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Abstract: A small-scale pile has been developed in the laboratory to investigate the thermo-mechanical behavior of energy piles subjected to a significant number of thermal cycles. The model pile (20 mm external diameter), installed in dry sand, was initially loaded at its head to 0, 20, 40 and 60% of its ultimate bearing capacity (500 N). At the end of each loading step, 30 heating/cooling cycles were applied to the pile. The long-term behavior of the pile was observed in terms of pile head settlement, axial force profile, soil and pile temperature, and stress in soil. The results evidence the irreversible settlement of the pile head induced by thermal cycles under constant load head. In addition, the incremental irreversible settlement, that accumulates after each thermal cycle, decreases when the number of cycles increases. The evolution of irreversible pile head settlement versus number of cycles can be reasonably predicted by an asymptotic equation.

Keywords: energy pile, physical model, long-term behavior, heating/cooling cycles, thermo-mechanical load

1. Introduction

Energy piles, or heat exchanger piles, have a dual function: (*i*) providing support for overhead structures as a conventional pile foundation; (*ii*) and exchanging heat with the ground for the purpose of heating and/or cooling the building. Energy piles have been used in some European countries during the last two decades. This technique has gained encouraging credit as an option to the use of renewable energy in modern cities and contributed to the reduction of CO_2 emissions [1–3]. However, the implementation of this technique is not homogeneous across countries due to the lack of design standards.

Many studies have been carried out to investigate the thermo-mechanical behavior of energy piles [2, 4–30]. Some involved in situ full-scale experiments [2, 4, 11, 27, 31, 32] or laboratory small-scale experiments [7, 14, 18, 21, 22, 24, 25]. The results evidence the effect of pile temperature on the pile/soil interaction. Indeed, the temperature of energy piles can vary in the range of 5°C to 40°C and can thus induce stress changes along the pile and movement of the pile head. These phenomena are the consequences of the pile thermal dilation/contraction and the effect of temperature on the behavior of the pile/soil interface. The above mechanisms were considered in various numerical studies to predict the behavior of energy piles under thermo-mechanical loadings [2, 9, 10, 12, 17, 29, 30, 33–38].

In spite of various studies on the thermo-mechanical behavior of energy piles, few works have investigated their long-term behavior. Actually, to deal with this aspect, some studies investigated the mechanical behavior of energy piles under numerous thermal cycles, which represent the seasonal variations of the pile temperature. Suryatriyastuti *et al*. [9] studied the behavior of free- and restraint-head piles in very loose sand using the pile-soil load transfer approach. The proposed *t-z* function comprised a cyclic hardening/softening mechanism, which allowed investigating the degradation of the soil/pile interface behavior under cyclic loading. This approach was then compared with a numerical simulation using the finite element method where the degradation of the soil-pile interface behavior under cyclic loading was considered. A simulation accounting for 12 thermal cycles shows: (*i*) a ratcheting of pile head settlement under constant working load; (*ii*) and a decrease in pile head load for the restraint-head pile.

Saggu & Chakraborty [12] investigated the behavior of a floating and end-bearing pile in loose and dense sands under various thermal cycles by using the finite element method and nonlinear transient analyses. The thermal load applied to the pile was in the same temperature range as in the experiments of Laloui *et al*. [2], with a temperature amplitude of 21°C. The results show an important settlement of the pile after the first thermal cycle. The subsequent thermal cycles induce pile heave. This phenomenon can be clearly seen in the case of dense sand where the pile and the soil surface move upward together after 50 cycles. Actually, the pile and soil were progressively heated during these 50 cycles. In addition, the pile shaft resistance in dense sand increases with the thermal cycles while this value does not change in loose sand. The authors explain this observation in the case of dense sand by the larger horizontal stress induced by soil thermal expansion which affects the mobilized pile shaft resistance. However, a parametric study shows a decreasing trend of the pile axial stress with thermal cycles. A similar result can be found in the numerical study of Olgun *et al*. [36] where pile head displacement and axial stress were investigated under three different climatic conditions for 30 years. After 30 annual thermal cycles, even if the pile was progressively cooled, its axial stress tends to increase. A decrease in axial stress is observed during a heating process. This was explained by the difference in the thermal dilations of the pile and the soil, respectively. Ng *et al*. [39] studied the horizontal stress change of soil element close to the pile when the pile was subjected to 50 heating-cooling cycles. The results show that the horizontal stress along the pile decreases with thermal cycles, this decrease being particularly affected by the thermal cycles amplitude and the pile diameter. Pasten & Santamarina [17] also used a modified one-dimensional load transfer model to predict the long-term response of shaft- and end-bearing piles subjected to thermal cycles. They show that the most plastic settlement of the pile took place during the first few cycles. More recently, Vieira & Maranha [35] investigated the behavior of a floating pile model in clay soil under different load levels and seasonal temperature during five years using the finite element method. The results indicate that when the pile works with a high factor of safety its displacement is reversible during the thermal cycles. However, a low factor of safety induces an increase in axial stresses while the rate of irreversible settlement reduces with the number of cycles.

Beside the numerical studies mentioned above, few experimental studies have been performed to investigate the long-term behavior of energy piles. Ng *et al*. [24] used centrifuge modeling to study the thermo-mechanical behavior of energy piles constructed in lightly and heavily over-consolidated clays under five thermal cycles. The results show that the most irreversible settlement of the pile is observed in the first thermal cycle. In the following cycles, the settlement increases at a lower rate. After 5 cycles, the accumulated settlement is about 3.8%D (pile diameter) for a pile in the lightly over-consolidated clay, and 2.1%D for heavily over-consolidated clay. Another study using centrifuge modeling to investigate the long-term behavior of energy pile under four thermal cycles can be found in [14]. An end-bearing pile, installed in unsaturated silt, worked under a constant head load and four thermal cycles (the temperature ranging from 29°C to 39°C). The observed thermal axial stress-strain behavior of the pile is in agreement with the results of in-situ experiments performed by Laloui *et al*. [2], Bourne Webb *et al*. [4] and McCartney & Murphy [40]. The profiles of axial stress, displacement and strain of pile does not change significantly along the four thermal cycles.

The objective of the present study is to investigate the long-term response of a small-scale energy pile. The pile model (20 mm external diameter) was installed in dry sand. 30 thermal cycles were applied while the pile head load was maintained at 0, 20, 40 and 60% of the pile ultimate bearing capacity. The results in terms of pile head settlement and axial force profile, obtained during these thermo-mechanical loadings, are presented and discussed. Note that while the long-term behavior of energy pile is usually considered under a high number of thermal cycles (up to 50 cycles in the case of Ng *et al*. [39]) in numerical studies, it is usually limited to few thermal cycles (up to 5 cycles in the case of Ng *et al*. [24]) in the experimental studies.

2. Experimental method

2.1 Experimental setup

A pile model (20-mm external diameter and 600-mm length) was installed in a dry sand sample (548-mm inner diameter and 900-mm height) as shown in Fig. 1. The pile model is an aluminum tube with an internal diameter of 18 mm and sealed at the bottom. The model pile surface was coated with sand to mimic the roughness of a full-scale pile surface. The sand used in this study (Fontainebleau sand) has the following physical properties: particle density ρ_s = 2.67 Mg/m^3;

maximal void ratio e_{max} = 0.94; minimal void ratio e_{min} = 0.54; and median grain size D_{50} = 0.23 mm.

