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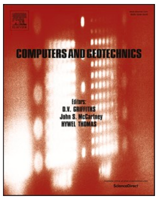

Research Paper

Thermo-plastic response of energy piles during long-term monotonic cooling

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ABSTRACT

Realistic numerical modeling of energy piles in soft soil requires advanced constitutive relationships capable of capturing the inherent thermo-plastic behavior of the surrounding ground. In this study, a newly developed rate-dependent, thermo-plastic constitutive model, called AVISA-T, is employed within the Plaxis Finite Element (FE) code to simulate the response of a well-instrumented energy pile embedded in multilayered soft soils subjected to thermo-mechanical loading. Following material parameter calibration and model prediction validation using non-isothermal laboratory tests on the soils surrounding the pile, the model was employed to simulate full-scale in-situ tests. In these simulations, the pile was initially subjected to either 0 % or 60 % of its bearing capacity and then exposed to continuous cooling over a period of up to three months. The AVISA-T model effectively reproduces the development of contractive and expansive strains, as well as compressive and tensile stresses that coexist along the pile shaft, including the accumulation of residual strains and stresses. In the absence of axial mechanical load, both residual contractive and expansive strains were observed, accompanied by irreversible uplift of the pile head, primarily attributed to non-uniform, unrecovered temperature changes. Moreover, under higher mechanical loading, the model captures dragdown effects resulting from thermal shrinkage of the surrounding soil, which contributes to the accumulation of permanent strains, stresses, and settlements. A comparison between simulations using the common Modified Cam Clay (MCC) model, the AVISA model without thermal effects and the AVISA-T model highlights the importance of using models including thermal plasticity for engineering practice.

1. Introduction

Energy geostructures—such as foundation piles, retaining walls, and tunnels— are structural systems that can be used to harness shallow geothermal energy. For this purpose, these structures are embedded with heat exchanger pipes connected to a ground source heat pump (GSHP), which facilitates the transfer of thermal energy between the ground and the building. In winter, heat is extracted from the ground to warm buildings, whereas in summer, excess heat from buildings is transferred back into the ground (Meibodi and Loveridge 2022; Rafai et al., 2024a, 2024b; Salciarini et al., 2025). In particular, energy piles represent an innovative solution that integrates geothermal heat exchange with structural foundation support. This dual functionality leads to significant cost savings during installation, as the energy piles simultaneously serve as structural foundation elements supporting the superstructure. In addition, they offer low maintenance requirements, long operational lifespans, and stable energy output with minimal seasonal variation compared to solar or wind power. Furthermore, they are considered environmentally friendly and highly cost-effective for sustainable building design (Rafai et al., 2025a).

During GSHP operations, continuous or intermittent modes may occur, inducing short-term (daily to hourly) and long-term (seasonal) monotonic or cyclic thermal loading in energy piles and the surrounding soils. These thermal loads may influence the structural and geomechanical performance of the system, making it essential to evaluate their behavior under realistic operational scenarios. To provide valuable insights into the thermo-mechanical behavior of energy piles, several field-scale tests on instrumented piles have been conducted under monotonic heating or cooling conditions (Laloui et al., 2006; Bourne-Webb et al., 2009; McCartney and Murphy 2012; De Santiago et al.,

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2016; Ren et al., 2023; Rafai et al., 2025b) and cyclic thermal loading (McCartney and Murphy, 2017; Rotta Loria and Laloui, 2018; Faizal et al., 2019a, 2019b; Feng et al., 2024; Jiang et al., 2021, 2023; Kong et al., 2023; Liu and Taborda, 2024; Qiu et al., 2025; Rafai et al., 2024b, 2025a; Sutman et al., 2019; Rafai et al., 2024a). Wang et al. (2015) investigated the impact of monotonic heating over a period of up to 52 days on the bearing capacity of the pile, installed in dry, very dense sand and clay. Their results showed that the pile shaft expanded radially during heating. During the subsequent natural cooling, the pile shaft contracted and almost returned to its initial condition, leading to a thermo-elastic behavior. Ren et al. (2023) investigated the effect of cooling over a period of up to 120 h on the bearing capacity of energy piles in the field. Their findings revealed a reduction in bearing capacity, which was attributed to differential deformation at the pile–soil interface caused by the imposed cooling load. Generally, there are a few studies on energy piles in soft soils. Soft soils can be susceptible to permanent deformations induced by thermal variations (Morteza Zeinali and Abdelaziz 2021), therefore, energy piles in such soils are also more prone to increased deformations. Rafai et al. (2025b) investigated a new type of energy piles called displacement cast-in-situ energy piles (presented for the first time by Rafai et al. (2024a)), during long-term monotonic cooling and under multiple mechanical load levels. Their results demonstrated that thermally induced compressive and tensile stresses could co-exist along the pile. Furthermore, different trends of irreversible displacements were observed. For instance, in the absence of applied mechanical load, permanent uplift of the pile was observed, while under coupled thermo-mechanical loading (60 % of the pile capacity), permanent settlement occurred, highlighting the significant impact of the applied mechanical load level on the pile response. Laboratory experiments have demonstrated ratcheting effects at the interface (Golchin et al., 2023; Rafai et al., 2023, 2024c; Li et al., 2025) and irreversible pile head settlements, especially in heavily loaded energy piles subjected to cyclic heating and cooling (Chang et al., 2025; Ng et al., 2014, 2015, 2016; Nguyen et al., 2017; Yavari et al., 2014a, 2016), with limited cases exceeding serviceability and ultimate limit state criteria (Ng et al., 2021). A similar ratcheting pattern has been observed in full-scale field tests (Fang et al., 2022; Rafai et al., 2025a). Furthermore, a laboratory study by Stewart and McCartney (2014), field tests by McCartney and Murphy (2017) and Rafai et al. (2024b, 2025a, 2025b), have demonstrated that thermal loading can alter the volumetric behavior of the surrounding soil, potentially inducing additional dragdown effects due to ground shrinkage that impose stresses on the energy pile and influence its long-term performance.

Numerical modeling plays a significant role in predicting the energy piles response due to the coupled thermo-mechanical loading. However, their reliability depends on well-calibrated and validated constitutive relationships, ensuring that accurate and meaningful conclusions can be drawn. To simulate the thermo-mechanical response of energy piles, linear elastic models or the Mohr-Coulomb (MC) yield criterion have been widely utilized (e.g., Dupray et al., 2014; Salciarini et al., 2017; Jeong et al., 2014; Di Donna et al., 2016; Sarma & Saggu, 2020; Bourne-Webb et al., 2022; Pei et al., 2022; Rafai et al., 2022), assuming that the soil is thermo-elastic. Rafai et al. (2022) suggested that employing relatively simple constitutive models, such as MC, Hardening Soil, or Modified Cam Clay (MCC), within a coupled modeling framework that incorporates thermal expansion effects is reasonable for analyzing the thermo-elastic response of energy piles in stiff soils. Their predictions were found to be in good agreement with field observations by Bourne-Webb et al. (2009). Similarly, they can be suitable for energy piles in heavily over-consolidated clays (Abuel-Naga et al., 2007; Ng et al., 2016). As stated previously, the behavior of soft soils can be thermo-plastic, therefore, their modeling requires a constitutive relationship that considers the thermo-plastic phenomena. Limited studies used advanced thermo-mechanical constitutive models in finite element (FE) calculations to simulate the response of energy piles (e.g., Di Donna and Laloui, 2015b; Vieira and Maranha, 2017; Iodice et al., 2023; Ng et al., 2024). The modeling results by Ng et al. (2024) demonstrated good agreement with laboratory element tests, which exhibited a permanent deformation, highlighting that the thermo-plastic model significantly outperformed the MCC model in capturing soil behavior. This underscores the importance of employing advanced constitutive models for accurate prediction (Golchin et al., 2022). The behavior of energy piles under field conditions is inherently more complex than what can be captured in laboratory settings. Rafai et al. (2025c) addressed this by incorporating an advanced rate-dependent constitutive model into the finite element code Plaxis to simulate a full-scale in-situ test. Their simulations were successfully validated against experimental results obtained under cyclic thermal loading at a constant mechanical load. However, the influence of varying mechanical load levels on the response of energy piles in soft soils under long-term monotonic thermal loading has not yet been explored numerically. Furthermore, to date, no numerical model has comprehensively accounted for the temporal evolution of thermal loads across different mechanical load conditions, which is an essential step toward accurately predicting the long-term performance of energy piles in soft soil environments.

This study aims to numerically investigate thermally induced strains, stresses, and displacements of a semi-floating energy pile (i.e., a pile whose bearing capacity is derived from both shaft friction and tip resistance) embedded in multilayered soft ground during long-term monotonic cooling at two mechanical load conditions, i.e., 0 and 211 kN. Particular emphasis is placed on assessing the influence of the applied mechanical load on the thermally induced mechanical response. To this end, an advanced rate-dependent thermo-hypoplastic constitutive model, the anisotropic visco-ISA model (Fuentes et al., 2018; Tafili and Triantafyllidis, 2020) enhanced with temperature (AVISA-T) (Tafili et al., 2023c, 2025), employed within the Plaxis finite element software is used. The model accounts for the accumulation of irreversible strains under cyclic thermal as well as cyclic mechanical loading. The coupled thermo-mechanical behavior of the energy pile is analyzed, and the simulation results are validated against a full-scale in-situ test on an energy pile in soft soils presented by Rafai et al. (2025b). In addition to the numerical analysis, this study emphasizes the practical implementation and validation of an advanced thermo-mechanical constitutive model within a commercial finite element software environment. By doing so, it addresses a common gap between academic model development and their application in practice, where simplified models often prevail due to robustness and usability concerns.

The paper begins by describing the field experiment, the constitutive model, and the associated material parameters. This is followed by a comparison of measured and computed results, which are analyzed to elucidate the effects of thermo-mechanical loading. Then the validated model was used to assess the impact of thermal load on the pile bearing capacity. The findings underscore the significant influence of mechanical load magnitude on the long-term performance of energy piles subjected to long-term monotonic thermal load.

2. Details of full-scale energy pile and test site

The full-scale energy pile field test was located in Delft, the Netherlands (Rafai et al., 2024b). A displacement cast-in-situ energy pile with a diameter of D = 380 mm and a length of L = 10.3 m was installed in multilayered soft soils. The cone penetration tests (CPTs) results are shown in Fig. 1. Five layers of soil (made ground, peat, silty sand, clay and sand) were identified along the energy pile depth. The groundwater table was located 1 m below the ground surface.

