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Modified Structured Cam Clay: A generalised critical state model for destructured, naturally structured and artificially structured clays

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ABSTRACT

This paper presents a generalised constitutive model for destructured, naturally structured and artificially structured clays that extends the Structured Cam Clay (SCC) model. This model is designated as "Modified Structured Cam Clay (MSCC) model". The influence of structure and destructuring on the mechanical behaviour of clay can be explained by the change in the modified effective stress, which is the sum of the current mean effective stress and the additional mean effective stress due to structure (structure strength). The presence of structure increases the modified mean effective stress and yield surface, enhancing the cohesion, peak strength and stiffness. The destructuring begins when the stress state is on the virgin yield surface. After the failure (peak strength) state, the abrupt destructuring occurs as the soil–cementation structure is crushed; hence the strain softening. The soil structure is completely removed at the critical state when the yield surface becomes identical to the destructured surface. The destructuring law is proposed based on this premise. In the MSCC model, the yield function is the same shape as that of the Modified Cam Clay (MCC) model. A plastic potential is introduced so as to account for the influence of structure on the plastic strain direction for both hardening and softening behaviours. The required model parameters are divided into those describing destructured properties and those describing structured properties. All the parameters have physical meaning and can be simply determined from the conventional triaxial tests. Thus, the MSCC model is a useful tool for geotechnical practitioners. The capability of the model is verified by the test results of destructured, natural structured and artificially structured clays.

1. Introduction

The inherent nature and diversity of the geotechnical process involved in soil formation are responsible for the wide variation in soil structure. Natural clay can be designated as "structured clay" [31,32,45,55]. The term "soil structure" is determined by both the particle associations and arrangements (fabric) and inter-particle forces (soil–cementation or bonding). The resistance of soil structure is responsible for the difference in the engineering behaviour of natural soils between the structured and destructured (remoulded) states [32,16,33,34,45,55,22]. The development of soil structure during the depositional and post-depositional processes has been reported by many researchers [41,44,53].

To improve soft ground with a chemical admixture such as the in situ deep mixing technique, the natural clay is disturbed by mixing wings and mixed with cement or lime. The natural structure is destroyed and taken over by the cementation structure. The cement- or lime-admixed clay is thus designated as "artificially structured clay". The mechanical properties of artificially structured clay have been investigated extensively [61,9,58,17,46,48,24,18,20].

In recent years, the rapid advances in computer hardware and the associated reduction in cost have resulted in a marked increase in the use of numerical methods to analyse geotechnical problems. The ability of such methods to provide realistic predictions depends on the accuracy of the constitutive model used to represent the mechanical behaviour of the soil. There has been great progress in constitutive modelling of the behaviour of soil with natural structure, such as those proposed by Gens and Nova [15] and Vatsala et al. [59]. Some frontier research in understanding and modelling the degradation of soil structure includes a kinematic hardening model [27,52,4]. Most of the previous constitutive models are, however, generally complicated and their model

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Nomenclature

b	destructuring index due to volumetric deformation
CSL	critical state line
$\delta\varepsilon_v$	volumetric strain increment
$\delta\varepsilon_v^e$	elastic volumetric strain increment
$\delta\varepsilon_v^p$	plastic volumetric strain increment
$\delta\varepsilon_d$	deviatoric strain increment
$\delta\varepsilon_d^e$	elastic deviatoric strain increment
$\delta\varepsilon_d^p$	plastic deviatoric strain increment
Δe	additional voids ratio sustained by soil structure
Δe_i	additional voids ratio sustained by soil structure at the initial virgin yielding
e	voids ratio
e_{IC}^*	voids ratio at a reference pressure (1 kPa) of the ICL
G'	shear modulus in terms of effective stress
ICL	intrinsic compression line (of destructured soil)
K'	bulk modulus in terms of effective stress
ξ	destructuring index due to shear deformation
κ	gradient of unloading or swelling line of structured clay
λ^*	gradient of isotropic compression line of destructured clay
M	gradient of critical state line in the q–p' plane
η	stress ratio, q/p'
$\bar{\eta}$	modified stress ratio, $q/(p' + p'_b)$
μ'	Poisson ratio in terms of effective stress
p'	mean effective stress
$\bar{p}'$	modified mean effective stress
p'_b	mean effective stress increasing due to structure or structure strength
p'_0	stress history or isotropic yield stress
p'_{b0}	initial structure strength in the q–p' plane
p'_p	parameter for describing the size of plastic potential
$p'_{y,i}$	initial yield stress
q	deviatoric stress
ψ	parameter defining shape of the plastic potential
σ'_c	effective confining pressure
θ	Lode angle

parameters are difficult to identify in practice and do not take into account the key features of artificially structured clay, especially the crushing of soil–cementation structure [19].

Recently, there have been many models for structured clay developed based on the Modified Cam Clay (MCC) model due to its simple pattern recognition. Chai et al. [8] have introduced the influence of structure on the compression behaviour and then modified the equation to predict plastic volumetric strain of the MCC model. Their model can simulate the volumetric deformation behaviour of naturally structured clay well. Liu and Carter [37] and Carter and Liu [7] introduced a simple predictive model, the Structured Cam Clay (SCC) model, for naturally structured clay. It has been formulated elegantly by introducing the influence of structure on the volumetric deformation behaviour and the plastic strain direction into the MCC model. The influence of structure on volumetric deformation is taken into account by the additional voids ratio that is sustained by the soil structure (Δe). The destructuring law due to volumetric deformation has been proposed as a decreasing function of the Δe. The concept of the development of the non-associated flow rule adopted in the SCC model is similar to that made by McDowell and Hau [43] for hard clay and sand, and by Horpibulsuk et al. [19] for artificially structured clay. Both the SCC model and the model proposed by Chai et al. [8] have not considered the influence of structure on strength characteristics (especially cohesion) and softening behaviour when stress states are on virgin yielding state. Cohesion is significant especially for stiff naturally structured clays [6] and artificially structured clays [61,9]. To explain the influence of structure on strength characteristics, Gens and Nova [15], Kasama et al. [26] and Lee et al. [30] have introduced the modified effective stress concept. Based on this concept and the critical state framework, Kasama et al. [26] have introduced a model that can predict the strength characteristics for artificially structured clay in normally and lightly over-consolidated states well. However, their model cannot describe the strain softening in virgin yielding state, which is generally observed as the soil–cementation structure is crushed [46,48,59,20,21]. In the models proposed by Chai et al. [8], Kasama et al. [26] and Lee et al. [30], the associated flow rule was adopted. Thus, those models cannot explain the influence of structure on the plastic strain direction, unlike the SCC model.

To form a model suitable for structured clay based on the critical state framework, the influence of structure and destructuring on the yield function, hardening rule and plastic potential must be incorporated. Recently, Horpibulsuk et al. [19] have summarised the main features of cemented clay behaviour and introduced the SCC model for cemented clay. In the model, the effective stress concept, yield function, hardening rule and plastic potential have been developed to take into account the effect of structure. Their model can simulate shear behaviour for both normally and lightly over-consolidated states. Some modifications are needed, however, to simply and practically implement the model for numerical analysis and to better capture the main features of the artificially structured clay with the model parameters simply obtained from a conventional laboratory.

