Engineering Geology 253 (2019) 47–54

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Volume change characteristics of fine-grained soils due to sequential thermo-mechanical stresses

Rakshith Shetty[a], D.N. Singh[a,*], Alessio Ferrari[b,c]

[a] Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India
[b] Laboratory of Soil Mechanics, School of Architecture, Civil and Environmental Engineering, Swiss Federal Institute of Technology, Lausanne (EPFL), Switzerland
[c] Department of Civil, Environmental, Aerospace, Materials Engineering, Università degli Studi di Palermo, Italy

ARTICLE INFO

Keywords:
Thermo-hydro-mechanical behavior of soils
Thermal stresses
Mechanical stresses
Structural rearrangement
Excess pore-water pressure
Thermal volumetric strains

ABSTRACT

Know-how of volume change characteristics, VCC, of the fine-grained soils, exposed to thermal stresses, is essential for design of various thermo-active structures. These stresses are known to induce excess pore-water pressure, Δu_θ, in the saturated state of such soils, which in turn affects their compression and shear strength characteristics. In this context, through several experimental studies, the effect of thermo-mechanical stress-path, the over-consolidation ratio (OCR) and degree of saturation on VCC (viz., thermally induced volumetric strain, $\varepsilon_{v\theta}$, compression and re-compression indices, c_c and c_r) of the fine-grained soils has been demonstrated by earlier researchers. However, the response of these soils when exposed to sequential thermal and mechanical stresses, STMS, due to temperature fluctuation and continued infrastructure development, on VCC has seldom been studied. This motivated us to investigate the VCC of the fine-grained soils, by subjecting them to STMS in a suitably modified oedometer setup which facilitates temperature controlled tests. From the results of STMS tests, it is seen that the $\varepsilon_{v\theta}$ of these soils exposed to thermal cycles (20-60-20 °C) is independent of the thermal stress history experienced at different applied vertical stress, σ_v, (= 60, 125, 250 kPa). Furthermore, from the analysis of deformation-time curve of the thermal loading phase, a methodology for direct determination of the volume change component of fine-grained soils, due to structural rearrangement, $\Delta V_{s\theta}$, has been proposed. The methodology enables direct computation of the coefficient of volume change due to structural rearrangement, $\alpha_{s\theta}$, that would aid in direct prediction of Δu_θ from the deformation-time curve of thermal loading phase.

1. Introduction

Several practical situations met in the design and realization of radioactive waste repositories (Delage et al., 2000; Zhang and Rothfuchs, 2004; Romero et al., 2005; Favero et al., 2016a; Jacinto and Ledesma, 2017), geothermal energy piles (Laloui and Ferrari, 2013; Di Donna et al., 2016), thermal pre-fabricated vertical drains (Abuel-Naga et al., 2007a), and buried cables and pipelines (Rao and Singh, 1999) necessitate the knowledge of how fine-grained soils, in particular, respond to the thermal stresses. This is mainly because thermal stresses, caused by temperature fluctuation or imposition of the thermal flux, result in volumetric expansion of the soil constituents that lead to development of excess pore-water pressure, Δu_θ, in case of geological formations with low hydraulic conductivity. It has been demonstrated by researchers like Pinyol et al. (2018) that in the case of saturated fine-grained soils, generation of Δu_θ could become critical in scenarios involving conversion of slow-moving landslides into fast-moving ones due to loss in effective stress, σ'. Furthermore, it is interesting to note that the subsequent dissipation of Δu_θ would result in volumetric deformation of the fine-grained soils (Delage et al., 2000; Tawati, 2010) and an increment in σ' could be observed. This concept has been successfully adopted by Abuel-Naga et al. (2007a) in enhancing the performance of pre-fabricated vertical drains for stabilization of the soft Bangkok clay. This phenomenon termed as *thermal consolidation*, involving development of Δu_θ and subsequent volumetric deformation, has been extensively studied with a focus on mechanisms and various influencing factors (viz., thermo-mechanical stress path, over-consolidation ratio, thermal stress history and degree of saturation etc.) that govern the process.

The underlying mechanism of the thermal consolidation phenomena was explained by Campanella and Mitchell (1968) in their pioneering study, which suggested that the differential thermal expansion occurring due to the difference between the volumetric expansion coefficient of soil-solids, α_s, and pore-water, α_w, of the constituents of the soil mass,

* Corresponding author.
E-mail addresses: shettyrakshith@iitb.ac.in (R. Shetty), dns@civil.iitb.ac.in (D.N. Singh), alessio.ferrari@epfl.ch, alessio.ferrari@unipa.it (A. Ferrari).

https://doi.org/10.1016/j.enggeo.2019.03.008
Received 22 October 2018; Received in revised form 8 March 2019; Accepted 13 March 2019
Available online 14 March 2019
0013-7952/

Nomenclature

α	coefficient of thermal expansion.
α_s	volumetric expansion coefficient of soil solids.
α_w	volumetric expansion coefficient of pore-water.
$\alpha_{s\theta}$	volume change coefficient due to structural rearrangement.
A	Area of specimen.
c_c	compression index.
c_r	recompression index.
$c_{s\theta}$	coefficient of secondary compression under thermal stress.
c_v	coefficient of consolidation.
c_α	coefficient of secondary compression under σ_v.
d	settlement.
d_{act}	corrected settlement.
E	modulus of elasticity.
E_r	stiffness.
e	instantaneous voids ratio.
e_o	initial voids ratio.
Δe	change in voids ratio.
Δe_{cum}	cumulative change in voids ratio.
ε_v	total volumetric strain.
ε_{vp}	total volumetric strain due to applied vertical (mechanical) stress.
$\varepsilon_{v\theta}$	volumetric strain due to thermal stress.
$\varepsilon_{v\theta}{}^e$	elastic volumetric strain due to thermal stress.
$\varepsilon_{v\theta}{}^p$	plastic volumetric strain due to thermal stress.
$\varepsilon_{v\theta cum}$	cumulative volumetric strain due to thermal stress.
H	hardness.
H_o	initial specimen height.
ΔH	deformation of specimen.
ΔH_m	correction for setup deformation under applied vertical (mechanical) stress.
ΔH_θ	correction for setup deformation under thermal stress.
I_p	plasticity index.
LVDT	linear variable displacement transducer.
m_v	compressibility of the soil matrix.
μ	dynamic viscosity of water.
η	porosity.
NC	normally consolidated.
OC	over-consolidated.
OCR	over-consolidation ratio.
σ_v	applied vertical stress.
σ'	effective stress.
$\sigma_p{}'$	pre-consolidation stress.
θ	temperature.
θ_{max}	maximum temperature.
$\Delta\theta$	change in temperature (thermal loading).
TC	thermal cycle.
t	time.
Δu	excess pore-water pressure.
Δu_θ	excess pore-water pressure due to thermal stress.
USCS	Unified Soil Classification System.
V	total volume of the soil mass.
ΔV_m	change in volume of the soil mass due to applied vertical (mechanical) stress.
ΔV_θ	change in volume of the soil mass due to thermal stress.
V_s	volume of soil solids.
V_w	volume of water (pore-fluid).
$\Delta V_{s\theta}$	volume change due to structural rearrangement under thermal stress.
w_L	liquid limit.
w_P	plastic limit.

