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Modeling the cyclic degradation of clays with an anisotropic bounding surface plasticity model

F. Palmieri[1], M. Taiebat[2]

[1]*Ove Arup & Partners, London, UK*
[2]*Department of Civil Engineering, University of British Columbia, Vancouver, BC, Canada*

ABSTRACT: Clayey soils exhibit continuous stiffness degradation only for cyclic strain amplitudes exceeding a specific threshold, known as the degradation strain threshold. Similarly, the accumulation of strains due to degradation is observed only for cyclic stress ratios (CSRs) above a certain threshold. In this paper, we propose an advanced bounding surface (BS) rate-independent plasticity model for the cyclic response of clays, based on a previous version of the Simple Anisotropic CLAY (SANICLAY) plasticity model. Our proposed SANICLAY-BS model introduces an activation mechanism triggered by the amplitude of cyclic shear loading. We formulate this mechanism using a novel state variable that acts as a proxy for the applied cyclic stress. By introducing a threshold for this state variable, our model can simulate the degradation strain threshold and CSR threshold that characterize the undrained cyclic shear response of clayey soils. We demonstrate the model's performance against experimental data for different materials subjected to undrained cyclic shearing across a wide range of constant strain and stress amplitudes.

Keywords: Constitutive modelling; Bounding surface; Cyclic degradation, Clay

1 INTRODUCTION

During the simulation of earthquake loading scenarios, the performance and stability of structures founded on saturated clayey deposits should be evaluated with constitutive models able to capture the salient features of the undrained response of clays under various cyclic shear amplitudes and number of cycles. Due to shearing, the secant stiffness exhibited by clayey soils progressively reduces with increasing strain. In addition, during undrained cyclic shearing at constant cyclic strain amplitude, the soil stiffness can further reduce due to the application of repeated cycles. This phenomenon, known as cyclic stiffness degradation, occurs only for cyclic strain amplitudes larger than the so-called degradation strain threshold (Diaz-Rodriguez and Santamarina, 2001; Mortezaie and Vucetic, 2016). During undrained cyclic shearing at constant cyclic stress amplitude, the cyclic stiffness degradation results into increasing strains for each loading cycle. When cyclic shear stresses are lower than a cyclic stress threshold, strains develop at an attenuating rate per cycle and the specimen does not fail even after a large number of cycles. Conversely, for cyclic shear stresses exceeding the threshold, the specimen experiences a major stiffness degradation with strains proceeding at an accelerating rate per cycle and leading to failure (e.g., Zergoun and Vaid, 1994).

For modelling the anisotropic response of clays, Dafalias et al. (1986) incorporated a distorted and rotated yield surface along with rotational hardening into a Critical State (CS) theory compatible constitutive model with associated flow rule. Non-associated flow rule was further implemented to capture the softening response exhibited by K_0-consolidated specimens during undrained compression (Dafalias et al., 2006). Eliminating the rotational hardening and changing the flow rule to associative, render the model identical to the well-known Modified Cam-Clay model. For this model, the name SANICLAY was chosen as the acronym for Simple ANIsotropic CLAY. Due to its simplicity, the SANICLAY model has been selected and extended by many researchers for capturing specific aspects of clayey-soil behaviour (e.g., Dafalias and Taiebat, 2013, 2014; Rezania et al. 2016, Dafalias et al. 2020).

