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Short communication

Improved Duncan-Chang model for reconstituted hydrate-bearing clayey silt from the South China Sea

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Abstract:
The experimental testing and analysis of strength and deformation characteristics of hydrate reservoirs is an integral part of natural gas hydrate exploitation. However, studies so far have failed to deeply explore samples from the South China Sea. Especially, there is a lack of a simple and applicable method to estimate their mechanical behaviors. Thus, based on test data, an improved Duncan-Chang model is established in this paper to characterize the strength and deformation of reconstituted samples with various hydrate saturation and stress states from this area. This model can accurately describe the strain-hardening characteristics, and failure strength is estimated by the improved Drucker-Prager criterion with high fitting accuracy. The initial elastic modulus and failure ratio are given by the proposed empirical models, which are obtained from experimental data and fitting methods. Generally, this model has several advantages including simple structure, favorable performances, and a limited number of model parameters. Therefore, it could be widely used in strength and deformation analysis. This study can support the prevention and control of geological risks during natural gas hydrate exploitation in the South China Sea.

1. Introduction

Natural gas hydrate (NGH) has good prospects in the development of clean energy resources (Chong et al., 2016). The field test production of NGH has been conducted worldwide, such as in Canada, America, Japan, and China (Wang et al., 2022). At the same time, hydrate-bearing sediments (HBS) are also associated with geological issues such as submarine landslide, sand production, wellbore stability, and subsidence (Ruppel and Waite, 2020). In this regard, it remains a challenge to accurately evaluate the mechanical characteristics of HBS with/without hydrate dissociation. Constitutive models comprise an efficient and useful method to analyze the deformation and strength characteristics of HBS.

Thus far, the mechanical behaviors of HBS have been primarily investigated by theoretical analysis, laboratory experiments, and measurements on artificial specimens/pressure samples (Lijith et al., 2019; Li et al., 2021). Experimental tests on artificial specimens containing gas hydrate were carried out to study the mechanical behaviors and failure mechanisms (Hyodo et al., 2017; Li et al., 2018). The results showed a significant increase in the strength of sediments with hydrate formation. Other factors such as the content of fines, particle characteristics, and hydrate occurrence mode, also affect the mechanical behaviors of HBS. In addition, tests on pressure samples from the Nankai Trough showed a variation in strength parameters versus hydrate saturation (Yoneda et al., 2017). The above studies focused mainly on deformation behaviors and strength characteristics. Nonetheless, the geomechanical characteristics of hydrate reservoirs

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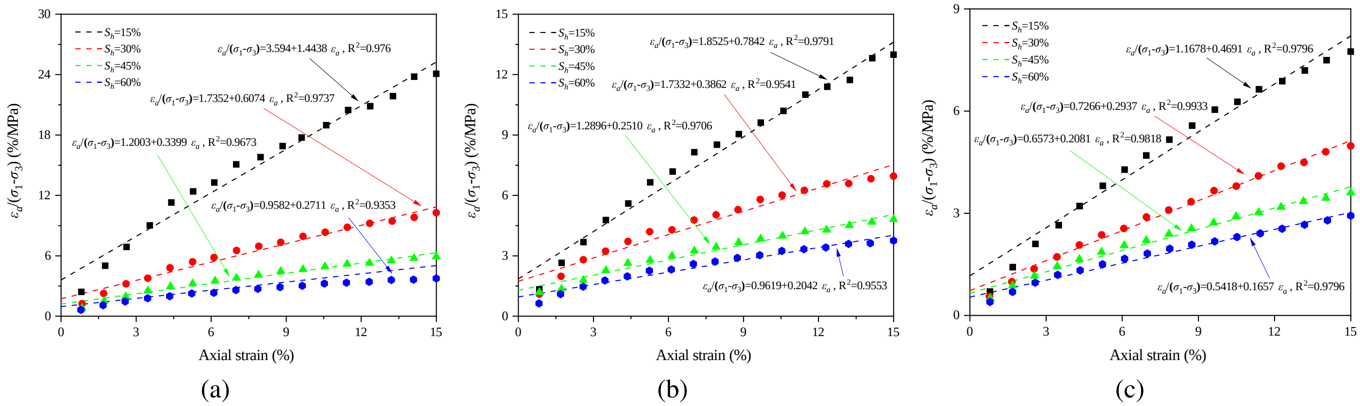


Fig. 1. Transformed stress-strain curves for HBS.

