DEM investigation of the creep behavior of methane hydrate-bearing sand

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Abstract. In this paper, the creep behavior of cemented methane hydrate-bearing sand is studied using discrete element model. Methane hydrate is modeled as contact bonds between particles, and the time-dependent bond strength method is adopted to simulate the creep procedure. The simulation results are in good agreement with laboratory test results, i.e., the creep of methane hydrate-bearing sands exhibits deceleration and acceleration phase, and strain rate is larger with higher deviator stress levels. Furthermore, the micro evolutions including bond breakage and shear band formation are revealed with the DEM model.

1. Introduction
Methane hydrates are ice-like material and mainly distributed in the sediments of marine area under high pressure and low temperature. In recent years, methane hydrates are viewed as an important potential energy resource, and many countries including the United States, China, Japan, et al., have carried out the trial production of natural gas from hydrate deposits.

The research on the mechanical properties of methane hydrate-bearing sands is closely related to the safety of natural gas production, because the dissociation and plastic flow of methane hydrate may lead to disasters, such as submarine landslide and earthquakes. To date, only limited laboratory test have been performed to study the mechanical properties of methane hydrate-bearing sands. Masui et al.[1] studied the triaxial shear behavior using the synthetic sample, and Hyodo et al.[2] studied the effect of hydrate dissociation to the hydrate-bearing sands in triaxial test. Miyazaki et al.[3-4] performed a series of laboratory tests to study the time-dependent properties of methane hydrate-bearing sands, and compared its creep behavior with hydrate-free sands. However, the laboratory test has limitations, such as the difficulty in sample preparation, and the strict test conditions required. In addition, the micro behavior of sands during the test can hardly be observed.

Therefore, the discrete element method is used in the study of methane hydrate-bearing sands. For example, Jiang et al.[5] used the discrete element model to study the drained shear behaviour of cemented hydrate-bearing sands, and Xu et al.[6-7] simulated the undrained shear behavior of sand containing dissociated gas hydrate. However, the existed simulation mainly focuses on the shear behavior of hydrate-bearing sands, and the creep behavior has not been simulated with DEM yet.

The aim of this paper is to present a DEM simulation to study the creep behaviour of methane hydrate-bearing sands. Using this DEM model, the macro and micro characteristics of the methane hydrate-bearing sands during creep are investigated.

2. Numerical Simulation
A discrete element code PFC2D was used to develop a model of cemented methane hydrate-bearing sand, as shown in figure 1(a). The model contains 19961 sample particles, and each particle is formed by two disks with unit thickness. The particle shape is shown in figure 1(b). The upper and lower boundaries of the model are rigid walls, and the left and right boundaries are flexible boundaries formed by a string of bonded disks. Methane hydrate is simplified as the contact bonds between sample particles. Bonding ratio \( R_b \), defined as \( R_b = N_b / N_t \), is proposed to reflect the hydrate saturation, where \( N_t \) is the total number of contacts between particles, and \( N_b \) is the number of contact bonds [8]. In the model, the value of \( R_b \) is set to be equal to the hydrate saturation \( S_{MH} \) of methane hydrate-bearing sand.

![Figure 1](image)

**Figure 1.** (a) DEM model of cemented hydrate-bearing sands; (b) shape of each sample particle

In the sample generation, four rigid walls were first generated, and then particles are generated within the box. After particles generation, the left and right walls were deleted and replaced by flexible boundaries. A given confining pressure was applied to the sample, and a certain number of contact bonds were added between particles to simulate the existence of methane hydrate. Thus, the DEM model of cemented methane hydrate-bearing sands was formed. Parameters of the model were calibrated based on the results of triaxial test performed by Miyazaki et al.[3]. The parameter values are listed in Table 1.

