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New constructive model for structures soil

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Abstract. A theoretical study of the behavior of structured soils is presented herein. By introducing the effect of soil structure and loading history into the Cam Clay model, a new model was formulated. The concept of differing void ratios was modified to combine structural parameters and the over consolidation ratio, and an evolution law was proposed. Upon introducing the concept of the subloading yield surface, a new two-yield surface model was obtained. The predicted results were compared to the experimental data, demonstrating that the new model provided satisfactory qualitative modeling of many important features of structured soils.

Keywords: structure; over consolidation; subloading yield surface; constitutive relationships

1. Introduction

Soils develop their natural structure in situ and may become over consolidated, dissimilar to their normal consolidated, reconstituted state (e.g., Burland 1990, Cuccovillo and Coop 1999). Due to their inherent structure and inter-particle cementation, natural clays can sustain higher pressures. For reconstituted clays, the non-linear normal compression line coincides with the linear normal compression line, coupling the degradation of inherent structure to inter-particle cementation (Liu and Carter 2002, Yang *et al*. 2014). At the same time, natural and artificial unloading processes allow natural clays to become over consolidated. The loading history has a significant effect on the behavior of natural clays, increasing the complexity of modeling the mechanical behavior of natural clays.

According to Burland (1990), the properties of a reconstituted soil can be referred to as intrinsic properties, and models based on reconstituted clays can be extended to consider the effects of their inherent structure and inter-particle cementation. Recently, important developments in the production of constitutive models have been made to account for the effects of the inherent structure and inter-particle cementation of natural clays, such as those proposed by Rouainia and Muir Wood (2000), Liu and Carter (2002), Suebsuk *et al*. (2011), Asaoka *et al*. (2000) and Hashiguchi and Mase (2007). Although these models are different, they are all variants of the isotropic critical state Modified Cam Clay model and can successfully describe the main features

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of natural clays. Meanwhile, some useful mechanical concepts that account for the effect of the loading history have been presented, including the subloading yield surface, which was proposed by Hashiguchi and Ueno (1977). The Superloading Modified Cam Clay model presented by Asaoka *et al*. (2000) is based on the concept of a subloading yield surface with a superloading yield surface and was introduced to reflect the effects of the inherent structure. Suebsuk *et al*. (2011) presented a critical sate model for over consolidated structured clays containing a bounding surface to account for the cohesion and strain softening of naturally structured stiff clays.

In this paper, a new two-yield surface elasto-plastic model, referred to as the Structured Subloading Cam Clay Model, is presented. Using a simple expression, the difference voids ratio proposed by Nakai and Hinokio (2004) was extended to contain the over consolidation ratio (*OCR*) and the structural parameter *B*. The extended difference voids ratio directly relates the structured subloading yield surface and the normalized yield surface. Variability in the relative location of the two-yield surfaces is governed by the evolution law of the extended difference voids ratio. The results calculated by the proposed model were compared to published experimental data, and the insights obtained by this comparison are discussed herein. The results showed that the proposed model is capable of describing the effects of the inherent structure and loading history on natural clays.

2. Generalization of the structured subloading cam clay model

The formation and development of soil structure often produces anisotropy in the mechanical response of soil to changes in stress and destructuring, which usually leads to a reduction in anisotropy (Liu and Carter 2002). In this paper, only the isotropic effects of the inherent structure and loading history were considered.

2.1 Influence of soil structure on virgin isotropic compression

As illustrated by Yang *et al*. (2014), the most characteristic feature of natural clays is its non-linearity in the e–lnp' plane, compared to the normal compression line of reconstituted clay. In the aforementioned work, the compression index, λ, was assumed to depend on the degradation of inherent structure. Liu and Cater (2002) implemented a simple expression to characterize the normal compression line of natural clays, which was adopted in this paper to reflect the evolution of the structure parameter B without considering the effects of shearing.