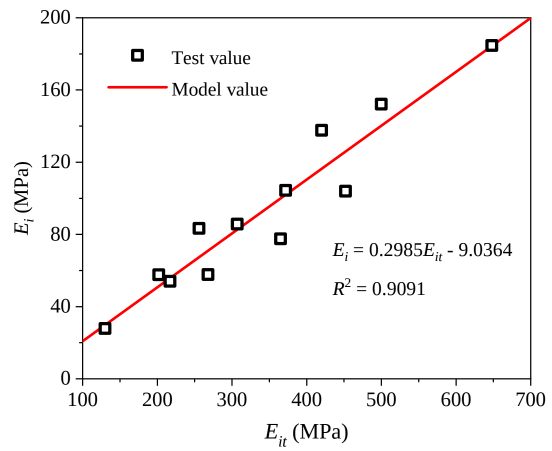


Fig. 2. Calculations of the initial elastic modulus.

in the South China Sea are still poorly known.

Constitutive models form an integral part of simulating the geomechanical response and predicting the strength parameters for gas hydrate reservoirs. Miyazaki et al. (2012) proposed a modified Duncan-Chang model to characterize the strength and deformation behaviors of HBS based on the traditional model. Yan et al. (2017) developed the Duncan-Chang model to reveal the deformation laws and the effect of hydrate formation. Pinkert et al. (2015) established a model for evaluating the deformation behaviors of hydrate-bearing sands. This model can well perform the analysis of some key geological issues concerning the mechanical behaviors of HBS. Uchida et al. (2012) established a model considering the critical state theory applicable to HBS, but has a limitation that the parameters are difficult to determine. Sánchez et al. (2017) developed a constitutive model considering inelastic mechanisms, which can accurately simulate the behaviors of samples during dissociation. It seems reasonable to use a specific constitutive model simulating a specific type of HBS. However, simple and reliable methods have not been developed for this purpose, which limits the mechanical evaluation of hydrate-saturated samples from the South China Sea.

In this paper, an improved Duncan-Chang model is proposed to characterize the strength and deformation characteristics of reconstituted samples from the South China Sea. In this model, the failure strength, initial elastic modulus, and failure ratio are calculated based on empirical formulas with high fitting accuracy. This work can support the prevention and control of geological risks during natural gas hydrate exploitation in the South China Sea.

2. Improved Duncan-Chang model

2.1 Duncan-Chang model

Duncan and Chang (1970) proposed a nonlinear elastic model to analyze the stress and strain of soils, which are given by:

$$\sigma_1-\sigma_3=\frac{\varepsilon_a}{a+b\varepsilon_a} \tag{1}$$

$$a=\frac{1}{E_i} \tag{2}$$

$$b=\frac{1}{(\sigma_1-\sigma_3)_{ult}} \tag{3}$$

where $\sigma_1-\sigma_3$ represents deviator stress, MPa; ε_a represents axial strain, %; a and b are model coefficients, E_i represents initial elastic modulus, MPa; and $(\sigma_1-\sigma_3)_{ult}$ is the deviator stress limit, which is difficult to reach in actual tests. Due to the high precision, simple structure, and few parameters, it is widely used in evaluating and predicting the mechanical behaviors of soils. According to previous studies (Duncan and Chang, 1970; Miyazaki et al., 2012), the deviator stress limit can be determined by both failure strength and damage ratio:

$$(\sigma_1-\sigma_3)_{ult}=\frac{(\sigma_1-\sigma_3)_f}{R_f} \tag{4}$$

where $(\sigma_1-\sigma_3)_f$ represents the failure strength, MPa; and R_f is the damage ratio.

