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1     **Long-term thermo-mechanical behavior of energy pile in dry sand**

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19 **Abstract:** A small-scale pile has been developed in the laboratory to investigate the thermo-  
20 mechanical behavior of energy piles subjected to a significant number of thermal cycles. The  
21 model pile (20 mm external diameter), installed in dry sand, was initially loaded at its head to 0,  
22 20, 40 and 60% of its ultimate bearing capacity (500 N). At the end of each loading step, 30  
23 heating/cooling cycles were applied to the pile. The long-term behavior of the pile was observed  
24 in terms of pile head settlement, axial force profile, soil and pile temperature, and stress in soil.  
25 The results evidence the irreversible settlement of the pile head induced by thermal cycles under  
26 constant load head. In addition, the incremental irreversible settlement, that accumulates after  
27 each thermal cycle, decreases when the number of cycles increases. The evolution of irreversible  
28 pile head settlement versus number of cycles can be reasonably predicted by an asymptotic  
29 equation.

30

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

## 33 **1. Introduction**

34 Energy piles, or heat exchanger piles, have a dual function: (i) providing support for overhead  
35 structures as a conventional pile foundation; (ii) and exchanging heat with the ground for the  
36 purpose of heating and/or cooling the building. Energy piles have been used in some European  
37 countries during the last two decades. This technique has gained encouraging credit as an option  
38 to the use of renewable energy in modern cities and contributed to the reduction of CO<sub>2</sub>  
39 emissions [1–3]. However, the implementation of this technique is not homogeneous across  
40 countries due to the lack of design standards.

41

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

51

52 In spite of various studies on the thermo-mechanical behavior of energy piles, few works have  
53 investigated their long-term behavior. Actually, to deal with this aspect, some studies  
54 investigated the mechanical behavior of energy piles under numerous thermal cycles, which  
55 represent the seasonal variations of the pile temperature. Suryatriyastuti *et al.* [9] studied the

56 behavior of free- and restraint-head piles in very loose sand using the pile-soil load transfer  
57 approach. The proposed  $t$ - $z$  function comprised a cyclic hardening/softening mechanism, which  
58 allowed investigating the degradation of the soil/pile interface behavior under cyclic loading.  
59 This approach was then compared with a numerical simulation using the finite element method  
60 where the degradation of the soil-pile interface behavior under cyclic loading was considered. A  
61 simulation accounting for 12 thermal cycles shows: (i) a ratcheting of pile head settlement under  
62 constant working load; (ii) and a decrease in pile head load for the restraint-head pile.

63

64 Saggi & Chakraborty [12] investigated the behavior of a floating and end-bearing pile in loose  
65 and dense sands under various thermal cycles by using the finite element method and nonlinear  
66 transient analyses. The thermal load applied to the pile was in the same temperature range as in  
67 the experiments of Laloui *et al.* [2], with a temperature amplitude of 21°C. The results show an  
68 important settlement of the pile after the first thermal cycle. The subsequent thermal cycles  
69 induce pile heave. This phenomenon can be clearly seen in the case of dense sand where the pile  
70 and the soil surface move upward together after 50 cycles. Actually, the pile and soil were  
71 progressively heated during these 50 cycles. In addition, the pile shaft resistance in dense sand  
72 increases with the thermal cycles while this value does not change in loose sand. The authors  
73 explain this observation in the case of dense sand by the larger horizontal stress induced by soil  
74 thermal expansion which affects the mobilized pile shaft resistance. However, a parametric study  
75 shows a decreasing trend of the pile axial stress with thermal cycles. A similar result can be  
76 found in the numerical study of Olgun *et al.* [36] where pile head displacement and axial stress  
77 were investigated under three different climatic conditions for 30 years. After 30 annual thermal  
78 cycles, even if the pile was progressively cooled, its axial stress tends to increase. A decrease in

79 axial stress is observed during a heating process. This was explained by the difference in the  
80 thermal dilations of the pile and the soil, respectively. Ng *et al.* [39] studied the horizontal stress  
81 change of soil element close to the pile when the pile was subjected to 50 heating-cooling cycles.  
82 The results show that the horizontal stress along the pile decreases with thermal cycles, this  
83 decrease being particularly affected by the thermal cycles amplitude and the pile diameter.  
84 Pasten & Santamarina [17] also used a modified one-dimensional load transfer model to predict  
85 the long-term response of shaft- and end-bearing piles subjected to thermal cycles. They show  
86 that the most plastic settlement of the pile took place during the first few cycles. More recently,  
87 Vieira & Maranhã [35] investigated the behavior of a floating pile model in clay soil under  
88 different load levels and seasonal temperature during five years using the finite element method.  
89 The results indicate that when the pile works with a high factor of safety its displacement is  
90 reversible during the thermal cycles. However, a low factor of safety induces an increase in axial  
91 stresses while the rate of irreversible settlement reduces with the number of cycles.

92  
93 Beside the numerical studies mentioned above, few experimental studies have been performed to  
94 investigate the long-term behavior of energy piles. Ng *et al.* [24] used centrifuge modeling to  
95 study the thermo-mechanical behavior of energy piles constructed in lightly and heavily over-  
96 consolidated clays under five thermal cycles. The results show that the most irreversible  
97 settlement of the pile is observed in the first thermal cycle. In the following cycles, the settlement  
98 increases at a lower rate. After 5 cycles, the accumulated settlement is about 3.8%D (pile  
99 diameter) for a pile in the lightly over-consolidated clay, and 2.1%D for heavily over-  
100 consolidated clay. Another study using centrifuge modeling to investigate the long-term behavior  
101 of energy pile under four thermal cycles can be found in [14]. An end-bearing pile, installed in

102 unsaturated silt, worked under a constant head load and four thermal cycles (the temperature  
103 ranging from 29°C to 39°C). The observed thermal axial stress-strain behavior of the pile is in  
104 agreement with the results of in-situ experiments performed by Laloui *et al.* [2], Bourne Webb *et*  
105 *al.* [4] and McCartney & Murphy [40]. The profiles of axial stress, displacement and strain of  
106 pile does not change significantly along the four thermal cycles.