To evaluate the thermo-mechanical performance of the energy pile, twelve Vibrating Wire Strain Gauges (VWSG) with integrated thermistors were installed at six distinct depths along the pile. The average depth of each pair of the strain gauges is illustrated in Fig. 1.

The energy pile system is shown in Fig. 2(a). Mechanical loading was applied using deadweight to represent the building (see the tank in Fig. 1 (a)), and the thermal load was applied using a GSHP. By heating the

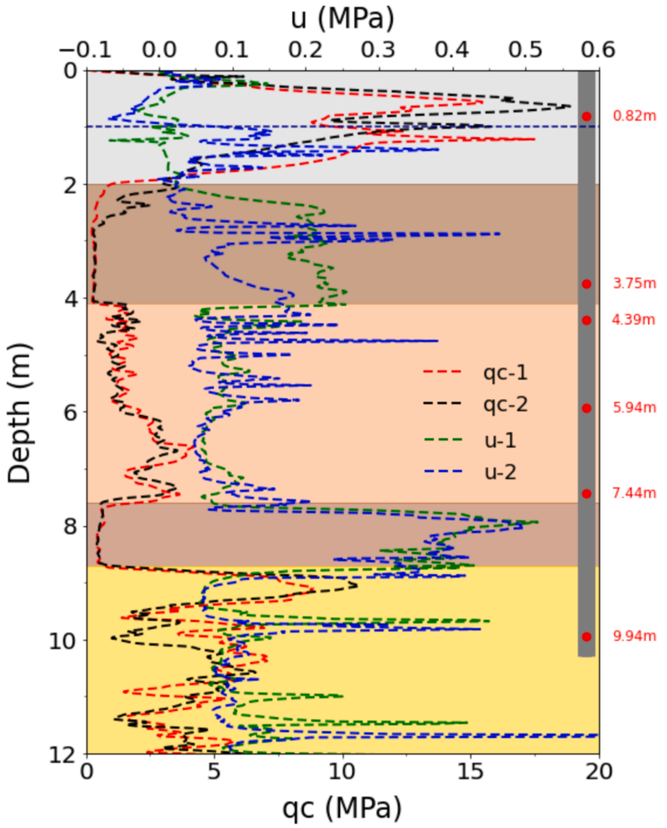

Fig. 1. The results of CPTs with soil profile and locations of VWSGs along the pile depth: cone resistance (qc); and pore water pressure (u).

tank, the pile was subjected to cooling. The pile was equipped with double-U high-density polyethylene heat exchanger tubes with an internal diameter of 28 mm (see Fig. 2(b)).

To monitor the pile head displacement, a Linear Variable Differential Transformer (LVDT), with an accuracy of 0.002 mm, was employed, while the applied load was recorded by load cell (see Fig. 2(c)). More detailed information on the full-scale in situ set-up can be found in Rafai et al. (2024b).

3. Analysis of energy piles

3.1. *Constitutive model: Thermo-mechanical anisotropic visco-ISA model (AVISA-T)*

The anisotropic visco-intergranular strain anisotropy model (AVISA), initially proposed by Tafili and Triantafyllidis (2020), and used in various applications (Dao et al., 2025; Staubach et al., 2022; Dao et al., 2024), combines a hypoplastic framework with the concept of intergranular strain anisotropy and has been successfully extended to capture thermo-mechanical effects in fine-grained soils by Tafili (2025), Ashrafi et al. (2025), Tafili et al. (2023c). The model includes temperature-dependent compressibility, a thermal collapse mechanism, and time-dependent (viscous) effects, making it capable of simulating both monotonic and cyclic loading under varying thermal conditions. It accounts for key phenomena such as heating-induced volume changes and irreversible strains during thermal cycles, which are particularly relevant in applications involving geothermal energy systems or underground thermal energy storage.

Mathematically, the model couples mechanical and thermal strain rates in a generalized evolution equation that incorporates thermo-elastic, viscoplastic, and thermo-plastic components, such that

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

where, $\dot{\boldsymbol{\sigma}}$ denotes the stress rate, while $\dot{\boldsymbol{\varepsilon}}$ represents the total rate of strain. The increase in elastic stiffness upon unloading is captured through the scalar function $m = m_R + (1 - m_R)y_h$, where m_R is a material parameter representing the maximum stiffness recovery. In the absence of material-specific experimental data under reversed or cyclic loading, the value of $m_R = 3$ was adopted based on prior experience and as a default commonly used in literature (Tafili & Triantafyllidis, 2020) for similar soil types and constitutive formulations. Upon a complete load reversal, characterized by $\dot{\boldsymbol{\varepsilon}} \propto \boldsymbol{h}$, where $\boldsymbol{h}$ denotes the intergranular strain, the internal variable y_h approaches zero, and the stiffness recovery factor m converges to m_R. Conversely, under fully mobilized conditions — i.e., during monotonic loading — $y_h = 1$, and the stiffness recovers to its original value, $m = 1$. $\dot{\boldsymbol{\varepsilon}}^{TE}$ is the thermo-elastic strain representing the strain rate resulting from thermal volume alterations of the solid particles (Khalili et al., 2010), characterized by the thermal expansion coefficient of the soil, α_s in $^\circ C$. The influence of temperature is further introduced through the so-called thermo-plastic strain rate, $\boldsymbol{\varepsilon}^{\dot{TP}}$, temperature-dependent parameters such as the compression index and reference void ratio, which are governed by two material parameters calibrated from thermal oedometer or isotropic compression tests. Time-dependent behavior is modeled via a viscosity index, I_v, and reference time, t_0, which are scaled automatically within the finite element framework to ensure consistent simulation results regardless of unit settings. For more details on the formulation of the model, readers are referred to studies by Tafili et al. (2023a, 2023b, 2024), Rafai et al. (2025c). The AVISA-T model was implemented in Plaxis by Rafai et al. (2025c) and validated against laboratory tests on clay, silty sand, and sand, as well as field-scale case studies.

Although the model was developed for fine-grained soils, which are characterized by pore-collapse when heating (Sultan et al., 2002), it can be used for granular materials where pore-collapse is not expected, but irreversible deformation is expected during thermal cycles (as shown in Pan et al. (2022), Rafai et al. (2024c, 2025e)) with the careful choice of parameters. For example, the parameters α_s and γ_T control the ratio between thermal expansion and thermal collapse, and the amount of continuing irreversible deformation can be controlled by l_T and n_T. By doing this, thermal expansion when heating (and not contraction when heating) at a low OCR with a thermally induced cyclic reduction in volume can be simulated. However, when reproducing other features of granular soils, which are not focused on here, e.g. liquefaction of loose samples, the use of an alternative constitutive model tailored to granular soils becomes more appropriate.

During cooling paths, both clays and sands contract (Di Donna and Laloui, 2015a; Ng et al., 2019; Pan et al., 2022; Rafai et al., 2024c) and since this study focused on cooling and then natural-heating, the model used here is considered reasonable for both soils under these conditions. Nevertheless, careful calibration of the model for different soil types and loading paths remains essential, particularly when applied to the heating of granular soils. Despite the fact that the mechanism governing both soils are different, sand is largely governed by thermally induced physical interactions among particles while clays behavior is associated with physico-chemical interactions between the particles composing fine-grained soils, the model was shown to capture the essential trends observed in laboratory experiments by Rafai et al. (2025c), including 10 thermal cycles, reinforcing its applicability within the intended range of conditions.

The implementation addressed challenges such as time unit scaling and the avoidance of numerical instabilities related to time-dependent parameters. The successful integration into Plaxis now enables robust, user-friendly simulation of temperature- and time-dependent soil behavior in real-world scenarios. This implementation of the model is

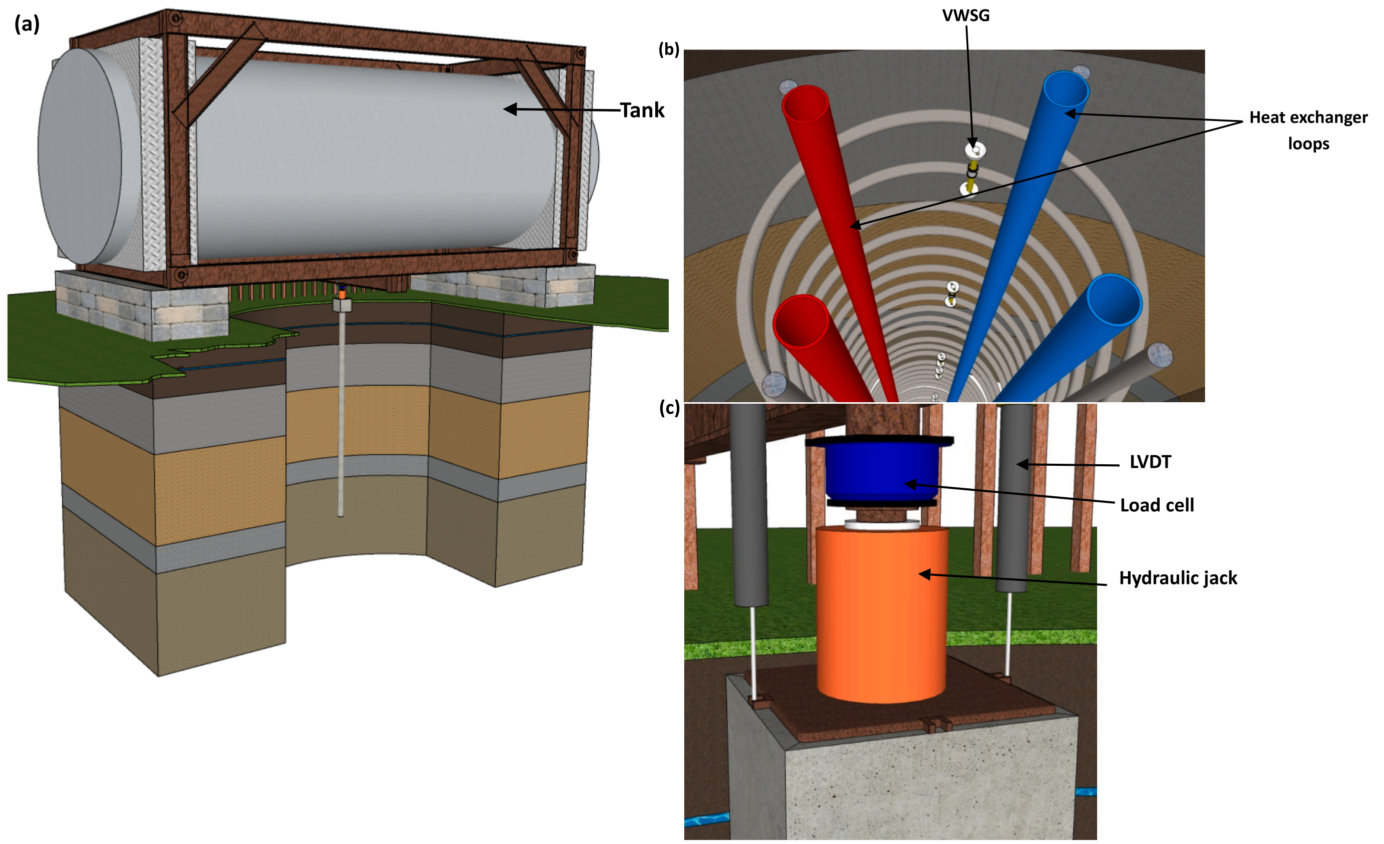

Fig. 2. Details of the full-scale energy pile: (a) Schematic of the energy pile system; (b) reinforcement cage with the heat exchanger loops; (c) locations of LVDT, hydraulic jack, and load cell.

employed in this study.

