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Thermo-mechanical aspects of pile heat exchangers

background and literature review

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DEPARTMENT OF CIVIL ENGINEERING
AALBORG UNIVERSITY

Thermo-mechanical aspects of pile heat exchangers: background and literature review

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by

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Abstract

Pile heat exchangers are thermo-active ground structures with built in geothermal heat exchanger pipes. As such, the foundation of the building both serves as a structural component and a heating/cooling supply element. The existing geotechnical and structural design standards do not consider the nature of the thermo-active foundations, what hampers their implementation. Several studies tackle different aspects of the thermo-mechanical behaviour of pile heat exchangers by experimental and numerical approaches. This document aims to compile the main literature in the field. We depart from understanding how an energy pile behaves under mechanical and thermal loads and then, we look into the different aspects affecting the phenomena. It is concluded that, even though the thermal loads resulted from the geothermal use applied to the energy piles are not likely to lead to geotechnical or structural failure, they need to be considered in the analysis and design of such structures. More data under operational conditions will ease the development of regulations and unified guidelines.

Abstract

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Scope

First, the main principles of ground source heat pump (GSHP) systems are presented in order to establish a framework. Then, the main challenges associated to the mechanical aspects of pile heat exchangers are treated. This document does not look into the thermal aspects of energy piles, treated in other documents linked to this series of technical reports.

Foundation piles as ground heat exchangers

Ground source heat pump (GSHP) systems produce renewable thermal energy that offer high levels of efficiency for space heating and cooling [1,2]. Ground heat exchangers are critical components in any GSHP system. Horizontal heat exchangers, vertical borehole heat exchangers and energy piles comprise the main different types of closed loop ground heat exchangers (Figure 1). Energy piles are concrete piles with built in geothermal pipes, i.e., they are thermo-active ground structures that utilize reinforced concrete foundation piles as vertical closed-loop heat exchangers [3]. They vary in length from 7 to 50 m with a cross section of 0.3 to 1.5 m and can be either cast in place or precast driven.

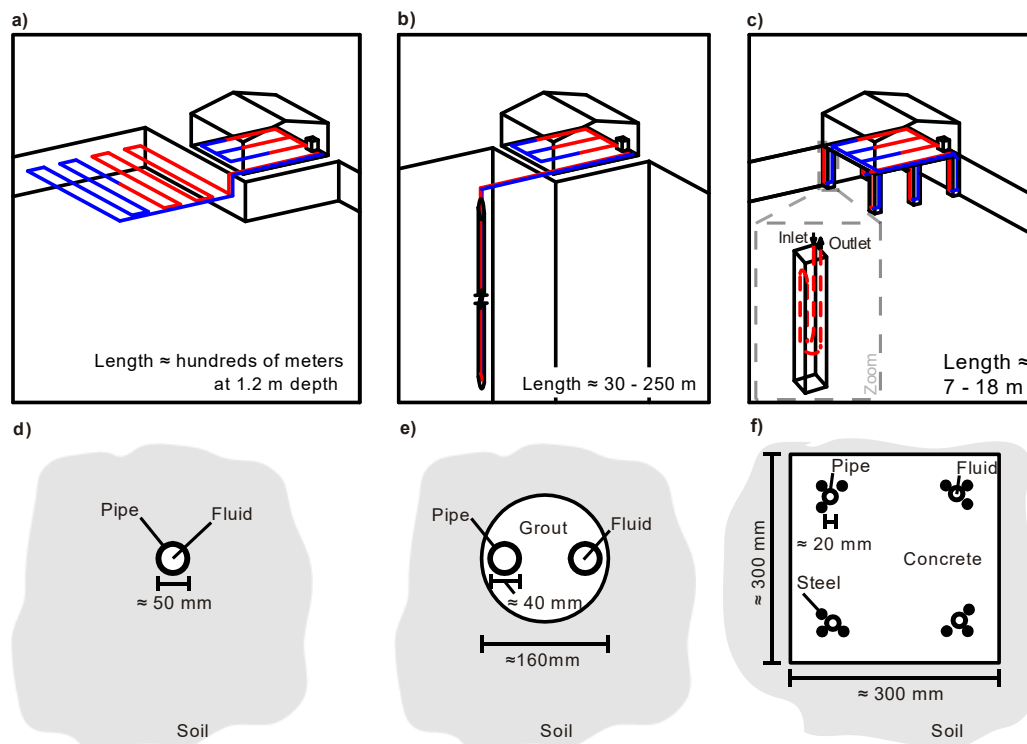


Figure 1: Description of main closed loop GSHP systems: a) horizontal heat exchangers; b) vertical borehole heat exchangers; c) pile heat exchangers. d), e) and f) illustrate the cross sections for horizontal, borehole and pile heat exchangers, respectively. Reproduced after [4].

The foundation of the building both serves as a structural and a heating and/or cooling component. Therefore, different aspects need to be considered (Figure 2). Thermal aspects affect the mechanical behaviour of soils and piles, whereas the influence of the mechanical loads on the temperature field is usually insignificant. Thermal loads may induce changes in pore pressure and in groundwater flow regime and fluids can transport heat through the pores of the soil. Finally, effective stresses are affected by variations of pore pressure [5]. The analysis of pile heat exchangers is mainly governed by thermo-mechanical influences, hence, the focus of this report.

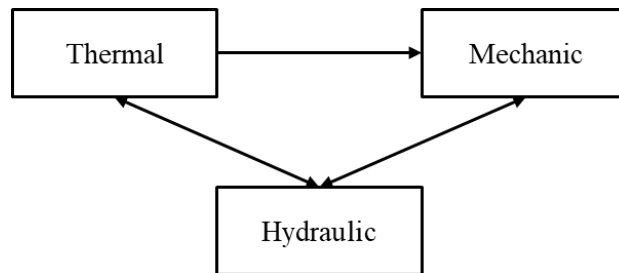


Figure 2: Relevant couplings in shallow geothermal energy systems, after [5].

Load transfer mechanisms of pile heat exchangers

Pile heat exchangers are structural elements subject to time varying thermal loads, additional to those due to static axial loading, and as such, an assessment of the structural implications needs to be carried out in any project. Pile design approaches in Europe are based on the determination of the ultimate and serviceability limit states, ULS and SLS respectively, according to the Eurocode 7 (DS/EN 1997-1/AC, 2010 [6]). Yet regulations do not consider the geothermal use in the foundation design process with regards to structural and geotechnical requirements.

Energy piles will be subject to a net change of the temperature relative to the initial condition over time, which causes thermal stresses and head displacements. Under thermo-elastic conditions, if the pile is a free body, i.e. it has no restraints, it will expand while heating and contract during cooling to yield a thermal free strain ε_{T-Free} :

$$\varepsilon_{T-Free} = \alpha \cdot \Delta T \quad (1)$$

where α [1/K] is the coefficient of thermal expansion of the reinforced concrete and ΔT [K] is the net change in temperature of the pile. This strain will provoke a change in the pile geometry and this way no axial load will be mobilised:

$$\Delta L = L_0 \cdot \varepsilon_{T-Free} \quad (2)$$

Where ΔL [m] is the change in length caused by the temperature change and L_0 [m] is the initial length of the body. If the pile is perfectly restrained, it will keep its length, but thermally induced stresses will be created $\Delta\sigma_T$ [N/m²]:

$$\Delta\sigma_T = \alpha \cdot \Delta T \cdot E \quad (3)$$

where E [MPa] is the Young's modulus of the pile material.

In reality, a pile will not expand or contract freely as it will be confined by the structure on top and the surrounding soil, at different levels of restraint (Figure 3). As a result, the measured strain changes due to temperature changes ε_{T-Obs} will be less than the free axial thermal strain ε_{T-Free} [7]:

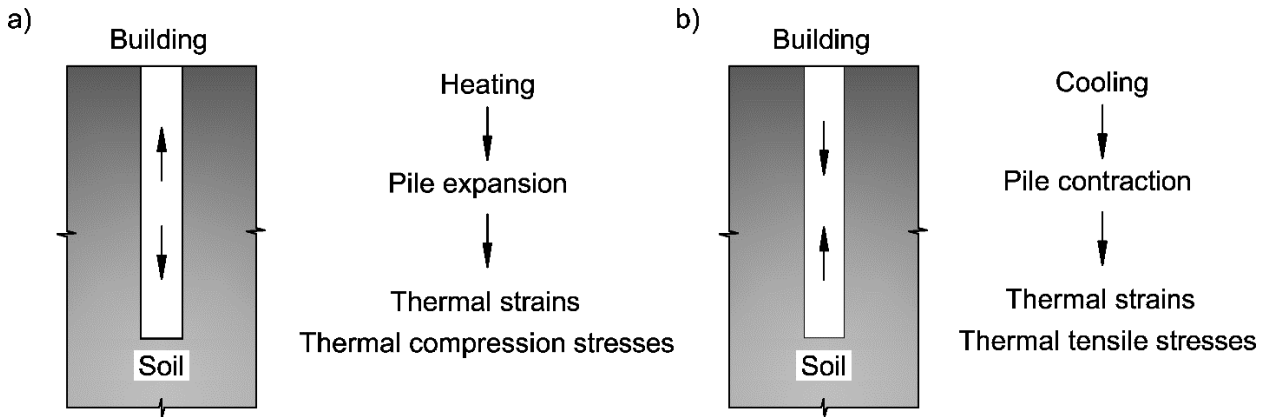


Figure 3: Response mechanism of a pile heat exchanger to thermal loading; a) for heating and b) for cooling. Reproduced after [8].