The installation process began with the compaction of two 100 mm-thick layers, then two layers of 50 mm in thickness. The model pile was then installed at its position inside the soil container and fixed by a steel bar fixed to the top surface of the soil container. Finally, other sand layers of 100 mm were compacted around the pile. The soil was compacted manually, by using a wooden tamper, at a dry unit weight of 15.1 kN/m^3.

During the compaction, three temperature sensors and two pressure gauges were installed as showed in Fig. 1. The two pressure gauges (P1 & P2) locate at 50 mm below the pile toe. P1 measures the horizontal pressure and P2 measures the vertical pressure of soil. The three soil temperature sensors (S5-S7) are placed at 300 mm below the soil surface and at three distances from the pile axis, 20, 40 and 80 mm, respectively. In order to measure the pile axial strain, five strain gauges (G1-G5) are distributed along the pile length. Three displacement transducers (LVDT) are used to measure the pile head displacement, and a load cell records the pile head load. The pile head load is controlled by the water level in a tank placed above the pile. A metallic U-tube, connected to a temperature-controlled bath, is placed inside the pile tube for heating and cooling the pile. The thermal conductivity of this latter is improved by filling the pile tube with water. A temperature sensor (S1) is placed inside the pile to measure its temperature. The soil container is thermally isolated to avoid heat exchange with the ambient air.

2.2 Test program

In this study, three tests have been performed. After each experiment, the pile model was reinstalled according to the procedure described above. The first two tests T1 and T2 were performed to investigate the behavior of the pile under mechanical loading and isothermal conditions. The test procedure follows the French Standard [41]. In the preparation step, the pile was first loaded to 50 N (10% of the pile resistance, which is 500 N, after Yavari *et al*. [21]) and then unloaded to remove the disturbed settlement component due to soil compaction related to the pile installation process. After this step, the pile was loaded in steps of 50 N up to 250 N (50% of the pile resistance), and then unloaded completely. Finally, the pile was loaded in steps of 50 N up to failure (corresponding, by convention, to a pile head settlement equal to 2 mm, *i.e*. 10% of the pile diameter). Each loading step was maintained for 60 min.

For the test T3, after the preparation step, the pile temperature was fixed at 20°C (similar to the room temperature) for two days to ensure the homogeneity of the soil and pile temperature at the initial state. After this phase, the pile was first heated from 20°C to 21°C for 4 h and then cooled to 19°C for 4 h. Finally, the initial temperature of 20°C was imposed to the pile for at least 16 h. Thus the total duration of one thermal cycle equals to 24 h. 30 thermal cycles were applied during this first stage. In the subsequent stage, an axial head load of 100 N (20% of the pile resistance) was applied. 30 thermal cycles were then applied under this pile head load. The same procedure was repeated at pile head loads of 200 N and 300 N (40% and 60%, respectively, of the pile resistance). The thermo-mechanical loading path of the test T3 is summarized in Fig. 2.

3. Results

Fig 3 shows the results obtained for the test T1. The pile head settlement is plotted against elapsed time for each loading step. The pile head settles immediately after the application of the axial load. Afterwards, the settlement increases with time but at a lower rate. In general, the relationship between the pile head settlement and the logarithm of time can be fitted using a linear function (for the last 30 min of each loading step). That function allows determining the creep rate as shown in equation (1).

$$\alpha = (S_{60} - S_{30})/\log(60/30) \quad (1)$$

where α is the creep rate; S_{60} and S_{30} are the settlements of the pile head at 60 min and 30 min, respectively. Fig. 4 shows the creep rate of all the three tests. It can be observed that the higher the pile head load the higher the creep rate, and that a linear function fits satisfactorily the relationship between these two quantities. The results of the three tests are quite similar showing the good repeatability of the experimental procedure. Other results concerning the mechanical behavior of the pile under mechanical loading are similar to that obtained by Yavari *et al*. [21] by using the same experimental setup and by testing the same sand. For this reason, these results (pile head settlement versus pile head load, pile axial stress profile, *etc*.) are not shown in the present paper. Only the results on creep rate are shown here because such results were not shown in the work of Yavari *et al*. [21] and they are important when investigating the long-term behavior of piles.

Fig. 5 shows the temperature measured at various locations together with the pile head settlement after the first heating-cooling cycle in the test T3 under a constant head load corresponding to 20% of the pile resistance. When the temperature of the pile is increased from 20°C to 21°C, the soil temperature at 20 mm (S5), 40 mm (S6), and 80 mm (S7) from the center of the pile increases subsequently. But the temperature change at 80 mm remains very small. It seems that the duration of 4 h for the heating phase is long enough for the soil temperature to reach equilibrium. The same conclusion can be drawn for the subsequent cooling phase (pile temperature is decreased to 19°C) and the final heating phase (pile temperature is increased to its initial value, 20°C). The results on the pile head settlement show that heating does not induce any significant movement but that cooling induces a settlement (the normalized settlement is the ratio between the pile head settlement and the pile diameter). In addition, the pile head settlement and the pile temperature stabilize at the same time.

In Fig. 6, the pile head settlement is plotted versus the pile temperature change during the first heating-cooling cycle for the four axial loads. It can be observed that the pile behavior depends on the mechanical load applied to it. The pile head heave associated to heating can only be observed when the pile is free of load (Fig. 6a). In this case, the displacement of the pile head is similar to the pile's thermal expansion curve, which corresponds to the temperature-induced deformation of a pile restrained at its toe but free to move at its head. In the three other cases, the pile head does not move during the initial heating phase. The subsequent cooling phase induces a settlement in all the four cases. The slope of the settlement is similar to the thermal expansion curve. The final heating phase, when temperature increases back to the initial temperature, does not induce any displacement in all the four cases. As a result, the first heating/cooling cycle induces irreversible pile head settlement in all the four cases. In addition, the higher is the axial load, the higher the irreversible settlement. This phenomenon is similar to that observed by Kalantidou *et al*. [7] and Yavari *et al*. [21] on dry sand and Yavari *et al*. [18] on saturated clay.

In Fig. 7, the irreversible pile head settlement and its ratio to the pile diameter (normalized settlement) are plotted versus the number of thermal cycles for all the four axial pile head loads. When pile is free of load, the irreversible settlement is negligible. In the other cases, the higher is the pile head load, the more important is the observed settlement. In addition, for a given pile head load, the irreversible settlement increases with the number of thermal cycles, while tending to stabilize for a high number of cycles. In addition, while the irreversible pile head settlement tends to stabilize after around 20 cycles for low pile head load (up to 40% of pile resistance), under higher pile head loads (60% of pile resistance), it continues to increase at a constant rate over the 30 applied thermal cycles.

For a deeper analysis of the pile head settlement with thermal cycles the irreversible pile head settlement was calculated using the following equation (see Pasten & Santamarina [17]):

$$\delta_1 = \delta_1|_{Nc\rightarrow\infty}(1 - \exp(-\beta . N_c)) \qquad (2)$$

Here, δ_I is the irreversible pile head displacement; N_c is the number of cycles; β is a model parameter obtained by fitting the experimental data (one value per pile head load). The result in Fig. 7 shows that this equation can fit correctly all the experimental data.

