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Small-scale cyclically thermally-activated pile under inclined mechanical loads

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Small-scale cyclically thermally-activated pile under inclined mechanical loads

Abstract: In this study, a series of 1-g physical model tests was carried out using an instrumented model energy pile installed in dry sand to characterize the influence of cyclic thermal loading on the response of energy pile subjected to inclined mechanical loading. The loading scheme considered in the model tests comprised a pre-applied axial load (10, 20, and 40% of the ultimate axial load) combined with a horizontal load (30, 50, and 70% of the ultimate horizontal load) followed by ten thermal cycles with temperature variation of ± 1 °C. The results indicated that imposing thermal cycles to the pile subjected in advance to inclined mechanical loading resulted in a pile head irreversible settlement and horizontal displacement, which would gradually accumulate over thermal cycles. By the end of the tenth thermal cycle, the amount of accumulated irreversible settlement and horizontal displacement were generally in the range of 0.1-0.6% and 1.1-2.3% of pile diameter, respectively. Under the same horizontal load, thermal cycles at a higher axial load induced a higher irreversible settlement but a lower horizontal displacement at the pile head. Under the same axial load, thermal cycles at a higher horizontal load induced a lower settlement but a higher horizontal displacement at the pile head. Despite the fact that ultimate horizontal bearing capacity of pile remained unchanged after ten thermal cycles, it is recommended that due to the accumulation of irreversible horizontal displacement during the cyclic thermal loading, the long-term performance of energy pile is controlled by horizontal displacement rather than capacity.

Keywords: Thermo-mechanical behavior, Energy pile, Physical model, Inclined mechanical load, Cyclic thermal load.

List of notations

ρ_s	Particle density
e_{\max}	Maximal void ratio
e_{\min}	Minimal void ratio
D_{50}	Mean grain size
F_v	Pile head axial load
F_h	Pile head horizontal load
Q_v	Ultimate axial load of the pile
Q_h	Ultimate horizontal load of the pile

D	Outer diameter of model pile
L	Length of pile
ε_T	Thermal strain
n	length scaling factor (prototype divided by model)
α_p	Thermal expansion coefficient of the prototype-scale pile
α_m	Thermal expansion coefficient of the model-scale pile
ΔT_p	Temperature change in the prototype-scale pile
ΔT_m	Temperature change in the model-scale pile
a	Soil thermal diffusivity
G	Soil stiffness
E	Elastic modulus
I	Moment of inertia

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26 **1. Introduction**

27 In the last few decades, to preserve the future generations from energy crises, significant effort has been
28 accomplished to collect energy from renewable sources, including shallow geothermal energy. Geothermal energy
29 piles are one of the most common and efficient systems of shallow geothermal energy, in which geothermal loops
30 are integrated into the foundation elements to extract/inject the heat from/into the ground with the purpose of
31 meeting the building heating and/or cooling demands. Since the mid-1980s, when the first energy piles were
32 installed in Austria, the use of energy piles has increased rapidly in many countries, including Canada, Australia,
33 Europe, UK, and China [1-7]. Even though lots of successful energy pile projects have been implemented in a
34 variety of important structures such as high rise buildings, underground transport projects and earth retaining
35 structures in the world, the application of this technology is still limited in the energy industry and the true potential
36 for adoption of energy piles is yet to be realized in highway bridges for deck de-icing and offshore platforms for
37 combined exploitation of offshore wind, wave and geothermal energy. In such applications, energy piles could be
38 subjected not only to axial loads, but also to cyclic horizontal loads and moments due to heavy wind, earthquakes,
39 earth pressure, slope failure, lateral spread induced by liquefaction and wave and current forces on offshore
40 structures.

