DEM simulation of triaxial compression tests on MHBS under different back pressures

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ABSTRACT

This paper investigates the mechanical behavior of Methane Hydrate-Bearing Sediments (MHBS) at different back pressures via the distinct element method (DEM). A series of triaxial compression test were carried out in order to analyze the micro- and macro-mechanical behavior under different back pressures, e.g. stress–strain relationship, void ratio and mechanical coordination number. Numerical results show that: the stress-strain relationships of MHBS exhibit more obvious strain softening characteristics at a lower confining pressure and higher back pressure. The final void ratio increases as back pressure increases. The increasing rate of the total mechanical coordination number with back pressure was significantly lower than that of hydrate cementation mechanical coordination number.

Keywords: methane hydrate-bearing sediment, DEM, triaxial compression test, stress-strain relationship

1 INTRODUCTION

Methane Hydrate (MH, also named natural gas hydrate) is widely distributed in most of the world's marine deep water areas and permafrost sedimentary environments. The sediment containing MH is usually referred to as the Methane Hydrate-Bearing Sediments (MHBS) (Jiang et al., 2010). The depressurization method is one of common techniques for hydrate exploitation. This method may lead to the decrease of hydrate strength and hydrate decomposition, which further results in the weakness of mechanical properties of MHBS. Consequently, a series of engineering geological disasters may occur, such as submarine landslide (Uchida et al., 2012; Sultan et al., 2004). Therefore, it is of great significance to study the mechanical properties of MHBS under different back pressures for the safe exploitation of gas hydrate.

Yun et al. (2007) synthesized tetrahydrofuran hydrate in four materials (sand, crushed silt, precipitated silt, and kaolinite), on which a series of triaxial compression tests was performed. The results showed that when the hydrate saturation is greater than 50%, the strength of the sample mainly depends on the mechanical properties of hydrates. Yu et al. (2011) studied stress strain behaviour of methane hydrate by conducting triaxial shear tests. The results showed that the peak deviator stress of methane hydrate increased with confining pressure. Song et al. (2014) studied the mechanical properties of methane hydrate-bearing sediments in the triaxial compression test. The results showed that the shear strength of the sample increases with the increase of the confining pressure. Zhang et al. (2010) synthesized four samples, i.e., ice hydrate, tetrahydrofuran hydrate, CO2 hydrate and methane hydrate in the skeleton of fine silty sand. Then a series of triaxial compression tests was carried out on the above four deposits. The results showed that: the four deposits all show plastic failure. The higher the confining pressure, the higher the strength of the sediment. Jiang et al. (2016) investigated the microscopic mechanisms that affect the macro-mechanical characteristics of methane hydrate-bearing soils by conducting the DEM biaxial compression tests. A series of DEM biaxial compression tests were conducted to investigate the link between mechanical properties of MHBS and backpressure (Jiang et al., 2015). Previous experiments provide a good understanding of the macro mechanical behaviour of MHBS. However, the microscopic mechanism of MHBS are poorly understood. It is well known that DEM is an effective method and has been widely employed to study the macro- and micro- mechanical behaviors of MHBS. Therefore, it is very important to study the mechanical properties and the microscopic mechanism of MHBS under triaxial stress conditions by using the distinct element method.

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This paper tries to numerically investigate the mechanical behaviour of MHBS under triaxial test conditions, in addition with the associated microscopic information. For this aim, a series of triaxial compression tests was simulated by DEM under different back pressures, where the macro and micro characteristics of MHBS were studied, including the stress-strain relationship, void ratio, mechanical coordination number.

2 DEM SIMULATION OF TRIAXIAL COMPRESSION TEST

A reasonable contact model is the key to accurately simulate the mechanical properties of cemented MHBS with three dimensional (3D) distinct element method. A 3D thermal-hydro-mechanical-chemical bond contact model is used in this research, which was implemented in a distinct element method software PFC5.0 to simulate the triaxial compression test on MHBS.

2.1 Sample preparation

The grain size distribution in the simulation is consistent with that of the Toyoura sand by Hyodo et al. (2013), as shown in Fig. 1(a). It shows that the grain size ranges from 0.1 mm to 0.3 mm. The multi-layer under-compaction method (UCM) (Jiang et al., 2003) was used to generate a homogeneous sample with the particle number of 40000. The initial void ratio is 1.0 and the sample size is 5.5 mm × 5.5 mm × 11 mm, as shown in Fig. 1(b). In addition, the material parameters of MHBS sample were carefully calibrated according to the laboratory tests of MHBS, and the calibration results are provided in Table 1 (Jiang et al., 2019).

![Graph of Grain size distribution and numerical assembly](image)

Fig. 1. (a) Grain size distribution of the numerical assemblies, (b) Numerical assembly for the analyses.

