An approach for modelling volume change of fine-grained soil subjected to thermal cycles

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Abstract: In consequence of cyclic heating and cooling about the ambient temperature under drained conditions, normally consolidated and lightly over-consolidated fine-grained soils experience accumulation of irreversible volumetric contraction. Most existing thermo-mechanical models were developed for one heating-cooling cycle and are not suitable for multiple thermal cycles. An approach is proposed to simulate the volume change of fine-grained soil induced by thermal cycles. In the proposed approach, a thermal stabilization line is introduced to control the stabilized volumetric contraction under thermal cycles. Comparison with experimental results shows that the proposed approach can reproduce well the cumulative feature of volumetric contraction of fine-grained soil subjected to thermal cycles.

Key words: thermal, cyclic, fine-grained soil, constitutive modelling.

Introduction

Thermal effects on soil behaviour have drawn attention from researchers throughout the past decades (Campanella & Mitchell, 1968; Leroueil & Marques, 1996; Hueckel et al., 2009; Gens, 2010). Under drained conditions, a monotonic temperature increase can induce irreversible volumetric contraction of normally consolidated (NC) and lightly over-consolidated (OC) fine-grained soils (e.g., Baldi et al., 1988; Sultan et al., 2002; Cekerevac & Laloui, 2004; Abuel-Naga et al., 2007; Uchaipichat & Khalili, 2009; Ng et al., 2016). When subjected to thermal cycles, irreversible volumetric contraction accumulates, and stabilizes within less than 5 thermal cycles (e.g., Campanella & Mitchell, 1968; Vega & McCartney, 2014; Di Donna & Laloui, 2015). The accumulation of irreversible volume contraction with thermal cycles is likely due to the degradation of the inter-particle shear strength under elevated temperatures (Campanella & Mitchell, 1968; Di Donna & Laloui, 2015) and the soil creep (Leroueil & Marques, 1996; Vega & McCartney, 2014).

To model the thermally induced volume change of fine-grained soil, the critical state framework was extended incorporating the shrinkage of yield surface with increasing temperature (e.g., Hueckel & Baldi, 1990; Graham et al., 2001; Laloui & Cekerevac, 2003). In some other models (e.g., Cui et al., 2000; Abuel-Naga et al., 2007), an extra thermal yield surface was introduced to improve the simulation of over-consolidated soil. It should be noted that these models simulate well one heating-cooling cycle, but cannot give the cumulative trend of irreversible volumetric contraction with thermal cycles. Although the thermo-mechanical models based on the concept of hypoplasticity can capture the cumulative trend (e.g., Mašín & Khalili, 2012; Zhou & Ng, 2015), they tend to overestimate the accumulated irreversible volumetric contraction. Di Donna & Laloui (2015) furthered the work by Laloui & François (2009) to account for cyclic thermal loading through modifying the rule governing the plasticity mobilization during cooling.

The accumulation and stabilization of irreversible volume contraction of fine-grained soil subjected to thermal cycles can be classified as a kind of shakedown (Collins & Boulbibane, 2000). The concept of shakedown has been used to model the soil behaviour subjected to mechanical cyclic loading (e.g., Habiballah & Chazallon, 2005) and wetting-drying cycles (Nowamooz et al., 2016). Based on the concept of shakedown, an approach is proposed for simulating the volume change of fine-grained soil subjected to thermal cycles, with focus on NC soil. The sign convention used herein is in accordance with soil mechanics, positive for volume decrease and negative for volume increase.

Proposed approach

Schematic illustration

As suggested by the experimental results on soil volume change under thermal cycles (e.g., Campanella & Mitchell, 1968; Vega & McCartney, 2014; Di Donna & Laloui, 2015), a thermal stabilization line (TSL) is proposed, which controls the stabilized soil state under cyclic thermal loading. For simplicity, it is assumed to be a straight line in the $\ln v - \ln p'$ space as shown in Fig. 1, where the normal compression line (NCL) and the thermal stabilization line (TSL) correspond to an elevated temperature. The point O represents the state of an NC soil specimen at the end of the first heating, and the point O' represents the stabilized state after several thermal cycles for the given temperature increase. The distance OO' reflects the accumulated irreversible volumetric contraction of the NC soil specimen after the first thermal cycle. If it equals 0, there is no accumulation of irreversible volumetric contraction. It is assumed that (1) As temperature changes the TSL shifts together with the NCL which is temperature dependent according to the experimental results (e.g., Campanella & Mitchell, 1968); (2) During heating, if the soil state is above the current TSL there is heating induced irreversible volumetric contraction; Otherwise the soil response is thermo-elastic; (3) During cooling, the soil response is thermo-elastic. Admittedly, the influence of temperature on the TSL is difficult to experimentally quantify. It is a postulation made by the authors to fit best the available data. In addition, the effect of pre-consolidation pressure on the TSL is likely to be small. This is because experimental results from Abuel-Naga et al. (2007) show that the thermally induced volume change of soil is almost independent of the pre-consolidation pressure. Based on the assumptions, it can be deduced that if the distance OO' equals 0 and the slope of the TSL equals that of the NCL, the proposed approach is reduced to that proposed by Hueckel & Baldi (1990) and Laloui & Cekerevac (2003).

