Modelling destructuration of sensitive clays

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1 Introduction

Soft sensitive clays typically exhibit stiffer responses beyond that of their reconstituted counterparts [1]. The additional strength can be attributed to the interparticle bonds, formed during complex geological process. Since bonds are often fragile in nature, their degradation as irreversible deformation accumulates under mechanical or chemical loading can result in obvious softening responses, giving rise to unexpected instabilities in geotechnical engineering problems [2]. Additionally, soft sensitive clays also exhibit cross-anisotropy due to the preferred orientation of the particles [3]. The consequence of fabric anisotropy is the obvious direction-dependent mechanical response.

In order to predict the strength and deformation of soft sensitive clays with reasonable accuracy, numerous constitutive models have been proposed within the framework of critical state theory. The effect of bonds is often described by an enlarged initial yield surface [4], the progressive reduction of which signifies bonding degradation and is governed by a destructuration law [5-6]. Anisotropy is further represented by the rotation of the yield surface with respect to the hydrostatic axis [5, 7], with the changes in the inclination reflecting the evolution of anisotropy.

For natural soft clays with high sensitivity, the S-CLAY1 model families show several advantages over the other existing models, as they can reasonably consider the effect of anisotropy (S-CLAY1: [8-9]), destructuration (S-CLAY1S: [5, 10]) and creep (Creep- S-CLAY1S: [11]) with relatively simple model formulations and well-defined parameter calibration methodologies. However, in both element-level and boundary value simulations, these models often tend to overpredict bond degradation, leading to excessive volumetric responses—particularly under high confining pressures—and predicting early and steep post-peak softening during undrained shearing.

For highly sensitive clays it may well be possible that the rate of destructuration is the most dominant component during the early stages of consolidation, when the effective stresses just exceed the preconsolidation stress. As effective stresses increase due to consolidation, the rate of destructuration gradually decreases [12], which will apparently influence the undrained strength, especially in the deep layers [13]. Therefore, to describe the effect of the mean effective stress on the bond degradation, a new destructuration law is proposed and incorporated into S-CLAY1S. To focus on the effect of destructuration, creep is not considered here. Model performance is validated through the comparison between simulations and tests data of natural Vanttila clay subjected to different loading paths.

The sign convention in soil mechanics is adopted, with positive for compression and negative for extension. All stresses are effective stresses unless otherwise stated. The deviatoric stress tensor is defined as $\boldsymbol{\sigma}_d=\boldsymbol{\sigma}-p\mathbf{I}$, with the general shear stress $q=[(3/2)\ \boldsymbol{\sigma}_d:\boldsymbol{\sigma}_d]^{1/2}$. The deviatoric strain tensor is expressed as $\boldsymbol{\varepsilon}_d=\boldsymbol{\varepsilon}-\varepsilon_v\mathbf{I}/3$, with the corresponding general shear strain $\boldsymbol{\varepsilon}_q=[(2/3)\ \boldsymbol{\varepsilon}_d:\boldsymbol{\varepsilon}_d]^{1/2}$. The deviatoric fabric tensor $\boldsymbol{\alpha}_d$ can be introduced as the multiaxial counterpart of the triaxial quantity α through $\alpha^2=3/2\boldsymbol{\alpha}_d:\boldsymbol{\alpha}_d$, where $\boldsymbol{\alpha}_d=\boldsymbol{\alpha}-\mathrm{tr}(\boldsymbol{\alpha})\mathbf{I}/3$. $\mathbf{I}$ is the Kronecker delta.

2 Key features of the model

The basic model platform, S-CLAY1S [14], is an extension of S-CLAY1 [8], which accounts for the effect of bonding and destructuration for sensitive clays, in addition to the plastic anisotropy. Since the model is primarily intended for normally consolidated or lightly over-consolidated soft clays, where plastic deformations are likely to dominate during the whole loading process, elastic behaviour is assumed to be isotropic, same as in the Cam-Clay models. The key plastic constitutive components are summarized as follows.

