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Thermo-elasto-plasticity and thermo-mechanical creep for energy pile systems

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In this study, a newly developed rate-dependent thermo-plastic constitutive model was enhanced to incorporate thermally accelerated creep and implemented into the Plaxis finite-element code, enabling the simulation of the behaviour of a well-instrumented energy pile in multilayered soft soils under thermomechanical loads. First, the model was validated against non-isothermal laboratory tests on soils surrounding the pile, and then against simulations of field tests. The results revealed that the inclusion of thermally accelerated creep improves the prediction of irreversible pile settlement, which is primarily attributed to the accumulation of volumetric contraction in the surrounding soil after each thermal cycle. The analysis also distinguishes between drag down effects resulting from thermo-elastic and thermo-plastic behaviour, as well as those induced by long-term creep.

KEYWORDS: elasticity; energy piles; numerical modelling; plasticity; thermal creep; thermal effects

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INTRODUCTION

In energy piles, the pile and the surrounding soils experience temperature change due to the heat exchange process, which may result in deformations. Experimental studies by McCartney & Murphy (2017) and Rafai *et al.* (2024b) have shown that thermal cycles affect the volumetric behaviour of surrounding soil, imposing additional drag down effects on the pile. Field and laboratory tests have shown that thermal cycles induce irreversible pile head settlement (Yavari *et al.*, 2014a, 2016; Nguyen *et al.*, 2017; Ng *et al.*, 2021; Fang *et al.*, 2022; Rafai *et al.*, 2024a, 2025a, 2025b, 2026c; Qiu *et al.*, 2025).

To account for the thermal elasticity-plasticity of soils, a handful of numerical investigations of energy piles used advanced constitutive models (Di Donna & Laloui, 2015a; Vieira & Maranha, 2017; Iodice *et al.*, 2023; Ng *et al.*, 2024; Rafai *et al.*, 2026a, 2026b). In addition, Tsutsumi & Tanaka (2012), Coccia & McCartney (2016a), and Kaddouri *et al.* (2019) confirmed that thermal loads accelerate creep. As the viscous flow of the soil skeleton is primarily responsible for any secondary deformations, Coccia & McCartney (2016b) formulated in a model that elevated temperatures would accelerate secondary behaviour and used this to describe the volume change response of a laboratory test during monotonic heating and a single heating–cooling cycle.

To assess the validity of constitutive models for the simulation of energy piles, validation against field tests is paramount (Rafai *et al.*, 2022). Ng *et al.* (2024) showed that a thermo-plastic model provided a closer representation of laboratory observations than the modified cam clay (MCC) model, underscoring the importance of using advanced constitutive formulations for thermo-mechanical problems. Rafai *et al.* (2026a) implemented the anisotropic visco ISA model with temperature enhancement (AVISA-T) in Plaxis and achieved significantly improved agreement with field data compared to both the original AVISA model (without thermal effects) and MCC.

The AVISA model, initially developed by Tafili & Triantafyllidis (2020), integrates a hypoplastic framework with the intergranular strain anisotropy concept introduced by Fuentes & Triantafyllidis (2015) and Fuentes *et al.* (2018). It has been extensively validated in elemental and finite-element simulations of various geotechnical structures under small and large strain conditions (e.g. Staubach *et al.*, 2022; Tafili *et al.*, 2023a, 2023b, 2024; Dao *et al.*, 2024, 2025). Recently, the model was extended by Tafili *et al.* (2023c), Ashrafi *et al.* (2025), and Tafili (2025) to incorporate the influence of temperature on the mechanical behaviour of fine-grained soils under both monotonic and cyclic thermal and mechanical loading conditions, leading to the AVISA-T formulation.

Using the AVISA-T model (with a class A prediction), good general responses of the pile behaviour were shown, yet quantitative differences were observed between the modelled and measured data (Rafai *et al.*, 2026a). Similar discrepancies between simulations and experimental results were also reported by Ng *et al.* (2024). These deviations were attributed to thermally accelerated creep, ratcheting at the pile–soil interface (as observed in laboratory tests by Rafai *et al.* (2024b)) or a combination of both phenomena. The extent to which thermally accelerated creep contributes to these deviations remains unclear.