Material parameter calibration for AVISA-T follows a structured process based on conventional laboratory tests (oedometer and triaxial) and thermal loading experiments. Parameters for stiffness and critical state behavior are calibrated similarly to Modified Cam Clay, while temperature and viscosity-related parameters are obtained from temperature- and strain-controlled as well as cyclic thermal tests. Overall, the AVISA-T model provides a comprehensive tool for simulating the long-term thermo-mechanical response of soils, bridging a key gap in modeling geotechnical systems exposed to temperature fluctuations and time-dependent effects.

3.2. Modelling procedures

A two-dimensional numerical model was developed to simulate a single energy pile with a radius of 0.19 m and a total length of 10.3 m, embedded within a multilayered soil profile. The model is considered to be axisymmetric and discretized using 19,180 -15-node-triangular elements and is presented in Fig. 3. The model domain was extended sufficiently in both radial and vertical (31×15 m^2) directions to minimize boundary effects. Following the recommendations of Yavari et al. (2014b), the radial domain was set to 100 times the modeled pile diameter, exceeding the commonly suggested minimum of 30 diameters. The vertical extent of the model was defined as three times the pile length, consistent with the guideline proposed by Ng et al. (2024). The bottom boundary was fixed in both vertical and horizontal directions, while the lateral boundary was constrained horizontally to replicate realistic in-situ confinement conditions. The soil domain was discretized using a fine finite element mesh with higher refinement near the pile–soil interface to capture stress concentration and potential interface shear deformations accurately. The mesh density was gradually coarsened away from the pile to optimize computational efficiency without compromising accuracy. Various mesh sizes and discretizations were tested until further refinement no longer affected the results.

To simulate the thermo-mechanical behavior of the energy pile system, thermal boundary conditions were incorporated into the axisymmetric model. The pile was assumed to operate under GSHP conditions, with a prescribed temperature variation applied uniformly along six segments of the embedded portion of the pile to replicate realistic field operations. The thermal input was defined as a time-dependent function to reflect long-term monotonic loading conditions. The initial ground temperature profile was assumed to be in thermal equilibrium with an initial temperature of 12 °C, based on a linear geothermal gradient typical for the site conditions. Heat exchange between the pile and the surrounding soil was governed by conduction, and the thermal properties for both the pile (e.g., thermal conductivity, specific heat capacity) and each soil layer were defined based on laboratory testing. The coupled thermo-mechanical analysis was performed using a fully coupled solver to account for the interaction between temperature changes and mechanical deformation over time. For the hydraulic boundary conditions, the groundwater table was located 1 m below the ground surface, with an initial hydrostatic pore water pressure distribution.

All soil layers were modeled using the AVISA-T model calibrated to represent their respective stress–strain and thermal behavior with time. This approach allowed for the evaluation of both immediate and time-dependent responses of the system under long-term thermal loading. The material parameters employed in the numerical simulations are illustrated in Table 1, based on calibration from element tests or calibration with field results where element tests were not available, as specified by Rafai et al. (2025c). It is worthwhile mentioning that sand has higher thermal expansion coefficient, which in conjunction with by l_T and n_T ensures that it expands when heating, yet results in contraction at the end of the cycle.

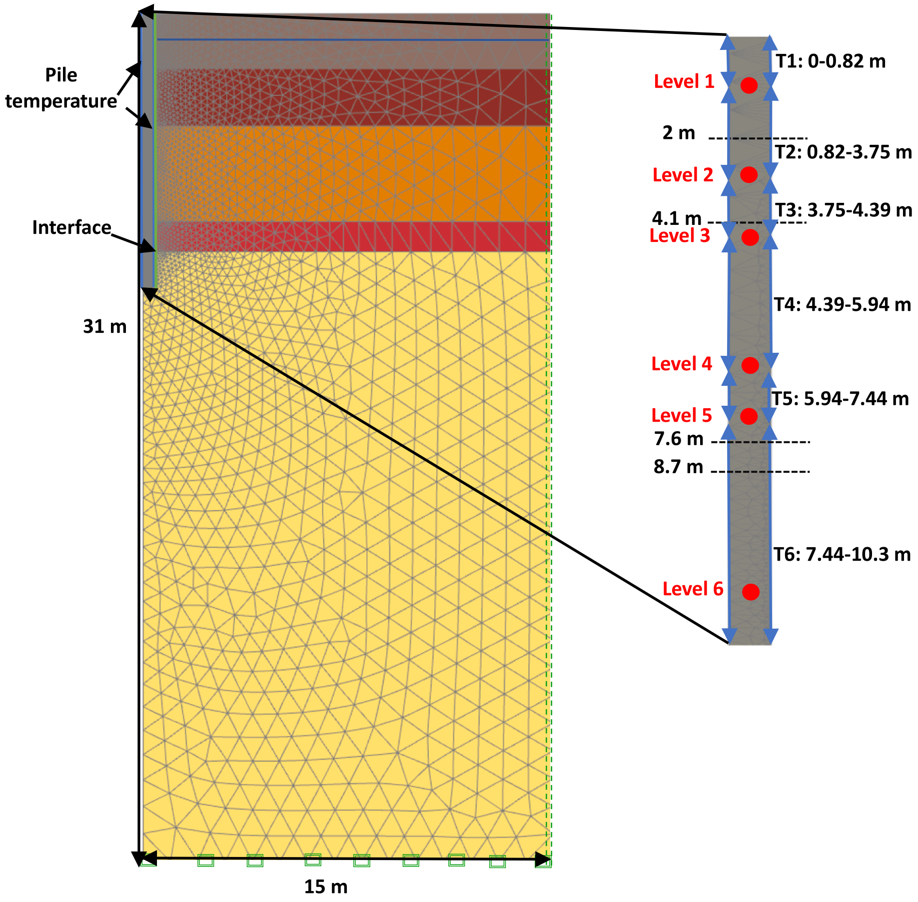

Fig. 3. FE model of the simulated energy pile along with boundary conditions.

Table 1
Model parameters.

	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	23	28	23	31
	n_T	0.02	0.02	0.03	0.02	0.03
	l_T	0.013	0.013	0.011	0.013	0.011
	γ_T	5.0	5.0	5.0	5.0	5.0
Thermal term (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
Parameters for the concrete pile.

	Parameter	Value
Mechanical term	E in GPa	41
	ν	0.2
Thermal term	c in MJ/(m^3·K)	1
	k_T in W/(m·K)	2.1
	α_s in 1/°K	10.71×10^{-6}

The intergranular strain anisotropy (ISA) parameters were set to default values, as proposed by Tafili and Triantafyllidis (2020), due to the absence of tests involving cyclic mechanical loading. Besides the AVISA-T parameters, three additional thermal parameters are required by Plaxis and presented in Table 1, where c is the specific heat capacity and k_T is the thermal conductivity, which were averaged from CPT correlations (Vardon and Peuchen, 2021) and needle probe tests of each soil layer. The linear thermal expansion coefficient, α_s, is calibrated from the soil contraction during the cooling process.

The pile was modeled as a linear elastic material, consistent with the properties of concrete, using the parameters listed in Table 2. The pile–soil interaction was represented by a rigid contact condition in the normal direction and a Coulomb friction model in the tangential direction, following the approach used by Ng et al. (2024). Based on direct shear test results, the friction angles for clay, silty sand, and sand were determined to be 19°, 32°, and 42.5°, respectively. In cases where such laboratory tests were unavailable, specifically for made ground and peat layers, the interface parameters for clay were adopted based on previous experience.

Importantly, no adjustment of the model parameters was performed to fit the experimental results in the finite element simulations. The analyses therefore qualify as Class A predictions as suggested by Lambe (1973), i.e., fully predictive simulations based solely on independently determined parameters from laboratory element tests. Although the field test experimental results were available to the authors, they were not used for any recalibration or fitting procedure.

In this study, strain and stress values are defined as positive for compression and negative for tension, following geotechnical conventions and previous studies. For pile head displacements, positive values indicate settlement while negative values represent uplift.

4. Testing and modeling program

The testing (and modeling) program is presented in Table 3. It should be noted that this pile had undergone mechanical and thermo-mechanical loading and was allowed to recover prior to the current testing program.

The test plan consists of three phases. In the first phase, i.e., during the mechanical phase, the pile was loaded up to 211 kN (60 % of the estimated bearing capacity, which is 353 kN, excluding the shaft resistance of made ground and peat layers) with increments of 10 %, and each loading step was maintained for at least 60 min as recommended by the Dutch code for static axial loading of piles (NEN NPR 7201:2017). Then the pile was completely unloaded.

In the second phase, i.e., during the thermal phase, the pile was subjected to three months of monotonic cooling without any applied mechanical load.

