

Modeling the Mechanical Behavior of Gas Hydrate Bearing Sediments Based on Unified Hardening Framework

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Abstract Gas Hydrate Bearing Sediments (GHBS) are natural soil deposits that contain methane hydrate inside their pores and they have been considered as a potential energy resource. Deformation behavior and change in shear strength of sediments are not clearly understood on the occasion of methane hydrate production and its modeling poses great challenges. In this study, a new GHBS model based on unified hardening framework has been proposed with less and easily determined model parameters. This analytical model incorporates modified Cam-clay yield surface, plus the effect of hydrate saturation parameters to capture the mechanical behavior of GHBS. Comparisons of tri-axial compression tests with model simulations have been conducted to show the proposed model is able to predict the mechanical behavior of GHBS at different hydrate saturations and confinement conditions.

Keywords Constitutive modeling · Gas hydrate bearing sediments · Unified hardening concept · Shear strength · Hydrate saturations

1 Introduction

Natural gas hydrate is a solid clathrate compound in which a large amount of methane is trapped within a crystal structure of water, forming a solid similar to ice. Originally thought to occur only in the outer regions of the Solar System, where temperature are low and water ice is common, significant deposits of methane clathrate have been found under sediments on the ocean floors of the Earth (Mahajan et al. 2007), called Gas Hydrate Bearing Sediments (GHBS). Natural perturbations in temperature and pressure may trigger gas hydrate dissociation, accompanied by methane gas and water production, resulting in a multi-phase fluid migration through the sediments bearing them. Natural gas hydrate dissociation not only changes the mechanical behavior of GHBS, but also leads to massive submarine landslides, involving large areas and affecting submarine infrastructures, e.g. pipeline cutoff; borehole instability; platform foundation failure (Collett 2002; Kvenvolden 1999). The further knowledge on the behavior of GHBS related to hydrate formation and dissociation is critically important to the drilling and production

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applications of the large amount of the potential energy resource.

A series of laboratory tests have been widely carried out using the tri-axial compression tests of in situ samples and remolded samples to study the mechanical behavior of GHBS (Yoneda et al. 2015; Hyodo et al. 2013; Miyazaki et al. 2011; Winters et al. 2007; Zhang et al. 2012, 2015). This mechanical response of GHBS is highly complex because its behavior not only depends on the amount of hydrate, but also on the type of pore habit such as poring filling, supporting matrix and cementation. There have been still several agreements achieved: elastic modulus and shear strength are generally improved with the hydrate saturation increased, while shear strength decreases with the porosity declined at the same hydrate saturation; plasticity hardening is occurred at the relatively low hydrate saturation while strain softening can be observed at the hydrate saturation of 25–45%. Apart from the impact factor of hydrate saturation, the temperature below freezing point leads to the formation of frozen GHBS, composed of ice, hydrate as well as silt clay, and the mechanical properties strengthen with the increase of the total saturation of hydrate and ice (Zhang et al. 2018). All these test results show that the mechanical behavior of GHBS (e.g. plasticity hardening and mechanical softening) is strongly influenced by the hydrate saturation.

Many types of constitutive models have been proposed in the last few years, to simulate the mechanical behavior of GHBS. In terms of previous studies, classical yield surfaces have been separately introduced by soil researchers. For example, based on Duncan–Chang concept, the nonlinear elastic model for hydrate bearing sands was proposed by Miyazaki et al. (2012). Modified Mohr–Coulomb model was employed by Rutqvist and Moridis (2007) to simulate the geo-mechanical responses during gas production from GHBS using the depressurization-induced method. With the framework of Modified Cam Clay, Sultan and Garziglia (2011) have built a model calibrated by Masui et al. using the experimental data gathered from tri-axial tests on synthetic hydrate sediments. Recently, a hypo-plastic model has been established by Zhang et al. (2018) to describe the 3-dimensional nonlinear stress–strain relation of GBHS. In this model, it is not necessary to take into account the yield surface, the plastic potential, and the hardening rules. All these aforementioned models are

able to simulate the basically mechanical property of GHBS. However, the number of model parameters increases and the strain softening and dilatant behavior are still difficult to take into account at the same time.