Vega & McCartney (2014) carried out odometer tests on the volume change of saturated silt with different OCRs subjected to 4 thermal cycles (18 – 91˚C). The results are shown in Fig. 2, where the open circle and solid circle represent the initial state and final state of the soil specimen, respectively. Although there are some discrepancies, the final stabilized states can be represented by the TSL proposed.

An NC soil specimen subjected to thermal cycles at constant effective stress is analysed to illustrate how the proposed approach works. Fig. 3 shows the state evolution of the NC soil specimen during thermal cycles. The open and solid circles represent the initial state and the current state of the soil specimen, respectively. The initial state means the soil state before the first thermal cycle. The dashed and solid lines correspond to the initial temperature ($\Delta T = 0$ ℃) and the elevated temperature ($\Delta T > 0$ ℃), respectively. During the first heating, both the NCL and the TSL shift downward, and the soil state stays on the NCL. Based on the experimental results (e.g., Abuel-Naga et al., 2007; Uchaipichat & Khalili, 2009), it is reasonable to assume that soil response is thermo-elastic during cooling. For traditional mechanical loading, the volume change is equivalent to the change of void ratio. However, the thermo-elastic soil deformation results in the change of soil volume, but not the void ratio. This is because for thermo-elastic soil deformation the volume change of voids and soil particles is proportional to each other (Khalili et al., 2010; Mašín & Khalili, 2012). Therefore, during cooling the soil state remains unchanged while the NCL and TSL return back to their initial positions. Fig. 3(a) shows the soil state after the first thermal cycle. The corresponding soil response during the first thermal cycle is qualitatively represented by the curve in Fig. 3(b), which shows a continuous irreversible volumetric contraction during heating and elastic response during cooling.

Upon re-heating, initially the soil state is below the TSL and the soil response is thermo-elastic according to the assumptions made previously. As temperature increases both the NCL and the TSL shift downward, with the TSL shifting more compared to the NCL. As the TSL crosses the soil state point, it attracts the soil state point to move downward. Therefore, there occurs more irreversible volumetric contraction. As stated in the introduction, the accumulation and stabilization of irreversible volumetric contraction with thermal cycles can be well characterized by the shakedown concept. According to the concept of shakedown, the soil specimen approaches the stabilized state after a certain number of cycles. Therefore, at the end of the second thermal cycle the soil state may stay slightly above the TSL (see Fig. 3c), which controls the stabilized state of the soil subjected to thermal cycles. Compared to the state after the first thermal cycle (see Fig. 3a), the vertical distance $\Delta \ln(1+e)$ between the soil state point and the TSL is reduced. Qualitatively, the soil response during the second thermal cycle is demonstrated by the curve in Fig. 3(d). At the beginning of heating, soil response is thermo-elastic and after temperature reaches some value it turns to be thermo-plastic. It is easy to predict that after several thermal cycles the soil state eventually approaches the TSL corresponding to the elevated temperature and the vertical distance $\Delta\ln(1+e)$ decreases to zero as presented in Fig. 3(e). Thus, during subsequent heating there is no irreversible volumetric contraction if the temperature does not exceed the history maximum value. As shown in Fig. 3(f) the soil response turns to be stabilized corresponding to the given maximum temperature increase.

Mathematical formulation

According to Mašín & Khalili (2012), the temperature dependent NCLs can be expressed as

$$\ln(1+e) = N(T) - \lambda(T) \cdot \ln(p'/p_{\mathrm{r}}) \tag{1}$$

where e is the void ratio; p' is the mean effective stress; p_{r} is the reference pressure (1 kPa); $\lambda(T)$ and $N(T)$ are the temperature dependent slope and intercept of the NCL, respectively. They are assumed to follow

$$N(T) = N(T_{\mathrm{r}}) + n_{\mathrm{T}} \cdot \ln(T/T_{\mathrm{r}}) \tag{2}$$

$$\lambda(T) = \lambda(T_{\mathrm{r}}) + l_{\mathrm{T}} \cdot \ln(T/T_{\mathrm{r}}) \tag{3}$$

where n_{T} and l_{T} are model parameters controlling the shift and slope change of the NCL with temperature, respectively; T_{r} is the reference temperature. According to the experimental results (e.g., Campanella & Mitchell, 1968), it is assumed that λ is independent of temperature, and thus l_{T} can be chosen as 0.

