PFC/FLAC 3-D COUPLED FLEXIBILITY FOR NATURAL GAS HYDRATE NUMERICAL SIMULATION TRIAXIAL EXPERIMENTAL STUDY

by

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In this study, based on the PFC-FLAC discrete-continuous coupled analysis method, we constructed a model of gas hydrate-bearing sediments (GHBS) and conducted triaxial compression numerical simulation experiments. The results show that high confining pressure (>5 MPa) destroys the cementation of hydrate, and the stiffness of GHBS specimens increases with increasing confining pressure. The strength and stiffness of highly saturated (>40%) GHBS specimens increase with the increase of saturation, but the destructive brittleness increases as well. In terms of microscopic contact force, the enclosing pressure effect inhibits the particle motion and the GHBS specimens show anisotropy after loading damage. The results of this study contribute to a better understanding and prediction of the macroscopic and microscopic mechanical properties of gas hydrate sediments, which is of great significance for the safe and efficient exploitation of gas hydrates.

Key words: *natural gas hydrate, triaxial compression test, numerical model*

Introduction

The GHBS are generally composed of deep-sea clays and gravels. When the environmental conditions, such as temperature and pressure, change, hydrates will dissociate into water and gas, resulting in changes in the pore pressure and effective stress of the sediments, and at the same time, the dissociation of the solid-phase components of the GHBS will change its strength and stiffness, which significantly affects the deformation characteristics of the sedimentary layer, and the process may induce engineering disasters, such as uneven subsidence of the seabed and instability of the extraction wells [1, 2]. Therefore, an in-depth study of the mechanical and deformation properties of GHBS is essential to ensure the safety of hydrate energy and improve the mining efficiency.

On the indoor laboratory scale, Miyazaki *et al.* [3] explored the effects of confining pressure, hydrate saturation, and temperature on the physical properties of GHBS. Hyodo *et al.* [4], and Kajiyama *et al.* [5] revealed the basic mechanical and dissociation properties of hydrate-containing sands through triaxial shear experiments. Previous studies have shown that

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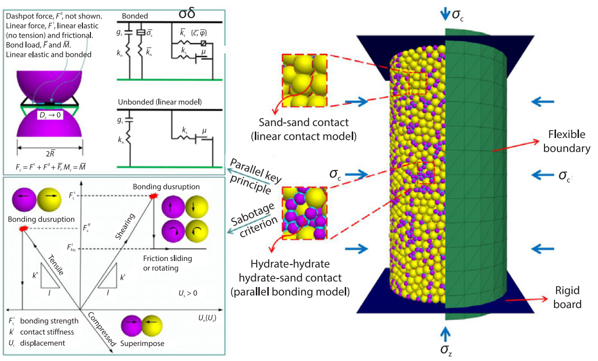
GHBS needs to maintain its original physical properties in a high pressure, low temperature environment, which is difficult to achieve in a laboratory environment, and the discrete-element method (DEM) to simulate hydrates is a new and efficient method [6]. In this paper, DEM simulation of GHBS was adopted and triaxial tests were carried out to describe the deformation process of the porous medium from the particle scale on the macroscopic scale, and then to elucidate the fine mechanical mechanism behind the macroscopic mechanical behavior on the fine scale. In terms of discrete elemental modelling of hydrates, Jiang *et al.* [7], You *et al.* [8] and others used DEM to simulate different types of hydrate-bearing sediments (HB), and investigated the macroscopic biaxial compression experiments on the 2-D model. Dou *et al.* [9], Brugada *et al.* [10], and Wang *et al.* [11] simulated different types of hydrate 3-D models using the cemented contact model, and investigated the damage mechanism of hydrate dissociation process, the transport law of fluid solids, and the mechanical properties of GHBS. However, there are almost no reported cases about the flexible boundary modelling of GHBS, therefore, in order to more accurately describe the deformation mechanism behind the macroscopic deformation analysis of GHBS, this paper adopts the flexible boundary for numerical modelling calculation.

