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Perspective

Geomechanical properties of hydrate-bearing strata and their applications

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Abstract:
Natural gas hydrate is an alternative potential energy source that contributes to depressurizing the pressure of energy supply and environmental pollution in the future. Field hydrate production has a close association with geological risks. In this regard, accurate estimation of strength and deformation properties is crucial to risk prevention and control during hydrate development. However, the geomechanical properties of hydrate-bearing sediments and their applications remain unclear. Herein, this work provides a comprehensive summary of studies on the mechanical characteristics of hydrate-bearing sediments and their applications in field trials. It starts with the main research methods, including laboratory tests, constitutive modeling, and numerical simulations, followed by the effects of clay content, hydrate distribution, and morphology on mechanical properties. Besides, typical applications of geomechanical parameters are examined and discussed. Finally, the challenges and perspectives of mechanical studies on hydrate-bearing sediments are presented, which is favorable for the evaluation and control of geological risks during hydrate exploration and development.

1. Introduction

Natural gas hydrate is considered a viable alternative energy resource, which mainly occurs in the permafrost and marine regions (Boswell and Collett, 2011; Chong et al., 2016). With the increasing energy demand, several hydrate production tests have been carried out in recent years (Shaibu et al., 2021; Gajanayake et al., 2023). However, explorations may cause large deformation and strength reduction due to hydrate dissociation and gas extraction, which closely correlates to the geological risks, such as wellbore instability, sand production, subsidence, and landslides (Yan et al., 2020; Li et al., 2023b). In addition, the feasibility of reservoir stimulation in marine hydrate strata is highly related to its mechanical properties (Lu et al., 2023; Wang et al., 2023). Estimation of mechanical behaviors of hydrate-bearing sediments (HBS) is the basis for both geological risk control and reservoir stimulation.

Mechanical behaviors of HBS have been widely investigated via laboratory tests, theoretical analysis, and numerical simulation (Wu et al., 2021a; Chen et al., 2023b; Dong et al., 2023b). Effects of hydrate formation, stress states, temperature, sediment type, particle arrangement, as well as shear rate on strength parameters and deformation were analyzed in many works (Lijith et al., 2019; Ding et al., 2022; Zeng et al., 2023). However, studies on heterogeneous formation and its failure mechanisms are still at their infant stage, which limits the geological risk prediction and control (Dong et al., 2019; Pei et al., 2022). Besides, the mechanical characteristics of HBS under special conditions differ from the laboratory conditions, which needs further studies by considering the practical engineering effects, such as wellbore instability during drilling hydrate and hydraulic fracturing in hydrate

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reservoirs (McConnell et al., 2012; Zhang et al., 2021; Pratama et al., 2023). Thus, there is an urgent to reveal the mechanical behavior of hydrate reservoirs and their engineering effects under special conditions.

Thus, this work highlights recent advances in the mechanical characteristics of HBS and their applications in risk control and reservoir stimulation. Several typical research methods are summarized to describe their traits and development trends. Besides, the effects of clay content, hydrate layered distribution, as well as hydrate morphology on mechanical behavior are reviewed. Moreover, engineering effects in hydrate reservoirs, especially wellbore stability and hydraulic fracturing, are analyzed briefly. Finally, challenges and perspectives are discussed to promote hydrate development. The result provides insight into the estimation of mechanical characteristics of HBS and facilitates the application of outcomes to field hydrate exploitation.

2. Methods for evaluating mechanical properties

2.1 Laboratory test and constitutive modeling

Currently, mechanical behaviors of HBS have been investigated through laboratory tests, analytical models, as well as numerical simulations (Lijith et al., 2019; Jiang et al., 2021; Hu et al., 2023). Laboratory tests are the basis for investigations of mechanical behaviors, including triaxial shearing test, pressure-coring test, direct shear test, CT-based triaxial shear test, and cone-penetration test (Chen et al., 2023b; Li et al., 2023b; Zeng et al., 2023). On the one hand, laboratory tests can obtain the test data, which is first-hand information for estimating the mechanical parameters of HBS (Ning et al., 2012). On the other hand, it provides a database for further numerical and analytical studies (Wang et al., 2021).