The newly introduced TSL is determined by its slope k_{T} and the point O' as shown in Fig. 1. It is expressed by

$$\ln(1+e) = \ln(1+e_{\mathrm{o'}}) - k_{\mathrm{T}} \cdot \ln(p'/p'_{\mathrm{o}}) \tag{4}$$

where p'_{o} is the pre-consolidation pressure; $\ln(1+e_{\mathrm{o'}})$ can be calculated from

$$\ln(1+e_{\mathrm{o'}}) = \ln(1+e_{\mathrm{o}}) + c_{\mathrm{T}} \cdot n_{\mathrm{T}} \cdot \ln(T/T_{\mathrm{r}}) \tag{5}$$

where e_{o} and $e_{\mathrm{o'}}$ represent the void ratio corresponding to point O and point O', respectively. If the temperature is lower than the reference temperature, $e_{\mathrm{o'}}$ is assumed to be equal to e_{o}.

The newly introduced parameter c_{T} determines the accumulated volumetric contraction after the first thermal cycle. If it equals 0, there is no accumulation. The slope parameter k_{T} influences the simulated irreversible volumetric contraction of OC soil. As k_{T} decreases, the simulated irreversible volumetric contraction of OC soil increases as it is more likely for the TSL to cross the soil state point during heating.

Implementation of the proposed approach

Implementation

The proposed approach is combined with the hypoplastic framework. The basic hypoplastic model for fine-grained soil developed by Mašín (2005) takes a nonlinear relationship between the Jaumann stress rate tensor $\dot{\boldsymbol{\sigma}}$ and the Euler strain rate tensor $\dot{\boldsymbol{\varepsilon}}$ as

$$\dot{\boldsymbol{\sigma}} = f_{\mathrm{s}}(\boldsymbol{\mathcal{L}} : \dot{\boldsymbol{\varepsilon}} + f_{\mathrm{d}}\boldsymbol{N}\|\dot{\boldsymbol{\varepsilon}}\|) \tag{6}$$

where $\boldsymbol{\mathcal{L}}$ and $\boldsymbol{N}$ are fourth-order and second-order constitutive tensors, respectively; f_{s} and f_{d} are scalar factors to consider the effects of stress level and void ratio, respectively; $:$ stands for double contraction and $\|\mathbf{X}\|$ denotes the Euclidean norm of the tensor $\mathbf{X}$. Detailed mathematical expressions and discussions of the terms involved can be found in Mašín (2005).

To model thermally-induced volume change of soil, Mašín & Khalili (2012) introduced a thermal term $f_{\mathrm{u}}\boldsymbol{H}_{\mathbf{T}}$ into Eq. 6 as

$$\dot{\boldsymbol{\sigma}} = f_{\mathrm{s}}[\boldsymbol{\mathcal{L}} : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{\mathrm{TE}}) + f_{\mathrm{d}}\boldsymbol{N}\|\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{\mathrm{TE}}\|] + f_{\mathrm{u}}\boldsymbol{H}_{\mathbf{T}} \tag{7}$$

$\dot{\boldsymbol{\varepsilon}}^{\mathrm{TE}}$ is the isotropic thermo-elastic strain rate tensor and calculated by

$$\dot{\boldsymbol{\varepsilon}}^{\mathrm{TE}} = \frac{1}{3}\alpha_{\mathrm{s}} \cdot \dot{T} \cdot \mathbf{I} \tag{8}$$

where α_{s} is the volumetric thermal expansion coefficient of soil skeleton and $\dot{T}$ is the temperature change rate. $\mathbf{I}$ is the second order unit tensor. The thermal part is coupled with the mechanical part through the void ratio, which influences the soil behaviour under both thermal and mechanical loading. In addition, thermal loading can change the size of the state boundary surface (Eqs. 1-2), and thus affect the soil behaviour under mechanical loading. Also, mechanical loading changes the size of the state boundary surface, which affects the thermal response for states at or close to the state boundary surface.

The mathematical expression for $\boldsymbol{H}_{\mathrm{T}}$ was derived by considering that when subjected to heating at constant effective stress, the NC soil stays on the NCL as it moves with temperature change (Mašín & Khalili, 2012). The collapse potential factor $0 \leq f_{\mathrm{u}} \leq 1$ controls the heating induced irreversible volumetric contraction. The larger the collapse potential factor f_{u} the more irreversible volumetric contraction heating can induce. For an NC soil specimen during the first heating f_{u} equals 1. When f_{u} equals 0 it implies the soil response is thermo-elastic.

