

A new structured subloading cam clay model

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ABSTRACT

A theoretical study of the behavior of structured soil is presented in this paper. By introducing the influence of soil structure and loading history into the Cam Clay model, a new model is formulated. The concept of the difference of void ratios is modified to combine the structure parameter and the overconsolidation ratio and the evolution law is proposed. The new model is a two yield surface model by introducing the concept of the subloading yield surface. By making comparisons of predictions with experimental results, it is demonstrated that the new model provides satisfactory qualitative modelling of many important features of the behavior of structured soils.

Keywords: structure, overconsolidation, subloading yield surface, constitutive relations

1 INTRODUCTION

Soils in situ usually process natural structure and may be overconsolidated, which is differently from a normal consolidated reconstituted state (e.g., Burland 1990; Cuccovillo and Coop 1999). Generally, the strength of structured soils is higher than the reconstituted soils and the loading history had significant influence on the behaviour of structured soils. Following the suggestion of Burland (1990), the properties of a reconstituted soil are called the intrinsic properties. Hence, under all stress conditions, the influence of soil structure can be measured by comparing its behaviour with the intrinsic behaviour. The mechanical concept of the subloading yield surface was proposed by Hashiguchi and Ueno (1977) and was suitable to describe the influence of the loading history on the behaviour of soils. Yao et al. (2008) proposed the UH model based on the concept of subloading yield surface which can describe the influence of the loading history successfully.

Recently, there have been important developments in formulating constitutive models incorporating the influence of soil structure and loading history, such as those proposed by Rouainia and Muir Wood (2000), Liu and Carter (2002), Suebsuk et al. (2011), Asaoka et al. (2000), Hashiguchi et al. (2007). In this paper, a new constitutive model for the structured clays is proposed which is called as the Structured Subloading Cam Clay model. Combining the structure parameter \( \mathcal{B} \) based on the work by Nakai (2004) and the overconsolidated ratio OCR, a new concept of structure parameter \( \mathcal{B} \) has been developed. The subloading yield surface is introduced and the new model is a two yield surface model which one is the Roscoe’s yield surface and another is the structured subloading yield surface. The relationships of the two yield surfaces are presented by the modified difference of void ratios. By making comparisons of predictions with experimental data it is demonstrated that the new model provides satisfactory qualitative modelling of many important features of the behavior of structured soils.

2 GENERALIZATION OF THE STRUCTURED SUBLOADING CAM CLAY MODEL

The formation and development of soil structure often produces anisotropy in the mechanical response of soil to changes in stress, and destructuring usually leads to the reduction of anisotropy (M. D. Liu and J. P. Carter, 2002). In this paper, only the isotropic effects of soil structure and loading history are considered.

2.1 Influence of soil structure on virgin isotropic compression

As be shown in Fig. 1, the isotropic compression behaviour of reconstituted and structured soils is quietly different. The structural consolidation lines (SCL) for most of structural geomaterials lie well above the corresponding intrinsic NCL; the location of the SCL relative to the NCL is shown to depend on the structure and the stress path. When virgin yielding of the structured soil begins, the structured compression line will be curved, and can be described by the following equation proposed by Liu and Carter (2002):

\[
e = e^*_{0c} + \Delta e_1 \left( \frac{p'_{c1}}{p'} \right)^b - \lambda \ln p'
\]  

(1)
Where \( e_{ic}^* \) is the voids ratio of the reconstituted soil when \( p' = 1 \) kPa during virgin isotropic compression, \( \Delta e_i \) is the additional voids at \( p' = p_i' \), where virgin yielding of the structured soil begins, and \( b \) is a parameter quantifying the rate of destruction.

\[
\rho = (\lambda - \kappa) \ln \left( \frac{p^*_N}{p_N} \right) = (\lambda - \kappa) \ln (OCR \cdot B)
\]

And if soil is reconstituted, SCL will coincide with NCL, and \( B = 1 \), the concept of \( \rho \) will regress to the original meaning proposed by Nakai (2004).