would lead to the development of excess pore-water pressure, Δu_θ, which in turn is the primary cause of *thermal consolidation*. In addition, simultaneous decrease in viscosity, μ, of water observed at higher temperature and structural rearrangement of the soil grains under thermal stresses would also contribute to the variation in the rate and amount of thermal consolidation of the soil mass, respectively. These authors have proposed Eq. 1 for computing Δu_θ of the soil mass, when it is exposed to an incremental change in temperature, $\Delta\theta$.

$$\Delta u_\theta = \frac{[\eta \bullet (\alpha_s - \alpha_w) \bullet \Delta\theta + \alpha_{s\theta} \bullet \Delta\theta]}{m_v} \quad (1)$$

where, η is the porosity, m_v is the compressibility of the soil matrix and $\alpha_{s\theta}$ is a coefficient (refer Eq. 2) that defines structural rearrangement of the grains of the soil mass due to thermal stresses. In a way, $\alpha_{s\theta}$ is analogous to the secondary compression that is defined in the 'mechanical consolidation' of the soils (Campanella and Mitchell, 1968).

$$\alpha_{s\theta} = \left[\frac{(\Delta V_{s\theta}/V)}{\Delta\theta}\right] \quad (2)$$

where, $\Delta V_{s\theta}$ is the volume change incurred due to structural rearrangement of the soil grains due to imposition of $\Delta\theta$ and V is the volume of the soil mass before exposing it to $\Delta\theta$.

However, determination of $\alpha_{s\theta}$ has largely remained elusive owing to the lack of clarity on precise determination of the 'point of initiation'

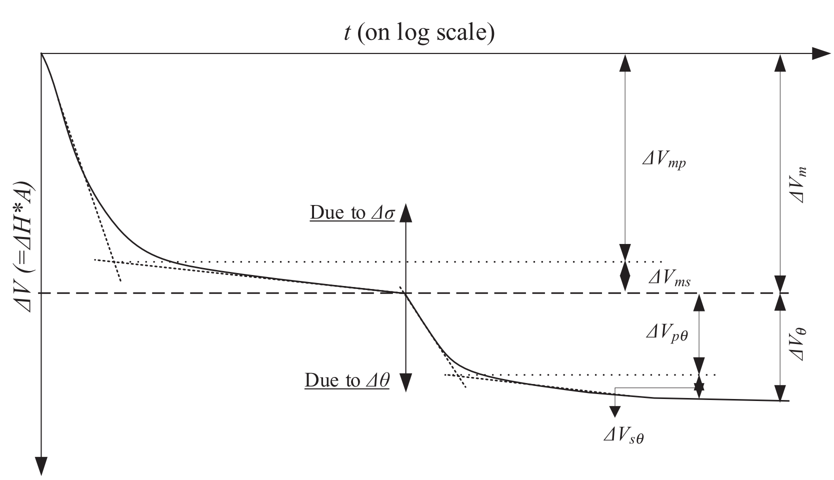

Fig. 1. Schematic representation of *EThIReS* methodology for determination of $\Delta V_{s\theta}$.

of structural rearrangement in the soil mass. This led to uncertainty in quantifying the contribution of the $\Delta V_{s\theta}$ from the total volumetric change, ΔV_θ, of the specimen under thermal stress directly from the deformation-time curves. Hence, more recently, Ghaaowd et al. (2017) have proposed an empirical relationship as given in Eq. 3, to obtain $\alpha_{s\theta}$ as a function of plasticity index, I_p.

$$\alpha_{s\theta} = 0.0001 \cdot e^{-0.014 \cdot I_p} \quad (3)$$

The authors of the above study utilized Δu_θ measured during undrained heating test to back-calculate the $\alpha_{s\theta}$ employing Eq. 1 for different soil types. The $\alpha_{s\theta}$ thus obtained for different soil types were correlated with corresponding I_p to arrive at Eq. (2). However, the measurement of Δu_θ requires additional undrained tests to be conducted with measurement of the pore-water pressure. With this in view, a methodology that facilitates delineation of the contribution of $\Delta V_{s\theta}$ from the deformation-time curve obtained during thermal consolidation has been proposed. Details of this methodology, designated as, Estimation of Thermally Induced Rearrangement of Soils, ***EThIReS***, are presented in Fig. 1. The methodology facilitates direct computation of $\alpha_{s\theta}$, by employing Eq. (2), using deformation-time curve obtained from thermal consolidation test.

Fig. 1 depicts the total volume change, ΔV, with respect to time, t, obtained from the change in specimen height, ΔH, for mechanical, $\Delta\sigma$, and thermal, $\Delta\theta$, loadings. These loadings are responsible for the volumetric changes undergone by the specimen designated as ΔV_m and ΔV_θ, respectively. It should be noted that ΔV_m comprises ΔV_{mp} and ΔV_{ms}, the primary consolidation and the secondary compression, respectively, that can be computed by following the methodology proposed by Casagrande (1936). Interestingly, ΔV_θ versus t trend is found to be similar to ΔV_m versus t trend. This can be attributed, and hypothesized, to the fact that the excess pore-water pressures, Δu_m and Δu_θ, generated due to imposition of $\Delta\sigma$ and $\Delta\theta$, respectively, dissipate in an identical manner. Hence, Casagrande's (1936) approach could be extended to analyze deformation-time curve obtained during thermal consolidation, which can further be divided in to the 'primary consolidation' and 'secondary compression', designated as $\Delta V_{p\theta}$ and $\Delta V_{s\theta}$, respectively. Thus, the new approach to determine secondary compression of the specimen under thermal loading regime, designated as, ***EThIReS*** has been employed for estimating the $\alpha_{s\theta}$, using Eq. (2). The results have been compared and discussed with the $\alpha_{s\theta}$ obtained using Eq. (3).