41
42 In the current design practice, the response of conventional pile under combined axial and horizontal loading is
43 separately analyzed and then superposed. This approach neglects the coupling effect while the optimum design of
44 pile foundations requires consideration of the influence of axial loads on their horizontal response. Most of previous
45 studies have investigated the behavior of conventional piles under pure horizontal loads. Only a limited number of
46 studies have investigated the response of conventional piles subjected to inclined loading using physical modelling
47 under single gravity [8-13] or multiple gravities [14] and field-scale tests [15-17]. Early studies, using physical
48 model, presented by Jain *et al* [8] and Lee *et al* [9,10] suggested an increase in pile head horizontal displacement in
49 the presence of axial loading. That was in contrast to the findings of more recent studies presented by Mu *et al* [11],
50 Lu & Zhang [14], Xu *et al* [12] and Zhang *et al* [13]. There is still a lot of complexities and uncertainties pertinent to
51 the coupling effects even on the conventional pile behavior. That might be intensified in the case of energy piles
52 because the thermal variations could affect the energy pile-soil interaction behavior, e.g., causing ratcheting

53 phenomena in case of cyclic thermal loads. Therefore, it is necessary to identify the influence mechanism of axial
54 compression loads on the horizontal behavior of energy piles.

55 As for traditional piles, the studies conducted so far have concentrated on the separate investigation of axial and
56 horizontal responses of energy piles neglecting the coupling effects on the thermally-induced displacements in both
57 axial and horizontal directions. Many researchers have put a lot of effort to better understand the thermo-mechanical
58 behavior of energy piles during monotonic heating or cooling and one or multiple thermal cycles. The works of
59 Vitali *et al* [18] and Zhao *et al* [19] could be considered as the only available studies investigating the influence of
60 monotonic heating and heating-cooling cycles on the flexural behavior of horizontally-loaded energy piles,
61 respectively. Several studies have been performed to assess the behavior of axially-loaded energy piles during
62 multiple thermal cycles through field scale tests [20-25], 1-g small-scale physical model tests [26-36] and centrifuge
63 model tests [37-41]. Dry sand was the most common type of soil used in these small-scale physical model tests. The
64 above-mentioned studies indicated that imposing thermal cycles upon the axially-loaded semi-floating energy piles
65 results in cumulative irreversible settlement, which has been identified qualitatively similar in 1-g small-scale
66 physical model tests and in centrifuge testing, even though quantitative differences have been observed. Therefore,
67 despite the inherent limitations of 1-g small-scale physical model tests compared to the field-scale and centrifuge
68 model tests, qualitative results obtained from the former could be used to gain an insight into the behavior of energy
69 piles under thermo-mechanical loading and the mechanism involved. Overall, model tests to analyze the
70 performance of energy piles subjected to combined mechanical and cyclic thermal loads are still limited and there is
71 a necessity to deeply investigate the potential effects of multiple thermal cycles on the energy pile-soil interaction
72 mechanism.

73
74 The objectives of the present research are twofold: (1) investigating the influence of multiple heating-cooling cycles
75 on the geotechnical responses of energy piles; (2) evaluating the coupling effects on the thermally-induced
76 mechanical response of energy piles. Therefore, a series of 1-g model experiments was carried out on a single model
77 energy pile embedded in dry sand. The model pile was initially subjected to axial static compressive load (10, 20,
78 and 40% of the ultimate axial load); in the subsequent stage, horizontal static load was incrementally applied (30,
79 50, and 70% of the ultimate horizontal load), while the axial load was kept constant. At each level of horizontal
80 load, to simulate the actual operating condition of energy piles, repeated ten thermal cycles with temperature

81 variation in the range of ± 1 °C were applied to the pile while the mechanical loads were maintained constant. The
82 obtained results, including pile temperature, soil temperature, horizontal and axial displacements of pile head were
83 finally analyzed and discussed.

84

85 2. Experimental approach

86 2.1 Experimental setup

87 The schematic view of the experimental setup is depicted in Fig. 1. To obtain a correct physical modeling, the

88 material type and dimensions of the model pile are selected by maintaining the dimensionless ratio of $\phi_1 = \frac{GL^4}{EI}$

89 identical in the model and the prototype piles (G = soil stiffness; E =elastic modulus; I = moment of inertia; L =length

90 of pile). Since the soil stiffness scales as $\left(\frac{1}{n}\right)^\lambda$ in 1-g model testing ($\lambda = 0.5$ for sandy soils; n = length scaling