The yield locus is an inclined ellipsoid in three-dimensional stress space, which can be expressed as:

$$f=\frac{3}{2}\left[\{\boldsymbol{\sigma}_d-p\boldsymbol{\alpha}_d\}^T\{\boldsymbol{\sigma}_d-p\boldsymbol{\alpha}_d\}\right]-\left[M(\theta_\alpha)^2-\frac{3}{2}\{\boldsymbol{\alpha}_d\}^T\{\boldsymbol{\alpha}_d\}\right](p_m-p)\,p=0 \tag{1}$$

where $M(\theta_\alpha)$ is Lode angle θ_α dependent critical stress ratio, defined as an interpolation function in multiaxial space [15]. Note that, the fabric tensor can be replaced by the corresponding scalar quantity when both the material and the stress state are cross-anisotropic, provided that the plane of material isotropy coincides with the plane of stress isotropy. The size of the yield surface is controlled by $p_m=p_{mi}+p_{mc}$, where p_{mi} represents the size of the inherent yield surface for remolded clay and p_{mc} reflects the additional resistance toward yielding due to bonding. The isotropic hardening consists of two parts, $\mathrm{d}p_{mi}$ and $\mathrm{d}p_{mc}$. The evolution of inherent yield surface follows the Cam-clay hardening law:

$$\mathrm{d}p_{mi}=\frac{1+e}{\lambda_i-\kappa}p_{mi}\mathrm{d}\varepsilon_v^p \tag{2}$$

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where e is the initial void ratio. λ_i and κ are the intrinsic compression index and swelling index, respectively. dp_{mc} reflects the bond degradation, which is driven by irreversible strains. Inspired by the structure of Equation (2) and the evolution rules in [6, 16], the evolution rule of p_{mc} is proposed as:

$$\mathrm{d}p_{mc} = -a\frac{1+e}{\lambda_i - \kappa} p_{mc}\mathrm{d}\xi_b \tag{3}$$

where a is a model parameter controlling the degradation rate. ξ_b is a newly introduced bonding-related internal variable, and its evolution is assumed to be dependent on the current mean pressure p and be driven by irreversible strains:

$$\mathrm{d}\xi_b = p_r\sqrt{\frac{\frac{3}{2}\left(\mathrm{d}\varepsilon_v^p\right)^2 + \frac{1}{3}b\left(\mathrm{d}\varepsilon_q^p\right)^2}{\left(p - p_{cs}\right)^2}} \tag{4}$$

where p_r=1 kPa is a reference pressure to keep dimensional consistency. b is a weighting factor that differentiates the contributions of plastic volumetric and deviatoric strains to destructuration. p_{cs} refers to the critical mean pressure, as:

$$p_{cs} = \frac{M\left(\theta_\alpha\right) + \alpha}{2M\left(\theta_\alpha\right)} p_m \tag{5}$$

where α is the triaxial quantity of fabric tensor. The denominator of Equation (4) incorporates a measure of the distance from the current stress state to the critical state, also accounting for the influence of mean pressure p on bond degradation. As p increases, ξ_b decreases, implying bonding degradation is inversely proportional to p. This is consistent with the hypothesis proposed by [12] and the gradually decreased compression curve slopes observed during consolidation process of many natural clays [1, 13]. The integration of Equation (3) is:

$$p_{mc} = p_{mc0}e^{-a\frac{1+e}{\lambda_i - \kappa}\xi_b} \tag{6}$$

where p_{mc0} is the initial value of p_{mc}. At critical state, p=p_{cs}, and $\xi_b \rightarrow \infty$. According to Equation (6), $\xi_b \rightarrow \infty$ yields p_{mc}=0, indicating that bonds are completely destroyed, satisfying critical state framework.

The anisotropy evolution is described by the rotational hardening rule, which can be expressed as:

$$\dot{\boldsymbol{\alpha}}_d = \left[\exp\left(\frac{p_{mc}}{p_m}\right)\right]^u \left(\left[\frac{3\boldsymbol{\eta}}{4} - \boldsymbol{\alpha}_d\right]\left\langle \dot{\varepsilon}_v^p \right\rangle + \beta\left[\frac{\boldsymbol{\eta}}{3} - \boldsymbol{\alpha}_d\right]\dot{\varepsilon}_d^p\right) \tag{7}$$

where $\boldsymbol{\eta}$ refers to the tensorial equivalent of the stress ratio, defined as $\boldsymbol{\eta}=\boldsymbol{\alpha}_d/p$. β governs the relative effectiveness of plastic deviatoric strain and plastic volumetric strain in rotating yield surface. u characterizes the effect of bonding on the rate of anisotropy evolution. When bonding is totally destroyed (p_{mc}= 0), the anisotropy evolution rate becomes 1.

