Behavior of Cemented Soft Clays in Undrained Situations

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Abstract

In this paper, a constitutive model for cemented clay is introduced. This model is designated as "Modified Structured Cam Clay (MSCC) model". In the model, the influence of cementation structure is incorporated into effective stress concept, yield function, hardening rule and plastic potential function to describe the mechanical behavior of cemented clay during strain-hardening and softening. The methodology of modeling the shear behavior of structured clay is simple, which is the same way as that of the other models of the Cam Clay family. The capability of the MSCC model is verified by comparing the simulated undrained shear response of cemented Ariake clay under various effective confining stresses and degrees of cementation with experimental data.

Keywords: cementation, clay, constitutive relation, structure, undrained situation.

1. INTRODUCTION

Soft clay that possesses low strength and high compressibility is widely found in coastal and lowland regions. These mechanical properties of the soil constitute a great challenge to geotechnical engineers, particularly in metropolitan areas. Ground improvement techniques are increasingly employed to prepare sites underlain by these soils for construction. Because of its relatively low cost and high efficiency, the use of cement to improve the soft ground is now widely adopted in geotechnical engineering. The influence of the special structure of the soil, the cementation, has a dominant effect on the mechanical properties of the soil and is difficult for theoretical modelling (Horpibulsuk et al, 2004b). Understanding and simulating the pore pressure development of the cemented clay and the influence of cementation on the undrained shear response become an important research topic for the prediction of the performance of geotechnical structures during various undrained loading situations including earthquake loading.

To form a model suitable for cemented clay based on the critical state framework, the influence of cementation structure and destructuring on the effective stress, yield function, hardening rule, and plastic potential function (flow rule) must be incorporated. Recently, Horpibulsuk et al. (2009) have summarized the main features of the cemented clay behavior and introduced the SCC model for cemented clay. In the model, the effective stress concept, yield function, hardening rule, and plastic potential function have been developed taking the effect of structure into account. For simplicity, the model has not considered the degradation of structure during virgin yielding. Their model can well simulate shear behavior for both normally and over consolidated states. Some modifications are however needed for simply and practically implementing into a finite element program and for better capturing the main features of the cemented clay with the model parameters simply obtained from the conventional laboratory.

In this present paper, attempts are made to develop a general and practical constitutive model based on the critical state framework for cemented clay. The proposed model, designated as the Modified Structured Cam Clay (MSCC) model, is formulated based on the SCC model for cemented clay (Horpibulsuk et al, 2009).

2. MODIFIED EFFECTIVE STRESS CONCEPT AND DESTRUCTURING LAW

With the presence of structure, the influence of structure is regarded akin to the effect of an increase in the effective stress and yield stress, hence yield surface (Gens and Nova, 1993; Horpibulsuk, 2001; Kasama et al., 2000; Kavvadas and Amorosi, 2000; Rouainai and Muir Wood, 2000; Baudet and Stallebrass, 2004; Lee et al, 2004; and Horpibulsuk et al., 2009). For cemented clay, the increase in the yield stress with cement content is clearly understood from the compression and shear test results (Horpibulsuk et al., 2004a and b, and Miura et al., 2001, etc.). The modified mean effective stress concept for cemented clay is presented in the form (Horpibulsuk et al., 2009):

$$\overline{p}' = (p + p'_b) - u \tag{1}$$

$$\overline{p}' = p' + p'_b \tag{2}$$

where $\overline{p}'$ is the modified mean effective stress of cemented clay or explicit mean effective stress, p' is the mean effective stress, and p'_b is the mean effective stress increasing due to cementation structure (structure strength). It shows that when no cementation prevails, the p'_b would be null and the $\bar{p}' = p'$. Thus, the modified stress ratio can be expressed as follows,

$$\bar{\eta} = \frac{q}{p' + p'_b} \tag{3}$$

Due to the p'_b caused by cementation structure, the cemented clay samples can stand without applied confining stress. Considering that the strength envelope moves towards the right giving zero cohesion intercept, the relationship between deviator stress and mean effective stress can be proposed as follows,