91 factor), the bending stiffness, EI , would scale as $\left(\frac{1}{n}\right)^{4.5}$ [42]. In the present study, a closed-end aluminum tube

92 having an outer diameter (D) of 20 mm, inner diameter of 18 mm, embedded length of 600 mm, and thermal

93 expansion coefficient of 22.2×10^{-6} /°C was selected as the model pile with a length scaling factor of 20. This is

94 used to simulate the prototype pile of 570 mm diameter solid section made of reinforced concrete with a

95 compressive strength of 30 MPa. Since the scaling of pile diameter depends on the scaling of pile bending stiffness,

96 the diameter and length of the pile could not be scaled in the same way. According to Das [43], for the properties of

97 sand and pile selected in this study, model pile having the length to diameter ratio (L/D) of 30 behaves as a long

98 flexible pile during horizontal loading at 50% relative density of the sand. Therefore, in response to horizontal

99 loading, the model pile is expected to bend from the top. A cylindrical steel tank with a diameter of 548 mm (\approx

100 27D) and a height of 980 mm was used as a soil tank, in which the distance between the pile toe and the base of the

101 model container was equal to 340 mm ($\approx 17D$). It is inferred from the literature that with a tank-to-pile diameter

102 ratio of 10D and a soil cushion with a depth of 3-4D below the pile toe, boundary effects of the tank could be

103 considered negligible while testing the model pile under a combination of axial, horizontal and thermal loads [29,44-

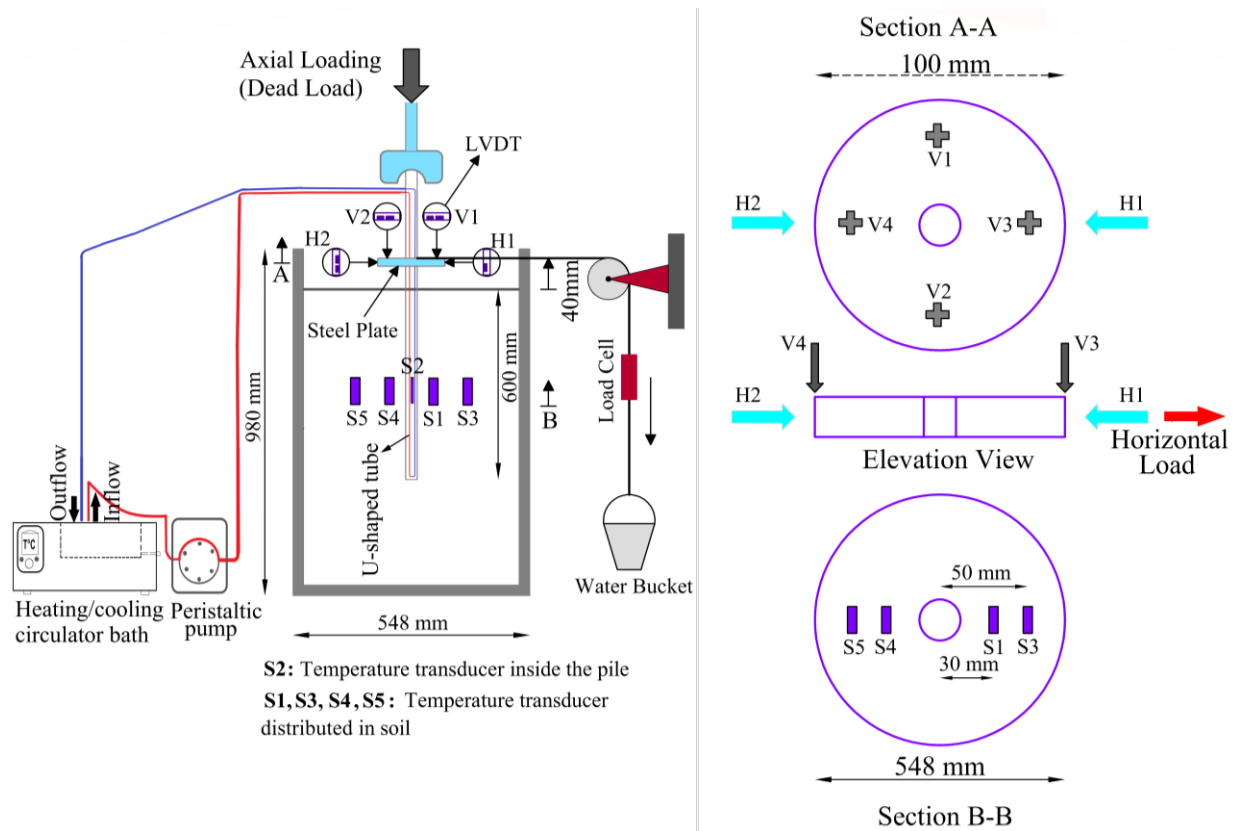
104 49]. In order to mimic the roughness of the prototype pile surface, the surface of the model pile was coated with