The triaxial shear test is the most widely adopted laboratory test method for mechanical properties of HBS. According to the shear strength measured under different confining pressures, the mechanical parameters such as cohesion and internal friction angle of HBS can be determined, based on failure criteria. However, hydrate is sensitive to environmental conditions, and a change in either pressure or temperature will cause hydrate decomposition. Therefore, the triaxial shear of hydrate-bearing sediment at normal temperature and pressure would inevitably lead to hydrate decomposition, which affects the correct evaluation of the original strength of hydrate-bearing sediment. Therefore, an integrated experimental device for hydrate synthesis, decomposition, and mechanical properties testing came into being, which improved the experimental efficiency and ensured the reliability of experimental data. At present, many integrated devices are built on the base of traditional triaxial shear mechanics. A constant temperature control device for circulating refrigeration is added to the triaxial shear instrument. The original chamber is used for the sample synthesis and decomposition, and gas supply and water injection pipeline systems are also added. The main features of these integrated devices include two aspects. Firstly, Hydrate synthesis, decomposition, and triaxial shear chamber are combined. The triaxial loading system and measurement system are basically unchanged. Secondly, hydrate synthesis, decomposition, and mechanical properties can be tested both individually and as a whole. The device can be used to test the mechanical properties of hydrate-bearing sediments under the influence of factors such as hydrate saturation, confining pressure, sediment composition, and loading rate.

Constitutive modelling is an effective approach to characterize the stress-strain relationships of HBS (Waite et al., 2009). These previously published constitutive models shall be primarily divided into 4 types, whicha are nonlinear elastic models, elastoplastic models, critical state models, and statistical damage models. The Duncan-Chang model, which is one of the nonlinear elastic model, can describe the stress-hardening behaviors of HBS, while not applicable to characterize the strain-softening behaviors. It was widely used in predicting mechanical behaviors due to its high precision, simple structure, and easy-determined parameters (Miyazaki et al., 2012). Different from the Duncan-Chang model, the elastoplastic model can accurately predict stress-softening behaviors without considering the effect of volumetric deformation. Critical state models can describe volumetric strains; however, it involves more coefficients that are difficult to be obtained. Moreover, statistical damage models are applicable for estimating mechanical properties and field applications during hydrate development.

2.2 Numerical simulations

The discrete-element method (DEM) is an alternative method to study geotechnical problems and has been widely applied to many fields of rock and soil (Cundall and Strack, 1979; Yang et al., 2018, 2019). Compared with synthetic specimens fabricated in the laboratory, it is easier and faster to generate target specimens containing hydrate and test their mechanical properties. Besides, distribution patterns of methane hydrate in soil pores can be simulated easily with DEM, e.g., pore filling (Brugada et al., 2010; Jung et al., 2012) and cementation (Jiang et al., 2014; Shen and Jiang, 2019). Hydrate morphology and its cementation with sediment particles can be well characterized to reveal the interactions between hydrate and sediment particles (Qian et al., 2023). In this regard, the DEM method provides an effective approach to discuss the heterogeneity of hydrate formation in the future.

Several researchers have conducted studies on the mechanical properties of hydrate sediments by using DEM. Hydrate formation can enhance the frictional instead of cohesive characteristics of sediments containing pore-filling hydrate (Brugada et al., 2010). Strength parameters, such as shear strength, stiffness, cohesion, and shear dilation of HBS increase with the rising backpressure (Jiang et al., 2015). Meanwhile, the effects of hydrate morphology and cementation on mechanical behaviors have been involved into deeper consideration (Jiang et al., 2013) Besides, investigations of the mechanical properties of HBS and their applications in field trials can also be characterized from the microcosmic to macroscopic, such as mechanical responses of HBS during hydrate production (Jiang et al., 2016), formation deformation

