection, usage of inhibitors and CO_2 replacement (Ji et al., 2001; Uchida et al., 2001; Tang et al., 2005).

Through the analysis of various natural gas hydrate recovery methods, the thermal injection method was an important choice for the extraction of natural gas hydrate (Zhang et al., 2008). Kamath et al. (1984, 1991) focused on the heat transfer between gases, liquids and solids during the process of the exploitation of hydrates by thermal stimulation, and reported that the gas production of hydrate was increased by injecting hot salt water. Sung et al. (2004) studied differences in energy efficiency during several exploitation methods for tapping hydrates by thermal injection.

Furthermore, gas hydrate may dissociate due to a temperature increase during drilling for exploration and production in marine sediments, which will result in a loss of integrity in boreholes and regional subsidence of the ground surface and may even lead to marine slope failures (Kayen et al., 1991; Grozic et al., 2010; Lee et al., 2010). Therefore, it is essential to study the mechanical properties of hydrate deposits. Hyodo et al. (2005, 2007) studied the effects of the temperature, confining pressure, hydrate saturation and strain rate on the strength of artificial hydrate-bearing sediments. 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 hydrate and the shear strength increased with the decrease of porosity holding the degree of saturation constant. Clayton et al. (2005, 2010) described laboratory experiments to synthesize disseminated methane hydrates and to characterize them under small-strain dynamic loading in a resonant column apparatus. They studied the effects of hydrate cement on the stiffness of some sands. Yun et al. (2005, 2007) and Santamarina and Ruppel (2008) found that the strength and stiffness of hydrate increased with the increasing effective confining pressure at low hydrate saturation, while this dependency became weaker with an increase in hydrate saturation. Song et al. (2010) and Yu et al. (2011a) focused on the effects of confining pressure and temperature on the mechanical properties of methane hydrate and methane hydrate-bearing sediment. Then, Yu et al. (2011b, 2011c) presented a constitutive stress–strain model for methane hydrate and methane hydrate-bearing sediment based on the nonlinear elastic Duncan–Chang mode.

Based on these studies, the deformation characteristics of

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* Corresponding authors.
E-mail addresses: liuwg@dlut.edu.cn (W. Liu), liy@dlut.edu.cn (Y. Li).
[1] These authors contributed equally to the work.

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Nomenclature

T	temperature (°C)
t	dissociation time of hydrate (hour)
ε_1	axial strain (%)
σ_1	major principal stress at failure (MPa)
σ_3	confining pressure (MPa)
q_f	failure strength (MPa)
q_0	initial yield strength (MPa)
$(\sigma_1-\sigma_3)$	deviator stress (MPa)
$(\sigma_1-\sigma_3)_{ult}$	ultimate deviator stress (MPa)
E_t	tangent modulus (MPa)
E_i	initial tangent modulus (MPa)
R_f	failure ratio
a	experimental coefficient (10^{-10})
b	experimental coefficient (10^{-8})

hydrate-bearing sediments during hydrate dissociation have been studied further. Lu et al. (2008) studied the mechanical properties of a tetrahydrofuran hydrate deposit and found that the mechanical properties were affected by hydrate dissociation. Masui et al. (2007) studied the compaction behavior of methane hydrate-bearing sediments during hydrate dissociation. Lee et al. (2010) studied the volume change rules for tetrahydrofuran hydrate-bearing sediments during hydrate dissociation. Hyodo et al. (2013, 2014) studied the deformation behavior of isotropically and K_0 consolidated methane hydrate-bearing sand which dissociated by heating and depressurizing.

Although there has been much research, as mentioned above, on the mechanical properties of hydrates or hydrate-bearing sediments, there has been little investigation of the mechanical properties of methane hydrate-bearing sediments during the decomposition process of hydrate under thermal stimulation. In this paper, to study the effect of methane hydrate dissociation at different temperatures on the stability of methane hydrate-bearing sediments, these porous sediments were made in the laboratory, and a series of triaxial compression tests of the sediments with 40% porosity were performed during hydrate dissociation at different temperatures. According to the literature (Fu et al., 2010), part of gas hydrates were uniformly distributed in dispersed state in pore space. Thus, in this paper, our study was focused on the homogeneous methane hydrate-bearing sediments.