Such time-dependent processes may occur concurrently with other thermally induced mechanisms, such as deformations due to temperature changes, for example, thermal expansion; the impact of temperature on the preloading surface, for example, thermal collapse; thermo-elasto-plastic behaviour arising from physico-chemical interactions between fine-grained particles and grain rearrangement or other system mechanisms due to coupled thermo-mechanical loads in long term. Therefore, it is essential to

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consider all these thermally induced phenomena for reasonable simulation of energy pile response. Such mechanisms have not previously been captured within a single constitutive framework. This provided the motivation for the present work, in which a systematic analysis is performed to disentangle their individual contributions. To enable this, the AVISA-T model is extended by introducing a thermal component that accounts for the temperature-dependent acceleration of creep during thermal cycling, called here the AVISA-TC model. After calibration and validation, the enhanced model is used to evaluate the relative significance of each mechanism in governing the thermo-mechanical response of energy piles.

FIELD TEST AND NUMERICAL MODELING

Field tests were carried out on a 10·3 m long, 380 mm dia. displacement-cast in situ energy pile. Detailed information on the pile installation and testing procedures is provided by Rafai *et al.* (2024b). The energy pile was embedded in five soil layers: made ground 0–2 m, peat 2–4·1 m, silty sand 4·1–7·6 m, clay 7·6–8·7 m, and sand 8·7–12 m. Extensive instrumentation was used to assess the impact of thermal loads on the pile's thermomechanical performance.

A two-dimensional finite-element model was developed to represent a single pile with a uniform radius of 0·19 m and a length of 10·3 m, embedded in a multilayered soil domain. The model is considered to be axisymmetric, and the domain extends 31 m in depth and 15 m radially from the pile centre, sufficiently large to minimise boundary effects. The computational domain is discretised into 19 180 15-node triangular elements, with a refined mesh near the pile–soil interface to capture stress concentrations.

The pile was modelled as a non-porous, isotropic linear elastic material. The surrounding soils were represented using the anisotropic visco-ISA model with temperature (AVISA-T), incorporating several enhancements, and implemented into the Plaxis finite-element framework.

As the field tests focused on cooling followed by natural heating, the applied model is considered suitable for both soil types under the intended conditions. During cooling, both clays and sands exhibit contraction (Di Donna & Laloui, 2015b; Ng *et al.*, 2019; Pei *et al.*, 2022; Rafai *et al.*, 2024b, 2025c). Moreover, the model parameters can be adjusted to prevent the thermal collapse observed in clays during heating, ensuring appropriate behaviour for sands, that is only heating-induced expansion. During cyclic thermal loads, the model would track the thermally induced irreversible contraction, both small (sand) and large (clay) magnitudes. Further details are provided by Rafai *et al.* (2026a).

The overall thermomechanical equation of the model reads:

$$\dot{\boldsymbol{\sigma}} = m\mathbf{E}\colon \left[(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{TE}) - y_h Y \|\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{TE}\| \mathbf{m} - \frac{I_V \lambda(T)}{t_0} \left(\frac{1}{OCR(T)} \right)^{\frac{1}{I_V}} \mathbf{m} - \dot{\boldsymbol{\varepsilon}}^{TP} \right] \tag{1}$$

relating the rate of stress $\dot{\boldsymbol{\sigma}}$ with the total rate of strain $\dot{\boldsymbol{\varepsilon}}$.

The tangent hypoelastic stiffness tensor is denoted by $\mathbf{E}$, while the thermoelastic and thermoplastic strain rates are represented by $\dot{\boldsymbol{\varepsilon}}^{TE}$ and $\dot{\boldsymbol{\varepsilon}}^{TP}$, respectively. The scalar functions m and y_h depend on the intergranular strain and serve to increase the stiffness and reduce the plastic strain rate during load reversals, thus accounting for cyclic loading effects (i.e. they are not parameters, please see Tafili & Triantafyllidis (2020) for details). The degree of non-linearity Y (which is a function of state variables and not a parameter) governs the intensity and non-linearity of the plastic strain rate, and $\mathbf{m}$ defines the direction of plastic flow. The temperature-dependent compression index is denoted by:

$$\lambda(T) = \lambda + l_T \cdot \log\left(\frac{T}{T_{ref}}\right) \tag{2}$$

where λ is the compression index at the reference temperature T_{ref}, while l_T is a material parameter governing the temperature dependence of the compression index. OCR(T) is the temperature-dependent overconsolidation ratio. In addition, t_0 refers to the reference time, and I_V is the viscosity index. In both AVISA and the original AVISA-T models, I_V was treated as a constant.