To implement the proposed approach within the hypoplastic framework, the key point lies in modifying the collapse potential factor f_{u}, which controls the thermally induced irreversible volumetric contraction of soil. Its expression should satisfy two requirements: (1) the NC soil stays on the NCL during the first heating; (2) as the soil state approaches the TSL the collapse potential decreases to zero. The revised expression is expressed as Eq. 9

$$f_{\mathrm{u}} = \left\langle \frac{e - e_{\mathrm{T}}^{*}}{e_{\mathrm{T}} - e_{\mathrm{T}}^{*}} \right\rangle^{\gamma} \tag{9}$$

where $\langle x \rangle$ is an operator obtaining the positive part of the scalar variable x, $\langle x \rangle = (x + |x|)/2$; e is the void ratio; e_{T} and e_{T}^{*} are the void ratios on the current NCL and TSL corresponding to the current mean effective stress, respectively (see point C in Fig. 1). They can be calculated from Eq. (1) and (4), respectively. γ is a new parameter controlling the rate of irreversible volumetric contraction development with respect to the heating rate. As a consequence, it controls the number of thermal cycles required to get the soil volumetric contraction stabilized.

Calibration of model parameters

In this section, calibration of the three newly introduced parameters c_{T}, k_{T} and γ is discussed. For the calibration of other relevant model parameters, please refer to Mašín (2005) and Mašín & Khalili (2012). To calibrate the parameter c_{T}, a volume change test of an NC soil specimen subjected to thermal cycles until stabilization is required. Regarding the slope parameter k_{T}, test results of soil specimens with different OCRs are necessary. It can be determined based on the threshold value of OCR corresponding to which there is no heating induced irreversible volumetric contraction for a given temperature increase. The crossing point of the thermal stabilization line for the given temperature increase and the unloading line corresponds to the threshold OCR. Ideally, experiments are required to calibrate the two parameters. However, performing cyclic thermal loading test could be very complex and time consuming. Based on the published experimental results (Campanella & Mitchell, 1968; Vega & McCartney, 2014; Di Donna & Laloui, 2015), a value between 0.4 and 0.5 is suggested for the parameter c_{T}. Regarding the parameter k_{T} values from 0.01 to 0.015 calibrated in this work can be adopted for simulations as a starting point. It should be noted that k_{T} is supposed to be larger than the unloading parameter κ (see Figs. 1 & 2). The thermal parameters adopted in this study are determined by back-analysing the experimental results, and best agreement is achieved through trial and error.

A sensitivity analysis was conducted to study the effect of the parameter γ on the accumulation of irreversible volumetric contraction of an NC soil specimen with thermal cycles. Model parameters used are these for the soil tested by Uchaipichat & Khalili (2009) (see Table 1). The four parameters $\varphi_c, \lambda, \kappa$ and N of the mechanical part in Table 1 are the same as those for the critical state theory. The parameter r controls the ratio of shear stiffness to bulk stiffness. Obtained results are shown in Fig. 4, which indicates that as γ decreases the soil volumetric contraction stabilizes within less number of thermal cycles. Specifically, for $\gamma = 0.1$ it stabilizes around the fifth thermal cycle, which is consistent with the experimental results (e.g., Vega & McCartney, 2014). Based on the sensitivity analysis, a default value of 0.1 is suggested for γ. It should be noted that the parameter γ does not affect the irreversible volumetric contraction corresponding to the first thermal cycle. For an NC soil specimen during the first heating, the soil state remains on the NCL, and thus its volumetric contraction is completely determined by the parameter n_T which controls the shift of NCL with temperature increase (see Eq. 2).

Typical results

Fig. 5 presents the computed volume change of soil specimens with 4 different OCRs (1, 1.3, 2 and 4) subjected to 15 thermal cycles (25 – 60 ^{o}C) using model parameters for the soil tested by Uchaipichat & Khalili (2009) (see Table 1). It can be seen that as the OCR increases, both the irreversible volumetric contraction after the first thermal cycle and that corresponding to the stabilized state decrease. For all the soil specimens the irreversible volumetric contraction stabilizes within roughly five thermal cycles. For the soil specimen with OCR of 4, there is no irreversible volumetric contraction, which indicates a thermo-elastic soil response. It can be predicted that for soil specimen with even higher OCRs, the simulated soil response is also going to be thermo-elastic. These trends are in good agreement with experimental results of saturated silt with different OCRs from Vega & McCartney (2014).

Evaluation of the proposed approach

Experimental test of remoulded illite from Campanella & Mitchell (1968) was simulated using the newly proposed approach and the approach proposed by Mašín & Khalili (2012) for comparison. The soil specimen was consolidated under isotropic condition to 200 kPa.

Then three heating-cooling cycles (from about 60 °C to 5 °C) were applied under drained conditions at constant mean effective stress. The initial temperature of the soil specimen was around 20 °C. Adopted model parameters are summarized in Table 1.

Fig. 6(a) compares the experimental results with that computed using the model proposed by Mašín & Khalili (2012). It is clear that, compared to the measured results, the model predicts excessive accumulation of irreversible volumetric contraction with thermal cycles.