In this study, a new elastic–plastic model based on unified hardening framework has been presented to improve the modeling and modified Cam-clay concept has been selected to provide a general and adaptable geo-mechanical model for gas hydrate bearing sediments. To calibrate this proposed model, the generally accepted experimental data on gas hydrate bearing sediments have been adopted, published by Masui et al. (2005) and Miyazaki et al. (2012), involving different hydrate saturations and varied stress paths. Special attention is paid to summarize the theory of unified hardening framework and its application. Also, the mechanical behavior of GHBS is presented by gathering the agreements among soil researchers.

2 Modeling the Behavior of Gas Hydrate Bearing Sediments

Tri-axial tests on GHBS have provided very useful information to understand the influence of hydrate saturation on the mechanical behavior of these materials. Generally, the presence of gas hydrate increases the shear strength of the sediments. After the peak stress, GHBS presents a softening behavior and more dilation than free hydrate samples. To model these properties of GHBS, a novel model is proposed in this section based on unified hardening concept.

2.1 Unified Hardening Framework

Yao and Sun (2000) and Yao et al. (2004, 2007) proposed Unified Hardening (UH) model to describe the stress–strain relation of over-consolidated soils, such as naturally deposited clays. Based on the relationship between the current surface and the reference yield surface, UH framework is established taking into account the change of the potential failure stress ratio related to Hvorsley envelope. This model adopts a new unified hardening parameter, independent of stress paths and it only requires one additional material parameters, compared with Cam-clay model. As a matter of fact, the introduced model parameter is the slope of the Hvorsley envelope, determined from

the tri-axial tests. For normally consolidated clays, the UH model degrades into the modified Cam-clay model.

The UH model is able to simulate many properties of over-consolidated clays, mainly including: dilatancy effect, strain hardening or softening and dependency behavior of stress path. Also, it can describe the elastic–plastic response during a reloading path in an isotropic stress state, stress–strain relations of clays with different over-consolidated ratio, variations of drained and undrained strength with over-consolidated ratio and cyclic behaviors under repeated loadings. Based on the spatially mobilized plane criterion and the corresponding transformed stress method, the UH framework can be applied directly to three-dimensional stress states and take into account the influence of intermediate principal stress on strength of clays.

In this context, the UH framework can be used to model the highly complex behavior of GHBS (one type of naturally deposited clay). The proposed model has to take into account two aspects related to the presence of hydrate in the over-consolidated soils: (1) the mechanical behavior of GHBS not only depends on the amount of hydrate, but also on the stress level; (2) the model considers the hardening, the softening and the dilation effect during hydrate dissociations. The proposed UH-based model and its mathematical formulation are detailed below. The model parameter and its calibration procedure are also introduced in the following section.

2.2 Mathematical Description

In this section, a new constitutive model for the mechanical behavior of GHBS is derived with the framework of UH model.

- Stress–strain relation

In case of one-dimensional elastic–plastic problem, the total strain (ε) can be divided into elastic part (ε^e) and plastic part (ε^p), and it can be written in the form of increment as follows:

$$d\varepsilon = d\varepsilon^e + d\varepsilon^p \tag{1}$$

The elastic response can be written more elegantly using bulk modulus (K) and shear modulus (G) to separate the effects of changing size and changing shape:

$$\begin{Bmatrix} dp' \\ dq \end{Bmatrix} = \begin{bmatrix} K & 0 \\ 0 & 3G \end{bmatrix} \begin{Bmatrix} d\varepsilon_v^e \\ d\varepsilon_d^e \end{Bmatrix} = [D^e] \begin{Bmatrix} d\varepsilon_v^e \\ d\varepsilon_d^e \end{Bmatrix} \tag{2}$$

where p' , q are the mean effective stress and the deviator stress, respectively. ε_v^e , ε_d^e are elastic volumetric strain and tri-axial elastic shear strain.

- Yield function and hardening rule

Considering associated flow rule, the yield function f is the same as the plastic potential g and Cam-clay model (or modified Cam-clay model) can be generally described as:

$$f = g = q^2 + M^2 p'^2 - M^2 p'_x = 0 \tag{3}$$

where p'_x is the volumetric yield stress, also known as pre-consolidation stress.

