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

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Abstract: In consequence of cyclic thermal loads under drained condition, normally consolidated and lightly over-consolidated fine grained soils experience accumulation of irreversible volumetric contraction. Most of existing thermo-mechanical models were developed for one heating-cooling cycle and 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; Gens, 2010). Under drained condition, 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, they can experience accumulation of irreversible volumetric contraction, which stabilizes after a few thermal cycles (e.g., Campanella & Mitchell, 1968; Vega & McCartney, 2014; Di Donna & Laloui, 2015).

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 soil with relatively high over-consolidation ratio (OCR). It should be noted that these models focus on one heating-cooling cycle and cannot give the cumulative trend of irreversible volumetric contraction with thermal cycles. For the thermo-mechanical models based on the concept of hypoplasticity (e.g., Mašín & Khalili, 2012; Zhou & Ng, 2015), although they can capture the cumulative trend, they may 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 objective of this study is to propose a new approach for simulating the volume change of fine grained soil subjected to thermal cycles. The sign convention used herein is positive for compression and negative for tension.

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 a given temperature higher than the reference temperature. The point O represents the state of an NC soil specimen at the end of first heating, and the point O' represents the stabilized state after several thermal cycles. The distance OO' reflects the accumulated irreversible volumetric contraction of the NC soil specimen after the first heating. 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 soil response is thermo-elastic; (3) During cooling, soil response is thermo-elastic. 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).

An NC soil specimen subjected to thermal cycles at constant effective stress is analysed to illustrate how the proposed approach works. Fig. 2 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 dashed and solid lines correspond to the initial temperature ($\Delta T = 0$ ℃) and the higher temperature ($\Delta T > 0$ ℃), respectively. During the first heating, both the NCL and the TSL shift downwards, and the soil state stays on the NCL. Fig. 2(a) shows the soil state after the first heating. During cooling it is assumed that soil response is thermo-elastic, and thus the soil state remains unchanged while the NCL and TSL return back to their initial positions. The corresponding soil volume change during the first heating-cooling cycle is qualitatively represented by the curve in Fig. 2(b), which shows a continuous irreversible volumetric contraction during heating and elastic thermal contraction during cooling.

Upon re-heating, initially the soil state is below the current TSL and the soil response is thermo-elastic according to the assumptions made previously. As the TSL continues to move downwards and crosses the soil state point, it attracts the soil state point to move downwards. Therefore, there occurs more irreversible volumetric contraction. Instead of staying exactly on the TSL, at the end of the second heating the soil state point may stay slightly above the current TSL as shown in Fig. 2(c). This is based on the consideration of the possibly viscous nature of soil behaviour under thermal loading (Leroueil & Marques, 1996). Compared to the state after the first heating (see Fig. 2(a)), the vertical distance $\Delta\epsilon_{\mathrm{v}}$ between the current soil state point and current TSL is reduced. The degree of reduction is influenced by the rate of irreversible volumetric contraction development with respect to the rate of temperature increase. Qualitatively, the corresponding soil volume change during the second thermal cycle is demonstrated by the curve in Fig. 2(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 and the vertical distance $\Delta\epsilon_{\mathrm{v}}$ decreases to zero as shown in Fig. 2(e). Thus, during subsequent heating there is no irreversible volumetric contraction if the temperature does not exceed the history maximum value, and soil response turns to be thermo-elastic as shown in Fig. 2(f).

Mathematical formulation

The mathematical formulation for isotropic stress condition is presented first and then extended to anisotropic stress condition. According to Mašín & Khalili (2012), the temperature dependent NCLs can be expressed as

$$\ln(1+e) = N(T) - \lambda(T) \cdot \ln(p'/p_r) \quad (1)$$

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

$$N(T) = N(T_r) + n_T \cdot \ln(T/T_r) \quad (2)$$

$$\lambda(T) = \lambda(T_r) + l_T \cdot \ln(T/T_r) \quad (3)$$

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), λ is almost independent of temperature, and thus l_T can often be chosen as 0.