105 sand. It is to be noted that the attached sand layer would not change the axial and flexural stiffness of the pile.

106 Expanded polystyrene sheets were wrapped around the soil tank to insulate it against heat exchange between the soil
107 and the ambient air.

108

109 The soil used for this study was dry Fontainebleau NE34 sand with the following physical properties [50]: mean
110 grain size $D_{50} = 0.21$ mm, particle density $\rho_s = 2.65$ Mg/m³, maximal void ratio $e_{\max} = 0.884$; minimal void
111 ratio $e_{\min} = 0.557$. In the developed model, the ratio between the pile diameter (20 mm) and the mean grain size
112 (0.21 mm) was equal to 95. The mentioned ratio was greater than the suggested limit by Fioravante [51], thereby the
113 grain-size scaling effect could be considered negligible. A wooden tamper was used to compact the dry sand to a
114 density of 1.54 Mg/m³ (that corresponds to a relative density of 50%). Before installation of the model pile, the sand
115 was placed and compacted in seven 50-mm-thick layers in the tank. After the compaction of these layers, a steel bar
116 was mounted and bolted to the upper surface of the soil tank as a temporary support for installing the model pile at
117 the center of the tank. Compaction of the remaining soil around the fixed pile was then continued by 50-mm-thick
118 layers except for the top layer, which had a thickness of 40 mm. The density was controlled by the mass of soil
119 being compacted and the thickness of each layer. The above-mentioned experimental setup and method of sand
120 samples preparation have already been adopted by Kalantidou *et al* [26], Yavari *et al* [27] and Nguyen *et al* [29].
121 The repeatability of these studies confirms the uniformity of sand samples prepared by this method.



138 allowing water flow in the plastic bucket linked to the pile head through a piece of rope over a pulley. The flow rate
 139 was controlled by a valve attached to the water tank. The applied horizontal load and pile head displacements were
 140 measured accurately using a load cell and displacement transducers (*VI-V4, HI-H2*), respectively.

141

142 **2.2 Test program**

143 In the present work, nine experiments were performed (Table 1), each one corresponds to a soil sample. In the test
 144 ID, notations of E and T denote the experiment (E) performed on one soil mass, and subtests (T) of the main
 145 experiment, respectively. Notations of M and TM after the first number denote loading type in experiments, i.e.
 146 mechanical loading (M), and thermo-mechanical loading (TM), respectively. The number after notations of E or T is
 147 the amount of pre-applied axial load (percent compared to ultimate axial load), and the number after notations of M
 148 or TM is the amount of applied horizontal load (percent compared to ultimate horizontal load).

149

150 Actually, for experiment E40M (and test T40M), after the installation of the setup, axial load (F_v) was first applied
 151 to 40% of the ultimate axial load (Q_v , which was estimated at 500 N by Nguyen *et al* [29] using the same system and
 152 the same soil). Afterward, the horizontal load (F_h) was increased progressively until failure (assumed to occur when
 153 pile head horizontal displacement exceeds 20%D). This value is in the range of pile horizontal displacements (at the
 154 sand bed surface level) often used to estimate the ultimate horizontal load capacity value [49,52]. The aim of
 155 experiment E40M (and test T40M) was to determine the mechanical behavior (and the ultimate horizontal load Q_h)
 156 of the pile under the increase of horizontal load while the axial load was maintained at 40% Q_v . Experiment
 157 E40M_R (and test T40M_R) is the replicate of experiment E40M (and test T40M). Experiments E20M (and test
 158 T20M) and E10M (and test T10M) are similar to E40M (and test T40M) but with F_v equal to 20% and 10% Q_v ,
 159 respectively. Experiments E20M_R and E10M_R are their replicates.

