A Modified Structured Cam Clay Model

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Abstract : In this paper, characteristics of the undrained shear behavior of induced cemented clays are summarized for the purpose of developing an appropriate constitutive model for solving practical geotechnical problems. The Modified Structured Cam Clay (MSCC) model is introduced for this purpose. It is formulated based on the modified effective stress concept and the Structured Cam Clay (SCC) model proposed by Liu and Carter [1 and 2]. The model parameters can be divided into those describing intrinsic soil properties and those for cementation, which can be simply determined from conventional triaxial tests on uncemented and cemented samples, respectively. The performance of the model is verified by comparisons of model simulations and experimental data for tests at various stress levels on clay samples with different degrees of cementation.

1. Introduction

The explicit nature of the stress-strain response of cemented soil in both naturally and induced cemented states mostly depends on fabric and bonding [3 and 4]. Despite the availability of a large number of constitutive relations describing the behavior of clays, there is still a large number of problems which have not been satisfactorily tackled. Most often, induced cemented clays are treated as if they are overconsolidated clays because they also exhibit similar mechanical features, like strain softening, higher initial stiffness, *etc.* But recent studies [6 and 7] have revealed that their behaviors are very different. Strain softening is observed in relation to cemented samples under effective confining stresses far higher than the mean effective yield stress. The most important difference is that softening is associated with positive pore pressure during undrained shearing and with positive volumetric strain during drained shearing; whereas the same does not happen in the case of uncemented clay samples.

Many researchers have developed constitutive models incorporating the influence of cementation bonding, such as those proposed by Gens and Nova [8], Rouainia and Muir Wood [9] and Kavvadas and Amorosi [10]. However, these constitutive models generally have many parameters, the values for some of which are difficult to determine by simple soil laboratory tests. Liu and Carter [1 and 11] and Carter and Liu [2] have proposed a new constitutive model for naturally cemented clay, known as "Structured Cam Clay, SCC". This model is relatively simple and has few parameters, each of which has a clear physical meaning and can be conveniently identified.

The Modified Cam Clay (MCC) model [12] is widely referenced and has now been widely used in solving boundary value problems in geotechnical engineering practice. Because of familiarity with the model by the geotechnical profession and its ability to simulate the essential behavior of reconstituted (uncemented) soil, the MCC model was chosen as basis for the SCC model. The SCC model is only suitable for natural cemented clay and lightly induced cemented clay in which the cohesion intercept is relatively small. But for induced cemented clay, the cohesion intercept is generally very significant and the softening behavior is realized even on virgin yielding [6 and 13-15]. Such behavior cannot be predicted by the SCC model. Therefore, the SCC model has been extended to formulate a practical model for induced cemented clay designated as the Modified Structured Cam Clay (MSCC) model in this paper. The role of the cementation is introduced into the SCC model in terms of the modified effective stress. The flow rule is modified to capture the softening behavior. The simulated results of triaxial shearing tests (deviator stress versus shear stain and effective stress paths) are compared with test data from Horpibulsuk *et al.* [6]. The comparisons of simulated result by SCC model and MSCC model are also shown.

2. Characteristics of Undrained Shear Behavior of Induced Cemented Clay

Understanding of characteristics of induced cemented clay is vital necessary to develop a rational constitutive model. The salient aspects have been summarized as follows:

1) Due to the effect of cementation, the void ratio of induced cemented clay is in a meta-stable state [5, 16]. Its void ratio is the summation of the void ratio sustained by intrinsic fabric and the additional void ratio due to the cementation bonds.
2) The cementation bonds increase the resistance to elastic deformation but reduce the resistance to plastic deformation. The greater the degree of cementation, the higher the compression index of the virgin compression line (λ) [5].
3) The yield stress and the size of yield surface increase with the increase in degree of cementation, which is mainly controlled by water content, cement content and curing time [4, 7, 17].
4) The strain softening behavior is realized both for pre-yield states (p' is lower than the initial yield stress) and post-yield states (p' is higher than the initial yield stress) due to the crushing of clay-cement structure [6]. After the failure state, the deviator stress reduces and levels off at critical state. Due to the cementation, the deviator stress and mean effective stress at critical state of the induced clay are not the same as those of uncemented state. However, the critical state lines of cemented and uncemented clays are the same.
5) A single failure envelope is observed for the induced cemented clay in both the pre- and post-yield states. On the other hand, two separate failure envelopes are evident for uncemented clays in normal and over consolidated states. This is because the interlocking is the main component imparting peak strength to the uncemented clay at the overconsolidated state. The slope of the failure envelope for induced cemented clay is higher than that of uncemented clay. This implies that the cementation bond increases the friction between grain contacts. However, the test results reported by Horpibulsuk *et al.* [6] indicate that this slope changes insignificantly with cement content.
6) Cementation bonds impart cohesion and tension to the induced cemented clays. The greater the degree of cementation, the higher the cohesion [6]. The stiffness of the induced cemented clay increases with degree of cementation, which is due to the increase in cohesion and the size of yield surface.

3. Modified Effective Stress Concept

For the induced cemented clay, the cohesion is mainly dependent upon the degree of cementation. Based on the effective stress concept (shear strength is controlled by effective stress), the cementation effect is regarded akin to the effect of an increase in the effective confining stress. An increase in cementation enhances not only the effective stress (effective confined stress) but also the yield stress. Two samples of the induced cemented clay having the same current stress but different degree of cementation would show different stress-strain and strength characteristics due to the difference in state of stress and the effective confining stress caused by the cementation bonding. As such, the modified effective stress concept can be written as follows:

$$\bar{p}' = p' + p'_b \tag{1}$$

where $\bar{p}'$ is the explicit mean effective stress, p' is the conventional mean effective stress and p'_b is the additional mean effective stress due to cementation bonding.

Due to p'_b, samples of the induced cemented clay can stand without an applied confining stress. It is assumed that p'_b decreases after the peak strength is reached and becomes zero at the critical state where the cementation is completely broken down. It is clearly seen that the failure envelope of the induced cemented clay is unique for both pre- and post-yield states and a cohesion intercept is induced by the effect of cementation. Hence, the shear resistance is dependent upon the explicit effective stress at the failure plane and the failure friction angle of the material. The relationship between deviator stress and mean effective stress at failure can be proposed as follows:

$$q = M\left(p' + p'_b\right) \tag{2}$$

In order to determine p'_b, the conventional (q, p') plot is required. p'_b is equal to q_0/M, where q_0 is the intercept of the failure line on the q axis.

It is of interest to mention that the modified Roscoe surface can be generated based on the modified effective stress concept as shown in Figure 1. $\bar{p}'_y$ is the explicit mean effective yield stress, which is the summation of the mean effective yield stress and p'_b. During virgin yielding, $\bar{p}'_y$ is equal to $(p'_0 + p'_b)$, where p'_0 is the pre-shear effective stress. Inside state boundary surface, $\bar{p}'_y$ is equal to $(p'_{y,i} + p'_b)$, where $p'_{y,i}$ is the initial mean effective yield stress obtained from the compression curve. It is found that the normalized effective stress paths for each cement content at post-yield state can be represented by a unique line, which is a state boundary surface. The unique line for each cement content shows that the undrained stress paths at post-yield states are of the same shape and consistent with one another. Samples at pre-yield states, especially $\bar{p}'/\bar{p}'_y < 0.7$, fail on the same failure line, 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.