| Classification    | Parameter                                      | Value            |
|-------------------|------------------------------------------------|-----------------|
| Sample            | Sample size (mm)                                | 160×80          |
|                   | Equivalent particle diameter (mm)               | 0.6–1.0         |
|                   | Frictional coefficient inter-particles in sample generation | 0.2             |
|                   | Frictional coefficient inter-particles in shearing | 0.95            |
|                   | Normal stiffness of particles (N/m)             | 1.2×10^9        |
|                   | Shear stiffness of particles (N/m)              | 0.8×10^9        |
|                   | Normal bond strength (N)                        | 6×10^4          |
|                   | Shear bond strength (N)                         | 6×10^4          |
| Flexible boundary | Boundary particle diameter(mm)                 | 0.2             |
|                   | Normal stiffness of boundary particles (N/m)    | 7.5×10^7        |
|                   | Shear stiffness of boundary particles (N/m)     | 5×10^7          |
|                   | Normal bond strength between boundary particles (N) | 1×10^{300}   |
|                   | Shear bond strength between boundary particles (N) | 1×10^{300}   |

After the bond added, the sample was sheared by controlling the displacement of the upper and
lower walls. The deviator stress $q$ was increased until the deviator stress level $q/q_{max}$ reached a specific value. Then $\sigma_3'$ and $q$ was kept constant as the start of creep test. The time-dependent bond strength method, in which the bond strength decreases with time [9-11], is adopted to control the creep procedure. The relationship between bond strength $B$ and time $t$ is described in equation (1) and (2):

$$B = B_0 \exp \left( \frac{t}{\lambda} \right)$$  \hspace{1cm} (1)
$$\lambda = C \left( \frac{N_{eq}}{B_{eq}} \right)^{-1}$$  \hspace{1cm} (2)

where $C$, $k$ are model parameters, $B_0$ is the initial bond strength, $B$ is the bond strength at time $t$, $N_{eq}$ is the equivalent axial force and $B_{eq}$ is the equivalent normal bond strength. The calculation method of $N_{eq}$ and $B_{eq}$ is introduced in Kwok et al.[10]. The parameters are determined based on the creep test performed by Miyazaki et al.[4] as $C=5 \times 10^7$s$^{-1}$ and $k=0.15$. The degradation curve of bond strength $B$ with time $t$ is shown in figure 2.

![Image](image.png)

**Figure 2.** Bond strength against time with $k=0.15$ and $C=5 \times 10^7$

3. Simulation Results

3.1. Macro-behavior

Drained biaxial tests were simulated using the DEM model with a confining pressure of 1 MPa, and figure 3 shows the relationship between deviator stress and axial strain of samples with $R_b=0\%$ and $40\%$ under shearing. The results indicate that methane hydrate-bearing sand has larger shear strength and elastic modulus, and more significant strain-softening behavior than hydrate-free sand, which are in agreements with the laboratory test results reported by Miyazaki et al.[3].
After the hydrate-bearing sample had been compressed to the given deviator stresses, the creep tests were simulated with different deviator stress levels ($q/q_{\text{max}} = 0.6$, $q/q_{\text{max}} = 0.8$). In the creep test, the bonding ratio $R_b$ of the sample is 40%, and the confining pressure is 1MPa. The bond strength degradation follows the curve in figure 2. The relationship between axial creep strain $\varepsilon_a$ and time $t$ is shown in figure 4(a). At a higher deviator stress level $q/q_{\text{max}}$, larger creep strain $\varepsilon_a$ is observed at a certain time $t$, and shorter time is needed to reach the acceleration phase.

Figure 4(b) shows the creep-strain rate $\frac{d\varepsilon_a}{dt}$ against $t$. According to the curves, the creep of methane hydrate-bearing sand mainly exhibits two stages as primary creep, in which the creep-strain rate $\frac{d\varepsilon_a}{dt}$ decreases, and tertiary creep, in which $\frac{d\varepsilon_a}{dt}$ increases. However, the secondary creep, in which $\frac{d\varepsilon_a}{dt}$ remains constant, is hardly observed. The results can be explained as follows: during the primary creep, the material hardening due to compression plays a leading role, so the crack formation rate and the creep-strain rate decreases with time. As the creep strain increases, a large number of small cracks accumulate and run through to form larger cracks, resulting in creep failure of the specimen, so the creep-strain rate increases sharply.

