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Research paper

Study on the mechanical properties of hydrate-bearing silty clay

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ABSTRACT

The mechanical properties are important for the evaluation of stratum deformation and instability in hydrate exploitation. By using an integrated test apparatus for synthesis of hydrate sediment and tri-axial tests, a series of compression tests is conducted on the silty clay containing tetrahydrofuran hydrate (SCTH) similar to that of South China Sea. The stress–strain curves and Mohr circles are obtained at different degree of hydrate saturations and confining pressures. The silty clay containing tetrahydrofuran hydrate shows typical ductile behavior, the shear strength increases linearly with the increase of hydrate saturation and confining pressure. The secant modulus increases with the increase of hydrate saturation. The shear strength is analyzed based on the Drucker–Prager criterion, Mohr–Coulomb criterion, Lade–Duncan criterion, while the secant modulus is analyzed using the mixed law of composite materials. It is shown that the strength can be well described by the Drucker–Prager criterion and Mohr–Coulomb criterion, and the secant modulus is close to the harmonic average of the modulus of soil skeleton and hydrate in SCTH.

1. Introduction

Hydrate, formed by methane, carbon dioxide, hydrogen sulfide, tetrahydrofuran and water molecules is a crystalline solid like ice under proper pressure and temperature. Natural gas hydrate is an important energy resource in the 21st century (Kvenvolden and Lorenson, 2001; Koh, 2002). Gas hydrate-bearing sediment (GHBS) has been sampled from many fields over the world such as Mallik in Canada (Numasawa et al., 2008), Alaska in America (ConocoPhillips, 2012), the northern continental slope in the South China Sea, Dongsha sea area and Qilian Mountains tundra in China.

Gas hydrate-bearing sediment is a mixture containing hydrate, soil/rock skeleton, water and gas. The mechanical properties of GHBS before and after hydrate dissociation are fundamental for soil response during hydrate exploitation and exploration.

The mechanical properties of GHBS are studied by tri-axial tests of artificial samples. The effects of hydrate occurrence mode, hydrate saturation, temperature, effective confining pressure on the modulus and the shear strength have been studied mainly by using hydrate-bearing sands (Clayton et al., 2005; Winters et al., 2004, 2007; Masui et al., 2007; Hyodo et al., 2007, 2014; Zhang et al., 2012; Li et al., 2012). The results indicate that the modulus and shear strength increase with the increase of effective confining pressure and hydrate saturation. Strain softening occurs when the hydrate saturation attains to 25%. Hydrate occurrence modes, such as pore filling and cementation, affect the micro interaction of hydrate and soil grains. The mechanical properties of THF hydrate soil are also investigated (Yun et al., 2007), and the results indicate that the tangent stiffness of THF hydrate-bearing soil decreases with the increase of shearing.

The modified Cam-Clay model, Duncan–Chang model and damage model have been used to formulate the stress–strain relationship of GHBS. The Duncan–Chang model and damage model are applied to model ideally elastic–plastic behavior (Yu et al., 2011; Li et al., 2012) and strain softening (Wei et al., 2011), respectively. The modified Cam-Clay model can account for shearing and volumetric dilation of hydrate-bearing sands. However, its verification for hydrate-bearing silty-clay is required (Mayazaki et al., 2008, 2011a,b; Uchida et al., 2012; Dai et al., 2012). Although the relationships of the modulus and shear strength with hydrate saturation are well fitted, their physical meaning remained unclear (Birchwood et al., 2008). Hence, it seems reasonable to use different constitutive models to simulate different GHBS.

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In this paper, the mechanical properties of SCTH are investigated by tri-axial tests and theoretical analysis. Firstly, silty clay is used as the soil skeleton, THF hydrate is formed in the pores of soils at different degrees of hydrate saturation, which is similar to GHBS sampled from the South China Sea in hydrate saturation, dry density and grain size distribution. Secondly, the tri-axial tests are conducted under different effective confining pressures. Finally, the mechanical properties are formulated to provide practical references.

2. Test illustration

The tests are conducted using the integrated test apparatus for synthesis of hydrate sediment and tri-axial tests. The test setup is shown in Figure 1. The apparatus can provide an effective confining pressure ranging from 0 to 20 MPa with an accuracy of 0.5% and a temperature from −20 °C to 20 °C with an accuracy of 2.5%. The maximum back-pressure is provided by a gas-supply cylinder as 10 MPa. Some detailed information about the apparatus is given by Zhang et al. (2012).

The grain size distribution of the silty-clay is shown in Figure 2. The specific gravity is about 2.7, and the dry density is 1.3 g/cm^3 with a porosity of 52.1%. So the pore volume of a specimen is 50 cm^3 in a specimen with a diameter of 3.91 cm and a height of 8.0 cm.