In the present work, thermally accelerated creep is incorporated into the model by introducing a temperature-dependent viscosity index:

$$I_V(T) = I_V + I_{VT} \cdot \log\left(\frac{T}{T_{ref}}\right) \tag{3}$$

where I_{VT} controls the sensitivity of creep to temperature. This modification is referred to as the AVISA-TC model in the subsequent analyses. For comparison, the same temperature-dependent viscosity formulation was also introduced into the original AVISA model (without the inclusion of thermo-plasticity), which is noted as AVISA-C in the following figures. Of note, in the present model, temperature-induced creep acceleration enters through a viscosity index, thus affecting only the creep component, while the thermal plasticity and mechanical creep are treated separately. In contrast, existing studies such as by Coccia & McCartney (2016b) introduce temperature effects by scaling the secondary compression index, treating thermal volumetric change as thermally enhanced secondary creep without distinguishing instantaneous thermal plasticity from time-dependent creep, and requiring the explicit identification of the end of primary consolidation as the reference state.

The extensions introduced here therefore allow the model to distinguish creep driven solely by mechanical loading from those accelerated by elevated temperatures. The pile–soil interaction in the finite element model was represented by a rigid contact (Yavari *et al.*, 2014b). The calibrated material parameters for surrounding soils during cyclic thermal load under oedometer conditions and pile are summarized in Tables 1 and 2, respectively; further details can be found in Rafai *et al.* (2026a, 2026b).

VERIFICATION OF SOIL CONSTITUTIVE MODEL – ELEMENT TEST

Figure 1(a) shows the evolution of volumetric strain with temperature for different variants of the proposed AVISA framework compared with experimental measurements on a clay sample reported by Rafai *et al.* (2026a). Positive and negative values correspond to compressive and expansive volumetric strains, respectively. The measured data are plotted as dashed blue lines, while the simulations are presented for several configurations: AVISA-TC including visco-plastic and thermo-visco-plastic (including thermally accelerated creep) effects (red), AVISA-T with visco-plastic and thermo-plastic effects (magenta), AVISA-T with purely thermo-plastic effects (black), AVISA-C with thermo-visco-plastic effects only (orange), AVISA with visco-plastic effects only (grey), and AVISA without time-dependent contributions (green). The results highlight that the combined visco-plastic and thermo-visco-plastic formulation (AVISA-TC) reproduces the measured thermo-mechanical response most accurately. At the

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Table 1. Model parameters

Model	Parameters	Made ground	Peat	Silty sand	Clay	Sand
Thermo-mechanical model (AVISA-T)	λ	2·0	2·0	0·07	0·095	0·063
	κ	0·3	0·3	0·011	0·03	0·0099
	ν	0·3	0·3	0·25	0·25	0·21
	e_{i0}	7·5	7·5	0·8	1·4	0·75
	φ_c	27.0	23	28	23	31
	n_T	0·02	0·02	0·03	0·03	0·03
	l_T	0·011	0·011	0·011	0·011	0·011
	γ_T	5·0	5·0	5·0	5·0	5·0
	I_V	0·02	0·02	0·02	0·02	0·02
	I_{VT}	0·02	0·02	0·02	0·02	0·02
Thermal terms (Plaxis)	c in MJ/(m^3·K)	1·52	0·89	2·8	2·5	2·4
	k_T in W/(m·K)	1·12	0·54	1·6	1·35	1·9
	α_s in (1/°K)	4×10^{-6}	4×10^{-6}	18×10^{-6}	6.6×10^{-6}	20×10^{-6}

Table 2. Model parameters for the concrete pile

Model terms	Parameter	Value
Mechanical terms	E in GPa	41
	ν	0·2
Thermal terms	c in MJ/(m^3·K)	1
	k_T in W/(m·K)	2·1
	α_s in 1/°K	10.71×10^{-6}

same time, AVISA-T (magenta) yields a similar accumulated volumetric strain after six cycles, indicating that thermo-plasticity governs the long-term strain accumulation, while the additional creep contribution mainly influences the early cyclic response. Figure 1(b) illustrates the influence of I_{VT} on the volumetric strain response. To match the experimental measurements, I_{VT} was calibrated to a value of 0·02. In the following section, the effect of varying this parameter and the corresponding implications for the thermo-mechanical response of energy piles are examined.

ENERGY PILE RESULTS

In both the field tests and the numerical simulations, the pile was first loaded to a target of 211 kN. The applied mechanical load was then held constant for 16 h to minimise mechanical creep effects before subjecting the system to ten cooling–natural heating cycles under constant load, as shown in Fig. 2. For the simulations, the measured pile temperatures from the field were directly imposed through prescribed thermal boundary conditions. The initial temperature of the pile and surrounding soil was assumed undisturbed and uniformly set to 12°C.