Due to hydrate bonding, GHBS exhibits both enhanced dilation and cohesion. Taking into account these effects, the yield function and relative associated flow rule can be defined by:

$$f = g = q^2 + M^2 (p' + p'_t) \cdot (p' - p'_t - p'_x) = 0 \tag{4}$$

in which, M is the critical state stress ratio in tri-axial compression. In addition, p'_t is related to the cementing effect of hydrate, expressed by the following equation according to Lee et al. (2004):

$$p'_t = p'_{t0} \cdot \exp(-k_p \cdot \varepsilon_d^p) \tag{5}$$

where k_p is a dimensionless parameter, controlling the degradation ratio of cementing effect during hydrate dissociation. p'_{t0} is an initial value of hydrate cementing, decided by the initial cohesion c and frictional angle φ . This parameter is given by Liu et al. (2013):

$$p'_{t0} = c(S_h) \cdot \cot \varphi \tag{6}$$

In this study, the cohesion of GHBS is the function of hydrate saturation.

Based on the framework of UH model, the new parameter H is introduced to the yield function and the mathematical representation is expressed by:

$$\begin{cases} p_x = p_0 \cdot \exp\left(\frac{H}{c_p}\right) \\ H = \frac{M_f^4 - \eta^4}{M^4 - \eta^4} \cdot d\varepsilon_v^p \end{cases} \tag{7}$$

where p_0 is initial mean pressure and $c_p = (\lambda - \kappa)/(1 + e_0)$. Note that λ , κ and e_0 are

originally introduced to represent the compression index, swelling index and initial void ratio for studied clays, respectively.

The unified hardening parameter H controls the rate of hardening and softening of the current surface during the soil deformation, expressed by:

$$dH \begin{cases} > 0 & \text{hardening stage} \\ = 0 & \text{peaking stage} \\ < 0 & \text{softening stage} \end{cases} \quad (8)$$

M_f is the peak value of stress ratio, taking into account the hydrate cementing, which can be defined by:

$$M_f = M \cdot \left(1 + \frac{p'_t}{p_x} \cdot b \right) \quad (9)$$

where b is a modified dimensionless coefficient, changing with the hydrate saturation.

In the framework of UH model, the current yield surfaces and reference yield surfaces are employed, combining a unified hardening parameter. For GHBS, the applied stress reaches the initial yield surface and the yield surface expands with loading. When the strength of GHBS arrives at the peak value, softening occurs, while yield surface contracts until the critical state is approached. The changing of yield surface during loading is illustrated in Fig. 1 and the modified Cam-clay model is also plotted to compare with the proposed yield surface in this study.

• Plastic strain

The yield function based on UH framework contains four variables: p' , q , p'_t , p_x . The consistency equation becomes:

$$df = \frac{\partial f}{\partial p'} dp' + \frac{\partial f}{\partial q} dq + \frac{\partial f}{\partial p'_t} dp'_t + \frac{\partial f}{\partial p_x} dp_x = 0 \quad (10)$$

Combining Eqs. (4), (5), (6), (7), the Eq. (10) changes into:

$$\begin{aligned} & [2M^2 p' - M^2 p_x] \cdot dp' + 2q \cdot dq \\ & + [-2M^2 p'_t - M^2 p_x] \cdot p'_t \cdot (-k_p) \cdot d\varepsilon_d^p \\ & + [-M^2 (p' + p'_t)] \cdot \frac{1}{c_p} \cdot p_x \cdot \frac{M_f^4 - \eta^4}{M^4 - \eta^4} \cdot d\varepsilon_v^p = 0 \end{aligned} \quad (11)$$

Taking into account the plastic potential function g and the following definition of plastic strain:

$$\begin{cases} d\varepsilon_v^p = \Lambda \frac{\partial g}{\partial p'} \\ d\varepsilon_d^p = \Lambda \frac{\partial g}{\partial q} \end{cases} \quad (12)$$