In the third phase, i.e., during the thermo-mechanical phase, the pile was first loaded to a target vertical load of 211 kN (equivalent to 60 % of the pile bearing capacity) in increments of 10 %. The applied mechanical load was held constant for 16 h to minimize the mechanical creep effects, then subjected to monotonic cooling while the applied mechanical load was held constant. To replicate the experimental conditions, a finite element simulation was conducted using the following procedure:

(a) Definition of the geometry, material properties, and initial boundary conditions;
(b) Simulation of the pile installation using the 'wished-in-place' method (Hong et al., 2015);
(c) Application of the mechanical loading consistent with the field test sequence at isothermal conditions;
(d) Prescription of the monotonic thermal loading to simulate the energy pile operation without any mechanical load;
(e) Increase of the mechanical load to 60 % with an increase of 10 % of the pile's bearing capacity. Once this level is reached, the mechanical load is kept constant, and the thermal load is applied.

5. Test results and analysis

5.1. Mechanical behavior of energy pile with no heating or cooling

As outlined earlier, the pile had undergone mechanical and thermo-mechanical loading prior to the current testing program. Fig. 4 presents the results of the initial mechanical test conducted on the pile (referred to as the virgin pile; not included in Table 3), as well as the results of the mechanical test T_M1 (referred to as 'after thermal recovery'). In addition, the figure includes the corresponding numerical simulation of test T_M1. It should be noted that the measured mechanical results are quantitatively similar under up to 50 % of the pile bearing capacity, while under 60 %, T_M1 results showed a slightly lower pile head displacement. This small difference was attributed to the densification of sand beneath as a result of the thermal cycles induced irreversible settlements as shown by Rafai et al. (2025a). The model closely tracks the mechanical pile results. This close alignment underscores the robustness and accuracy of the numerical model in predicting the pile's mechanical response across a range of service load conditions.

Table 3
Test program.

Test No.	Mode	Cycle	Cooling/ Natural-heating duration	Static load (kN)
T_M1	Mechanical	_	_	0, 36, 71, 106, 141, 176, 211
T_0	Thermal	1	3 months	0
T_60	Mechanical + thermal	1	5 days	211

5.2. Pile temperature profiles

In the numerical simulations, the measured temperature profiles along the pile depth from the field were directly imposed using thermal (prescribed temperature) boundary conditions. The initial temperatures of both the pile and the surrounding soil were assumed to be undisturbed and uniformly set at 12 °C. In test T_0, the GSHP was operated under natural control, resulting in hourly and/or daily temperature fluctuations. These fluctuations occurred because the GSHP automatically switches off upon reaching the target temperature and restarts once the temperature drops below the set threshold, thereby maintaining a quasi-constant thermal regime.

In the field test, the activation of the GSHP system led to a reduction of both the pile and the surrounding soil temperatures due to the subsurface heat extraction. Following system deactivation during natural heating or GSHP stoppage, passive thermal recovery was induced, characterized by an increase in soil temperature preceding the pile temperature response. This temporal lag highlights the differential thermal inertia between the soil mass and the pile structure; hence, the pile strain/stress may be affected.

Fig. 5 presents the measured and simulated (smoothed and prescribed) temperature variations over time for tests T_0 (Fig. 5a) and T_60 (Fig. 5b), recorded at different depths along the pile, referred to as "levels" as defined in Fig. 3. It should be noted that the temperature distribution along the pile depth is heterogeneous in both tests. In test T_60, a significantly higher average temperature change of approximately 11 °C was observed, compared to about 5 °C in test T_0. At the end of test T_0, the residual temperature difference at the shallowest measurement point (level 1) was approximately 4 °C, decreasing to around 2 °C at intermediate depths (levels 2 and 3). In contrast, the lower part of the pile (levels 4 to 6) exhibited residual temperature differences as low as –2 °C. For test T_60, the residual temperature difference at the pile remained slightly above –1 °C.

5.3. Thermally-induced strain

Fig. 6(a) (test T_0) and Fig. 6(b) (test T_60) show the measured and computed thermally induced strains along the pile shaft as functions of elapsed time, while their variations with temperature change are illustrated in Figs. 7(a) and 7(b). As expected, thermal contraction was observed in the concrete pile during the cooling phase, primarily due to the reduction in temperature below the initial baseline. Upon subsequent natural heating, thermal expansion occurred, partially offsetting the prior contraction. When pile temperatures exceeded the initial baseline, net expansion was observed, indicating a reversal from compressive to expansive behavior of the pile. Generally, the thermal axial strain was observed to vary with depth in the foundation, depending on the temperature change and the restraint provided by the soils along the pile.

In test T_0, as illustrated in Fig. 6(a), the results indicate the coexistence of compressive and expansive strains along the pile depth during GSHP operation, leading to residual compressive/expansive strains at the end of this test. In general, the strain profile mirrors the temperature profile, with cooling leading to contraction and heating resulting in expansion. The model effectively captures these phenomena, with the computed results closely aligning with the measured data.

In test T_60, as presented in Fig. 6(b), the experimental results show contractive strains during cooling and only small compressive residual strain at the end of the test, which is also well predicted by the model. It should be noted that the experiments exhibit a certain degree of hysteresis as illustrated in Fig. 7. In the numerical model, the datasets from tests T_0 and T_60 were partially and fully smooth, respectively. In test T_0, the extended duration of the long-term cooling phase, combined with the (hourly and daily) intermittent operation of the GSHP, resulted in cyclic variations of thermally induced strain, which could be the main reason for the observed hysteresis. Another potential reason is that the

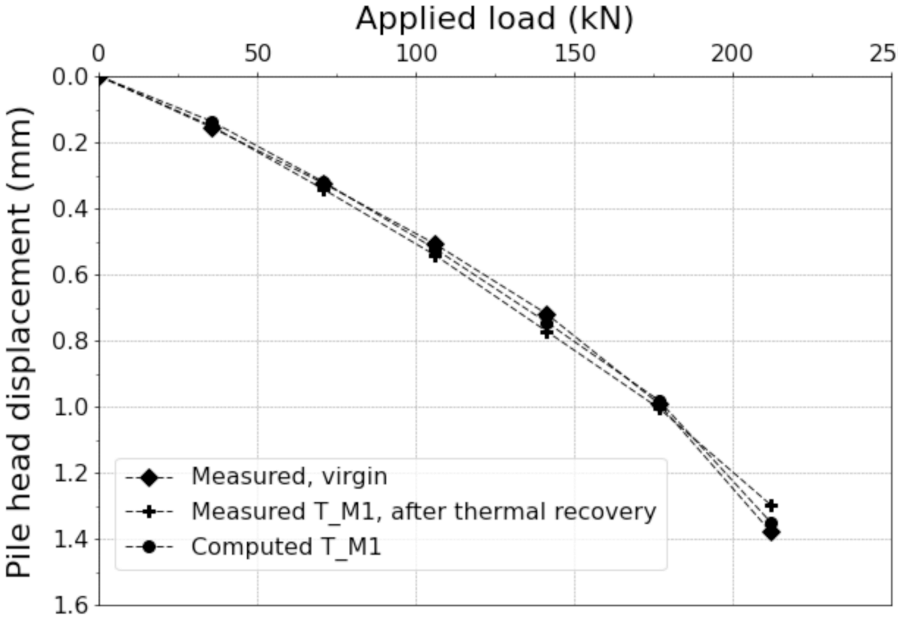

Fig. 4. Measured and computed pile head displacement versus the applied mechanical load.

hysteresis could be due to the restraint of the soil (the pile is cooler than the soil) and the recovery, where the soil is the same temperature as the pile (providing it heat), follows a linear trend. The residual strains appear to correspond closely with the residual temperature distribution along the pile. For instance, at the end of this test (T_0), residual expansive and contractive strains were recorded at levels 1 and 6, respectively, aligning with the higher residual temperature near the top and lower residual temperature near the bottom of the pile at the end of the test (see Fig. 5). However, the hysteresis observed in test T_60 may be attributed to the plastic deformation effect at the interface, or to dragdown effects caused by ground shrinkage, or to a combination of both mechanisms. This behavior has been documented in laboratory studies on soil–structure interaction (Golchin et al., 2023; Guo et al., 2023; Rafai et al., 2023), where thermal loading induces progressive shear displacements following a ratcheting pattern. These findings highlight the significant influence of applied mechanical loading on the development of the influence of operational patterns on the long-term strain accumulation, hysteresis, and ratcheting. A more detailed discussion of ratcheting effects is presented in the section on pile head displacements.

5.4. *Thermally-induced stress profiles*

The results of thermally induced stresses over time during thermal loading are presented in Figs. 8(a), and (b) for the energy foundation subjected to 0 %, and 60 % of the estimated bearing capacity, respectively. Corresponding variations with temperature change are shown in Fig. 9(a) for the tests T_0 and Fig. 9(b) for the test T_60. These data illustrate the evolution of axial stress within the pile in response to the applied thermal load. In test T_0 illustrated in Fig. 8(a) and Fig. 9(a), the cooling phase induced both compressive and tensile stresses, demonstrating that such stresses can coexist within a single pile during GSHP operation. Notably, tensile residual stresses developed in the upper four levels, while compressive residual stresses were observed in the lower two levels. This behavior was accurately reproduced by the model and is primarily attributed to the heterogeneous temperature distribution along the pile, driven by the intermittent operation (stoppage periods) of the GSHP and the resulting fluctuations in the pile and the soil temperatures, which generate residual strains and stresses.

In test T_60 presented in Fig. 8(b) and Fig. 9(b), at the beginning of the cooling phase (before the cold load was transferred to the subsurface), the stress was initially higher but then decreased significantly. This stress decrement during cooling is well captured by the model. Subsequent natural heating led to the development of significant compressive stresses along the pile shaft, with the model showing a stronger stress decrement compared to field data and smaller residual compressive stresses at the end of this test (T_60). As stated previously, in the model, the pile was the source of cooling and also heating, while in the field, the soil recovers first before transferring heat to the pile.

When energy piles are embedded in expansive/contractive soils, the stresses within the pile can be partially released and transferred to the surrounding ground, as the soil mass responds to thermally induced loading. This time-dependent soil behavior has been reported in previous studies (e.g., Gawecka et al., 2017). Both the modeling and experimental results indicate that the increase in tensile stress in test T_60 was significantly greater than in test T_0, particularly at the upper levels (levels 1 and 2) as shown in Fig. 9. This can be attributed to the proximity of the applied mechanical load to these levels, which constrained the pile's thermal contraction and expansion, thereby transforming the restrained thermally induced strains into elevated internal axial stresses. At the conclusion of the test, residual compressive strains were observed along the entire pile. Overall, the model qualitatively and quantitatively captures the observed behavior, however, slight quantitative discrepancies were noted. These can be attributed generally to (i) the stronger decrease in compressive stress, following the method of applying natural heating in the model, which may be influenced by external weather (given the limited length of the pile), and (ii) the absence of an interface element accounting for strength degradation induced by the contraction–expansion of the pile. These two reasons may co-exist and influence the amount of the residual contractive stress. At level 3 a stronger discrepancy is observed with higher tension stresses observed than simulated; this is likely to be due to one or more material parameters not representing the in-situ material behavior.