160

161 **Table 1.** Test program.

Experiment	Test	F_v / Q_v (%)	F_h / Q_h (%)	Number of thermal cycle
E40M	T40M	40	>100	0
E40M_R	T40M_R	40	>100	0

E40TM	T40TM_30	40	30	10
	T40TM_50	40	50	10
	T40TM_70	40	70	10
E20M	T20M	20	>100	0
E20M_R	T20M_R	20	>100	0
E20TM	T20TM_30	20	30	10
	T20TM_50	20	50	10
	T20TM_70	20	70	10
E10M	T10M	10	>100	0
E10M_R	T10M_R	10	>100	0
E10TM	T10TM_30	10	30	10
	T10TM_50	10	50	10
	T10TM_70	10	70	10

162

163 In order to simulate typical load combinations of energy piles implemented in high-rise buildings, highway bridges,
164 earth-retaining structures and those located on sloping ground, the loading scheme of model tests in the present
165 study comprised pre-axial static loading followed by horizontal static loading before subsequent heating-cooling
166 cycles. In such a loading scheme, the additional rotational restraint induced by pile cap, group effects and the cyclic
167 nature of horizontal loading were not taken into consideration to isolate the coupling effects on the energy pile
168 behavior during cyclic thermal loading. Therefore, for experiment E40TM, F_v was first increased to 40% Q_v ,
169 followed by an increase of F_h to 30% Q_h . Afterward, under this inclined mechanical load, thermal cycles were
170 applied (test T40TM_30). Owing to the fact that the pile temperature was controlled manually in the experiments, a
171 duration of 2 h was adopted for the heating and cooling phases, which was long enough for the soil temperature to
172 reach equilibrium according to the temperature history of soil obtained by Nguyen *et al* [29] using identical pile and
173 soil under the same temperature change applied to the pile. Therefore, in each thermal cycle, pile temperature was
174 manually increased from an ambient temperature of 22 °C to 23 °C over a 2-h heating phase prior to being decreased
175 to 21 °C over a 2-h cooling phase. Finally, during the recovery phase, it was rapidly increased to an ambient

176 temperature of 22 °C and maintained over 20 h prior to the subsequent thermal cycle. For the tests continued during
177 the weekends, the duration of the recovery phase of some thermal cycles was increased to more than 20 h.

178

179 To scale the heat diffusion time in thermal cycles, Fourier's number could be used [48]:

$$180 \left(\frac{at}{(D/2)^2} \right)_m = \left(\frac{at}{(D/2)^2} \right)_p$$

181 (1)

182 Where a , t , and D are soil thermal diffusivity, heat diffusion time, and pile diameter, respectively. The subscripts
183 "m" and "p" mean model and prototype, respectively. Since the same sand was considered in model and prototype
184 scale, the scaling factor for soil thermal diffusivity is one. Hence, the heat diffusion time must be scaled by $\left(\frac{D_p}{D_m}\right)^2$.

185

186 As already noted by Zhao *et al* [54], thermal strains ($\varepsilon_T = \alpha\Delta T$) should be scaled by the same scaling factor as
187 mechanical strains (i.e. $N^{0.5}$). Hence, the temperature changes in the prototype-scale concrete pile (ΔT_p) are given
188 by:

$$189 \Delta T_p = N^{0.5} \times \frac{\alpha_m \Delta T_m}{\alpha_p}$$

190 (2)

191 Since the model-scale aluminum pile has a thermal expansion coefficient (α_m) of $22.2 \times 10^{-6} / ^\circ\text{C}$, which is 2.2
192 times that (α_p) of a prototype-scale concrete pile, temperature changes of $\pm 1^\circ\text{C}$ (ΔT_m) during 2-h heating and cooling
193 phases in the model-scale pile could simulate temperature changes of $\pm 10^\circ\text{C}$ during 2.25-month heating and cooling
194 phases in the prototype-scale pile. This temperature variation range of the prototype pile is within the range of 3-37
195 °C of field-scale energy piles [25,53].