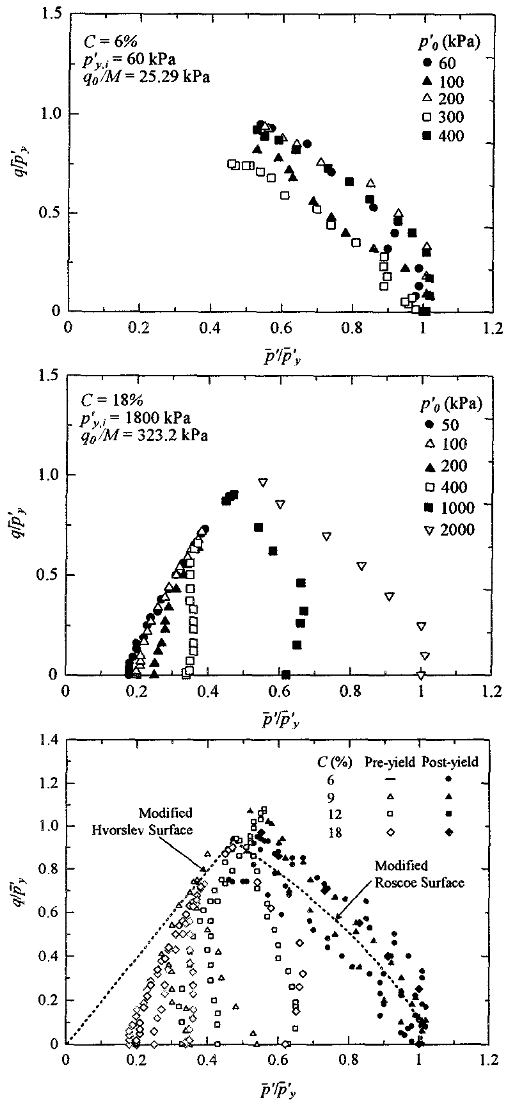

Figure 1 Test paths in $q/\bar{p}'_y : \bar{p}'/\bar{p}'_y$ space for an undrained test on 6%, 9%, 12% and 18% cement samples.

4. Description of the Modified Structured Cam Clay Model

A brief introduction to the MSCC model for soils with induced cementation is presented here. In this model, the stress and strain parameters are the same as those commonly adopted in soil mechanics. The major aim of formulating the Modified Structured Cam Clay model is to provide a constitutive model suitable for the solution of boundary value problems encountered in geotechnical engineering practice, *i.e.*, a practical tool. It is therefore necessary to keep the model relatively simple and with the model parameters conveniently and unambiguously determinable from conventional tests. Based on the modified effective stress concept, in the formulation of the MSCC model, the stress ratio is modified as

$$\bar{\eta} = q / \bar{p}' \tag{3}$$

4.1 Material idealization

In the MSCC model, soil is idealized as an elastic and virgin yielding material. The yield surface varies isotropically with the change in plastic volumetric deformation. Soil behavior is assumed to be elastic for any stress excursion inside the current cemented yield surface. Virgin yielding occurs for a stress variation originating on the cemented yield surface and causing it to change. During virgin yielding, the current stress of a soil stays on the cemented yield surface. Idealization of the mechanical behavior of cemented clays is illustrated in Figure 2. In this figure, the yield surface of cemented soil in q-p' space is also assumed to be elliptical (Figure 2a). The effect of cementation is expressed as an increase of size of the yield surface, p'_s. It is due to the shift of the explicit mean effective stress at $q = q_0$ to the left along the op' axis by q_0/M. Hence, p'_s and $\bar{p}'_y$ values are the same.

The schematic diagram (Figure 2b) is introduced to describe the compression behavior of cemented clay using the uncemented line as a reference. The symbol, e represents the void ratio for a cemented clay and e^* is the void ratio for the corresponding uncemented clay at the same stress state. $p'_{y,i}$ is the mean effective stress at which virgin yielding of the cemented clay begins. Δe, the additional void ratio, is the difference in void ratio between a cemented clay and the corresponding uncemented soil at the same stress state. Hence, the virgin compression behavior of a cemented clay can be expressed by the following equation

$$e = e^* + (\Delta e_i - c)\left(\frac{p'_{y,i}}{p'}\right)^b + c \tag{4}$$

where b and c are soil parameters describing the additional void ratio sustained by cementation. Δe_i is the value of the additional void ratio at the start of virgin yielding (Figure 2b). Parameter c is defined by the following equation,