As shown in Fig. 1, the structural normal compression line (denoted as SCL) for most of the structural clays was located well above the corresponding intrinsic normal compression line (denoted as NCL), indicating that structured natural clays can sustain higher pressures. The destruction and loading history of a soil has a significant effect on the relative location of the SCL and NCL. At the beginning of the isotropic compression test, the void ratio of structured natural clays decreases slowly, and the volume change can be regarded as elastic deformation. After virgin yielding begins, the void ratio decreases dramatically, compared to the degradation process. According to Liu and Cater (2002), the structured compression line can be described by the following equation

$$e = e_{IC}^{*} + \Delta e_i \left(\frac{p'_{y,i}}{p'} \right)^{b} - \lambda \ln p' \tag{1}$$

where e^*_{IC} is the voids ratio of reconstituted soil when p' = 1 kPa during virgin isotropic compression, Δe_i is the additional void space at $p' = p'_{y,i}$, where virgin yielding of the structured soil begins, and b is the destruction index due to volumetric deformation. If the void ratios of the structured natural clay and reconstituted clay are the same at the reference pressure, Δe_i can be expressed as

$$\Delta e_i = (\lambda - \kappa)\ln\left(\frac{p'_{y,i}}{p'}\right) \tag{2}$$

where p'_r = 1 kPa.

2.2 Modified difference in the void ratios

A structured natural clay can be compressed to point J along the SCL, then unloaded to point A along the swelling line, as shown in Fig. 2. Along the SCL, the structure degenerated gradually during the compressive process due to compression, and the loading process causes the structured natural clay to become over consolidated. Therefore, based on the definition of the over consolidation ratio (denoted as *OCR*), the *OCR* can be expressed as

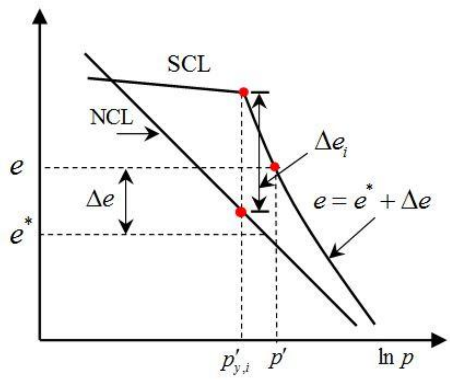

Fig. 1 Isotropic compression lines of reconstituted and structured soils

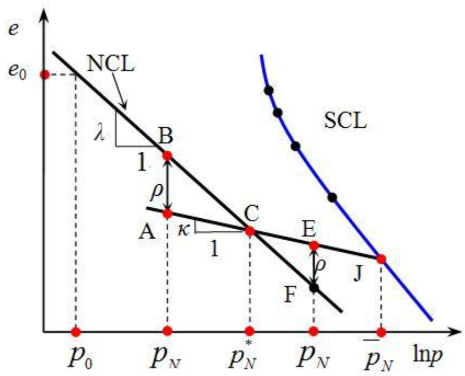

Fig. 2 Concept of the modified difference in the voids ratio

$$OCR = \bar{p}_N / p_N \tag{3}$$

where $\bar{p}_N$ is the pre-consolidation stress of the structured natural clay, and p_N is the current effective mean stress. Due to the inherent structure of natural clay, the value of the *OCR* may be less than 1, and the clay may be regarded as under consolidated soil.

To consider the effect of the inherent structure, the quantitative index of the inherent structure should be introduced. During the unloading process, elastic deformation will be recovered, and the inherent structure remains unchanged; thus, the inherent structure can be quantified according to the relative location of the NCL and SCL. In the present study, a new state variable (*B*) for the inherent structure was introduced and was defined as

$$B = p_N^* / \bar{p}_N \tag{4}$$

where p_N^* is the consolidation stress of the reconstituted soil. The value of *B* can range between 0 and 1, and *B* has a similar meaning to the soil sensibility index.

The concept of ρ is used to express the relationship between the present stress state and the normal consolidation state. Considering Eqs. (3)-(4), ρ was expressed based on the work of Nakai (2004) and was extended as

$$\rho = (\lambda - \kappa)\ln\left(\frac{p_N^*}{p_N}\right) = (\lambda - \kappa)\ln(OCR \cdot B) \tag{5}$$

Although Eq. (5) is simple, the relation is significant to the proposed model, which contains the inherent structure and over consolidation ratio in a single expression. If structured natural clay is reconstituted, the SCL will coincide with the NCL and B = 1. As a result, the concept of ρ will regress to the original meaning proposed by Nakai (2004).