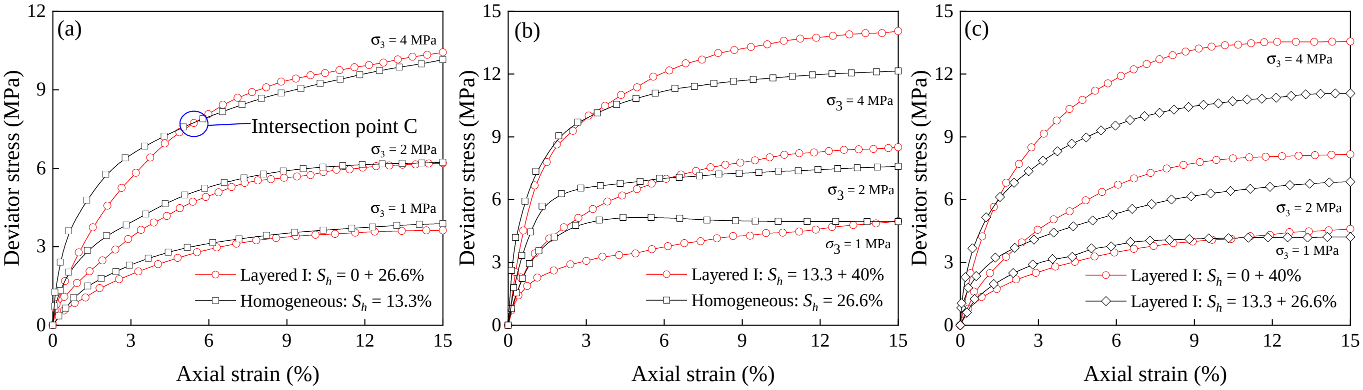

Fig. 1. The effect of hydrate distribution on mechanical characteristics of hydrate-bearing sediments (Li et al., 2021).

(Zhang et al., 2019), and even landslides (Jiang et al., 2018). These studies form a base for further evaluation and control of geological risks during hydrate development.

3. Mechanical characteristics

3.1 Effect of clay content

Clay is an important component of hydrate reservoir. Most of previous studies used quartz sand to prepare hydrate-bearing sediment, ignoring the effect of clay content on the mechanical properties of hydrate-bearing sediments (Jung and Santamarina, 2011; Miyazaki et al., 2012; Yoneda et al., 2015). Actually, clay content has influence on the shear strength, cohesion and internal friction angle of hydrate-bearing sediment (Wu et al., 2021b). Under a certain hydrate saturation and effective confining pressure, the shear strength increases with the increasing clay content. This is mainly related to the content and distribution of hydrate and clay in the pores of sediments. The cohesion increases with the increasing clay content. This is mainly because the clay fills the pores of sediment particles, which improves the particle contact area and enhances the friction resistance during the shearing process. In addition, clay plays the role of connecting adjacent sediment particles, which changes the particle contact mode from hard contact among sediment particles to clay connection through hydrate cementation, thus improving the cohesion. The influence of the clay content on the internal friction angle is not significant. The internal friction angle increases slightly with the increasing clay content, but the internal friction angle of hydrate-bearing sediments with different clay contents generally ranges from 25° to 30° with little variation (Liu et al., 2022).

3.2 Effect of hydrate layered distribution mode

Analysis of pressure cores recovered from hydrate reservoirs indicates that hydrate distribution in sediments shows obvious heterogeneity (Rees et al., 2011; Lei and Santamarina, 2019). Layered distribution of hydrate has been observed frequently in marine regions, such as the northern South China Sea (Su et al., 2018), Nankai Trough (Zhou et al., 2018), and Ulleung Basin (Kim et al., 2017). Due to significant vertical differences in hydrate cementation and sediment features, sediments with hydrate layered distribution exhibit distinct mechanical behaviors during the shearing process.

Investigations focus on the effects of hydrate layered distribution patterns on the mechanical behaviors of layered sediments (Dong et al., 2019; Li et al., 2021). Stress-strain curves of layered sediments are compared with homogeneous ones, indicating that hydrate layered distribution patterns can alter the failure strength and strain softening/hardening mechanisms (Li et al., 2021). Besides, with the same hydrate volume, an intersection point appears in stress-stain curves of layered and homogeneous sediments, as shown in Fig. 1. Similarly, Li et al. (2023a) investigated the effects of hydrate layer inclination and thickness on the mechanical properties of permafrost interlayered HBS. Results show that strength parameters have an obvious increasing tendency with an increase in inclination and thickness of hydrate layers.

Compared with homogeneous sediments, layered sediments are significantly different due to various hydrate layered distribution patterns (Dong et al., 2019). The deformation behaviors of layered sediments are determined by all sublayers (Li et al., 2021), as shown in Fig. 2. The load capacity of the low hydrate-saturated sublayer is smaller than the high hydrate-saturated sublayer. Deformation appears firstly in the low hydrate-saturated sublayer, corresponding with internal structural changes. After a point, damage and deformation will occur randomly in both two sublayers until the load process is completed (Yoneda et al., 2016; Kida et al., 2021). Microscopically, hydrate damage and sediment particle movement determine the microstructure changes, further deciding the deformation and failure of layered sediments (Terzariol et al., 2020; Chen et al., 2023a).