Comparison of the experimental results and the computed results from the newly proposed approach is shown in Fig. 6(b). Overall, it shows a reasonably good correlation between them, and the excessive accumulation is well avoided. The irreversible volumetric contraction accumulates at a decreasing rate. The temperature at which irreversible volumetric contraction occurs increases cycle after cycle. It should be noted that the proposed approach has some limitation in simulating the nonlinearity during the cooling and initial re-heating process. The adopted elastic assumption during cooling and initial re-heating is for simplicity. Actually, published results show somehow contradictory trend during the cooling and initial re-heating process (e.g., Campanella & Mitchell, 1968 and Ng et al., 2016). Therefore, more research is certainly required to confirm the trend experimentally and then improve the approach further.

Summary

Based on the experimental results, a thermal stabilization line is introduced in the $\ln v - \ln p'$ space, which controls the stabilized soil state under cyclic thermal loading. Two parameters are needed to characterize the thermal stabilization line. One determines the accumulated irreversible volumetric contraction for an NC soil specimen, and the other influences the simulated results of OC soil. By taking use of the introduced thermal stabilization line, a method is proposed to model the volume change of fine-grained soil subjected to thermal cycles. The proposed method is realized within the hypoplastic framework and tested against experimental results. The comparison shows that the proposed method is able to simulate the overall trend of accumulation and stabilization of irreversible volumetric contraction with thermal cycles.

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Tables and Figures

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Table 1. A summary of model parameters.

Soil tested by	Soil type	Mechanical part					Thermal part						
		φ_c (°)	λ	κ	N	r	l_T	n_T	α_S (°C^{-1})	T_r (°C)	k_T	c_T	γ
Uchaipichat & Khalili (2009)	Silt	29.5	0.06	0.002	0.772	0.2	0	-0.01	3.5×10^{-5}	25	0.01	0.5	0.1
Campanella & Mitchell (1968)	Clay	22	0.092	0.027	1.178	Nil*	0	-0.009	3.5×10^{-5}	20	Nil*	0.4	0.1

* This parameter is irrelevant to the simulations conducted in this study.

FIGURE 1 Concept of the newly proposed thermal stabilization line (TSL).