THF solutions are prepared to keep the fluid mass content at a level of 30%, and the volume of fluid is about 37.5 ml in the specimens. The geotechnical parameters such as the volume of water and THF before SCTH synthesis are given in Table 1.

The hydrate saturation is calculated by equation (1).

$$S_H = \frac{V_H}{V_p} \tag{1}$$

where S_H, V_H, and V_p are the hydrate saturation, the volume of hydrate, and the volume of pores, respectively.

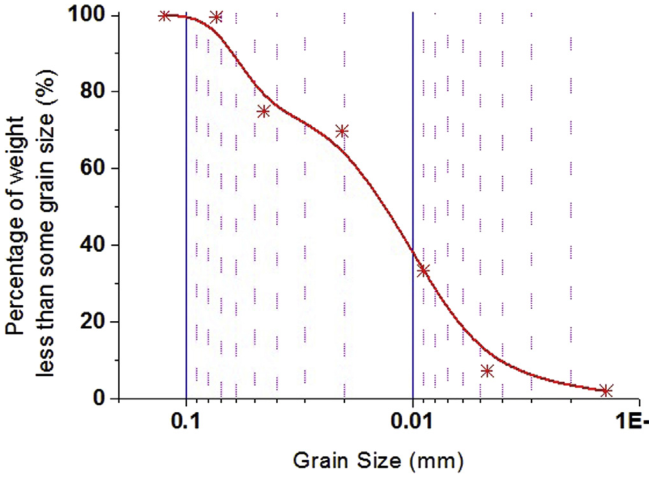

Figure 2. Grain size distribution.

Table 1
Geotechnical parameters.

S_h/%	G_d	ρ_d/g/cm^3	φ	V_w/ml	V_{THF}/ml	V_H/ml
0	2.7	1.3	0.52	0	37.5	0
5	2.7	1.3	0.52	2.0	35.5	2.5
15	2.7	1.3	0.52	6.0	31.5	7.5
25	2.7	1.3	0.52	9.9	27.6	12.5
35	2.7	1.3	0.52	13.9	23.6	17.5
45	2.7	1.3	0.52	17.9	19.6	22.5

Here S_h, G_d, ρ_d, φ, V_w, V_{THF}, and V_H represents THF hydrate saturation, soil specific weight, dry density, porosity, the volume of water, the volume of THF, and the volume of THF hydrate, respectively.

After filling with THF solution, the specimens are placed into the pressure chamber and kept at a temperature of 2 °C for 2 days to ensure the synthesis of SCTH. The effective porosity of the unsaturation soil after hydrate formations are 52.1%, 49.5%, 44.3%, 39.1%, 33.9%, 28.6%, respectively. Then the effective confining pressure is applied, an axial displacement rate is controlled at 0.9 mm/min, and the axial force and displacement as the stress and strain are recorded. The effective confining pressures are 2.5 MPa, 5 MPa, 8 MPa, respectively, and the temperature is 2 °C, which is similar to the existing condition of the hydrate in South China Sea (Shi et al., 2015).

3. Test results

Based on a series of tests, the stress–strain curves and Mohr circles are shown in Figures 3–8. Three specimens in a same degree of hydrate saturation and the three different effective confining pressures are tested according to the requirement of the Mohr

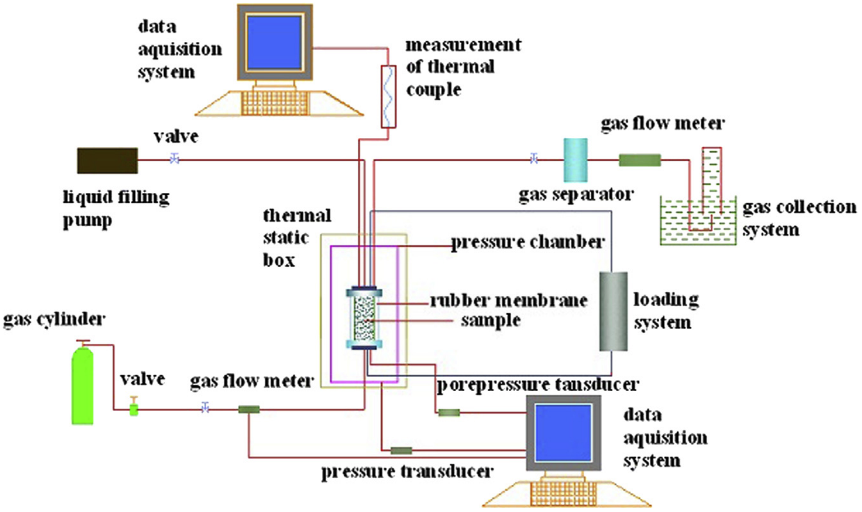

Figure 1. The integrated test apparatus for synthesis of hydrate sediment and tri-axial tests.