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Analysis of Stress-Strain Behavior and Constitutive Relation of Methane Hydrate-Bearing Sediments with Various Porosity

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To study the stress-strain behavior of methane hydrate-bearing sediments with various porosity that was tremendously affected by environmental conditions a series of triaxial tests was performed using artificial samples of methane hydrate-bearing sediments under various conditions with confining pressures (P) at 2.5, 3.75 and 5 MPa, temperatures (θ) at −5°C, −10°C and −20°C, and strain rates at 0.1, 0.5 and 1%/min. The variation of deviator stress with axial strain was observed, and the strain type was analyzed systematically under different experimental conditions. In addition, based on the experimental and analysis results of the stress-strain behavior of triaxial tests, this paper proposes the modified nonlinear elastic Duncan-Chang constitutive model, whose coefficients contain the main factors affecting stress-strain behavior.

INTRODUCTION

Many researchers (Kvenvolden and Lorenson, 2001) have considered gas hydrate to be one of the most promising new forms of energy to replace oil. Gas hydrate is a solid clathrate compound in which a large amount of methane is trapped within the crystal structure of water ice. It is stable at low temperature and high pressure. By some estimates, the energy locked up in gas hydrate deposits is more than twice the global reserves of all conventional gas, oil and coal deposits combined (Alexei, 2004).

However, the dissociation of gas hydrate in marine sediments may result in seafloor-slope instability and a large-scale release of methane under unfavorable circumstances during the drilling and exploration process (MacDonald et al., 1994; Glasby, 2003). Thus, a lot of attention has been paid to the mechanical properties of hydrate sediments. Hyodo et al. (2002) and Song et al. (2010) showed that the strength of methane hydrate increased with the enhancement of pressures, the decrease of temperature and the enhancement of the strain rate. However, natural gas hydrate always exists in the sediments, which include soil, ice/water and air. It is difficult to evaluate the mechanical properties of the hydrate sediment with the experimental measurements of pure hydrates in the laboratory. Winters et al. (2004, 2007) and Masui et al. (2007, 2008) reported that the mechanical strength of artificial hydrate-bearing sediments was similar to that of natural hydrate-bearing sediments. Although the volumetric strain between the natural and synthetic gas hydrate is obviously different, as well as the elastic modulus E50, because of the difference in distribution of the sand particle size. For the tests using artificial methane hydrate-bearing sediments (MHS) in the laboratory, the shear strength and elastic modulus increased with the increase in methane hydrate saturation and confining pressure and the decrease in temperature (Masui et al., 2005; Hyodo et al., 2005; Miyazaki et al., 2010). Further, the porosity of the specimen was lower, and the shear strength was higher (Masui et al., 2005; Hyodo et al., 2005). Poisson's ratio v50 does not have an increasing tendency against hydrate saturation (Masui et al., 2005). In addition, in their study Yun et al. (2007) and Lu et al. (2008) used tetrahydrofuran hydrate, which forms more easily. The research reflected the mechanical behavior of methane hydrate to some extent, because the properties of tetrahydrofuran hydrate are similar to those of methane hydrate. Miyazaki et al. (2008) developed a variable-compliance type of constitutive model to formulate a stress-strain relationship based on the experimental results of triaxial tests. The model took into account the time-dependent property, which was influenced by the methane hydrate saturation and effective confining pressure.

Considering the porosity of gas hydrate-bearing sediments was the only constant in previous research; the present experimental studies were carried out to systematically analyze the stress-strain behavior of MHS with different porosity. Further, the constitutive model suitable for artificial hydrate-bearing sediments was established to predict the stress-strain behavior on the basis of the nonlinear elastic Duncan-Chang model. The results are in reasonable agreement with the experimental data.

EXPERIMENTAL METHOD

Hydrate and Sample Preparation

In this study the methane hydrate was synthesized in a high-pressure reactor using the ice-seeding method (Stern and Kirby, 1998). In general, the ice powder was broken by the block shaving machine and put into the reactor. The ice powder was sieved with the standard 60-mesh sieve; the mean particle size is about 250 μm. Then the closed reactor was filled with high-pressure methane gas and put in the refrigerator for forming methane hydrate at a low temperature ranging from −5°C to −10°C and high pressure ranging from 10 MPa to 15 MPa. The formation of methane hydrate needs a long preparation time; in this study, it was 48 to 72 h. The methane hydrate mentioned below represents unsaturated methane hydrate: the mixture of methane hydrate and ice. The methane hydrate saturation which was 20% to 30% can be calculated on the basis of the amount of methane gas from hydrate dissociation in the sample.

The samples were prepared by compacting the kaolinite clay and the unsaturated methane hydrate using a pressure crystal device. The distribution of the kaolinite-clay particle size was analyzed using a centrifugal particle-size analyzer. The mean particle

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