$$\varepsilon_{T-Free} \geq \varepsilon_{T-Obs} \quad (4)$$

From here, the restrained axial strain ε_{T-Rstr} can be estimated as:

$$\varepsilon_{T-Rstr} = \varepsilon_{T-Free} - \varepsilon_{T-Obs} \quad (5)$$

The restrained strain provokes a thermal stress in the pile and the thermally induced axial load P_T [N] for a given strain increment is calculated as:

$$P_T = -E \cdot A \cdot \varepsilon_{T-Rstr} = -E \cdot A \cdot (\alpha \cdot \Delta T - \varepsilon_{T-Obs}) \quad (6)$$

where A [m²] is the cross-sectional area of the body. When a mechanically loaded pile is heated or cooled, the total mobilised strain ε_{Total} is the sum of the mechanically imposed strain ε_M and thermal strains ε_{T-Obs} :

$$\varepsilon_{Total} = \varepsilon_M + \varepsilon_{T-Obs} \quad (7)$$

The mechanical strain is directly developed by a mechanical load P_M applied in the pile head:

$$P_M = -E \cdot A \cdot \varepsilon_M \quad (8)$$

Consequently, the total load P_{Total} is the sum of the mechanical load P_M and the thermal load P_T :

$$P_{Total} = P_M + P_T \quad (9)$$

Pile foundations are used when settlements of buildings need to be limited, to increase bearing capacities or to reach a deeper soil layer which is more resistant. Therefore, the geotechnical bearing capacity of the pile and the prediction of its displacements need to be considered when designing a pile [9].

Under structural (mechanical) load only (Figure 4a), the maximum axial stress is found at the pile head, reducing with depth as load is transferred into the ground by the shaft friction (or side shear resistance) mobilised at the soil-pile interface. I.e., the surrounding soil confines the movement of the pile and mobilises the reaction forces along the pile shaft and the pile toe. The axial stress will decrease to zero if the shaft resistance is enough to support the building load; otherwise, the remaining load is transferred at the pile toe and supported by the underlying material, known as end-bearing resistance [10–12].

The maximum load that an axially loaded pile can support Q_{LIM} is defined as a sum of the tip (toe or base) and friction (side shear or shaft) resistances:

$$Q_{LIM} = Q_S + Q_P - W_P \quad (10)$$

Where Q_S is the share of the pile bearing capacity provided by the friction between the pile and the soil and Q_P is the share of the pile bearing capacity delivered by the soil below the pile tip and W_P is its own weight. The tip resistance Q_P depends on the resistance of the soil below the pile toe (undrained shear strength and vertical stress) whereas the shaft resistance Q_S depends on the friction angle at the interface and the stress state of the pile-soil interface. The total load applied to the pile P_{Total} should be less than the design limit, considering a safety factor [6].

Depending on the way the load is transferred to the soil, we may find three different types of piles: i) end-bearing piles where the main resistive mechanism is the pile tip resistance; ii) floating piles (a.k.a. friction piles or surface bearing piles) where the shaft friction provides the main resistance capacity; iii) semi-floating piles which involve an intermediate configuration between the previous two.

The pile-soil interaction under working mechanical and thermal loads provokes complex systems which depend on: ground conditions, different levels of pile confinement and magnitude of the thermal loads. Therefore, the behaviour of the piles is place dependent and it makes it hard to establish general rules. Fortunately, simple descriptive mechanistic frameworks have been established based on observed behaviours, which make it easier to understand the phenomena [13–15].

In the following the main load transfer mechanisms occurring due to combined mechanical and thermal solicitations are described. Simplified axial load and shaft resistance distribution diagrams are shown where the effect of standard mechanical load and combined thermo-mechanical loads are described. A soil with uniform strength, a linear elastic pile with constant cross-sectional area and a linear variation in strain and load along the pile's length are considered. When temperature changes are applied, the change is considered uniform over the pile length.

Figure 4 represents a floating pile heat exchanger. It is assumed that the mechanical load (Figure 4a) will be resisted by the shaft resistance, which is assumed uniform along the shaft for this simple model. When cooling occurs, the pile contracts and any restriction offered to the pile shaft will lead to tensile strains and stresses developing. Along the upper part of the shaft, shear stress on the pile-soil interface will be mobilised in the same direction as that mobilised by compression loading applied at the pile head. It will take the opposite direction in the lower part of the pile (Figure 4b). When heating (Figure 4d), the pile expands, and any restriction offered to the pile shaft will lead to compressive strains and/or loads developing. At the shaft resistance development, the opposite effect to a cooling load will occur. Shear on the pile-soil interface will have the same direction in the lower part of the pile and will oppose that induced by compressive pile loading in the upper. When cooling occurs in combination with compression loading (Figure 4c), axial loads become less compressive (potentially tensile stresses), while the mobilised shaft resistance reduces in the lower part of the pile and increases in the upper part. When a heating cycle is applied to a pile under compressive mechanical load (Figure 4e), the axial load will become more compressive and while the mobilised shaft resistance reduces in the upper part of the pile, it increases in the lower part.

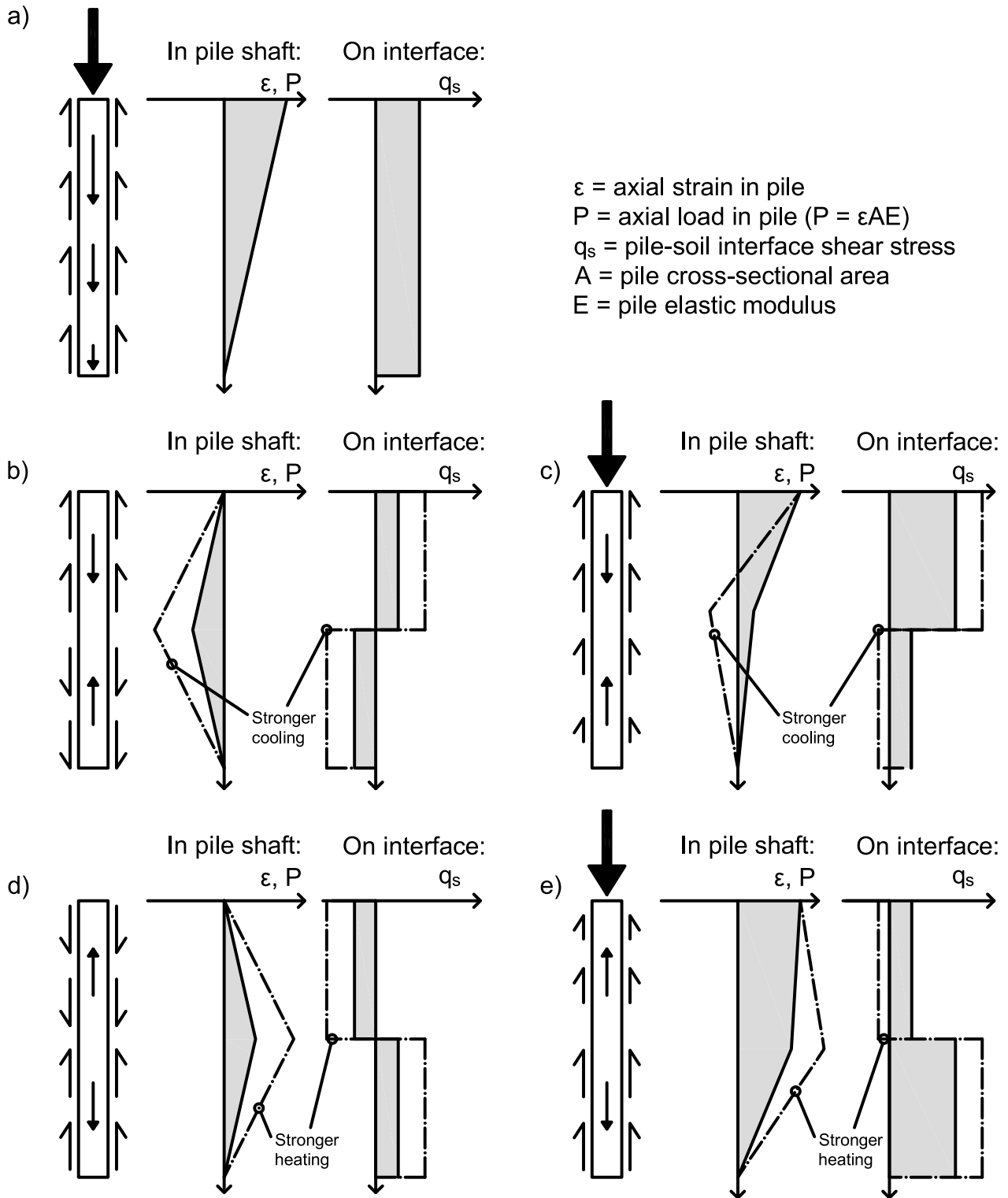


Figure 4: Response mechanism for pile undergoing thermo-mechanical loading: heating and cooling with no end restraint: a) load only; b) cooling only; c) combined load and cooling; d) heating only; e) combined load and heating. After [13]. The figure is not to scale neither to relative scale.