1.1. Factors influencing volume change characteristics

Although, the primary cause of thermal consolidation phenomena remains the same irrespective of soil types and their stress-state, several influencing factors such as thermo-mechanical stress path, over-consolidation ratio, thermal stress history (i.e., number of thermal cycles) and degree of saturation of the fine-grained soils are known to affect their volume change characteristics, VCC. In this context, initial studies were conducted by employing conventional oedometer and maintaining the temperature of the water bath to establish the effect of elevated temperature on consolidation characteristics of the fine-grained soils by Campanella and Mitchell (1968). These investigations revealed that the pre-consolidation pressure, σ_p', of the fine-grained soils decreases with an increase in temperature. However, the influence of elevated temperature was found to be insignificant on the compression, c_c, and recompression, c_r, indices. Conversely, several studies (Plum and Esrig, 1969) that were conducted to establish the effect of sequential heating and cooling (defined as the 'thermal cycle'), under application of a constant applied vertical stress, σ_v, have reported that when fine-grained soils are heated from 24 °C to 50 °C, the c_c gets significantly (1.24 to 1.40) affected, for $\sigma' < 210$ kPa. The authors have also reported that the specimens of the fine-grained soils when subjected to a 'thermal cycle' exhibit over-consolidated behavior, with an increase in σ'. This phenomena has been termed as 'thermal hardening' by Cui et al. (2000) and Abuel-Naga et al. (2007b). It has also been opined that though the over-consolidation ratio, OCR, generated during the 'thermal cycle', is independent of σ_v, it is a function of the maximum temperature, θ_{max}, to which the specimen is exposed. Furthermore, to establish the role of number of 'thermal cycles' on the volumetric strain, $\varepsilon_{v\theta}$, of the fine-grained soils, Ma et al. (2017) have re-synthesized experimental results obtained by (Campanella and Mitchell, 1968; Di Donna and Laloui, 2015; Vega and McCartney, 2015), and it has been demonstrated that after about 4 to 5 thermal cycles the specimen ceases to exhibit any significant $\varepsilon_{v\theta}$, under a constant σ'.

Further, several studies (Baldi et al., 1988; Cui et al., 2000; Sultan et al., 2002; Abuel-Naga et al., 2007a) have revealed that $\varepsilon_{v\theta}$ is dependent on the OCR of the soil. The normally consolidated, NC, specimen would exhibit irreversible contraction whereas the over-consolidated, OC, specimens would undergo reversible expansion (elastic volumetric strain, $\varepsilon_{v\theta}^e$), when exposed to thermal cycles. In this context, Favero et al. (2016b) have concluded that the soils with $\sigma' < \sigma_p'$ and $\sigma' > \sigma_p'$ when exposed to thermal stress would exhibit elastic and plastic volumetric strains, respectively. In short, the influence of θ_{max}, the number of thermal cycles, and OCR on VCC, of the fine-grained soils has been studied. More recently, studies (Tang et al., 2008; Coccia and McCartney, 2016) have also tried to establish the influence of degree of saturation on the compressibility and shear strength parameters of fine-grained soils subjected to thermal stresses.

However, aforementioned studies deal with behavior of soils subjected to thermal stresses under the influence of specific σ' value, without bringing in the concept of sequential 'thermo-mechanical stresses', STMS, that nature of manmade activities impose on the fine-

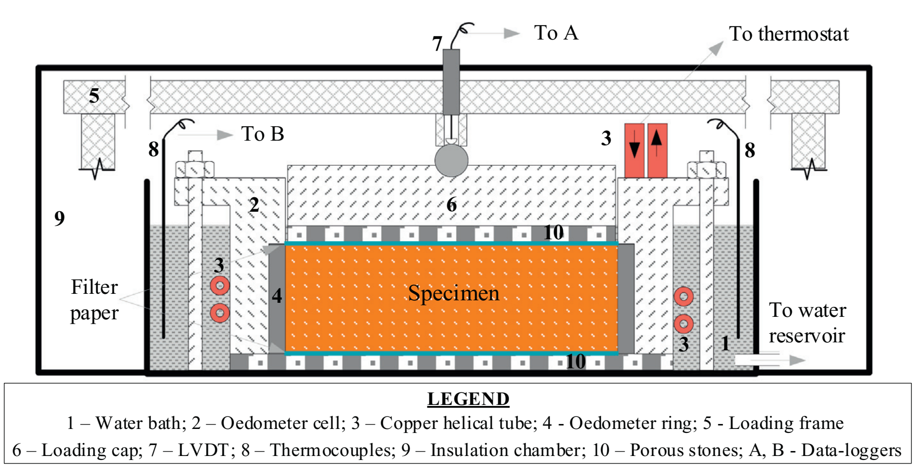

Fig. 2. Schematic of the experimental setup.

grained soils. With this in view, the response of the fine-grained soils to a sequence of alternate thermal and mechanical stress was investigated and its details are presented in this manuscript. The study focusses on the effect of varying σ_v on the $\varepsilon_{v\theta}$ of the specimen upon exposure to thermal cycle. The range of temperature imposed in the thermal cycle comprising heating (from 20 to 60 °C) and cooling (60 to 20 °C) phases has been selected to simulate naturally occurring temperature fluctuations.

2. Experimental setup

The response of fine-grained soils exposed to sequential thermo-mechanical stresses, STMS, has been studied by employing a standard oedometer setup, wherein the specimen temperature is controlled by placing it in the water-bath (unit 1), as depicted in Fig. 2 (Di Donna and Laloui, 2015). As depicted in the figure, the standard oedometer cell (unit 2) is surrounded by two copper helical tubes (unit 3) through which heated fluid (demineralized water) is circulated. The temperature of the heating fluid is controlled using a thermostat (make Huber®, Germany). The water-bath is connected to a water reservoir in order to compensate for the evaporation loss. The specimen (60 mm in diameter and 15 mm height), is prepared in the oedometer ring (unit 4), which is made of *invar*, an alloy of Ni and steel, for which the coefficient of thermal expansion, α, is 5.5×10^{-7} °C. Selection of *invar* as the oedometer ring facilitates negating the relative contraction and expansion with respect to the specimen, during thermal cycle i.e., heating and cooling. The specimen is sandwiched between the top and bottom filter papers and porous stones, as in the case of standard oedometer tests. The mechanical load is applied on the specimen by using a reaction-loading frame (unit 5), which transmits the load to the loading cap (unit 6). The vertical deformations undergone by the specimen are recorded with the help of a linear variable displacement transducer, LVDT, (unit 7), which has a least count of 0.1 μm. The temperature of water in the water-bath is data-logged with the help of two K-type thermocouples (unit 8), of least count of 0.1 °C, as depicted in Fig. 2. The average of the temperatures measured by these thermocouples is considered the temperature of the specimen. Since the pore-fluid and the water bath are inter-connected, and heating of the specimen is through the oedometer ring (unit 4) and cell (unit 2) which are good conductors of heat, it is apparent that the specimen temperature would equilibrate with that of water bath after some initial time lag. The entire setup has been enclosed in a thermally insulated chamber to minimize the heat losses (unit 9).