3 Model calibration

The model comprises 8 parameters in total. Four Cam-Clay parameters, M, λ_i, κ and v, can be determined from conventional triaxial and oedometer tests. Fabric evolution related parameter β and u can be correlated with K_0 following the expression in [8] and subsequently determined through trial-and-error calibration against test data obtained under different loading and unloading paths, respectively. Specifically, to highlight the advantages of the modified law, the initial rotational hardening rate $(\exp(p_{mc}/p_m))^u$ is set as 20, consistent with that adopted in S-CLAY1S model, thus, u = 3.4 when the initial values of p_{mc}=16.5 kPa and p_m=18.5 kPa, respectively. Destructuration associated parameters a is recommended to be initially determined from isotropic compression tests, in which the influence of deviatoric strains is minimal. Once a is fixed, b can be calibrated based on the experimental results under different loading paths.

In addition to parameter calibration, initializations of the internal variables p_{mc} and $\boldsymbol{\alpha}_d$ are also essential. The initial inclination degree of the yield surface is assumed to link with η_{K0} [8], as:

$$\alpha_{K0} = \frac{\eta_{K0}^2 + 3\eta_{K0} - M_c^{\,2}}{3} \tag{8}$$

The initial value of p_{mc} is assumed to be associated with the sensitivity S_t [10], as:

$$p_{mc0} = \left(S_t - 1\right)p_{mi0} \tag{9}$$

Following the above calibration and initialization procedures, all model parameters can be determined. Table 1 lists the parameters set for natural Vanttila Clay with p_{mc0}=16.5 kPa and α_{K0}= 0.3.

4 Model performance

The model is implemented through the second- and third-order Runge–Kutta integration algorithms [17] and is validated with the test data of natural Vanttila clay and Murro clay. Part results of Vanttila clay are shown here.

Table 1. Model parameters for natural Vanttila Clay.

	M	λ_i	κ	v	a	b	u	β
Natural Vanttila Clay	1.35	0.3	0.06	0.2	0.05	40	3.4	0.91

Vanttila clay is a highly sensitive clay, located in the Southern coast of Finland. Incremental anisotropic stress path -controlled tests and undrained triaxial tests were carried out [10] to investigate the influence of anisotropy evolution and destructuration on the mechanical responses of sensitive soft clays. For loading-unloading cycles CAE 3485, the specimen was first loaded from the initial stress state to the target stress along η_1=-0.52, then unloaded along the same loading path to p=15 kPa and subsequently reloaded and unloaded along η_2=0.51. The applied and simulated stress paths are shown in Figure 1 (b). Figure 2 compares the test results with the corresponding simulations in terms of ε_v-p, ε_s- ε_v and ε_s- q relationships. For comparison, the simulations of the original S-CLAY1S are also presented in dash lines. It is obvious that S-CLAY1S overpredicts volumetric strain, especially during the reloading stage. By considering the effect of p on bonding degradation, the proposed model can capture the gradually decreased degradation at higher mean pressure during reloading, resulting in less volumetric strain, improving notably the agreement with the test results.

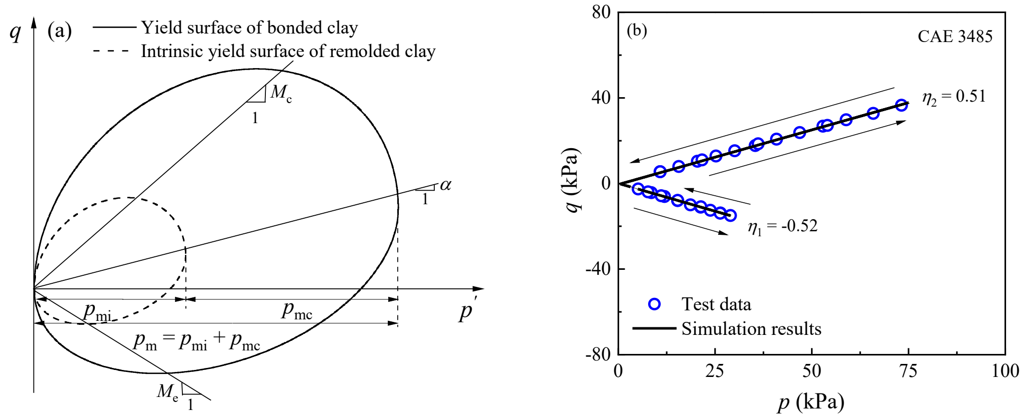

Figure 1. Illustration of yield surfaces (a) and test data and simulations of stress paths subjected on Vanttila Clay (b).