Figure 5 represents the effects of end-restraints, provided by the building and a stiff bearing layer around the tip. During heating, the restricted pile expansion strains will generate additional compressive stresses. Therefore, the resultant load profile will change depending on the relative stiffness of the end-restrains (Figure 5a). And because of the restrained axial deformation, the mobilised shaft resistance will be less than for the case of the pile without end-restraint. Pile cooling will result in opposite responses (Figure 5b) [16].

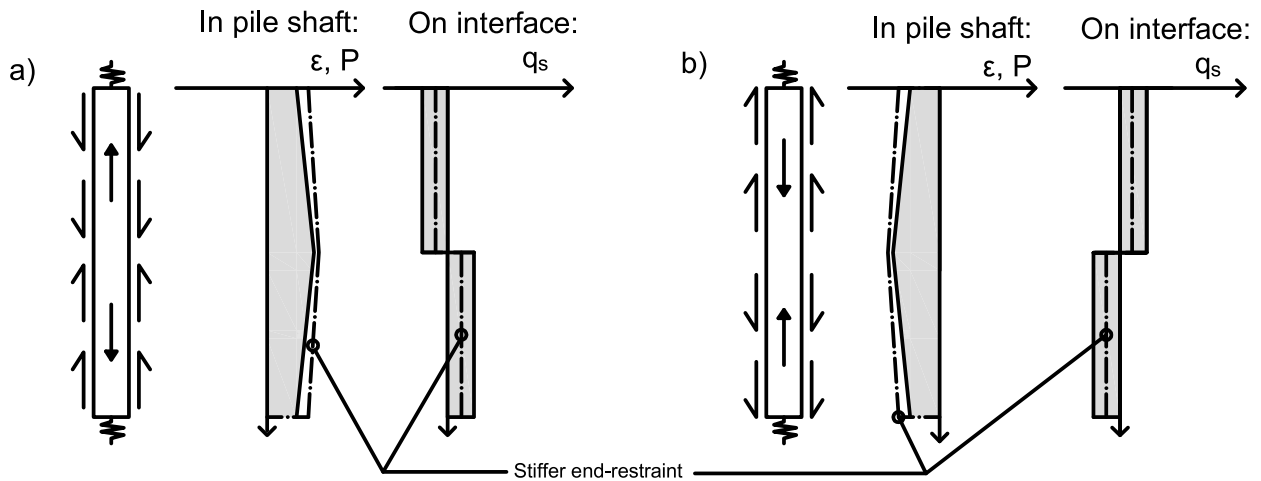


Figure 5: Effect of end-restraint on the thermal response: a) pile heated; b) pile cooled. After [16]. The figure is not to scale neither to relative scale.

A pile heat exchanger will expand or contract at different levels of restraint [7]. The level of restraint n is defined as the ratio between the observed and the free axial strains [15] and it is minimal in the null-point, which represents the plane where zero thermally induced displacement occurs in the pile [17]:

$$n = \frac{\varepsilon_{T-Obs}}{\varepsilon_{T-Free}} \quad (11)$$

The section of the pile above the null point experiences upward displacements when heated and downward displacements during cooling, whereas the pile section below the null point experiences downward displacements during heating and upward movements when cooled down. As it has been shown in Figures 4 and 5, as a result of the temperature change, the mobilised end-bearing and shaft resistances of energy piles will vary and will be redistributed according to the position of the null point [18].

Influence of temperature on soil behaviour

In the previous section, it has been described how the load transfer from the pile to the soil is expected to rearrange due to temperature variations of the pile. In the following, it is analysed whether the temperature variations resulted from the geothermal use affect the stress state at the pile-soil interface and the shear strength of the soil. I.e., a review of the influences of temperature on the soil resistance parameters is provided.

The temperature range imposed by the geothermal exploitation of the foundations are relatively modest, falling between 2 °C to 30 °C [15], and the nature of the ground thermal loads depend on the needs of the building [19]. The upper temperature limit might be more restrictive due to environmental regulations. E.g. in Denmark, the injection temperature can be limited to 25 °C [20]. Ref. [21] shows operational temperatures in cooling mode of a 1.2 m diameter energy pile, with centrally placed pipes: the temperature of the fluid in the geothermal pipes shows quick variation in response to the building thermal needs while the temperature changes near the edge of the pile are smoother. The changes in pile temperature in the centre vary from 12.5 °C (end of winter) to 27 °C (end of summer), while the corresponding temperatures near the edge vary from 14 °C to 19 °C. Therefore, any temperature change in the ground will show rather small amplitude and seasonal period. The temperature disturbance and its magnitude in the pile-soil system will also depend on the thermal properties of the concrete and the surrounding soil. Hence, an assessment of the induced temperature changes with respect to the initial undisturbed temperature needs to be carried out in order to estimate the induced thermal stresses and strains.

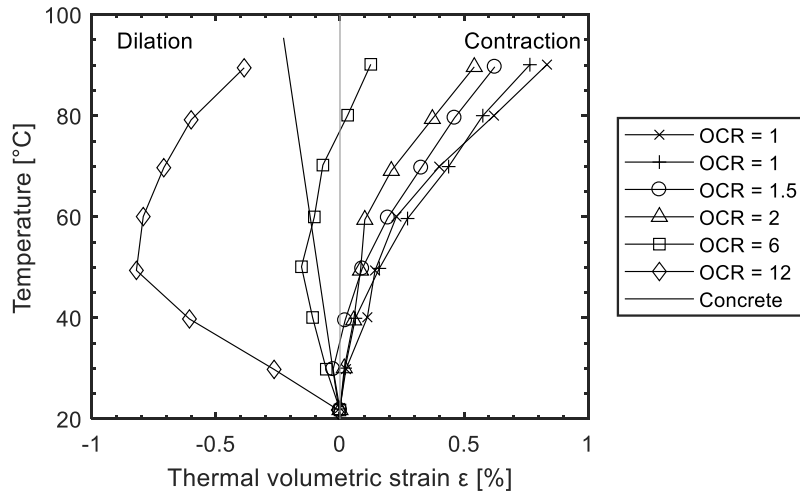
Soil behaviour

The temperature dependency of the geotechnical properties of the soil has mainly been treated by the nuclear waste disposal research, where much greater temperature variations are expected [21]. The principal thermo-hydro-mechanical processes that affect the mechanical behaviour of soils are the thermal hardening, the thermally induced water flow, the excess pore pressure development and the volume changes due to thermal consolidation, possibly the most critical factor [21,22].

When a thermal load is transmitted from the pile to the soil, the soil reacts by changing its volume (expansion or contraction of the porewater and soil structure) and by modifying the strength of contact between soil particles [23,24]. Coarse-grained soils do not seem to be affected by temperature variations due to their drained behaviour [25]. On the other hand, fine-grained soils show a densification and a reduction in the undrained shear strength with increasing temperature due to an increase in the pore water pressure that cannot be dissipated. This results in a reduction in effective stresses (short-term). Ref. [26] reported that an excess pore water pressure of 0.7% of the effective stress is generated by 1 °C increase in soil temperatures. In the long term (drained

conditions), the behaviour differs for over- and normally-consolidated clays since the void ratio might increase for the first while it may decrease for the latter (Figure 6a) [7]. Normally consolidated clays show an irreversible volume change while highly over-consolidated clays show reversible behaviour, as shown in Figure 6b. The thermally induced volumetric strains expected for energy pile applications fall in the lower part of the curves in Figure 6, where the thermally induced volumetric strains are very low. To the knowledge of the authors, the range from 0 to 10 °C has not been measured.

a)



b)

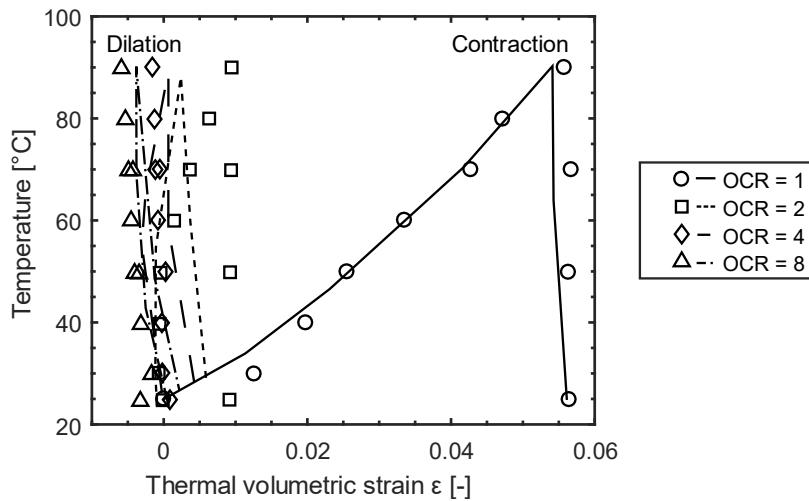


Figure 6: a) Thermal volumetric strain of Kaolin clay during drained heating from 22 to 90 °C; initial consolidation pressure 600 kPa, after [27] and [28]. b) Numerical simulations of a heating-cooling cycle at different degrees of consolidation under oedometric conditions (vertical preconsolidation pressure= 200 kPa). Points: experimental results; lines: numerical simulations, after [29]. OCR stays for Over-Consolidation Ratio, defined as the ratio of the vertical effective preconsolidation stress to the current effective stress.

According to [21], soft normally consolidated clays require main attention because large plastic volume changes may occur upon heating. However, after hardening, further cycles of temperature

change within the same temperature range will show an elastic behaviour. Hence, temperature changes can affect the stress state at the pile-soil interface and the shear strength of the soil that affects the tip resistance of the pile [22].

