Effect of inter-particle cementation on compression behavior of clay

J.C. Chai, N. Miura and G. Aramaki
Department of Civil Engineering, Saga University, Japan

Introduction

The inter-particle cementation effect plays an important role on mechanical behavior of clay, but it is still not clear about the magnitude of bond existed between clay particles. Discrete element method (DEM) is capable to simulate the interaction between soil particles with considering the possible sliding between particles and rotation of particles. So, it is possible to quantify the inter-particle cementation effect by DEM.

For an assumed 2D numerical assembly, 1D compression was simulated by DEM. The simulated results are analyzed in terms of void ratio (e) - vertical stress ($\sigma'_v$) relation, fabric orientation, and the variation of stress ratio, $k=\sigma'_v/\sigma'_v$. The importance of considering cementation effect on explaining the actual clay behavior is emphasized.

DEM Modeling of Clay

(1) Modeling clay particles. A clay particle was divided into a number of discrete elements, and each discrete element was represented mathematically by a segment of straight line with thickness.

(2) Modeling inter-particle cementation effect. The magnitude of the inter-particle cementation was controlled by the strength assigned at inter-particle contact. It was assumed that the inter-particle contact is able to carry the normal force, shear force, and moment.

(3) Physicochemical forces between particles. Double layer repulsive force and van der Waals attractive force between particles were modeled by using the methods proposed by Anandarajah (1994) and Anandarajah and Chen (1997).

1D Compression Simulation

(1) Assumed conditions. A numerical specimen with 287 particles and 653 discrete elements was generated as shown in Fig. 1. The particle length was varied from 0.5 to 2.5 $\mu$m, and the thickness was 0.03 $\mu$m. The assumed cation exchange capacity (CEC) was 56 meq/100g, and the specific surface area was 430 m$^2$/g. It was assumed also that the inter-particle liquid contains a mono-valent cation, Na$^+$ with a concentration of 0.001M. The dielectric constant, $\varepsilon$, used was 80 (for water).

The assumed values of inter-particle cementation strength are listed in Table 1. For defining the values for set I, the following assumptions were used. (a) The inter-particle contact area was the same as the cross-sectional area of particle. (b) The relative displacement for a tension failure was about 1/2 of particle thickness. (c) The relative displacement for a shear failure was 2 times of tension failure. (d) The moment strength was determined as that the average bending stress (tension side) equals to tension strength. The values of set II were 1/10 of those for set I.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, N/$\mu$m</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Shear strength, N/$\mu$m</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Moment strength, N-$\mu$m/$\mu$m</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>

![Fig. 1 Initial numerical specimen](image)

Table 1. The strength of inter-particle contact

Three (3) analyses were conducted. One not considering the cementation effect, and other two considered the cementation effect. As shown in Fig. 1, at initial state, there was no mechanical inter-particle contact. When loaded to a void ratio of about 2.0, there were 79 inter-particle contacts. At this stage, for the analyses with cementation effect, the cementation effect was introduced for these 79 contacts. During further compression loading, the newly formed contacts were not cemented.

(2) Simulated $e$-$\ln(\sigma'_v)$ relationships are shown in Fig. 2. For the case of not considering cementation effect, the yielding stress was only...
about 2 kPa, which is lower than actual clay. For analysis with higher cementation strength (parameter set I), the yielding stress was about 40 kPa, which is comparable with that of actual clay. From the numerical results, it can be seen that the inter-particle cementation effect plays an important role on mechanical behavior of clay.

![Simulated e ln(σ′v) relation](image)

(3) Fabric orientation. The fabric tensor (particle orientation), Fp, is used to quantify the degree of anisotropy of the numerical sample during loading. The ratio of Fp/Fa, is used to indicate the fabric anisotropy. Fp/Fa < 1 means more particles oriented in x direction than y direction. The simulated fabric tensors are depicted in Fig. 3. It clearly indicates that during loading, the particles were gradually oriented toward x direction. Comparing the results of with and without cementation effect, it shows that the cementation effect constricted the certain displacement degree of freedoms of particles, the degree of anisotropy during loading was less than that of without cementation effect case.

(4) Horizontal to vertical stress ratio, k = σ′h/σ′v. The stress ratio (σ′h/σ′v) was also analyzed from numerical results (Fig. 4). For not considering cementation effect case, the variation of k value can be explained in three stages. (a) When the vertical stress was less than about 2 kPa (before yielding), k was small (about 0.2) which simulates the 'sedimentation process'. (b) With the increase of vertical stress, k value increased to about 1.0 for σ′v from about 10 kPa to 100 kPa. The numerical sample behaved like 'slurry'. (c) For σ′v larger than 100 kPa, k value reduced rapidly to about 0.3 due to particle anisotropy. For with cementation cases, when vertical stress is less than 100 kPa, the k values were less than those without cementation case. When vertical stress is larger than 100 kPa, the failure of cemented contacts occurred and resulted in an increase in σ′h/σ′v value.

It must be emphasized that the above results are for assumed conditions with idealized clay particles. Further study is needed for using a close to actual clay particle arrangement, such as by referring to electron microscopic picture of clay sample, and directly comparing the numerical results with experimental data.

![Comparison of fabric tensor](image)

![Variation of stress ratio (σ′h/σ′v)](image)

Conclusions

The discrete element method was applied to simulate the 1D compression of clay. The numerical results indicate that by introducing a proper cementation effect, the simulated results, e-ln(σ′v) curve and stress ratio k (k = σ′h/σ′v) are comparable with actual clay. The cementation effect also restricted a part of displacement degree of freedoms of the system and reduced the degree of anisotropy.

Acknowledgment

In this study, the discrete element program for clay developed by Prof. A. Anandarajah at Johns Hopkins University, USA, was used.

References