Besides, irreversible settlement was also normalized with respect to the settlement obtained during the first cycle as suggested by Suryatriyastuti *et al*. [9]. This ratio of pile settlement is plotted versus the number of cycles in Fig. 8 for all the four pile head loads. The results show that this ratio increases quickly during the first ten cycles and then tends to stabilize at a high number of cycle. Note that in the study of Suryatriyastuti *et al*. [9], at a pile head load of 33% of the pile resistance, 12 heating/cooling cycles induce a ratio of approximately 1.2. This value is similar to the one found in the present work for the case of 40% of the pile resistance.

The results on the axial force along the pile, measured by the strain gages and the pile head load sensor, are plotted in Fig. 9. The axial force Q is normalized with respect to the pile resistance Q_{ult} = 500 N and the depth z is normalized with respect to the pile length H = 600 mm. At the initial state, when no pile head load is applied, the axial force along the pile remains smaller than 5% of Q_{ult}. The subsequent thermal cycles do not significantly modify the axial force. When a load of 20% of Q_{ult} is applied to the pile head, the axial force along the pile also increases. Afterwards, the first heating phase leads to a slight increase of the axial force and the subsequent cooling phase leads to a slight decrease. After 30 cycles of heating/cooling, the axial force is higher than the initial one (under mechanical load). Note that the axial force after the 30th heating phase is also higher than that after the 30th cooling phase. The cases of loads corresponding to 40% and 60% of Q_{ult} lead to similar observations.

Fig. 10 shows the pile head load, the horizontal and vertical pressures in soil at 50 mm under the pile toe as a function of the number of thermal cycles. The initial stress (10 kPa and 5 kPa for vertical and horizontal ones, respectively) corresponds to the weight of the soil specimen. The coefficient of horizontal pressure at rest of 0.5 is in the usual range for dry sand [12, 21, 42]. These pressures increased significantly when the pile head load was increased but the thermal cycles did not influence these values.

In Fig. 11, the irreversible settlement of the pile head measured after 30 thermal cycles is plotted versus the pile head load. In this figure, the pile head settlement, estimated from the creep rate (shown in Fig. 4) and the duration of the thermal phase, is also plotted. The difference between these two values can be attributed to the settlement related uniquely to the thermal cycles. It can be seen that the settlement related to thermal cycles is much larger than that related to creep. The higher is the pile head load, the higher is the irreversible settlement.

4. Discussion

In the present work, the temperature variation was imposed at ±1°C. This range is much smaller than the temperature variation of the energy piles which can reach up to ±20°C [2, 4, 11, 21, 25, 27]. Actually, in this small-scale model, the dimension of the pile is 20 times smaller than a full-scale pile of 0.4 m in diameter and 12 m length. As a consequence, the strain related to the mechanical load is 20 times smaller than that at the full scale [2, 8, 11, 24]. For this reason, the temperature variation was reduced 20 times in order to have a thermal dilation of the pile 20 times smaller than that at the full scale. The thermo-mechanical behavior of the pile observed at the small scale can then be used to predict the behavior of energy piles at the full scale.

The irreversible evolution of the pile head settlement with thermal cycles observed in the present work (Fig. 7) is similar to that obtained by Ng *et al*. [24] on saturated clay using centrifuge modeling. These authors applied five thermal cycles and observed a ratcheting of pile head settlement. A similar behavior can be found in the numerical study of Vieira & Maranha [35]. In the present work, with 30 thermal cycles (which can represent 30 years of seasonal temperature changes of energy piles), the results confirm that the increment of irreversible settlement per cycle is higher during the first cycles but becomes negligible after 20 cycles for the cases of axial loads lower than 40% of the pile resistance (which corresponds to the service load of piles in real cases). The irreversible settlement continues to increase after 20 cycles only when the pile head load is high (60% of the pile resistance).

When comparing the results obtained in the present work to those obtained in the numerical work of Pasten & Santamarina [17], common trends can be found, as shown in Fig. 7. The parameter β represents the shape of the curve. The results obtained do not show a clear trend in the relationship between this parameter and the pile head load. A similar conclusion can be drawn from the Fig. 8 where the irreversible pile head settlement is normalized with respect to its value after the first thermal cycle. The mechanisms considered is the work of Suryatriyastuti et al. [9] can be used to explain the results obtained in the present work. These authors embedded a strain hardening/softening mechanism at the pile-soil interface into the proposed *t-z* function to consider cyclic degradation effects during the thermal cycles. The numerical investigation of Ng *et al*. [39] also confirms the decrease in resistance of pile-soil interface versus the number of thermal cycles. In addition, Vargas & McCarthy [43] show that thermal cycles induce thermal volume change of grains, which can lead to compaction under constant stress. These authors explain this structural rearrangement by the thermal effect generating an increase in the average contact forces between soil particles. In addition, Fityus [44] studied the behavior of a model footing on expansive clay under wetting/drying cycles and found a similar trend as far as the accumulating irreversible settlement is concerned.

The study of Saggu & Chakraborty [12] shows an opposite trend compared with the present experiment. Actually, the axial stress decreased after fifty cycles and the pile settlement was observed only in the first thermal cycle. This phenomenon was explained by the stress transfer into the surrounding soil, and the progressive heating of pile with thermal cycles.

Figure 9 shows an increase of the axial force along the pile when the number of thermal cycles increases. This behavior is similar to that predicted by numerical approaches ([9, 17, 35]). Actually, in these studies, this behavior can be explained by the degradation of the pile-soil interface resistance with the accumulating cycles. In a different case, Pasten & Santamarina [17] show the axial force profile of pile during fifty cycles. The axial force along the pile was larger in the heating phase than in the cooling phase. However, the axial force in the cooling phase was similar to that at the initial state.

Fig. 11 shows that the thermal settlement response of pile head shows a trend similar to the result from the study of Yavari *et al*. [18] and Vieira & Maranha [35]. Especially, all these studies have investigated the thermal response of a pile when it works under different constant head loads. The results showed that the long-term performance of energy piles induced significant irreversible settlement and that the thermal settlement is greater at higher constant head loads.

5. Conclusions

The long-term behavior of energy piles was investigated using a small-scale model. 30 heating/cooling cycles were applied to the model pile under various constant pile head loads varying from 0 to 60% of pile resistance. The following conclusions can be drawn:

- Thermal cycles under constant head load induces irreversible settlement of the pile head
- The irreversible settlement of the pile head is higher at a higher pile head load
- The first thermal cycle induces the highest irreversible pile head settlement. The incremental irreversible settlement, accumulating after each thermal cycle, decreases when the number of cycles increases. It becomes negligible at high number of thermal cycles and/or low pile head load. The evolution of irreversible pile head settlement versus the number of cycles can be reasonably predicted by an asymptotic equation.
- The axial force measurement along the pile increases progressively with the increase of the number of thermal cycles. The axial force at the end of a heating phase is higher than that at the end of the subsequent cooling phase.

