Effect of hydrate saturation on the shear bands of methane hydrate-bearing sediments based on the DEM simulation

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Abstract. As the most important strategic resource, Methane hydrate (MH) that is an ice-like clathrate crystalline compound has been paid more and more attention by more and more scientists and researchers. In order to investigate mechanical behaviors and the mechanism of the progressive failure of methane hydrate-bearing sediments, in this paper, a new sample preparation technique is developed to better simulate the microstructure of hydrate-bearing sediments. Then a series of biaxial compression tests are conducted to investigate the mechanical behaviors and strain localization of hydrate-bearing sediments. The results show that as methane hydrate saturation increases, the strength and stiffness of the methane hydrate-bearing sediments increase and the trend of volumetric dilation is becoming more and more obvious. Methane hydrate saturation has a great influence on the properties of shear bands.

1. Introduction

As the most important strategic resource, Methane hydrate (MH) that is an ice-like clathrate crystalline compound has been paid more and more attention by many countries like the United States, China, the United Kingdom due to its huge carbon content [1-2]. And the methane hydrate-bearing sediments (MHBS) are composed of methane hydrate, sediment skeleton, water, gas, which only exists in deep seabed and permafrost regions. At present, the most acceptable exploitation methods like heat injection and depressurization method are mainly to break the temperature and pressure environment in which the methane hydrate is stable so that the temperature and pressure conditions is close to the phase equilibrium curve of the methane hydrate to cause the dissociation of methane hydrate. However, these methods could lead to a series of geotechnical issues, such as submarine landslide and wellbore collapse [3]. Hence, it is significant to investigate the mechanism of the progressive failure of methane hydrate-bearing sediments.

Some previous works were carried out to study the strain location of methane hydrate-bearing sediments. Yoneda et al [4] studied the micro-structural large-strain behaviors and the characteristic of shear bands of methane-hydrate-bearing sediments using the microfocus X-ray computed tomography. Jiang et al [5-8] studied the mechanical behavior and strain location of methane hydrate-bearing sediments with different conditions by regard hydrate as the cementing contact between sand particles using the discrete element method. However, this method does not take into account the effect of hydrate particles entering the soil skeleton pores after the failure of hydrate bonding on the mechanical properties of sediments.

In this study, a new sample preparation method is developed firstly to better simulate the microstructure of hydrate-bearing sediments. Then a series of biaxial compression tests with three different hydrate saturation is carried out to the macroscopic mechanical response including stress-...
strain and volumetric strain and the evolution of displacement field and distribution of hydrate bonding.

2. Numerical simulation based on DEM

For hydrate-bearing sediments, Bragada et al [9] has proved that different techniques of sample preparation would have an effect on the macroscopic response of MHBS with different conditions. Hence in this study, a new technique that can effectively describe the different hydrate distribution patterns which includes pore-filling and cementation in the hydrate-bearing sediments.

The samples are rectangle in shape with a width of 7mm and a height of 14mm. Firstly, the host sand sample is preparation by the ‘radii expansion method’ which is incorporated in PFC2D. The ‘soil’ particles are modeled by the disk particles with a diameter range from 0.1 to 0.4mm. And two-dimensional model is employed in this study while three-dimensional specimens are used in the laboratory triaxial compression tests. At present, there is no quantitative relationship of porosity between two-dimensional conditions and three-dimensional conditions. Hence the initial planar void ratio is chosen to be 0.21 and the material densities used in the study correspond to that of Toyoura sand whose densities are 2650 kg/m$^3$.

Secondly, the method of generating and positioning hydrate particles one by one is accepted. The hydrate particles are modeled by disk particles with a diameter of 0.06mm. Saturation degree is defined as methane hydrate $S_{MH}$ is defined as the ratio of the hydrate area $A_{MH}$ to the total pore area $A_p$ in the two-dimensional condition:

$$S_{MH} = \frac{A_{MH}}{A_p} \times 100\%$$

Hence the number of hydrate particles required for generating the specified saturation is as follows:

$$T = \frac{A_{MH}}{1 - \frac{\pi d_{MH}^2}{4}}$$

where $T$ is the number of methane hydrate particles; $d_{MH}$ is the diameter of methane hydrate particles. Substituting Eq. (1) into Eq. (2), we have:

$$T = \frac{A_p S_{MH}}{1 - \frac{\pi d_{MH}^2}{4}}$$

When one hydrate particle, whose particle number is $i$, is generated, it can be positioned in the sand sample randomly. Then the relationship between the distance $l$ between the hydrate particle center and the soil particle center and the sum of the two-particle radii:

$$l = R_s + R_{mh}$$

where $R_s$ is the diameter of soil particles; $R_{mh}$ is the diameter of hydrate particles. When the distance between the two particles does not satisfy equation (4), the hydrated particle is deleted and continues to generate one hydrate particle in which the particle number is still counted as $i$. If the distance between two particles satisfies equation (4), it is necessary to judge whether the number $i$ of generated particles is less than the number $T$ of hydrate particles required:

$$i < T$$

When the number of hydrate particles $i$ does not satisfy equation (5), the cycle stops. The prepared samples are subjected to isotropic consolidation by applying a confining pressure of 0.5MPa. The numerical sample for methane hydrate-bearing sediments by DEM is shown in Figure 1.

