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Dynamic strength characteristics of methane hydrate-bearing sediments under seismic load

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ABSTRACT

The research on the mechanical properties of hydrate-bearing sediments has attracted great attention to ensure the safety production of methane from hydrates. To study the dynamic strength characteristics of methane hydrate-bearing sediments under seismic load, a series of dynamic triaxial tests was performed on artificial methane hydrate-bearing sediments under various conditions, with confining pressures at 2, 1 and 0.5 MPa; temperatures at −5, −3 and −1 °C; and porosities at 40% and 80%. The dynamic stress-strain behavior and curves of dynamic strain versus number of cycles were obtained and analyzed. The dynamic strength curves showed that the failure number of cycles was significantly affected by the dynamic stress amplitude. The dynamic strength of methane hydrate-bearing sediments increased with increasing confining pressure and decreased with increasing temperature and porosity. Based on the Mohr–Coulomb strength criterion, Mohr's circles and strength envelopes were drawn, and the mechanism of the influence of temperature and porosity on the dynamic strength of the sediments was revealed. The results indicated that increasing temperature would reduce the dynamic strength by reducing the soil cohesion and internal friction angle, while increasing porosity would reduce the dynamic strength mainly by reducing the soil internal friction angle.

1. Introduction

Methane hydrate has attracted global attention due to its widespread occurrence and potential as an energy resource (Dawe and Thomas, 2007; Lee and Holder, 2001). Sediments containing natural gas hydrates occur worldwide in permafrost regions below the Earth's continental surface, in marine continental and insular slopes and rises of active and passive margins and in the deep-water environments of inland lakes and seas (Kvenvolden et al., 1993). Gas hydrates may be dissociated during drilling operations, which results in a decrease in geomechanical strength and deformation of gas hydrate reservoirs (Rutqvist et al., 2009). Moreover, the loss of the structural stability of gas hydrate reservoirs may induce significant methane gas leakage and potentially have an impact on global climate change (Archer, 2007; Glasby, 2003). Therefore, it is necessary to assess the stability of gas hydrate reservoirs and enable their safe exploitation by studying the strength and deformation characteristics of gas hydrate-bearing sediments.

Recently, the mechanical properties of hydrate-bearing sediments have been studied systematically. Yun et al. (2007) reported on the results of comprehensive axial compression triaxial tests conducted at up to 1 MPa confining pressure on sand, crushed silt, precipitated silt, and clay specimens with closely controlled concentrations of synthetic hydrate. Winters et al. (2007) studied the effect of gas hydrate on sediment acoustic and strength properties through the sound wave detecting method. In detail, they studied: (1) the effects of gas hydrate and ice on acoustic velocity in different sediment types, (2) effect of different hydrate formation mechanisms on measured acoustic properties, (3) dependence of shear strength on pore space contents, and (4) pore pressure effects during undrained shear. Miyazaki et al. (2010a, 2010b, 2011a, 2011b) studied the effects of saturation, confining pressure, particle diameter, strain rate and unloading-reloading on the strength and deformation characteristics of methane hydrate-bearing sediments. Grozic (2010) studied the shear strength and volume change characteristics of gas hydrate bearing sand, and the results indicated that the strength of hydrate bearing sand is strongly related to how the hydrate has formed within the sediment. Rees et al. (2011a,b) developed an X-ray transparent triaxial test cell. Based on the cell, they noted that: (1) the presence of clay would lead to the reduction of the strength of hydrate-bearing sand, and (2)

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unlike the non-hydrate bearing sediments, peak strength was reached at much lower strains than the partially saturated and frozen sediments. Hyodo et al. (2005, 2013, 2014a, 2014b) also conducted a series of triaxial compressive tests and studied the effects of temperature, effective confining pressure, porosity, strain rate and hydrate dissociation on the mechanical properties of methane hydrate-bearing sediments. Moreover, they analyzed the mechanical behavior of gas-saturated methane hydrate-bearing sediments and compared the mechanical properties of carbon dioxide hydrate-bearing sediments with the properties of methane hydrate-bearing sediments. Li et al. (2011, 2012, 2013) reported the mechanical properties of gas hydrate-bearing sediments using kaolin clay and proposed a piecewise linear strength criterion and a nonlinear strength criterion under high confining pressures.