$$q = \mathrm{M}(p' + p'_b), \tag{4}$$

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

Destructuring consists of two processes during shearing: degradation of structure and crushing of soil-cementation structure. The degradation of structure occurs when the stress state is on the yield surface whereas the crushing of the soil-cementation structure happens at post-failure during strain softening (Horpibulsuk et al., 2009). For the MSCC model, the effect of destructuring on the compressibility is described by the compression equation by Liu and Carter (2000). The decrease in p'_b due to destructuring is directly related to the magnitude of plastic shear strain, ε_s^p. The p'_b is assumed to be constant up to the virgin yielding. During virgin yielding (plastic shear strain occurs), the p'_b gradually decreases due to degradation of structure until the failure state. Beyond this state, sudden decrease in the p'_b occurs due to the crushing of soil-cementation structure and diminishes at the critical state. Figure 1 explains the reduction in p'_b due to destructuring as plastic shear strain increases. The reduction in p'_b due to the degradation of structure (pre-failure) and the crushing of soil-cementation structure (post-failure) is proposed in terms of plastic shear strain as follows,

$$p'_b = p'_{b0} \exp\left(-\varepsilon_s^p\right) \qquad \text{for pre-failure (hardening)} \tag{5}$$

$$p'_b = p'_{b,f} \exp\left[-\xi\left(\varepsilon_s^p - \varepsilon_{s,f}^p\right)\right] \qquad \text{for post-failure (softening)} \tag{6}$$

where p'_{b0} is the initial structure strength, $p'_{b,f}$ is the structure strength at failure (peak strength), $\varepsilon_{s,f}^p$ is the plastic shear strain at failure, and ξ is the destructuring index. The higher the ξ, the greater the reduction in p'_b at post failure, hence the faster the reduction in deviator stress. From Eqs.(5) and (6), it is noted that change in p'_b is dependent upon the plastic shear strain, which is governed by the effective stress path and the plastic potential function.

3. MATERIAL IDEALIZATION

In the MSCC model, cemented clay is idealized as an isotropic material with elastic and virgin yielding behavior. The yield surface varies isotropically with plastic volumetric deformation. Soil behavior is assumed to be elastic for any stress excursion inside the current structural yield surface. Virgin yielding occurs for a stress variation originating on the structural yield surface and causing it to change. During virgin yielding, the current stress of a soil stays on the structural yield surface.

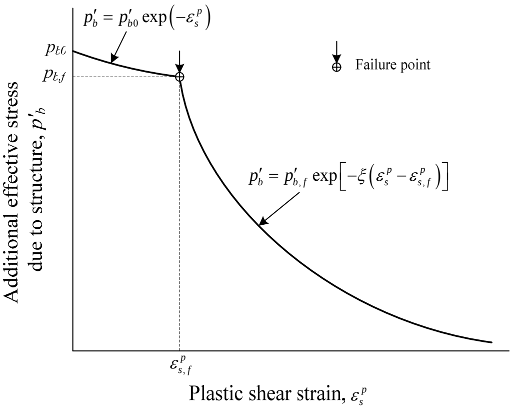
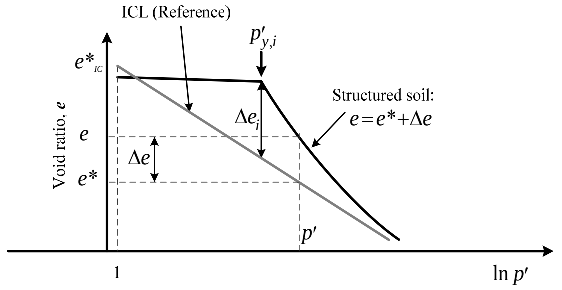
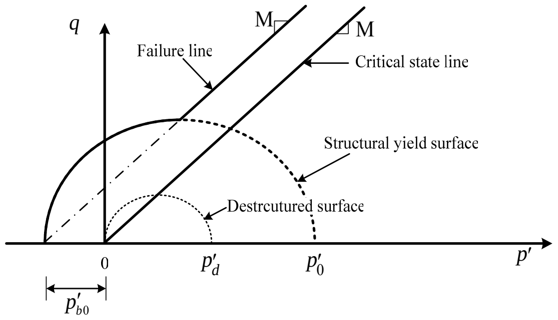


Fig 1 Schematic diagram of reduction in p_b' due to destructuring.



(a) Compression behaviour of structured soil



(b) Structural yield and destrucutured surfaces

Fig 2 Material idealization for MSCC model.