For structured natural clays, inherent structure degradation is caused by plastic strain, which includes plastic volume strain and plastic shear strain. However, during the isotropic compression test, plastic shear strain does not occur, and the inherent structure degradation is dependent on plastic volume strain. Thus, the structure parameter *B* should be a function of the effective mean stress when shearing is not considered.

For normal consolidated structured soils, the initial stress points lie on the structured normal compression line (SCL), and the initial value of the structural parameter *B* changes as a function of the confining pressure. However, if the structured soil has a loading history, the soil becomes over consolidated, and the initial stress point lies on the structured swelling line. During unloading process, the elastic deformation is recovered, the inherent structure will not be damaged and the swelling index κ remains constant. According to the definition of the structure parameter *B*, the value of *B* does not change at different confining pressures.

As shown in Fig. 2, when a structural material is compressed to point J along the SCL, then unloaded to point C along the swelling line, the void ratio of point C can be easily calculated according Eq. (1)

$$e_c = e_{IC}^* + \Delta e_i\left(\frac{p'_{y,i}}{\bar{p}_N}\right)^b - \lambda \ln \bar{p} - \kappa\left(\frac{\bar{p}_N}{p_N}\right) \tag{6}$$

Because point C lies on the normal compression line (NCL), the void ratio can also be calculated

$$e_C = e_{IC}^* - \lambda \ln p_N^* \tag{7}$$

Combining Eqs. (4), (6) and (7), the relationship between the structure parameter $B$and the effective mean stress can be described as

Table 1 Material parameters for structured natural clay

Parameter	v	e_{IC}^*	$p'_{y,i}$ (kPa)	λ	κ
Value	0.25	2.37	104.2	0.16	0.05

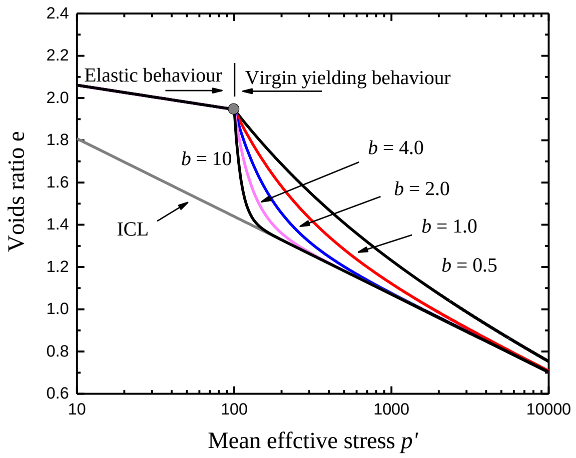

Fig. 3 The e-ln$p$' curves of structured natural clays with various b values

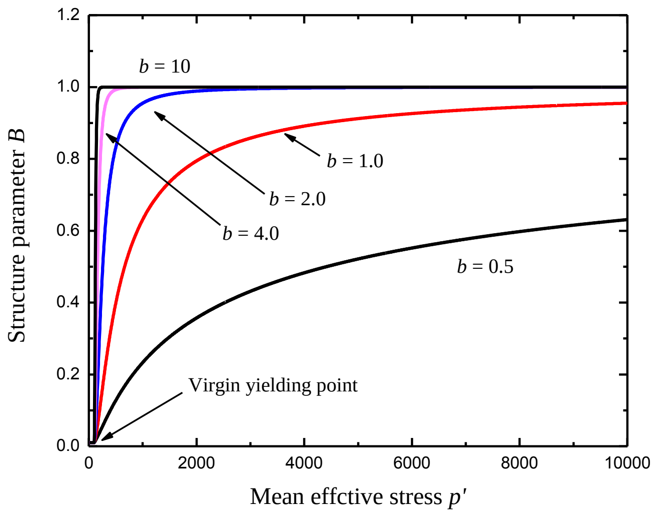

Fig. 4 The evolution of B without considering the effect of shear strain

Table 2 Material parameters for cemented Ariake clay

Amount of cement	ν	e^{*}_{IC}	$p'_{y,i}$ (kPa)	λ	κ	b
A_w = 6%	0.25	4.37	60.5	0.44	0.06	0.25
A_w = 9%	0.25	4.37	270.2	0.44	0.03	0.2
A_w = 18%	0.25	3.8	2000.0	0.44	0.01	0.1

$$B = \exp\left\{ \frac{\Delta e_i}{\kappa - \lambda} \cdot \left(\frac{p'_{y,i}}{\bar{p}_N} \right)^b \right\} \tag{8}$$

Here, $\bar{p}_N$ is the preconsolidation stress.