$$c = \lim_{p' \to \infty} \Delta e \tag{5}$$

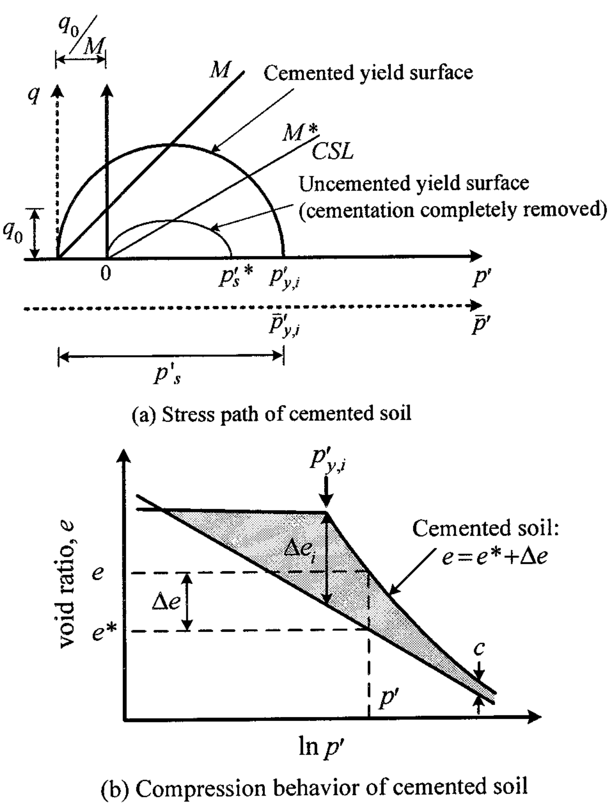

Figure 2 Material idealizations for the MSCC model.

4.2 Elastic behavior

For stress excursions within the current virgin yielding boundary, only elastic deformation occurs. The elastic deformation of a cemented clay is described by Hook's law, *i.e.*,

$$d\varepsilon_v^e = \frac{3(1-2\nu)}{E} d\bar{p}' \tag{6}$$

$$d\varepsilon_s^e = \frac{2(1+\nu)}{3E} dq \tag{7}$$

where ν is Poisson's ratio and E is Young's modulus. E, ν, p', and κ are related by

$$E = \left[3(1-2\nu)(1+e)p'\right]/\kappa \tag{8}$$

Therefore, for loading inside the yield surface in an undrained test, the mean effective stress, p' rises vertically until reaching the yield surface, as shown in Figures 3a and 3b for wet and dry sides of the failure envelope, respectively.

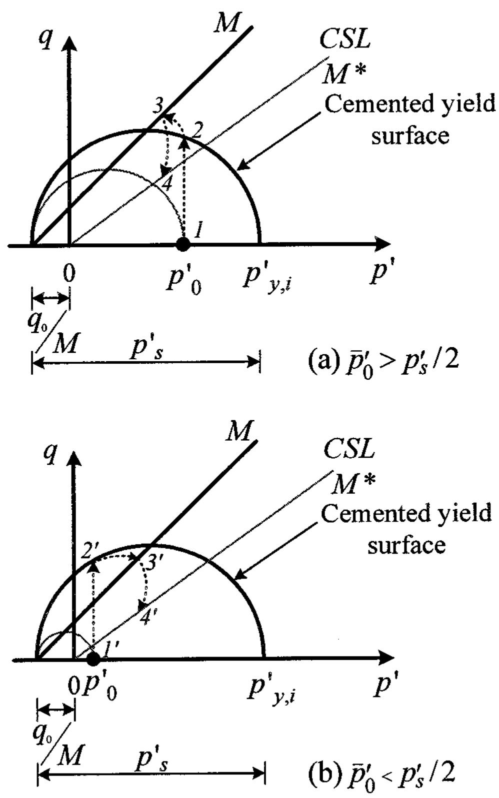

Figure 3 Schematic diagrams showing undrained stress path.