The stress and strain relations occurring in soils due to temperature changes is described by constitutive models. Ref. [30] proposed a thermo-plastic model based on the modified cam-clay and Prager's thermo-plasticity theory. Ref. [29,31] developed a thermo-elastoplastic model, which considers the possible plastic behaviour under non-isothermal conditions. This type of models define yield surfaces that depend on temperature and outside their limits, the soil behaves thermo-plastically. Further discussions and literature reviews are available in [5,32].

Soil-pile interface behaviour

Recent studies on the impact of thermal loading at the pile-soil interface indicate that the pile bearing capacity is not reduced to a critical level in terms of structural integrity [7,9,33,34]. Mechanical cyclic load studies of the pile-soil interface at +1.1 °C to -16 °C are reported by [35–37] but studies of the long-term behaviour of energy piles under cyclic thermal loads for the operational range have not been reported. Ref. [9,34] have analysed monotonic temperature variations in the range from 6 °C to 50 °C - 60 °C and have concluded that higher temperatures increase the strength of the clay-concrete contact. This is explained by the thermal consolidation of the clay that results in an increase of the contact surface, even though the interface friction angle is reduced. Ref. [38] analysed the interface between concrete and a low plasticity clay and observed no impact of temperature on the interface shear strength as observed in Figure 7. The sand-concrete interface is hardly affected by the monotonic temperature changes [9].

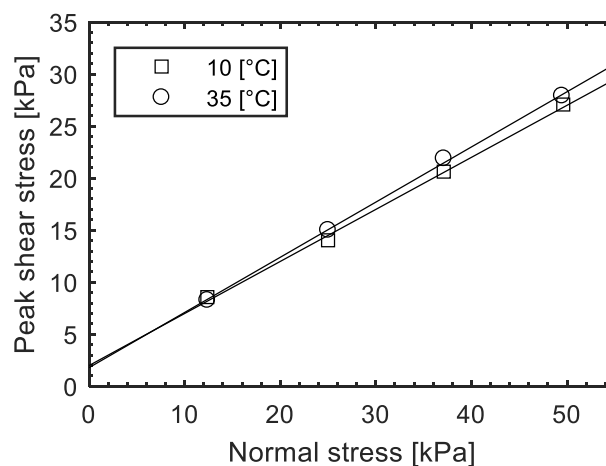


Figure 7: Clay/concrete interface behaviour assessed using thermal borehole shear device. Impact of temperature on failure envelope, after [38].

In order to characterize the degradation of the pile-soil interface under thermal cyclic loads, constitutive laws, such as the Modjoin law [39] and numerical models [40,41], can be applied to reproduce the cyclic behaviour of energy piles.

Observed behaviour of energy piles

The main research programs covering the thermo-mechanical behaviour of the energy pile-soil systems encompass full-scale, lab-scale and numerical studies which are shortly described in the following and in appended tables. A comprehensive review on published studies is available in [26].

Full-scale setups

Two main full scale studies of energy piles have led the investigation in the field: the Lambeth College setup in London [13,42], which behaves as a floating pile, and the EPFL setup in Lausanne [33,43,44], which shows a semi-floating behaviour. Both studies conclude: i) short-term plastic response of soils has not been observed due to the geothermal use since effective stresses typically are within yield surfaces, i.e., within the thermo-elastic domain; ii) the additional stresses produced in the energy pile due to thermal loads depend on the level of restraint of the pile, i.e., they depend on the allowance of the pile to move (expand or contract).

Full scale demonstrations of precast energy piles have also been reported in [45]. The 17.4 m long pile, with a 35-cm side size and centrally placed pipes, is subjected to 14 cycles of heat injection at 80 W/m during 14 hours per day, resembling cooling operation mode. The results show that the increase of the axial load in the pile (compared to the existing mechanical) is in the order of 12% and that the maximum increase of temperature in the pile during the test does not reach 5 °C at any depth. The maximum displacement observed during heating is 0.4 mm after 6 cycles and the elastic recovery is 0.2 mm. An accumulated permanent upward displacement of 0.2 mm is measured. The recovery to initial conditions is not shown.

A similar behaviour has been reported in [46], where the thermal strains and stresses for intermittent tests (20 days long at different operation modes resembling building heating, i.e., pile cooling) were cyclic and returned to initial values, i.e., the pile experiences thermo-elastic behaviour for daily thermal cycles. The maximum thermal strain measured 0.09 mm downwards and the thermally induced average stress are around 900 kPa for 8 hours working cycles. The absolute decrease of temperature in the pile at the end of the test is 9 °C and 10 °C, for 8 hours and 16 hours operation cycles, respectively. It was concluded that intermittent operation (resembling operational conditions) is advantageous in terms of generating lower pile thermal loading for long term operations and regarding a more efficient heat transfer capacity than a continuous operation.

As a rule of thumb, it could be said that 1 °C of increased temperature results in an increase of the pile axial stress of approximately 100 - 200 kPa and a change in mobilised shaft friction at the soil-pile interface of - 2.1 to + 2.5 kPa, corresponding to the upper- and the lower-half of the pile [13,14,43].

Group effects

Current research focuses on the analysis of energy pile group effects [44,47–50]. Combined experimental and numerical studies of energy piles operating in groups [51] suggest that the assessment of thermally induced vertical strains needs to be assessed by considering group effects. This happens because, as the number of operating energy piles increases, higher thermally induced vertical strains arise. Conversely, as the number of operating energy piles increases, lower thermally induced vertical stresses arise. Hence, analyses of single energy piles are valid and conservative for the assessment of additional stresses. In addition, the same authors suggest in [48] that the serviceability mechanical performance of energy pile groups (i.e., deformation related) depends on the relative thermally induced deformation of the soil to that of the energy piles, i.e., the ratio between the linear thermal expansion coefficient of the soil and the pile. Meaning that in the long term, if the thermal expansion coefficient of the soil exceeds the pile's, the deformation of energy pile groups is governed by the thermally induced deformation of the soil surrounding the piles.

Numerical studies

Numerical tools are used to analyse not just experimental conditions but also potential scenarios, supporting the understanding of the physics behind the problem and assisting the development of behavioural rules. Several numerical studies explore the thermo-mechanical phenomena of energy piles by different methods. Regarding load transfer mechanisms, [43,52–54] encompass good examples of finite element models validated with experimental data. The load transfer method [15,55], modified to account for thermal loads has been used by [15,18,40,56,57]. This method allows reliable analysis of mechanical and monotonic thermal changes in a practical way. Computational tools such as ThermoPile [58] and Oasys Pile [59] have been developed based on this approach. Ref. [26,40,60] have adapted the load transfer model to account for cyclic thermal loads.

Operational demonstration

Ref. [61] analyses two energy piles that have been coupled to a conventional GSHP system. Measurements under operational conditions over a period of 658 days show fluid temperatures ranging from 7 to 35 °C. It concludes that the values of thermal axial displacement and the thermo-mechanical axial stresses are within reasonable limits and are not expected to cause any structural damage to the building. However, it is highlighted that in complex soil layers, the pile soil systems might not behave in a thermo-elastic manner in the long term. This is also in accordance with

numerical studies [54] that highlight that it is critical to maintain stable temperature of the ground over seasons for long-term sustainability of heat exchange operations to avoid potential plastic effects on the soil around the piles. Ref. [3] states that appropriate operating conditions of energy pile installations, where the temperatures range from 5 to 20 °C, hardly affect the shaft resistance of the pile. More operational data will aid the understanding of the performance of energy foundations in terms of structural integrity.

Recent developments on the design of energy pile foundations

Regulations do not consider the geothermal use in the foundation design process with regards to geotechnical and structural requirements. To ensure that the geotechnical performance of the pile is not negatively affected, conservative safety procedures are applied, which potentially reduce their cost-effectiveness. The fluid temperature in the ground loop is not allowed to go below 0 - 2 °C, to avoid freezing of the pile interface, and there is a tendency to place more energy piles than required [7,33,62–65].

The analysed research concludes that the thermal loads and displacements resulted from the geothermal use of the energy piles are not likely to lead to geotechnical or structural failure. However, energy piles are structural elements and they need to be treated as such. Therefore, the energy pile design needs to integrate geotechnical, structural and heat transfer considerations [66].

Ref. [57] launched the development of a design method that could be incorporated within the Eurocode agenda, based on the load transfer method. The pile (15 m long and 0.6 m square section) head-building structural interaction was modelled by means of a spring restraint with different stiffness. For a typical application of +10 K temperature change from initial undisturbed soil temperature and a 200 MN/m pile head stiffness, the thermally induced compression axial load is 175 kN and the pile heave, 0.5 mm. See Figure 8 for more stiffness. A discussion about this can be followed in [67,68].

To build a design framework, it needs to be decided how the thermal loads derived from the geothermal use are considered in the load combination processes and whether their consideration is relevant just for SLS or it also needs to be addressed in ULS.

Ref. [18] demonstrated that under monotonic thermal loading the null point (previously described) will always move towards the pile end in order to maintain the equilibrium, even if the ultimate bearing force (friction and base) is mobilised, as it happened at the Lambeth College pile [13]. Regarding serviceability, it was demonstrated that over-sizing energy piles, by projecting a longer length, can have a negative impact. This happens because the null point will prevent excessive settlement/heave since at least, this point remains stable under temperature variations. If a pile is over dimensioned

structurally, the head heave or settlement will increase with temperature because there is a considerable amount of bearing force that the pile could still mobilise after mechanical loading. This has been observed in the Lambeth College test pile [18]. Therefore, enlengthening for geothermal reasons could go against safety.