The results obtained in the present work could be helpful to predict the long-term settlement of a building having all the foundation piles equipped with a heat exchanger system. A similar test program should be conducted on full-scale piles, for further researches, in order to confirm quantitatively these observations. In general, the results suggest that the stress/strain behavior of energy piles would continue to evolve even several years after their installation.

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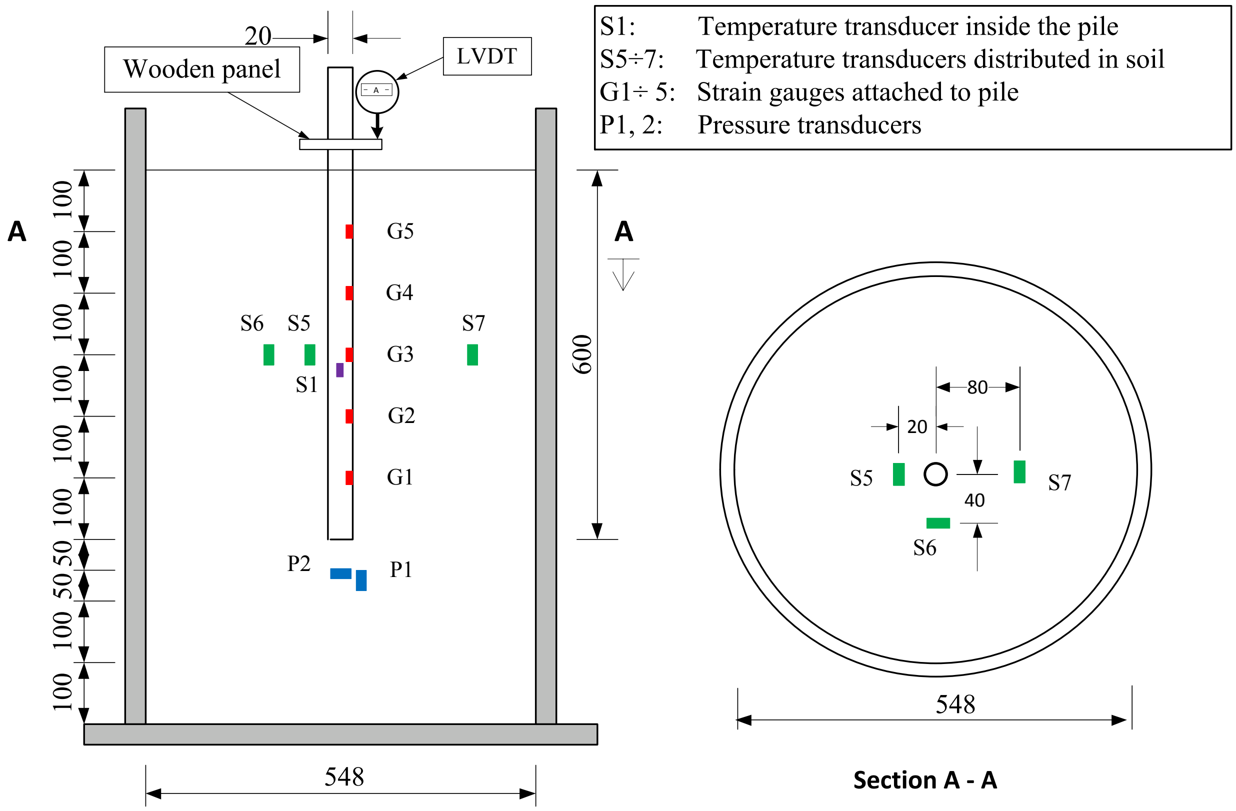

Fig. 1 Experiment setup

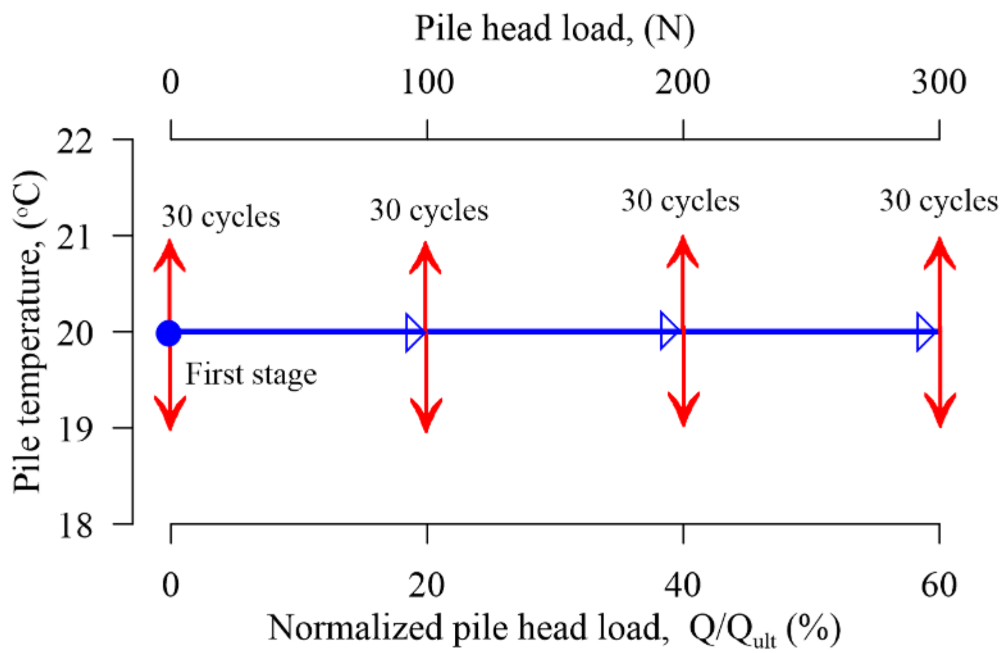

Fig. 2 Thermo-mechanical loading path of the test T3.