Fig. 3shows the effect of the destruction index b on the structured normal compression line, and the model parameters are given in Table 1. The rate of reduction in the additional voids ratio, which is maintained by the inherent structure, increases with an increase in the magnitude of b. At the beginning of isotropic compression, structured natural clays show elastic deformation without structure degradation.

Fig. 5 compares the model simulation results with the measured data for cemented Ariake clay with different cement contents, and the degradation of inherent structure in the absence of shear strain is shown in Fig. 6. The results indicated that samples with higher cement contents exhibited less destruction, which is controlled by b.

As mentioned above, the degradation of the inherent structure is induced by plastic strain, and the effect of shear strain should be considered during the shear test. In the following sections, a new elasto-plastic model will be proposed with extended difference void ratios, ρ, and a reasonable developing law of ρ will be presented, concluding the effect of shear strain on the inherent structure degradation. Eq. (8) will be used to define the initial structure parameter B at the beginning of the triaxial tests.

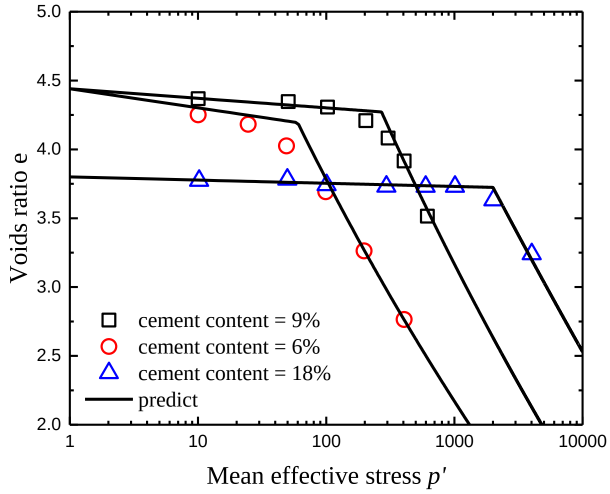

Fig. 5 The e-lnp' curves of Ariake clay with various cement contents

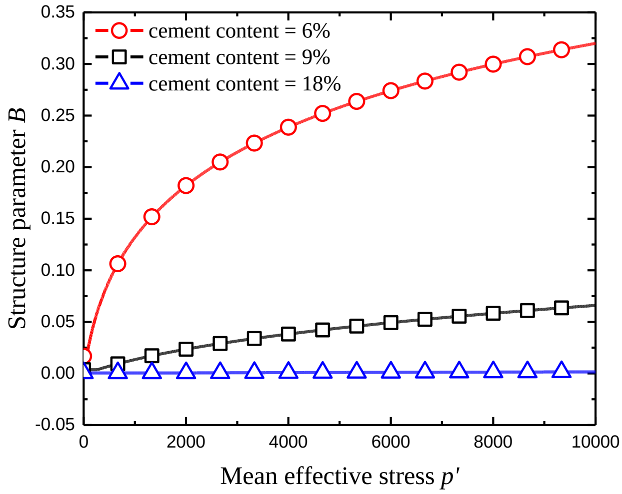

Fig. 6 The evolution of *B*at various cement contents (data by Suebsuk *et al*. 2011)

2.3 Structured subloading yield surface

In situ, the structured natural clays always display varying degrees of over consolidation, which is induced by the loading history. The loading-unloading-reloading cycle promotes additional plastic deformation, and the loading history has a significant effect on the structured natural clays. The subloading yield surface proposed by Hashiguchi and Mase (2007) accurately describes the effect of the loading history and was extended to reflect the mechanical behavior of structured natural clays, according to the extended difference void ratios, ρ. The subloading yield surface has the following features:

(1) The subloading yield surface has a continuous, smooth, elastic-plastic stress-strain relationship.
(2) The subloading yield surface passes though the current stress point and is geometrically similar to the normal yield surface.