As stated previously, dragdown of the surrounding soils as a result of the ground shrinkage could induce additional stress on the pile. These observations align with the previous studies by Stewart and McCartney (2014), McCartney and Murphy (2017), and Rafai et al. (2024a, 2025a).

5.5. *Thermally-induced pile displacements*

Fig. 10 presents the computed and measured normalized irreversible pile head settlement (as a ratio to pile diameter) together with data from

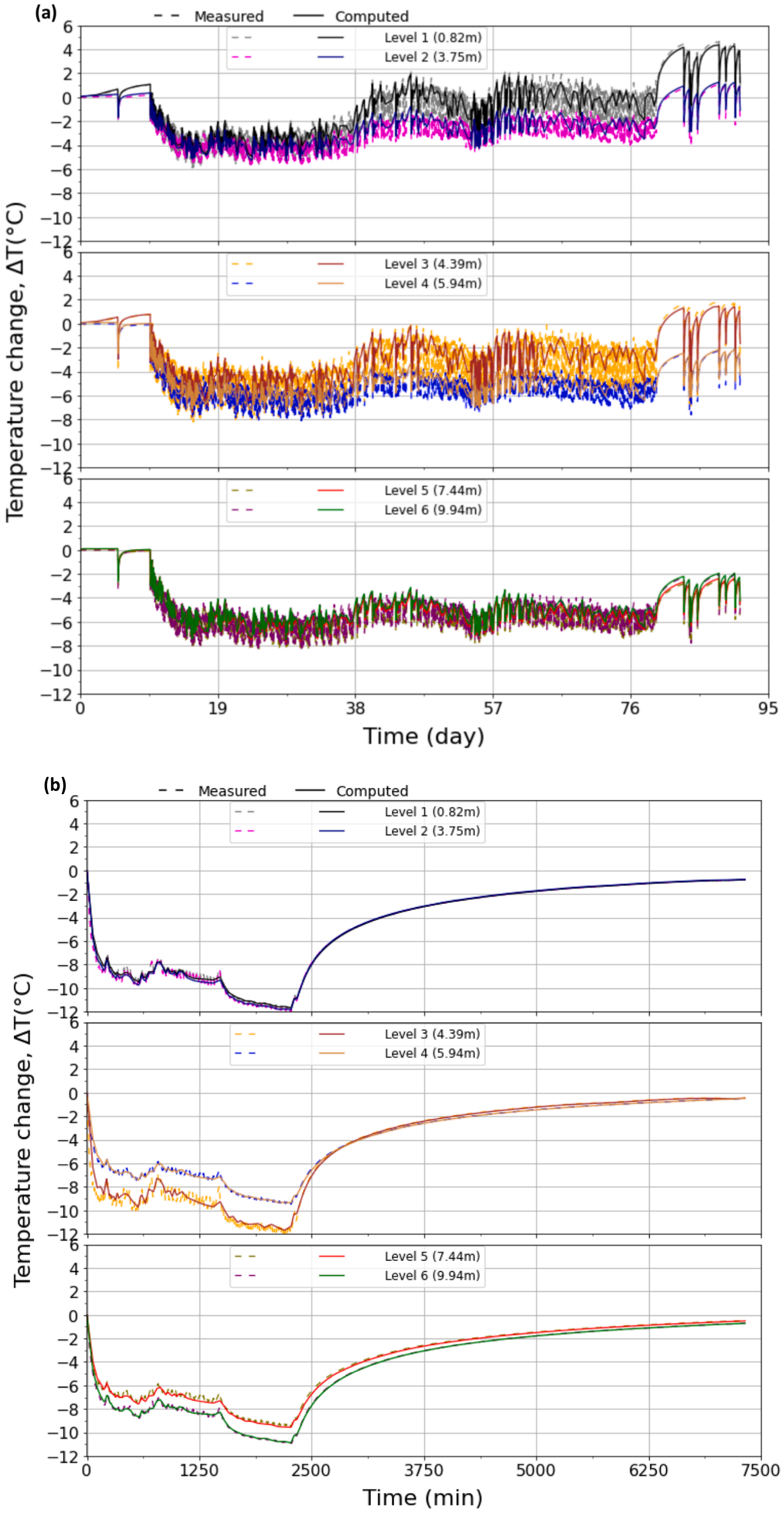

Fig. 5. Temperature history along the pile shaft of tests: a) T_0; b) T_60.

the literature after one thermal cycle. Note these are settlements due to only the application of the temperature. To demonstrate the practical applicability of the proposed model, Fig. 10 also compares the computed results obtained with MCC and AVISA. The AVISA model was calibrated with the same parameters as AVISA-T but without thermal effects, while MCC used the first five AVISA-T parameters listed in Table 1. This figure illustrates thermo-mechanical behavior of energy pile under different degrees of freedom (restraints at the pile head). An obvious trend of the

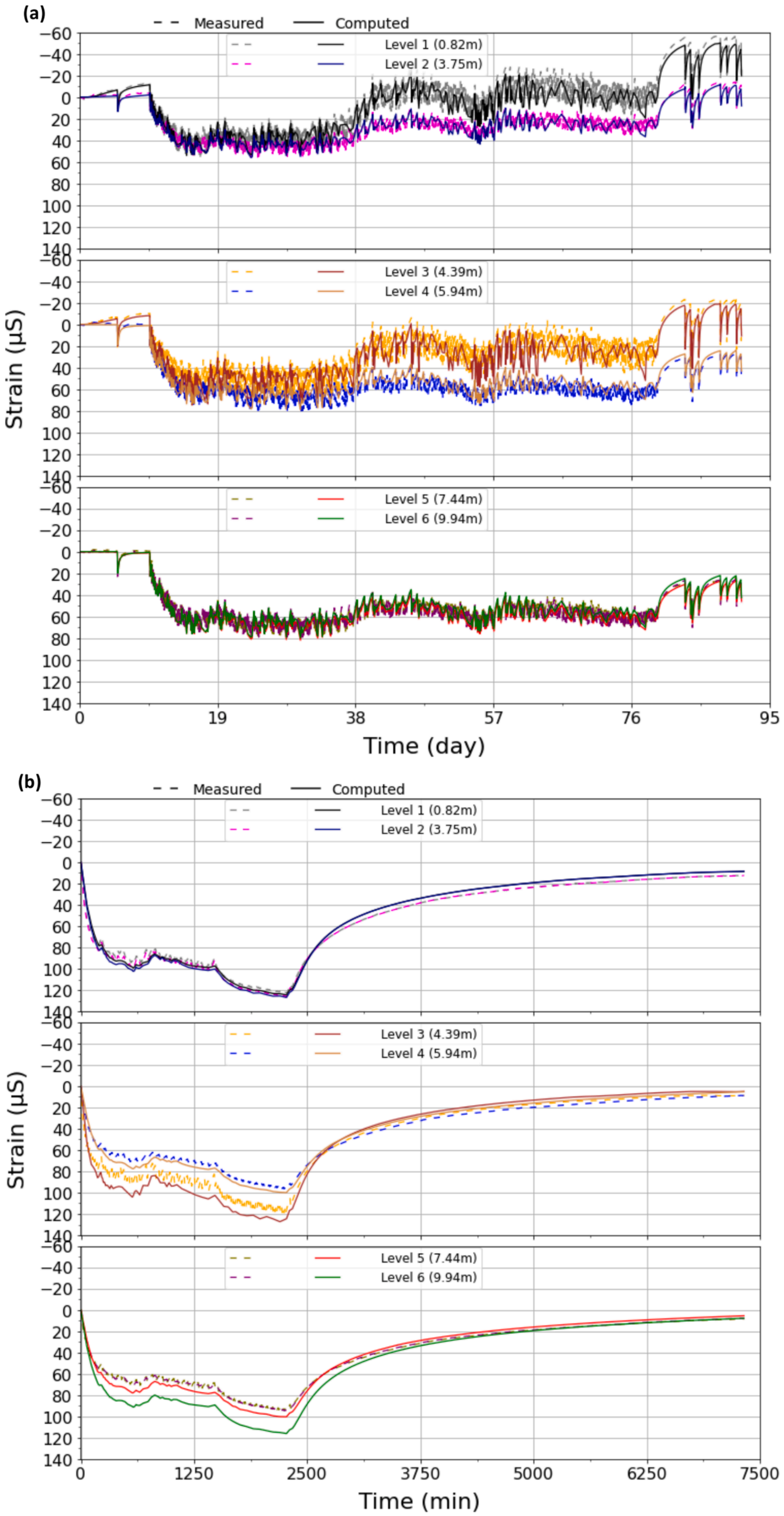

Fig. 6. The computed and measured thermally induced axial strain along the pile shaft during thermal loads versus elapsed time of tests: (a) T_0; (b) T_60.