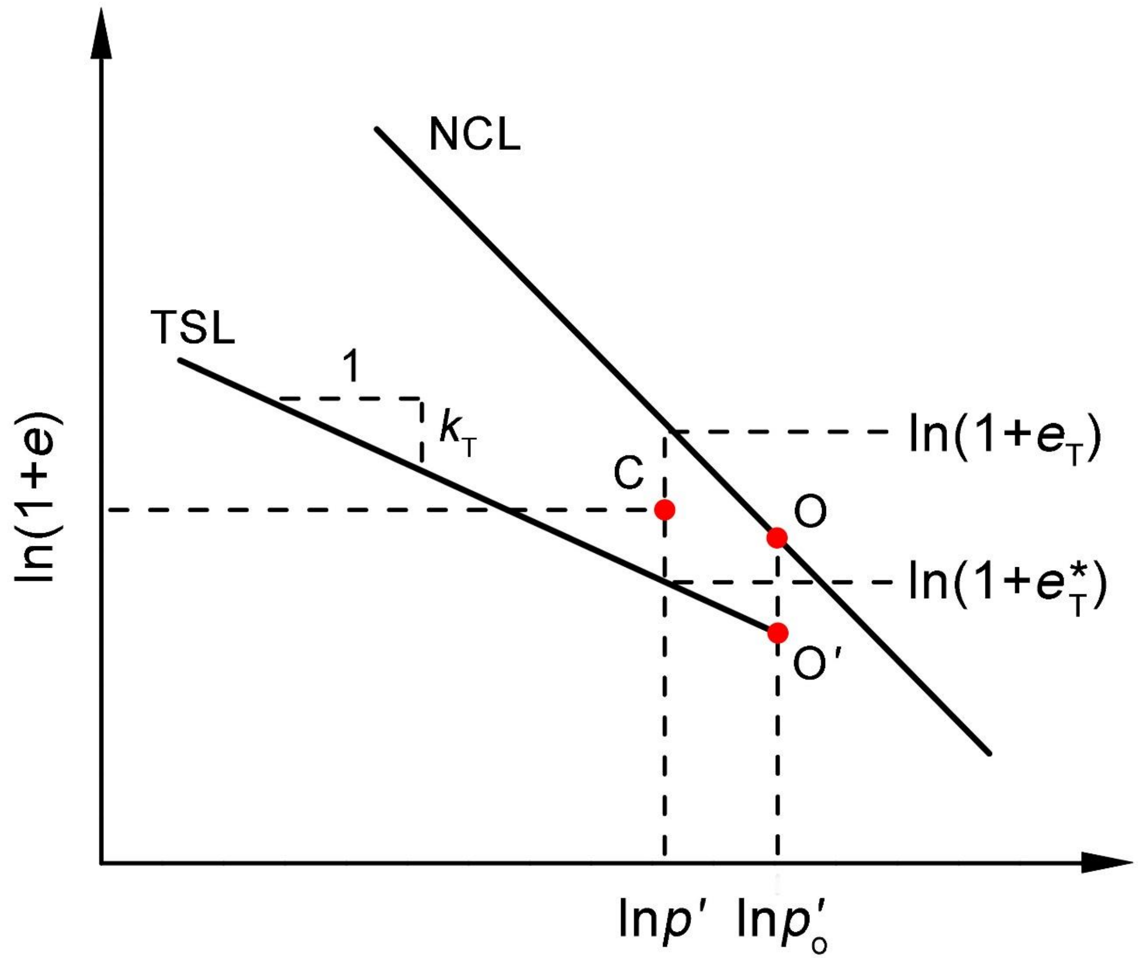

FIGURE 2 Validation of the proposed thermal stabilization line (TSL) by experimental results from Vega & McCartney (2014).

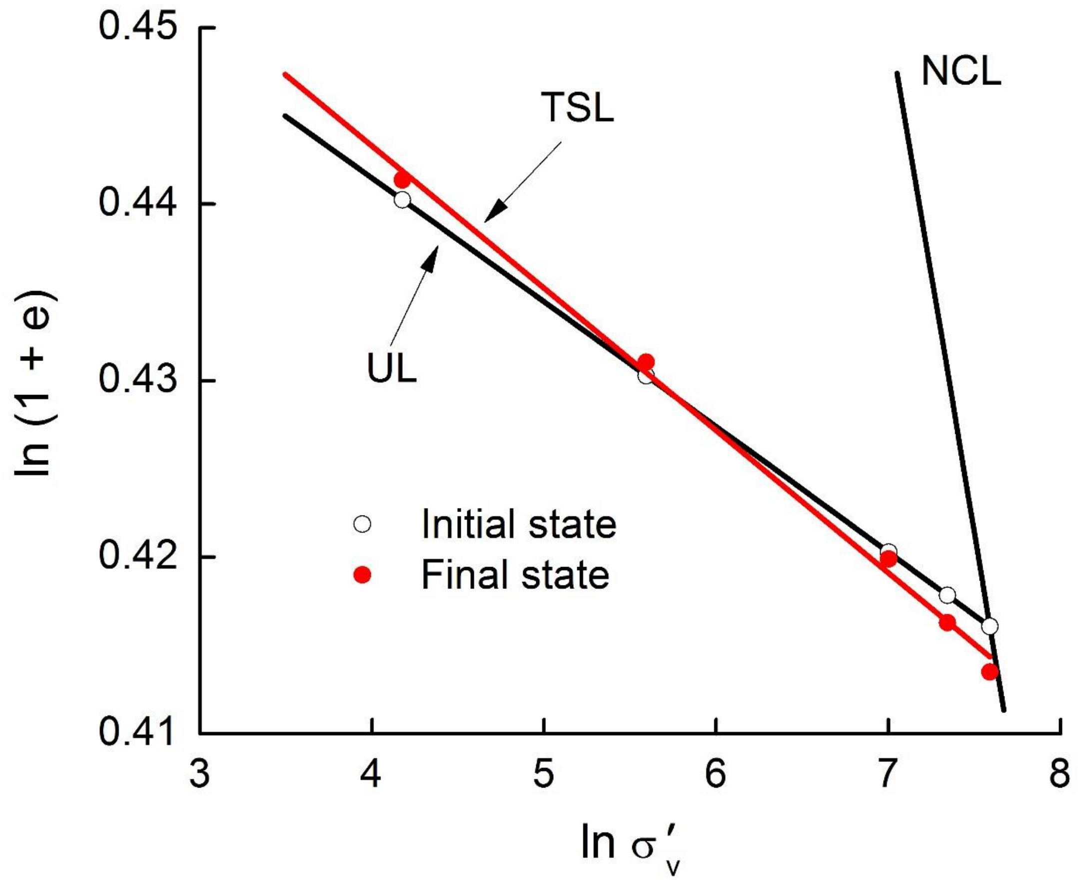

FIGURE 3 Schematic illustration of the proposed approach for simulating volume change of an NC soil specimen subjected to thermal cycles with a constant amplitude: (a) soil state after the first thermal cycle; (b) soil response during the first thermal cycle; (c) soil state after the second thermal cycle; (d) soil response during the second thermal cycle; (e) soil state after stabilization; (f) soil response after stabilization.