Therefore, the mathematical expression of deviator stress of HBS during the shearing process is expressed as:

$$\sigma_1-\sigma_3=\frac{\varepsilon_a}{\dfrac{1}{E_i}+\dfrac{\varepsilon_a R_f}{(\sigma_1-\sigma_3)_f}} \tag{5}$$

Miyazaki et al. (2012) and Yan et al. (2017) used the above model to describe the stress-strain relations of hydrate-saturated sands, which verifies the applicability of this model

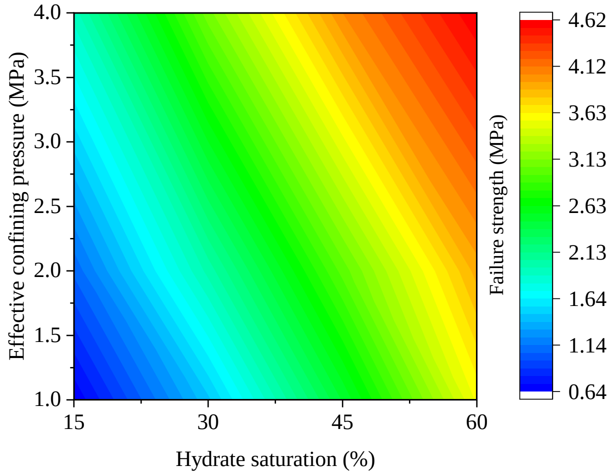


Fig. 3. Prediction results of failure strength.

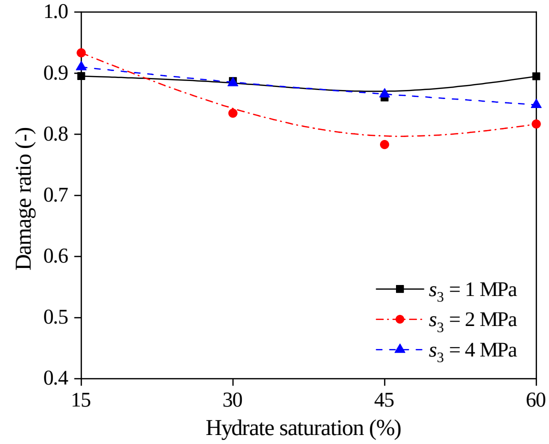


Fig. 4. Variation in damage ratio versus hydrate saturation.

to NGH reservoirs. Our previous studies (Dong et al., 2022) showed that tetrahydrofuran hydrate-saturated samples from the Shenhu area exhibit strain-hardening characteristics at low effective confining pressures and can be characterized by the Duncan-Chang model (Duncan and Chang, 1970). Therefore, an improved model based on this traditional Duncan-Chang model is proposed for describing the geomechanical behaviors of reconstituted hydrate-bearing clayey silt.

2.2 Determination of model coefficients

Due to the different mechanical properties of various samples, coefficients of this improved Duncan-Chang model for reconstituted clayey silt differ from the recorded data (Miyazaki et al., 2012; Yan et al., 2017). To determine the model coefficients, Eq. (1) can be transformed into a linear one:

$$\frac{\varepsilon_a}{\sigma_1-\sigma_3} = a + b\varepsilon_a \tag{6}$$

Afterwards, model coefficients can be obtained through the linear approximation of curve $\varepsilon_a/(\sigma_1-\sigma_3)$. According to the curve shapes and linear relationships, the middle section of the transformed curve is selected to calculate the model coefficients.

Fig. 1 shows the determination of model parameters according to Eq. (6). The stress-strain curves of the reconstituted clayey silt containing (THF) hydrate were presented in our previous work (Dong et al., 2022), which are used here to identify the above-mentioned coefficients. The results indicate that correlations between the $\varepsilon_a/(\sigma_1-\sigma_3)$ and ε_a are almost linear. Thus, both E_i and $(\sigma_1-\sigma_3)_{ult}$ can be identified by knowing the values of model coefficients.

2.3 Initial elastic modulus

In order to calculate the value of parameter a, the initial elastic modulus should be obtained. The correlations between the experimental and model value of the initial elastic modulus are shown in Fig. 2. The results imply that the values of test results and model calculation are different. However, they have an approximate linear relation, which can be obtained by combining the fitting method and test data from our previous work (Dong et al., 2022). Furthermore, the parameter a can be approximately identified by determining the initial elastic modulus from tests.