Model construction

The coupling wall refers to the shell unit in FLAC3-D through the data interface to transfer the data to PFC3-D, so as to complete the coupling, the generated coupling wall can ensure the free deformation of the specimen, which is a kind of flexible boundary. The advantage of the coupling wall is that the generated boundary has the function of deformation co-ordination, and in the process of simulation experiments, the specimen will not leak because of the gap, and can be used with the triaxial compression experiments indoors to achieve similar results with the rubber membrane, scholars have verified the feasibility of the method [12]. Previous studies have shown that hydrate particles have a certain bonding effect on sediment particles [13], and the parallel bonding model is usually used to characterize the mechanical behavior between bonded particles [14]. The numerical model for this study is schematically shown in fig. 1.

According to previous studies, hydrates are usually located between 0.20 km and 0.47 km below the seafloor, and the saturation of hydrates generally ranges from 10%-20 % in some formations, while it may be as high as 30 %-40 % in a few formations [15, 16]. Therefore, three sets of porous media core models with different hydrate saturations (20%, 40%, and 60%) were set up at the macro scale, and numerical simulations were carried out at 1 MPa, 5 MPa, and 10 MPa, respectively, under the surrounding pressure.



Material parameters	Notation	Value
Sand grain size	R_{min}, R_{max} [mm]	0.24, 0.3
Hydrate particle size	Rs [mm]	0.15
Particle density	ρ [kgm^{-3}]	2650
Porosity	n	0.35
Particle stiffness	μ	$4 \cdot 10^7$
Bonded stiffness ratio	kn/ks	1
Normal/tangential bond strength	$\bar{\sigma}_c$ [MPa]	$0.74 \cdot 10^6$
	$\bar{c}$ [MPa]	$0.34 \cdot 10^6$
Bonding radius	λ	10
Effective modulus	E^*	$3 \cdot 10^7$

Figure 1. Schematic diagram of the numerical model

In this paper, the conventional triaxial compression test of hydrate-bearing sandy sediments with different saturation levels completed by Lee *et al.* [17] was numerically simulated. Trial and error method is used for calibration [18]. The simulation results are in good agreement with the stress-strain curves of the indoor experiments carried out by [17]. The error rates are less than 10%, and the numerical model can be considered to have good credibility, as shown in fig. 2.

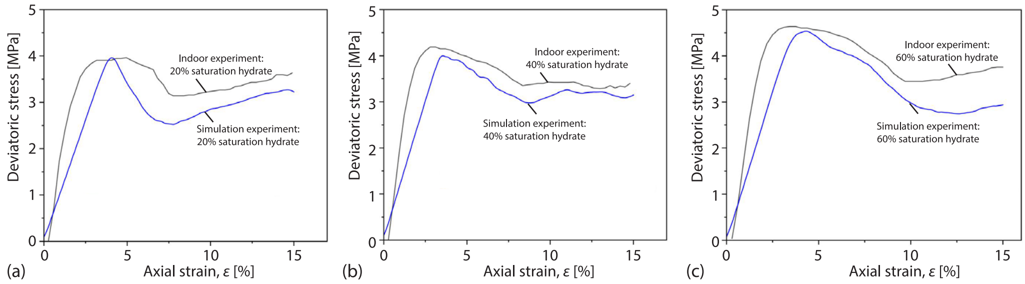


Figure 2. Comparison of numerical test and indoor test results; (a) 20% saturation, (b) 40% saturation, and (c) 60% saturation

Influence of different confining pressure effects on the mechanical properties of GHBS

Based on the aforementioned numerical model, the following results were obtained by applying confining pressure of 1 MPa, 5 MPa, and 10 MPa to three groups of simulated specimens with different saturations and performing servo loading calculations are shown in fig. 3.