In this paper, attempts are made to develop a generalised constitutive model based on the critical state framework for destructured, naturally structured and artificially structured clays. The proposed model, designated as the Modified Structured Cam Clay (MSCC) model, is formulated based on the SCC model for cemented clay [19]. In this paper, based on a quantitative examination of test data describing the behaviour of cemented soils, the application of the modified effective stress concept to describe the compression and shear behaviour of structured clays is illustrated, and the yield function, hardening rule and plastic potential are developed based on the modified effective stress concept. A new plastic potential that reliably describes the effect of soil structure is introduced. A new general destructuring law that describes the degradation and crushing of the structure is also proposed. In this law, the destructuring is assumed to depend on the plastic distortional strain. Both new plastic potential and destructuring law better explain and simulate the structured clay behaviour than those of the original models [37,19]. The MSCC model is verified by simulating the undrained and drained shear behaviour of destructured, naturally structured and artificially structured clays under a wide range of pre-shear consolidation pressure (both in normally and over-consolidated states). The naturally structured clays are Osaka clay [1] and Marl clay [2], and the artificially structured clays are cemented Araike clay [17,20] and cemented Bangkok clay [58]. The simulated shear behaviour of the same clay in both destructured and structured states using the same destructured model parameters is illustrated by the test results of destructured and artificially structured Ariake clay. This shows an advantage of the MSCC model using the destructured state as a reference.

2. Conceptual framework of the MSCC model

The MSCC model is developed by generalising the theoretical framework of the SCC model [37,7,19]. The major aim of formulating the MSCC model is to provide a constitutive model that is suitable for the routinely solving boundary value problems encountered in geotechnical engineering practice. Therefore, it is necessary to keep the model relatively simple. The model parameters can be simply determined from conventional compression and triaxial tests.

The stress and strain quantities used in the present formulation are defined as follows. σ'_{ij} and ε_{ij} are the Cartesian components of effective stress and strain, respectively. The simplified forms for stress and strain conditions in conventional triaxial tests are also listed, where σ'_1 (or ε_1) and σ'_3 (or ε_3) are the axial effective stress (strain) and the radial effective stress (strain), respectively.

The mean effective stress, p', deviatoric stress, q, and stress ratio, η are given by,

$$p' = \frac{1}{3}(\sigma'_{11} + \sigma'_{22} + \sigma'_{33}), \quad (1a)$$

$$= \frac{1}{3}(\sigma'_1 + 2\sigma'_3) \quad \text{for conventional triaxial tests}, \quad (1b)$$

$$q = \left[\frac{(\sigma'_{11} - \sigma'_{22})^2 + (\sigma'_{33} - \sigma'_{11})^2 + (\sigma'_{22} - \sigma'_{33})^2}{2} + 3(\sigma'^2_{12} + \sigma'^2_{23} + \sigma'^2_{31})\right]^{\frac{1}{2}}, \quad (2a)$$

$$= \sigma'_1 - \sigma'_3 \quad \text{for conventional triaxial tests}, \quad (2b)$$

and

$$\eta = \frac{q}{p'}. \quad (3)$$

Corresponding to the stress parameters, volumetric strain, $\delta\varepsilon_v$, and deviatoric strain, $\delta\varepsilon_d$, are defined as follows,

$$\delta\varepsilon_v = \delta\varepsilon_{11} + \delta\varepsilon_{22} + \delta\varepsilon_{33}, \quad (4a)$$

$$= \delta\varepsilon_1 + 2\delta\varepsilon_3 \quad \text{for conventional triaxial tests}, \quad (4b)$$

and

$$\delta\varepsilon_d = \frac{\sqrt{2}}{3}\left((\delta\varepsilon_{11} - \delta\varepsilon_{22})^2 + (\delta\varepsilon_{22} - \delta\varepsilon_{33})^2 + (\delta\varepsilon_{33} - \delta\varepsilon_{11})^2 + 6\left(\delta\varepsilon^2_{12} + \delta\varepsilon^2_{23} + \delta\varepsilon^2_{31}\right)\right)^{\frac{1}{2}}, \quad (5a)$$

$$= \frac{2}{3}(\delta\varepsilon_1 - \delta\varepsilon_3) \quad \text{for conventional triaxial tests}. \quad (5b)$$

2.1. Modified effective stress concept and destructuring law

The influence of structure is regarded akin to the effect of an increase in the effective stress and yield stress and, therefore, the yield surface [15,26,27,52,17,4,30,19]. For artificially structured clay, the increase in the yield stress with cement content is clearly understood from the compression and shear test results [46,18,20]. Consequently, two samples of artificially structured clay under the same current stress (pre-shear consolidation pressure) but with different degrees of cementation show different stress–strain and strength characteristics due to the differences in the structural state and yield surface. Thus, the modified mean effective stress concept for structured clay is presented in the form:

$$\bar{p}' = (p + p'_b) - u, \quad (6a)$$

$$\bar{p}' = p' + p'_b, \quad (6b)$$

where $\bar{p}'$ is the modified mean effective stress of structured clay or explicit mean effective stress and p'_b is the mean effective stress that increases due to structure (structure strength). When no cementation exists, the p'_b is null and the $\bar{p}' = p'$. Thus, the modified stress ratio can be expressed as follows:

$$\bar{\eta} = \frac{q}{p' + p'_b}. \quad (7)$$

Due to the p'_b caused by structure, the structured clay samples can stand without applied confining stress. Considering that the strength envelope moves toward the right, which establishes a zero cohesion intercept, the relationship between deviatoric stress and mean effective stress can be proposed as follows,

$$q = M(p' + p'_b), \quad (8)$$

where M is the gradient of the failure envelope in the q–p' plane. Due to the destructuring, p'_b decreases when the stress state is on the yield surface.

Based on the isotropic compression behaviour of structured clays, the SCC model is formulated on the fundamental assumption that both hardening and destructuring of natural soils depends on plastic volumetric deformation. It has been demonstrated the model predicts accurate results for natural soil with weak or no cementation [35–37]. However, for stiff structured clay, the destructuring is mainly related to the plastic strain, which depends on two parts: those are from volumetric deformation and shear deformation [27,52,10,4,30,29]. The destructuring mechanism is the process of reducing the structure strength, p'_b, due to the degradation and crushing of the structure. In this study, the simplified destructuring, is assumed to be related directly to the plastic deviatoric strain, ε^p_d. The p'_b is constant up to the virgin yielding. During virgin yielding (when plastic deviatoric strain occurs), the p'_b gradually decreases due to the degradation of structure until the failure state. This failure state is defined as the peak strength state in which the soil structure begins to be crushed. Thus, beyond this state, a sudden decrease in p'_b occurs and continues to the critical state where the soil structure is completely removed ($p'_b = 0$). Fig. 1 explains the reduction in p'_b due to destructuring as the plastic deviatoric strain increases. The reduction in p'_b due to the degradation of structure (pre-failure) and the crushing of soil–cementation struc-

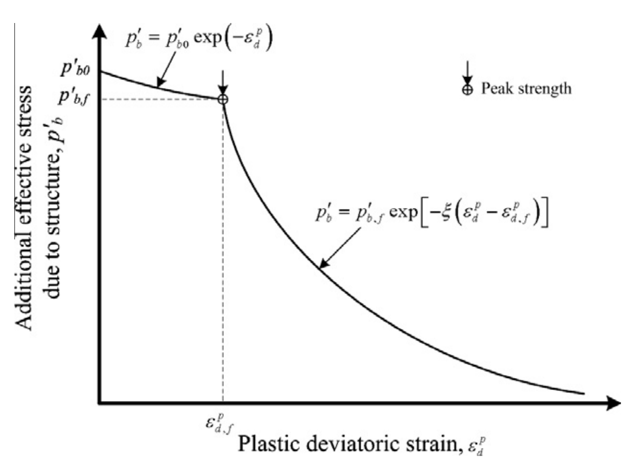

Fig. 1. Schematic diagram of reduction in p'_b due to destructuring process.

ture (post-failure) is proposed in terms of plastic deviatoric strain as follows,

$$p'_b = p'_{b0}\exp(-\varepsilon^p_d), \tag{9}$$

for pre-failure(degradation of soil structure)

$$p'_b = p'_{b,f}\exp\left[-\xi(\varepsilon^p_d - \varepsilon^p_{d,f})\right], \tag{10}$$

for post-failure(crushing of soil structure)

where p'_{b0} is the initial structure strength, $p'_{b,f}$ is the structure strength at failure (peak strength), $\varepsilon^p_{d,f}$ is the plastic deviatoric strain at failure and ξ is the destructuring index due to shear deformation. From Eqs. (9) and (10), it is noted that the change in p'_b depends upon the plastic deviatoric strain, which is governed by the effective stress path and the plastic potential.