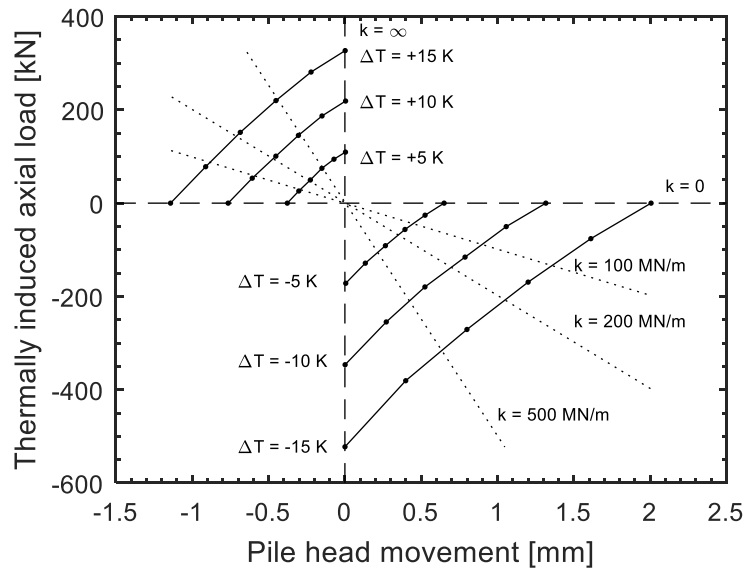


Figure 8: Interaction diagram relating change in thermally induced pile axial load and pile head movement as function of applied temperature change and pile head stiffness, after [57].

Based on these findings, the EPFL research team has continued developing a method to consider the thermal loads within the Eurocode framework. The latest work is still under review [69], but personal communication with the authors and the recent attendance to a course in EPFL [70], provided the following main outcomes:

The thermal loads are deformation related problems. Hence, for geotechnical design, the thermal loads are more relevant in SLS than in ULS. This happens because the presence of the null point will always ensure equilibrium with regards to a collapse mechanism. Hence, it should suffice with checking that the thermally induced pile head heave or settlement resulted from thermal expansion or contraction, respectively, remain within acceptable limits for the structure. For this verifications, numerical tools such as the load transfer method [15,26,40,60,71], can be used. Stresses caused by thermal loads may be generated in the reinforced concrete section. Hence, sufficient compressive and tensile strengths need to be ensured to verify structural ULS [26]. Extensive reviews about this topic are available in [10,67,68].

Conclusions

The literature review shows a vast amount of information and studies regarding thermo-mechanical aspects of pile heat exchangers. However, more data of the thermo-mechanical behaviour under operational conditions is required to ease the development of regulations and unified guidelines and to boost the implementation of this technology.

The analysed research concludes that the thermal loads and displacements resulted from the geothermal use of the energy piles are not likely to lead to geotechnical or structural failure. However, energy piles are structural elements and they need to be treated as such. Therefore, the energy pile design needs to incorporate geotechnical, structural and heat transfer considerations.

The induced thermal stresses and strains depend on the temperature change caused by the ground thermal load, which results from the building heating and/or cooling needs. The temperature disturbance and its magnitude in the pile-soil system will also depend on the thermal properties of the concrete and the surrounding soil. Hence, a prior assessment of the induced temperature changes with respect to the initial undisturbed temperature needs to be carried out in order to estimate the induced thermal stresses and strains. The ULS and SLS verifications for geotechnical design can be addressed by numerical tools such as the load transfer method.

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References

- [1] S.J. Rees, 1 - An introduction to ground-source heat pump technology, in: *Adv. Ground-Source Heat Pump Syst.*, Woodhead Publishing, 2016: pp. 1–25. doi:<http://dx.doi.org/10.1016/B978-0-08-100311-4.00001-7>.
- [2] J.W. Lund, T.L. Boyd, Direct utilization of geothermal energy 2015 worldwide review, *Geothermics*. 60 (2016) 66–93.
- [3] H. Brandl, Energy foundations and other thermo-active ground structures, *Geotechnique*. 56 (2006) 81–122. <http://www.scopus.com/inward/record.url?eid=2-s2.0-33644596527&partnerID=40&md5=778cc8fddf57ca9555395cb6465c77e8>.
- [4] M. Alberdi -Pagola, S.E. Poulsen, F. Loveridge, S. Madsen, R.L. Jensen, Comparing heat flow models for interpretation of precast quadratic pile heat exchanger thermal response tests, *Energy*. 145 (2018) 721–733. doi:10.1016/j.energy.2017.12.104.

- [5] A. Vieira, M. Alberdi-Pagola, P. Christodoulides, S. Javed, F. Loveridge, F. Nguyen, F. Cecinato, J. Maranhã, G. Florides, I. Prodan, G. Van Lysebetten, E. Ramalho, D. Salciarini, A. Georgiev, S. Rosin-Paumier, R. Popov, S. Lenart, S.E. Poulsen, G. Radioti, Characterisation of Ground Thermal and Thermo-Mechanical Behaviour for Shallow Geothermal Energy Applications, *Energies* . 10 (2017). doi:10.3390/en10122044.
- [6] DS/EN 1997-1/AC, Eurocode 7: Geotechnical design - Part 1: General rules, (2010).
- [7] GSHP Association, Thermal Pile: Design, Installation & Materials Standards., (2012). http://www.gshp.org.uk/pdf/GSHPA_Thermal_Pile_Standard.pdf.
- [8] M. Alberdi-Pagola, S. Madsen, R.L. Jensen, S.E. Poulsen, Numerical investigation on the thermo-mechanical behavior of a quadratic cross section pile heat exchanger, in: Proc. IGSHPA Tech. Conf. Expo, Denver, USA, March 14-16, 2017. doi:<http://dx.doi.org/10.22488/okstate.17.000520>.
- [9] A. Di Donna, L. Laloui, Thermo-mechanical aspects of energy piles, École polytechnique fédérale de Lausanne EPFL, 2014. doi:doi:10.5075/epfl-thesis-6145.
- [10] C.G. Olgun, J.S. McCartney, Outcomes from international workshop on thermoactive geotechnical systems for near-surface geothermal energy: from research to practice, *DFI Journal-The J. Deep Found. Inst.* 8 (2014) 59–73. doi:<https://doi.org/10.1179/1937525514Y.0000000005>.
- [11] K.D. Murphy, J.S. McCartney, K.S. Henry, Evaluation of thermo-mechanical and thermal behavior of full-scale energy foundations, *Acta Geotech.* (2014) 1–17.
- [12] M.E. Suryatriyastuti, S. Burlon, H. Mroueh, On the understanding of cyclic interaction mechanisms in an energy pile group, *Int. J. Numer. Anal. Methods Geomech.* 40 (2016) 3–24.
- [13] P.J. Bourne-Webb, B. Amatya, K. Soga, T. Amis, C. Davidson, P. Payne, Energy pile test at lambeth college, London: Geotechnical and thermodynamic aspects of pile response to heat cycles, *Geotechnique*. 59 (2009) 237–248. <http://www.scopus.com/inward/record.url?eid=2-s2.0-58049214205&partnerID=40&md5=8847275985af4148a4ad28dad671efb6>.
- [14] B.L. Amatya, K. Soga, P.J. Bourne-Webb, T. Amis, L. Laloui, Thermo-mechanical behaviour of energy piles, *Geotechnique*. 62 (2012) 503–519. <http://www.scopus.com/inward/record.url?eid=2-s2.0-84871024108&partnerID=40&md5=fda0d47a907be64a2115ed30ee55c501>.
- [15] C. Knellwolf, H. Peron, L. Laloui, Geotechnical analysis of heat exchanger piles, *J. Geotech. Geoenvironmental Eng.* 137 (2011) 890–902.

