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Micromechanics-based model for cement-treated clays

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Abstract Cementation is produced by mixing a certain amount of cement with the saturated clay. The purpose of this paper is to model the cementation effect on the mechanical behavior of cement-treated clay. A micromechanical stress–strain model is developed considering explicitly the cementation at inter-cluster contacts. The inter-cluster bonding and debonding during mechanical loading are introduced in two ways: an additional cohesion in the shear sliding and a higher yield stress in normal compression. The model is used to simulate isotropic compression and undrained triaxial tests under various confining stresses on cement-treated Singapore clay with various cement contents. The applicability of the present model is evaluated through comparisons between numerical and experimental results. The evolution of local stresses and local strains in inter-cluster planes is discussed in order to explain the induced anisotropy due to debonding at contact level under the applied loads.

Keywords microstructure, cementation, constitutive model, clay, anisotropy, debonding

Stabilization of soft ground by deep cement mixing and jet grouting methods, which both introduce cement into the ground, has been widely used in geotechnical projects. The proper understanding of the cementation influence on the mechanical behavior of cement-treated clay is of great importance. Experimental results show an increase of shear strength and shear modulus with cement content, accompanied by a large post-peak reduction in the strength of the treated soil.1–5 Cementation also makes the yield stress and swelling index higher than those of untreated soil. Bond degradation is often observed if the compression load exceeds the yield stress, as it has also been observed in natural structured soils.6–12

In this study, the recently developed micromechanical model of remolded clay is first briefly introduced. The model is then extended by considering the cementation effect on the mechanical properties of cement-treated clays. The model is used to simulate isotropic compression and undrained triaxial tests under various confining stresses on cement-treated clays with different cement contents. The evolution of local stresses and strains in inter-cluster planes due to externally applied loads is also discussed in order to describe the mechanism of induced anisotropy due to debonding at the micro contact level.

Yin et al.13–15 assumed that clay material can be considered as an assembly of clusters. The deformation of a representative volume of clay is generated by mobilizing and compressing of all clusters. Thus, the stress–strain relationship can be derived as an average of the deformation of all local contact planes. The model includes the inter-cluster behavior, the influence of density state, and the overall stress–strain relationship.16

For the $\alpha$-th contact plane, the local forces $f^\alpha$ and the local movements $\delta^\alpha$ can be denoted as follows: $f^\alpha = \{f^\alpha_n, f^\alpha_s, f^\alpha_t\}$ and $\delta^\alpha = \{\delta^\alpha_n, \delta^\alpha_s, \delta^\alpha_t\}$ (see Fig. 1 for local coordinate system). In order to obtain a more direct comparison between the local behavior and the overall stress–strain behavior, we define a local normal stress $\sigma^\alpha = f^\alpha_n N/l$ and a local shear stress $\tau^\alpha = f^\alpha_s N/l$, where $l$ is branch length and $N/V$ is the total number of contact per unit volume. The corresponding local normal strain is defined as $\varepsilon^\alpha = \delta^\alpha_n/l$ and a local shear strain is defined as $\gamma^\alpha = \delta^\alpha_s/l$.

Isotropic compression and oedometer tests by Horpibulsuk et al.4 and Kamruzzaman et al.5 on two cement-treated clays show the significant influence of the cement content on the swelling index (see Fig. 2(a)) and on the compression yield stress (see Fig. 2(b)). This influence can be expressed by Eq. (1) for the swelling index $\kappa$ and by Eq. (2) for the bonding pressure $p_b$ defined as the difference of the compression yield stress between cement-treated clay $p_{yc}$ and untreated clay $p_{yc}$: $p_b = p_{yc} - p_{yu}$, as follows

\[
\kappa = \kappa_0 \exp(-\beta_\kappa c),
\]

\[
p_b = \beta_{p1} \left[ \exp(\beta_{p2} c) - 1 \right],
\]

where $\kappa_0$ is the swelling index for untreated clay, $c$ is the cement content, $\beta_\kappa$, $\beta_{p1}$ and $\beta_{p2}$ are material constants (see Figs. 2(a) and 2(b)).

By comparing the post-yield stress–strain curves of cement-treated samples to those of untreated samples,4,5 a mechanical bond degradation process can be observed. This bond degradation is an irreversible phenomenon that, experimentally, appears to be controlled by plastic strain accumulation.13,19 The bonding and debonding can be linked directly to the inter-cluster bonds due to the cementation formed when adding cement into clay slurry.