The state boundary surface was first proposed by Roscoe et al. [50] for destructured (remoulded) clay. It is a normalised unique curve (Roscoe and Hvorslev surfaces) in q/p'_e and p'/p'_e, where p'_e is the equivalent stress. The state boundary surface separates states that soils can achieve from states that soils can never achieve [3]. It is known that this original state boundary surface cannot describe structured clay behaviour [12,6]. The state boundary surface for structured clay can be generated based on the modified effective stress concept as shown in Fig. 2 (test results were from Horpibulsuk et al. [20]. The $\bar{p}'_y$ is the explicit mean effective yield stress, which is the sum of p'_y and p'_b. p'_y is the equivalent stress for undrained shearing. During virgin yielding (normally consolidated state), $\bar{p}'_y$ is equal to $(p'_0 + p'_b)$, where p'_0 is the pre-shear effective stress or the yield stress in the isotropic compression condition. For the over-consolidated state, $\bar{p}'_y$ is constant and equal to $(p'_{y,i} + p'_b)$, where $p'_{y,i}$ is the initial mean effective yield stress obtained from the compression curve. In this figure, p'_b is assumed to be p'_{b0} because the reduction in p'_b due to the degradation of structure is insignificant in the pre-failure state for cemented clay [19]. The degradation is insignificant because the change in plastic deviatoric strain is usually small in the pre-failure state for stiff (artificially) structured clay [17,20,19]. It is found that the normalised modified effective stress paths for various cement contents during virgin yielding can be represented by a unique curve. This surface can be referred to as the modified Roscoe surface. These results show that the undrained stress paths on the state boundary surface are of the same shape and consistent with one another. Samples inside the state boundary surface, especially $\bar{p}'/\bar{p}'_y < 0.7$, fail on the same failure line, which designated as the modified Hvorslev surface. The state boundary surface and the modified effective stress concepts are fundamental to the development of the MSCC model.

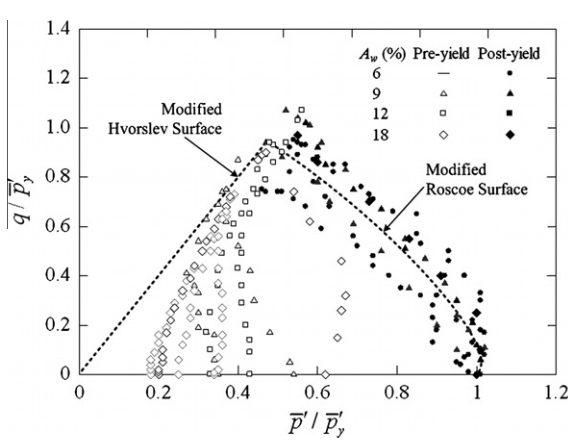

Fig. 2. Test paths in $q/\bar{p}'_y$:$\bar{p}'/\bar{p}'_y$ space for an undrained test on artificially structured clay at 6%, 9%, 12% and 18% cement (data from Horpibulsuk et al. [20]).

2.2. Material idealisation

Structured soils usually possess anisotropic mechanical properties, and destructuring usually leads to the reduction of anisotropy. It is observed that the variation of mechanical properties of some artificially structured clays is basically isotropic [23,51]. To concentrate on introducing the effect of structure and destructuring and to avoid the unnecessary complexity of mathematical details, only the isotropic effects of soil structure are considered in the development of the MSCC model.

In the MSCC model, structured clay is idealised as an isotropic material with elastic and virgin yielding behaviours. The yield surface varies isotropically with plastic volumetric deformation. Soil behaviour is assumed to be elastic for any stress excursion inside the current yield surface. Virgin yielding and destructuring occur for stress variation originating on the yield surface. During virgin yielding, the current stress of structured clay stays on the yield surface.

Based on an examination of a large body of experimental data, material idealisation for the compression behaviour of structured clay is introduced in Fig. 3a. Due to the structure, the structured clay can be stable above the intrinsic state (remoulded compression) line. In other words, the structured clay possesses a higher voids ratio than the destructured clay at the same effective vertical stress [17]. This stable state is defined as meta-stable [45]. The compression strain of the structured clay is negligible up to the yield stress, $p'_{y,i}$. Beyond this yield stress, there is sudden compression with a relatively high magnitude, which is indicated by the steep slope and caused by the destructuring. For further loading, the difference in the voids ratio between structured and destructured states (Δe) decreases with stress level and finally diminishes at a very high effective stress. Therefore, the virgin compression

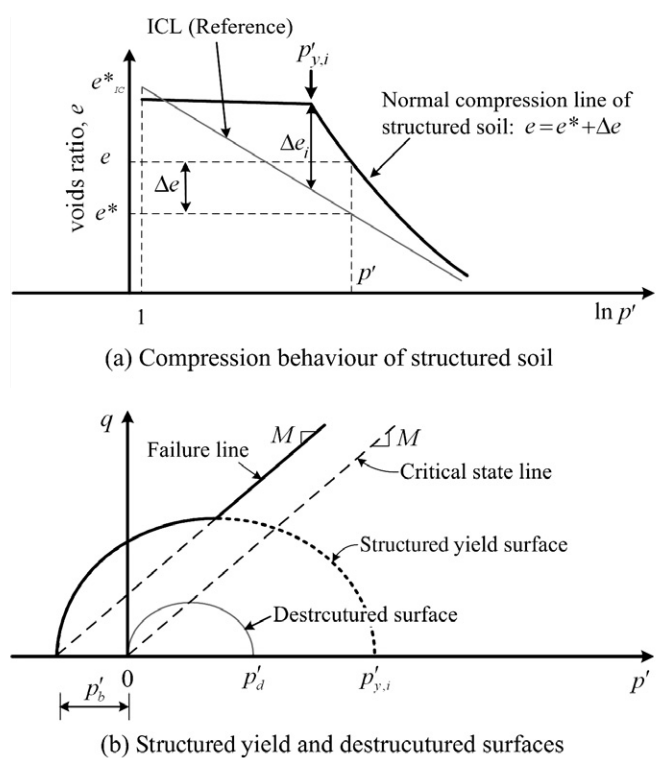

Fig. 3. Material idealisation for the MSCC model.

behaviour during the destructuring process of structured clay can be expressed by the following equation,

$$e = e^* + \Delta e, \tag{11}$$

where e is the voids ratio of structured clay and e^* is the voids ratio of destructured clay at the same stress state. The ICL of destructured clay is generally expressed in the form,

$$e^* = e^*_{IC} - \lambda^* \ln p', \tag{12}$$

where e^*_{IC} is the voids ratio at a reference mean effective stress (1 kPa) of the ICL and λ^* is the gradient of the ICL.

It has been proved that the compression equation for the additional voids ratio (Δe) of naturally structured clay proposed by Liu and Carter [35,36] is also applicable for artificially structured clay [19]. The following compression equation for structured clay is proposed:

$$e = e^* + \Delta e_i \left(\frac{p'_{y,i}}{p'_0}\right)^b, \tag{13}$$

where b is the destructuring index due to volumetric deformation, Δe_i is the additional voids ratio at the isotropic yield stress (Fig. 3a) and p'_0 is the stress history or isotropic yield stress.