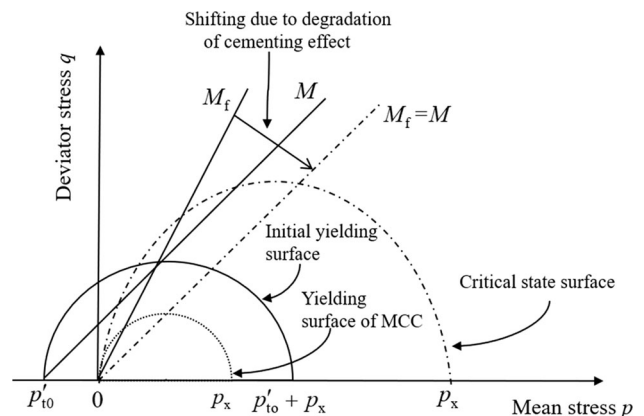
in which, Λ is a plastic scalar multiplier.

The relationship between the stress increment tensor and the elastic strain increment tensor can be given by:

$$\begin{aligned} \begin{Bmatrix} dp' \\ dq \end{Bmatrix} &= [D^e] \cdot \left[\begin{Bmatrix} d\varepsilon_v \\ d\varepsilon_d \end{Bmatrix} - \begin{Bmatrix} d\varepsilon_v^p \\ d\varepsilon_d^p \end{Bmatrix} \right] \\ &= [D^{ep}] \cdot \begin{Bmatrix} d\varepsilon_v \\ d\varepsilon_d \end{Bmatrix} \end{aligned} \quad (13)$$

Substitute Eqs. (12) and (13) into Eq. (11), we obtain the following plastic scalar multiplier:

Fig. 1 The changing of yield surface during loading



$$A = \frac{K(2M^2p' - M^2p_x) \cdot d\varepsilon_v + 6Gq \cdot d\varepsilon_q}{H} \tag{14}$$

where

$$H = [K(2M^2p' - M^2p_x) + 12Gq^2] + (2M^2p'_t + M^2p_x)p'_t(-k_p)2q + M^2(p' + p'_t) \frac{1}{c_p} p_x \frac{M_f^4 - \eta^4}{M^4 - \eta^4} (2M^2p' - M^2p_x) \tag{15}$$

• Stress–strain relationship in p' - q space

The elastoplastic stress–strain relation of UH model in p' - q plane can be expressed as follows:

$$\begin{aligned} \begin{Bmatrix} dp' \\ dq \end{Bmatrix} &= [D^{ep}] \cdot \begin{Bmatrix} d\varepsilon_v \\ d\varepsilon_d \end{Bmatrix} \\ &= \begin{bmatrix} D_{pp} & D_{pq} \\ D_{qp} & D_{qq} \end{bmatrix} \cdot \begin{Bmatrix} d\varepsilon_v \\ d\varepsilon_d \end{Bmatrix} \end{aligned} \tag{16}$$

where

$$\begin{cases} D_{pp} = K \cdot \left(1 - \frac{K(2M^2p' - M^2p_x)^2}{H} \right) \\ D_{pq} = 3KG \cdot \frac{(-2)q(2M^2p' - M^2p_x)}{H} \\ D_{qp} = 3KG \cdot \frac{(-2)q(2M^2p' - M^2p_x)}{H} \\ D_{qq} = 3G \cdot \left(1 - \frac{12Gq^2}{H} \right) \end{cases} \tag{17}$$

Therefore, GHBS model is established with the framework of UH concept, including nine model parameters: $\lambda, \kappa, \nu, e_0, p_0, M, p'_{t0}, k_p, b$. In which, six model parameters of $\lambda, \kappa, \nu, e_0, p_0, M$ are the same as the modified Cam-clay model. The other three parameters p'_{t0}, k_p, b are easily calibrated by experimental results, presented in the section of model validation.