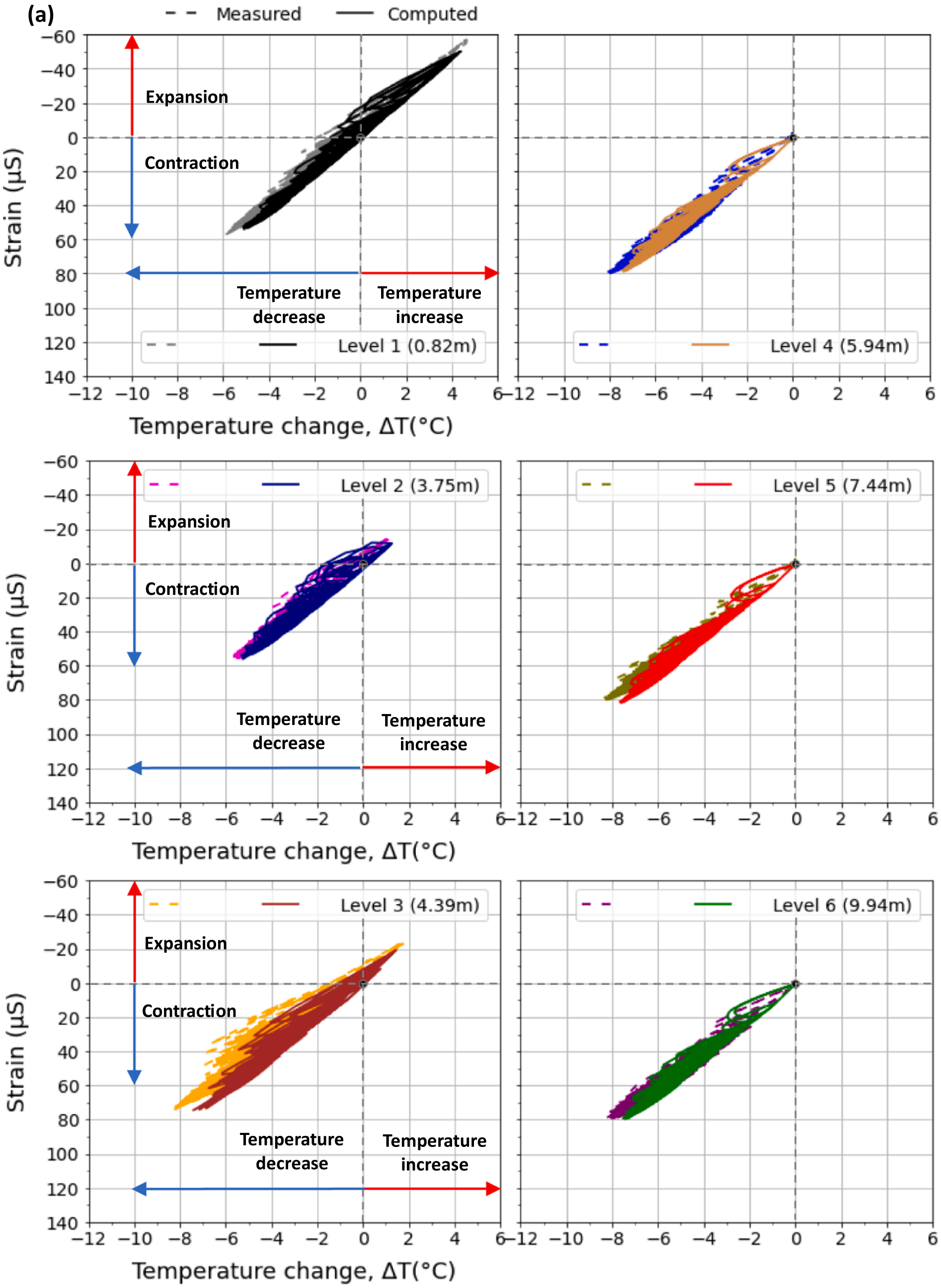

Fig. 7. The computed and measured thermally induced axial strain along the pile shaft during thermal loads versus temperature change of tests: (a) T_0; (b) T_60.

impact of mechanical load is seen.

In this study, in the free expansion test (T_0), the results reveal an irreversible pile head uplift of 0.2 mm, which is well captured by the AVISA-T model. In contrast, MCC and AVISA slightly overestimate the observed uplift.

This uplift aligns with the residual expansive strains in the upper part of the pile (see Fig. 6). However, in tests by Nguyen et al. (2017) and Rafai et al. (2025a) negligible irreversible displacement was observed after one thermal cycle.

In this study, the temperature increased at the end of test T_0, while in their studies (Nguyen et al., 2017; Rafai et al., 2025a) it was recovered, hence, the differences in the pile head displacement trend can be largely attributed to the fact that the temperature increased at the end of the test (above the initial temperature), and thus an increase in strain and pile head uplift could be induced. It should be noted that all the used models showed a similar qualitative trend, however, there is quantitative difference between the conventional models (i.e., AVISA and MCC) and AVISA-T. This difference implies the co-existence of plastic yield at the lowest point in soil over three months of thermal load along with the thermo-elastic response of the pile concrete.

The conventional models captured only the pure thermo-elastic response of the piles (uplift due to the temperature increase in the pile and soil), while AVISA-T model captured both, the small thermo-plastic response of the soil and the thermo-elastic response of the pile and soil. For this reason, the results by AVISA-T model are reasonably closer to the field tests.

In the thermo-mechanical test (T_60), an irreversible pile head settlement was observed and well predicted by only the AVISA-T model, while the other models (AVISA and MCC) significantly underestimate the thermally induced pile head settlement. The computed small values

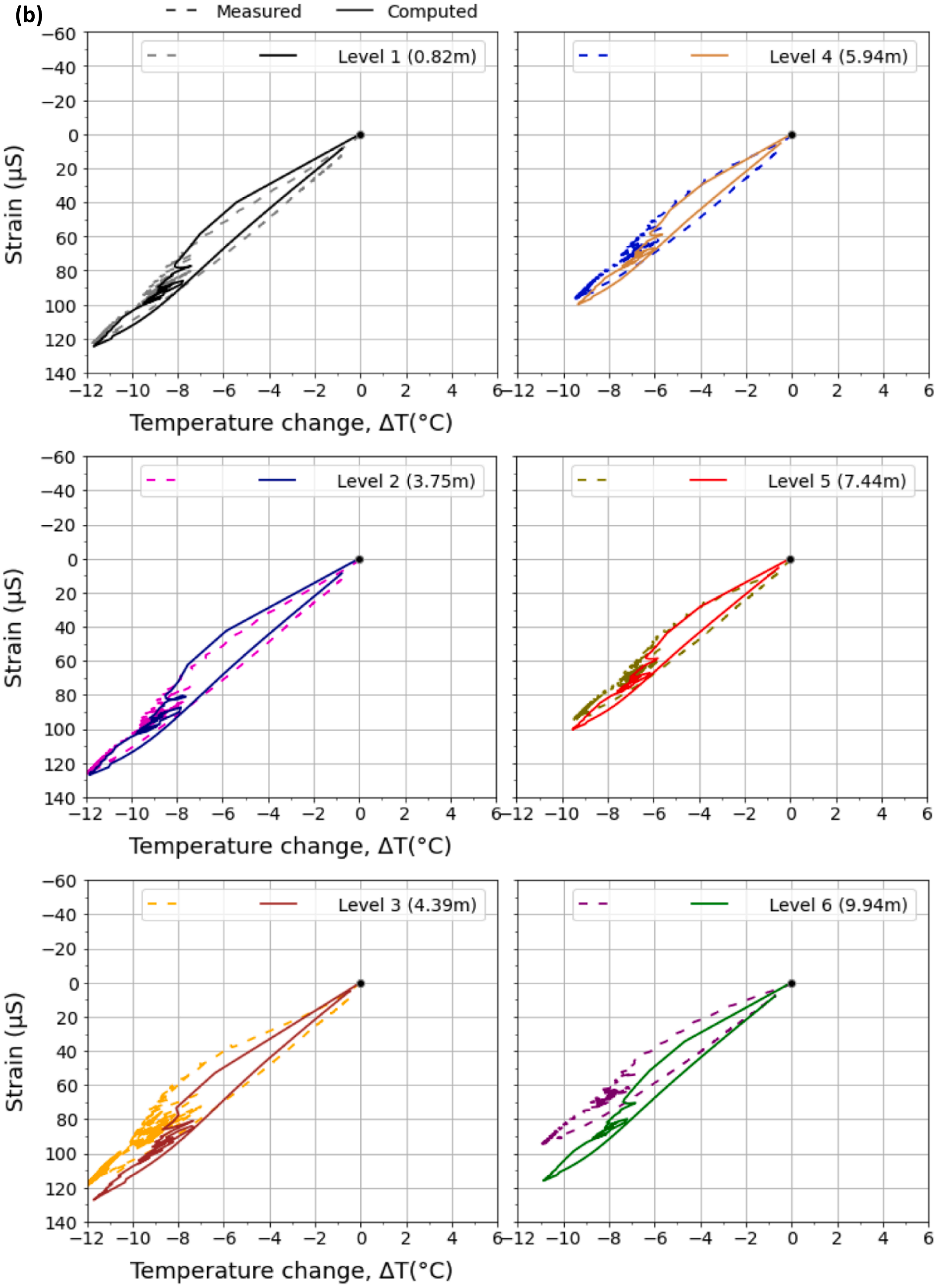

Fig. 7. (*continued*).

using AVISA and MCC models reflect the thermo-elastic response of the pile due to the decrease of the pile and soils temperature (see Fig. 5b); if a full recovery had occurred, the resulting settlement would have been negligible. The enhanced AVISA-T model outperforms the alternatives by capturing the thermal plasticity of soils.

This permanent settlement quantitatively aligns with the field study by Rafai et al. (2025a). However, it is lower compared to laboratory studies by Rafai et al. (2025d) and Nguyen et al. (2017). The difference in the pile head settlement between field results in this study and laboratory tests by Rafai et al. (2025d) and Nguyen et al. (2017) can be attributed to several reasons: i) The stress condition in laboratory tests differs from that in the field. ii) Tip resistance in floating piles is not involved to compensate for the shaft degradation, hence they are more susceptible to ratcheting. However, in semi-floating piles, the tip resistance could compensate for shaft degradation and thus result in less ratcheting. The results after one thermal cycle from the study by Ng et al. (2019), conducted under 50 % of the pile capacity, are lower than those reported by Rafai et al. (2025d) and Nguyen et al. (2017), which is attributed to the lower mechanical load applied in the Ng et al. (2019) study. This further endorses the significant impact of the applied mechanical load on the thermally induced settlements.