The friction angle at failure was measured based on undrained triaxial tests by Horpibulsuk et al.4 and
Kamruzzaman et al.\textsuperscript{5} on both cement-treated clays by extending the curves to an axial strain up to 15\% according to the previous trend. As shown in Fig. 2(c), for Ariake clay, having an initially high friction angle, the cement content influences slightly the friction angle at failure (we obtained $\phi_{\mu} = 40^\circ$ measured from undrained stress paths, which is slightly different from $\phi_{\mu} = 38^\circ$ provided by Horpibulsuk et al.\textsuperscript{4}). However, for Singapore clay with an initially small friction angle, the cement content influences significantly the friction angle at failure. This influence can be expressed by Eq. (3) as follows

$$\phi_{\mu} = \phi_{\mu 0} + (\phi_{\mu \text{ max}} - \phi_{\mu 0}) [1 - \exp (-\beta f c)],$$

where $\phi_{\mu 0}$ is the friction angle at failure for the untreated clay, $\phi_{\mu \text{ max}}$ is the maximum friction angle at failure, and $\beta f c$ is the bonding intercept cohesion.

Fig. 2. Effect of cement content on properties of cement treated clays.
failure for the cement-treated clay, and $\beta_f$ is a material constant.

The apparent cohesion due to cement bonds is measured from the position of the failure line in the $p' - q$ plane. Figure 2(d) shows the significant influence of the cement content on the apparent cohesion $c_b$ for both cement-treated clays. This influence can be expressed by Eq. (4), having a form similar to Eq. (2) for the cement content on the apparent cohesion plane. Figure 2(d) shows the significant influence of the cement content on the apparent cohesion plane.

$$c_b = \beta_{c1} \left[ \exp (\beta_{c2} c) - 1 \right],$$

where $\beta_{c1}$ and $\beta_{c2}$ are material constants.

The stress-strain curves of the two cement-treated clays show also the influence of the cement content on the initial shear modulus, which is similar to its influence on the swelling index (or bulk modulus). Since the shear modulus can not be accurately measured based on digitized data, we will not discuss it in this paper. Upon increase of the applied shear stresses, the inter-cluster bonds are progressively damaged. As a result, a decrease of the deviatoric stress takes place after the peak for cement-treated samples.

The critical state lines (CSL) are obtained from the undrained triaxial tests for untreated clays, as shown in Figs. 3(a) and 3(b). The void ratio corresponding to this state is $e_c$. The CSL can be written as follows for clay

$$e_c = e_{cr} - \lambda \log \left( \frac{p'}{p_{ref}} \right),$$

where $p$ is the mean effective stress, $\lambda$ is the slope of the CSL in the $e$-lg$p'$ plane, $e_{cr}$ is the reference void ratio at critical state corresponding to $p_{ref} = 100$ kPa.

For cement-treated clays, if the failure state in the $p' - q$ plane (corresponding to 15% of axial strain) is considered as the critical state, the CSL in the $e$-lg$p'$ plane can be obtained for all cement-treated samples. For cement-treated Ariake clay (see Fig. 3(a)), the critical state line can be assumed to be parallel to that of the untreated clay. If this assumption is also adopted for cement-treated Singapore clay, the critical state lines can be obtained as shown in Fig. 3(b). Therefore, the influence of cement content on the location of the critical state line can be obtained by making the reference void ratio function of the cement content, as shown in Fig. 3(c), expressed as follows

$$e_{cr} = e_{cr0} + (e_{cr max} - e_{cr0}) \left[ 1 - \exp \left( -\beta_c c \right) \right],$$

where $e_{cr0}$ is the reference critical state void ratio for the untreated clay, $e_{cr max}$ is the maximum reference critical state void ratio for cement-treated clay, $\beta_c$ is a material constant.

Horpibulsuk et al.\textsuperscript{4} have shown that the clay fabric consists of clay cluster (aggregation of clay particles) and that the role of the induced cementation is to weld clay clusters. Kamruzzaman et al.\textsuperscript{5} have made SEM photos untreated and cement treated by Singapore clay with various cement contents under various consolidation pressures, which demonstrate that the size of the clay clusters can be considered the same for all cases. Therefore, the cement-treated clay can be seen as an assembly of clusters (aggregates of clay-cement particles). The deformation of an assembly can be obtained by integrating the movement of the inter-cluster contacts in all orientations. Thus, the effect of the inter-cluster bonding can be explicitly taken into account.
As the orientation dependent properties are explicitly introduced, the induced anisotropy due to inter-cluster debonding can be modeled in a direct way. Therefore, the micromechanics-based model developed by Yin et al.\textsuperscript{13,14} for natural clays can be extended for cement-treated clays. In addition to the micromechanical model at inter-cluster contacts proposed by Yin et al.\textsuperscript{13,14} for natural clays, three modifications were made to account for the effect of cement content on the inter-cluster bonding and debonding, listed below.