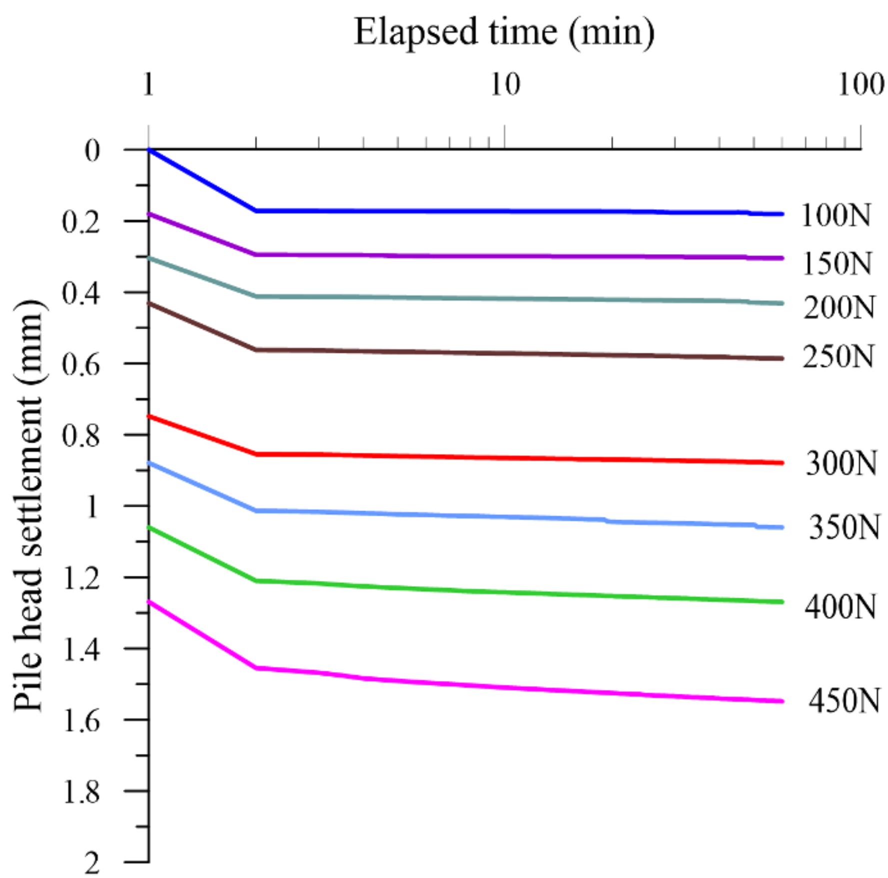

Fig. 3 Mechanical settlement of pile in test T1

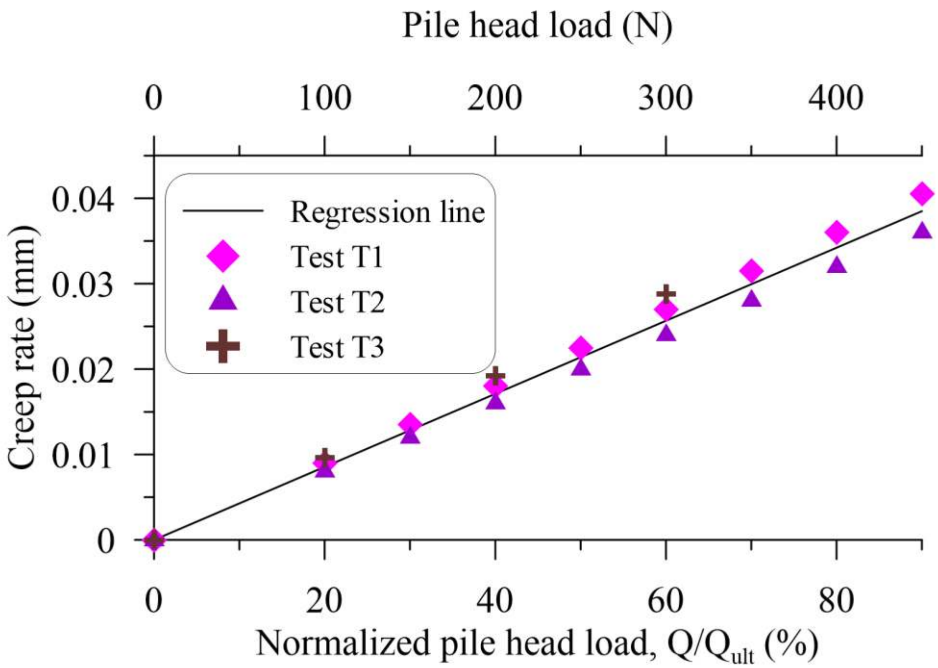

Fig. 4 Creep behavior of pile for all the three tests.

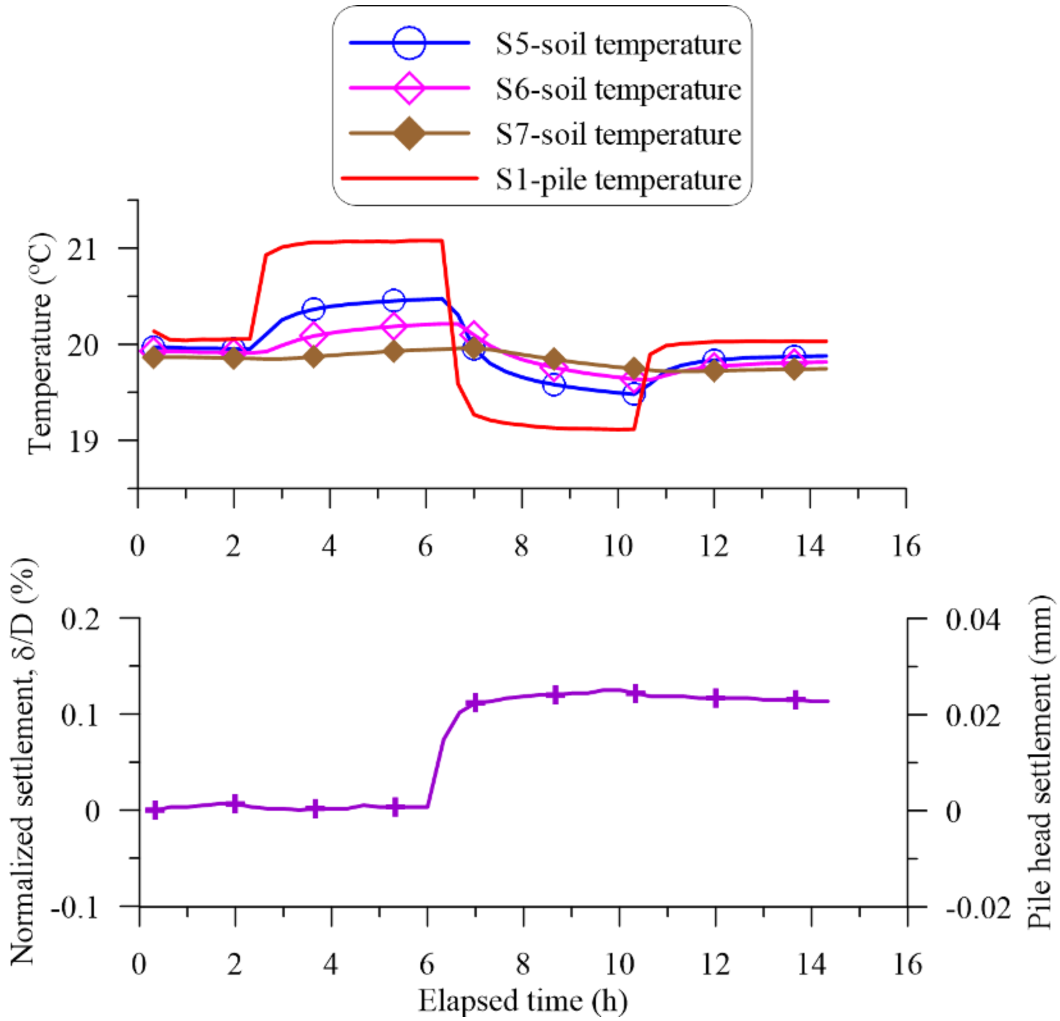

Fig. 5 Pile head settlement, soil and pile temperature versus elapsed time during the first thermal cycle at 20% of pile resistance.