The newly introduced TSL is determined by its slope k_T and the position of point O' $(\ln p'_o, \ln(1+e_{o'}))$ as shown in Fig. 1. It is expressed by

$$\ln(1+e) = \ln(1+e_{o'}) - k_T \cdot \ln(p'/p'_o) \quad (4)$$

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

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

where e_{o} and $e_{\mathrm{o}'}$ represent the void ratio corresponding to point O and point O', respectively. The newly introduced coefficient c_{T} determines the accumulated volumetric contraction from the second thermal cycle on. 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 because it is more likely for the TSL to cross the soil state point during heating.

To extend the mathematical formulation from isotropic condition to anisotropic condition, the expression of NCL for the general anisotropic condition needs to be adopted

$$\ln\left(1+e\right)=N^{*}(T)-\lambda(T)\cdot\ln\left(p'/p_{\mathrm{r}}\right) \tag{6}$$

with

$$N^{*}(T)=N(T)-\left(\lambda(T)-\kappa\right)\cdot\ln\left(p'_{\mathrm{o}}/p^{\mathrm{SBS}}\right) \tag{7}$$

where p^{SBS} is the mean effective stress obtained by radial mapping of the stress state onto the state boundary surface from stress origin corresponding to the current void ratio. For isotropic condition p'_{o} is equal to p^{SBS} and equation (6) reduces to equation (1).

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

$$\dot{\boldsymbol{\sigma}} = f_{\mathrm{s}}(\boldsymbol{\mathcal{L}} : \dot{\boldsymbol{\varepsilon}} + f_{\mathrm{d}}\boldsymbol{N}\|\dot{\boldsymbol{\varepsilon}}\|) \tag{8}$$

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 $\mathbf{X}$.

To model thermally-induced volume change of soil, Mašín & Khalili (2012) introduced a thermal term $f_{\mathrm{u}}\boldsymbol{H}_{\mathbf{T}}$ into equation (8) as

$$\dot{\boldsymbol{\sigma}} = f_{\mathrm{s}}[\boldsymbol{\mathcal{L}} : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{\mathrm{TE}}) + f_{\mathrm{d}}\boldsymbol{N}\|\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{\mathrm{TE}}\|] + f_{\mathrm{u}}\boldsymbol{H}_{\mathbf{T}} \tag{9}$$

where $\dot{\boldsymbol{\varepsilon}}^{\mathrm{TE}}$ is the isotropic thermal elastic strain rate tensor. Mathematical expression for $\boldsymbol{H}_{\mathbf{T}}$ was derived by considering that when subjected to heating at constant effective stress, the NC soil stays on the current NCL as it moves with temperature change. Detailed mathematical expressions and discussions of the terms involved can be found in Mašín (2005) and 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 heating induced irreversible volumetric contraction is. For an NC soil specimen during the first heating f_{u} equals 1. When

f_u equals 0 it implies soil response is thermo-elastic.

To implement the proposed approach within the hypoplastic framework, the collapse potential factor f_u is modified as

$$f_u = \left\langle \frac{e - e_T^*}{e_T - e_T^*} \right\rangle^{\gamma} \tag{10}$$

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 current mean effective stress, respectively (see point C in Fig. 1). They can be calculated from equations (6) 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, 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 a given temperature and the unloading line corresponds to the threshold OCR. Alternatively, it can be determined by trial and error to achieve an overall reasonable simulation of OC soil.

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). Obtained results are shown in Fig. 3, 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, which will be further validated against experimental results later. 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 current NCL, and thus its volumetric contraction is completely determined by the parameter n_{T} controlling the shift of NCL with temperature increase (see equation (2)).

Typical results

Fig. 4 presents the computed volume change of soil specimens with 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. The irreversible volumetric contraction stabilizes within roughly five thermal cycles for all the soil specimens except that with OCR of 4. 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

Isotropic condition

By using the proposed approach, experimental test of remoulded illite from Campanella & Mitchell (1968) was simulated. 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 condition with constant mean effective stress. The initial temperature of the soil specimen was around 20 °C. Adopted model parameters are summarized in Table 1.

