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

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Draft

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

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

32 Introduction

33 Thermal effects on soil behaviour have drawn attention from researchers throughout the
34 past decades (Campanella and Mitchell 1968; Leroueil and Marques 1996; Hueckel et al.
35 2009; Gens 2010). Under drained conditions, a monotonic temperature increase can induce
36 irreversible volumetric contraction of normally consolidated (NC) and lightly
37 over-consolidated (OC) fine-grained soils (e.g., Baldi et al. 1988; Sultan et al. 2002; Cekerevac
38 and Laloui 2004; Abuel-Naga et al. 2007; Uchaipichat and Khalili 2009; Ng et al. 2016). When
39 subjected to thermal cycles, irreversible volumetric contraction accumulates, and stabilizes
40 within less than 5 thermal cycles (e.g., Campanella and Mitchell 1968; Vega and McCartney
41 2014; Di Donna and Laloui 2015). The accumulation of irreversible volume contraction with
42 thermal cycles is likely due to the degradation of the inter-particle shear strength under
43 elevated temperatures (Campanella and Mitchell 1968; Di Donna and Laloui 2015) and the
44 soil creep (Leroueil and Marques 1996; Vega and McCartney 2014).

45 To model the thermally induced volume change of fine-grained soil, the critical state
46 framework was extended incorporating the shrinkage of yield surface with increasing
47 temperature (e.g., Hueckel and Baldi 1990; Graham et al. 2001; Laloui and Cekerevac 2003).
48 In some other models (e.g., Cui et al. 2000; Abuel-Naga et al. 2007), an extra thermal yield
49 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., Mašin and Khalili 2012; Zhou and Ng 2015), they tend to overestimate the accumulated irreversible volumetric contraction. Di Donna and Laloui (2015) furthered the work by Laloui and 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 and Boulbibane 2000). The concept of shakedown has been used to model the soil behaviour subjected to mechanical cyclic loading (e.g., Habiballah and 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.,

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

87 be deduced that if the distance OO' equals 0 and the slope of the TSL equals that of the NCL,
88 the proposed approach is reduced to that proposed by Hueckel and Baldi (1990) and Laloui
89 and Cekerevac (2003).

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

95 An NC soil specimen subjected to thermal cycles at constant effective stress is analysed to
96 illustrate how the proposed approach works. Fig. 3 shows the state evolution of the NC soil
97 specimen during thermal cycles. The open and solid circles represent the initial state and the
98 current state of the soil specimen, respectively. The initial state means the soil state before
99 the first thermal cycle. The dashed and solid lines correspond to the initial temperature
100 ($\Delta T = 0^{\circ}\text{C}$) and the elevated temperature ($\Delta T > 0^{\circ}\text{C}$), respectively. During the first heating,
101 both the NCL and the TSL shift downward, and the soil state stays on the NCL. Based on the
102 experimental results (e.g., Abuel-Naga et al. 2007; Uchaipichat and Khalili 2009), it is
103 reasonable to assume that soil response is thermo-elastic during cooling. For traditional
104 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; Mašin and 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 Mašin and 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

139 with temperature, respectively; T_r is the reference temperature. According to the
 140 experimental results (e.g., Campanella and Mitchell 1968), it is assumed that λ is
 141 independent of temperature, and thus l_T can be chosen as 0.

142 The newly introduced TSL is determined by its slope k_T and the point O' as shown in Fig. 1. It
 143 is expressed by

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

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

$$\ln(1 + e_{o'}) = \ln(1 + e_o) + c_T \cdot n_T \cdot \ln(T/T_r) \quad (5)$$

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

148 The newly introduced parameter c_T determines the accumulated volumetric contraction
 149 after the first thermal cycle. If it equals 0, there is no accumulation. The slope parameter k_T
 150 influences the simulated irreversible volumetric contraction of OC soil. As k_T decreases, the
 151 simulated irreversible volumetric contraction of OC soil increases as it is more likely for the
 152 TSL to cross the soil state point during heating.

153 **Implementation of the proposed approach**

154 Implementation

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

$$\dot{\boldsymbol{\sigma}} = f_s(\mathcal{L} : \dot{\boldsymbol{\varepsilon}} + f_d \mathbf{N} \|\dot{\boldsymbol{\varepsilon}}\|) \quad (6)$$

158 where $\mathcal{L}$ and $\mathbf{N}$ are fourth-order and second-order constitutive tensors, respectively; f_s and
 159 f_d are scalar factors to consider the effects of stress level and void ratio, respectively; :
 160 stands for double contraction and $\|\mathbf{X}\|$ denotes the Euclidean norm of the tensor $\mathbf{X}$. Detailed
 161 mathematical expressions and discussions of the terms involved can be found in Mašín
 162 (2005).

163 To model thermally-induced volume change of soil, Mašín and Khalili (2012) introduced a
 164 thermal term $f_u \mathbf{H}_T$ into Eq. 6 as

$$\dot{\boldsymbol{\sigma}} = f_s[\mathcal{L} : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{\text{TE}}) + f_d \mathbf{N} \|\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{\text{TE}}\|] + f_u \mathbf{H}_T \quad (7)$$

165 $\dot{\boldsymbol{\varepsilon}}^{\text{TE}}$ is the isotropic thermo-elastic strain rate tensor and calculated by

$$\dot{\boldsymbol{\varepsilon}}^{\text{TE}} = \frac{1}{3} \alpha_s \cdot \dot{T} \cdot \mathbf{I} \quad (8)$$

166 where α_s is the volumetric thermal expansion coefficient of soil skeleton and $\dot{T}$ is the
 167 temperature change rate. $\mathbf{I}$ is the second order unit tensor. The thermal part is coupled with

168 the mechanical part through the void ratio, which influences the soil behaviour under both
169 thermal and mechanical loading. In addition, thermal loading can change the size of the
170 state boundary surface (Eqs. 1-2), and thus affect the soil behaviour under mechanical
171 loading. Also, mechanical loading changes the size of the state boundary surface, which
172 affects the thermal response for states at or close to the state boundary surface.