When the pile head is free of mechanical load, the stress state at the pile-soil interface remains small and predominantly within the elastic zone. In this case, the pile response is governed mainly by temperature fluctuations and the resulting elastic expansion or contraction along with small plasticity of the soils. During thermal recovery, the concrete pile exhibits an almost fully elastic response. In contrast, when a mechanical load is applied, ground shrinkage becomes more pronounced due to the higher temperature magnitude and also the induced stress in the soils, leading to a significant reduction in generated stress in the pile (see Fig. 8). This can decrease the interface pressure, allowing the applied load to further influence the stress state, potentially pushing it

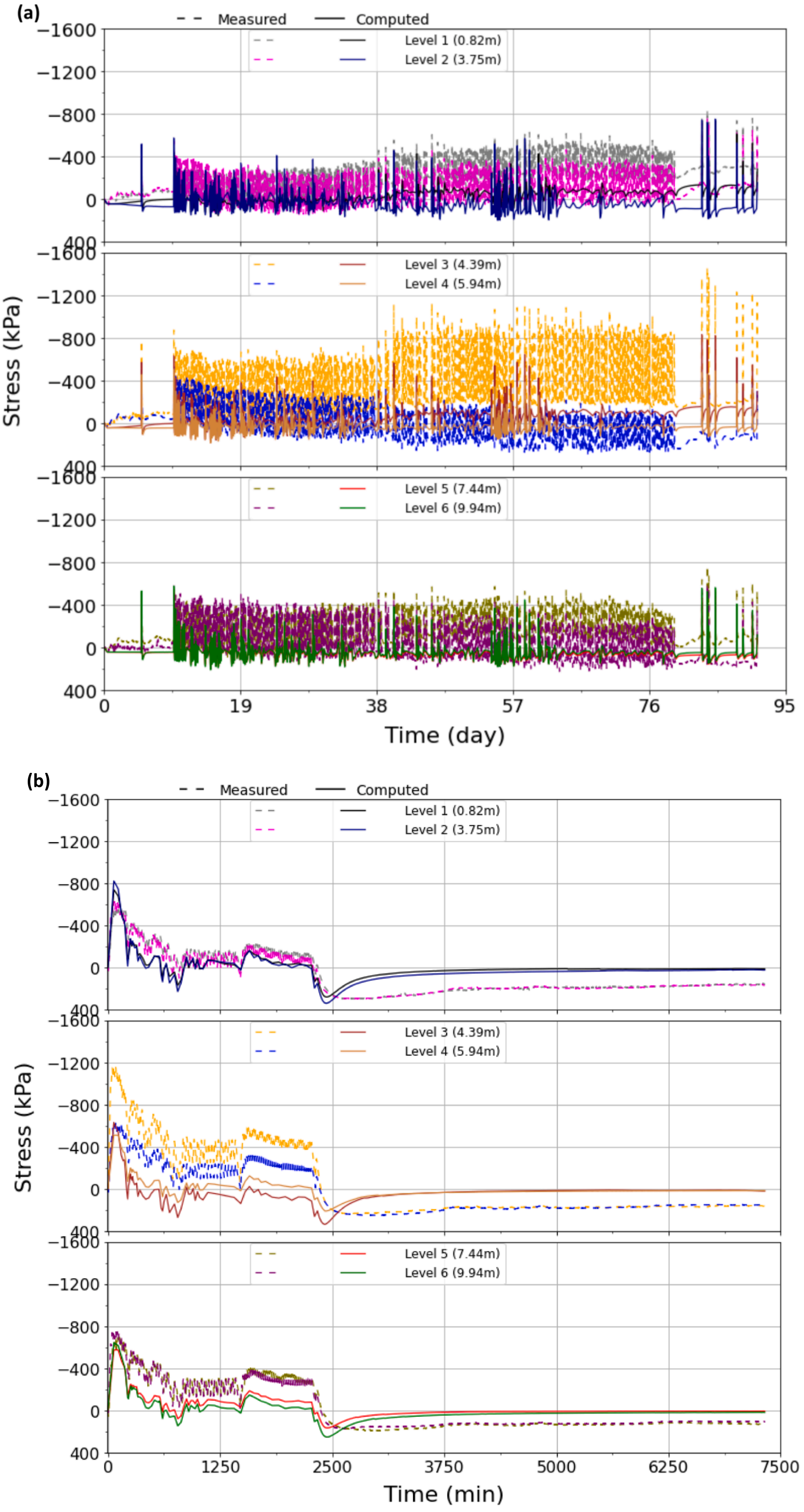

Fig. 8. The computed and measured thermally induced axial stress profiles along the pile shaft during thermal loads versus elapsed time of tests: (a) T_0; (b) T_60.

toward settlement. The impact of the applied mechanical stress on the thermally induced contraction was also experimentally demonstrated by Sittidumrong et al. (2019) and Rafai et al. (2024c, 2025e). The higher the mechanical load, the more complex the stress distribution becomes, increasing the likelihood of approaching the non-linear zone of the pile-soil interface and the soil also approaches the yield surface. As a result, irreversible pile head settlements may occur.

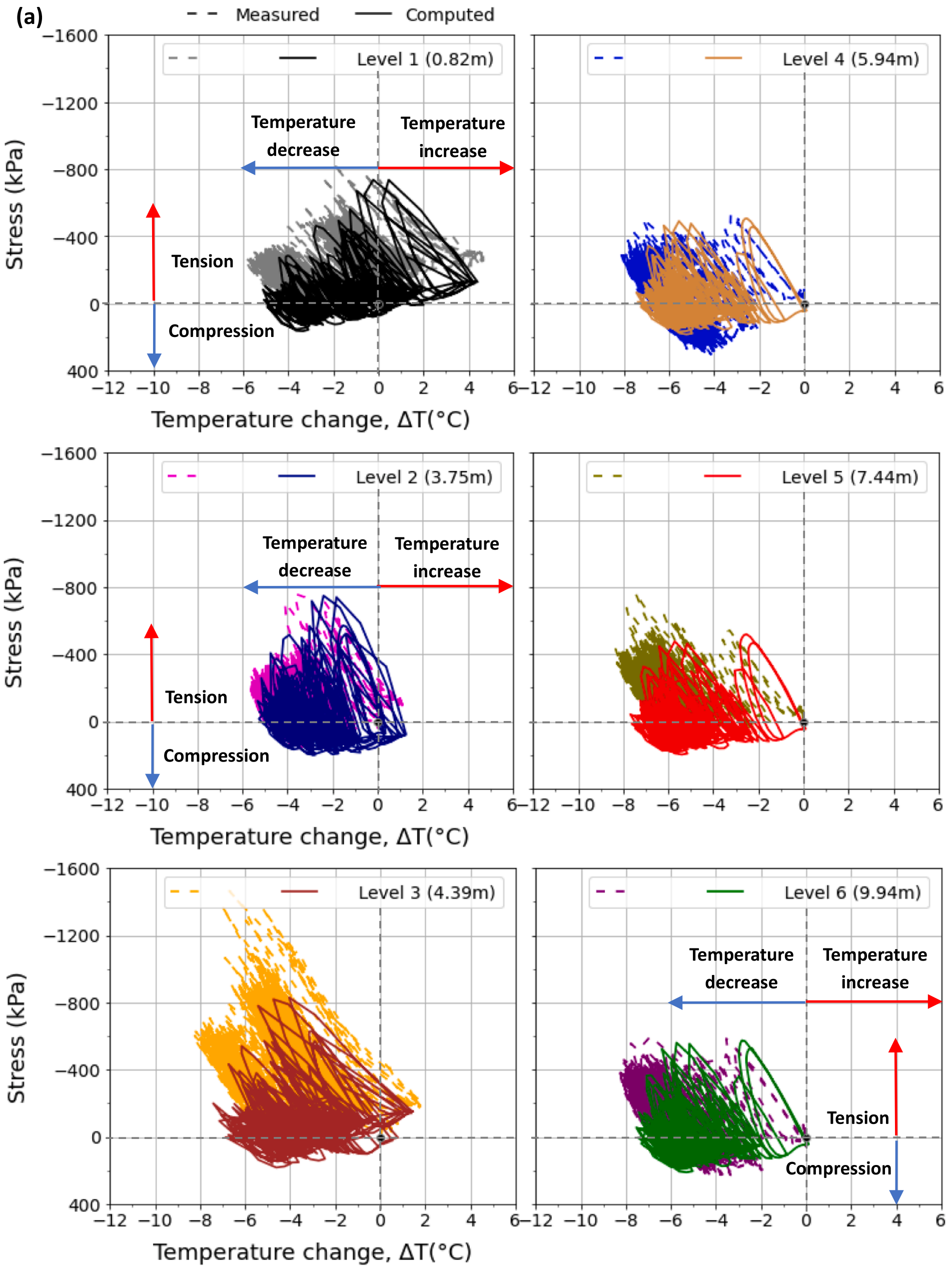

Fig. 9. The computed and measured thermally induced axial stress profiles along the pile shaft during thermal loads versus elapsed time of tests: (a) T_0; (b) T_60.

5.6. *The impact of thermal loads on pile bearing capacity*

Since complete information regarding pile behavior is often challenging in the field conditions, mainly due to the high costs. Alternatively, numerical simulation can be a powerful tool to deepen the understanding of experimental studies.

The good agreement between experimental results and numerical simulations confirms that the numerical analysis can be further used to evaluate the impact of thermal load on the pile bearing capacity.

A bearing capacity test was performed after cooling phases (i.e., T_0 and T_60) using both AVISA and AVISA-T, based on suggestions by EN (1997), with the results shown in Fig. 11. After three months of cooling (T_0), the AVISA-T model (including thermal effects) predicted almost no change in pile bearing capacity. Interestingly, the AVISA model indicated a slight increase in bearing capacity. This increment can be attributed to the elevated temperature at the end of the test, which is expected to induce radial pile expansion and thus promote shaft resistance. In contrast, the AVISA-T model accounts for this radial expansion and also for soil thermal plasticity. These two mechanisms (radial expansion enhancing shaft resistance and soil thermal plasticity), counterbalance each other, in this case resulting in negligible net change in pile capacity. For this reason, the pile head uplift shown in Fig. 10 using AVISA-T is smaller than by using AVISA, as the enhanced version of the model could capture the plasticity of the soils and its resulting impact on the pile bearing capacity.

After test T_60, the simulation with AVISA-T predicted a reduction in pile bearing capacity, whereas the AVISA simulation indicated no change. In the case of AVISA-T, contraction of the surrounding soils led to additional pile head settlement (as shown in Fig. 10) and reduced interface pressure, ultimately lowering pile bearing capacity and contributing to further settlement.