Comparison of the experimental results and the computed results is shown in Fig. 5. Overall, it shows a reasonably good correlation between them. The irreversible volumetric contraction accumulates at a decreasing rate. The temperature at which irreversible volumetric contraction occurs increases cycle after cycle. However, for the cooling and re-heating phase there are some discrepancies. One possible reason is the temperature dependence of the thermal expansion coefficient α_s of soil skeleton (Laloui & Cekerevac, 2003), which is assumed to be a constant in this study for simplicity. In addition, the thermo-elastic assumption corresponding to the cooling and initial re-heating process can also result in some inaccuracies. This assumption is adopted also for the convenience of modelling, and can be dropped in future if necessary.

1D condition

One oedometer test from Di Donna & Laloui (2015) on natural silty-clay subjected to thermal cycles was also simulated. The in-situ condition was considered to be normally consolidated with the vertical effective stress around 149 kPa. Test procedure was that the soil specimen was loaded under 1D condition to a vertical effective stress of 125 kPa. Then three thermal cycles (from 60 °C to 5 °C) were applied under drained condition with the initial temperature around 20 °C. The vertical effective stress remained constant during the thermal loading. Model parameters used are summarized in Table 1.

Fig. 6 compares the experimental results to the computed results. It can be seen that the proposed approach can simulate the main features of volume change behaviour under thermal cycles reasonably well. It should be noted that at the beginning of the first heating phase the experimental results show a continuous volumetric contraction compared to the computed results, which show slight volumetric expansion followed by large volumetric contraction. This computed initial volumetric expansion is due to the adopted assumption of elastic response when the soil state is below the TSL. According to some other literatures (e.g., Towhata et al., 1993; Sultan et al., 2002; Abuel-Naga et al., 2007), lightly over-consolidated soils experience initial volumetric expansion and then volumetric contraction after temperature exceeds some threshold value, which is consistent with the computed results. If the continuous volumetric contraction for lightly over-consolidated soil is intrinsic, which may depend on the soil type, the proposed approach can result in some discrepancies for the initial phase of first heating.

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 controls 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 measured and computed results are fairly consistent. 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
Di Donna & Laloui (2015)	Silty-clay	24	0.023	0.01	0.676	0.6	0	-0.0055	1.8×10^{-5}	20	0.015	0.4	0.1