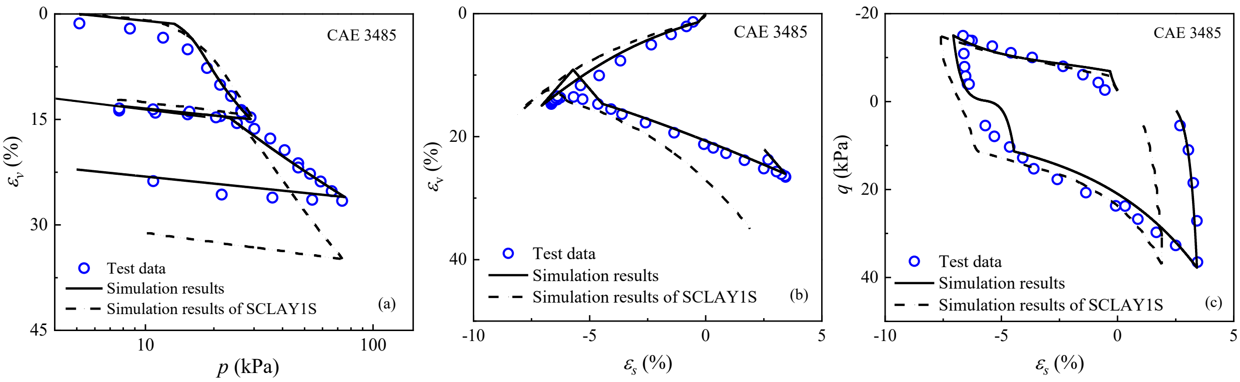

Figure 2. Comparison between simulations and test results in terms of p-ε_v curves (a), ε_s-ε_v curves (b) and ε_s-q curves (c).

For undrained triaxial tests CAUC 3449 and CAUC 3453, the specimens were firstly consolidated to different initial anisotropic stress states and then sheared under undrained condition. The proposed model simulated the whole consolidation and shearing process. Figure 3 summarizes the undrained stress paths and stress–strain relationships. In S-CLAY1S model, most of the bonding has already been degraded during anisotropic compression. As a result, no pronounced softening responses are observed in following undrained shearing. Compared with S-CLAY1S, the proposed model with enhanced destructuration rule can match the test data much better, particularly in reproducing the peak strength and the subsequent softening responses.

5 Conclusions

In this study, we presented a modified S-CLAY1S model for soft sensitive clays, where the effect of current mean pressure on destructuration is considered. For highly structured soils, the destructuration rate gradually decreases as the effective stresses increase during consolidation. The comparison between model simulations and experimental data of soft sensitive clay demonstrates that the new bonding degradation law can effectively improve the model performance. In particular, it successfully mitigates the tendency of S-CLAY1S to overestimate the development of volumetric deformation under relatively high confining pressures.

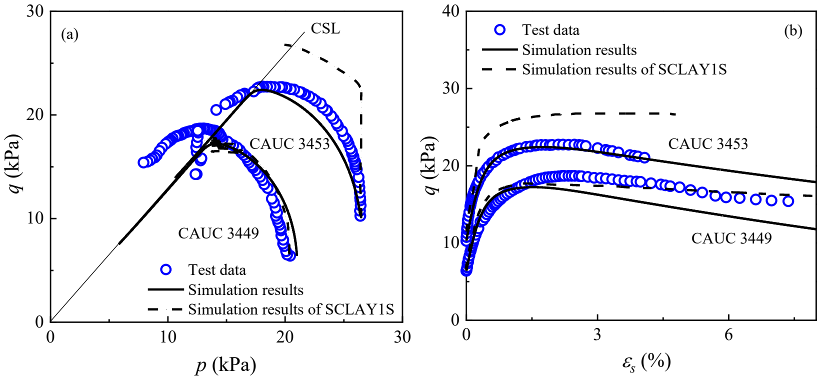

Figure 3. Comparison between undrained triaxial simulations and test results: stress paths (a); stress-strain relationships (b).

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