These findings highlight the necessity of advanced constitutive

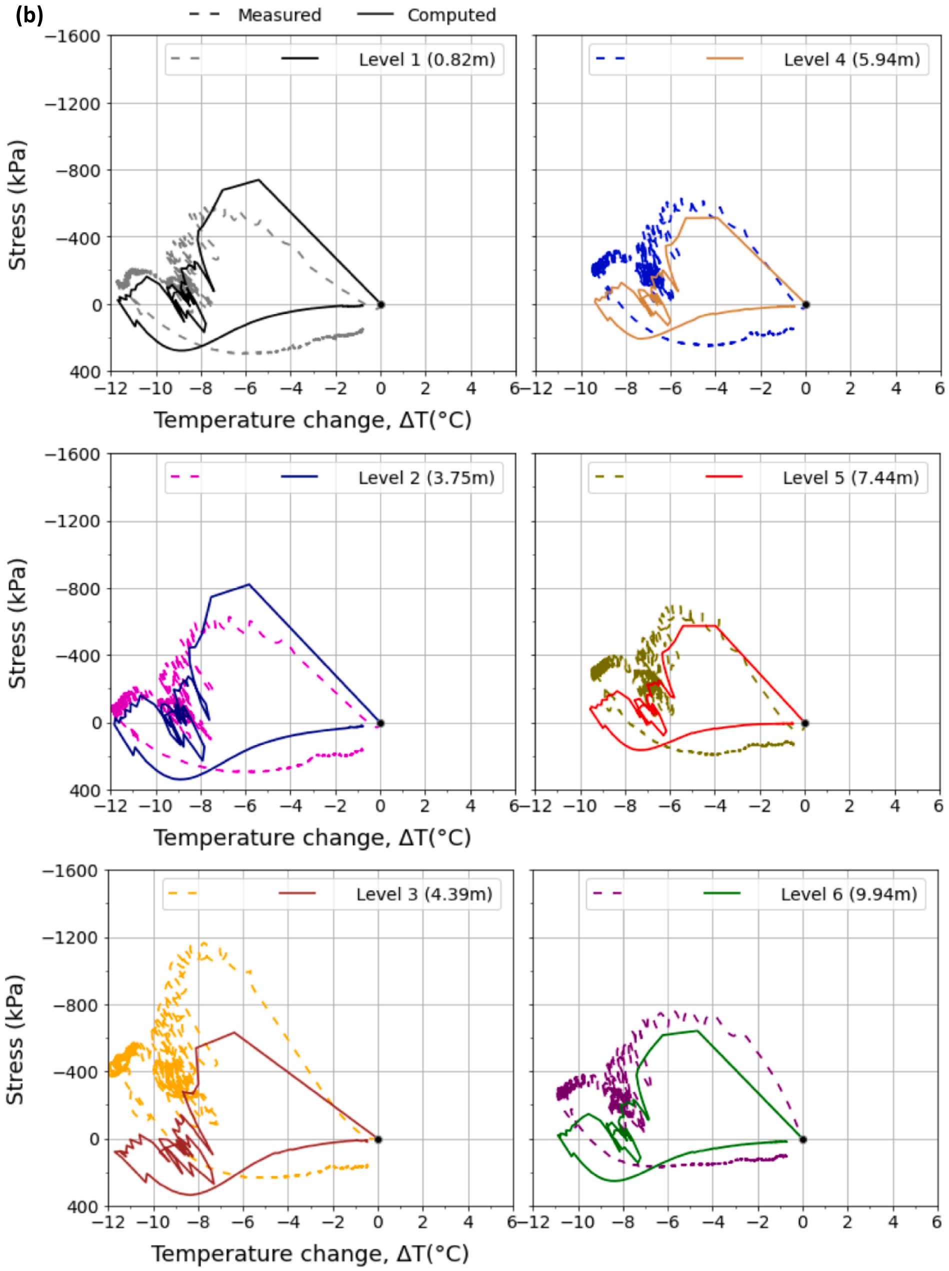

Fig. 9. (*continued*).

models to adequately capture both small- and large-strain mechanisms and their combined effect on pile capacity under thermal loading.

6. Conclusions

An advanced thermo-hypoplastic model named AVISA-T was developed and implemented within a finite element framework to investigate the thermo-mechanical behavior of a displacement cast in-situ semi-floating energy pile embedded in soft soils.

First, the model was well-calibrated using non-isothermal laboratory element tests. Then, it was used to simulate the energy pile response at two constant mechanical load levels and long-term cooling load. The computed results for the energy pile are compared with relevant full-scale in-situ tests. The main conclusions are summarized below:

- Under zero mechanical load, monotonic cooling induced both compressive and expansive strains and stresses, leading to residual compressive or expansive strain/stress along the pile at the end of the test, depending on the depth level. Further, a permanent uplift of the pile head was observed at the end of this test. The proposed model tracked these phenomena well.
- Under a high fixed mechanical load (60 % of the pile bearing capacity), cooling induced compressive residual strains and stresses, along with a higher but limited irreversible pile head displacement, indicating a shift (from pile head uplift to settlement) in the thermo-mechanical response of energy piles due to the combined mechanical and thermal loads. The model satisfactorily predicted the pile response in comparison with field data.
- The results obtained with AVISA-T showed better agreement with the experimental data compared to the reference model, AVISA, or the MCC model never of which accounts for thermo-plastic effects. This highlights the importance of adopting such a thermo-plastic model in engineering practice.

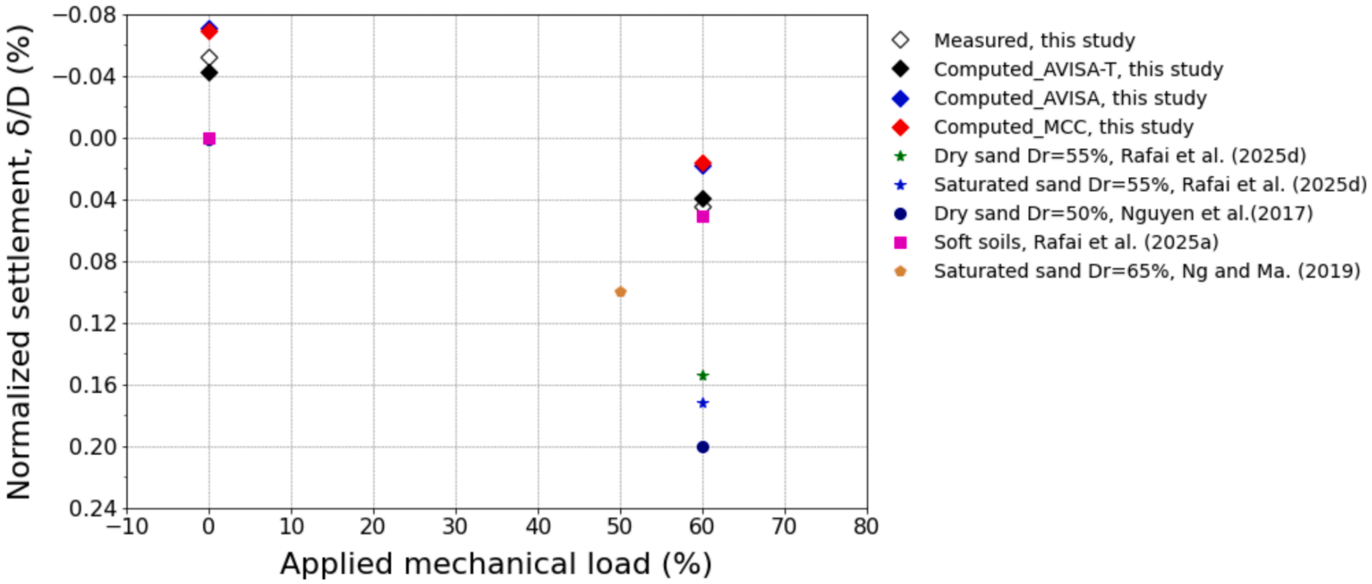

Fig. 10. The measured and computed normalized pile head displacements as a function of applied mechanical load, including field and laboratory data from independent studies.

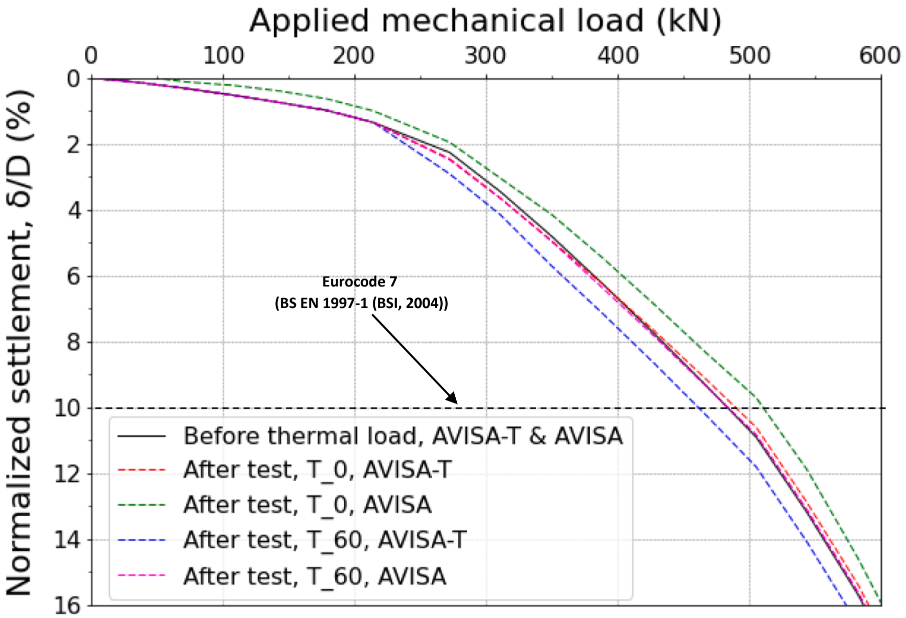

Fig. 11. Load-displacement curves (normalized by pile diameter D).

- The dragdown effect surrounding soils could result in the pile head settlements and reduction of the pile bearing capacity, which in turn may further cause pile head settlements. Such implications could be obtained only by using AVISA-T model. While the conventional version of this model (AVISA) fails to capture the pile behavior.
- This study demonstrates that, with an adequate and well-calibrated constitutive model grounded in physical principles, key mechanisms of energy pile behavior, such as the reduction of the internal stresses due to soil reaction, the coexistence of compressive and tensile stresses, and pile head uplift or settlement, can be effectively captured.
- A limitation that the model was designed for fine grained soils remains, and can therefore not reproduce all behaviors associated with sands. Within certain bounds and carefully selected parameters, the model is shown to be able to reproduce key behavior, i.e. accumulating irreversible deformation during thermal cycles while not showing thermal collapse during heating.

CRediT authorship contribution statement

Mouadh Rafai: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Merita Tafili:** Writing – review & editing, Validation, Funding acquisition. **Yuepeng Dong:** Writing – review & editing, Funding acquisition. **Philip J. Vardon:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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