3 Model Validation of the Proposed Model

3.1 Laboratory Test Results

To prepare test natural hydrate core specimen, Masui et al. (2007) has cut the in situ samples of Nankai Trough into an appropriate size in length of 100 mm

and 50 mm in diameter. Tri-axial compression test has been conducted at the strain rate of 0.1% per minute in drained condition through confining pressure at 10 MPa and back pressure at 9 MPa. After the compression test, strength can be decided and the pore saturation is able to be calculated by the volume of methane gas which is released from the dissociation. In this test, tri-axial testing apparatus has been employed with a capacity of 200 kN load along with maximum confining pressure and back pressure of 20 MPa.

3.2 Parameter Calibration Procedures

- Parameters: $\lambda, \kappa, \nu, e_0, p_0, M$

In the proposed GHBS model, gradient of the normal consolidation line in e - $\ln(p')$ space λ , slope of unloading and reloading lines in e - $\ln(p')$ space κ , Poisson’s ratio ν , initial void ratio e_0 , reference size of yield locus p_0 , value of the stress ratio at the critical state M , are the same as the parameters in Cam-clay model, obtained from standard oedometer or tri-axial compression tests. According to the tri-axial compression tests conducted by Masui et al. (2007), parameters of $\lambda, \kappa, \nu, e_0, p_0, M$ are presented in the Table 1.

- Parameter: p'_{t0}

p'_{t0} is an initial value of hydrate cementing, depending on initial cohesion c and frictional angle φ , presented in Eq. (6). According to Liu et al. (2013), the following expression of soil cohesion with hydrate saturation are employed:

$$c(S_h) = A \cdot S_h^3 + B \tag{18}$$

Based on the tri-axial compression tests on natural hydrate core specimens, parameter p'_{t0} is also presented in Table 1.

- Parameter: k_p

k_p a dimensionless parameter (see Eq. 5), controls the degradation ratio of cementing effect during hydrate dissociation. Figure 2 illustrates the evolution of k_p value with different hydrate saturations. The larger k_p value, the larger hydrate saturation, because of stronger cementing effects. Finally, a linear relation between k_p value and hydrate saturation S_h is proposed in this study:

Table 1 The model parameters for natural hydrate core specimen

Parameter	Value	Parameter	Expression
e_0	0.54	p'_{t0}/MPa	$(A \cdot S_h^3 + B) \cot \varphi$
ν	0.2	k_p	$C + D \cdot S_h$
M	1.37	b	$E + F \cdot S_h + G \cdot S_h^2$
p_0/MPa	1.0	Where $A = 10$; $B = 0.15$; $C = 3.25$; $D = 45.34$; $E = 4.72$; $F = 97.73$; $G = -219.25$; $\varphi = 33.8$	
λ	0.15		
κ	0.01		

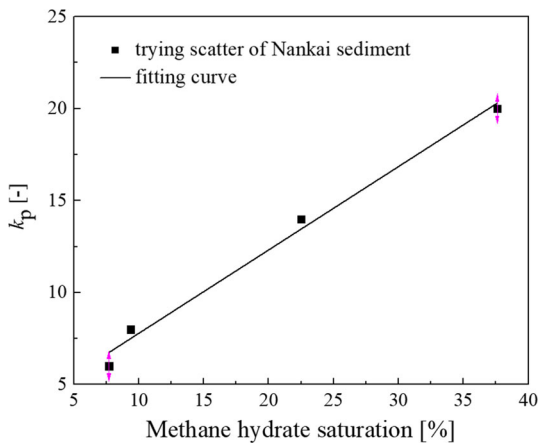


Fig. 2 The evolution of k_p value with different hydrate saturations

$$k_p = C + D \cdot S_h \tag{19}$$

where C and D are material constants. Table 1 shows the variation of these parameters for natural hydrate core specimen.

- Parameter: b
 b presented in Eq. (9), is a modified coefficient, changing with hydrate saturations. Figure 3 illustrates the evolution of b value with different hydrate saturations. In this figure, a quadratic interpolation agrees well with the test result. Therefore, a parabolic fit is employed between b value and S_h parameter in this study:

$$b = E + F \cdot S_h + G \cdot S_h^2 \tag{20}$$

where E , F and G are material constants, presented in Table 1.