2. Apparatus and experiments

2.1. Testing apparatus and experimental procedure

The testing apparatus included a pressure reactor for generating methane hydrate, a pressure molding device for making cylindrical methane hydrate-bearing specimens and a DDW-600 triaxial testing device (Changchun Rising Sun Testing Instrument Co. Ltd., Changchun, China).

Ice powder and methane gas were used to generate methane hydrate (Stern et al., 1998). The schematic diagram of the pressure reactor is shown in Fig. 1. Ice powder of an average particle size of 250 μm was manufactured by using an ice crusher to break the prepared freezing distilled water. Then, the ice powder was put into a pressure chamber and methane gas of 99.99% purity was injected into the reactor through a connecting hose and a constant pressure pump until the pressure of the pressure chamber reached 8 MPa. The reactor was put into a cold storage freezer at a constant temperature of −10 °C for 72 h. Then, the methane hydrate was generated and the saturation was in the range of 25–30%.

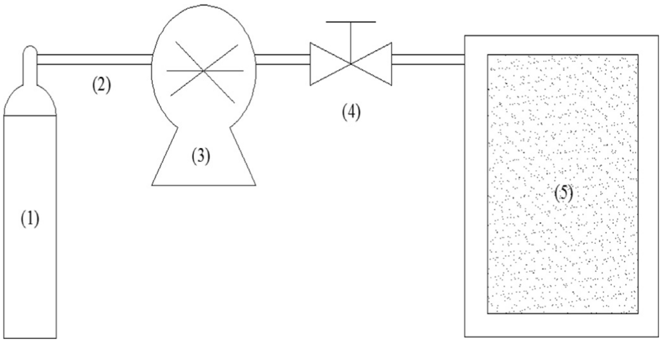

Fig. 1. The schematic diagram of the pressure reactor for generating methane hydrate.

The prepared methane hydrate-ice mixture and kaolin clay were used to manufacture methane hydrate-bearing sediments in the pressure molding device. The grain size distribution curve of kaolin is shown in Fig. 2, and the median particle diameter of kaolin clay is 5.545 μm. The pressure molding device and specimen preparation process are shown in Fig. 3. The cylindrical methane hydrate-bearing specimen (61.8 mm diameter × 125 mm height) was formed under an axial stress of 30 kN. The porosity of the generated specimens was approximately 40%. To prevent hydrate dissociation during specimen preparation, all of the above processes were carried out in a freezer (−10 °C).

The schematic diagram of the DDW-600 triaxial testing device is shown in Fig. 4. The technical specifications of the device were shown in our previous work (Song et al., 2014). The prepared samples were removed from the pressure molding device, wrapped with a rubber membrane, and then put into the pressure chamber. After the specimen was jacketed inside the pressure chamber, a predetermined confining pressure and temperature were applied and kept constant during hydrate dissociation. During the shear process, axial stress and axial strain were controlled and measured by a load cell and a displacement sensor. The amount of axial strain rate was entered at the start of the test, and then the shear tests were conducted automatically from start to finish by using the triaxial testing software.

2.2. Test conditions

The experimental conditions are shown in Table 1. All of the specimens were consolidated at the confining pressure of 10 MPa

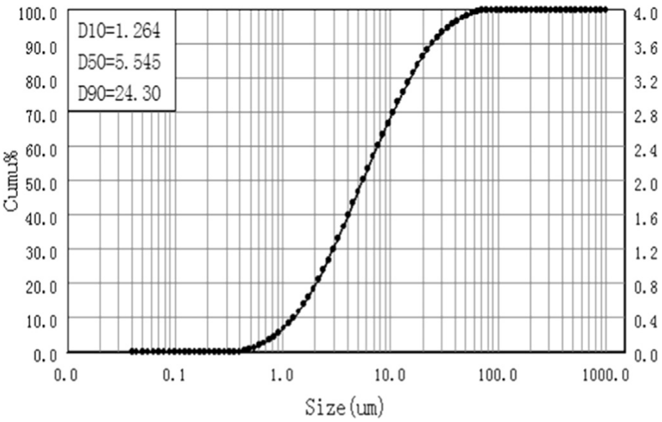

Fig. 2. Grain size distribution curve of kaolin clay.