Figure 3 presents the evolution of irreversible pile head settlement with increasing number of cycles. To disentangle the contributions of mechanical loading, thermal creep, thermoelastic, and thermoplastic effects to the observed permanent thermally induced displacements, simulations were carried out using the different variants of the proposed models.

The AVISA-T (magenta) and AVISA-TC (red) models with active time-dependent mechanisms realistically reproduce the overall energy pile behaviour, with AVISA-TC showing superior performance. By contrast, AVISA (green

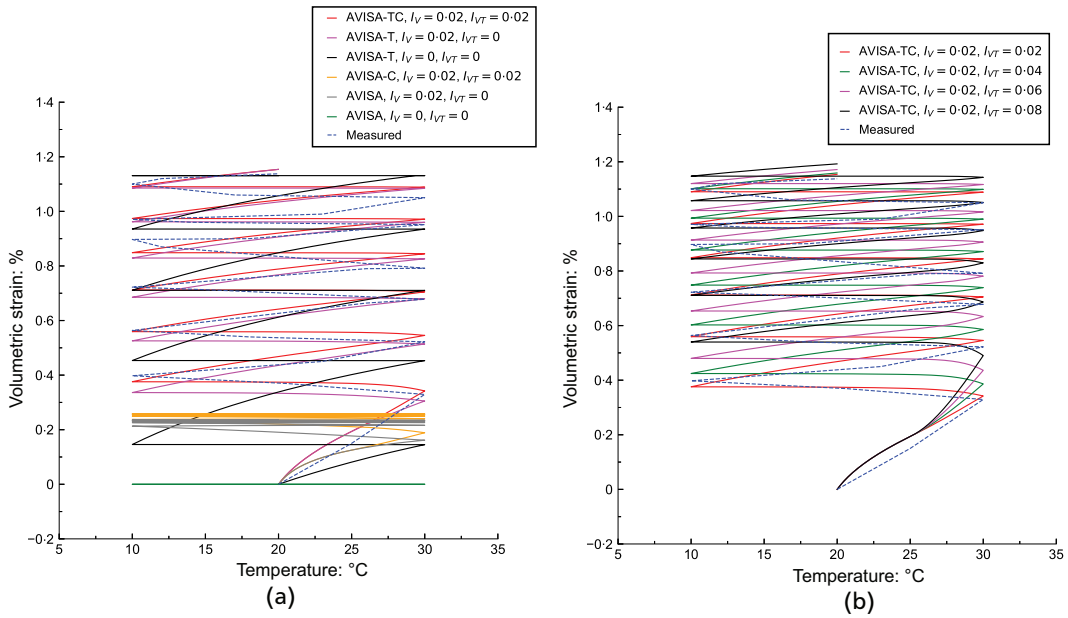


Fig. 1. Comparison of measured and computed thermally induced strain in a clay specimen under heating and cooling cycles: (a) using different models' enhancements; (b) using AVISA-TC with different I_{VT} values. Experimental reference: Rafai *et al.* (2026a)

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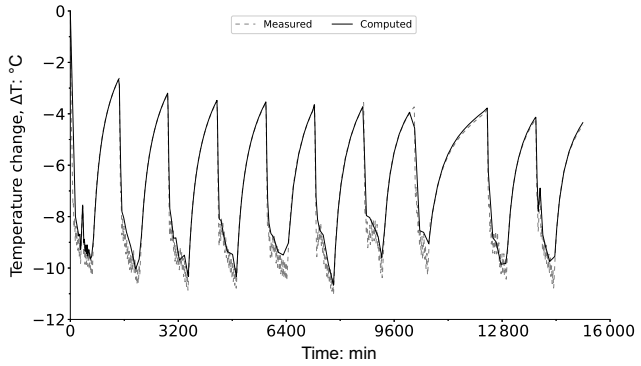