3. Experimental investigations

In order to establish the influence of sustained thermal and mechanical loads on the volume change characteristics of soils, the specimens were subjected to the sequential thermal and mechanical stresses, STMS, as depicted by the stress-paths in Fig. 3. The isothermal consolidation tests on specimen were conducted at $\theta = 20$ °C to study the effect of STMS on $\varepsilon_{v\theta}$. Thus, the experimental program comprises of two separate thermo-mechanical paths being imposed on the specimen: (i) standard oedometer test, SOT (refer Fig. 3a), wherein the standard consolidation test with loading (from A to B) and unloading phase (from B to C) has been performed at $\theta = 20$ °C, (ii) STMST (refer Fig. 3b), wherein the specimen is mechanically consolidated until 60 kPa (from A″ to B″) at $\theta = 20$ °C, followed by imposition of thermal cycle comprising of heating (B″ to C″) and cooling (C″ to B″). At every temperature increment, $\Delta\theta$, of 10 °C, which is attained at the rate of 2–3 °C/h (Di Donna and Laloui, 2015) to avoid instantaneous generation of high pore-water pressure, the vertical deformation undergone by the specimen was allowed to stabilize before imposing the subsequent $\Delta\theta$. These incremental steps of $\Delta\theta$ are represented by the arrowheads in Fig. 3. The settlement of the specimen after imposition of each $\Delta\theta$ was monitored until the observed changes were minimal (usually for a duration of 24 h). The specimen was further consolidated under $\sigma_v = 125$ kPa (B″ to D″) followed by imposition of a thermal cycle (D″-E″-D″). The process was repeated at 250 kPa (D″-F″ and F″-G″-F″) followed by which the sample was consolidated under a maximum $\sigma_v = 1000$ kPa (depicted as F″-H″).

3.1. Calibration of the setup

It should be realized that various components of the test setup would undergo deformations measured by the LVDT due to $\Delta\sigma_v$ and $\Delta\theta$. Hence, to obtain the *actual* deformations undergone by the specimen, suitable corrections for the setup under mechanical and thermal loadings, ΔH_m and ΔH_θ should be applied, respectively. A stainless steel cylindrical unit with dimensions similar to the specimen, for which the modulus of elasticity, *E,* and α are 210 GPa and $1.2{\cdot}10^{-5}$ °C^{-1}, respectively, was taken as the calibrating specimen. Subsequently, ΔH_m and ΔH_θ were determined for various combinations of thermo-mechanical paths depicted in Fig. 3. Hence, during the specimen runs, the

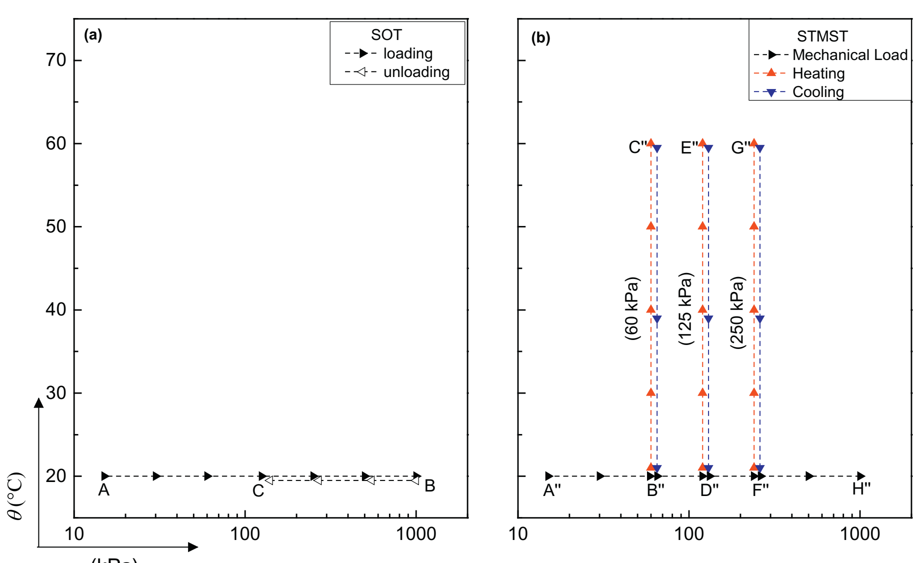

Fig. 3. Various thermo-mechanical paths used in the present study: (a) SOT and (b) STMST.

ΔH_m and ΔH_θ were subtracted from the LVDT measurements of the specimen for obtaining the actual deformation of the specimen.

3.2. Details of the specimen

Two fine-grained soils (naturally occurring terrestrial clay sample, and a kaolinite clay, designated as Soil S1 and S2, respectively), which exhibit low and high plasticity as per Unified Soil Classification System, USCS, (ASTM-D2487, 2017) were used in this study. These soils were characterized to obtain specific gravity, G, Atterberg's Limits, and particle-size distribution characteristics by following the guidelines presented in ASTM-D5550 (2014); ASTM-D4318 (2017); ASTM-D7928 (2017), respectively, and the results are listed in Table 1. Several identical specimens of these soils were prepared for conducting SOT and STMST, as depicted in Fig. 3. The specimen, in the slurry form was prepared by adding the quantity of water equal to 1.65 times the liquid limit, w_L, to the oven-dried soil. Enough care was taken to avoid entrapment of air voids during specimen preparation. The specimen was pre-consolidated to σ' of 30 kPa, (which also ensures saturation) at room temperature, θ, equal to 20 °C to ensure that the loading cap (unit 6) does not get lifted up due to generation of Δu_θ, particularly at the lower magnitude of the applied vertical stress, σ_v.

4. Results and discussion

The following subsections present the results obtained from the study and discusses the effect of sequential thermo-mechanical stress, STMS, path on the volume change characteristics, VCC, of the clays. Also, the computation of the $\alpha_{s\theta}$, by using ***EThIReS*** methodology, and its comparison with that obtained from Eq. (3) is presented.

4.1. Effect of STMS on the VCC

The deformation characteristics, of specimens of Soils S1 and S2, obtained from the SOT and STMST, as volumetric strains, ε_v, are presented in Fig. 4. The TC, in Fig. 4, corresponds to the thermal cycle imposed on the specimen during STMST.