3.3 HBS containing nodular and interlaminar hydrate blocks

Mechanical simulation tests of nodular and interlaminar gas hydrate sediments were conducted using PFC2D, mainly focusing on the stress-strain relationship, failure strength, fracture development, partial body strain curve, and force chain distribution. Generally, sediments containing nodular hydrate show different characteristics in mechanical behavior compared with homogeneous deposits. Tensile cracks pri-

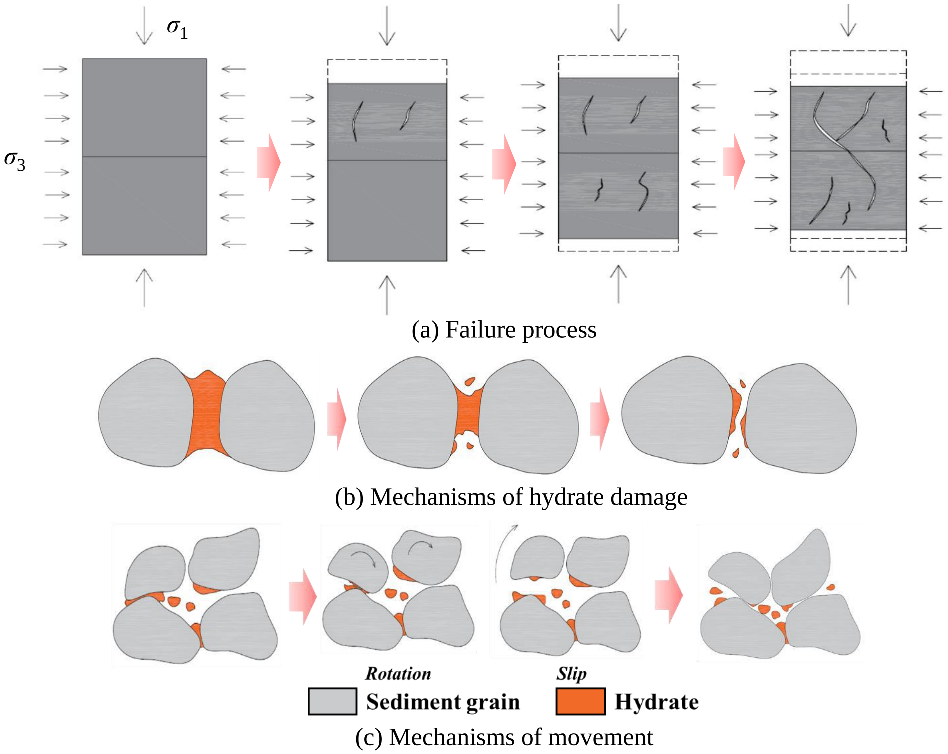

Fig. 2. Failure mechanisms of sediments with hydrate layered distribution (Li et al., 2021).

marily form in fractures containing round nodular hydrate sediments during the shear process, which is more than shear cracks. Behaviors of shear expansion are commonly observed with hydrate saturation exceeding 10%. Furthermore, the strain-softening behavior gradually transforms into strain-hardening ones with the effective confining pressure over 1 MPa. Moreover, the porosity changes inside the sample played an important role in the formation and evolution of the shear band during simulation. Specifically, the porosity around the shear band was larger.

Mechanical behaviors of interlaminar gas hydrate sediments correlate to the interlayer properties. The strength of entire specimens alters with the interlayer thickness and its hydrate saturation. The increasing interlayer thickness and hydrate saturation bring in larger strength as well as evident shear expansion. In addition, failure patterns of hydrate containing interlayers are different from those of the overlying and underlying layers. Therefore, analyzing the interlayer property plays a key role in further studies of mechanical behaviors.

4. Typical applications of geomechanical parameters

4.1 *Wellbore stability evaluation and control*

Wellbore instability has been observed during drilling in hydrate reservoirs. Wellbore failure shall occur once the redistributed stresses induced by drilling fluid invasion exceed the strength of hydrate formation (Xu et al., 2024). It may further cause geological risks with continuous drilling fluid invasion and hydrate dissociation. Wellbore instability and related issues can also extend the drilling period and increase drilling costs, limiting the realization of safe and efficient drilling (McConnell et al., 2012).