4.3 Virgin yielding behavior

For stress states on the yield surface and with $dp'_s > 0$ (point 2 in Figure 3a), virgin yielding occurs. The plastic volumetric strain increment for the MSCC model is derived from the assumption that both hardening behavior and break-up of cementation are dependent on volumetric deformation, and given as

$$d\varepsilon_v = d\varepsilon_v^e + \left[(\lambda^* - \kappa) + b\left[\langle \Delta e - c \rangle\right] \frac{dp'_s}{(1+e)p'_s} \right] \tag{9}$$

where λ^* is the compression index of the uncemented line and

$$\langle \Delta e - c \rangle = \begin{cases} \Delta e - c & ,\text{if } \Delta e - c \geq 0 \\ 0 & ,\text{if } \Delta e - c < 0 \end{cases} \tag{10}$$

It is noted that in Eq. (9), the κ is used in spite of κ^* since κ is not constant (dependent upon the degree of cementation) and much lower than κ^*. The shear strain increment is given as follows via a proposed flow rule, *i.e.*,

$$d\varepsilon_s^p / d\varepsilon_v^p = 2\bar{\eta} / \left(\left| M^2 - \bar{\eta}^2 \right| + \omega \left| 1 - \sqrt{p_s'^* / p_s'} \right| \right) \tag{11}$$

where ω is a model parameter, and $p_s'^*$ is the size of the uncemented yield surface (Figure 2a). The uncemented yield surface is defined as the yield surface for the same clay in an uncemented state (no cohesion intercept) with the same stress state. Thus, the $\bar{p}'_y$ of the current stress, p'_s, and the p'^*_s. Based on the intrinsic isotropic compression equation, the following equation for $p_s'^*$ can be found as

$$p_s'^* = \left[\exp\left(\frac{e_{IC}^* - e}{\lambda^* - \kappa} \right) \right] / p'^{\left(\frac{\kappa}{\lambda^* - \kappa}\right)} \tag{12}$$

where e^*_{IC} is the void ratio of uncemented clay at unit mean effective stress.

For stress states on the yield surface and with $\bar{\eta} > M$ (point 2′ in Figure 3b), the crushing of clay-cement structure starts [5]. At this state, the cemented yield surface shrinks. During the softening process (stress path 2′-3′), the volumetric deformation of soil is described by the same equations as those for virgin yielding, *i.e.*, equations (9) and (10). A modification of the shear strain increment is made to ensure that the shear deformation contributed by crushing of clay-cement structure always has the same sign as that associated with the clay in an uncemented state.

4.4 Crushing of clay-cement structure

This model assumes that when the stress state reaches the failure envelope, the cemented clay undergoes crushing of the clay-cement structure and eventually reaches the critical state ($d\varepsilon_s^p / d\varepsilon_v^p = 0$). It is assumed that the reduction in q_0 during the crushing of the clay-cement structure (stress paths 3-4 and 3′-4′ in Figure 3) is described by the following equation,

$$dq_0 = \left[\left(\frac{q}{p'} \right)^3 - M^{*3} \right] |dp'| \tag{13}$$

In this case, a general stress and strain relationship for this process can be obtained as,

$$\begin{aligned} dq &= M^* dp' - dq_0 \\ d\varepsilon_v &= \left(\frac{\kappa}{1+e} \right) \frac{dp'}{p'} + d\varepsilon_v^p \\ d\varepsilon_s &= \frac{2(1+v)}{9(1-2v)} \left(\frac{\kappa}{1+e} \right) \frac{dq}{p'} + \frac{2\bar{\eta}\beta |d\varepsilon_v^p|}{|M^{*2} - \eta^2|} \end{aligned} \tag{14}$$

It is found from equations (14) that when the stress state ($p'_b = 0$) is at the critical state ($\eta = M^*$), the plastic shear strain increment approaches infinity.