107

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

116

## 117 **2. Experimental method**

### 118 *2.1 Experimental setup*

119 A pile model (20-mm external diameter and 600-mm length) was installed in a dry sand sample  
120 (548-mm inner diameter and 900-mm height) as shown in Fig. 1. The pile model is an aluminum  
121 tube with an internal diameter of 18 mm and sealed at the bottom. The model pile surface was  
122 coated with sand to mimic the roughness of a full-scale pile surface. The sand used in this study  
123 (Fontainebleau sand) has the following physical properties: particle density  $\rho_s = 2.67 \text{ Mg/m}^3$ ;

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

126

127 The installation process began with the compaction of two 100 mm-thick layers, then two layers  
128 of 50 mm in thickness. The model pile was then installed at its position inside the soil container  
129 and fixed by a steel bar fixed to the top surface of the soil container. Finally, other sand layers of  
130 100 mm were compacted around the pile. The soil was compacted manually, by using a wooden  
131 tamper, at a dry unit weight of  $15.1 \text{ kN/m}^3$ .

132

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

145

146 *2.2 Test program*



147 In this study, three tests have been performed. After each experiment, the pile model was  
148 reinstalled according to the procedure described above. The first two tests T1 and T2 were  
149 performed to investigate the behavior of the pile under mechanical loading and isothermal  
150 conditions. The test procedure follows the French Standard [41]. In the preparation step, the pile  
151 was first loaded to 50 N (10% of the pile resistance, which is 500 N, after Yavari *et al.* [21]) and  
152 then unloaded to remove the disturbed settlement component due to soil compaction related to  
153 the pile installation process. After this step, the pile was loaded in steps of 50 N up to 250 N  
154 (50% of the pile resistance), and then unloaded completely. Finally, the pile was loaded in steps  
155 of 50 N up to failure (corresponding, by convention, to a pile head settlement equal to 2 mm, *i.e.*  
156 10% of the pile diameter). Each loading step was maintained for 60 min.

157

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

167

### 168 **3. Results**

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

$$175 \quad \alpha = (S_{60} - S_{30})/\log(60/30) \quad (1)$$

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

187

188 Fig. 5 shows the temperature measured at various locations together with the pile head settlement  
189 after the first heating-cooling cycle in the test T3 under a constant head load corresponding to  
190 20% of the pile resistance. When the temperature of the pile is increased from 20°C to 21°C, the  
191 soil temperature at 20 mm (S5), 40 mm (S6), and 80 mm (S7) from the center of the pile

192 increases subsequently. But the temperature change at 80 mm remains very small. It seems that  
193 the duration of 4 h for the heating phase is long enough for the soil temperature to reach  
194 equilibrium. The same conclusion can be drawn for the subsequent cooling phase (pile  
195 temperature is decreased to 19°C) and the final heating phase (pile temperature is increased to its  
196 initial value, 20°C). The results on the pile head settlement show that heating does not induce  
197 any significant movement but that cooling induces a settlement (the normalized settlement is the  
198 ratio between the pile head settlement and the pile diameter). In addition, the pile head settlement  
199 and the pile temperature stabilize at the same time.

200

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

214

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

224

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

$$227 \delta_1 = \delta_1|_{N_c \rightarrow \infty} (1 - \exp(-\beta \cdot N_c)) \quad (2)$$

228 Here,  $\delta_1$  is the irreversible pile head displacement;  $N_c$  is the number of cycles;  $\beta$  is a model  
229 parameter obtained by fitting the experimental data (one value per pile head load). The result in  
230 Fig. 7 shows that this equation can fit correctly all the experimental data.

231

232 Besides, irreversible settlement was also normalized with respect to the settlement obtained  
233 during the first cycle as suggested by Suryatriyastuti *et al.* [9]. This ratio of pile settlement is  
234 plotted versus the number of cycles in Fig. 8 for all the four pile head loads. The results show  
235 that this ratio increases quickly during the first ten cycles and then tends to stabilize at a high  
236 number of cycle. Note that in the study of Suryatriyastuti *et al.* [9], at a pile head load of 33% of

237 the pile resistance, 12 heating/cooling cycles induce a ratio of approximately 1.2. This value is  
238 similar to the one found in the present work for the case of 40% of the pile resistance.

239  
240 The results on the axial force along the pile, measured by the strain gages and the pile head load  
241 sensor, are plotted in Fig. 9. The axial force  $Q$  is normalized with respect to the pile resistance  
242  $Q_{ult} = 500$  N and the depth  $z$  is normalized with respect to the pile length  $H = 600$  mm. At the  
243 initial state, when no pile head load is applied, the axial force along the pile remains smaller than  
244 5% of  $Q_{ult}$ . The subsequent thermal cycles do not significantly modify the axial force. When a  
245 load of 20% of  $Q_{ult}$  is applied to the pile head, the axial force along the pile also increases.  
246 Afterwards, the first heating phase leads to a slight increase of the axial force and the subsequent  
247 cooling phase leads to a slight decrease. After 30 cycles of heating/cooling, the axial force is  
248 higher than the initial one (under mechanical load). Note that the axial force after the 30<sup>th</sup> heating  
249 phase is also higher than that after the 30<sup>th</sup> cooling phase. The cases of loads corresponding to  
250 40% and 60% of  $Q_{ult}$  lead to similar observations.

251  
252 Fig. 10 shows the pile head load, the horizontal and vertical pressures in soil at 50 mm under the  
253 pile toe as a function of the number of thermal cycles. The initial stress (10 kPa and 5 kPa for  
254 vertical and horizontal ones, respectively) corresponds to the weight of the soil specimen. The  
255 coefficient of horizontal pressure at rest of 0.5 is in the usual range for dry sand [12, 21, 42].  
256 These pressures increased significantly when the pile head load was increased but the thermal  
257 cycles did not influence these values.