Wellbore instability is a complicated process coupled with multiple fields, including pressure, temperature, chemical, as well as deformation fields (Dong et al., 2023a; Wan et al., 2023). Mechanical properties and stress states are the main factors related to wellbore failure. The invaded drilling fluid may cause hydrate dissociation and further reduce the formation strength (Merey, 2019). Besides, high-temperature drilling fluid can promote the hydrate dissociation process, while the high pressure of the borehole will accelerate the drilling fluid invasion rate (Dong et al., 2022).

As mentioned above, preventing hydrate dissociation during drilling fluid invasion is the key step for controlling the wellbore stability (Wei et al., 2019). In this regard, some suggestions are proposed to inhibit hydrate dissociation: (a) shorten the drilling period, (b) increase the density of drilling fluid, (c) reduce the temperature of drilling fluid, and (d) use hydrate inhibitors (Dong et al., 2022). These measures can prevent massive hydrate dissociation during the drilling process, which contributes to wellbore stability.

4.2 *Feasibility evaluation of hydraulic fracturing in HBS*

In the view of the low production capacity of hydrate by in-situ depressurization, some scholars have proposed hydraulic fracturing technology to stimulate hydrate reservoirs to improve gas production (Ito et al., 2008; Konno et al., 2016; Liu et al., 2020b). Since marine hydrate reservoir is not diagenetic, and the degree of sediment cementation is weak, hydrate decomposes during hydraulic fracturing, which further reduces the strength of sediment cementation. In this regard, whether hydraulic fracturing can be used in hydrate reservoir development is an urgent problem to be answered, and the feasibility evaluation should be carried out before hydraulic fracturing is used in hydrate reservoirs. Therefore, considering hydrate saturation, cementing strength of the hydrate reservoir, clay content, and in-situ stress difference, the fracability evaluation model of the hydrate reservoir was established based on the analytical hierarchy process and entropy method, and fracability index was further proposed (Liu et al., 2020a). The feasibility of hydraulic fracturing in hydrate reservoir was evaluated combining hydrate hydraulic fracturing experiment and fracability index.

The fracability index determined by the properties of the hydrate reservoir plays a key role in feasibility evaluation. The higher the fracability index is, the greater the feasibility of hydraulic fracturing in hydrate reservoir. Construction parameters, such as fracturing fluid viscosity, fracturing fluid injection rate, also affect the fracability of hydrate reservoir. To reduce fracturing fluid loss and clay component slime, it is recommended to use high-viscosity fracturing fluid and add anti-clay swelling components. On the whole, hydrate reservoirs with fracability index less than 0.48 are basically not suitable for hydraulic fracturing. Hydrate reservoirs with fracability index between 0.48 and 0.60 have a certain ability for hydraulic fracturing, but large injection rate and high viscosity fracturing fluid should be used to reduce the loss of fracturing fluid. Hydrate reservoirs with fracability index greater than 0.60 are basically the priority of hydraulic fracturing for reservoir stimulation (Liu et al., 2020a).

5. Challenges and perspectives

Studies on geomechanical properties of HBS have been lasted for several decades. Various laboratory test methods and numerical simulation techanics have been developed. Joint application of these methods/techanics resulted thorough understanding of the geomechanical responses of the HBS. However, it is worthy of noting that only few consensus have been reached so far. One of the main obstacals is that the testing methods applied by different research groups differs with each other significantly. Standardization of the testing method is urgently needed in the current state.

Triaxial shearing is widely adopted in the previous studies, whereas it only enables us to test traditional geomechanical properties of the HBS. With the development of natural gas hydrate, more complicated engineering boundaries are exposed, which in-turn promote the advancement of the testing method. Introducing novol test method, such as CT and ultrasonic measurment into the triaxial shearing is essential to understand the geomechanical responses of the HBS.

Both the geological risks and reservoir stimulation evaluation are highly related to geomechanical properties of the HBS. Bridging the laboratory test, numerical simulation, and field test are essential, although the current field test data are limited. Besides, comparative and cooperative study among different research groups are the best choice for promoting the advancement of the testing techniques, deepening the understanding of the geomechanical properties.

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Conflict of interest

The authors declare no competing interest.

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