Taiebat et al. (2010a) introduced both isotropic and frictional destructuration mechanisms to the SANICLAY framework for capturing the extreme strain softening of natural clays. This model was implemented in FLAC3D program and used for the seismic response of structured slopes by Taiebat et al. (2011). A bounding surface (BS) framework was originally implemented into a SANICLAY model by Taiebat et al. (2010b) to simulate the strain-amplitude dependency of the stiffness. This framework has been subsequently employed in various other SANICLAY models for simulating the cyclic loading conditions, e.g., the model by Seidalinov and Taiebat (2014a) firstly introduced a damage mechanism for generating additional plastic strains with cycles and improving the predictions of the cyclic stiffness degradation. It must be noted that the existing BS extensions of SANICLAY models also include the isotropic destructuration mechanism by Taiebat et al. (2010a), which resembles the proposition by Wood (1995), for capturing the response of structured soils during monotonic loading. This model was implemented in OpenSEES program and used for nonlinear site response analysis by Seidalinov and Taiebat (2014b, 2014c, 2019), and for multidirectional cyclic shearing of clays in Seidalinov et al. (2017) and Yang et al. (2019).

Both damage and destructuration are degradation mechanisms affecting the prediction of stiffness by means of cumulative plastic strains. With the exception of the work by Palmieri et al. (2021), which represents a precursor of this work, the degradation mechanisms characterizing the currently existing SANICLAY models do not account for the presence of a stress and/or strain threshold and, therefore, always predict cyclic stiffness degradation regardless of the applied cyclic shear amplitude. To overcome this limitation, different sets of degradation parameters are sometimes used depending on the cyclic shear amplitude during the simulation of laboratory tests (Shi et al., 2018). This solution, although practical for simulating nearly constant amplitude loading, would not be applicable to boundary value problems subjected to variable amplitudes of cyclic shearing.

The aim of this research is to derive a SANICLAY model extension that successfully captures the stress-strain response of clayey soils under different cyclic loading amplitudes and the number of cycles. In contrast to the existing SANICLAY models, the proposed model, named SANICLAY-BS, adopts a destructuration, and not a damage, mechanism to model the cyclic stiffness degradation. A peculiarity of the SANICLAY-BS model is the presence of the so-called activation mechanism controlling the application of destructuration based on the cyclic shear level. By setting a threshold for a newly introduced state variable, the proposed model can mimic the existence of the cyclic stress threshold during simulations of stress-controlled cyclic tests and the degradation strain threshold during simulations of strain-controlled cyclic tests. In the following, first, the model formulation is presented in the triaxial space, then its performance is separately evaluated during stress-controlled and strain-controlled cyclic tests against experimental data on different soils.

2 MODEL FORMULATION

The SANICLAY-BS model is here presented by means of the triaxial stress quantities $p = (\sigma_a+\sigma_r)$ and $q = \sigma_a - \sigma_r$, and strain quantities $\varepsilon_v = \varepsilon_a + 2\varepsilon_r$ and $\varepsilon_q = 2(\varepsilon_a - \varepsilon_r)/3$. In these definitions, subscripts a and r denote the axial and radial directions, respectively, while subscripts v and q denote the volumetric and deviatoric components, respectively. The additive decomposition of the strain rate is assumed, i.e., $\dot{\varepsilon} = \dot{\varepsilon}^e + \dot{\varepsilon}^p$, with superscripts e and p indicating the elastic and plastic components, respectively, while the superimposed dot implying rate.

The proposed model follows the original SANICLAY model formulation by Dafalias et al. (2006) and includes the isotropic destructuration by Taiebat et al. (2010a) and the BS concept with radial mapping. According to this concept, the plastic modulus K_p is expressed as a function of the distance between the stress state and the BS via the non-dimensional distance ratio b expressed by

$$b = \frac{r}{r-\delta} \tag{1}$$

where the stress distances r and δ are defined by mapping the current stress on the BS. For the mapping rule, a projection centre relocating at each stress reversal is used like Seidalinov and Taiebat (2014a) and Shi et al. (2018). A representation of the characteristic surfaces of the SANICLAY-BS model and variable b is given in Figure 1.