Based on the state boundary surface for structured clay, the yield loci are of the same shape and consistent with one another. The yield surface of the MSCC model is assumed to be elliptical for both structured and destructured clays (anisotropic effect is not considered). By considering the effect of structure on the yield surface, the proposed yield function of the MSCC model in q–p' plane is given by (Fig. 3b),

$$f = q^2 - M^2(p' + p'_b)(p'_0 - p') = 0. \tag{14}$$

The MSCC model assumes that the gradient of the failure envelope and the critical state line is the same. This concept has been employed in the previous works, such as those by Muir Wood [47], Kasama et al. [26], and Lee et al. [30]. The structural and destructured yield surfaces are thus similar in shape (*vide* Fig. 3b).

2.3. Stress states inside yield surface

As stated in the material idealisation, only elastic deformation occurs for stress excursions within the virgin yielding boundary. The elastic response of structured clay obeys Hooke's law, i.e.,

$$\delta\varepsilon^e_v = \frac{\delta p'}{K'}, \tag{15a}$$

$$\delta\varepsilon^e_d = \frac{\delta q}{3G'}, \tag{15b}$$

where K' is the bulk modulus and G' is the shear modulus. When shear modulus is constant, K' and Poisson's ratio, μ', are related to p', G' and the elastic swelling index, κ, as follows:

$$K' = \frac{p'(1+e)}{\kappa}, \tag{16}$$

$$\mu' = \frac{3K' - 2G'}{6K' + 2G'}. \tag{17}$$

It was observed experimentally that the elastic deformation stiffness, $E' = 3(1 - 2\mu')K'$, generally increases with structure strength [23,20]. This is reflected by Eq. (16) where the bulk modulus is linked to κ, which depends on structure strength.

2.4. Stress states on yield surface

Destructuring occurs with stress states on the yield surface for both hardening and softening behaviours. For models in the Cam Clay family, the plastic strain direction is determined from the plastic potential. Even though the MSCC model employs a yield surface with a shape similar to that of the MCC model, the original plastic potential is not used in the proposed model because the plastic potential of the MCC model generally produces too much plastic deviatoric strain and therefore leads to overprediction of the earth pressure at rest [42,43]. It was also shown that the plastic deviatoric strain predicted by the original plastic potential is not suitable for artificially structured clay [19]. The plastic potential proposed by McDowell and Hau [43] is modified by accounting for the structure effect. The plastic potential in the MSCC model is thus introduced as follows;

$$g = q^2 + \frac{M^2}{1-\psi}\left[\left(\frac{p' + p'_b}{p'_p + p'_b}\right)^{\frac{2}{\psi}}(p'_p + p'_b)^2 - (p' + p'_b)^2\right] = 0, \tag{18}$$

where p'_p is the parameter that describes the magnitude of the plastic potential and ψ is the parameter that describes the shape of the plastic potential. It should be noted that the critical state strength M, a parameter widely used in the Critical State Soil Mechanics, may vary with the Lode angle, θ, in three dimensional stress space depending on the methodology used for model generalisation [28]. A simple and accurate function that represents M in terms of the θ has been proposed by Sheng et al. [54] as follows:

$$M(\theta) = M_{\max}\left(\frac{2\alpha^4}{1 + \alpha^4 + (1 - \alpha^4)\sin 3\theta}\right)^{1/4}, \tag{19}$$

where $M_{\max}$ is the slope of the critical state line under triaxial compression ($\theta = -30°$) and the parameter α depends on a friction angle of soil at the critical state line, ϕ', as follows:

$$\alpha = \frac{3 - \sin\phi'}{3 + \sin\phi'}, \tag{20}$$

With this generalisation, the plastic potential is applicable for general stress states. The shape of the plastic potential is shown in Fig. 4 for various ψ-values and $p'_b = 0.2p'_p$ and $M = 1.2$. For a completely destructured state ($p'_b = 0$), this plastic potential becomes that of the MCC model if $\psi = 2$ is assumed.

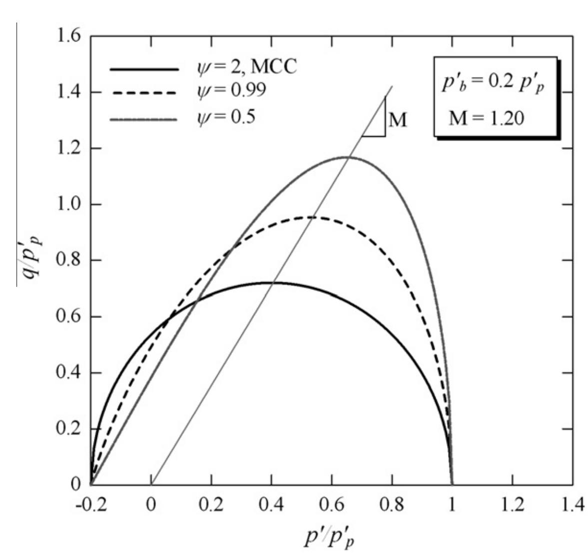

Fig. 4. Shape of the plastic potential for the MSCC model.

For stress states on the yield surface and with $\bar{\eta} < M$ ($\delta p'_0 > 0$), both volumetric hardening and destructuring occur. The plastic volumetric strain increment, $\delta\varepsilon_v^p$, for the MSCC model is derived from the assumption that the plastic volumetric strain depends on the change in stress history, $\delta p'_0$ and the current shear stress. The plastic volumetric strain increase during hardening is derived from Eq. (13) as follows:

$$\delta\varepsilon_v^p = \left\{(\lambda^* - \kappa) + b\Delta e\left[\frac{M}{M-\bar{\eta}}\right]\right\}\frac{\delta p'_0}{(1+e)p'_0}. \tag{21}$$

The term $\frac{M}{M-\bar{\eta}}$ is introduced to take into account the effect of current shear stress. The derivation of this equation has been provided by Liu and Carter [37,38]. The effect of destructuring on the $\delta\varepsilon_v^p$ is reflected in the parameter b and thus also in the $\delta p'_0$.

During the softening process ($\bar{\eta} > M$ and $\delta p'_0 < 0$), the effect of current shear stress is not significant. The plastic volumetric strain increment during softening is thus proposed as follows:

$$\delta\varepsilon_v^p = \{(\lambda^* - \kappa) + b\Delta e\}\frac{\delta p'_0}{(1+e)p'_0}. \tag{22}$$

From the plastic potential (Eq. (18)) and the hardening rule (Eqs. (21) and (22)), the hardening and the softening behaviours can be modelled in the same way as for other models in the Cam Clay family [47,39,38]. When the stress state is on the yield surface with $\bar{\eta} < M$, hardening occurs (the yield surface expands) due to the positive flow rule. Softening occurs when the stress state is on the yield surface with $\bar{\eta} > M$ where the flow rule becomes negative, which causes the yield surface to shrink.

The effect of ψ and ξ on the shear behaviour is illustrated in Figs. 5 and 6 using the model parameters listed in Table 1. The parameter ψ significantly affects the plastic strain direction and, therefore, the stress–strain–strength relationships. The effect of ψ on the stress–strain–strength relationships for a particular destructuring rate (a particular ξ of 30) is shown in Fig. 5. It is noted that as ψ decreases, the plastic deviatoric strain at failure, $\varepsilon_{d,f}^p$, decreases while the strength and stiffness increase. Fig. 6 shows the effect of ξ on the strain-softening behaviour for ψ with a value of 0.1. As ξ increases, the p'_b at post-failure decreases; thus, the deviatoric stress decreases more rapidly.