In general, major research on the mechanical properties of methane hydrate-bearing sediments was focused on statics analysis. To understanding the dynamic characteristics of hydrates and hydrate-bearing sediments, Clayton et al. (2005) developed a specially constructed Gas Hydrate Resonant Column and investigated the effects of depositing varying quantities of methane hydrate within the sand on their shear and bulk modulus, and damping. Priest et al. (2006) studied the effect of distribution and volume of gas hydrate within marine sediments on the compressional wave (*P* wave) and shear wave (*S* wave) velocities from remote seismic methods. Based on these above researches, Kingston et al. (2008) investigated the effects of the particle shapes and sizes on the dynamic geophysical properties of gas hydrate-bearing sediments such as compressional wave velocity, shear wave velocity and their respective attenuation characteristics. Also the corresponding work has been done by Santamarina's group (Lee et al., 2010; Yun et al., 2005). Lee et al. (2010) measured the compressional and shear velocities of sand, silts, and clay with and without hydrate, complementing the earlier results on velocities for sands alone detailed by Yun et al. (2005). Moreover, Zhang et al. (2011) conducted a series of dynamic tests on tetrahydrofuran (THF) hydrate. They compared the liquefaction characteristics of the sediment after hydrate dissociation and the corresponding saturated sand. The dynamic characteristics of gas hydrate-bearing sediments have been researched recently, but these are not sufficient. In reality, sediments containing methane hydrate in the permafrost region and deep sea would be subject to the effects of dynamic loading, such as seismic loading and wave loading. For this reason, it is essential to study the dynamic strength characteristics of methane hydrate-bearing sediments by the dynamic triaxial tests.

The seismic load is random wave, and the change of mechanical properties of the soil caused by random vibration should be considered in the shallow surface. The random vibration can be described by its amplitude, frequency and phase. All these characteristic quantities of an earthquake are random and the theory of random process should be applied to solve this problem. Through the numerical analysis, this process can be modeled by computer which is used to generate random numbers. However, this process is very complex for the experimental research and huge numbers of experiments will be conducted. In order to simplify this problem, by analyzing plenty of earthquake data, De Alba et al. (1975) indicated that the random seismic load can be described by an equivalent cyclic load of which amplitude is 65% of the peak value of seismic load and equivalent cyclic number is determined based on the earthquake magnitude. For the following years, this method has been widely used in the dynamic triaxial tests. So, this paper tries to utilize the equivalent load method to study the dynamic strength of methane hydrate-bearing sediments.

According to the literature, to study the dynamic strength of methane hydrate-bearing sediments subjected to seismic loads, the seismic waveform, which was a random variable, can be simplified into an equivalent harmonic (Seed and Idriss, 1971). The equivalent cyclic number N_e was determined based on the earthquake intensity, and the frequency of the harmonic was 1–2 Hz (Seed and Idriss, 1971). In this paper, based on a dynamic triaxial test system, a series of triaxial cycle tests of constant stress amplitude was conducted under conditions simulating seismic loading. According to the experimental results, the dynamic strength characteristics of methane hydrate-bearing sediments have been analyzed.

2. Experimental program

2.1. Experimental apparatus

The DDW-600 triaxial testing device (Changchun Rising Sun Testing Instrument Co. Ltd., Changchun, China), which has been introduced in our previous work (Song et al., 2014), was used in this study. A schematic diagram of the experimental apparatus is shown in Fig. 1. Compared with the previous apparatus, the testing device used in this work is equipped with the same confining pressure servo-system, temperature control system, and computer control system. Instead, the axial loading system is upgraded to conduct dynamic triaxial tests. Although the axial loading frame and the axial loading cylinder remained the same as before, the servo oil-source and the servo valve are replaced completely. This new servo oil-source consists of a three-phase AC motor, a precise hydraulic pump, an overflow valve, two pressure gauges, a water-cooler, a filter, an oil tank and several connectors. It can provide a maximum working pressure of 25 MPa and a maximum flow of 30 L/min. The new servo valve connects the axial loading cylinder and the new servo oil-source to control the speed and stability of the axial loading. Based on the improvements introduced above, sediments within the pressure chamber can be not only loaded statically, but also loaded dynamically in axial direction under standard waves such as sine waves, triangle waves, square waves and half sine waves. Thus, the device can provide the static and dynamic mechanical parameters of methane hydrate-bearing sediments. The technical specifications of the upgraded device are listed in Table 1.

2.2. Experimental procedures

The methane hydrate-bearing sediment preparation method used in our previous work was also employed in this study (Song et al., 2014). It has been known that natural gas hydrates are widespread in the permafrost region and polar underwater permafrost, and usually hosted in the pores of clay sediments coexisting with ice (Guggenheim and van Groos, 2003; Tsypkin, 1993; Worthington, 2010). And it is difficult to generate methane hydrate in well-consolidated rocks such as siltstone, mudstone or oil shale in laboratory, so kaolin clay was chosen as the host material in this work. In addition, because of the low permeability, it is still difficult to generate methane hydrate in the clay sediments. Thus, finally a mixture method was selected to manufacture the methane hydrate-bearing sediment containing ice. Compared to the natural clay rich samples referred by Rees et al. (2011a,b), the methane hydrate-bearing sediments manufactured in our laboratory is not the type of hydrate veins structure. As mentioned above, our work is to simulate the clay sediments that gas hydrates hosted in the pores coexisting with ice. Synthesized methane hydrate was formed by using 250 μm ice powder and methane gas in a pressure reactor at a constant temperature of −10 °C and a pressure of 8 MPa for 72 h. According to the difference between the mass of the methane hydrate-ice mixture before and after hydrate dissociation, the calculated results of methane hydrate saturation were