Compared to the other existing SANICLAY models, the proposed version is characterized by a degradation mechanism combining the original destructuration law with a novel activation mechanism capable of triggering destructuration based on the amplitude of cyclic loading. The adopted destructuration law describes the size of the structured BS by means of the state variable $p_0 = S_i\, p_{0,d}$ where $p_{0,d}$ and S_i are further state variables representing the size of the destructured BS and isotropic structuration factor, respectively. To link the destructuration rate to the plastic strain rate, an auxiliary state variable, named destructuration plastic strain ε_d^p, is adopted with its rate equation expressed by

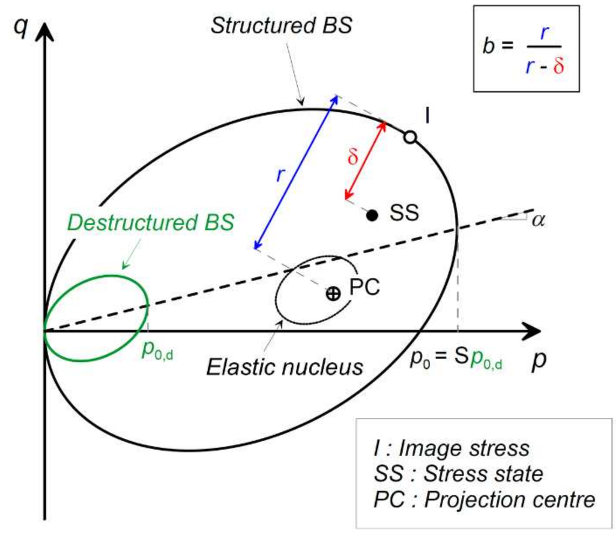

Figure 1 . SANICLAY-BS model in the triaxial stress space

$$\dot{\varepsilon}_d^p = \sqrt{(1-a)\left|\dot{\varepsilon}_v^p\right| + a\left|\dot{\varepsilon}_q^p\right|} \tag{2}$$

where a is the model constant controlling the relative contribution given by deviatoric and volumetric plastic strain increments to the value of $\dot{\varepsilon}_d^p$. Given this quantity, the proposed degradation equation for the state variable S_i controlling the size of the structured BS is

$$\dot{S}_i = -A\left(\frac{1+e}{\lambda-\kappa}\right)(S_i - 1)k_i\dot{\varepsilon}_d^p \qquad (3)$$

where e is the current void ratio, λ and κ are the slopes of the compression and rebound lines in the e-ln p plane, respectively, k_i is the model constant characterizing the destructuration rate, while the term A is the novel activation mechanism which can only assume values equal to 0 or 1. The condition for the activation mechanism is expressed by

$$A = H(b_{sr}^{thr} - b_{sr}) \qquad (4)$$

with b_{sr} being a state variable appositely introduced here as a proxy for the cyclic stress amplitude, b_{sr}^{thr} is the model constant representing its threshold, while the Heaviside step function H(x) is used to ensure A = 0 for negative arguments (x < 0) and A = 1 for non-negative arguments (x ≥ 0). Recalling that the state variable b represents the similarity ratio between the loading surface and the BS (Figure 1), the state variable b_{sr} is defined as the value of b updated at the last stress reversal. With a stress reversal occurring at any time that the loading index $L \leq 0$, the instance of stress reversal is chosen to represent the applied cyclic stress level. By combining the activation mechanism with the destructuration law, if $b_{sr} > b_{sr}^{thr}$, destructuration is prevented (A = 0). In contrast, if $b_{sr} \leq b_{sr}^{thr}$ the occurrence of destructuration is not altered (A = 1).