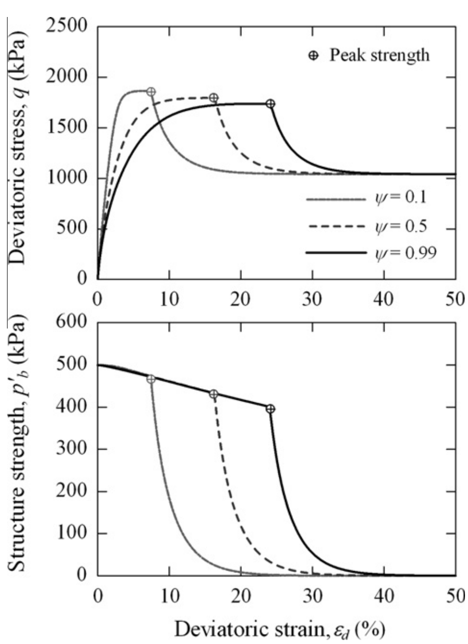

Fig. 5. Parametric study on the parameter ψ.

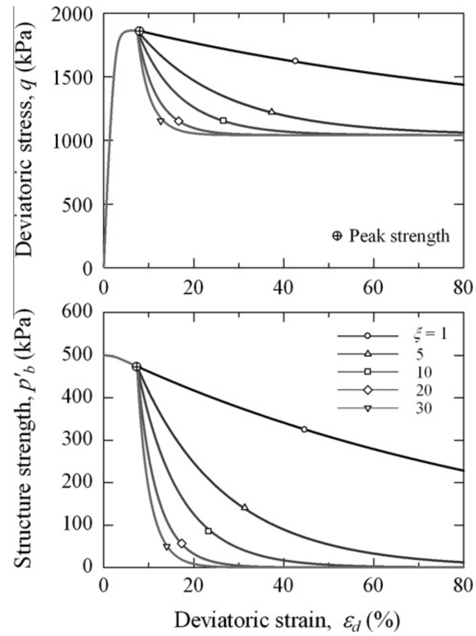

Fig. 6. Parametric study on the parameter ξ.

Table 1
Parameters of the MSCC model for parametric study.

Model parameters	Values	Physical meaning
λ^*	0.16	Intrinsic gradient of compression in the e–ln p' plane
κ	0.001	Current Gradient of unloding–reloading line in e–ln p' plane
e^*_{IC}	2.86	Voids ratio at reference stress (p' = 1 kPa) of intrinsic compression line
b	0.3	Destructured index due to volumetric deformation
Δe_i	0.75	Additional void ratio at the start of virgin yielding
M	1.10	Critical state ratio in the q–p' plane
p'_{b0}	500	Initial of bonding strength in the q–p' plane (kPa)
$p'_{y,i}$	600	Initial yield stress of isotropic compression line of cemented soil (kPa)
ψ	0.1–0.99	Parameter define the volumetric strain during softening
ξ	1–30	Destructured index due to shear deformation
G'	30,000	Shear modulus in terms of effective stress (kPa)
σ'_c	600	Confining pressure (kPa)

3. Application and verification of the MSCC model

In this section, the MSCC model is employed to simulate the compression and shear behaviour of naturally and artificially structured clays. The capability of the MSCC model is evaluated based on comparisons between model simulations and experimental data. The following clays are evaluated: a destructured clay (Ariake clay), two naturally structured clays (Osaka and Marl clays) and two artificially structured clays (cemented Ariake and Bangkok clays). Some basic and engineering properties of the natural Osaka and Marl clays and of the destructured Ariake and Bangkok clays are presented in Table 2.

The model parameter values are listed in Tables 3 and 4 for the naturally and artificially structured clays, respectively. Parameters e^*_{IC}, λ^*, κ, $p'_{y,i}$, b and Δe_i were determined from the results of isotropic compression test and G' was approximated from the q–ε_d curve. The parameters denoted by an asterisk were tested from a remoulded sample [5]. In the absence of the ICL, parameters e^*_{IC} and λ^* can be approximated from the intrinsic state line in terms of the liquid limit voids ratio [49], which was achieved by Horpibulsuk et al.

Table 2
Physical properties of the simulated clays.

Properties	Osaka clay	Marl clay	Ariake clay	Bangkok clay
Reference	Adachi et al. [1]	Anagnostopoulos et al. [2]	Horpibulsuk et al. [20]	Uddin [58]
Specific density	2.67–2.703	2.72	2.70	2.67–2.69
Apparent pre-consolidation pressure (kPa)	93.1	3250	80	40
Compression index ($\lambda = C_c/2.303$)	0.355	0.065	0.446	0.252
Swelling index ($\kappa = C_s/2.303$)	0.048	0.020	0044	0.056
Natural water content	65–72%	20–21%	135–150%	81.60–86.00
Liquid limit	69.2–75.1%	24–38%	120%	103%
Plasticity index	41.9–50.6%	2.5–12%	63%	60%
Liquidity	0.745–1.13	N/A	1.24–1.47	0.62
Sensitivity	14.5	N/A	N/A	7.3
Activity	0.54	0.75–1.25[b]	N/A	0.87
Clay fraction	44%[a]	13–24%	55%	69%
Silt fraction	49%	75–87%	44%	28%
Sand fraction	7%	<12%	1%	3%
Confining pressure	20–235 kPa	98–4000 kPa	50–4000 kPa	50–600 kPa
Insitu voids ratio	1.67–1.92	0.55–0.60	3.65–4.05	2.20–2.44
Strain rate of shearing (mm/min)	0.006 1–0.00632[c]	0.009[c,d]	0.0075[c], 0.0025[d]	0.009[c], 0.0018[d]

Remark
[a] Less than 2 μm.
[b] Clay-sized fraction.
[c] Undrained test.
[d] Drained test.

Table 3
Parameters of the MSCC model for naturally structured clays.

Model parameters	Natural structured clays	
	Osaka	Marl
λ^*	0.147	0.025
κ	0.027	0.009
e^*_{IC}	1.92	0.67
b	0.6	0.7
Δe_i	0.62	0.085
M	1.15	1.30
p'_{b0} (kPa)	30	300
$p'_{y,i}$ (kPa)	100	4150
G' (kPa)	3000	45,000
ξ	1	1
ψ	2	1.5

[19]. The values of the strength parameters M and p'_{b0} were obtained by plotting the peak strength in the q–p' plane. The value for ψ was estimated from the simulation of anisotropic compression test results of structured clay with different η values. The parameter ψ is determined as shown in Fig. 7 for the artificially structured Bangkok clay. In the absence of the anisotropic compression test results, ψ can be estimated from the stress–strain relationship. It is found that the ψ value decreases with the degree of cementation. The ψ-value is close to 2.0 for the naturally structured clays as shown in Table 3. It is 2.0 for Osaka and 1.5 for Marl clays. Because ξ is a parameter that reflects the rate of strain softening, it is estimated from the stress–strain relationship at post-failure.

Based on the parameters presented in Tables 3 and 4, the isotropic compression behaviours of all four structured clays were simulated and compared with experimental data as shown in Fig. 8. The compression behaviour of both naturally structured and artificially structured clays are well represented.

A comparison of the model simulations and experimental data for isotropically consolidated undrained triaxial (CIU) tests on Osaka clay is shown in Fig. 9. A comparison of the model simulations and experimental data for isotropically consolidated drained triaxial (CID) tests on Marl clay is shown in Fig. 10. Unlike a completely destructured clay, natural Osaka clay shows strain softening in the (q–ε_d) relationship in both normally consolidated states and overconsolidated states. This type of behaviour is frequently found in naturally structured soils [5,7] and has been captured satisfactorily by the MSCC model. The model simulations and experimental data for the two sets of tests on natural soils are in very good agreement.

The capacity of the MSCC model to describe the influence of cementation is verified by simulating both undrained and drained shear behaviour of artificially structured Ariake clay and Bangkok clay under different pre-shear consolidated pressures and cement contents. Comparisons between the test data and model simulations are shown in Figs. 11–15 for the destructured and artificially

Table 4
Parameters of the MSCC model for artificially structured clays.