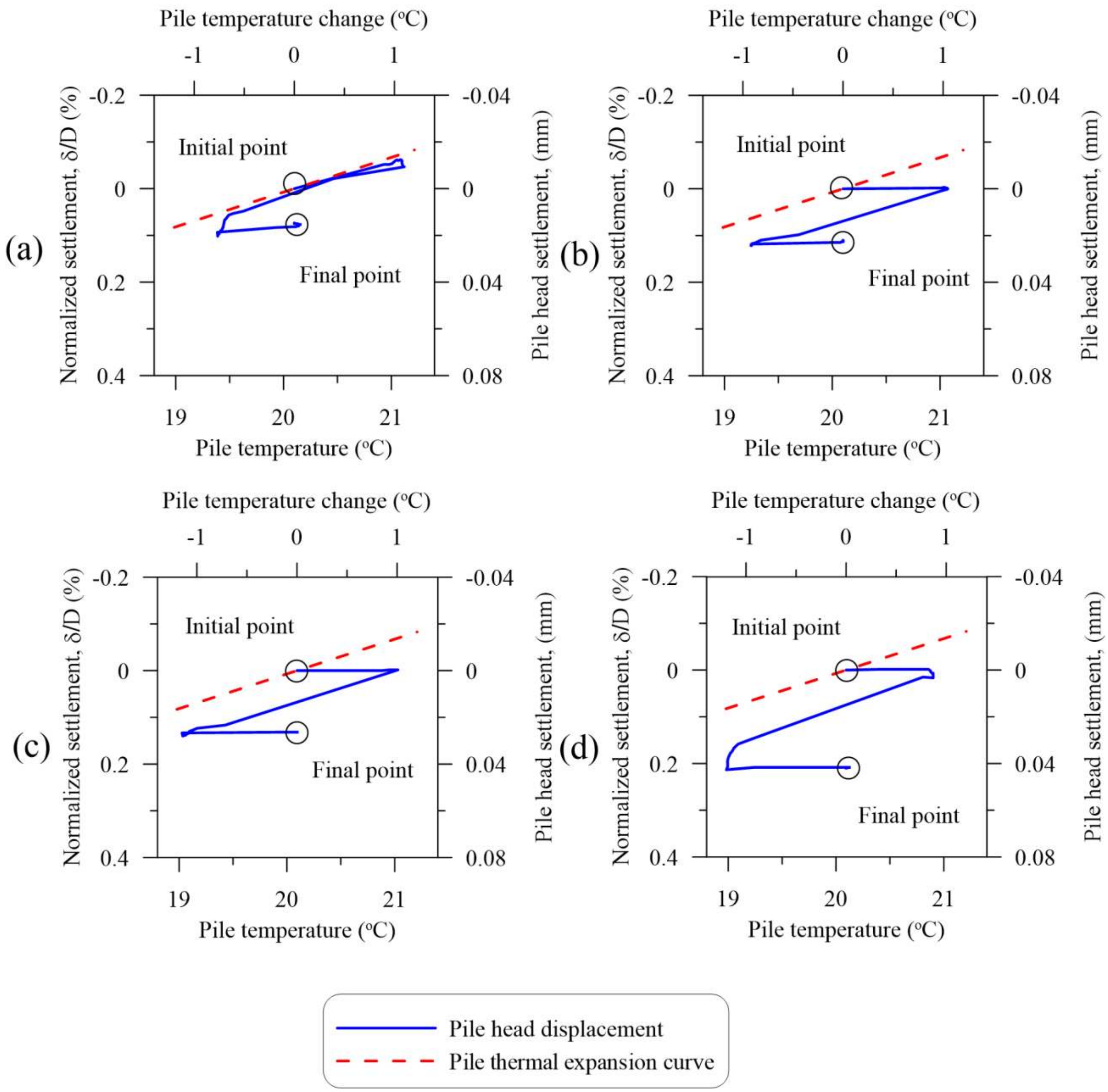

Fig. 6 Pile head settlement versus temperature change during the first cycle at axial load of (a) 0%; (b) 20%; (c) 40%; (d) 60% of pile resistance.

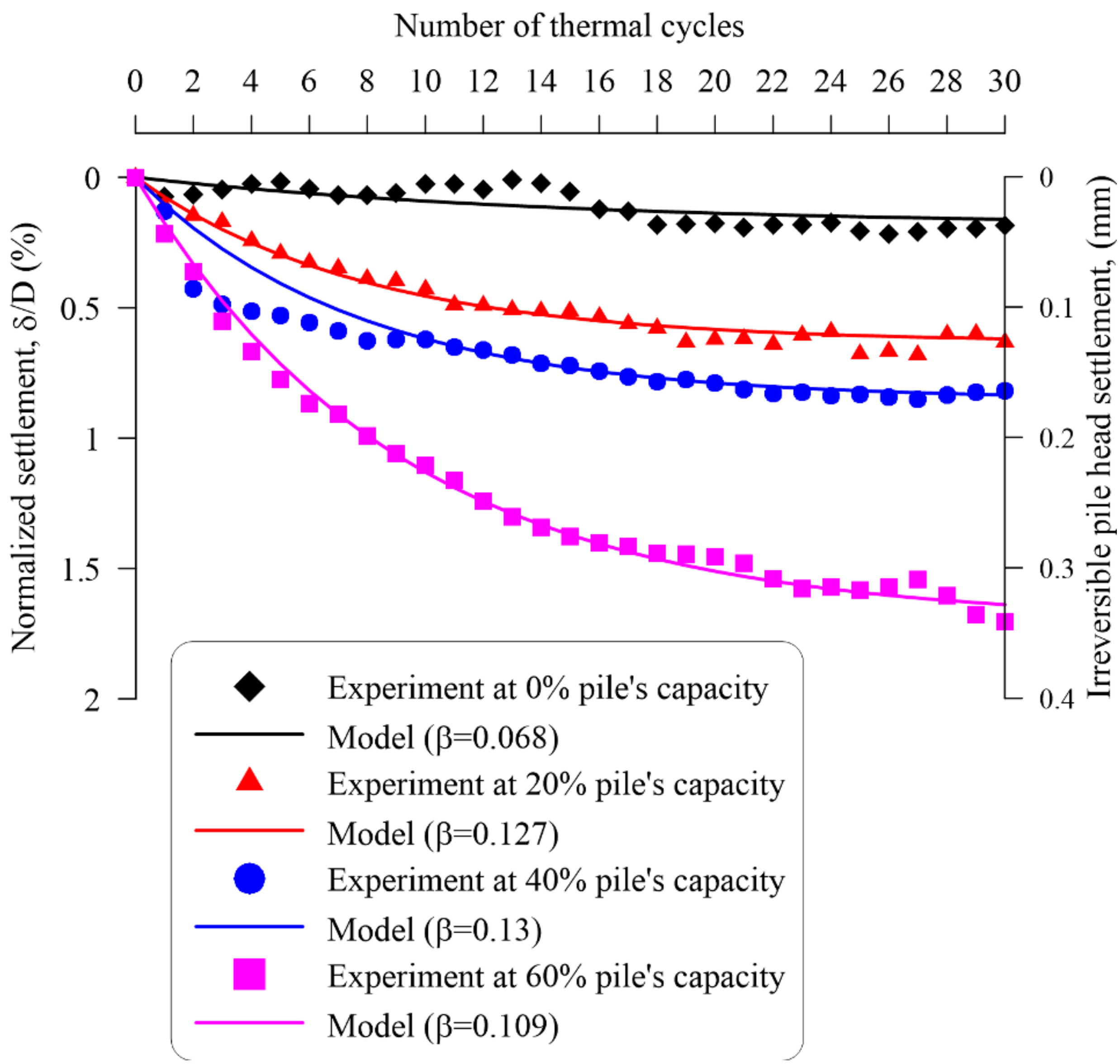

Fig. 7 Irreversible pile head settlement versus number of thermal cycles.