- [16] P.J. Bourne-Webb, B. Amatya, K. Soga, A framework for understanding energy pile behaviour, *Proc. Inst. Civ. Eng. Geotech. Eng.* 166 (2013) 170–177. <http://www.scopus.com/inward/record.url?eid=2-s2.0-84885000834&partnerID=40&md5=a1ff5f429f63d45acedf0447c7856dac>.
- [17] L. Laloui, M. Moreni, L. Vulliet, Comportement d'un pieu bi-fonction, fondation et échangeur de chaleur, *Can. Geotech. J.* 40 (2003) 388–402. doi:10.1139/t02-117.
- [18] T. Mimouni, L. Laloui, Towards a secure basis for the design of geothermal piles, *Acta Geotech.* 9 (2014) 355–366.
- [19] A. Di Donna, L. Laloui, Soil Response under Thermomechanical Conditions Imposed by Energy Geostructures, in: *Energy Geostructures*, John Wiley & Sons, Inc., 2013: pp. 3–21. doi:10.1002/9781118761809.ch1.
- [20] S. Haehnlein, P. Bayer, P. Blum, International legal status of the use of shallow geothermal energy, *Renew. Sustain. Energy Rev.* 14 (2010) 2611–2625. doi:10.1016/j.rser.2010.07.069.
- [21] F. Loveridge, J. Low, W. Powrie, Site investigation for energy geostructures, *Q. J. Eng. Geol. Hydrogeol.* 50 (2017) 158–168. doi:10.1144/qjegh2016-027.
- [22] C.G. Olgun, T.Y. Ozudogru, C.F. Arson, Thermo-mechanical radial expansion of heat exchanger piles and possible effects on contact pressures at pile–soil interface, *Géotechnique Lett.* 4 (2014) 170–178. doi:10.1680/geolett.14.00018.
- [23] R.G. Campanella, J.K. Mitchell, Influence of temperature variations on soil behavior, *J. Soil Mech. Found. Div.* (1968).
- [24] M. Boudali, S. Leroueil, B.R. Srinivasa Murthy, Viscous behaviour of natural clays., in: *13th Int. Conf. Soil Mech. Found. Eng. ICSMFE*, New Delhi, India, 1994.
- [25] T. Hueckel, B. François, L. Laloui, Explaining thermal failure in saturated clays, *Geotechnique.* 59 (2009) 197–212.
- [26] M. Sutman, *Thermo-Mechanical Behavior of Energy Piles: Full-Scale Field Testing and Numerical Modeling*, (2016).
- [27] C. Cekerevac, L. Laloui, Experimental study of thermal effects on the mechanical behaviour of a clay, *Int. J. Numer. Anal. Methods Geomech.* 28 (2004) 209–228. doi:10.1002/nag.332.
- [28] T.M. Bodas Freitas, F. Cruz Silva, P.J. Bourne-Webb, The response of energy foundations under thermo-mechanical loading, in: *Proc. 18th Int. Conf. Soil Mech. Geotech. Eng.*, 2013: pp. 1–4.
- [29] L. Laloui, B. François, ACMEG-T: soil thermoplasticity model, *Artic. J. Eng. Mech.* (2009).

doi:10.1061/ASCEEM.1943-7889.0000011.

- [30] T. Hueckel, R. Pellegrini, Thermoplastic modeling of undrained failure of saturated clay due to heating, *Soils Found.* 31 (1991) 1–16.
- [31] L. Laloui, C. Cekerevac, Non-isothermal plasticity model for cyclic behaviour of soils, *Int. J. Numer. Anal. Methods Geomech.* 32 (2008) 437–460.
- [32] L. Laloui, C.G. Olgun, M. Sutman, J.S. McCartney, C.J. Coccia, H.M. Abuel-Naga, G.A. Bowers, Issues involved with thermoactive geotechnical systems: characterization of thermomechanical soil behavior and soil-structure interface behavior, *DFI J. - J. Deep Found. Inst.* 8 (2014) 108–120. doi:10.1179/1937525514Y.0000000010.
- [33] T. Mimouni, Lyesse Laloui, Thermomechanical Characterization of Energy Geostructures with Emphasis on Energy Piles, *École polytechnique fédérale de Lausanne EPFL*, 2014. doi:doi:10.5075/epfl-thesis-6452.
- [34] X. Suguang, M.T. Suleiman, J.S. McCartney, S. Xiao, M.T. Suleiman, J.S. McCartney, Shear behavior of silty soil and soil-structure interface under temperature effects, in: *Geo-Congress 2014 Tech. Pap. Geo-Characterization Model. Sustain.*, ASCE, Atlanta, Georgia, USA, 2014: pp. 4105–4114. doi:doi:10.1061/9780784413272.399.
- [35] L. Zhao, P. Yang, J.G. Wang, L.C. Zhang, Cyclic direct shear behaviors of frozen soil–structure interface under constant normal stiffness condition, *Cold Reg. Sci. Technol.* 102 (2014) 52–62. doi:http://dx.doi.org/10.1016/j.coldregions.2014.03.001.
- [36] J. Liu, Y. Cui, P. Wang, P. Lv, Design and validation of a new dynamic direct shear apparatus for frozen soil, *Cold Reg. Sci. Technol.* 106–107 (2014) 207–215. doi:http://dx.doi.org/10.1016/j.coldregions.2014.07.010.
- [37] J. Liu, P. Lv, Y. Cui, J. Liu, Experimental study on direct shear behavior of frozen soil–concrete interface, *Cold Reg. Sci. Technol.* 104–105 (2014) 1–6. doi:http://dx.doi.org/10.1016/j.coldregions.2014.04.007.
- [38] K.D. Murphy, J.S. McCartney, Thermal Borehole Shear Device, *Geotech. Test. J.* 37 (2014) 20140009. doi:10.1520/GTJ20140009.
- [39] I. Shahrour, F. Rezaie, An elastoplastic constitutive relation for the soil-structure interface under cyclic loading, *Comput. Geotech.* 21 (1997) 21–39. doi:http://dx.doi.org/10.1016/S0266-352X(97)00001-3.
- [40] M.E. Suryatriyastuti, H. Mroueh, S. Burlon, A load transfer approach for studying the cyclic behavior of thermo-active piles, *Comput. Geotech.* 55 (2014) 378–391.

doi:10.1016/J.COMP GEO.2013.09.021.

- [41] Suryatriyastuti M. E., Mroueh H., Burlon S., Habert J, Numerical analysis of the bearing capacity in thermo-active piles under cyclic axial loading, in: Energy Geostructures Innov. Undergr. Eng., Hoboken, ISTE Ltd. and John Wiley and Sons, 2013: pp. 139–154.
- [42] T. Amis, P.J. Bourne-Webb, The effects of heating and cooling energy piles under working load at Lambeth College, UK, 2009. <http://www.slideshare.net/Tonyamis/the-effects-of-heating-and-cooling-energy-piles-under-working-load-at-lambeth-college-uk>.
- [43] L. Laloui, M. Nuth, L. Vulliet, Experimental and numerical investigations of the behaviour of a heat exchanger pile, *Int. J. Numer. Anal. Methods Geomech.* 30 (2006) 763–781. doi:10.1002/nag.499.
- [44] A. Di Donna, A.F. Rotta Loria, L. Laloui, Numerical study of the response of a group of energy piles under different combinations of thermo-mechanical loads, *Comput. Geotech.* 72 (2016) 126–142. doi:<http://dx.doi.org/10.1016/j.compgeo.2015.11.010>.
- [45] F.P. de Santayana, C. de Santiago, M. de Groot, J. Ucheguía, J.L. Arcos, B. Badenes, Effect of Thermal Loads on Precast Concrete Thermopile, *Environ. Geotech.* 0 (n.d.) 1–54. doi:10.1680/jenge.17.00103.
- [46] M. Faizal, A. Bouazza, R.M. Singh, An experimental investigation of the influence of intermittent and continuous operating modes on the thermal behaviour of a full scale geothermal energy pile, *Geomech. Energy Environ.* 8 (2016) 8–29. doi:10.1016/j.gete.2016.08.001.
- [47] A.F. Rotta Loria, L. Laloui, The interaction factor method for energy pile groups, *Comput. Geotech.* 80 (2016) 121–137. doi:<http://dx.doi.org/10.1016/j.compgeo.2016.07.002>.
- [48] A.F. Rotta Loria, L. Laloui, Impact of Thermally Induced Soil Deformation on the Serviceability of Energy Pile Groups, in: Springer, Cham, 2017: pp. 421–428. doi:10.1007/978-3-319-52773-4_50.
- [49] A.F. Rotta Loria, Thermo-mechanical performance of energy pile groups, (2018). doi:10.5075/EPFL-THESIS-8138.
- [50] A.F.R. Loria, L. Laloui, The equivalent pier method for energy pile groups Thermo-mechanical performance of energy pile groups View project Reduction of fuel consumption by farming, a new practice-oriented Tool View project, (2017). doi:10.1680/jgeot.16.P.139.
- [51] A.F. Rotta Loria, L. Laloui, Group action effects caused by various operating energy piles, *Géotechnique.* (2017) 1–8. doi:10.1680/jgeot.17.P.213.

- [52] M.E. Suryatriyastuti, H. Mroueh, S. Burlon, Understanding the temperature-induced mechanical behaviour of energy pile foundations, *Renew. Sustain. Energy Rev.* 16 (2012) 3344–3354. doi:<http://dx.doi.org/10.1016/j.rser.2012.02.062>.
- [53] E. Hassani Nezhad Gashti, M. Malaska, K. Kujala, Evaluation of thermo-mechanical behaviour of composite energy piles during heating/cooling operations, *Eng. Struct.* 75 (2014) 363–373. doi:<http://dx.doi.org/10.1016/j.engstruct.2014.06.018>.
- [54] C.G. Olgun, T.Y. Ozudogru, S.L. Abdelaziz, A. Senol, Long-term performance of heat exchanger piles, *Acta Geotech.* 10 (2015) 553–569. doi:10.1007/s11440-014-0334-z.
- [55] H.M. Coyle, L.C. Reese, Load transfer for axially loaded piles in clay, *J. Soil Mech. Found. Div.* 92 (1966).
- [56] H. Péron, C. Knellwolf, L. Laloui, A method for the geotechnical design of heat exchanger piles, in: *Proc. Geo-Frontiers 2011 Conf.*, 2011: pp. 470–479.
- [57] S. Burlon, J. Habert, F. Szymkiewicz, M. Suryatriyastuti, H. Mroueh, Towards a design approach of bearing capacity of thermo-active piles, in: *Eur. Geotherm. Congr.*, 2013: pp. 1–6.
- [58] T. Mimouni, L. Laloui, Thermo-Pile: A Numerical Tool for the Design of Energy Piles, in: *Energy Geostructures*, John Wiley & Sons, Inc., 2013: pp. 265–279. doi:10.1002/9781118761809.ch13.
- [59] Oasys, Pile Version 19.5. Pile Oasys Geo Suite for Windows. User manual., London, UK, 2014.
- [60] M. Suryatriyastuti, Numerical study of the thermoactive piles behavior in cohesionless soils, (2013). <https://www.researchgate.net/publication/259829225> (accessed June 22, 2018).
- [61] K.D. Murphy, J.S. McCartney, Seasonal response of energy foundations during building operation, *Geotech. Geol. Eng.* 33 (2015) 343–356.
- [62] VDI, VDI 4640 Thermal use of the underground. Part 2: Ground source heat pump systems, The Association of German Engineers (VDI), 2001.
- [63] SIA, Utilisation de la chaleur du sol par des ouvrages de fondation et de soutènement en béton: guide pour la conception, la réalisation et la maintenance, SIA, Société suisse des ingénieurs et des architectes, 2005. <http://books.google.dk/books?id=Ki>.
- [64] A. Phillips, B.R. Establishment, B.R.E. Staff, N. Foundation, N.F. Staff, NHBC Foundation, Efficient Design of Piled Foundations for Low-Rise Housing: Design Guide, Building Research Establishment, 2010. http://www.nhbcfoundation.org/Portals/0/NF_Pubs1/NF21_Efficient

design of piled foundations for low-rise housing.pdf.