As shown in Fig. 7, a new structured subloading yield surface, f_s, has been presented according

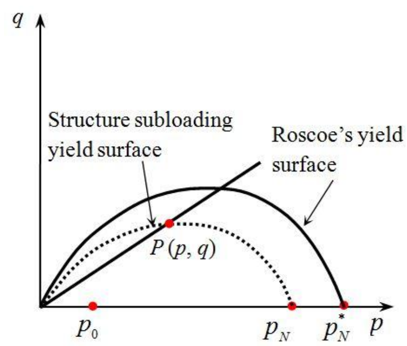

Fig. 7 Concepts of the structured subloading yield surface and the normal yield surface

to the extended difference void ratios, ρ. The structured subloading yield surface passes through the current stress state P, and can be expressed as follows in the normal stress space.

$$f_s = \ln\frac{\sigma_m}{\sigma_{m0}} + \frac{\sqrt{3}}{M}\frac{\sqrt{J_2}}{\sigma_m} - \frac{1}{C_p}\left(\varepsilon_v^p - \frac{\rho}{1+e_0}\right) = 0 \tag{9}$$

where σ_m is the mean stress (= $\sigma_{ij}\delta_{ij}$ / 3, δ_{ij} is the Kronecker tensor), e_0 is the void ratio at the reference mean stress, σ_m0, J_2 is the second invariant of the deviatoric stress tensor s_{ij} ((= $\sigma_{ij} - I_1\delta_{ij}$ / 3), where I_1 is the first invariant of the stress tensor), M is the ratio of the shearing stress at the critical state, and ε_v^p is the plastic volumetric strain and is defined as $C_p = (\lambda - \kappa) / (1 + e_0)$.

The structured subloading yield surface may be outside of the normal yield surface when ρ <0, which is indicative of a unique natural clay with a heavily inherent structure. This feature is quite different from the previous models and contributes a flexible description of the mechanical behavior of structured natural clays.

The associated flow rule was adopted, and the plastic strain was calculated as

$$d\varepsilon_{ij}^p = \Lambda\frac{\partial f_s}{\partial \sigma_{ij}} \qquad \text{and} \qquad d\varepsilon_v^p = \Lambda\frac{\partial f_s}{\partial \sigma_{ii}} \tag{10}$$

The consistency equation of the proposed model was obtained as

$$\frac{\partial f_s}{\partial \sigma_{ij}}d\sigma_{ij} - \frac{1}{C_p}d\varepsilon_v^p + \frac{1}{C_p(1+e_0)}d\rho = 0 \tag{11}$$

where

$$\frac{\partial f_s}{\partial \sigma_{ij}} = \left(\frac{1}{\sigma_m} - \frac{\sqrt{3}}{M}\frac{\sqrt{J_2}}{\sigma_m^2}\right)\frac{\delta_{ij}}{3} + \frac{\sqrt{3}}{M}\frac{s_{ij}}{2\sqrt{J_2}}\frac{1}{\sigma_m} \tag{12}$$

$$\frac{\partial f_s}{\partial \sigma_{ii}} = \left(\frac{1}{\sigma_m} - \frac{\sqrt{3}}{M}\frac{\sqrt{J_2}}{\sigma_m^2}\right) \tag{13}$$

The evolution law for ρ reflects the development of the over consolidation ratio, *OCR*, and the structure parameter, *B*, especially the contribution of plastic shear strain to the degradation process of structured natural clays. Zhang *et al*. (2005) investigated the evolution of ρ but assumed that over consolidation disappeared, evolution was dependent on the present value of ρ and σ_m, and evolution was proportional to the positive variable Λ. Although the difference in void ratios between the normal consolidation state and the present stress state was extended from reconstituted clays to structural natural clays, the evolution equation for the extended ρ was formulated similarly.

$$-\frac{1}{1+e_0}d\rho = g(\sigma_m, B, OCR)\Lambda \tag{14}$$

where g (σ_m, B, OCR) is a function of σ_m, B and OCR. Outside factors such as the temperature will affect the evolution equation for the extended ρ (Zhang and Zhang 2009, Zhang *et al*. 2012). Thus, only the loading pressure was considered in the present study.