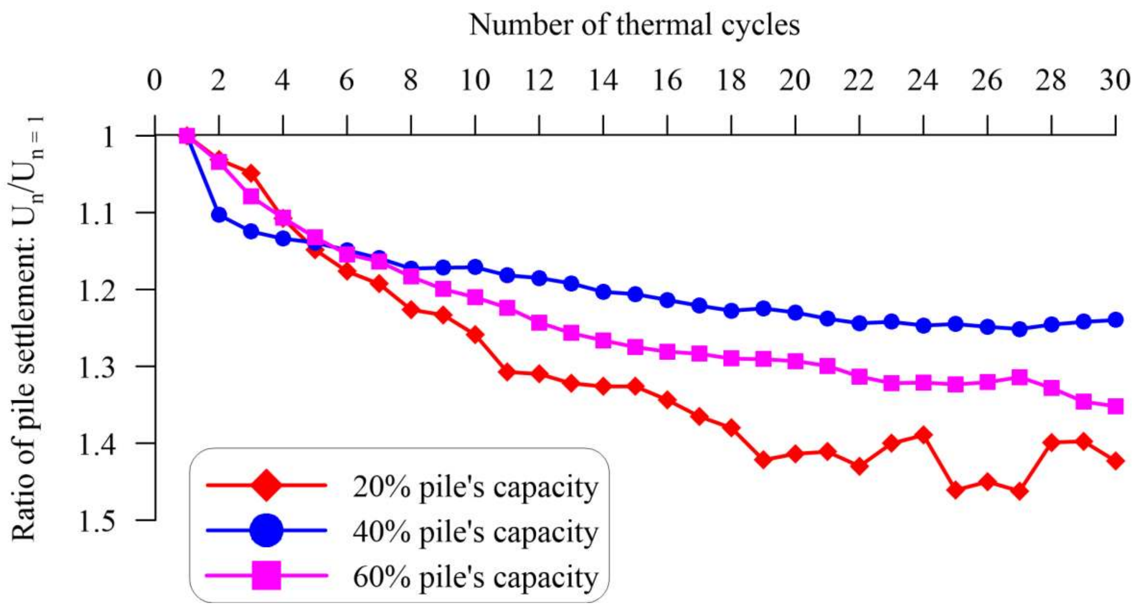

Fig. 8 Ratio of pile settlement versus number of cycles.