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

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

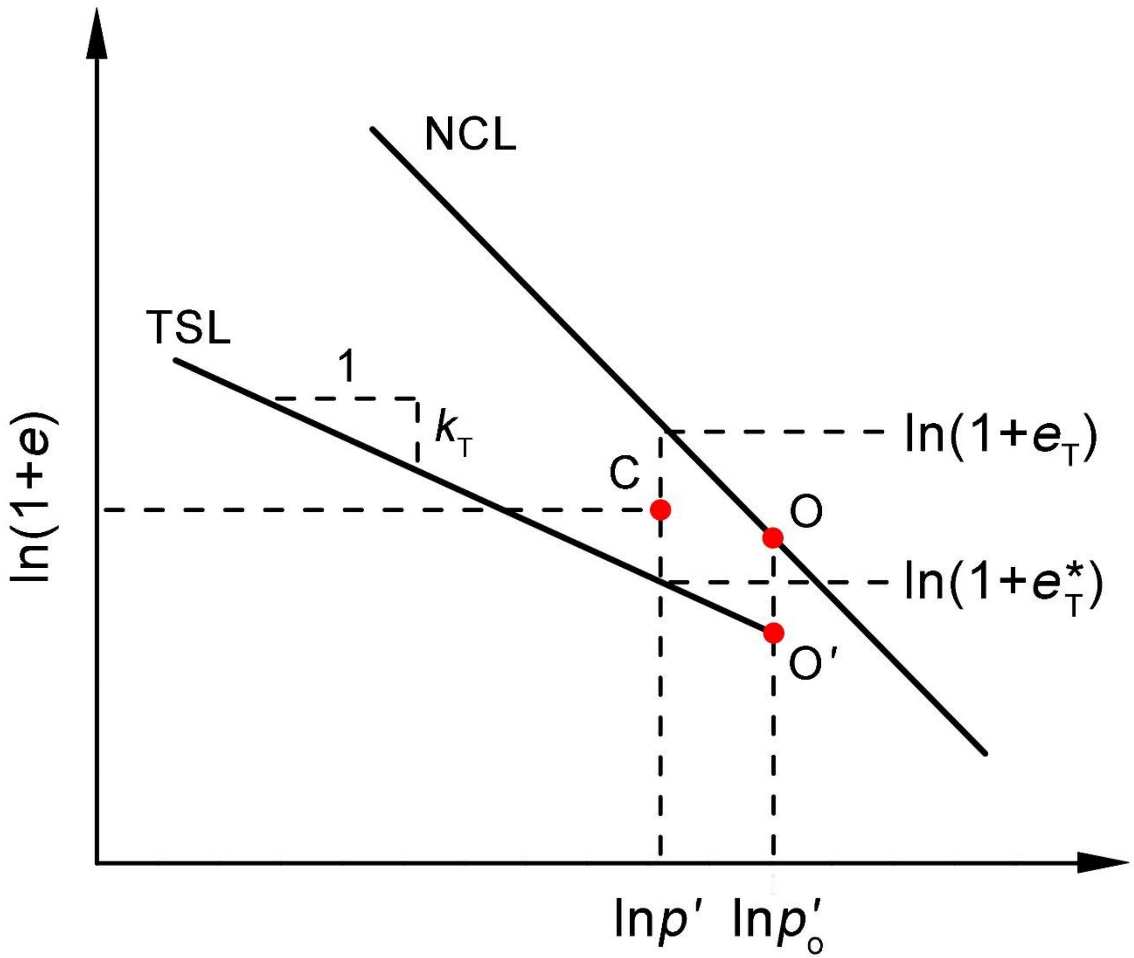

FIGURE 2 Schematic illustration of the proposed approach for simulating volume change of an NC soil specimen subjected to thermal cycles