258

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

265

#### 266 **4. Discussion**

267 In the present work, the temperature variation was imposed at  $\pm 1^\circ\text{C}$ . This range is much smaller  
268 than the temperature variation of the energy piles which can reach up to  $\pm 20^\circ\text{C}$  [2, 4, 11, 21, 25,  
269 27]. Actually, in this small-scale model, the dimension of the pile is 20 times smaller than a full-  
270 scale pile of 0.4 m in diameter and 12 m length. As a consequence, the strain related to the  
271 mechanical load is 20 times smaller than that at the full scale [2, 8, 11, 24]. For this reason, the  
272 temperature variation was reduced 20 times in order to have a thermal dilation of the pile 20  
273 times smaller than that at the full scale. The thermo-mechanical behavior of the pile observed at  
274 the small scale can then be used to predict the behavior of energy piles at the full scale.

275

276 The irreversible evolution of the pile head settlement with thermal cycles observed in the present  
277 work (Fig. 7) is similar to that obtained by Ng *et al.* [24] on saturated clay using centrifuge  
278 modeling. These authors applied five thermal cycles and observed a ratcheting of pile head  
279 settlement. A similar behavior can be found in the numerical study of Vieira & Maranhã [35]. In  
280 the present work, with 30 thermal cycles (which can represent 30 years of seasonal temperature  
281 changes of energy piles), the results confirm that the increment of irreversible settlement per

282 cycle is higher during the first cycles but becomes negligible after 20 cycles for the cases of axial  
283 loads lower than 40% of the pile resistance (which corresponds to the service load of piles in real  
284 cases). The irreversible settlement continues to increase after 20 cycles only when the pile head  
285 load is high (60% of the pile resistance).

286

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

303

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

308

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

316

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

322

## 323 **5. Conclusions**

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



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

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

342

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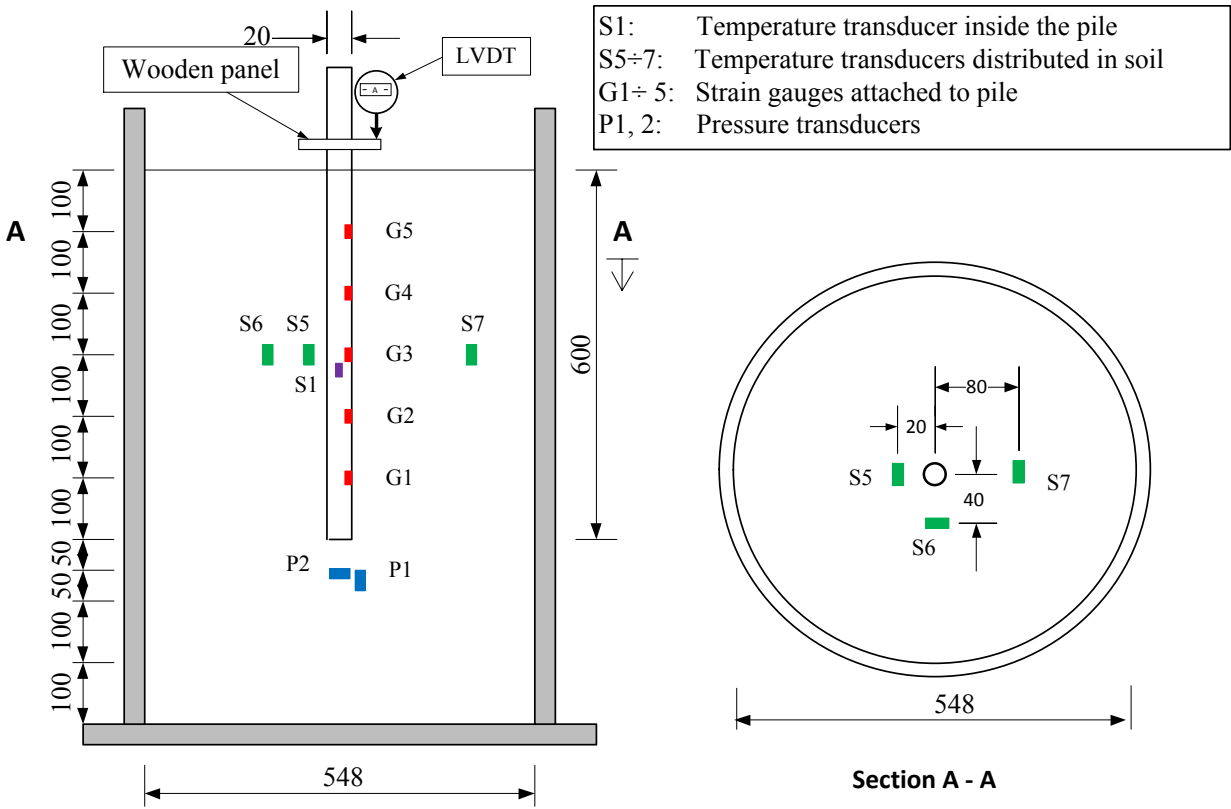
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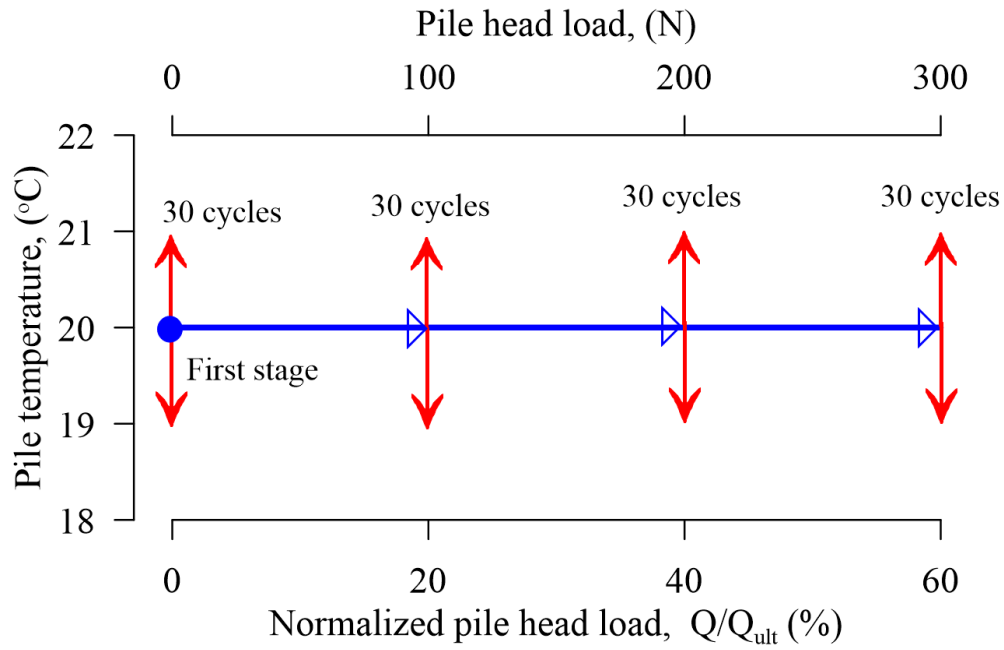