As shown in figure 4(b), $m$ is the slope of the log($\frac{d\varepsilon_a}{dt}$)-log($t$) in primary creep. According to the curves in figure 4(b), $m = -0.48$ at $q/q_{\text{max}} = 0.8$, and $m = -0.50$ at $q/q_{\text{max}} = 0.6$, which are within the range of $-0.7$ to $-0.4$ observed by Miyazaki et al.[4].
3.2. Bond-breakage
In DEM simulation, the bonds break when the normal force exceeds the normal bond strength, or the shear force exceeds the shear bond strength. The bond failure corresponds to the debonding or breakage of methane hydrate between soil particles. Figure 5 shows the relationship between bond breakage number $N_{br}$ and axial creep strain $\varepsilon_a$, suggesting that $N_{br}$ increases approximately linearly as $\varepsilon_a$ increases. The vertical intercept of the curve is not zero, because 25 bonds have been broken at the end of initial loading.

![Figure 5](image)

Figure 5. The number of bond breakage against axial creep strain with deviator stress level $q/q_{\text{max}}=0.8$

The formation process of shear band during creep is shown in figure 6 by recording the distribution of bond breakage. The black line in the figure indicates that the bond here has broken. It appears that X-shaped shear band is formed during creep, and bond breakage mainly occurs inside the shear band.

![Figure 6](image)

Figure 6. The evolution of shear band during the creep test with deviator stress level $q/q_{\text{max}}=0.8$

4. Conclusions
In this paper, discrete element method is adopted to build the model of methane hydrate-bearing sands, and the creep procedure is simulated using the time-dependent bond strength method.

The macro results of DEM simulation are consistent with existing experimental results, suggesting that the creep of methane hydrate-bearing sands mainly exhibits two stages: primary creep and tertiary...
creep, and that higher deviator stress level leads to larger creep-strain rate.

As to the micro aspect, the bond breakage in DEM reflects the breakage or debonding of methane hydrate between soil particles. According to the DEM results, the bond breakage number increases approximately linearly with axial creep strain. The bond breakage is not uniformly distributed, and most of the bond breakage occurs inside the creep shear band.

The simulation results can be used for the further study of macro and micro relationship of methane hydrate-bearing sands during creep.

Acknowledgements

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References

[1] Masui A, Haneda H and Ogata Y 2005 Effects of methane hydrate formation on shear strength of synthetic methane hydrate sediments Proceedings of the 15th International Offshore and Polar Engineering Conference pp 364-369
[2] Hyodo M, Yoneda J, Yoshimoto N and Nakata Y 2013 Mechanical and dissociation properties of methane hydrate-bearing sand in deep seabed Soils and Foundations 53 No.2 pp 299-314
[3] Miyazaki K, Masui A, Aoki K, Sakamoto Y, Yamaguchi T and Okubo S 2010 Strain-rate dependence of triaxial compressive strength of artificial methane-hydrate-bearing sediment International Journal of Offshore and Polar Engineering 20 No.4 pp 256-264
[4] Miyazaki K, Yamaguchi T, Sakamoto Y and Aoki K 2011 Time-dependent behaviors of methane hydrate bearing sediments in triaxial compression test International Journal of the JCRM 7 No.1 pp 43-48
[5] Jiang M, Zhu F, Liu F and Utili S 2014 A bond contact model for methane hydrate-bearing sediments with interparticle cementation Int. J. Numer. Anal. Meth. Geomech 38 pp 1823–1854
[6] Xu M, Song E, Jiang H and Hong J 2016 DEM simulation of the undrained shear behavior of sand containing dissociated gas hydrate Granular Matter 18 No.4 p 79
[7] Hong J and Xu M 2020 DEM study on the undrained mechanical behavior of gassy sand Acta Geotechnica 15 No.6
[8] Wang X and Xu M 2021 Discrete element simulations of the shear behavior of cemented methane hydrate-bearing sands Engineering Mechanics 38 No.2 pp 44-51 (in Chinese)
[9] Xu M, Hong J and Song E 2018 DEM study on the macro- and micro-responses of granular materials subjected to creep and stress relaxation Computers & Geotechnics 102 pp 111-124
[10] Kwok C. Y. and Bolton M. D. 2013 DEM simulation of soil creep due to particle crushing Geotechnique 63 No.16 pp 1365-1376
[11] Zhou M and Song E 2016 A random virtual crack dem model for creep behavior of rockfill based on the subcritical crack propagation theory Acta Geotechnica 11 No.4 pp 827-847