Model parameters	Ariake clay				Bangkok clay		
	A_w = 0%	A_w = 6%	A_w = 9%	A_w = 18%	A_w = 5%	A_w = 10%	A_w = 15%
λ^*	0.44	0.44	0.44	0.44	0.26	0.26	0.26
κ	0.08	0.06	0.024	0.001	0.02	0.01	0.005
e^*_{IC}	4.37	4.37	4.37	4.37	2.86	2.86	2.86
b	–	0.15	0.01	0.001	0.02	0.01	0.01
Δe_i	–	1.50	2.25	2.65	0.55	0.60	0.75
M	1.58	1.60	1.45	1.35	1.13	1.13	1.13
p'_{b0} (kPa)	–	50	100	650	60	400	500
$p'_{y,i}$ (kPa)	–	50	200	1800	150	430	600
G′ (kPa)	4000	6000	8000	40,000	14,000	16,000	30,000
ξ	–	10	10	30	10	30	30
ψ	2.0	1.8	0.5	0.1	1.5	0.2	0.1

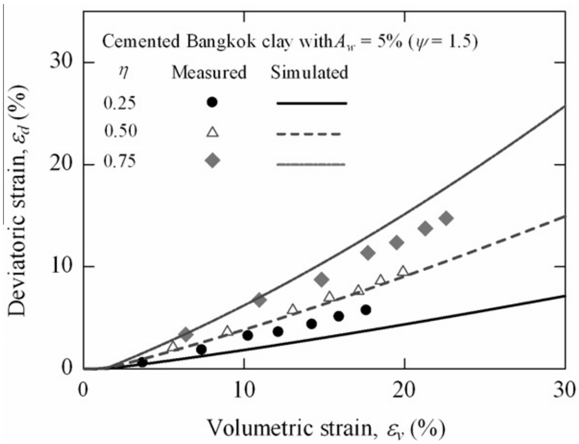

Fig. 7. Determination of the ψ for artificially structured Bangkok clay (data from Uddin [58]).

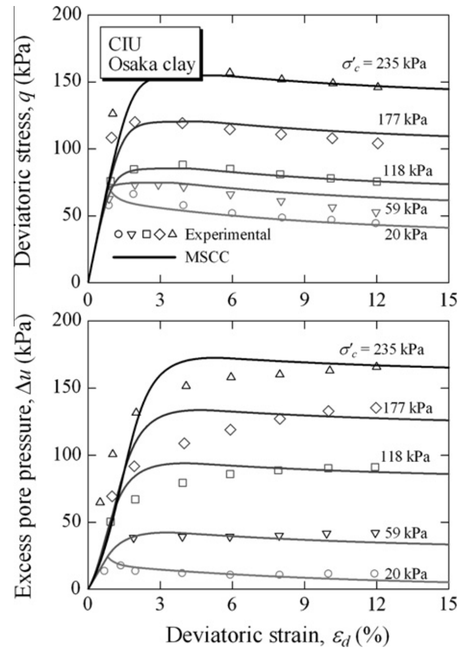

Fig. 9. Comparison of experimental and simulated CIU test results of natural Osaka clay.

structured Ariake clay, and in Figs. 16 and 17 for the artificially structured Bangkok clay. It is interesting to note that the same destructured parameters can be used to simulate the shear behaviour of clay in destructured and structured states.

The critical state (very large strain) of the structured clay cannot be measured due to the limitation of the triaxial apparatus. For the simulation, this state can however be presented where the structure strength (p'_b) is completely removed. Overall, the general patterns of the behaviour of artificially structured clays, i.e., the increase in stiffness and peak strength with cementation and the rapidness of the reduction in deviatoric stress during strain softening, have been captured. The model simulations cover a wide range of cement contents (from 0% to 18% by weight) and a wide range of pre-shear consolidated pressures (50–3000 kPa) and are made with the model parameter values that are determined based on their physical meanings.

4. Discussion

Based on the modified effective stress concept, yield function, hardening rule and the plastic potential proposed, the methodology for simulating the stress–strain behaviour of structured clay is simpler and provides better quantitative and qualitative performance than the MCC model and the original SCC model. As seen in the comparisons of the simulations shown in Figs. 18 and 19, the performance of the MSCC model is significantly better than that of the SCC and MCC models. It is found that the destructuring law proposed in terms of plastic deviatoric strain provides a reasonably good simulation. The values of model parameters for the MCC and the SCC are given in Tables 5 and 6, respectively.

This model can be simply implemented into a numerical analysis. The MSCC model is identical to the MCC model when clay is in a destructured state, i.e., $\Delta e = 0$ and $p'_b = 0$. A study of the microstructure of some structured clays has shown that some elements of structure remain in the clay even at very large strains or a

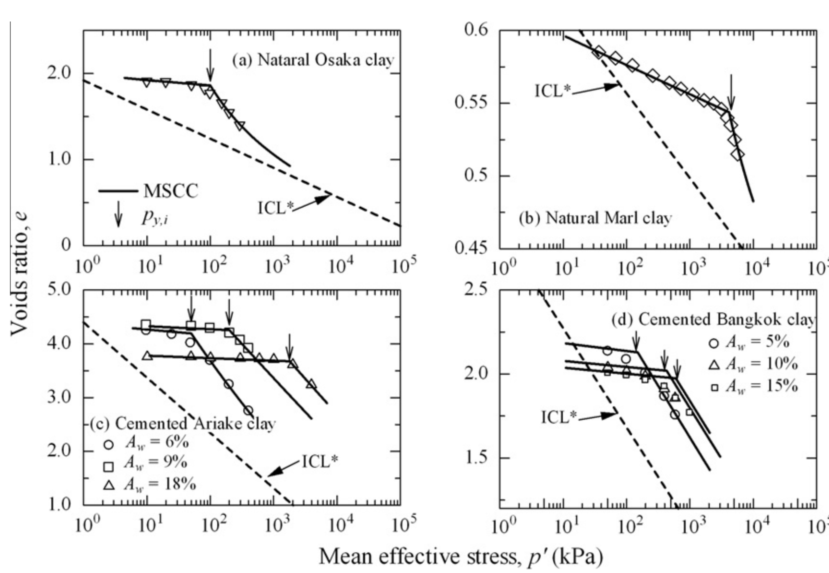

Fig. 8. Simulation of isotropic compression curves of studied structured clays.

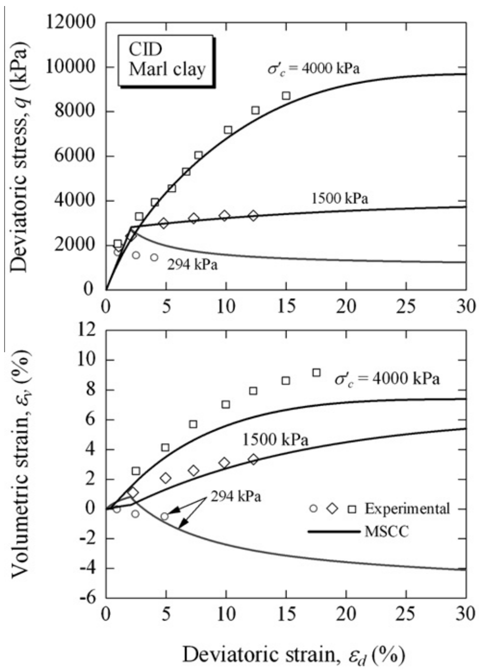

Fig. 10. Comparison of experimental and simulated on CID test results of natural Marl clay.