The initial elastic modulus can be determined by Eq. (7). The predicting accuracy is more than 90%.

$$E_i = 0.2985E_{it} - 9.0364 \tag{7}$$

where E_{it} represents the initial elastic modulus obtained from the test data, MPa.

2.4 Damage ratio

The failure strength of hydrate-saturated samples is primarily determined by the hydrate concentration and stress state (Uchida et al., 2012; Sánchez et al., 2017). Thus, the failure strength $(\sigma_1-\sigma_3)_f$ can be obtained based on the improved Mohr-Coulomb criterion (Dong et al., 2020):

$$(\sigma_1-\sigma_3)_f = \frac{2\sigma_3\sin\varphi}{1-\sin\varphi} + \frac{2c\cos\varphi}{1-\sin\varphi} \tag{8}$$

where $\varphi=\varphi(S_h)$ and $c=c(S_h)$ represent the internal friction angle and cohesion, MPa; respectively.

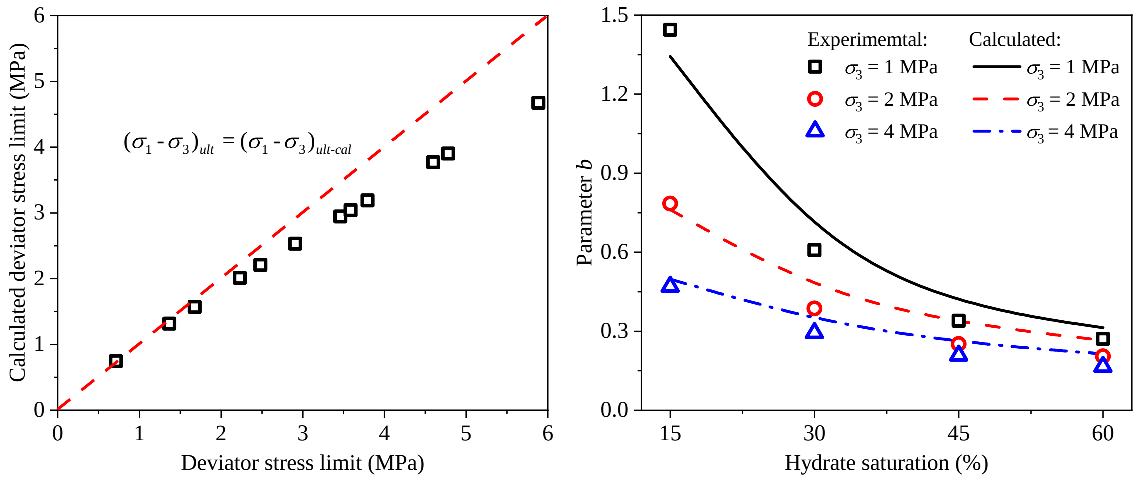
Fig. 3 shows the predicted failure strength versus hydrate saturation. The values of the coefficients were all determined by experiments. It is observed that the improved Mohr-Coulomb criterion has good application in these calculations. This prediction method could previously provide a practical reference for numerical simulations of hydrate exploitation in the South China Sea (Liao et al., 2022).

Duncan and Chang (1970) have shown that the damage ratio R_f can be identified by:

$$R_f = \frac{(\sigma_1-\sigma_3)_f}{(\sigma_1-\sigma_3)_{ult}} \tag{9}$$

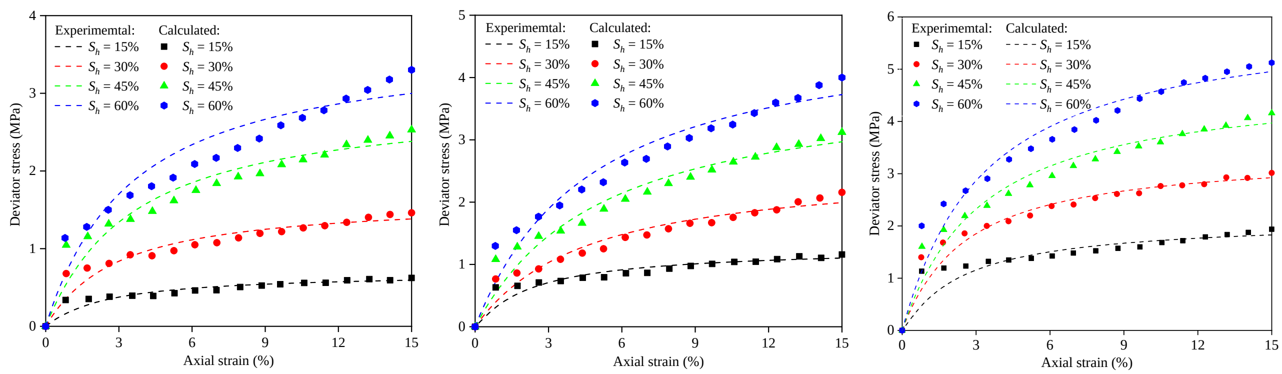
Furthermore, Miyazaki et al. (2012) and Yan et al. (2017) discussed the variations in R_f of HBS, and indicated that R_f is independent of hydrate content.

Fig. 4 illustrates the variation in the damage ratio of reconstituted samples containing THF hydrate. The range of the damage ratio of HBS is 0.8029-0.9448, which is different from that of hydrate-saturated sands (0.7-0.9 from Miyazaki et al. (2012)). Besides, the agreement of damage ratio and hydrate saturation is low, implying that the damage ratio is



(a) (b)

Fig. 5. Prediction of model parameters.



(a) (b) (c)

Fig. 6. Comparisons between experimental and calculated results (Dong et al., 2022). The values of σ_3 are (a) 1 MPa, (b) 2 MPa and (c) 4 MPa.

assumed to be independent of the effect of hydrate. Therefore, for simplicity, the average damage ratio of 0.87 is used in the calculations.

Furthermore, both deviator stress limit and parameter b are calculated according to the predicted values of failure strength and damage ratio, as shown in Fig. 5. This proves that the above-mentioned predicted results can be used for calculating model coefficient b, which is an integral part of the improved model.

In general, coefficients of the traditional Duncan-Chang model are mainly determined by laboratory tests, which vary considerably with the sediment type and test condition. Meanwhile, model coefficients for the hydrate-saturated clayey silt are still unclear. To this end, an improved Duncan-Chang model is proposed that can obtain the key parameters effectively.

3. Model verification

In this section, we propose an improved Duncan-Chang model for the characterization of strength and deformation of reconstituted samples from the South China Sea. It is assumed that the stress increment can be calculated based on the tangent elastic modulus and corresponding axial strain. The value of elastic modulus E_t can be determined by:

$$E_t = \frac{\partial(\sigma_1 - \sigma_3)}{\partial \varepsilon_a} = \left[1 - \frac{R_f(\sigma_1 - \sigma_3)}{(\sigma_1 - \sigma_3)_f}\right]^2 E_i \tag{10}$$

The experimental and calculated results of reconstituted samples from the Shenhu area of the South China Sea are compared in Fig. 6. It is observed that the presented model can reflect the deformation properties and strength parameters of HBS, thus can be used for the prediction of geomechanical responses and risk control. Nonetheless, some differences still exist at small strains resulting from the linear hypothesis during the modeling process.

4. Conclusions

In this paper, an improved Duncan-Chang model for reconstituted clayey-silt samples is developed, which can accurately characterize its strain-hardening behaviors. The failure strength, initial elastic modulus, and failure ratio can be accurately identified by knowing the stratum stress and hydrate saturation. The proposed model has advantages, including simple structure, favorable performances, and few model parameters, thus can be widely used in stress increment analysis. This work improves the understanding of deformation behaviors of hydrate reservoirs, and offers a practical reference for the assessment and control of geological risks related to NGH development in the South China Sea.

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Conflict of interest

The authors declare no competing interest.

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