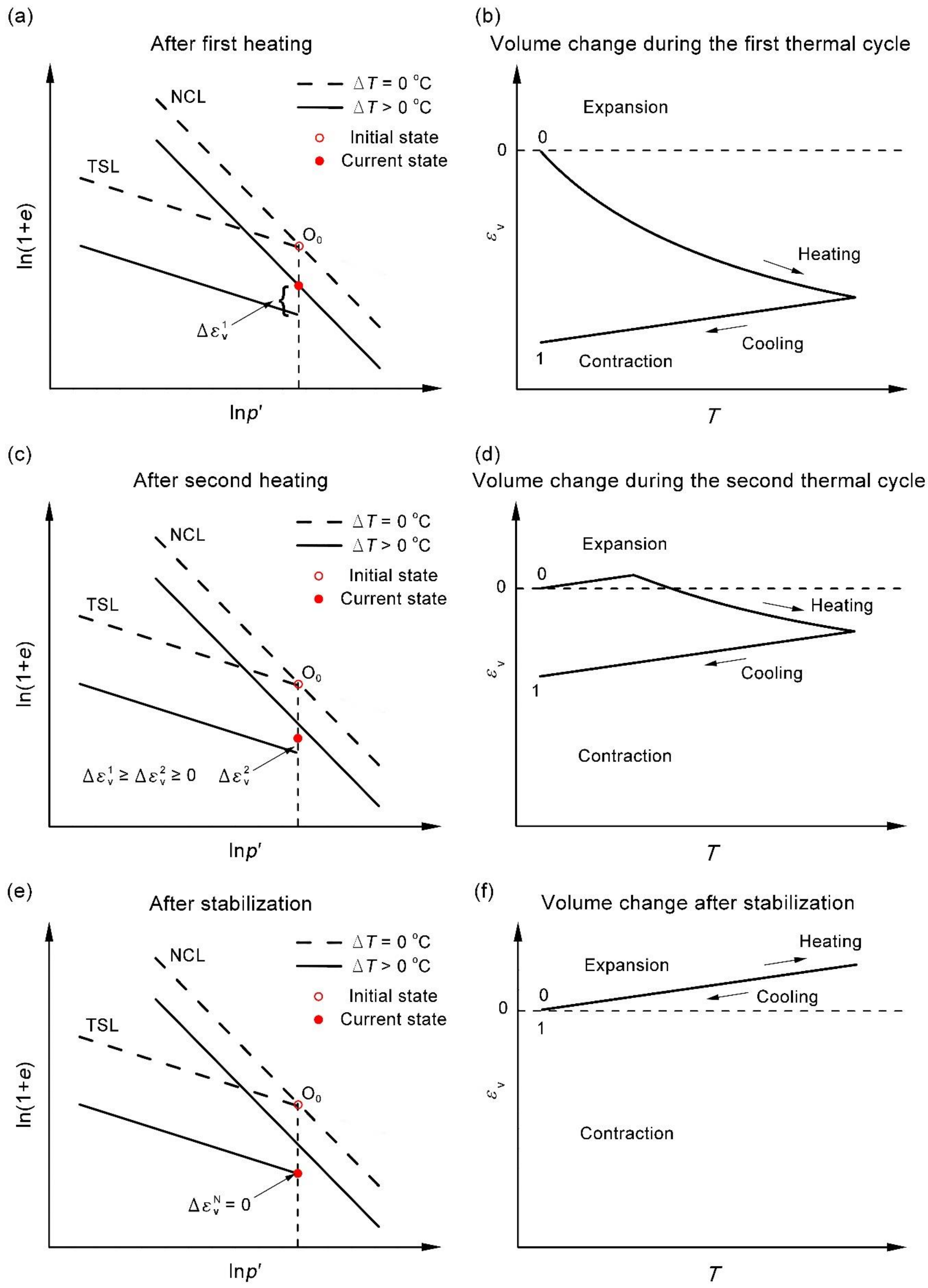

FIGURE 3 Effect of the parameter γ on simulated volume change of an NC soil specimen subjected to thermal cycles