The destructing process of structured soils during loading is generally considered to be irreversible and is induced by plastic deformation (Liu and Carter 2002, Asoka *et al*. 2000, Hashiguchi and Mase 2007). Based on the work of Hashiguchi and Mase (2007) and Huang *et al*. (2011), the evolution law of the structure parameter B can be expressed as follows

$$dB = \beta \ln B \cdot d\varepsilon_d^p \tag{15}$$

Where β is a material parameter that controls the rate of destruction, and $d\varepsilon_d^p$ is the equivalent plastic deformation and can be described as

$$d\varepsilon_d^p = \sqrt{(1-R)\cdot\left(d\varepsilon_v^p\right)^2 + R\cdot\left(d\varepsilon_s^p\right)^2} \tag{16}$$

where $d\varepsilon_v^p$ is the change in plastic volumetric strain, $d\varepsilon_s^p$ is the change in plastic shear strain and R is a non-dimensional scaling parameter that controls the relative contribution to the change in destruction of volumetric and distortional plastic strain, $d\varepsilon_v^p$ and $d\varepsilon_s^p$, respectively. Eqs. (15)-(16) suggest that destruction is entirely distortional when R = 1, while destruction is entirely volumetric when R = 0.

As mentioned above, the evaluation law of the modified ρ has a similar form as the expression proposed by Zhang *et al*. (2005). Thus, referring to the evaluation of the structure parameter B described in Zhang *et al*. (2005), which indicated g (σ_m, B, OCR) and considered that over consolidation disappeared and destruction occurred, the evolution of ρ can be described as

$$d\rho = -(1+e_0)\cdot\frac{\alpha[\rho-(\lambda-\kappa)\ln B]}{\sigma_m}\cdot\Lambda - (\lambda-\kappa)\frac{1}{\sigma_m}\beta\ln B\cdot\Lambda \tag{17}$$

where α is the material parameter that controls the rate of disappearance of the over consolidation ratio. The evaluation law for ρ was divided into two parts to separately consider the effect of the loss of over consolidation and the occurrence of destruction.

By substituting Eqs. (12), (13) and (17) into Eq. (11), the value of Λ was determined

$$\Lambda = \frac{\dfrac{\partial f_s}{\partial \sigma_{ij}} d\sigma_{ij}}{h_{ps}/C_p} \tag{18}$$

where

$$h_{ps} = \frac{\partial f_s}{\partial \sigma_{ii}} + g(\sigma_m, B, OCR) \tag{19}$$

The loading criteria were expressed as

$$\left\| d\varepsilon_{ij}^{p} \right\| > 0 \quad \text{if} \quad \Lambda > 0 \quad \text{and} \quad \begin{cases} \dfrac{\partial f_s}{\partial \sigma_{ij}} d\sigma_{ij} > 0 \; hardening \\ \dfrac{\partial f_s}{\partial \sigma_{ij}} d\sigma_{ij} > 0 \; softening \end{cases} \tag{20}$$

$$\left\| d\varepsilon_{ij}^{p} \right\| = 0 \quad \text{if} \quad \Lambda \le 0 \quad \text{elastic} \tag{21}$$

Considering the effects of the inherent structure and the loading history, the proposed model is a two-yield surface model, and the relative location of the two-yield surface is governed by the value of the extended difference void ratios. Compared to previous models for structured natural clays, the proposed model is more flexible and can be implemented easily.

3. Performance of the proposed model

In this section, the results of the parameter tests that were performed to investigate the effect of parameter α and β on the strain-stress curves of structured natural clays are discussed. To consider the effect of the loading history, structured natural clays were assumed to be over-consolidated, and the *OCR* was set to 16. The Poisson's ratio of soils, referred as v, is hard to determined using laboratory tests, and in this simulation, it is assumed to be 0.25. The material parameters are presented in Tables 3-4, and the value of parameter α and β were changed separately.