In order to take into account the effect of the inter-cluster bonding, the plastic law of the shear sliding at inter-cluster contacts proposed by Yin et al.\textsuperscript{14,15} is adopted. The yield function for shear sliding is assumed to be of Mohr–Coulomb type, written in a contact plane (e.g. \(\sigma, \tau, \tau_l\), see coordinate system in Fig. 1) as follows

\[
F_1(\sigma, \tau, c_b, H_1) = \frac{\tau}{\sigma + c_b/\tan \phi_{\mu}} - H_1(\gamma^p),
\]

where \(c_b\) is the inter-cluster cohesion due to the inter-cluster bonding, \(H_1(\gamma^p)\) is a hardening/softening function. The values of \(c_b\) and \(\phi_{\mu}\) depend upon the cement content (see Eqs. (4) and (3)). The influence of the cement content on the shear behavior is thus introduced. For untreated clay, \(c_b = 0\), and the equation can be reduced to that by Yin et al.\textsuperscript{15–18}

The local dilatancy equation is derived from that proposed by Yin et al.\textsuperscript{16–19} as follows

\[
\frac{d \varepsilon^p}{d \gamma^p} = D \left| \left( \tan \phi_{\mu} - \tan \phi_m \right) \left( \frac{\tan \phi_m}{\tan \phi_{\mu}} \right) \right| \left( \frac{\varepsilon}{\varepsilon_c - 1} \right),
\]

where \(\tan \phi_m = \tau / (\sigma + c_b / \tan \phi_{\mu})\), \(D\) is a material constant which controls the dilatancy rate during shearing. The void ratio at critical state \(\varepsilon_c\) is calculated using Eq. (5) where the influence of the cement content is introduced by \(\varepsilon_{cr}\) (see Eq. (6)).

The degradation of the inter-cluster bonds can be modeled as a damage of the bonded contacts. Therefore, the damage law proposed by Yin et al.\textsuperscript{13,14} is adopted in the expression of the inter-cluster cohesion, as follows

\[
c_b = c_{b0} \exp \left( -\xi_d \gamma^p \right),
\]

where \(c_{b0}\) is the initial inter-cluster cohesion, \(\xi_d\) is the factor of damage representing the influence of the tangential displacement in the damage law. Therefore, during loading each contact sliding produces a progressive damage of the cohesion.

In order to account for the inter-cluster bonding effect on the compressive behavior of cement-treated clay, we adopt the plastic law for the normal compression of inter-cluster contacts proposed by Yin et al.\textsuperscript{13,14}

\[
F_2(\sigma, \sigma_p) = \sigma - \sigma_p,
\]

where \(\sigma_p = \sigma_{pi}(1 + \chi)\) is the compression yield stress, \(\sigma_{pi}\) is the intrinsic compression yield stress corresponding to the yield stress measured from an isotropic compression test on a reconstituted sample of untreated clay, \(\chi\) is the bonding ratio defined by \(\chi = \sigma_p / \sigma_{pi} - 1\). The value of \(\sigma_{pi}\) depends on the cement content \((\sigma_{pi} = \sigma_{pi} + p_n\), see Eq. (2) for \(p_n\)). Thus, the influence of the cement content on the compression behavior is introduced.

The hardening function controlling the evolution of \(\sigma_{pi}\) is defined as follows

\[
\sigma_{pi} = \sigma_{pi0} \exp \left( \frac{\varepsilon^p}{c_p} \right),
\]

where \(c_p\) is the compression index determined from the compression curve plotted in the \(\varepsilon^p-\varepsilon\) plane.

The damage law proposed by Yin et al.\textsuperscript{13,14} is also adopted in the expression of the bonding ratio at inter-cluster level

\[
\chi = \chi_0 \exp \left( -\xi_n \varepsilon^p \right),
\]

where \(\chi_0\) is the initial bonding ratio depending of the cement content, \(\xi_n\) is the factor of damage representing the influence of the normal displacement in the damage law. Therefore, during loading each contact produces a progressive damage of the bonding ratio. For untreated clay \(\chi_0 = 0\) (or \(\sigma_p = \sigma_{pi}\)), the equation can be reduced to that by Yin et al.\textsuperscript{15–18}

Based on experimental investigation, the dependency of the CSL location on the cement-content is implemented into the model, i.e. the Eq. (12) is replaced by the Eqs. (5) and (6).

Combined all above equations with others by Yin et al.,\textsuperscript{13,14} the model can be used to reproduce mechanical behavior of cement-treated clays.