3 PERFORMANCE IN STRESS-CONTROLLED CYCLIC TESTS

Capabilities of the SANICLAY-BS model in simulating the presence of a CSR threshold during undrained cyclic shearing at constant stress amplitude, i.e., in stress-controlled conditions, are shown against experimental data of the natural Cloverdale clay (Zergoun, 1991; Zergoun and Vaid, 1994) and reconstitutied Ariake clay (Yashuara et al., 1992). Both clays were subjected to undrained cyclic triaxial tests with different levels of CSR starting from an isotropic initial condition with an initial mean effective stress p_{in}=200kPa and OCR=1. During shearing, a two-way cyclic loading pattern was followed with deviatoric stress q varying in between ±q_{cyc}, being q_{cyc} the single amplitude of the deviatoric stress. According to Zergoun and Vaid (1994), the CSR threshold for Cloverdale clay corresponds to $q_{cyc}/(2s_u) = 0.55$, where s_u is the undrained shear strength observed during monotonic triaxial. The experiments from Yashuara et al. (1992) suggest a threshold CSR (=$q_{cyc}/(2p_{in})$) ranging between 0.188 and 0.255. Note that different definitions of CSR are used for the two materials for easier comparison with the original references. Steps for the SANICLAY-BS model calibration and initialization are detailed in Palmieri (2022), while only a summary of the adopted model constants and initial values of the state variables is given in Table 1 and Table 2, respectively.

Table 1. Model constants for Cloverdale clay and Ariake clay

Parameter	**Cloverdale clay**	**Ariake clay**
κ	0.009	0.05
ν	0.2	0.2
λ	0.21	0.41
M_c	1.29	1.68
M_c	1.27	1.65
C	3	15
X	1.73	1.76
s	1	1
N	1	2
h	1000	500
k_i	0.21	1.1
b_{sr}^{thr}	1.35	1.6

Table 2. Initial values of the model state variables for Cloverdale clay and Ariake clay

Parameter	**Cloverdale clay**	**Ariake clay**
e	1	1.84
p_0 (kPa)	200	200
α	0	0
S_i	1.73	2.37
b_{sr}	1	1

The stress-strain response of Cloverdale clay for cyclic stress amplitudes smaller and larger than the threshold is shown in Figure 2. Although a large number of cycles is applied (N=80), for CSR = 0.47, the proposed model predicts a minor degradation of the stress-strain loop. In contrast, for CSR = 0.79, a marked stiffness non-linearity and cyclic degradation develop since the beginning of cyclic loading. These two predicted responses agree with the experimental results.

Similarly, Figure 3 shows the evolution of the cyclic axial strain under different cyclic stress amplitudes for Ariake clay. Below the threshold, the SANICLAY-BS model predicts attenuating strains under the application of 100 cycles. Above the threshold, the development strains accelerate with cycles and become very large within N=20. Also, in this figure, the model simulations are consistent with the experimental observations.

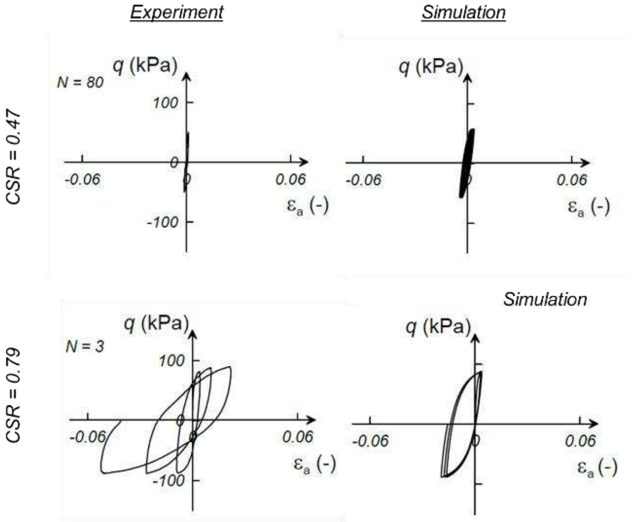

Figure 2. Stress-strain response as predicted by the model in comparison with experiments for Cloverdale clay