The parameters of the MSCC model are divided into two categories: those that may be treated as intrinsic material parameters (λ^*, e_{IC}^* and M^*) and those dependent on cementation. It is suggested that the v, q_0, $p'_{y,i}$, Δe_i, b, c, ω, β and κ are all treated as cementation parameters. The ω and β control the stiffness of the clay at pre- and post-peak deviator stress, respectively. The parametric study on these two parameters is done by Suebsook et al. [18]. More details on the other parameters can be referred to Liu and Cater [1 and 2]. The performance of the model would be verified by comparisons of the model simulations and experimental data in the next section.

5. Simulating Undrained Shear Behavior of Cemented Clay

The undrained test results reported by Horpibulsuk *et al.* [6] are considered for verifying the proposed model. The base clay is Ariake clay, collected in Fukudomi town, Saga, Japan. The clay is highly plastic with natural water content in a range of 135-150 percent. The liquid and plastic limits are in the order of 120 and 57 percent. The apparent pre-consolidation pressure is 80 kPa. The effective strength parameters in compression are $c' = 0$ and $\phi' = 38°$. This ϕ' is quite high since Ariake clay gets influenced from natural cementation.

The effective confining pressures, σ'_c, were from 50 to 2000 kPa. The model parameters adopted for the analysis are listed in Tables 1 and 2.

Table 1 Model parameters for uncemented clay

λ^*	e_{IC}^*	M^*
0.44	3.23	1.58

Table 2 Model parameters for cementation bonding

C	$p'_{y,i}$ (kPa)	Δe_i	b	c	v
6	60	2.80	1.0	0	0.35
12	380	3.50	0.5	0	0.35
18	1800	3.80	0.5	0	0.35

C	κ	q_0 (kPa)	M	ω	β
6	0.078	44	1.74	0.10	10
12	0.065	210	1.87	0.20	25
18	0.011	585	1.81	0.20	30

Values of parameters e^*_{IC}, λ^*, b, Δe_i and $p'_{y,i}$ were determined from the results of isotropic compression tests on both uncemented and cemented samples. For simplicity, the value of c was taken as zero for the range of mean effective stress considered. Values of q_0 and M were determined from the (q, p') plot for induced cemented clay. The values for parameters ω and β can be obtained by curve fitting.