2.2 Modified difference of the void ratios

A structural materials is compressed to point J along the SCL, then unload to point A along the swelling line and also become to the consolidation state, as shown in Fig. 2. During the compressive process along the SCL, the structure degenerate gradually because of compression. Therefore, based on the concept of OCR, and can be expressed as:

\[
OCR = \frac{\bar{p}_N}{p_N}
\]

In order to considering the structure, a new state variable \( B \) describing structure is defined as:

\[
B = \frac{p^*_N}{\bar{p}_N}
\]

where \( p^*_N \) is the consolidation stress for reconstituted soil, \( \bar{p}_N \) is the consolidation stress for structured soil, and \( 0 < B \leq 1 \) which has the similar meaning with sensibility index of soil.

The concept of \( \rho \) is used for formulating the relation between the present stress state and the normal consolidation state. Considering Eqs. (2) and (3), it can expressed based on the work of Nakai (2004) but extended as:

\[
e_c = e_{ic}^* + \Delta e_i \left( \frac{p'_{s,\lambda}}{p_N} \right)^b - \lambda \ln \frac{p_N - \kappa \ln \left( \frac{p^*_N}{p_N} \right)}{p_N}
\]

Because the point C lies on the normal compression line (NCL), so the void ratio also can be calculated:

\[
e_c = e_{ic}^* - \lambda \ln p^*_N
\]

Combine the Eq. (3), (5) and (6), the initial structure parameter \( B_0 \) can be calculated as:

\[
B_0 = \exp \left\{ \frac{\Delta e_i}{\lambda - \kappa} \left( \frac{p'_{s,\lambda}}{p_N} \right)^b \right\}
\]
Here, $p_s$ is the preconsolidation stress. Fig. 4 shows the response of natural soil (Pisa clay) to one dimensional compression (Callisto and Calabresi, 1998). The “undisturbed” intact sample bear higher yield stress than the reconstituted one. Fig. 5 shows the relationship between structure parameter $B_0$ with the preconsolidation stress, and the destruction process can be seen upon continuous loading.

The plastic strain increment can be easily calculated as:

$$d\varepsilon^p_\nu = \Lambda \left[ \frac{\partial f}{\partial \sigma_{ij}} d\sigma_{ij} \right] \quad \text{and} \quad d\varepsilon^p_v = \Lambda \left[ \frac{\partial f}{\partial \sigma_i} d\sigma_i \right]$$

(9)

Because associated flow rule is adopted, the proposed plastic potential is also the yield function. Consistency equation can then be obtained as:

$$\frac{\partial f}{\partial \sigma_0} d\sigma_0 - \frac{1}{C_p} d\varepsilon^p_v + \frac{1}{C_p (1 + e_0)} d\rho = 0$$

(10)

Where,

$$\frac{\partial f}{\partial \sigma_0} = \left( \frac{1}{\sigma_m} - \frac{\sqrt{3}}{M \sigma_m^2} \right) \delta + \frac{\sqrt{3}}{M} \frac{s}{2} \frac{1}{\sigma_m}$$

(11)

The following step is determining $d\rho$, or the evolution law for $\rho$ including OCR and $B$. Zhang et al. (2005) has investigated the evolution of $\rho$ with only considering the overconsolidation disappear, it is assumed that the evolution is dependent on the present $\rho$ and $\sigma_m$ and is proportional to the positive variable $\Lambda$. Although the difference of void ratios between the normal consolidation state with the present stress state, has been extented from the reconstituted soil to structural soil, the evolution equation for the modified $\rho$ can be formulated as the similar way:

$$- \frac{1}{1 + e_0} d\rho = g(\sigma_m, B, OCR) \Lambda$$

(12)

Where, $g(\sigma_m, B, OCR)$ is the function of variables $\sigma_m$, $B$ and OCR. The outside factors such as temperature will have influence on the evolution equation for the modified $\rho$ (Zhang S et al, 2009, 2012). So it is suitable to considering the influence of the current $B$.