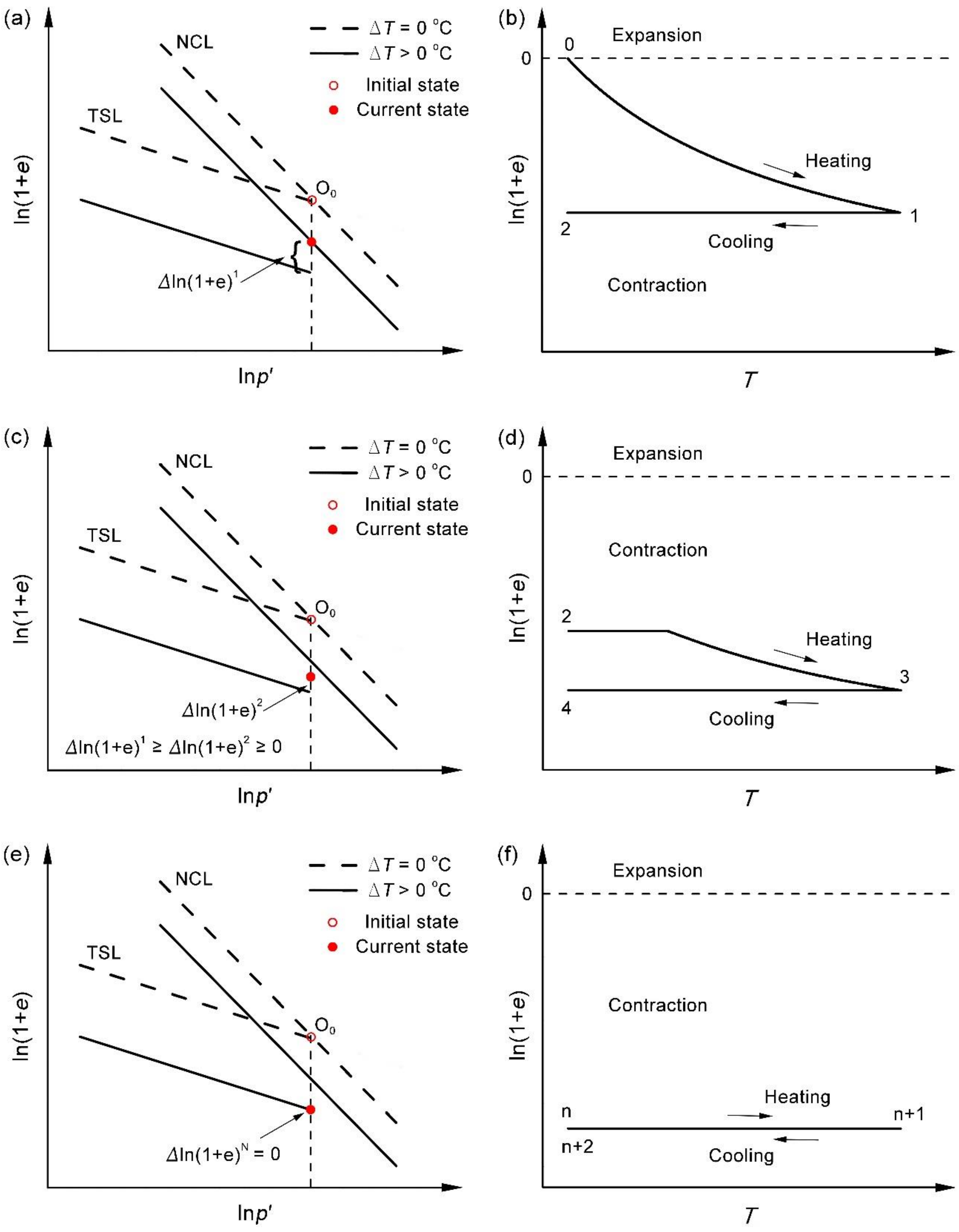

FIGURE 4 Effect of the parameter γ on simulated volume change of an NC soil specimen subjected to thermal cycles.