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461 Fig. 1 Experiment setup

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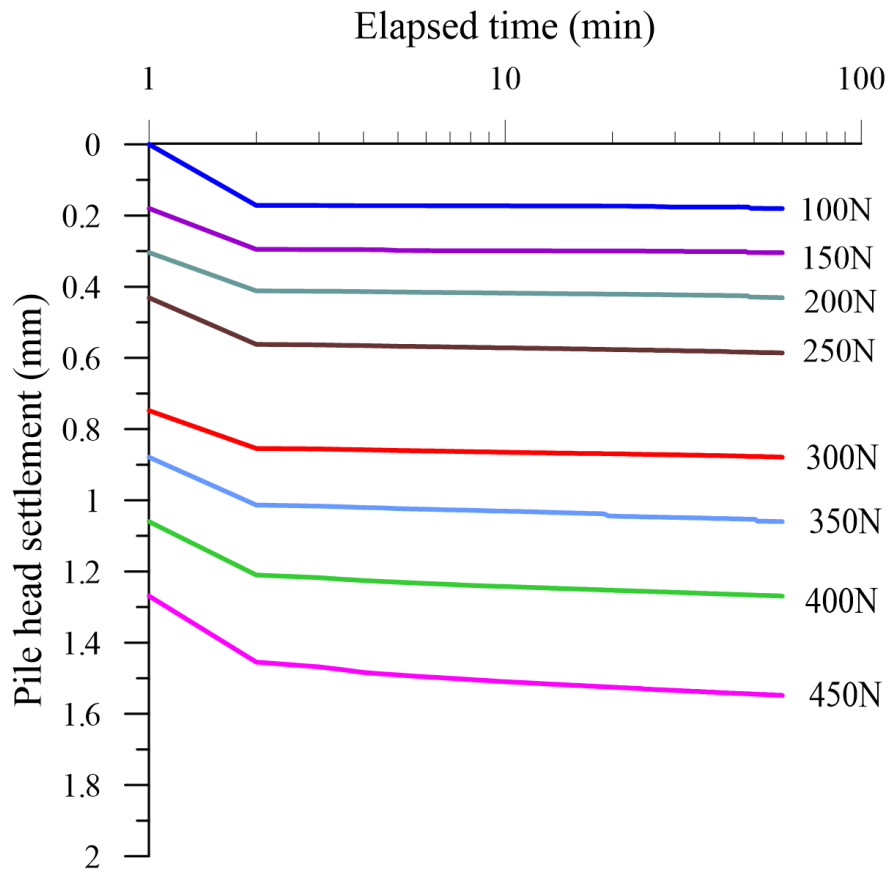


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465 Fig. 2 Thermo-mechanical loading path of the test T3.

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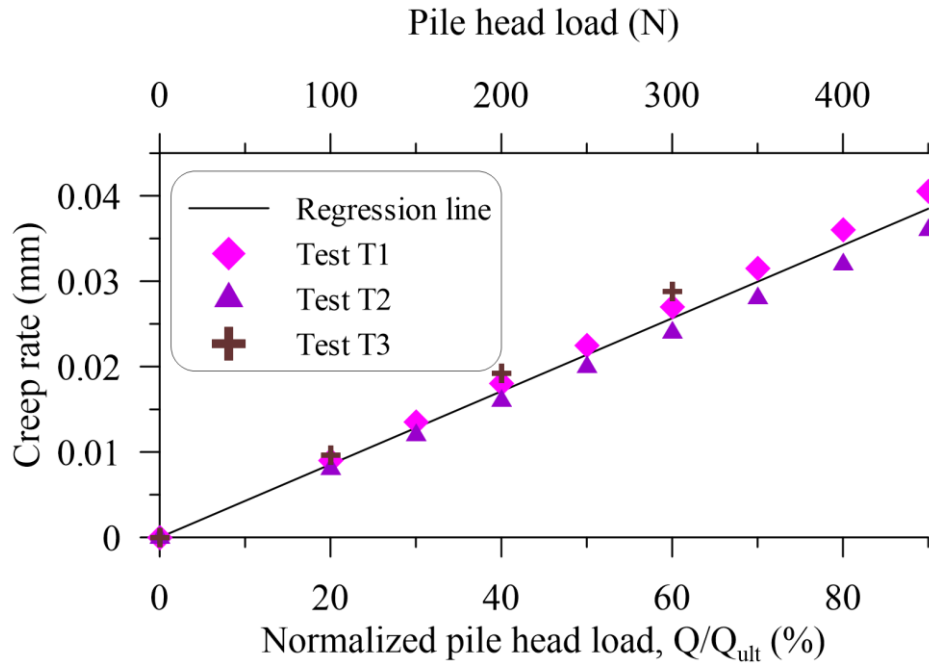


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469 Fig. 3 Mechanical settlement of pile in test T1