The strain-stress curves of structured clay with different values of α are shown in Fig. 8, while curves corresponding to different values of β are plotted in Fig. 9. The calculated results indicated that the maximum strength of clay gradually increased with an increase in the parameter α, and the clay tended to become more brittle as the axial strain of the maximum strength decreased gradually (Fig. 8). Parameter β affected the maximum strength of the clay significantly: as the value of β increased from 0.5 to 10, the maximum strength of the clay increased by 28% (Fig. 9).

Next, the performance of the proposed model was evaluated by comparing the results obtained herein to the consolidated-undrained triaxial test results for Shanghai soft clay (Huang *et al*. 2011). The basic properties of Shanghai soft soil are summarized in Tables 5-6, and Fig. 10 shows the e-lnp' curve of Shanghai soft soil. Fig. 11 presents the predicted and measured strain-stress curves for Shanghai soft clay at confining pressures of 100, 150 and 200 kPa. Although several disparities between the predicted and measured results were observed in the peak strength, the results were

Table 3 Material parameters for structured soft clay

Parameter	ν	e_{IC}^{*}	$p'_{y,i}$ (kPa)	b
Value	0.25	2.37	650.0	0.5

Table 4 Material parameters of structured soft clay

Parameter	M	λ	κ	OCR	R
Value	1.275	0.095	0.0082	16.0	0.5

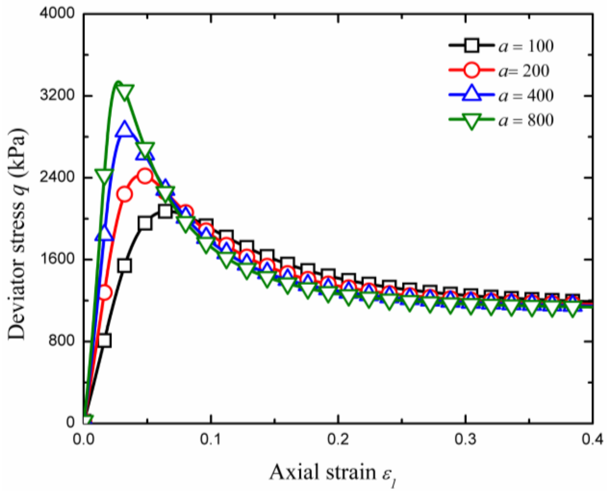

Fig. 8 The strain-stress curves of structured clay with various values of α

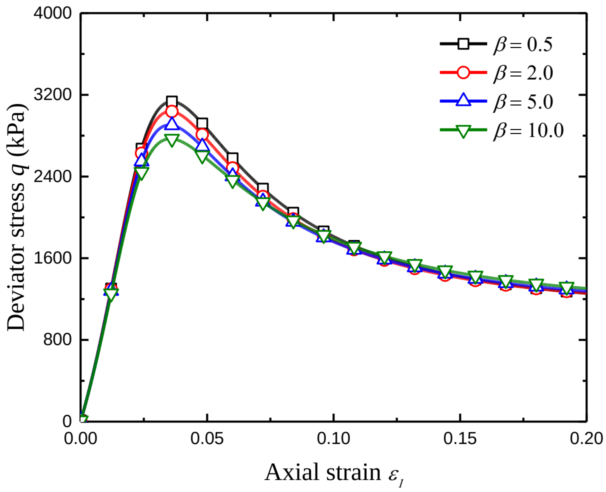

Fig. 9 The strain-stress curves of structured clay with various values of β

Table 5 Material parameters of structured soft clay

Parameter	ν	e^*_{IC}	$p'_{y,i}$ (kPa)	b
Value	0.2	1.402	104.2	3.4

acceptable, with less than 8% error. Fig. 12 displays the predicted and measured stress paths for Shanghai soft clay, which indicated that the proposed model could accurately describe the stress paths for Shanghai soft clay. According to the measured results, the stress paths for Shanghai soft clay tended to approach the critical state line, due to the degradation of the inherent structure. As shown in Figs. 11-12, the predictions of the proposed model were in agreement with the experimental results.