2.2 Simulation procedures

First, the sample was compressed isotropically to 200 kPa to make the sample stable. Then hydrate cementation was formed by applying hydrate cementation parameters between particles, after which the sample was isotropically compressed to an effective confining pressure of 1 MPa, 3 MPa and 5 MPa respectively. Finally, the triaxial compression test was carried out by moving the upper and lower walls in the opposite direction at a certain strain rate until the specimen reached the critical state. Methane hydrate saturation was 40%. The environmental temperature was 278K. Back pressures were 5 MPa, 10 MPa, 15 MPa respectively.

| Parameter                          | Value          |
|------------------------------------|----------------|
| Particle modulus $E_p$ (N/m²)      | 7×10⁸          |
| Particle normal tangential stiffness ratio $\xi$ | 5.0          |
| Particle anti-rotation coefficient $\beta$ | 0.25          |
| Particle local crushing coefficient $\zeta$ | 4.0          |
| Coefficient of particle friction $\mu$ | 0.5           |
| Elastic modulus of hydrate $E_h$ (N/m²) | 1.73×10⁸ |
| Hydrate poisson ratio $\nu_{h}$ | 0.32          |
| Tensile strength of hydrate $\sigma_t$ (N/m²) | 1.42×10⁹×30 |
| Compressive strength of hydrate $\sigma_c$ (N/m²) | 1.73×10⁹×30 |
| Critical slenderness ratio of hydrate $m_{cs}$ | 0.05          |
| Hydrate radius multiplier $\lambda$ | 0.9           |

3 SIMULATION RESULTS

3.1 Stress–strain relationships

Fig. 2 provides the evolutions of deviator stress with axial strain of MHBS under different back pressures along with the stress-strain relationship of pure sand for comparison. It can be observed that the cemented MHBS exhibits obvious strain softening characteristics. And the strain softening is more obvious at a lower confining pressure and higher back pressure. When the axial strain reaches a certain value, the sample reaches the residual shear strength. And then the residual shear strength keeps nearly constant with the increase of axial strain. The peak shear strength and residual shear strength increase with the increase of the back pressure. This indicates that more methane hydrates are generated in the MHBS samples under high back pressures, which improves the shear strength of MHBS.

The hydrate cementation is destroyed rapidly under low back pressure ($P = 5$ MPa). Therefore, the stress-strain relationship of MHBS is similar to that of pure sand.

In order to investigate the effects of back pressure on the strength of MHBS, Fig. 3 presents the variation of peak and residual strength of MHBS with different back pressures in triaxial compression tests. It can be observed that the peak and residual strength of MHBS increase with the increase of back pressure under different confining pressures. The peak (residual) strength of MHBS increases by 0.8 (0.1) MPa with an increase of 1MPa in back pressure.

3.2 Void ratio

Fig. 4 provides evolutions of void ratio of MHBS under different back pressures along with the void ratio of pure sand for comparison. Under high confining pressures (3MPa, 5MPa), the void ratio evolves in a similar trend to that of pure sand. The void ratio firstly decreases and then increases slightly to a stable value as
The final void ratio of MHBS increases with the increase of the back pressure. Methane hydrate cementation is not easy to be destroyed under low back pressure, which reduces the compressibility of MHBS.

Fig. 2. Deviator stress-axial strain for MHBS sample under different confining pressures: (a) $\sigma_3 = 1$ MPa (b) $\sigma_3 = 3$ MPa (c) $\sigma_3 = 5$ MPa.

Fig. 3. The peak and residual strength of MHBS versus the back pressure under different confining pressures: (a) The peak strength (b) The residual strength.

Fig. 4. Void ratio versus axial strain for MHBS sample under different confining pressures: (a) $\sigma_3 = 1$ MPa (b) $\sigma_3 = 3$ MPa (c) $\sigma_3 = 5$ MPa.

axial strain increases. The final void ratio is smaller than the initial void ratio. In the case of low confining pressure (1 MPa), the void ratio first decreases and then increases obviously to a stable value as axial strain increases when the back pressure is high (10 MPa, 15 MPa). In contrast to the case of high confining pressure, the final void ratio is larger than the initial void ratio. The higher the back pressure is, the higher the final void ratio is.

In order to study the effects of back pressure on the compression deformation of MHBS, Fig. 5 presents the variation of the final void ratio with different back pressures. Under the specific confining pressure, the final void ratio of MHBS increases with the increase of the back pressure. Methane hydrate cementation is not easy to be destroyed under low back pressure, which reduces the compressibility of MHBS.

Fig. 5. The final void ratio versus the back pressure under different confining pressures.
3.3 Mechanical coordination number

Fig. 6 provides the evolutions of mechanical coordination number (i.e., total and hydrate cementation mechanical coordination number) with different back pressures under different confining pressure. It shows that the total mechanical coordination number increases slightly with the increase of back pressure, while the hydrate cementation mechanical coordination number increases obviously with the increase of back pressure. When the back pressure is low, there is little residual methane hydrate cementation between particles in the MHBS sample due to the decomposition of methane hydrate, and the hydrate cementation mechanical coordination number is equal to 0.

![Graph](image)

Fig. 6. The total and hydrate cementation mechanical coordination number versus the back pressure under different confining pressures: (a) The total mechanical coordination number (b) The hydrate cementation mechanical coordination number.

4 CONCLUSIONS

This paper reported the results of triaxial test simulations on MHBS under different back pressures using the distinct element method. The following conclusions can be drawn.

1. The stress-strain relationships of MHBS exhibit more obvious strain softening characteristics at a lower confining pressure and higher back pressure. The peak and residual strength of MHBS increase almost linearly with the increase of back pressure.

2. The final void ratio increases with back pressure. The final void ratio is larger than the initial void ratio under high back pressures.

3. The total mechanical coordination number of MHBS increases slightly with the increase of the back pressure, while hydrate cementation mechanical coordination number increases obviously with the increase of back pressure.

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