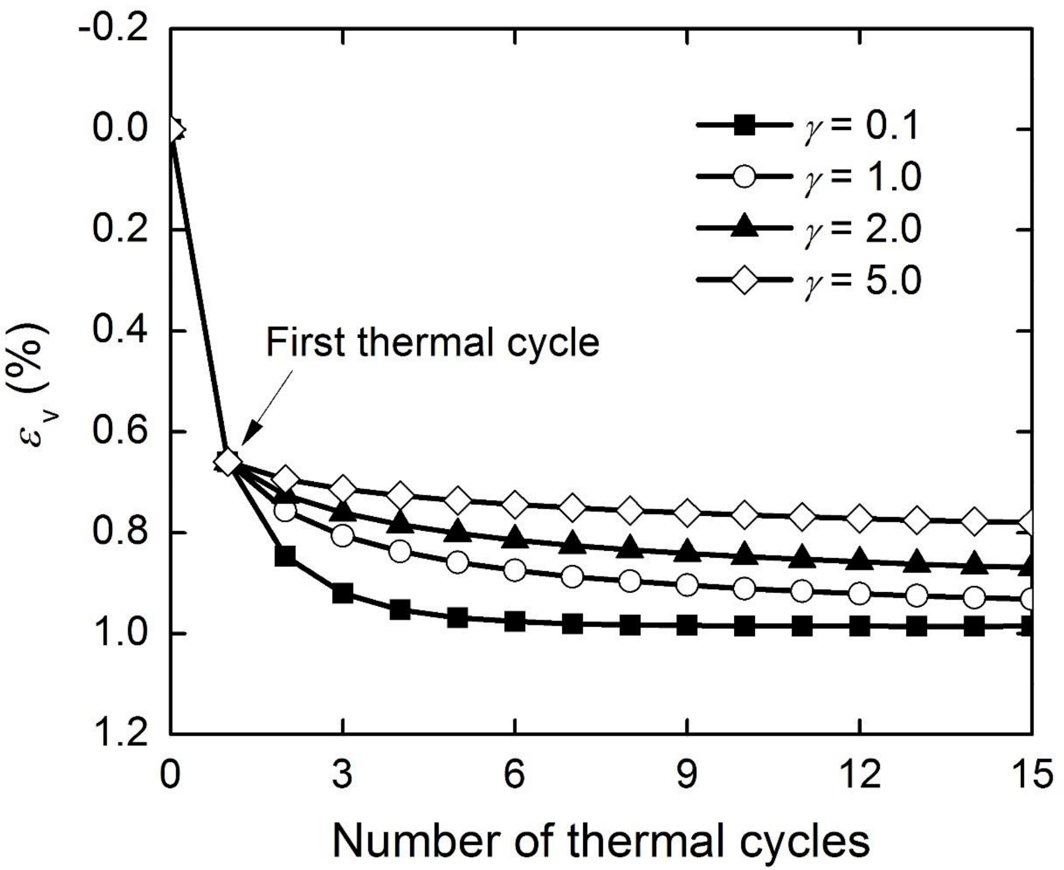

FIGURE 5 Typical results of volume change of soil specimens with different OCRs subjected to thermal cycles from the newly proposed approach.

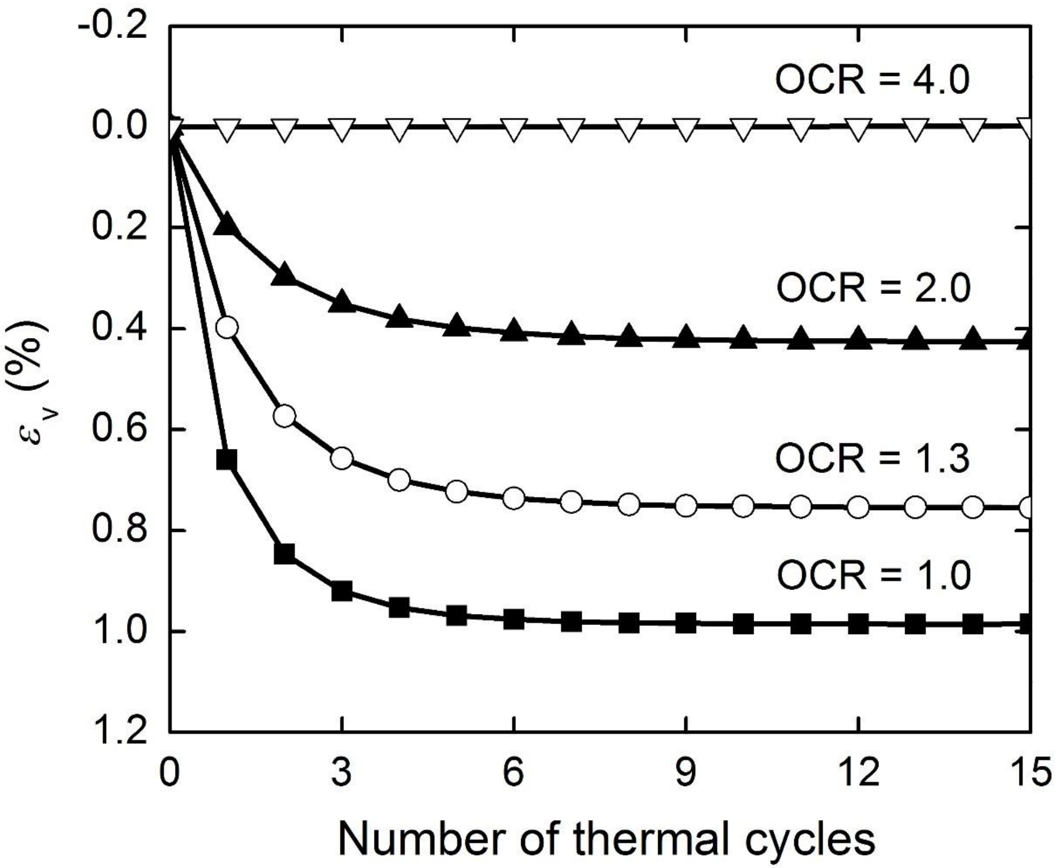

FIGURE 6 Comparison of measured and computed results: (a) computed results from the approach proposed by Mašín & Khalili (2012); (b) computed results from the newly proposed approach.