The idealization of the mechanical behavior of cemented clays is illustrated in Fig. 2. In this figure e represents the void ratio for a cemented clay, e^* is the void ratio for the soil with the same mineralogy in a uncemented state at same stress state, $p'_{y,i}$ is the mean effective stress at which virgin yielding of the cemented soil begins, and Δe, the additional void ratio, is the difference in void ratio between a cemented soil and the corresponding ideal state of the soil at the same stress state. Hence, the virgin compression behavior of a cemented soil can be expressed by the following equation,

$$e = e^* + \Delta e \tag{7}$$

It is found that the additional void ratio for cemented clays can be described by the following equation,

$$e = e^* + \Delta e_i \left(\frac{p'_{y,i}}{p'_0} \right)^b \tag{8}$$

where b is soil parameter, describing the additional void ratio sustained by cementation. Δe_i is the value of the additional void ratio at the start of virgin yielding (Fig. 2a).

By consideration of the effect of cementation structure in the yield surface, the proposed yield function, f, of the MSCC model in q - p'plane is given by (Fig. 2b),

$$f = q^2 - \mathrm{M}^2 \left(p' + p'_b\right)\left(p'_0 - p'\right) = 0 \tag{9}$$

where p'_0 is the yield stress in the isotropic compression condition.

3.1 Stress States on Yield Surface

For models of the Cam Clay family, the direction of plastic strain increment can be determined from the plastic potential function. Even though the MSCC model employs the yield surface similar in shape to that of the MCC model, the original plastic potential function (flow rule) is not used in the proposed model. This is because the plastic potential function of MCC model generally produces too much shear strain and therefore leads to overprediction of the earth pressure at rest (McDowell and Hau, 2003). It was also shown that the plastic shear strain predicted by the original plastic potential function is not suitable for cemented clay (Horpibulsuk et al., 2009). The plastic potential function proposed by McDowell and Hau (2003) is employed with the consideration of cementation structure for cemented clay. The plastic potential function, g, in the MSCC model is thus introduced as follows,

$$g = q^2 + \frac{\mathrm{M}^2}{1-\psi}\left[\left(\frac{p' + p'_b}{p'_p + p'_b}\right)^{\frac{2}{\psi}}\left(p'_p + p'_b\right)^2 - \left(p' + p'_b\right)^2\right] = 0 \tag{10}$$

where p'_p is the parameter for describing size of plastic potential function, ψ is the parameter describing the shape of the plastic potential function. The shape of plastic potential is shown in Fig. 3 for various ψ-values. This figure is for $p'_b = 0.2 p'_p$ and M = 1.2. When $\psi = 2$ and $p'_b = 0$, this plastic potential function becomes that of the Modified Cam Clay model. The lower the ψ, the lower the plastic shear strain at failure, $\varepsilon^p_{s,f}$, associated with higher strength and stiffness.

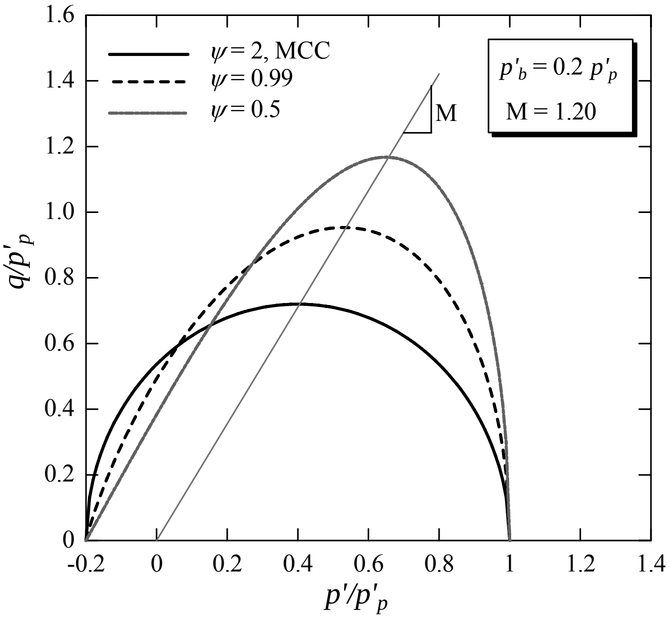


Fig 3 Shape of the plastic potential for the MSCC model.