It can be observed from Fig. 4 that for specimens of Soils S1 and S2, during SOT and STMST, as σ' increases the ε_v increases. The steep drop in the ε_v value of the specimen, corresponds to the volumetric strain due to imposition of TC, $\varepsilon_{v\theta}$, applied under a specific σ' (=60, 125 and 250 kPa). The summation of plastic volumetric strains of all the TCs, designated as, $\varepsilon_{v\theta}{}^p$, of specimens of Soils S1 and S2 is equal to 2.90% and 0.86%, respectively, refer Table 2. From Fig. 4, it is interesting to note that the deformation curves of the specimens of the soil, subjected to SOT and STMST eventually coincide. A closer look at the deformation curves of SOT and STMST of both the soils reveal that the slope of the latter in the mechanical loading portion, followed by the application of TCs, is lesser than the corresponding portion of the former. The change in slope in case of the STMST indicates that the compressibility of the specimens subjected to STMS path decreases on exposure to TCs. This could mainly be attributed to the enhancement in stiffness, E_r, and hardness, H, of the soil solids due to exposure to elevated temperatures. This observation gets corroborated with the findings reported by Kadali et al. (2013), who have employed nano-indentation technique to highlight the effect of temperature on E_r and H of various clay minerals and soils. As depicted in Fig. 5, the results for the Soil S2, for the θ range used in the present study, the E_r and H of the specimen increase by ~1.5 and ~3 times that of the values corresponding to the room temperature (Kadali et al., 2013). The contribution of change in E_r and H value of the soil solids on the thermal hardening behavior reported by the several researchers (Plum and Esrig, 1969; Cui et al., 2000; Abuel-Naga et al., 2007b), in addition to the densification of the soil matrix by thermal consolidation, needs to be determined. Such an exercise would reveal the precise magnitude of thermal consolidation in the thermal hardening behavior observed due to increment in σ'.

In addition to the analysis of deformation characteristics, it is also important to know the (i) the nature of $\varepsilon_{v\theta}$ (i.e., reversible (elastic), $\varepsilon_{v\theta}{}^e$, irreversible (plastic), $\varepsilon_{v\theta}{}^p$ or both (elasto-plastic) and (ii) the effect of σ' on $\varepsilon_{v\theta}$. For the sake of brevity, the variation of $\varepsilon_{v\theta}$ due to imposition of TC, during STMST for the Soil S1, only is being depicted in Fig. 6. From Fig. 6, it can be noted that $\varepsilon_{v\theta}$ of the soil consist of elastic- and plastic-volumetric strains, $\varepsilon_{v\theta}{}^e$ and $\varepsilon_{v\theta}{}^p$, which develop due to cooling and heating of the specimen, respectively. The $\varepsilon_{v\theta}$, however, is predominantly irreversible (i.e., having greater plastic component, as reported by Baldi et al., 1988; Cui et al., 2000; Sultan et al., 2002; Abuel-Naga et al., 2007a) for the normally consolidated (NC) state of the soil. Table 2 presents these components of the $\varepsilon_{v\theta}$ for the Soils S1 and S2. The values of the settlement and the resulting strain undergone by the Soil S1 during heating and cooling are listed in Table 3.

From the data presented in Table 2, it can be observed that σ' has little influence on $\varepsilon_{v\theta}$, and for all practical purposes it remains unchanged. Interestingly, this finding is similar to those reported in the literature (Abuel-Naga et al., 2007b), wherein $\varepsilon_{v\theta}$ of different specimens, pre-consolidated to various σ' remains unaltered. Hence, it can be opined that the mechanical loading on these soils, during the STMST, has little significance on $\varepsilon_{v\theta}$ undergone by it for 60 kPa ≤ σ' ≤ 250 kPa. However, this observation needs to be validated for different types of soils when σ' > 250 kPa.

Furthermore, it can be noticed that exposure to a TC, at a particular σ', has no effect on the $\varepsilon_{v\theta}$ undergone by the specimen at subsequent TCs, at a higher σ'. This is contrary to the behavior of the specimen, exposed to repeated TCs under a specific σ', for which a decrease in $\varepsilon_{v\theta}$ for subsequent TCs imposed has been reported Ma et al. (2017). These scenarios have been depicted as Case 1 (TCs imposed under varying σ') and Case 2 (TCs imposed under constant σ') in Fig. 7.

It should be noted that in Case 1, despite the reduced availability of water content, due to mechanical consolidation undergone by the specimen, $\varepsilon_{v\theta}$ remains practically constant under varying σ', as depicted in Fig. 7. This could be attributed to amount of freely available water in pores that would be expelled under the work done by thermal cycle imposition. However, this amount of work done by imposition of identical TC would be insufficient to expel an equivalent amount of water held under attractive forces at the solid-liquid interface (bound water) due to electrostatic forces. Thus, until V_v (i.e., V_w in saturated case) falls below a critical value due to the expulsion of all the available free-water from the pores and only the bound water remains, there would not be any significant change in $\varepsilon_{v\theta}$ for the completely saturated specimens. Furthermore, $\varepsilon_{v\theta}$ is a function of Δu_θ, and Eqs. (1) and (2) indicate that it is dependent on $\Delta V_{s\theta}$. It has been shown through several studies (Campanella and Mitchell, 1968) that repeated application of TC would reduce the extent of $\Delta V_{s\theta}$ in each of the subsequent TC imposition. This would result in a lesser Δu_θ generation, which is responsible for a reduced $\Delta V_{v\theta}$ and $\varepsilon_{v\theta}$, as depicted in Case 2, Fig. 7.

However, in Case 1, the soil matrix is alternatively loaded to a higher σ' after every imposition of TC. This leads to an equivalent scope of structural rearrangement of the specimen due to thermal stresses under the new σ'. Thus, the $\Delta V_{s\theta}$, remains constant under each TC and hence $\varepsilon_{v\theta}$ achieved in the subsequent TC remains unaltered. In other words, STMS erases the effect of a TC on $\varepsilon_{v\theta}$ undergone by the specimen during subsequent TCs.

Table 1
Basic characteristics of the soils used in the study.

Soil	G	Size fraction (%)			w_L (%)	I_p (%)	USCS
		Sand	Silt	Clay			
S1	2.56	01	37	62	64	41	CH
S2	2.64	00	55	45	48	24	CL

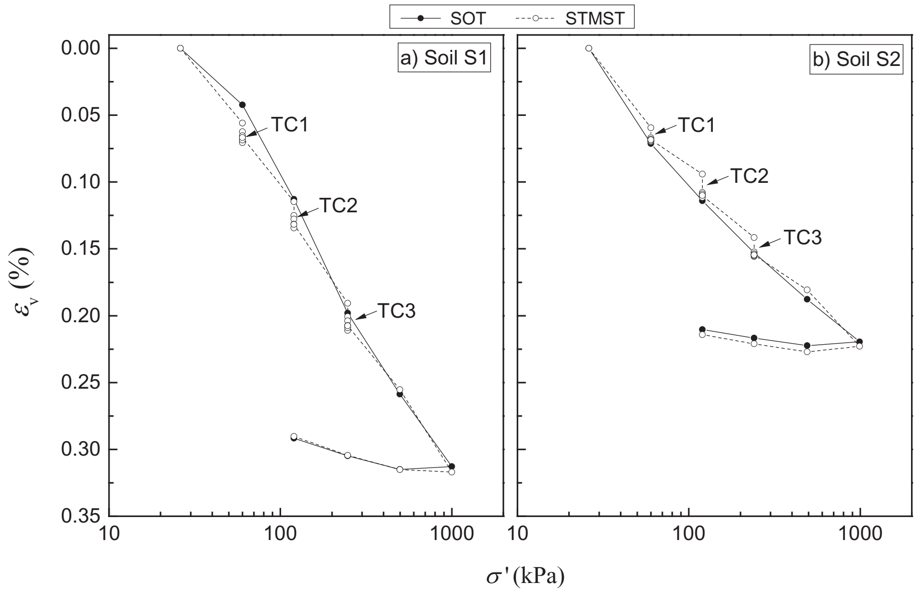

Fig. 4. Deformation characteristics of the specimens of (a) Soil S1 and (b) Soil S2.