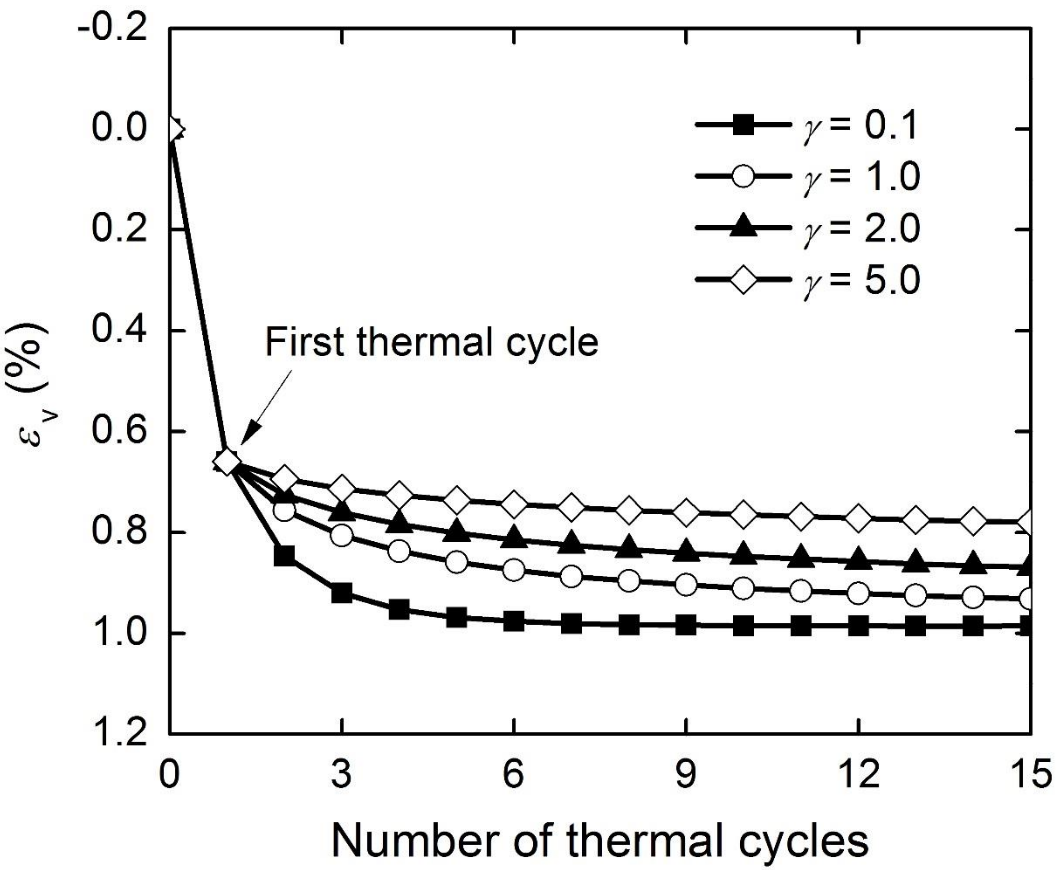

FIGURE 4 Typical results of volume change of soil specimens with different OCRs subjected to thermal cycles from the proposed approach

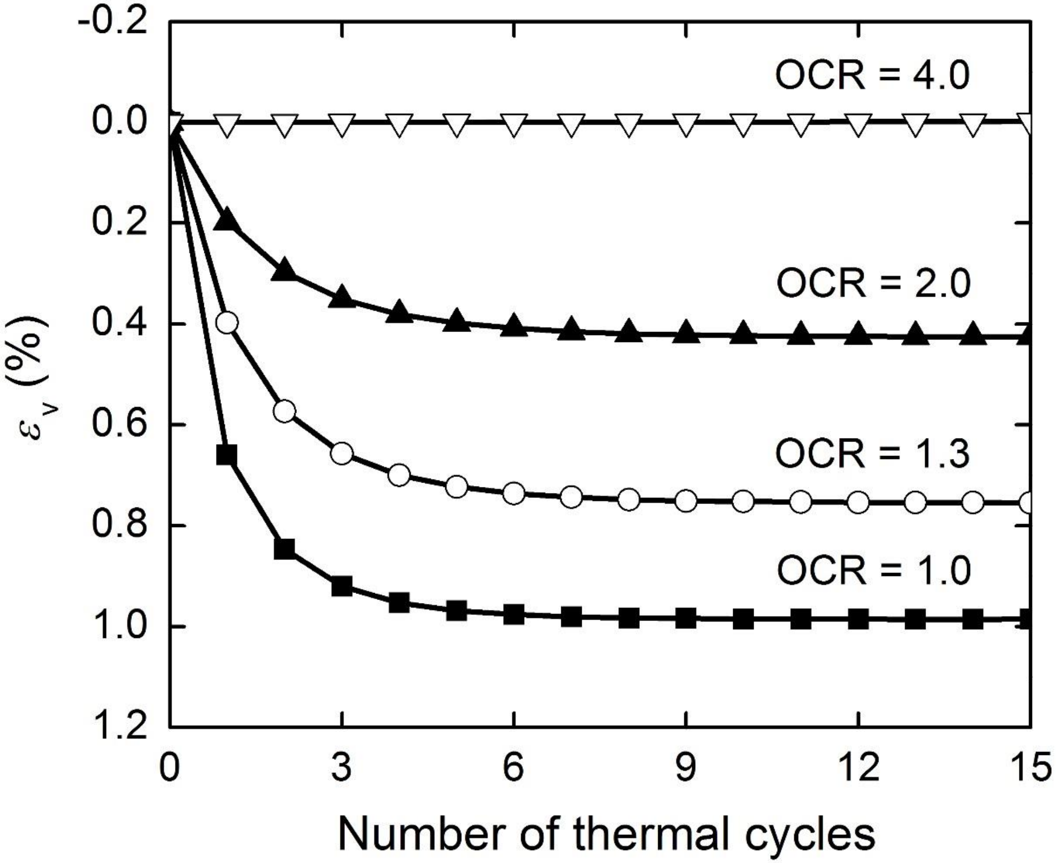

FIGURE 5 Comparison of measured and computed results: Normally consolidated remolded illite under isotropic stress condition