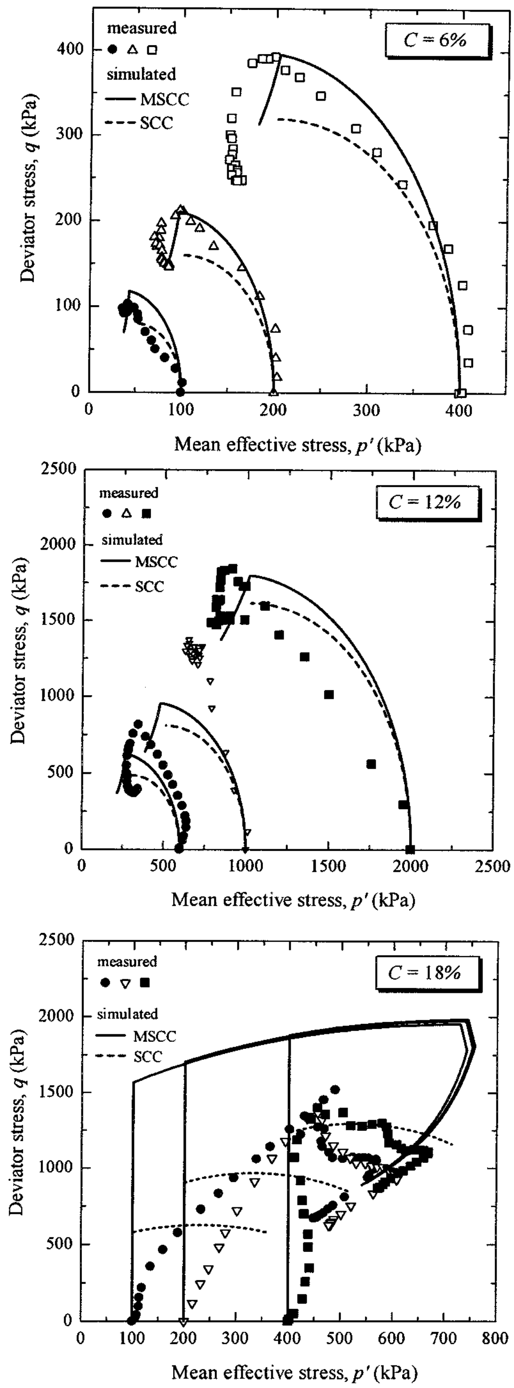

Figure 4 Simulated and measured undrained stress path of 6- 18% cement samples.

Comparisons of simulated and measured test results for various cement contents are shown in Figures 4 and 5. The simulation was done by both SCC and MSCC models. The simulation is divided into two states: pre-yielding (C = 18%) and post-yielding (C = 6 and 12%) states.

Figures 4 and 5 show (q-p') and (q-ε_s) relationships for the 6% and 12% cement samples at post-yield state and 18% cement samples at pre-yield state, respectively. It is found that the MSSC model can capture the softening behavior for both states of stress inside and on the state boundary surface.

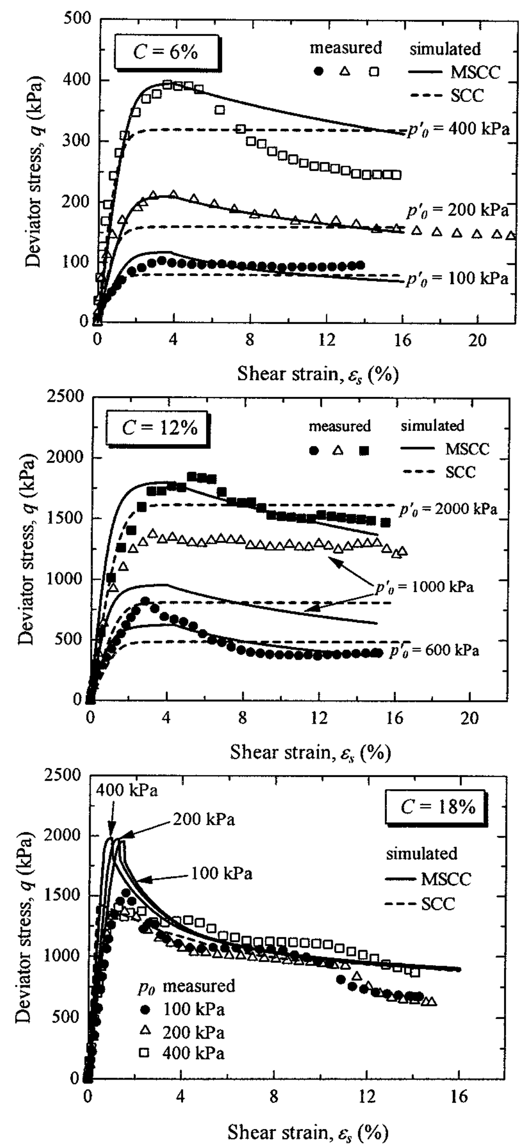

Figure 5 Simulated and measured (q-ε_s) relationships of 6-18% cement samples.

However, the model cannot well capture the undrained response for the samples at pre-yield state. The q_{max} of the sample simulated by MSCC model is higher than the test result (about 25%) since the material is not purely elastic as assumed.

6. Conclusions

The conclusions of the present paper can be drawn as follows:

1) The modified effective stress concept was introduced to take the effect of cementation into account and is found to be useful for interpreting the behaviour of cemented soil.
2) Based on the modified effective stress and the state boundary surface concepts, the modified structured cam clay (MSCC) model was developed. The intrinsic (uncemented) and cementation parameters can simply be obtained from the results of conventional triaxial compression. Thus, the MSCC model can be considered as a valuable tool for geotechnical practitioners.

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