Table 2
The values of elastic and plastic volumetric strains (in %) for different soils.

Thermal cycle	Soil S1			Soil S2		
	$\varepsilon_{v\theta}^{e}$	$\varepsilon_{v\theta}^{p}$	$\varepsilon_{v\theta}$	$\varepsilon_{v\theta}^{e}$	$\varepsilon_{v\theta}^{p}$	$\varepsilon_{v\theta}$
TC1 (60 kPa)	0.38	0.84	1.22	0.15	0.31	0.46
TC2 (125 kPa)	0.27	0.97	1.24	0.14	0.30	0.44
TC3 (250 kPa)	0.36	1.09	1.45	0.12	0.25	0.37

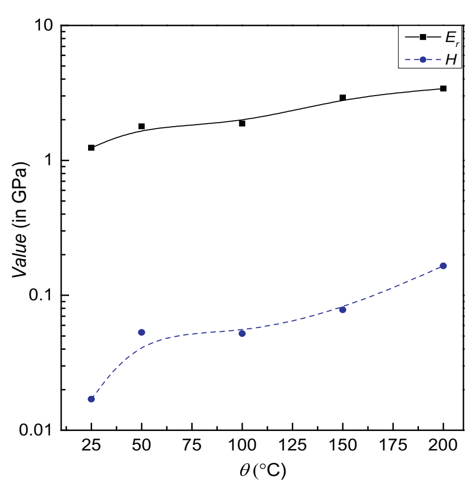

Fig. 5. The variation of stiffness (E_r) and hardness (H) of the white clay (S2) with temperature (Kadali et al., 2013).

4.2. Determination of $\alpha_{s\theta}$by employing EThIReS

The volume change coefficient of structural rearrangement, $\alpha_{s\theta}$, has been computed for Soils S1 and S2, by employing ***EThIReS*** methodology, as described in Section 1 (refer to Fig. 1). The methodology involves determination of volume change during the secondary consolidation process under thermal loading, $\Delta V_{s\theta}$, from deformation versus time curves by extending the Casagrandes' approach. The deformation versus time curves of Soil S1 are depicted in Fig. 8a during the imposition of first TC under σ' of 60 kPa. For the sake of brevity, the computation of $\Delta V_{s\theta}$ (= $\Delta H_{s\theta}$ × A, where A is the area of cross-section of the specimen) from the deformation versus time curve is briefed for the final temperature increment, $\Delta\theta_4$, in Fig. 8. For the deformation versus time curves terminating before 24 h, or for the ones extending beyond 24 h, the $\Delta V_{s\theta}$ corresponding to 24 h was determined by using the coefficient of secondary consolidation for thermal stress, $c_{\alpha\theta}$, of the corresponding $\Delta\theta$ step. Thus twelve values of $\Delta V_{s\theta}$, corresponding to four $\Delta\theta$ steps for each of the three σ' (=60, 120 and 250 kPa) were obtained from which $\alpha_{s\theta}$ for each soil was computed by employing Eq. (2). The average of the so obtained $\alpha_{s\theta}$ was considered as the representative value of the soil, which has been further compared with those obtained by using Eq. (3) (refer to Table 4).

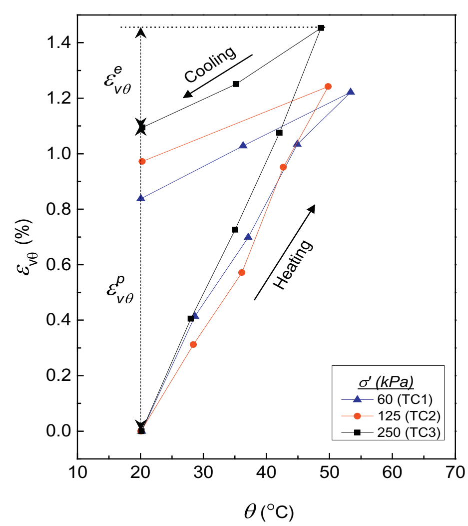

Fig. 6. The variation of volumetric strain with temperature for Soil S1.

As depicted in Table 4, contrary to the Soil S1, the $\alpha_{s\theta}$ value for the Soil S2 exhibits a good match with that obtained from Eq. (3). However, it is worth noticing that as Soil S1 is more compressible (c_c = 0.49) when compared to Soil S2 (c_c = 0.26), and would exhibit a higher $\varepsilon_{v\theta}$, as depicted in Table 2, and hence a higher $\alpha_{s\theta}$. This leads to a discussion on the validity of Eq. (3), which indicates that $\alpha_{s\theta}$ is only dependent on I_p. It should be realized that I_p being an index property would not include in it the characteristics of the soil matrix and fabric (Gumaste et al., 2014), which in turn gets influenced by the imposed thermal

Table 3
The settlement and strain values due to TC1 on the Soil S1.

θ (°C)	$\Delta\theta$ (°C)	ΔH_m (mm)	ΔH_θ (mm)	d (mm)	d_{act} (mm)	H (cm)	e	Δe	Δe_{cum}	$\varepsilon_{v\theta}$ (%)	$\varepsilon_{v\theta cum}$ (%)
20.2	0.0	0.13	0	4.38	4.25	0.980	1.433	0.000	0.000	0.00	0.00
28.6	8.4	0.13	0.03	4.45	4.29	0.976	1.422	0.011	0.011	0.41	0.41
37.1	8.5	0.13	0.04	4.50	4.32	0.973	1.415	0.007	0.018	0.28	0.70
44.9	7.8	0.13	0.06	4.55	4.36	0.969	1.406	0.009	0.027	0.34	1.03
53.4	8.5	0.13	0.08	4.59	4.38	0.967	1.402	0.005	0.032	0.19	1.22
36.3	−17.1	0.13	0.04	4.53	4.36	0.969	1.407	−0.005	0.027	−0.19	1.03
20.1	−16.2	0.13	0.01	4.48	4.34	0.971	1.412	−0.005	0.022	−0.19	0.84

where, d is the settlement; d_{act} is the corrected settlement; e is the instantaneous voids ratio; e_0 is the initial voids ratio (=1.584 at 30 kPa); Δe is the change in the voids ratio; Δe_{cum} is the cumulative change in Δe; $\varepsilon_{v\theta}$ is the volumetric strain (in %) due to thermal loading; $\varepsilon_{v\theta cum}$ is the cumulative volumetric strain. The values in the first row correspond to the completion of mechanical consolidation under σ' = 60 kPa at room temperature (= 20.2 °C).

stresses. Hence, though out of the scope of this study, extensive investigations on different types of soils, compacted to different matrix, should be conducted to modify $\alpha_{s\theta}$ and I_p relationship, which would facilitate a quick and accurate determination of Δu_θ, without resorting to elaborate testing protocols.