To simulate the bonding properties of hydrate, the contacts between soil particles are given a linear contact models, while the soil-hydrates contacts and hydrate-hydrates contacts are given a linear parallel bond contact model. The material properties used in the DEM simulation are shown in Table 1.
3. Numerical Results

As we all know, mechanical behavior and strain location have been affected strongly by methane hydrate saturation. To understand the mechanism of formation and evolution of shear band, a series of biaxial compression tests on the methane hydrate-bearing sediments with different hydrate saturation are carried out.

3.1. Macroscopic mechanical response

Figure 2 illustrates the stress-strain and volumetric response of methane hydrate-bearing sediments with three hydrate saturation ($S_h=20\%, 30\%, 40\%$) obtained from DEM simulation. It is shown in Figure 3 that the stress-strain curves of hydrate-bearing sediments can be divided into three stages: The first stage is characterized by elastic deformation. In this stage, with the increase of axial strain, the deviator stress increases linearly and the volume of MHBS decreases. The cement between hydrate and soil particles is not damaged and the contact deformation between particles is elastic. The characteristic of the second stage is yield deformation. As the applied load is further increased, the slip and rolling gradually appear between the particles and cementation between soil particles and hydrate particles begins to be damaged. Then the plastic deformation may occur. In the third stage, the strain-softening phenomenon after the peak is observed in the stress-strain curve of methane hydrate-bearing sediments. With the increase of hydrate saturation, the strain-softening phenomenon of the stress-strain curve becomes stronger and stronger.

Table 1. Contact parameters used in DEM simulation

| property                     | soil-soil | hydrate-hydrate | soil-hydrate |
|------------------------------|-----------|-----------------|--------------|
| Normal contact stiffness $k_n$ (N/m) | $1 \times 10^8$ | $7 \times 10^7$ | $7 \times 10^7$ |
| Shear contact stiffness $k_s$ (N/m) | $1 \times 10^8$ | $1 \times 10^7$ | $1 \times 10^7$ |
| Normal parallel bond stiffness (N/m) | 0 | $7 \times 10^7$ | $7 \times 10^7$ |
| Shear parallel bond stiffness (N/m) | 0 | $1 \times 10^7$ | $1 \times 10^7$ |
| Tensile strength $\sigma_t$ (MPa) | 0 | $8.3 \times 10^7$ | $8.3 \times 10^7$ |
| Cohesion $\tau$ (MPa) | 0 | $8.3 \times 10^7$ | $8.3 \times 10^7$ |
| Inter-particle friction $\mu$ | 0.75 | 0.5 | 0.5 |
Figure 2. stress-strain and volumetric response of methane hydrate-bearing sediments with three different saturation obtained from DEM simulation

3.2. Displacement field

Figure 2 can be observed that six points (O-E) are selected to investigate the development process of strain location of methane hydrate-bearing sediments numerical sample with different hydrate saturation under effective confining pressure 1MPa. Point O, which the axial strain equal to 0, is the initial state. Point A is defined as ‘yield point’ that is the transition point from elastic deformation to plastic deformation. Point B refers to the peak point. Point C indicates the strain-softening state which corresponding to the 6% strain. And point D corresponds to a 10% stain. The point E signals the end of tests.

It is shown in Figure 3 that the development process of the displacement field of hydrate-bearing sediment samples with three hydrate saturations (20%, 30%, 40%) simulated by DEM. It can be observed that two shear bands for the MHBS samples with the methane hydrate saturations of 20% similar to ‘K’ are formed in the process of shearing. However, when the methane hydrate saturations are 40%, two shear bands that are opposite to the ‘K’ shape are observed during the shearing process. When the methane hydrate saturation is 30%, two conjugate shear bands which one develops from the top-left to the bottom-right and another develops from the upper-right to the bottom-left respectively similar to ‘X’ shape appear during the shearing process. It is obvious that during the shearing process, the shear band formed in the MHBS sample with a saturation of 30% is a transition state from low saturation to high saturation.