GHBS model parameters are calibrated by tri-axial compression tests on natural hydrate core specimen and comparisons of model simulations with test results

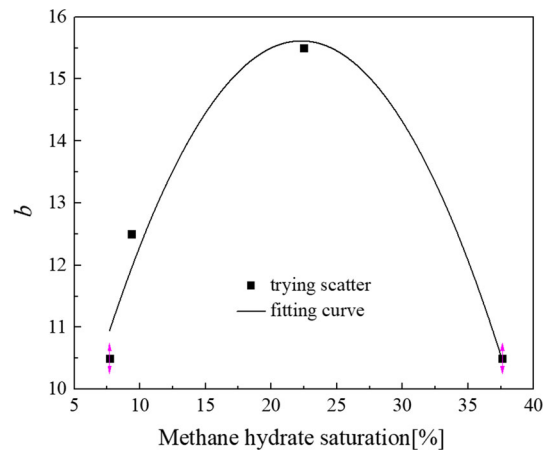


Fig. 3 The evolution of b value with different hydrate saturations

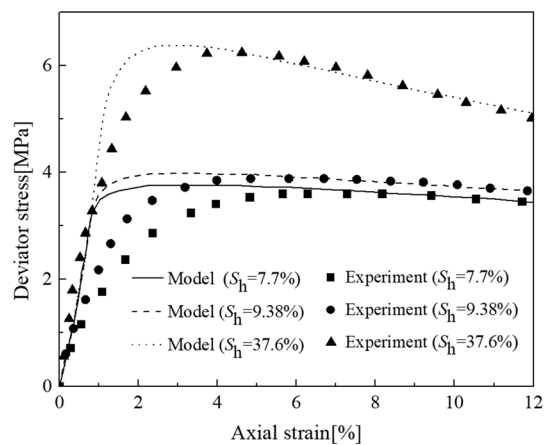


Fig. 4 The comparison of test results of natural hydrate core specimen and model calculations with different hydrate saturations

are presented in Fig. 4. These comparisons are able to

Table 2 The model parameters for Masui sample

Parameter	Value	Parameter	Expression
e_0	0.59	p'_{t0}/MPa	$(A \cdot S_h^3 + B) \cot \varphi$
ν	0.2	k_p	$C + D \cdot S_h$
M	1.4	b	$E + F \cdot S_h + G \cdot S_h^2$
p_0/MPa	1.0	Where $A = 10; B = 0.5; C = 6.32; D = 54.10; E = 3.52; F = 10.39; G = -15.15; \varphi = 34.6$	
λ	0.16		
κ	0.01		

Table 3 The model parameters for Miyazaki sample

Parameter	Value	Parameter	Expression
e_0	0.608	p'_{t0}/MPa	$(A \cdot S_h^3 + B) \cot \varphi$
ν	0.2	k_p	$C + D \cdot S_h$
M	1.37	b	$E + F \cdot S_h + G \cdot S_h^2$
p_0/MPa	1.0	Where $A = 10; B = 0.3; C = 4.49; D = 63.16; E = 4.83; F = 15.15; G = -31.11; \varphi = 33.8$	
λ	0.16		
κ	0.009		

demonstrate the capacity of the proposed model to simulate the mechanical behavior of GHBS.

3.3 Validation of GHBS Model

Test 1 (Masui et al. 2005): Water and sand are used as host specimen of the synthetic methane hydrate, and methane hydrate formation is performed at 278 K with a pore gas pressure of 8.0 MPa and a confining water pressure of 9 MPa. The tri-axial compression tests are carried out on this material at the constant strain rate of 0.1% per minute in the drained condition. With increase in methane hydrate saturation, distinctive strain softening in stress–strain behaviors and peak deviator stresses are obtained in the test results.

Test 2 (Miyazaki et al. 2011): Drained tri-axial compression tests have been conducted on artificial methane hydrate bearing sediment samples under hydrate-stable temperature pressure conditions. Toyoura sand, number 7 silica sand and number 8 silica are employed as the skeleton of each specimen. Axial loading has been applied on the specimens maintaining the same loading rate and experimental temperature as Test 1, and the mechanical behavior of GHBS has been illustrated in the deviator stress-axial strain curves.