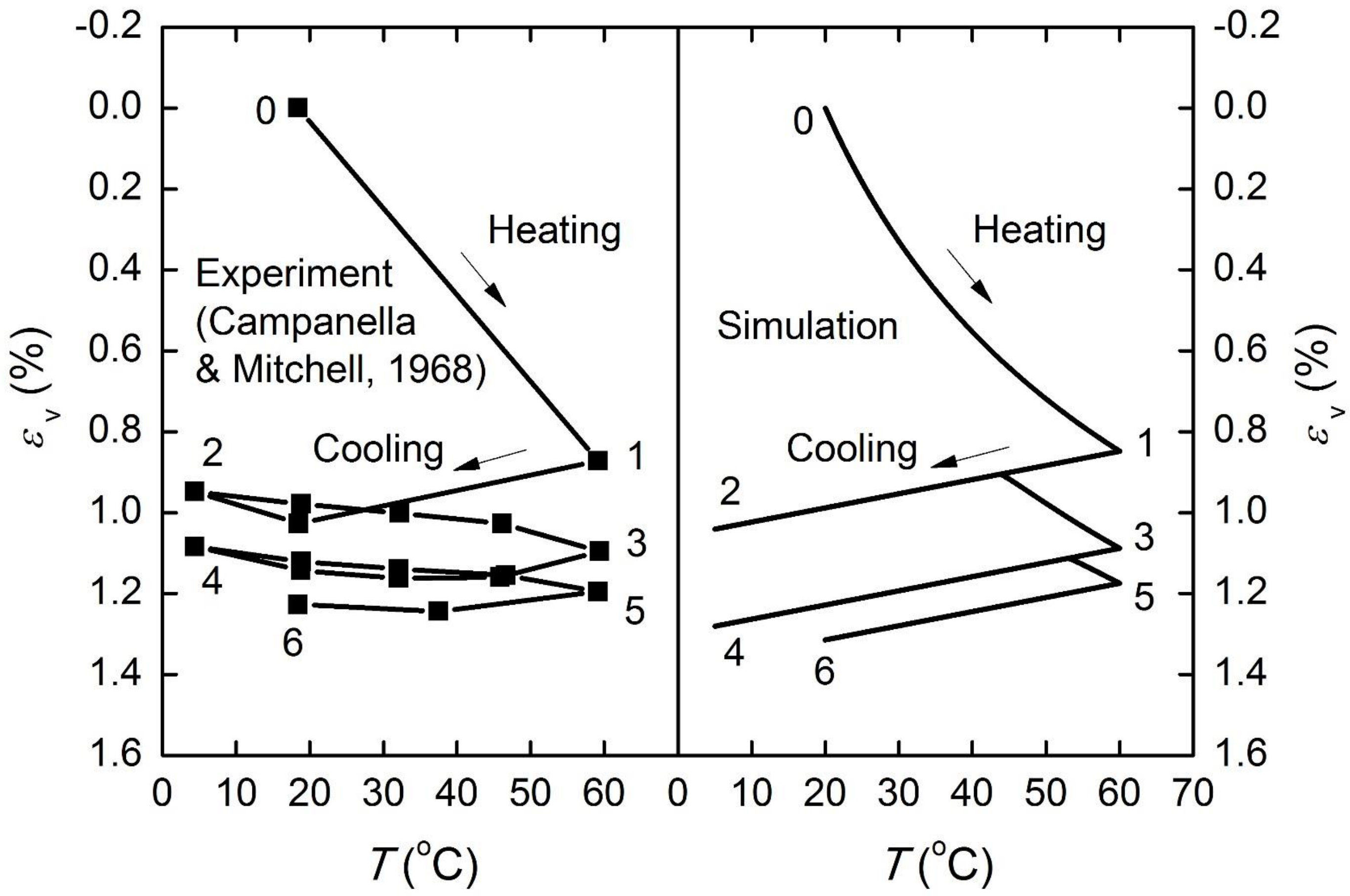

FIGURE 6 Comparison of measured and computed results: Lightly over-consolidated natural silty-clay under one-dimensional stress condition