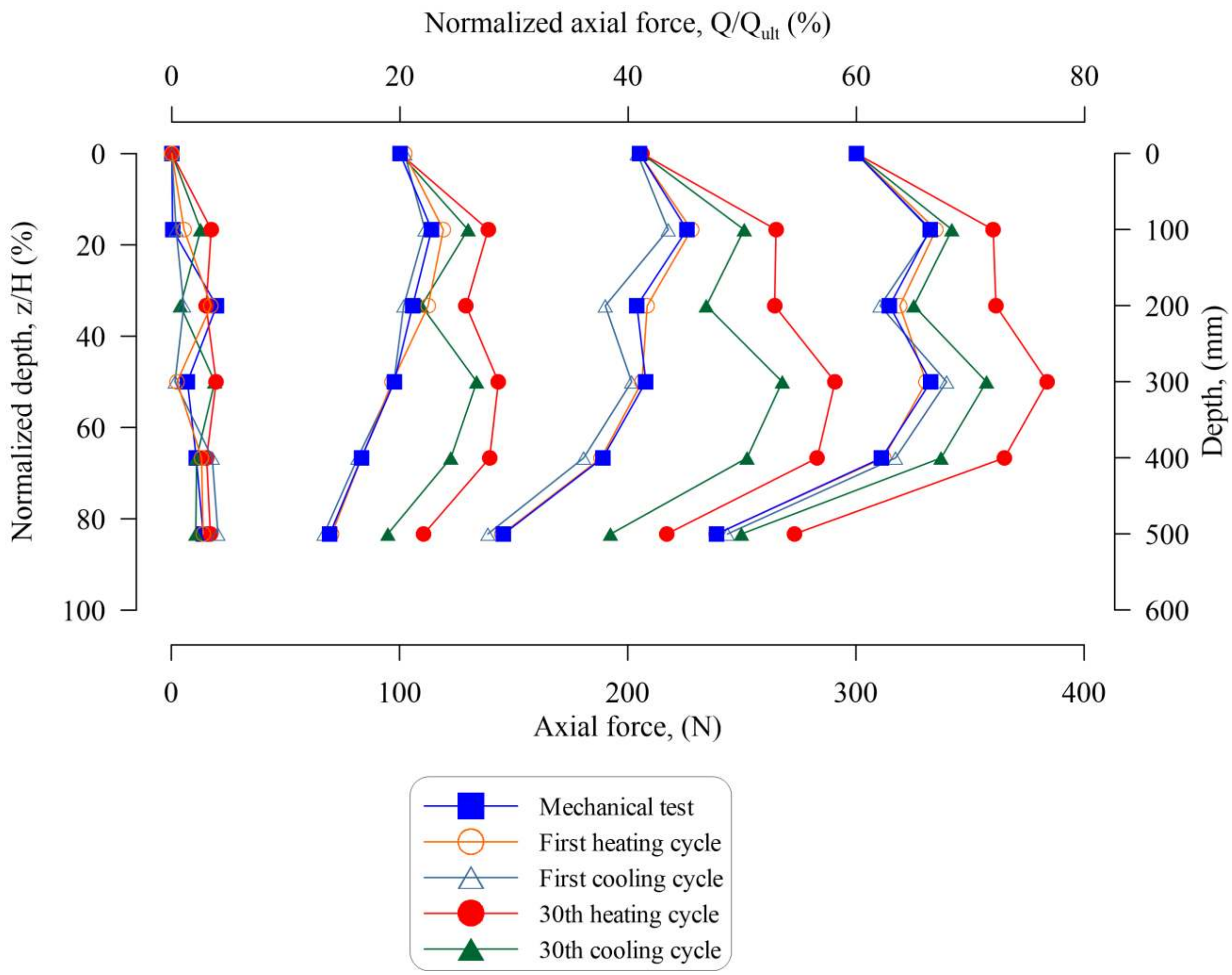

Fig. 9 Axial force profile during thermal cycles

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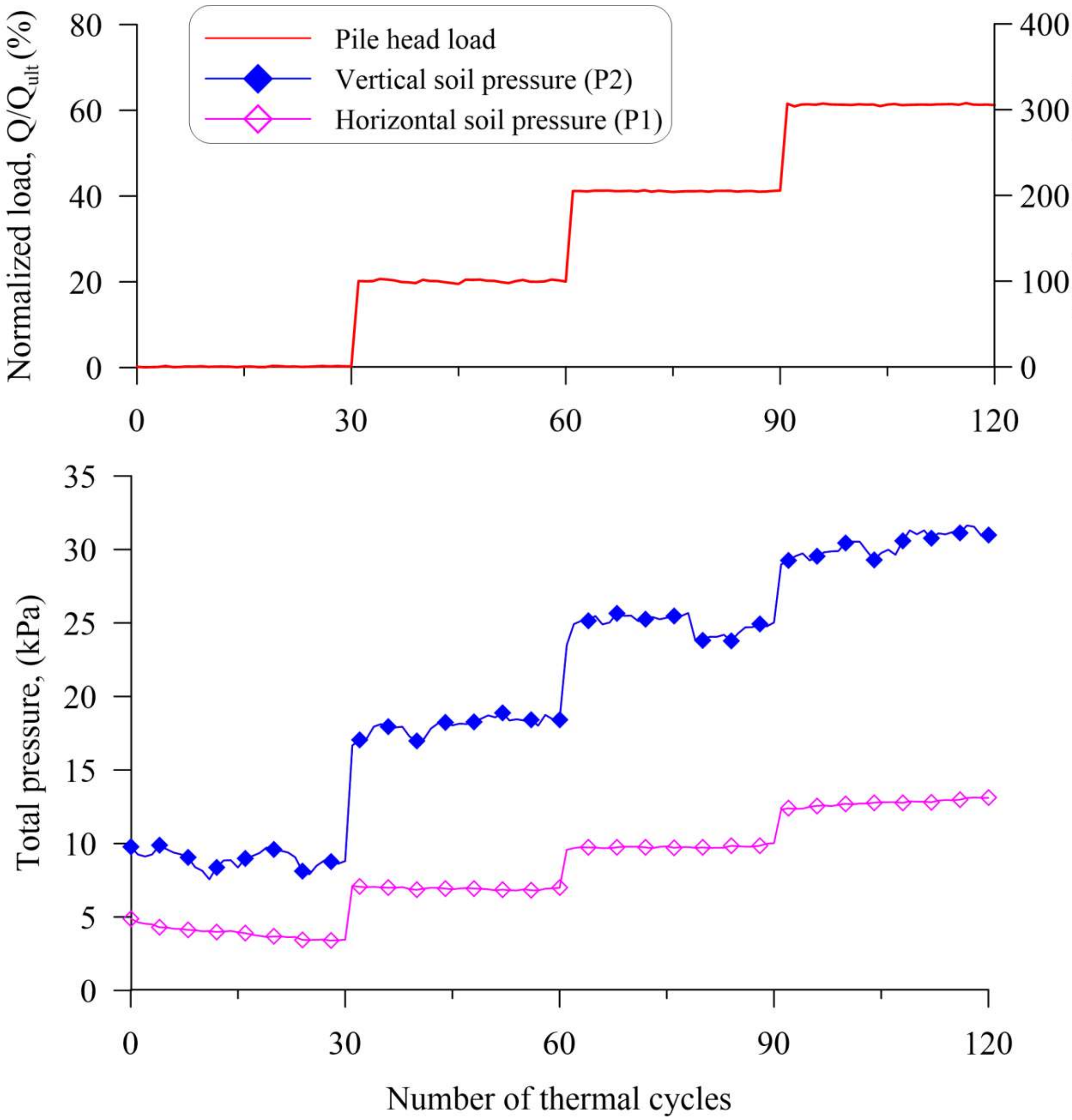

488 Fig. 10 Pile head load and total pressures in soil versus number of thermal cycles

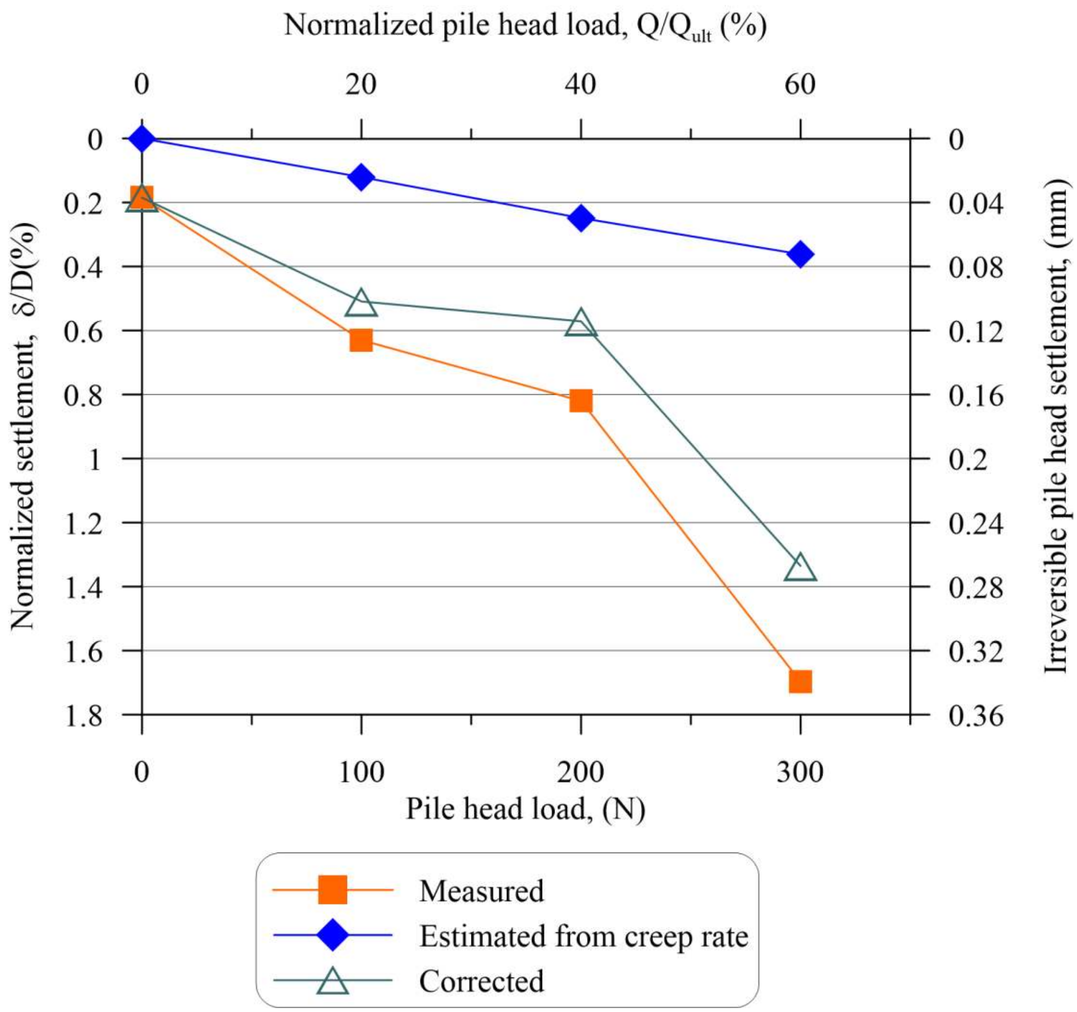

Fig. 11 Pile head settlement after 30 cycles versus pile head load