5. Concluding remarks

Efforts have been made to understand the effect of sequential thermo-mechanical stress, STMS, on the volume change characteristics of the fine-grained soils. Based on the study, it can be opined that the volumetric strain of the soil mass due to thermal stress is independent of the thermal history that has been defined as number of thermal cycles, TCs, experienced by the specimen when it is imposed at different effective stresses (σ' ranging from 60 to 250 kPa). Although, the results of STMS path exhibit a similar value of thermal volumetric strain, at different σ', it did not result in substantial additional consolidation of the specimen (as the cumulative plastic strain, $\varepsilon_{v\theta}^{P}$, is about 2.90%), which is majorly due to the stiffening and hardening of the soil solids (grain minerals) subjected to elevated temperatures. Study to this extent needs to be carried out to quantify the effect of stiffening of various soil minerals and their role in reducing the efficacy of thermal volume change of the specimen. In addition, this study successfully demonstrates the utility of the methodology ***EThIReS*** for enabling a simple and direct way for computing the volume change coefficient of structural rearrangement, $\alpha_{s\theta}$, from the deformation versus time curve. However, the study reveals that extensive investigations should be conducted on different types of soils, compacted to different matrix, so that a better $\alpha_{s\theta}$ and I_p relationship could be developed. It is believed that such an improvement of Eq. (3) would facilitate a quick and accurate determination of Δu_θ, without resorting to elaborate testing protocols.

Declarations of interest

None

Acknowledgment

The present study is an outcome of the collaboration between Environmental Geotechnology Laboratory, Department of Civil Engineering, Indian Institute of Technology Bombay, India, and Laboratory of Soil Mechanics, Swiss Federal Institute of Technology, Lausanne, Switzerland under the GREAT project (FP7 Marie Curie

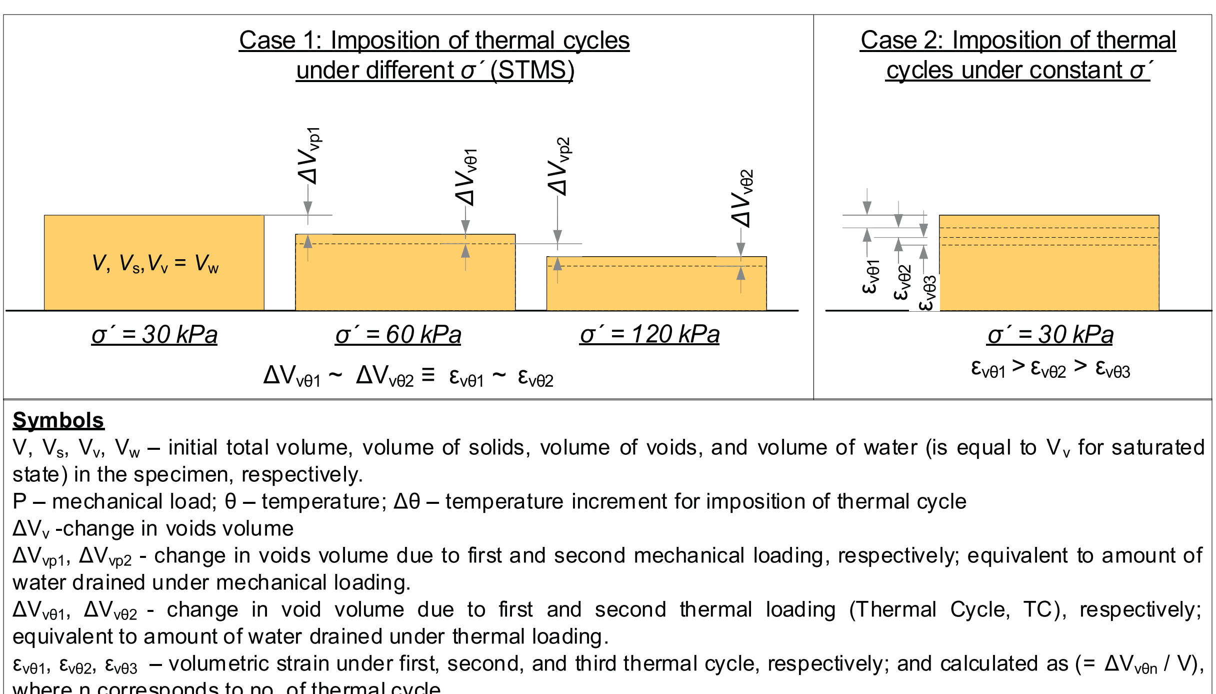

Fig. 7. Representation of volumetric strains under thermo-mechanical loadings.

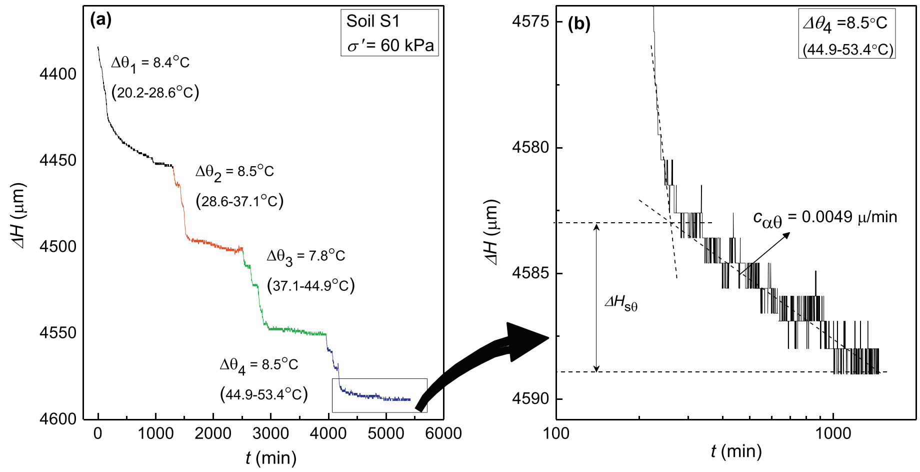

Fig. 8. Deformation versus time characteristics for the Soil S1 subjected to STMST.

Table 4
Comparison of the values of $\alpha_{s\theta}$ obtained from Eq. (3) and *EThIReS*.