According to the experimental results of Test 1 and Test 2 on GHBS, parameters in the proposed model are decided based on the parameter calibration procedures. The required parameters of GHBS model are presented in Table 2 as well as Table 3, and the evolution laws of b and k_p are plotted in Figs. 5 and 6, respectively. Taking into account the calibrated model parameters, model validations are carried out on the studied materials of Test 1 and Test 2. Figures 7 and 8

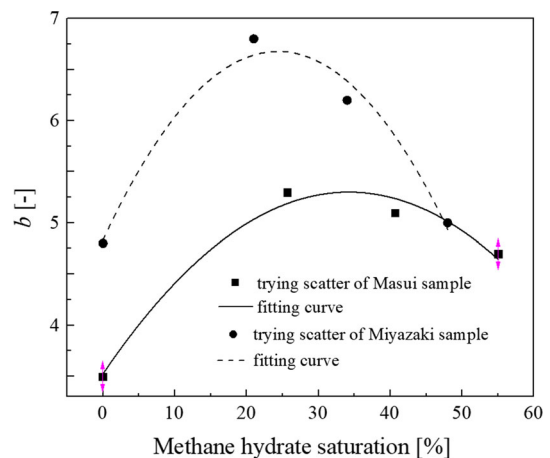


Fig. 5 The evolution of b value with different hydrate saturations of the Miyazaki and Masui sample

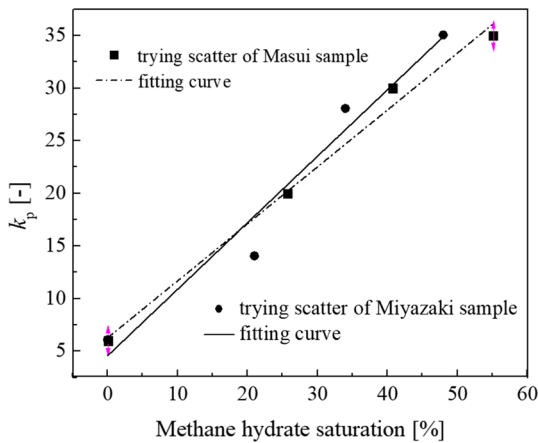


Fig. 6 The evolution of k_p value with different hydrate saturations of the Miyazaki and Masui sample

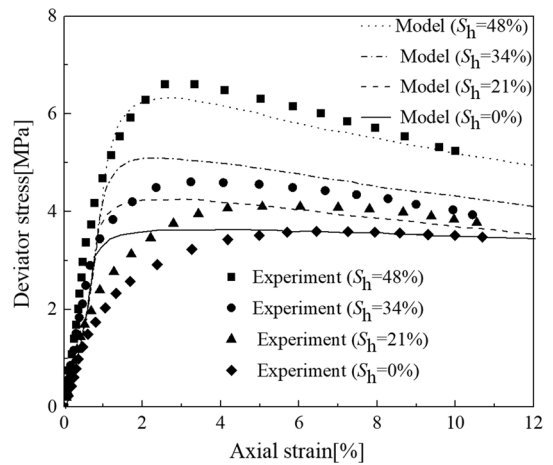


Fig. 8 The comparison of test results of Miyazaki sample and model calculations with different hydrate saturation

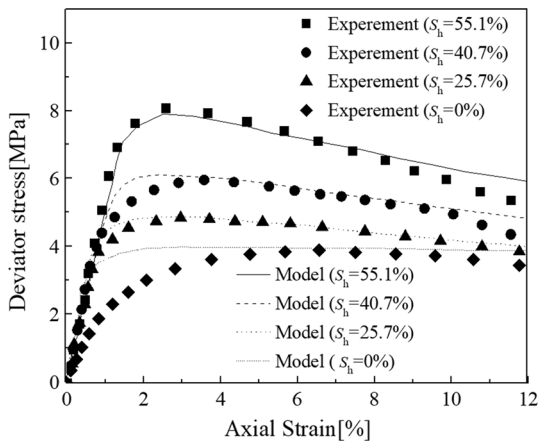


Fig. 7 The comparison of test results of Masui sample and model calculations with different hydrate saturation