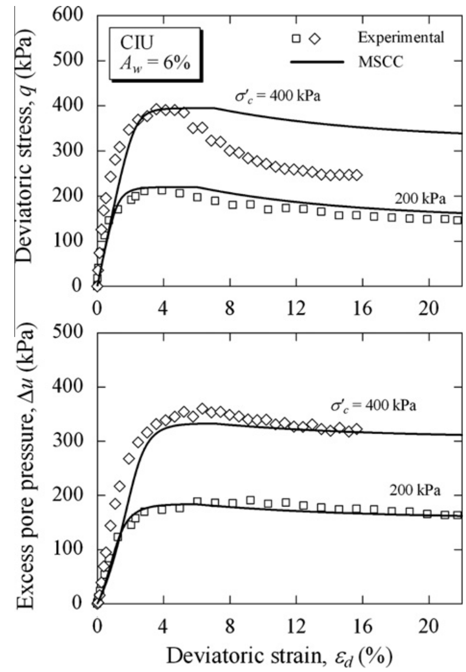

Fig. 12. Comparison of experimental and simulated CID test results of 6% cement Ariake clay.

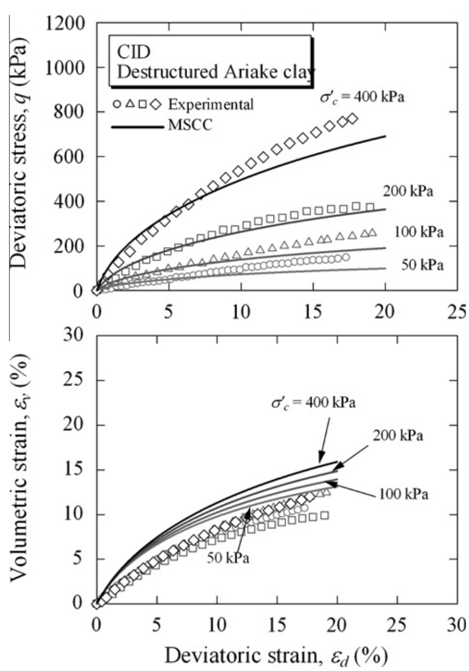

Fig. 11. Comparison of experimental and simulated CID test results of destructured Ariake clay.

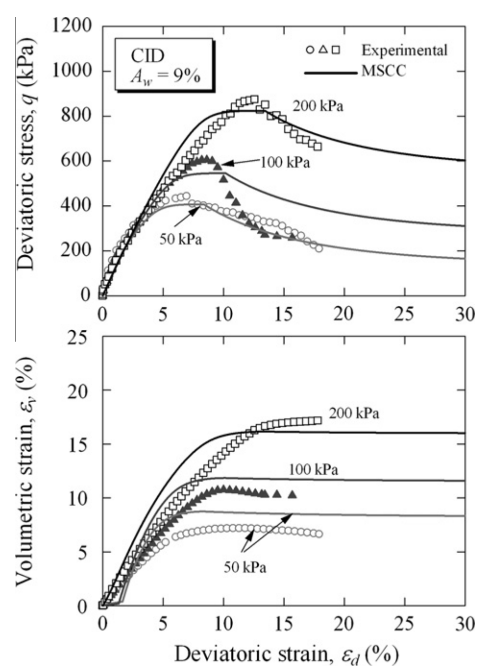

Fig. 13. Comparison of experimental and simulated CIU test results of 6% cement Ariake clay.

destructured state [11,14]. The MSCC model also follows this premise. Even though the critical state lines in the q–p' plane are the same for destructured and structured states, the critical state lines in e–ln p' plane are not the same.

In the MSCC model, the structured soil is treated as an isotropic elastic-virgin yielding material. The two mechanisms are separated by the current yield surface. The soil shows purely elastic behaviour when the stress state is inside the yield surface. When the stress state reaches the yield surface, the plastic behaviour occurs. At this point, there is a sharp change in the stiffness of the soil response, as shown in the simulated results. Further development to obtain more precise simulation can be easily attained by implementing a hardening equation during subloading into the model. The implementation of a simple and predictive hardening equation in the original SCC model has been successfully achieved for natural clay by Suebsuk et al. [56].

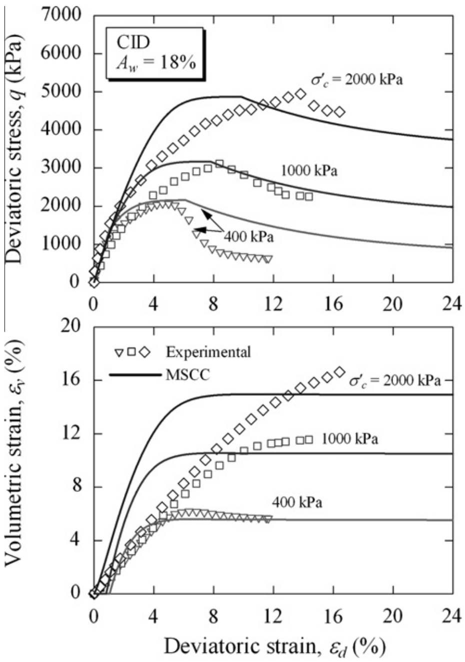

Fig. 14. Comparison of experimental and simulated CID test results of 18% cement Ariake clay.

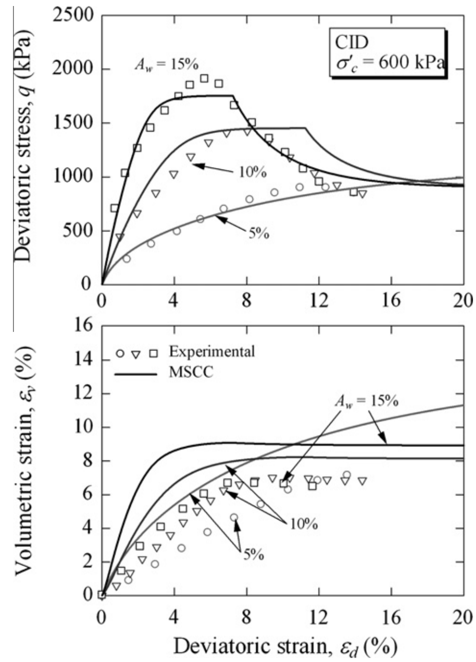

Fig. 16. Comparison of experimental and simulated CID test results of cemented Bangkok clay under σ'_3 = 600 kPa ($\sigma'_3 > p'_y$) for A_w = 5–15%.

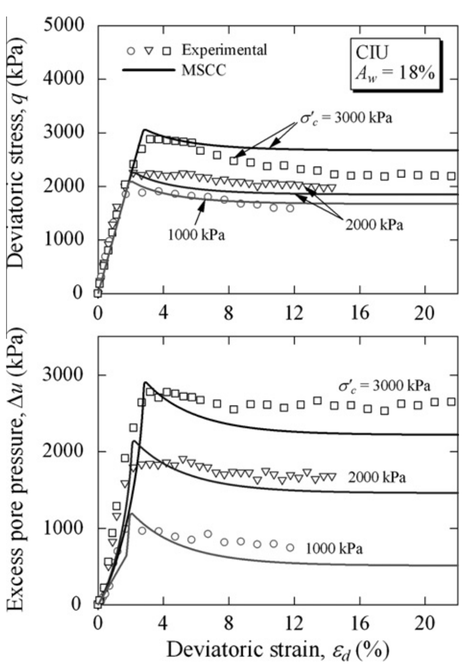

Fig. 15. Comparison of experimental and simulated CIU test results of 18% cement Ariake clay.