Fig. 2. Measured and computed temperature change in the pile

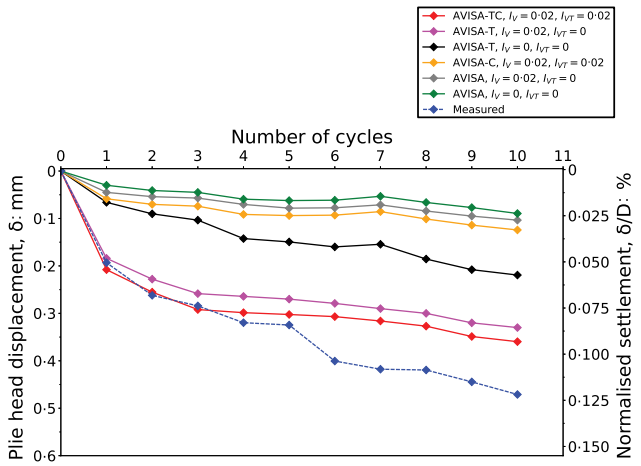


Fig. 3. Computed and measured pile head displacement versus number of thermal cycles

and grey) and AVISA-C (orange) significantly underestimate the response under thermal cycling. The higher settlements predicted by AVISA-T (black) (without mechanical creep, that is $I_V = 0$) compared to results by AVISA (with and without creep) (grey and green) further emphasise the dominant role of thermoplasticity in energy pile performance. The lowest settlement was predicted by AVISA (without mechanical creep, that is, $I_V = 0$) (green) which could be largely due to accumulation of cooling effects. No model was able to reproduce the increase in head displacement at the 5th cycle, which is likely due to ratcheting at the interface.

To further investigate the performance of AVISA-TC, Fig. 4 presents additional pile test simulations conducted with different values of I_{VT}. The results indicate that increasing thermally accelerated creep leads to larger initial pile head settlements, causing the model to overestimate the response compared to the field measurements, particularly during the first two cycles. However, in the subsequent cycles, the modelled settlement rate becomes lower than the measured response. This trend aligns with the observations on element tests (see Fig. 2(b)). The key point explaining this behaviour is that the creep rate decreases exponentially with increasing overconsolidation ratio (OCR). At the beginning of loading, the soil is modelled to be in a normally consolidated state (clays) or relatively loose state (sands) and therefore exhibits a relatively high viscous strain rate, but as deformation progresses, densification increases the OCR and relative density and rapidly suppresses creep, so the observed "strong short-term

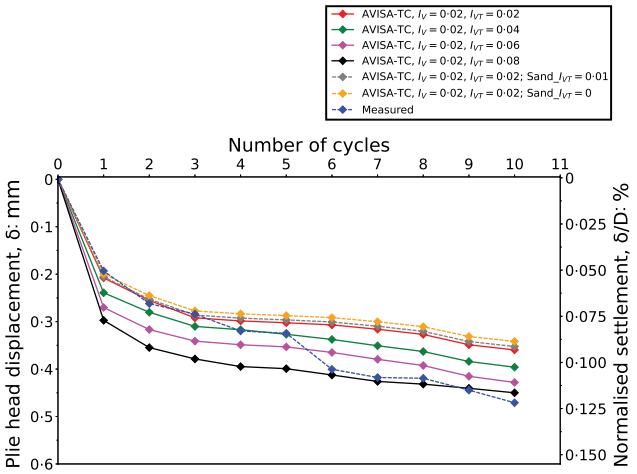


Fig. 4. The influence of I_{VT} on the thermally induced irreversible pile head settlement in all soil layers and in sandy layer

creep" reflects this NC-to-OC or loose-to-dense transition. According to the analysis in Fig. 4, thermally accelerated creep in the sandy layer has only a minor effect, likely due to the limited embedment depth of the pile in this layer.

In the field (blue curve in Fig. 4), displacements increase uniformly until the fifth cycle, after which a sudden increase in the settlement rate is observed between cycles 5 and 6. This sudden acceleration is likely linked to changes in interface strength caused by repeated expansion–contraction (Pei *et al.*, 2022; Golchin *et al.*, 2023; Rafai *et al.*, 2023, 2024a). As a result, the governing mechanism transitions from soil drag down to accelerated ratcheting at the pile–soil interface. This behaviour is not reproduced by the present FE model, as no interface element or specific interface behaviour was introduced.

CONCLUSIONS

Thermally accelerated creep was introduced into an advanced thermo-hypoplastic model, referred to as AVISA-TC. The model was implemented within a finite element framework to investigate the thermomechanical behaviour of a displacement cast in situ semi-floating energy pile embedded in soft soils. When validated against non-isothermal laboratory element and field tests, AVISA-TC provided a closer reproduction of the thermally induced pile head settlement compared to AVISA and AVISA-T. The computed results further revealed that the irreversible settlement originates from a combination of thermal elasticity-plasticity and thermo-mechanical creep, with their relative contributions varying in different portions, thereby confirming the co-existence of these mechanisms.

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