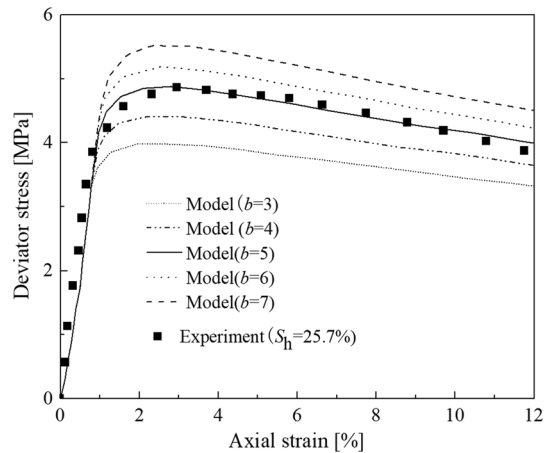


Fig. 9 The model predictions of different b

illustrate the comparisons of model calculations with test results. As can be seen from these figures that the stress–strain results obtained by model predictions are in good agreement with the experimental results.

Model discussion: Apart from Cam Clay model parameters $\lambda, \kappa, \nu, e_0, p_0, M$, the parameters p'_{t0}, b and k_p are also required for the proposed GHBS model with the framework of UH concept. In terms of new parameters, the evolution law of p'_{t0} is identical to the previous model (Masui et al. 2007). Therefore, the influence of different model parameters b and k_p on mechanical behavior of GHBS is studied at the same hydrate saturation. Taking the hydrate saturation of

25.7% for Masui sample for example, Figs. 9 and 10 show the model predictions of different b and k_p at the constant hydrate saturation. In Fig. 10, k_p has a very small impact on the mechanical behavior of GHBS when axial strains are lower than 1.5%. With the increase of k_p , the deviatoric stress decreases and the softening of GHBS is easily occurred. Therefore, the strength of GHBS reduces with k_p increasing. For parameter b in Fig. 9, the larger b , the larger peak value of deviatoric stress, while b has no influence on softening behavior of GHBS because all predicted curves are approximately parallel. Hence, parameter k_p and b are critical model parameters which decide the mechanical behavior of GHBS.

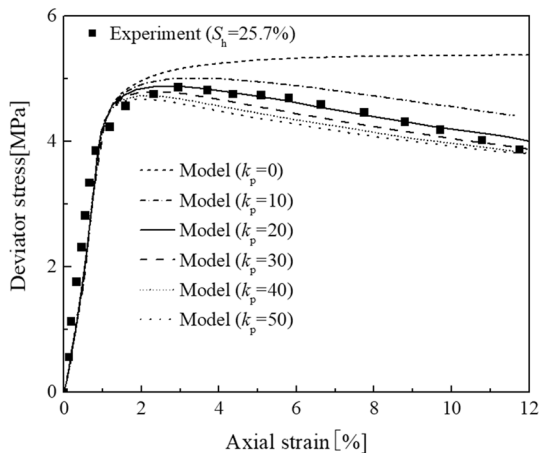


Fig. 10 The model predictions of different k_p

4 Conclusion

To simulate the complex features of GHBS behavior, a constitutive model based on UH concept is presented in this paper. According to the Modified Cam-clay model, the proposed model introduces hydrate saturations and UH parameters to reflect the impact of hydrate cementations on the mechanical behavior of GHBS, including the shear strength, the shear dilation and the softening. In the new model, it contains nine parameters: $\lambda, \kappa, v, e_0, p_0, M, p'_{10}, k_p, b$, where $\lambda, \kappa, v, e_0, p_0, M$ are the same as Modified Cam-clay model. The rest of model parameters are easily determined by the tri-axial compression tests on natural hydrate specimens. The comparisons of the experimental results with the model estimations demonstrate that the proposed model is able to describe the change of soil strength, shear dilation with hydrate saturations. Therefore, the proposed model is verified to be a simple and practical reference for the evaluation of soil deformation and failure behaviors in methane gas extraction. Future programming based on this proposed model in a finite element code can be conducted to simulate the mechanical behavior of GHBS when in situ exploitation is performed.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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