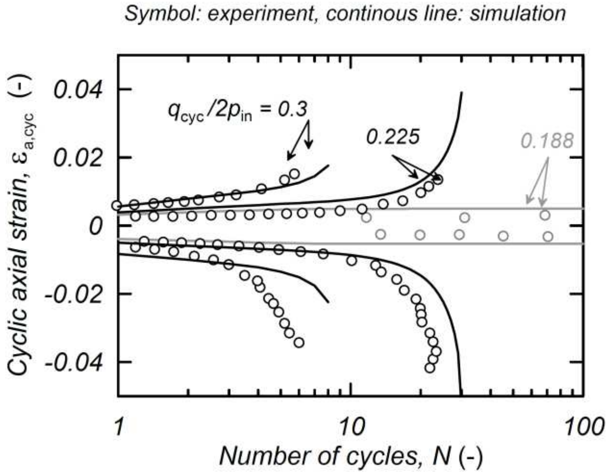

Figure 3. Evolution of the strain with cycles predicted by the model in comparison with experiments for Ariake clay

4 PERFORMANCE IN STRAIN-CONTROLLED CYCLIC TESTS

Capabilities of the SANICLAY-BS model during undrained cyclic simple shearing at constant strain amplitude, i.e., in strain-controlled conditions, are here shown against experimental ranges derived based on the response of different soils with OCR ranging between 1-15. Simulations are conducted with model constants and initial values of the state variables for Cloverdale clay listed in Table 1 and Table 2, respectively. For a better representation of the initial conditions characterizing the experiments, prior to shearing, specimens were first isotropically unloaded to p=1kPa, then K_0-consolidated up to reach an OCR=2.5.

The stress-strain response derived from simulations at various cyclic shear strain amplitude γ_{cyc} and N = 100 is shown in Figure 4. Different color lines are used for the first 10 and remaining 90 cycles. Results show that under γ_{cyc}=0.01%, the observed response is practically linear and degradation is not detected; under γ_{cyc}=0.1%, the stress-strain loops exhibit a minor degradation mostly developing within the first 10 cycles; under γ_{cyc} = 1%, non-linearity and degradation can be noticed for the entire cyclic loading.

Figure 5 plots the modulus reduction curve and damping ratio as obtained from various simulations exploring different levels of γ_{cyc} and value of the model parameter h regulating the stiffness. Specifically, within the BS framework, the parameter h affects the distant-dependent component of the plastic modulus K_p, thus controlling the dependency of stiffness on the amplitude of strains. In this plot, the modulus reduction curve was derived by normalizing the secant stiffness G_s with respect to the maximum shear modulus G_{max}, the latter derived as the value of G_s at γ_{cyc}=0.0001% and N=1. Damping ratios were instead calculated as $\xi=E_d/(4\pi E_s)$ with E_d being the dissipative energy within a cycle equivalent to the area of a stress-strain loop, while $E_s=1/2G\gamma^2$ is the elastic strain energy stored at the maximum strain.