- [65] F. Loveridge, T. Amis, W. Powrie, Energy pile performance and preventing ground freezing, 2012 Int. Conf. Geomech. Eng. 1 (2012). <http://eprints.soton.ac.uk/342799/>.
- [66] S.L.A.M. Abdelaziz, Deep energy foundations: geotechnical challenges and design considerations, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 2013.
- [67] P. Bourne-Webb, J.-M. Pereira, G.A. Bowers, T. Mimouni, F.A. Loveridge, S. Burlon, C.G. Olgun, J.S. McCartney, M. Sutman, Design tools for thermoactive geotechnical systems, DFI Journal-The J. Deep Found. Inst. 8 (2014) 121–129.
- [68] P. Bourne-Webb, S. Burlon, S. Javed, S. Kürten, F. Loveridge, Analysis and design methods for energy geostructures, Renew. Sustain. Energy Rev. 65 (2016) 402–419. doi:10.1016/J.RSER.2016.06.046.
- [69] A.F. Rotta Loria, M. Bocco, C. Garbellini, A. Muttoni, L. Laloui, The role of thermal loads in the performance-based design of energy piles, Géotechnique. (2018).
- [70] L. Laloui, A.F. Rotta Loria, Energy geostructures analysis and design, (n.d.).
- [71] L. Laloui, Thermo-Pile. A software for the geotechnical design of energy piles. Theoretical aspects. , 2016.
- [72] P. Bourne-Webb, J.-B. Bernard, W. Friedemann, N. von der hude, N. Pralle, V.M. Uotinen, B. Widerin, Delivery of Energy Geostructures, in: Energy Geostructures, John Wiley & Sons, Inc., 2013: pp. 229–263. doi:10.1002/9781118761809.ch12.
- [73] M. Alberdi-Pagola, R.L. Jensen, S.E. Poulsen, A performance case study of energy pile foundation at Rosborg Gymnasium (Denmark), in: 12th REHVA World Congr. Clima2016, Department of Civil Engineering, Aalborg University, Aalborg, Denmark, 2016: p. 10. http://vbn.aau.dk/files/233716932/paper_472.pdf.
- [74] D. Pahud, M. Hubbuch, Measured thermal performances of the energy pile system of the Dock Midfield at Zürich Airport, in: Proc. Eur. Geotherm. Congr., 2007.
- [75] F. Bockelmann, H. Kipry, S. Plesser, M.N. Fisch, Evaluation and optimization of underground thermal energy storage systems of Energy Efficient Buildings (WKSP) - A project within the new German R&D-framework EnBop, in: Proc. Eighth Int. Conf. Enhanc. Build. Oper., Berlin, Germany, 2008.
- [76] Y. Hamada, H. Saitoh, M. Nakamura, H. Kubota, K. Ochifuji, Field performance of an energy pile system for space heating, Energy Build. 39 (2007) 517–524.
- [77] H.I. Henderson, S.W. Carlson, A.C. Walburger, North American monitoring of a hotel with

room size GSHPS, 1999.

- [78] C.J. Wood, H. Liu, S.B. Riffat, Comparison of a modelled and field tested piled ground heat exchanger system for a residential building and the simulated effect of assisted ground heat recharge, *Int. J. Low-Carbon Technol.* 5 (2010) 137–143. <http://www.scopus.com/inward/record.url?eid=2-s2.0-79551701460&partnerID=40&md5=ecc189d295c6f554d6f5bea55918f34c>.
- [79] K. Sekine, R. Ooka, S. Hwang, Y. Nam, Y. Shiba, M. Eng, Development of a ground-source heat pump system with ground heat exchanger utilizing the cast-in-place concrete pile foundations of buildings, 2007.
- [80] M.N. Fisch, R. Himmler, International Solar Centre, Berlin-A Comprehensive Energy Design, (2005).
- [81] C.J. Wood, H. Liu, S.B. Riffat, An investigation of the heat pump performance and ground temperature of a piled foundation heat exchanger system for a residential building, *Energy.* 35 (2010) 4932–4940. doi:<http://dx.doi.org/10.1016/j.energy.2010.08.032>.
- [82] Małgorzata JASTRZĘBSKA, B. WAWRZYŃCZYK, The analysis of the direct foundation with energy foundations on the basis of the office building “A4 Business Park” in Katowice at Francuska street, *ACEE Silesian Univ. Technol.* 2 (2016).
- [83] Y. Ouyang, K. Soga, Y.F. Leung, Numerical back-analysis of energy pile test at Lambeth College, London, in: 211 GSP, 2011: pp. 440–449. <http://www.scopus.com/inward/record.url?eid=2-s2.0-79956367294&partnerID=40&md5=07b724c34a506741bb2aca22dc4a3940>.
- [84] L. Laloui, M. Moreni, A. Fromentin, D. Pahud, L. Vuillet, In-situ thermo-mechanical load test on a heat exchanger pile, (1999).
- [85] L. Laloui, M. Nuth, Numerical modelling of the behaviour of a heat exchanger pile, *Rev. Eur. Génie Civ.* 9 (2005) 827–839.
- [86] T. Mimouni, L. Laloui, Behaviour of a group of energy piles, *Can. Geotech. J.* 52 (2015) 1913–1929. doi:10.1139/cgj-2014-0403.
- [87] A. Di Donna, A.F. Rotta Loria, L. Laloui, Numerical study of the response of a group of energy piles under different combinations of thermo-mechanical loads, *Comput. Geotech.* 72 (2016) 126–142. doi:10.1016/J.COMP GEO.2015.11.010.
- [88] J.S. McCartney, K.D. Murphy, Strain Distributions in Full-Scale Energy Foundations (DFI Young Professor Paper Competition 2012), *DFI J. - J. Deep Found. Inst.* 6 (2012) 26–38.

doi:10.1179/dfi.2012.008.

- [89] K.D. Murphy, J.S. McCartney, K.S. Henry, Evaluation of thermo-mechanical and thermal behavior of full-scale energy foundations, *Acta Geotech.* 10 (2015) 179–195. doi:10.1007/s11440-013-0298-4.
- [90] M. De Groot, C. De Santiago, F. Pardo de Santayana, Heating and cooling an energy pile under working load in Valencia, 23rd Eur. Young Geotech. Eng. Conf. (2014).
- [91] M. Sutman, T. Brettmann, C.G. Olgun, Thermo-mechanical behavior of energy piles: full-scale field test verification, in: DFI 39th Annu. Conf. Deep Found. Atlanta, GA, 2014: pp. 1–11.
- [92] S. Baycan, C. Haberfield, G. Chapman, B. Wang, A. Bouazza, R.M. Singh, D. Barry-Macaulay, Field investigation of a geothermal energy pile: Initial observations, in: 18th Int. Conf. Soil Mech. Geotech. Eng., Paris (France), 2013.
- [93] A. Bouazza, R.M. Singh, B. Wang, D. Barry-Macaulay, C. Haberfield, G. Chapman, S. Baycan, Y. Carden, Harnessing on site renewable energy through pile foundations, (n.d.).
- [94] R. Poudyal, Thermal-mechanical Behavior of a Multiple-loop Geothermal Heat Exchanger Pile, (2014). <https://shareok.org/handle/11244/25704> (accessed June 26, 2018).
- [95] J.S. McCartney, J.E. Rosenberg, Impact of heat exchange on side shear in thermo-active foundations, in: *Geo-Frontiers 2011 Adv. Geotech. Eng.*, ASCE, 2011: pp. 488–498.
- [96] C.A. Kramer, An Experimental Investigation on Performance of a Model Geothermal Pile in Sand, The Pennsylvania State University, 2013.
- [97] C.A. Kramer, P. Basu, Performance of a model geothermal pile in sand, in: *Proc. 8th Int. Conf. Phys. Model. Geotech.* Perth (Gaudin, C. White, D. (Eds)). Leiden CRC Press. Pp. 771–777., 2014.
- [98] A. Kalantidou, A.M. Tang, J.-M. Pereira, G. Hassen, Preliminary study on the mechanical behaviour of heat exchanger pile in physical model, *Geotechnique.* 62 (2012) 1047.
- [99] N. Yavari, A.M. Tang, J.-M. Pereira, G. Hassen, Experimental study on the mechanical behaviour of a heat exchanger pile using physical modelling, *Acta Geotech.* 9 (2014) 385–398.
- [100] A.-M. Tang, A. Kalantidou, J.-M. Pereira, G. Hassen, N. Yavari, *Mechanical Behaviour of Energy Piles in Dry Sand*, 2014.
- [101] A. Marto, A. Amaludin, M.H. Bin Satar, Experiments on Shallow Geothermal Energy Model Piles Embedded in Soft Soil, *EJGE.* 20 (2015).