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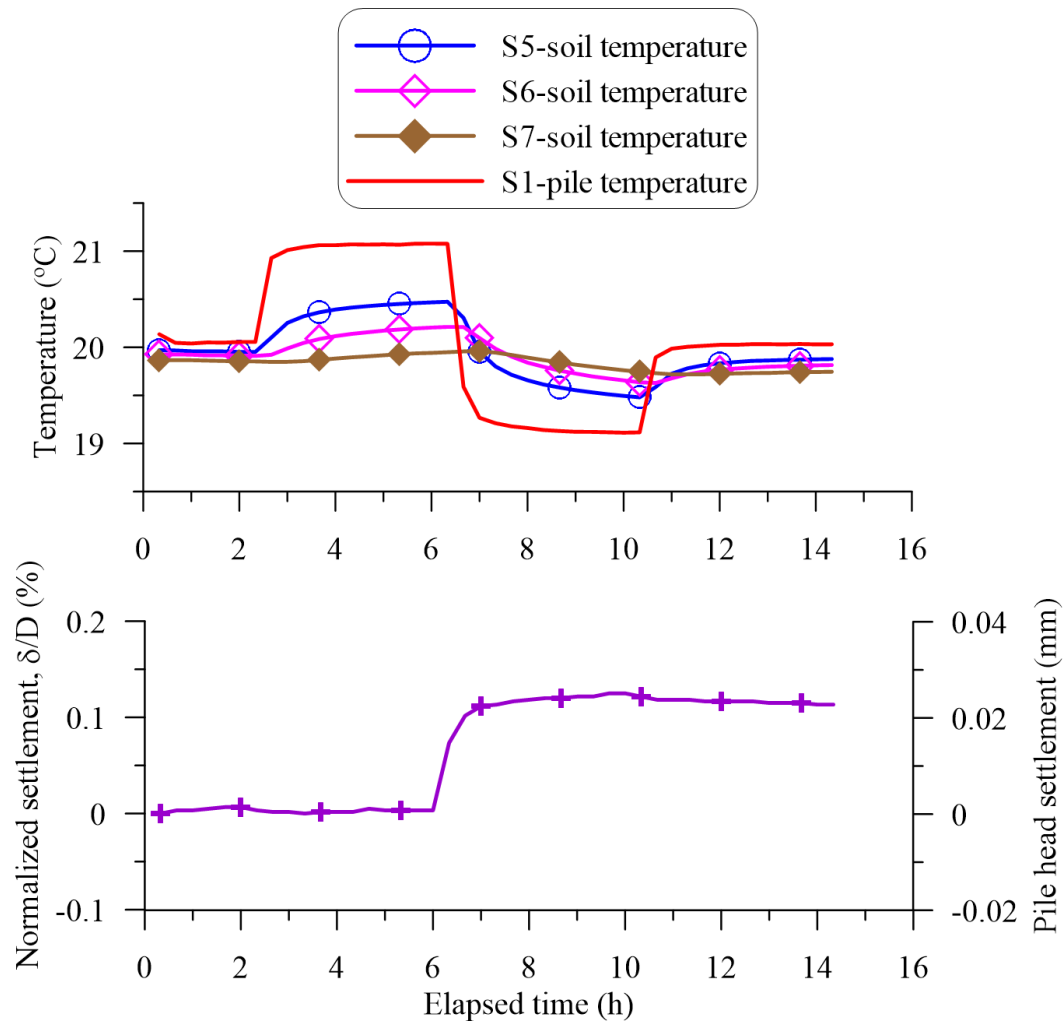
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473 Fig. 4 Creep behavior of pile for all the three tests.

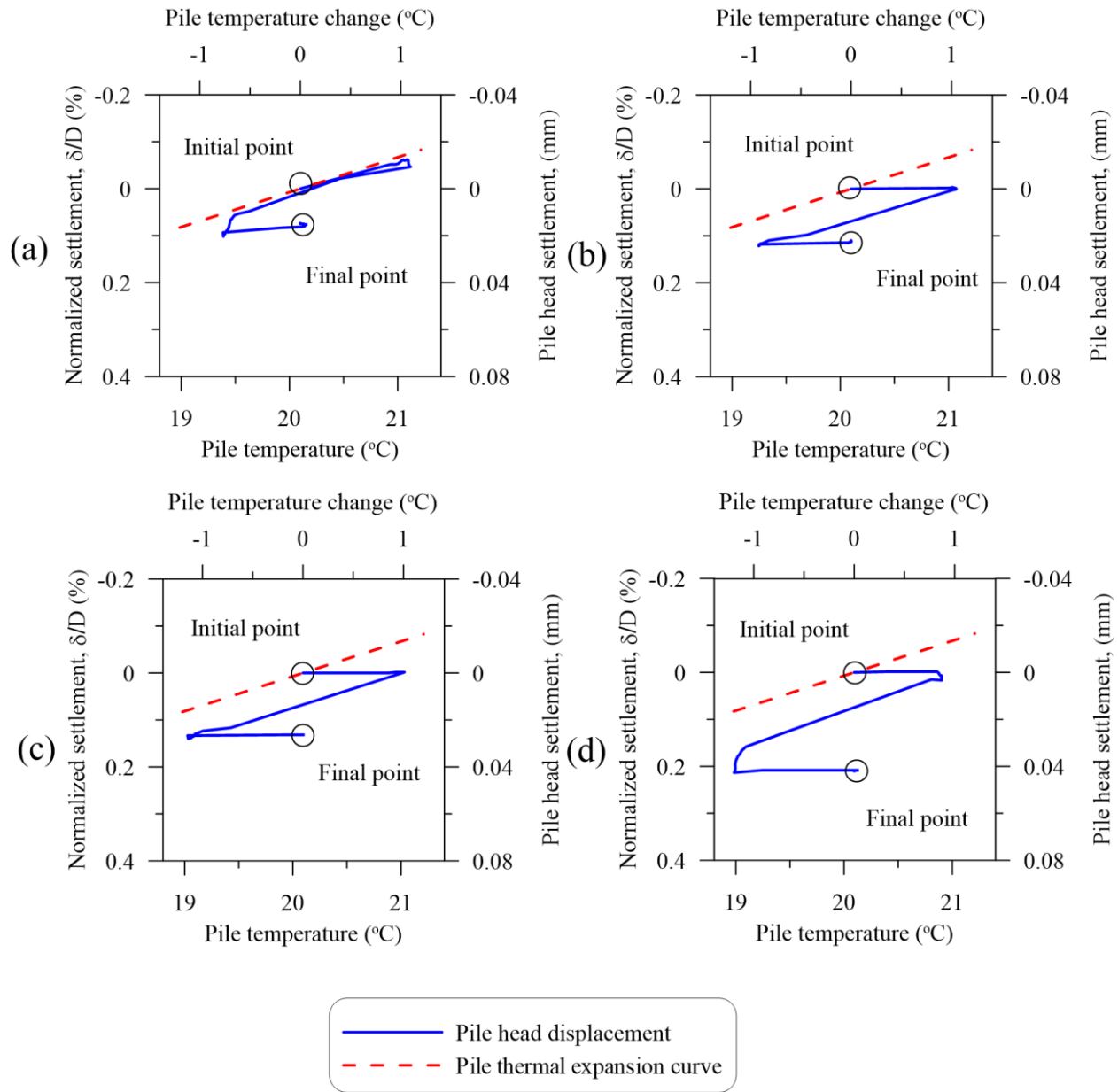




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475 Fig. 5 Pile head settlement, soil and pile temperature versus elapsed time during the first thermal