In addition, it is observed in Figure 3 that at Point A corresponding to yield point, the shear bands in the sample do not form while at point B, that is peak point, shear bands begin to appear in the sample. The possible reason is that the contact deformation between the particles at the yield point is in a transition state from elastic deformation to plastic deformation, and the cement damage between
the soil particles and hydrate particles is less and occurs locally, so there is no shear band formation in the sample. However, at the peak point, most of the slip between particles occurred in a narrow range and eventually formed a shear zone.

| $S_h=20\%$ | $S_h=30\%$ | $S_h=40\%$ |
|-------------|-------------|-------------|
| ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |

Figure 3. the development process of displacement field of hydrate-bearing sediments samples with three hydrate saturation (20%, 30%, 40%) simulated by DEM

3.3. Distribute of hydrate bonding
In cementation pattern methane hydrate-bearing sediments, the compacted soil skeleton is bonded by the hydrates, while the contacts between the soil particles are not bonded. Hence, hydrate cementation plays an important role in the strength and stiffness of the methane hydrate-bearing sediments. Figure 4 illustrates that the development process of the bond distribution of methane hydrate-bearing sediment samples with three hydrate saturation (20%, 30%, 40%) simulated by DEM. It is observed that before point B, corresponding to the peak point, the hydrate bonding almost did not break, while after the peak point, the hydrate bonding did not break in a large range inside the sample, but mainly concentrated in two bands zone. By comparing Figure 5 with Figure 4, it can be found that the shear bands observed by the displacement field is consistent with that observed by hydrate bonding distribution.

| $S_h=20\%$ | $S_h=30\%$ | $S_h=40\%$ |
|-------------|-------------|-------------|
| ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
4. Conclusion
The DEM simulations can effectively capture the macroscopic mechanical response including stress-strain and volumetric strain and the evolution of displacement field and distribution of hydrate bonding. As methane hydrate saturation increases, the strength and stiffness of the methane hydrate-bearing sediments increase and the trend of volumetric dilation is becoming more and more obvious. There are some differences in strain location due to different hydrate saturation. Two conjugate shear bands, one of which develops from the top-left to the bottom-right and another develops from the upper-right to the bottom-left respectively, are similar to ‘X’ shape appear in the MHBS sample of 30% saturation, while two shear bands for the MHBS samples with the methane hydrate saturation of 20% and 40% are similar to ‘K’ are formed in the process of shearing.

References
[1] Kvenvolden, K. A. (2001). *The Global Occurrence of Natural Gas Hydrate. Natural Gas Hydrates: Occurrence, Distribution, and Detection*. American Geophysical Union.
[2] Hyodo, M., Nakata, Y., Yoshimoto, N., & Yoneda, J. (2007). Mechanical behavior of methane hydrate-supported sand. In *Proc. of Int. Symp. on Geotechnical Engineering, Ground Improvement and Geosynthetics for Human security and Environmental Preservation* (pp. 195-208).
[3] Masayuki, H., Yukio, N., Norimasa, Y., & Toshiro, E. (2005). Basic research on the mechanical behavior of methane hydrate-sediments mixture. *Soils and foundations, 45*(1), 75-85.
[4] Yoneda, J., Jin, Y., Katagiri, J., & Tenma, N. (2016). Strengthening mechanism of cemented hydrate-bearing sand at microscales. *Geophysical Research Letters, 43*(14), 7442-7450.
[5] Jiang, M., Sun, Y., & Yang, Q. (2013). A simple distinct element modeling of the mechanical behavior of methane hydrate-bearing sediments in deep seabed. *Granular Matter, 15*(2), 209-220.
[6] Jiang, M., Chen, H., Tapia, M., Arroyo, M., & Fang, R. (2014). Study of mechanical behavior and strain localization of methane hydrate bearing sediments with different saturations by a new DEM model. *Computers and Geotechnics, 57*, 122-138.
[7] Jiang, M., Peng, D., & Ooi, J. Y. (2017). DEM investigation of mechanical behavior and strain localization of methane hydrate bearing sediments with different temperatures and water pressures. *Engineering Geology, 223*, 92-109.
[8] Jiang, M., Shen, Z, Zhou, Wei, Marcos, A., & Wangcheng, Z. (2018). Coupled CFD–DEM method for undrained biaxial shear test of methane hydrate bearing sediments. *Granular Matter, 20*(4), 63-.
[9] Brugada, J., Cheng, Y. P., Soga, K., & Santamarina, J. C. (2010). Discrete element modelling of geomechanical behaviour of methane hydrate soils with pore-filling hydrate distribution. *Granular Matter, 12*(5), 517-525.