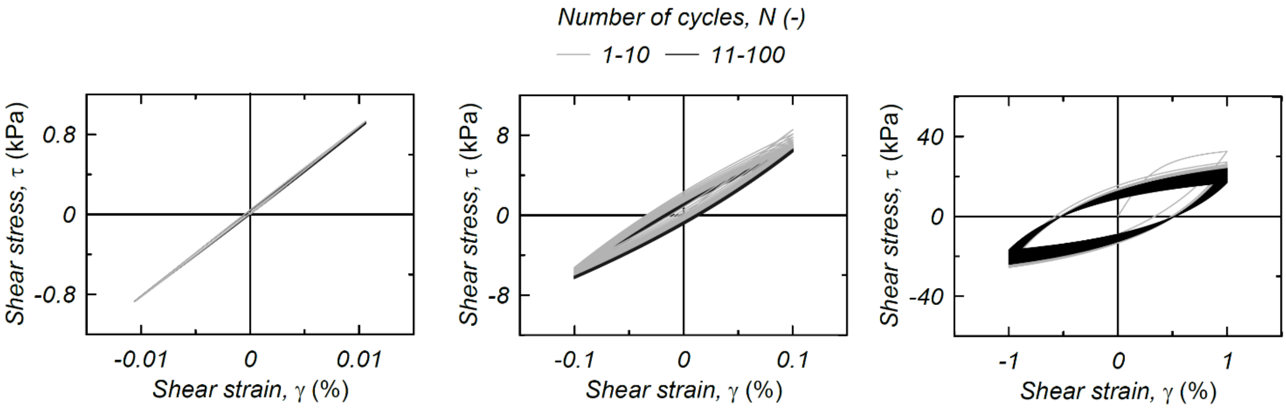

Figure 4. Stress-strain model predictions during cyclic simple shear under various strain amplitudes (different axis limits)

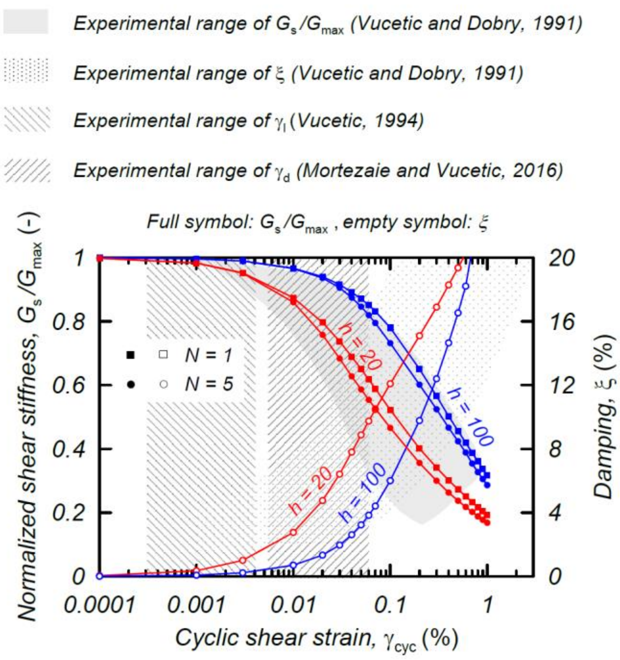

Figure 5. Model performance during undrained cyclic simple shear

Following the approach from Seed et al. (1986), damping ratios are plotted for $N = 5$. In contrast, the effect of N is shown for the modulus reduction curve. To evaluate the model predictions, the figure includes some characteristic ranges of G_s/G_{max} and ξ from Vucetic and Dobry (1991) valid for soils with plasticity index PI between 0-200%, the ranges of variation for the linear strain threshold by Vucetic (1994) valid for soils with PI between 0-60%, and the ranges of variation for the degradation strain threshold by Mortezaie and Vucetic (2016) characteristic of soils with PI between 10-55%.

The cyclic strain thresholds γ_l and γ_d define the onset of the stiffness reduction (i.e., G_s=G_{max} <1) and stiffness degradation with cycles, respectively. The inspection of the figure shows that, with the calibration for Cloverdale clay (h = 100), the reference experimental ranges are all satisfactorily captured. In addition, by reducing h, lower stiffness and larger damping can be predicted under the same γ_{cyc} for capturing the response of different materials.

5 CONCLUSIONS

This paper presents a summary of the key new component of the formulation of a SANICLAY model with BS for simulating the strain and stress thresholds characterizing the cyclic stiffness degradation of clayey soils during undrained cyclic shearing. For cyclic amplitudes below the thresholds, the stiffness non-linearity is modelled with the mere use of the BS formulation. In contrast, above the thresholds, cyclic stiffness degradation developing with cumulative plastic strains is additionally simulated. Compared to the other existing SANICLAY models, the proposed model adopts destructuration, and not damage, as a degradation mechanism. Regardless of this specific choice, the model novelty is represented by an activation mechanism capable of detecting the amplitude of cyclic loading by means of a state variable used as a proxy for the applied cyclic stress. The proposed activation mechanism requires only one model constant and can be combined with any degradation mechanism in BS models.

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