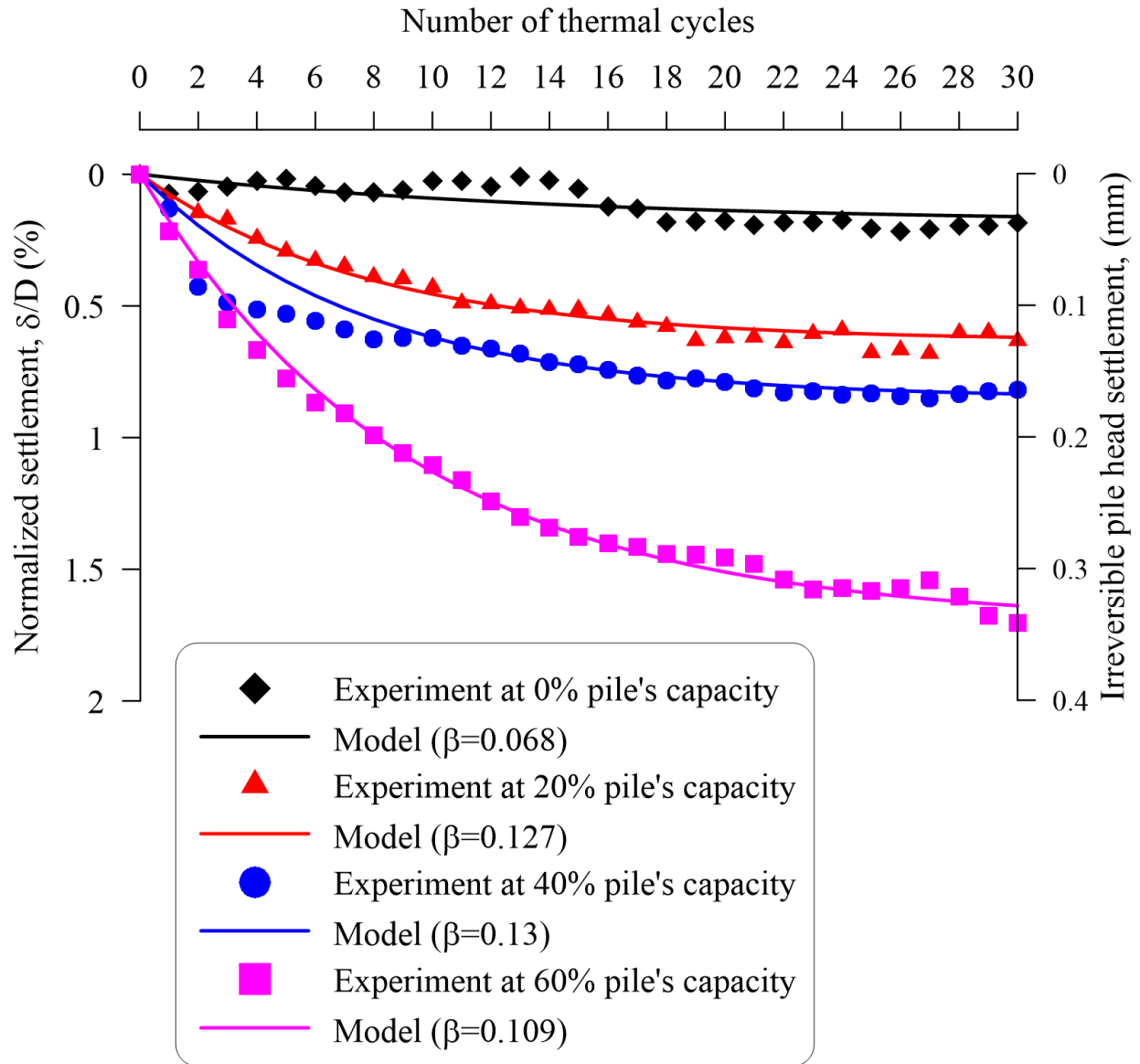
476 cycle at 20% of pile resistance.



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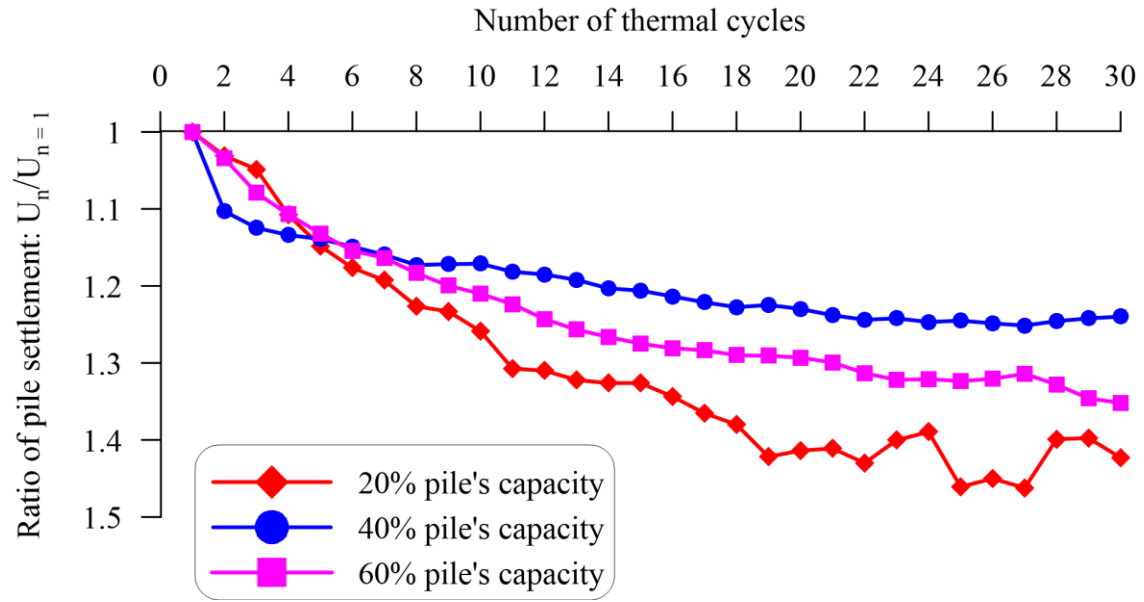
478 Fig. 6 Pile head settlement versus temperature change during the first cycle at axial load of (a)

479 0%; (b) 20%; (c) 40%; (d) 60% of pile resistance.