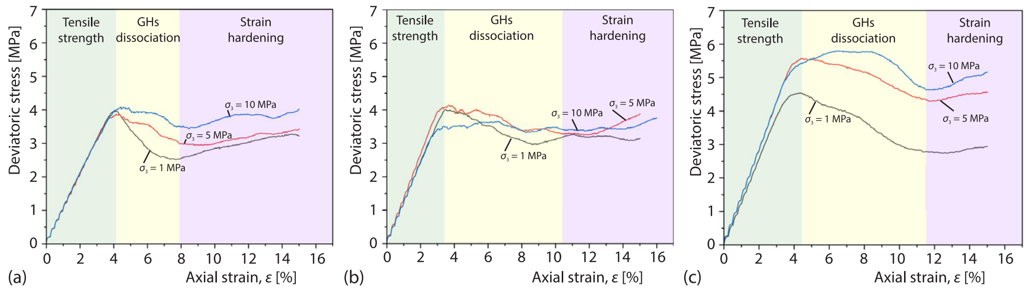


Figure 3. Stress-strain curves of hydrate specimens under different confining pressures; (a) 20% saturation, (b) 40% saturation, and (c) 60% saturation

It was found that the damage strength of low saturation (≤40 %) specimens under high confining pressure (>5 MPa) decreased instead, and the strength of higher saturation (>40 %) specimens under high confining pressure did not increase significantly, which was because the high confining pressure destroyed the cementation of the hydrate, and the residual solid hydrate affected the occlusal force between the sand grains, which led to difficulties in the exertion of the compression-hardening characteristics of the specimens. It can be concluded that with the increase of the peripheral pressure, the compression stiffness characteristics of the GHB specimens are weakened, and the stiffness of the specimens is not significantly affected by the peripheral pressure.

The number of microscopic particle contacts in the specimens at different strains decreases as the strain increases, indicating that the specimens expand in volume. The effect of confining pressure on the number of contacts is small at low strains, and the number of contacts and contact force chains increase with increasing confining pressure at high strains, because at high strains, the confining pressure action restrains the particle movement to inhibit the volume expansion and prevent the development of cracks, as shown as fig. 4(a). We also found that the change rule of contact force chain of GHBS specimens was basically the same under different confining pressure effects, and the overall force chain distribution was similar when the strain of the specimen was 8% with 60% saturation specimen as an example, and it could be obtained that the confining pressure effects on the anisotropy of the contact force were not obvious, as shown in fig. 4(b).

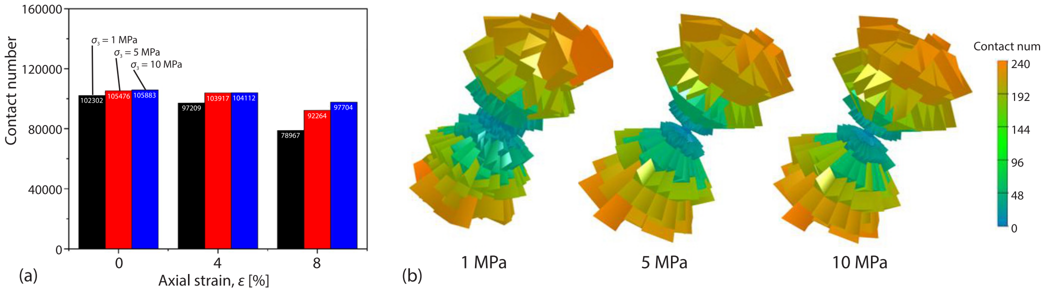


Figure 4. Analysis of 60% saturated GHBS specimens under different confining pressures; (a) contact number-strain plots of 60% saturated GHBS and (b) 8% strain contact force chain distribution

Effect of different saturation levels on the mechanical properties of GHBS

Figure 5 depicts the stress-strain curves of GHBS specimens with different saturations at three confining pressures, and when the hydrate saturation degree was less than or equal to 40%, the effect of saturation degree on the breaking strength of the specimens was relatively small compared with that of the highly saturated specimens, which was attributed to the fact that the hydrate specimens with low saturation degree had fewer cementing bonds, and the strength of the specimens was mainly provided by the basic skeleton, when the saturation degree is 60%, the strength of the GHBS specimens increases significantly. In addition, the slope of the descending section of the strain curve of the GHBS specimen increases with the increase of saturation, which leads to the conclusion that the brittleness of the specimen increases at high saturation.