173 The mathematical expression for H_T was derived by considering that when subjected to
174 heating at constant effective stress, the NC soil stays on the NCL as it moves with
175 temperature change (Mašín and Khalili 2012). The collapse potential factor $0 \leq f_u \leq 1$
176 controls the heating induced irreversible volumetric contraction. The larger the collapse
177 potential factor f_u the more irreversible volumetric contraction heating can induce. For an
178 NC soil specimen during the first heating f_u equals 1. When f_u equals 0 it implies the soil
179 response is thermo-elastic.

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

$$f_u = \left(\frac{e - e_T^*}{e_T - e_T^*} \right)^\gamma \quad (9)$$

185 where $\langle x \rangle$ is an operator obtaining the positive part of the scalar variable x , $\langle x \rangle = (x +$
 186 $|x|)/2$; e is the void ratio; e_T and e_T^* are the void ratios on the current NCL and TSL
 187 corresponding to the current mean effective stress, respectively (see point C in Fig. 1). They
 188 can be calculated from Eq. (1) and (4), respectively. γ is a new parameter controlling the rate
 189 of irreversible volumetric contraction development with respect to the heating rate. As a
 190 consequence, it controls the number of thermal cycles required to get the soil volumetric
 191 contraction stabilized.

192 Calibration of model parameters

193 In this section, calibration of the three newly introduced parameters c_T , k_T and γ is
 194 discussed. For the calibration of other relevant model parameters, please refer to Mašín
 195 (2005) and Mašín and Khalili (2012). To calibrate the parameter c_T , a volume change test of
 196 an NC soil specimen subjected to thermal cycles until stabilization is required. Regarding the
 197 slope parameter k_T , test results of soil specimens with different OCRs are necessary. It can
 198 be determined based on the threshold value of OCR corresponding to which there is no
 199 heating induced irreversible volumetric contraction for a given temperature increase. The
 200 crossing point of the thermal stabilization line for the given temperature increase and the

201 unloading line corresponds to the threshold OCR. Ideally, experiments are required to
202 calibrate the two parameters. However, performing cyclic thermal loading test could be very
203 complex and time consuming. Based on the published experimental results (Campanella and
204 Mitchell 1968; Vega and McCartney 2014; Di Donna and Laloui 2015), a value between 0.4
205 and 0.5 is suggested for the parameter c_T . Regarding the parameter k_T values from 0.01 to
206 0.015 calibrated in this work can be adopted for simulations as a starting point. It should be
207 noted that k_T is supposed to be larger than the unloading parameter κ (see Figs. 1 & 2). The
208 thermal parameters adopted in this study are determined by back-analysing the
209 experimental results, and best agreement is achieved through trial and error.

210 A sensitivity analysis was conducted to study the effect of the parameter γ on the
211 accumulation of irreversible volumetric contraction of an NC soil specimen with thermal
212 cycles. Model parameters used are these for the soil tested by Uchaipichat and Khalili (2009)
213 (see Table 1). The four parameters φ_c , λ , κ and N of the mechanical part in Table 1 are the
214 same as those for the critical state theory. The parameter r controls the ratio of shear
215 stiffness to bulk stiffness. Obtained results are shown in Fig. 4, which indicates that as γ
216 decreases the soil volumetric contraction stabilizes within less number of thermal cycles.

217 Specifically, for $\gamma = 0.1$ it stabilizes around the fifth thermal cycle, which is consistent with
218 the experimental results (e.g., Vega and McCartney 2014). Based on the sensitivity analysis,
219 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 °C) using model parameters for the soil tested by Uchaipichat and 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 and McCartney (2014).

Evaluation of the proposed approach

Experimental test of remoulded illite from Campanella and Mitchell (1968) was simulated

238 using the newly proposed approach and the approach proposed by Mašín and Khalili (2012)
239 for comparison. The soil specimen was consolidated under isotropic condition to 200 kPa.
240 Then three heating-cooling cycles (from about 60 °C to 5 °C) were applied under drained
241 conditions at constant mean effective stress. The initial temperature of the soil specimen
242 was around 20 °C. Adopted model parameters are summarized in Table 1.

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

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

256 experimentally and then improve the approach further.

257 **Summary**

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

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Fig. 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.

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

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

Fig. 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.

Table 1. A summary of model parameters.

Soil tested by	Soil type	Mechanical part					Thermal part						
		$\varphi_c (^\circ)$	λ	κ	N	r	h_T	n_T	$\alpha_s (^\circ\text{C}^{-1})$	$T_r (^\circ\text{C})$	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.

Fig. 1. Concept of the newly proposed thermal stabilization line (TSL).
235x195mm (300 x 300 DPI)

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

297x231mm (300 x 300 DPI)

Fig. 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.

493x637mm (200 x 200 DPI)

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

297x231mm (300 x 300 DPI)

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

297x231mm (300 x 300 DPI)

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

309x420mm (300 x 300 DPI)