Specimen	$\alpha_{s\theta}$ ($\times 10^{-5}$ °C^{-1})	
	From Eq. (3)[a]	*EThIReS*
Soil S1	5.60	34.10
Soil S2	7.15	7.45

[a] (Ghaaowd et al., 2017).

International Research Staff Exchange Scheme program) funded by the European Commission (vide Grant Agreement PIRSES-GA-2013-612665).

References

Abuel-Naga, H.M., Bergado, D.T., Bouazza, A., 2007a. Thermally induced volume change and excess pore water pressure of soft Bangkok clay. Eng. Geol. 89, 144–154. https://doi.org/10.1016/j.enggeo.2006.10.002.

Abuel-Naga, H.M., Bergado, D.T., Bouazza, A., Ramana, G.V., 2007b. Volume change behaviour of saturated clays under drained heating conditions: experimental results and constitutive modeling. Can. Geotech. J. 44, 942–956. https://doi.org/10.1139/t07-031.

ASTM-D2487, 2017. Classification of Soils for Engineering Purposes (Unified Soil Classification System). *American Society for Testing and Materials*, Pennsylvania, United States.

ASTM-D4318, 2017. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. *American Society for Testing and Materials*, Pennsylvania, United States.

ASTM-D5550, 2014. Standard Test Method for Specific Gravity of Soil Solids by Gas Pycnometer. *American Society for Testing and Materials*, Pennsylvania, United States.

ASTM-D7928, 2017. Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis. *American Society of Testing and Materials*, Pennsylvania, United States.

Baldi, G., Hueckel, T., Pellegrini, R., 1988. Thermal volume changes of the mineral–water system in low-porosity clay soils. Can. Geotech. J. 25, 807–825. https://doi.org/10.1139/t88-089.

Campanella, R.G., Mitchell, J.K., 1968. Influence of temperature variations on soil behaviour. J. Soil Mech. Found. Div. 94, 609–734.

Casagrande, 1936. Determination of the preconsolidation load and its practical significance. In: *Proceedings of the International Conference on SMFE* Harvard University, pp. 60–64 Cambridge, MA.

Coccia, C.J.R., McCartney, J.S., 2016. Thermal volume change of poorly draining soils I: critical assessment of volume change mechanisms. Comput. Geotech. 80, 26–40. https://doi.org/10.1016/j.compgeo.2016.06.009.

Cui, Y.J., Sultan, N., Delage, P., 2000. A thermomechanical model for saturated clays. Can. Geotech. J. 37, 607–620.

Delage, P., Sultan, N., Cui, Y.J., 2000. On the thermal consolidation of Boom clay. Can. Geotech. J. 37, 343–354.

Di Donna, A., Laloui, L., 2015. Response of soil subjected to thermal cyclic loading: experimental and constitutive study. Eng. Geol. 190, 65–76. https://doi.org/10.1016/j.enggeo.2015.03.003.

Di Donna, A., Ferrari, A., Laloui, L., 2016. Experimental investigations of the soil–concrete interface: physical mechanisms, cyclic mobilization, and behaviour at different temperatures. Can. Geotech. J. 53, 659–672. https://doi.org/10.1139/cgj-2015-0294.

Favero, V., Ferrari, A., Laloui, L., 2016a. On the hydro-mechanical behaviour of remoulded and natural Opalinus Clay shale. Eng. Geol. 208, 128–135. https://doi.org/10.1016/j.enggeo.2016.04.030.

Favero, V., Ferrari, A., Laloui, L., 2016b. Thermo-mechanical volume change behaviour of Opalinus Clay. Int. J. Rock Mech. Min. Sci. 90, 15–25. https://doi.org/10.1016/j.ijrmms.2016.09.013.

Ghaaowd, I., Takai, A., Katsumi, T., McCartney, J.S., 2017. Pore water pressure prediction for undrained heating of soils. Environ. Geotech. 4, 70–78. https://doi.org/10.1680/jenge.15.00041.

Gumaste, S.D., Iyer, K.R., Sharma, S., Channabasavaraj, W., Singh, D.N., 2014. Simulation of fabric in sedimented clays. Appl. Clay Sci. 91-92, 117–126. https://doi.org/10.1016/j.clay.2014.01.011.

Jacinto, A.C., Ledesma, A., 2017. Thermo-hydro-mechanical analysis of a full-scale heating test. Environ. Geotech. 4, 123–134. https://doi.org/10.1680/jenge.15.00049.

Kadali, S., Sharma, S., Singh, D.N., 2013. Application of nanoindentation to establish influence of heat on soils. Eng. Geol. 162, 14–21. https://doi.org/10.1016/j.enggeo.2013.05.004.

Laloui, L., Ferrari, A.E., 2013. Multiphysical Testing of Soils and Shales. Springer, Berlin, Heidelberg.

Ma, Q.J., Ng, C.W.W., Mašín, D., Zhou, C., 2017. An approach for modelling volume change of fine-grained soil subjected to thermal cycles. Can. Geotech. J. 1–6. https://doi.org/10.1139/cgj-2016-0459.

Pinyol, N.M., Alvarado, M., Alonso, E.E., Zabala, F., 2018. Thermal effects in landslide mobility. Geotechnique 68, 528–545. https://doi.org/10.1680/jgeot.17.P.054.

Plum, R.L., Esrig, M.I., 1969. Some Temperature Effects on Soil Compessibility and Pore Water Pressure. Highway Research Board, The National academy of sciences, U.S.A., pp. 231–242 (Highway Research Board Special Report, Issue (103)).

Rao, M.V.B.B.G., Singh, D.N., 1999. A generalized relationship to estimate thermal resistivity of soils. Can. Geotech. J. 36, 767–773.

Romero, E., Villar, M.V., Lloret, A., 2005. Thermo-hydro-mechanical behaviour of two heavily overconsolidated clays. Eng. Geol. 81, 255–268. https://doi.org/10.1016/j.enggeo.2005.06.011.

Sultan, N., Delage, P., Cui, Y.J., 2002. Temperature effects on the volume change behaviour of Boom clay. Eng. Geol. 64, 135–145.

Tang, A.M., Cui, Y.J., Barnel, N., 2008. Thermo-mechanical behaviour of a compacted swelling clay. Geotechnique 58, 45–54. https://doi.org/10.1680/geot.2008.58.1.45.

Tawati, A.E., 2010. Impact of the Rate of Heating on the Thermal Consolidation of Compacted Silt. Master of Science, University of Colorado.

Vega, A., McCartney, J.S., 2015. Cyclic heating effects on thermal volume change of silt. Environ. Geotech. 2, 257–268. https://doi.org/10.1680/envgeo.13.00022.

Zhang, C., Rothfuchs, T., 2004. Experimental study of the hydro-mechanical behaviour of the Callovo-Oxfordian argillite. Appl. Clay Sci. 26, 325–336. https://doi.org/10.1016/j.clay.2003.12.025.