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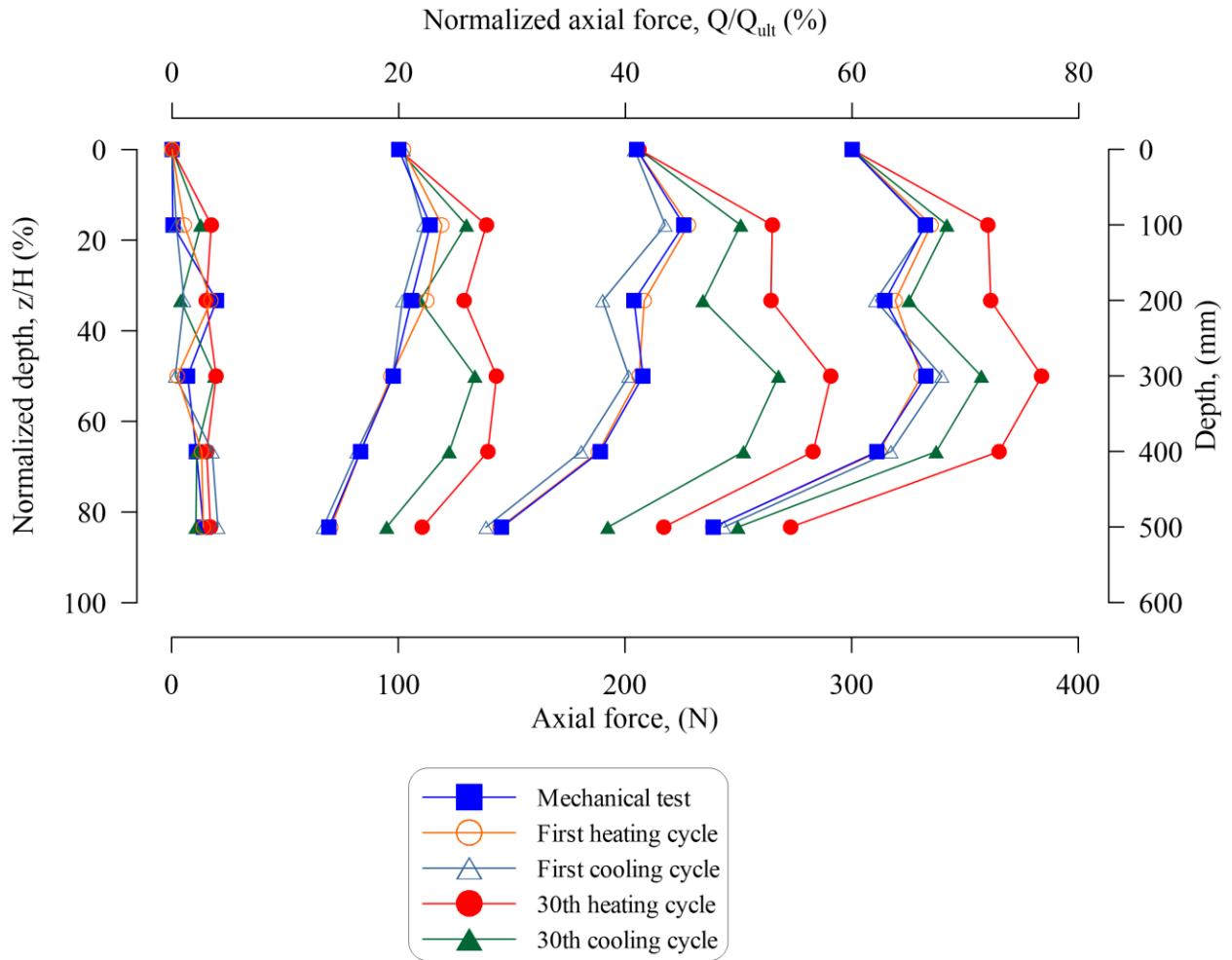
481 Fig. 7 Irreversible pile head settlement versus number of thermal cycles.