- [102] A.F.R. Loria, A. Gunawan, C. Shi, L. Laloui, C.W.W. Ng, Numerical modelling of energy piles in saturated sand subjected to thermo-mechanical loads, *Geomech. Energy Environ.* 1 (2015) 1–15.
- [103] A.F. Rotta Loria, A. Di Donna, L. Laloui, Numerical study on the suitability of centrifuge testing for capturing the thermal-induced mechanical behavior of energy piles, *J. Geotech. Geoenvironmental Eng.* 141 (2015) 4015042.
- [104] W. Wang, R.A. Regueiro, M. Stewart, J.S. McCartney, Coupled thermo-poro-mechanical finite element analysis of an energy foundation centrifuge experiment in saturated silt, in: *GeoCongress 2012 State Art Pract. Geotech. Eng.*, ASCE, 2012: pp. 4406–4415.

Appendix

Table A: Main case studies reported in literature.

More case studies are available in [72].

Pile type, length [m] / diameter [m]	Pipe configuration	Number of energy piles	Seasonal performance factor [SPF]	Heat transfer rate [W/m]	Reference
Precast driven, 15 / 0.3m x 0.3m	W-shape	220	Heating: 3	Max. 43; average 12.	[73], updated
Precast driven, 12	-	52	Heating: 4.3	-	[72]
Cast in place, 26.8 / 0.9 to 1.5	5U	306	Heating: 3.9	Max. 72; average 45.	[74]
Cast in place, 8.5	1U	196	Cooling: 6.5	Average heating 50; average cooling 5-35.	[75]
Precast driven, 9 / 0.30	1U	26	Heating: 3.2		[76]
Cast in place, 26	-	198	Heating: 4.0; cooling: 4.4	Max. heating 18.5; average heating 1; max. Cooling 23.3; average cooling 11.6.	[77]
Cast in place, 10/0.3	1U	21	Heating: 3.2	Average heating 26.	[78]
Cast in place, 14.8/0.91	3U	1	-	Average heating 91.	[61]
Cast in place, 13.4/0.91	4U	1	-	Average heating 95.	
Cast in place, 20/1.5	8U	2	Heating: 3.2; cooling: 3.7	Average heating 44-52; average cooling 100-120.	[79]
Cast in place (-)	-	196	Heating 5.4; free-cooling: 24.5	Max. heating: 12 heating; Max. cooling: 17.	[80]
Cast in place, 10 / 0.3	1U	16	Heating: 3.62	Average heating 26 W/m.	[81]
Cast in place, 15 / 0.5	1U	54	-	Max. 300.	[82]

Table B: Main full-scale studies reported in literature.

Pile type, length [m]/ diameter [m]	Ground conditions	Restrain condition	Induced temperature changes	Mechanical load	Main conclusions	Source
2 cast in place piles, 23-26/0.6	5 m river deposits over London clay	Floating pile	Fluid temperature imposed in test pile: - 6 to 40 °C; test pile $\Delta T = - 20$ °C; sink pile: $\Delta T = + 30$ °C, 3-day tests.	1200 kN (failure 3600 kN)	Pile-soil system shows thermo-elastic behaviour. Sufficient margin between mobilised shaft.	[13,42,83] Lambeth College (UK)
Cast in place, 25.8/0.88	Alluvial deposits 12 m, glacial till to 25 m, driven to sandstone	End-bearing	TRT conditions: $\Delta T = + 21$ and $+ 15$ °C, 12 days heating and 16 days recovery.	Building load (1300 kN)	Pile strain shows thermo-elastic behaviour and depends on the surrounding soil.	[43,84] and numerical analysis [85]. EPFL (CH)
4 cast in place piles, 25.8/0.88	Alluvial deposits 12 m, glacial till to 25 m, driven to sandstone	End-bearing	Two test modes: i) 1 pile heated at a time; ii) 3 piles heated before last. TRT for 6 days and recovery, $\Delta T = + 10$ °C.	Building load (800 - 2100 kN)	Group effect: differential displacements between test piles are reduced as more piles are heated.	[86,87] EPFL (CH)
Cast in place, 9/1.2	Silty sand/clayey silt over highly fissured weathered stiff clayey, sandy silt	Head restrained (raft) + floating	Operational conditions: 5 to 20 °C.	1100 kN	Appropriate operating of energy piles hardly affects the shaft resistance.	[3]
2 cast in place piles, 13.4 - 14.8/0.91	Embedded into 7.6 m of claystone (Denver Blue Shale)	End-bearing	Operational conditions: 7 to 35 °C.	Building load (3700 kN)	Thermal axial strains are within acceptable limits.	[61,88]
8 cast in place piles, 15.2/0.61	12 m of dense sand, silt and gravel on top of sandstone	End-bearing	TRT conditions: 10 - 50 °C, 120 - 500 hours.	Building load (833 kN)	Linear thermo-elastic behaviour observed. Pile head displacements should not cause significant angular distortions.	[89]
Precast driven, 17/0.35x0.35	Driven into gravel with coarse sand	End-bearing	TRT conditions: 23-29 °C, 120 hours; stages TRT 20 days and cyclic thermal loads for 15 days.	1000 kN	The increase of the axial load in the pile is around 12% of the mechanical load. The maximum increase of temperature in the pile does not reach 5 °C at any depth.	[45,90]
3 cast in place piles, 14/0.46	8.7 m of clay on top of dense sand	-	Different thermal patterns between 7 and 45 °C, 4 to 14 days.	2560 kN	The thermal loads need to be considered during the design of energy piles. The behaviour of energy piles depends on the level of restrictions of the pile.	[26,91] Virginia Tech (Richmond, Texas, USA)

Pile type, length [m] / diameter [m]	Ground conditions	Restrain condition	Induced temperature changes	Mechanical load	Main conclusions	Source
5 cast in place piles, 35/0.25	Silty sand layer (13-19 m) underlain by a shale layer	End-bearing	Different thermal patterns between 6 and 50 °C, 2 to 16 days.	1300 kN (ultimate load)	The thermal loads need to be considered during the design of energy piles.	[66] Virginia Tech (Virginia, USA)
Cast in place, 16.1/0.6	Unsaturated, very dense sand	-	TRT conditions: 15 - 50 °C; 3 to 52 days.	1850 kN	The pile shaft resistance gained strength during thermal heating loads.	[92,93] Monash University (AU)
Cast in place, 16.1/0.6	Unsaturated, very dense sand	-	Intermittent thermal loads for 20 days.	-	Thermal strains and stresses for intermittent tests were cyclic and returned to initial values. Intermittent operation is advantageous since generates lower pile thermal loading for long term operations.	[46] Monash University (AU)
Cast in place, 12.20/1.07	3 m soft clay topping shale	End-bearing	TRT conditions: 17 - 37 °C, 39 days.	-	The load transfer model reproduces the monotonic thermal load implications.	[94] Oklahoma State University (USA)

Table C: Main laboratory-scale studies reported in literature.

Laboratory studies, either physical or centrifuge models, allow to uncouple uncertainties as they are reproduced under controlled environments.

Pile type	Methodology	Soil	Heat source	Restraints	Main conclusions	Source
Concrete	Experimental data	Dry sand	PVC 1U tube	Free thermal expansion	Increase in bearing capacity after heating pile. Similar behaviour in [95].	[96,97]
Aluminium pipe pile	Experimental data	Dry sand	Aluminium 1U	End-bearing	During thermal cycles under constant axial head load, for a head load lower than 30 % of the pile resistance, thermo-elastic behaviour of the pile is observed. For higher head load, significant cumulative settlement can be observed.	[98–100]
Stainless steel	Experimental data	Soft Kaolin clay	Metallic 1U	-	The working load for shallow geothermal energy pile embedded in soft soil should be reduced adequately to prevent failure of the pile.	[101]
Steel pipe pile	Centrifuge experimental data + THM* FEM analysis	Saturated sand	Heating wire	-	The null point position depends on the magnitude of the thermal and mechanical loads.	[102]
Reinforced concrete	Centrifuge experimental data + TM FEM analysis	Dry Nevada sand	-	-	Negligible variation between the evolutions of the load settlement curves. This indicates a very limited impact of temperature on the bearing behaviour of the pile.	[103]
Concrete	Centrifuge data + axisymmetric TPM*2 FEM analysis	Partially saturated silt	PFA 3U tube	Semi-floating	Thermally-induced liquid water and water vapor flow inside the soil were found to have an impact on soil-structure interaction.	[104]
Reinforced concrete	Centrifuge experimental data + load transfer analysis	Bonny silt	Aluminium 1U	-	By heating the pile, its bearing capacity increased, because of an increase in drained shear distribution along the pile due to soil compression during the heating phase.	[95]

* THM: Thermo-hydro-mechanical; *2 TPM: Thermo-poro-mechanical