For stress states on the yield surface and with $\bar{\eta} < \mathrm{M}$ ($\mathrm{d}p'_0 > 0$), both volumetric hardening and destructuring occur. The plastic volumetric strain increment, ε_v^p, for the MSCC model is derived from the assumption that the plastic volumetric strain is dependent upon the change in the p'_0 and the magnitude of current shear stress. The plastic volumetric strain increment during hardening is thus derived from Eq. (8) as follows,

$$\mathrm{d}\varepsilon_v^p = \left\{\left(\lambda^* - \kappa\right) + b\Delta e\left[\frac{\mathrm{M}}{\mathrm{M}-\bar{\eta}}\right]\right\}\frac{\mathrm{d}p'_0}{\left(1+e\right)p'_0} \qquad (11)$$

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

$$\mathrm{d}\varepsilon_v^p = \left\{\left(\lambda^* - \kappa\right) + b\Delta e\right\}\frac{\mathrm{d}p'_0}{\left(1+e\right)p'_0} \qquad (12)$$

4. VERIFICATION OF MSCC MODEL

Few model parameters are considered for the development of MSCC model for the sake of practical work. Most of the model parameters are the same as those of Modified Cam Clay model. There are only five additional parameters defining the structure effect. They are b, Δe_i, p'_{b0}, ξ and ψ and simply determined from the conventional laboratory tests.

Table 1 MSCC model parameters for the cemented Ariake clay.

Model parameters	Cement content	
	A_w = 6%	A_w = 18%
λ*	0.44	0.44
κ	0.06	0.001
e^*_{IC}	4.37	4.37
b	0.15	0.001
Δe_i	1.50	2.65
M	1.60	1.35
p'_{b0} (kPa)	50	650
$p'_{y,i}$ (kPa)	50	1,800
G'	6,000	40,000
ξ	10	30
ψ	1.8	0.1

Cemented Ariake clay for low and high cement contents (6% and 18%) are taken for the verification of the MSCC model. Values of model parameters identified are listed in Table 1. Parameters e^*_{IC}, λ^*.,κ, $p'_{y,i}$, b and Δe_i were determined from the results of isotropic compression test and G' was obtained from triaxial shear test. The values of strength parameters M and p'_{b0} were obtained by plotting the peak strength in the q - p' plane. Value for parameter ψ was estimated from the simulation of the stress-strain relationship. It is found that the ψ value decreases with the degree of cementation. Since the ξ is parameter reflecting the rate of strain softening, it is estimated from the stress-strain relationship at post-failure.

The capacity of the MSCC model for describing the influence of cementation is verified by simulating undrained shear behavior of cemented Ariake clay under different effective confining stresses and cement contents. Comparisons between the test data and model simulations are shown in Fig. 4. Overall speaking, the general patterns of the behavior of cemented clays i.e., the increment in stiffness and peak strength with cementation and the rapidness of the reduction in deviator stress during softening, have been captured. The model simulations cover low to high cement contents (from 6 to 18% by weight) and over a wide range of stress level (200 kPa to 3,000 kPa). The simulations are made with the values of model parameters essentially determined via their physical meanings. It is a useful tool for describing the behavior of cemented clays. The assessment of some model parameters for different cement contents by empirical equations can be referred to the work by Horpibulsuk et al. (2009).