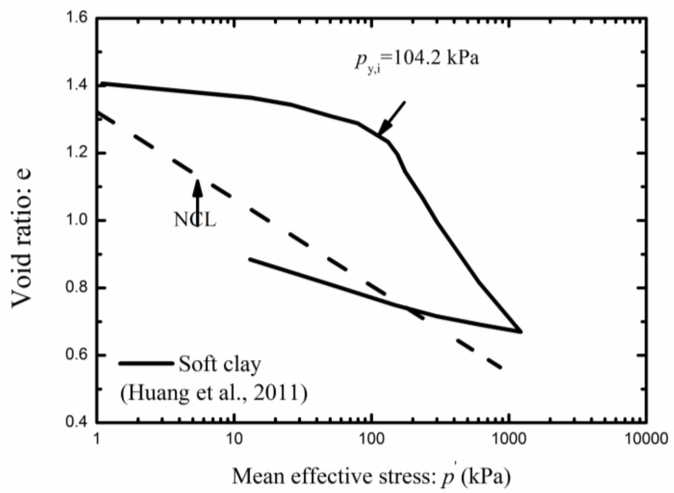

Fig. 10 1-D Compression behavior of Shanghaisoft clay

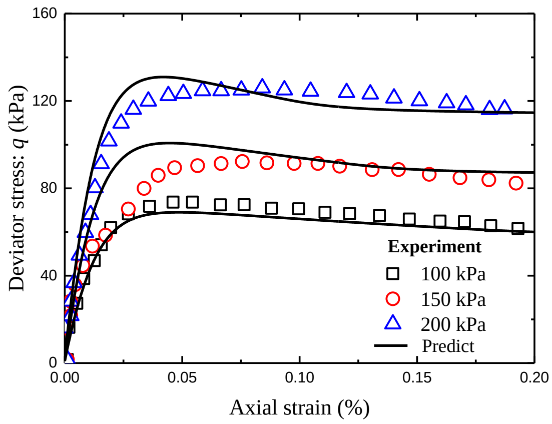

Fig. 11 The strain-stress curves of Shanghai soft clay at various confining pressures

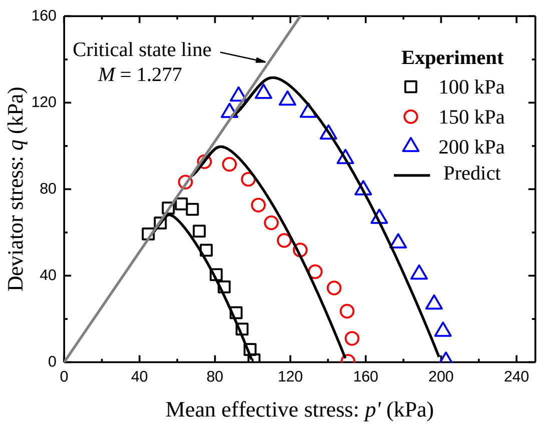

Fig. 12 The stress paths of Shanghai soft clay at various confining pressures

Table 6 Material parameters of structured soft clay

Parameter	*M*	*λ*	*κ*	*OCR*	*α*	*β*	*R*
Value	1.277	0.142	0.062	1.0	500	13.0	0.5

4. Conclusions

In the present study, the difference voids ratio proposed by Nakai and Hinokio (2004) were extended to consider the over consolidation ratio and structural parameters in a simple equation. As a result, a new elasto-plastic model for structured natural clays was developed, and the proposed model possessed the following features:

(1) The structure parameter *B* was defined according to the relative location of the structured normal compression line and the referenced normal compression line. Without considering shear strain, *B* was a function of the effective mean stress and could be used to define the initial structure parameters at the beginning of the triaxial test.

(2) The structured subloading yield surface was introduced, and the relative location between the structured subloading yield surface and normal yield surface in *p*-*q* space was governed by the extended difference void ratios.

(3) The effect of plastic shear strain on the degradation of the inherent structure was included in the development law for extended difference void ratios.

(4) The proposed model was flexible and accurately described the effects of the inherent structure and loading history in a simple manner. The predictions of the model and the experimental data were compared, proving that satisfactory qualitative modeling of the behavior of structured soils was achieved using the proposed model.

Acknowledgments

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