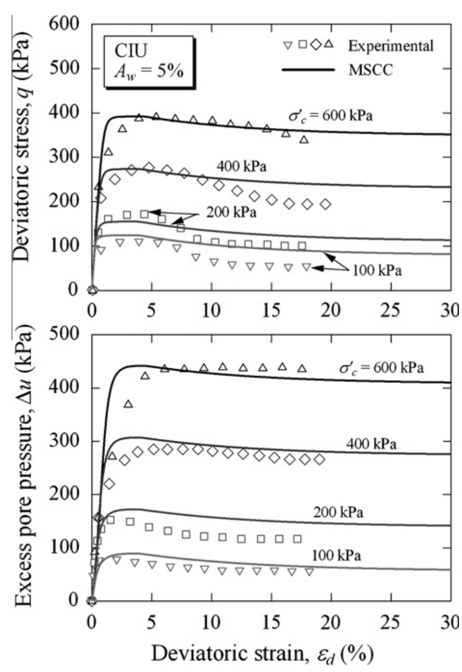

Fig. 17. Comparison of experimental and simulated CIU test results of 5% cement Bangkok clay.

It is seen from the shearing test results that there is some discrepancy between the model simulations and the experimental data in the volumetric deformation (e.g., Figs. 13, 14 and 16). This discrepancy may be inherited from the Modified Cam Clay model, which does not accurately simulate the behaviour of destructured Ariake clay (Fig. 11). Further study on this topic is needed, perhaps with considering the influence of anisotropy. Some frontier research accounting for the influence of anisotropy has been reported in works by Rouainia and Muir Wood [52], Wheeler et al. [60], Dafalias et al. [13] and Taiebat et al. [57]. If the influence of anisotropy on the yield loci is considered, the destructuring law should be extended to include the reduction of anisotropy and isotropy during the destructuring process.

The MSCC model is developed based on the simple predictive SCC model with the purpose to solve some practical geotechnical problems. Although the model has 11 parameters, six parameters

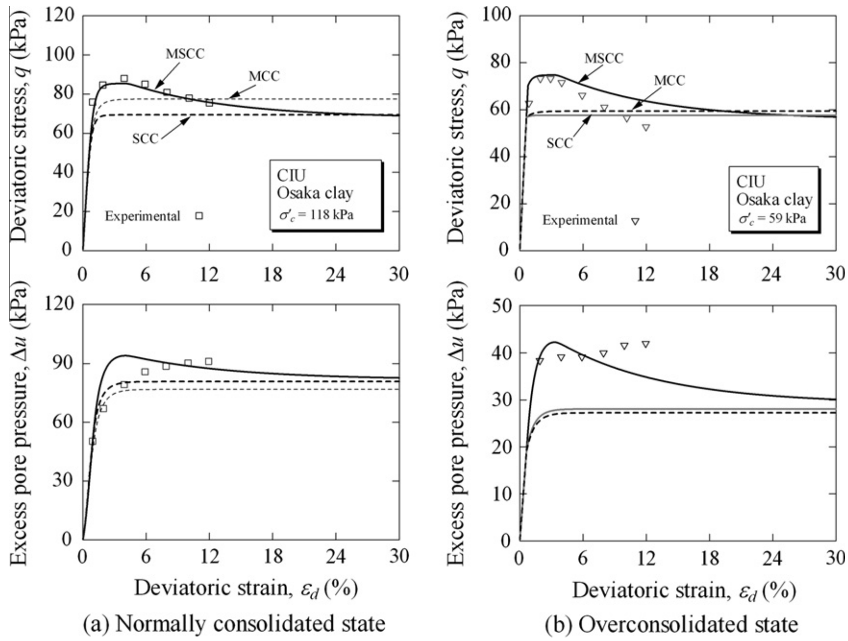

Fig. 18. Comparisons of experimental and simulated on CIU test results of natural Osaka clay for different models.

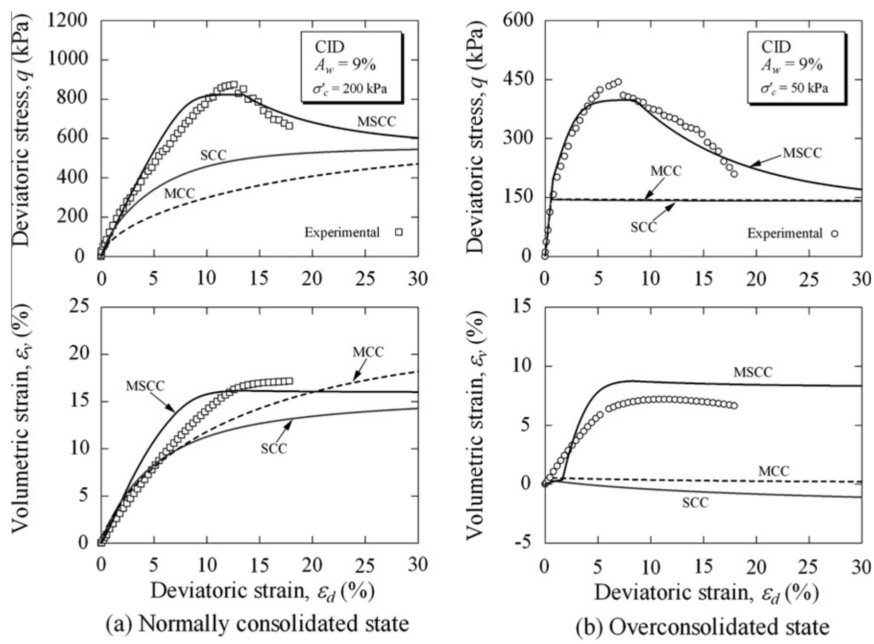

Fig. 19. Comparisons of experimental and simulated on CID test results of cemented Ariake clay for different models.

Table 5
MCC model parameter for natural Osaka and cemented Ariake clays.

Model parameters	Natural Osaka clay	Cemented Ariake clay with 9% cement content
λ	0.147	0.44
κ	0.027	0.024
e^*_{IC}	1.92	4.37
M	1.15	1.45
$p'_{y,i}$ (kPa)	100	200
G' (kPa)	3000	8000

Table 6
SCC model parameter for natural Osaka and cemented Ariake clays.

Model parameters	Natural Osaka clay	Cemented Ariake clay with 9% cement content
λ^*	0.147	0.44
κ	0.027	0.024
e^*_{IC}	1.92	4.37
b	0.6	0.01
Δe_i	0.62	2.25
M	1.15	1.45
$p'_{y,i}$ (kPa)	100	200
G' (kPa)	3000	8000
ψ	2	0.5

are the same as those used in the MCC model to describe the basic mechanical properties of soil. The other parameters can be determined or estimated relatively conveniently from conventional laboratory tests on structured clay specimens. For practical use, the MSCC model will be used in a numerical analysis to solve geotechnical boundary value problems in future research. Recently, some important works in numerical analysis with constitutive models for structured soils such as those by Zhao et al. [62], Karstunen et al. [25] and Liyanapathirana et al. [40] have been published.

5. Conclusions

In this paper, the MSCC model is developed by extending the simple predictive SCC model. In the MSCC model, the destructuring law due to shearing is proposed to describe the effect of degradation and crushing of the soil–cementation structure on the reduction in p'_b. Destructuring begins when the stress state is on the virgin yielding. p'_b gradually decreases due to the degradation of the structure until the failure state. It rapidly decreases when the stress state reaches the failure state and is completed removed at the critical state due to the crushing of the soil–cementation structure. The effect of structure and destructuring is incorporated into the effective stress concept, yield function, hardening rule and plastic potential to describe the mechanical behaviour of structured clay during strain hardening and softening. The methodology of modelling the shear behaviour of structured clay is simple, as in other models of the Cam Clay family.

Simulations were performed using the MSCC model for different clays with both natural and artificial structures under different pre-shear consolidated pressures, drainage conditions and cement contents, and these simulations were compared with experimental data. Overall, a reasonable description of the influence of various types of soil structures on soil behaviour has been achieved. It is seen that the MSCC model has unified the clay behaviour in destructured, naturally structured and artificially structured states into one consistent theoretical framework. Because the MSCC model is simple and the model parameters can be determined from conventional laboratory tests, the model has the potential to solve geotechnical engineering problems involving various types of structured soils.

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