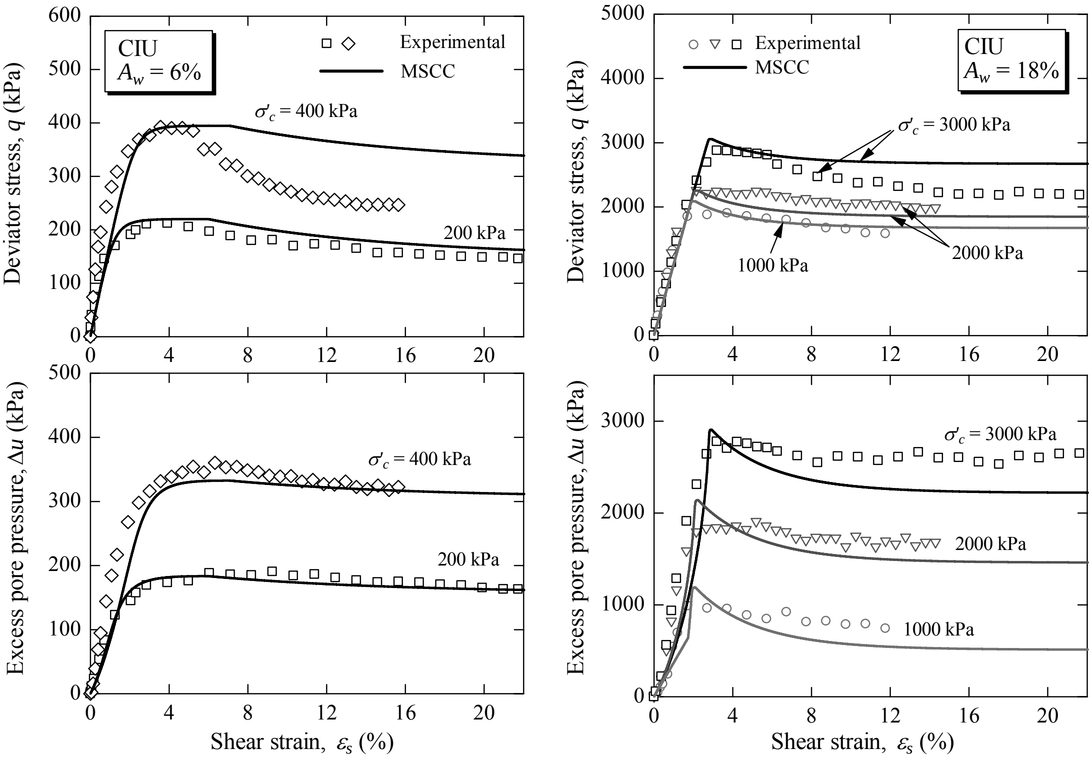


Fig 4 Comparison of experimental and simulated CIU test results of 6% and 18% cement Ariake clay.

5. CONCLUSION

In this paper, a rational and practical model, Modified Structured Cam Clay (MSCC) model, is developed by the extension of a simple predictive, Structured Cam clay (SCC) model for cemented clay. In the MSCC model, the influence of cementation structure is incorporated into effective stress concept, yield function, hardening rule and plastic potential function to describe the mechanical behavior of cemented clay during strain-hardening and softening.

Simulations are made by using the MSCC model for cemented Ariake clay with different cement contents under different effective confining stresses and these simulations are compared with experimental data. Overall speaking, a reasonably well description of the influence of soil-cementation structure on the soil behavior has been achieved.

6. ACKNOWLEDGMENTS

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7. NOTATION

b	Parameter describing the rate of destructuring in compression
CSL	Critical state line
$\mathrm{d}\varepsilon_v$	Volumetric strain increment
$\mathrm{d}\varepsilon_v^e$	Elastic volumetric strain increment
$\mathrm{d}\varepsilon_v^p$	Plastic volumetric strain increment
$\mathrm{d}\varepsilon_s$	Shear strain increment
$\mathrm{d}\varepsilon_s^e$	Elastic shear strain increment
$\mathrm{d}\varepsilon_s^p$	Plastic shear strain increment
Δe	Additional void ratio sustained by soil structure
Δe_{i}	Additional void ratio sustained by soil structure at the start of virgin yielding
e	Void ratio
e^*_{IC}	Void ratio at $p' = 1$ kPa of the intrinsic compression line (ICL)
G'	Shear modulus
ICL	Intrinsic compression line (destructured)
K'	Bulk modulus
ξ	Destructuring index
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 on q-p' space
η	Stress ratio (q / p')
$\bar{\eta}$	Modified stress ratio ($q / \left(p' + p'_b\right)$)
ν'	Poisson ratio
p'	Mean effective stress
$\bar{p}'$	Modified mean effective stress
p'_b	Mean effective stress increasing due to structure or structure strength
p'_0	The yield stress in the isotropic compression condition

p'_{b0}	Initial structure strength in q-p' plane
p'_{yi}	Initial yield stress in the isotropic compression condition
q	Deviator stress
ψ	Parameter defining shape of the plastic potential function
σ'_c	Effective confining pressure

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