The destructing process of the structured soils during the load is generally considered to be irreversible and is induced by the plastic deformation (M. D. Liu and J. P. Carter, 2002; Asoka et al., 1998; Hashiguchi et al., 2003). Based on the work of Hashiguchi (2007) and Huang M. et al., (2011), the evolution law of the structure parameter $B$ can simply expressed as follows:

$$dB = \beta \ln B \cdot d\varepsilon^p_d$$

(13)

Where $\beta$ is a material parameter which controls the rate of destruction. $d\varepsilon^p_d$ is the equal plastic deformation and is described as:

$$d\varepsilon^p_d = \sqrt{(1 - R) \cdot (d\varepsilon^p_{vp})^2 + R \cdot (d\varepsilon^p_{v})^2}$$

(14)

Where $d\varepsilon^p_v$ is plastic volumetric strain increment, $d\varepsilon^p_s$ is the plastic shear strain increment, $R$ is a non-dimensional scalling parameter which controls the
relative contributions to destruction of volumetric and distortional plastic strain increments $d\varepsilon_v^p$ and $d\varepsilon_d^p$. Eq. (14) suggests that for $R=1$ the destruction is entirely distortional, while for $R=0$ the destruction is entirely volumetric.

As mentioned above, the evaluation law of the modified $\rho$ has the similar form as the expression proposed by Zhang et al. (2005), so referencing the evaluation of structure parameter $B$ and the work by Zhang et al. (2005), $g(\sigma_m,B,OCR)$ considering the overconsolidation disappear and destruction can be described as:

$$dp = -(1+e_b) \cdot \frac{a[(\lambda - \kappa) \ln B]^2}{\sigma_w} \cdot \Lambda$$

$$- (\lambda - \kappa) \cdot \frac{1}{\sigma_m} \cdot \beta \ln B \cdot \Lambda$$

Where $a$ is the material parameter which controls the disappear rate of the overconsolidation ratio. The evaluation law for $\rho$ is divided into two parts to consider the influence of the overconsolidation disappear and destruction separately.

Substituting Eqs. (9) and (11) into Eq. (10), the value of $\Lambda$ can be determined:

$$\Lambda = \frac{\partial f}{\partial \sigma_{ij}} \cdot d\sigma_{ij}$$

Where,

$$h_{\sigma} = \frac{\partial f}{\partial \sigma_{ij}} + g(\sigma_m,B,OCR)$$

The loading criteria are given as:

$$\|d\varepsilon_v^p\| > 0 \text{ if } \Lambda > 0 \text{ and } \frac{\partial f}{\partial \sigma_{ij}} d\sigma_{ij} > 0 \text{ hardening}$$

$$\|d\varepsilon_d^p\| = 0 \text{ if } \Lambda \leq 0 \text{ elastic}$$

3 PERFORMANCE OF THE PROPOSED MODEL

In this section, the performance of the proposed model is examined by simulating the behaviour of shanghai soft clay (Huang et al. 2011). Undrained shear behaviour of shanghai soft soil in conventional triaxial test with different levels of confining pressures are considered. The basic properties of shanghai soft soil are summarized in Table 1 and 2. The e-lnp curve of shanghai soft soil is shown in Fig. 6. Comparison of the model simulations and experimental data for shanghai soft clay is shown in fig. 7. Based on the comparison between the model predictions and the experimental data, it is seen that the new model predicts the shearing behaviour of shanghai soft soil reasonably well at various stress levels.

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$e_0$</th>
<th>$p'_{cr}$ (kPa)</th>
<th>$\Delta \varepsilon$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>1.402</td>
<td>104.2</td>
<td>0.38</td>
<td>3.4</td>
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</table>

Table 1. Material parameters for the structured soft clay

<table>
<thead>
<tr>
<th>$M$</th>
<th>$\lambda$</th>
<th>$\kappa$</th>
<th>OCR</th>
<th>$a$</th>
<th>$\beta$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.277</td>
<td>0.142</td>
<td>0.062</td>
<td>1.0</td>
<td>500</td>
<td>13.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 2. Material parameters of the structured soft clay

Fig. 6. 1-D Compression behaviour of the structured soft clay

Fig. 7. Simulation of undrained triaxial compression tests on the structured soft clay

64
4 CONCLUSION

In this paper, a constitutive model for structured soils is presented. The main features of the new proposed model are as follows:

1. The structure parameter $B$ is defined which is similar to the sensitive index of structured soils;
2. The difference of void ratios is modified to include the influence of soil structure and overconsolidation, which presents the connection between the structured subloading yield surface and the Roscoe’s yield surface;
3. By making comparisons of predictions with experimental data, it is demonstrated that the new model provides satisfactory qualitative modelling of the behavior of structured soils.

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