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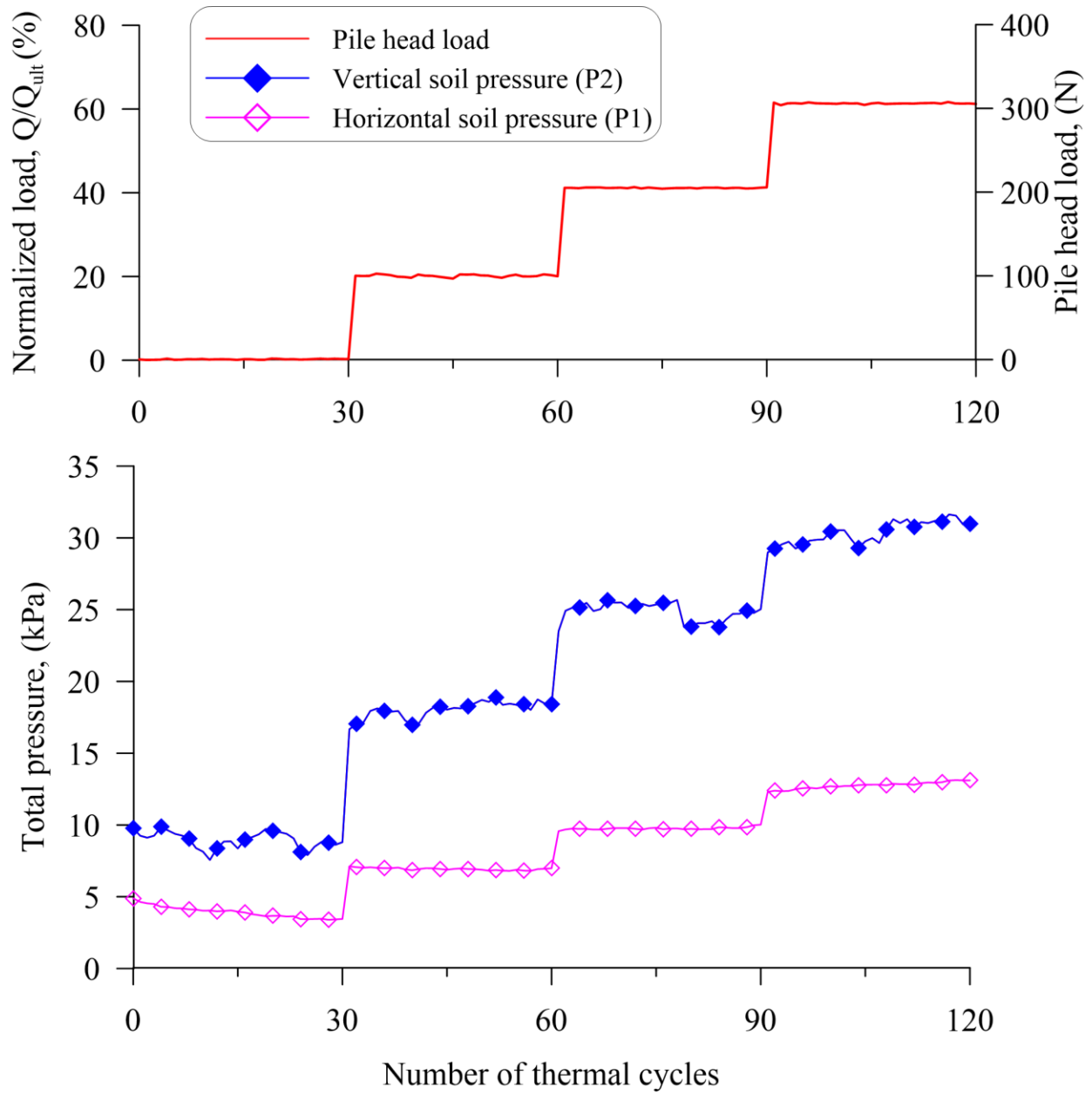
483 Fig. 8 Ratio of pile settlement versus number of cycles.

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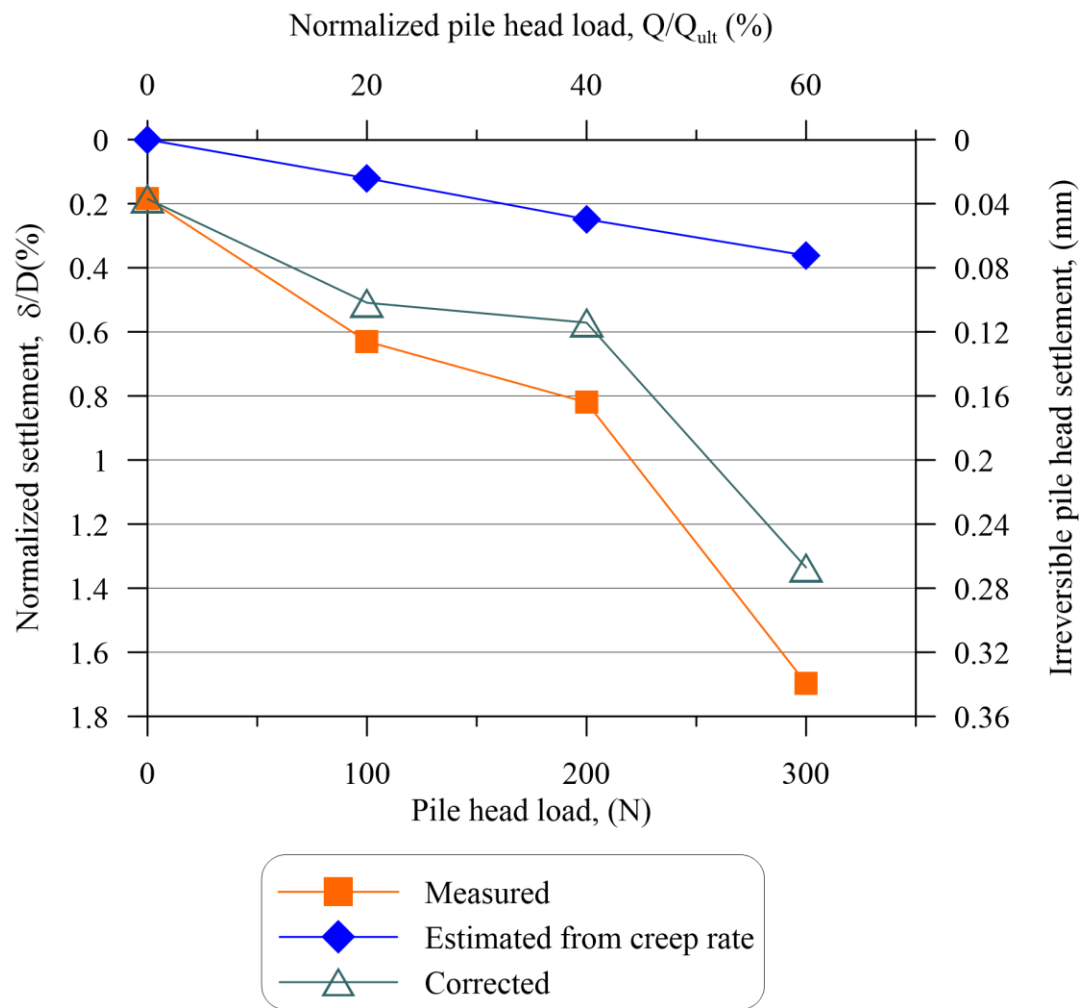
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486 Fig. 9 Axial force profile during thermal cycles



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



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