The determination of parameters for cement-treated Ariake clay was based on the isotropic compression and undrained triaxial tests under a consolidated stress of

![Fig. 4. Comparisons between experiments and simulations for isotropic compression tests on cement treated Ariake clay with cement content of 0%, 6%, 9%, 12%, 18%.](image-url)
Table 1. Local coordinate at inter-particle contact.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$e_0$</th>
<th>$\kappa_0$</th>
<th>$\lambda$</th>
<th>$\sigma_{p0}$</th>
<th>$\phi_n$</th>
<th>$k_p$</th>
<th>$D$</th>
<th>$\epsilon_{cr0}$</th>
<th>$\xi_n$</th>
<th>$\xi_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ariake clay</td>
<td>3.44</td>
<td>0.086</td>
<td>0.446</td>
<td>10</td>
<td>40º</td>
<td>0.15</td>
<td>6</td>
<td>1.911</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>

200 kPa on the untreated Ariake clay. All determined parameters, summarized in Table 1, were used to predict all the other tests.

Figure 4 shows the comparison between experimental results and numerical simulations of isotropic compression tests on untreated and cement-treated Ariake clay with different cement content. A satisfactory agreement is achieved by using the corresponding set of parameters in Table 1.

Figure 5 shows the comparisons between experiments and simulations for undrained triaxial tests on samples of Ariake clay with different cement contents consolidated up to 200 kPa. The influence of the cement content on the behavior of cement-treated Ariake clay was well reproduced by the proposed model: (1) The increase of stiffness and shear strength with cement content, accompanied by a large post-peak reduction in the strength of the treated soil; (2) Samples with low cement content ($c = 0\%$, 6\%, 9\%, 12\%) exhibit a contractive behavior and samples with high cement content ($c = 18\%$) a dilative one.

The distributions of the local normal stiffness and bond in contact planes of various orientations are plotted in Fig. 6 (Fig. 6(1a) for untreated clay, Fig. 6(2a) for cement content of 9\% and Fig. 6(3a) for cement content of 18\%):

(a) The normal stiffness is a function of the normal stress and of the amount of cement. The normal stiffness distribution at the end of the isotropic consolidation has a circular shape (see the bold line in Fig. 6(a)) which corresponds to an isotropic distribution of the normal stress for all contact planes. During the undrained shearing, different cement contents give different evolutions of the stiffness distribution: For 0\% cement content, the distribution becomes anisotropic with an elliptical shape having the long axis in the vertical direction; For 9\% cement content, the distribution becomes also anisotropic with higher stiffness in the vertical direction and lower stiffness in the horizontal direction, and then shrinks during shearing due to bond damage; The same evolution is found for 18\% cement content with higher stiffness values due to stronger bonds.

(b) During the undrained shearing, the shear stress distribution expands while maintaining a similar shape for all cases (Fig. 6(b)). This distribution shows a concentration of the maximum local shear stresses between the 45º and 55º orientations.
(c) During the undrained shearing, the shear strain distribution for all cases (Fig. 6(c)) shows that very large strains occurred at the end of the loading in contact planes around the 70° orientation.

(d) The distribution of shear bonding cohesion changes slightly from step 1 to 2 due to small mobilized shear plastic strains for both 9% and 18% cement contents. Then, from step 2 to 3, the bonding cohesion reduces significantly in the 55°–70° contact planes, but does not change very much in the other planes. This agrees with the shear strain distribution in Figs. 6(2d) and 6(3d), because the damage of the shear bonding cohesion is controlled by the amount of plastic shear strain.

In the present model, stresses and bonds in each plane are considered as internal state variables and their different evolution in each individual plane introduces, in a natural manner, the stress-induced anisotropy. Since many soil properties are stress-dependent (e.g. the plastic hardening parameter \( k_p \) and the shear modulus \( k_s \) are related to \( k_n \) which is stress-dependent), the induced anisotropic behavior during undrained shearing is linked to the stress distribution in each plane.

Based on experimental results, a micromechanical stress-strain model was developed considering explicitly the cementation at inter-cluster contacts. The inter-cluster bonding is introduced by considering two aspects: an additional cohesion in shear sliding and a higher yield stress in normal compression. Then, isotropic compression and undrained triaxial tests under various confining stresses on cement-treated Ariake clay with different cement contents were simulated to evaluate the capability of the present model to take into account the changes in mechanical properties linked to the cement content. Finally, the predicted behavior in contact planes was examined in the case of undrained triaxial tests with different cement content, which clearly indicates the development of anisotropy induced by the externally applied loads.

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