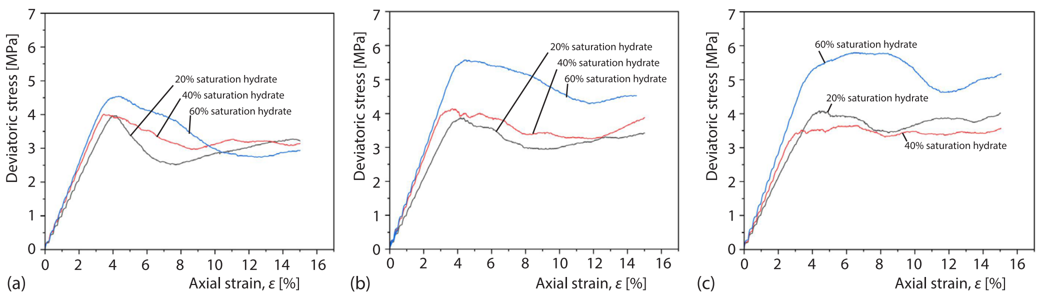


Figure 5. Stress-strain curves of hydrate specimens under different confining pressures; (a) 1 MPa, (b) 5 MPa, and (c) 10 MPa

Figure 6 depicts the number of GHBS specimen contacts increased significantly with the increase of hydrate particles with increasing saturation. The contact force chain of GHBS specimens after servo loading is dominated by the vertical direction, and the higher the saturation degree of the specimen, the lower the number of contact force chain in the horizontal direction at the critical damage. It can be concluded that the saturation degree has a certain effect on the contact force chain, and the damage mode of GHBS specimens is shear-expansion damage, reflecting that the GHBS specimens exhibit anisotropic characteristics after loading damage.

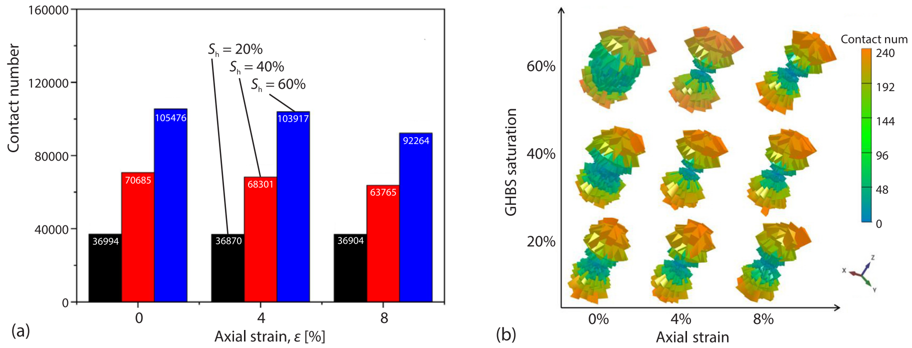


Figure 6. Distribution of GHBS contact number-contact force chain under different strain stages with different saturation of 5 MPa confining pressure; (a) contact number-strain plots and (b) contact force-strain distribution

Conclusion

This research contributes to understanding the mechanical properties of GHBS and ensures the safe extraction of hydrates. In PFC 3-D, the coupled-flex method is used to generate hydrate specimens, which can obtain reliable numerical simulation results, and is more relevant to the actual situation compared to the usually adopted rigid wall. High confining pressure destroys the cementation of hydrate, and as the confining pressure increases, the strength of hydrate specimen increases, the occlusion of sand particles decreases, and the compressive stiffness is weakened. With the increase of saturation, both strength and stiffness of hydrate specimen increase, and brittleness of specimen increases. The damage mode of GHBS specimen is shear damage, and it shows anisotropy after loading damage, the effect of confining pressure inhibits the hydrate particle movement, and the saturation degree has an effect on the contact force. In future research, the author's team will continue to explore the effects of considering variable factors such as coupled temperature field and pore water pressure on the GHBS, and establish hydrate core and stratigraphic models that are more consistent with real in-situ environments.

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