196 four hours of temperature changes of $\pm 1^\circ\text{C}$ in the model-scale pile (ΔT_m) could simulate five months of temperature
197 changes of $\pm 10^\circ\text{C}$ in the prototype-scale pile.

198

199 After performing test T40TM_30, F_h was increased to 50% and 70% Q_h prior to the application of the thermal
200 cycles in tests T40TM_50 and T40TM_70, respectively. Experiments E20TM and E10TM are similar to E40TM but
201 with F_v equal to 20% and 10% Q_v , respectively. Normally, in each thermo-mechanical test (TM), model pile was

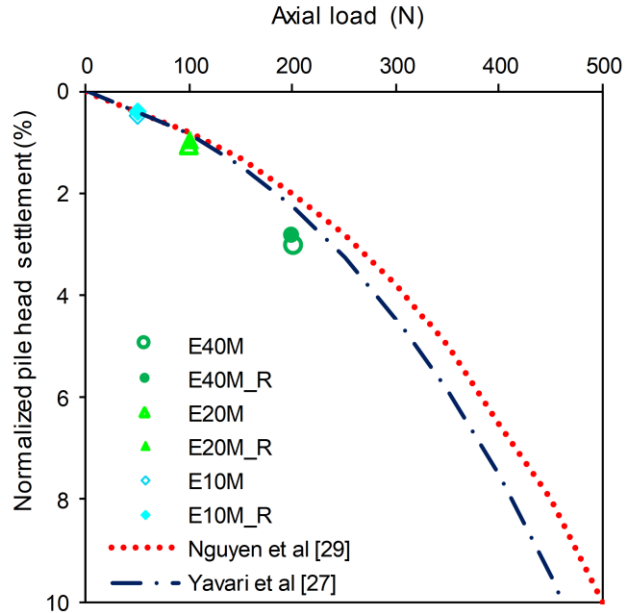
202 subjected to 10 heating-cooling cycles over a period of two weeks. There were two reasons to simulate the cyclic
203 thermal load using 10 heating-cooling cycles. First, each heating-cooling cycle required about one day for
204 completion and hence, in order to investigate different loading conditions, the number of thermal cycles should be
205 optimized. Second, the results obtained from the first thermo-mechanical test (test T10TM_30) indicated that the
206 increment rate of irreversible displacement in both axial and horizontal directions is unsteady during the first
207 thermal cycles and, as the number of thermal cycles increased, it tended to be stable. To measure pile head axial
208 displacement, in all experiments except E20M_R and E40M_R, axial displacement sensors *V1* and *V2* were
209 mounted in the perpendicular direction to horizontal load and opposite to each other at a distance of 40 mm from the
210 pile axis. Conversely, in experiments E20M_R and E40M_R, axial displacement sensors *V3* and *V4* were mounted
211 in the horizontal load direction and opposite to each other at a distance of 40 mm from the pile axis. In all
212 experiments, pile head horizontal displacement was measured at a height of 40 mm above the soil surface by two
213 horizontal displacement sensors (*H1* and *H2*) mounted directly opposite to each other at a distance of 50 mm from
214 the pile axis (see Fig. 1).

215

216 **3. Results and discussions**

217 ***3.1. Load-displacement response of the model pile subjected to purely mechanical load***

218 In the mechanical experiments, the data collected in terms of axial load and settlement of the model pile while being
219 subjected to pure axial loading are plotted in Fig.2. The load-settlement curves corresponding to the previous studies
220 conducted using identical pile and soil are drawn in the same figure for comparison purpose [27,29]. It is clearly
221 seen that the measured settlements in the present study is similar to those reported in previous works, confirming the
222 repeatability of the model preparation and loading system.

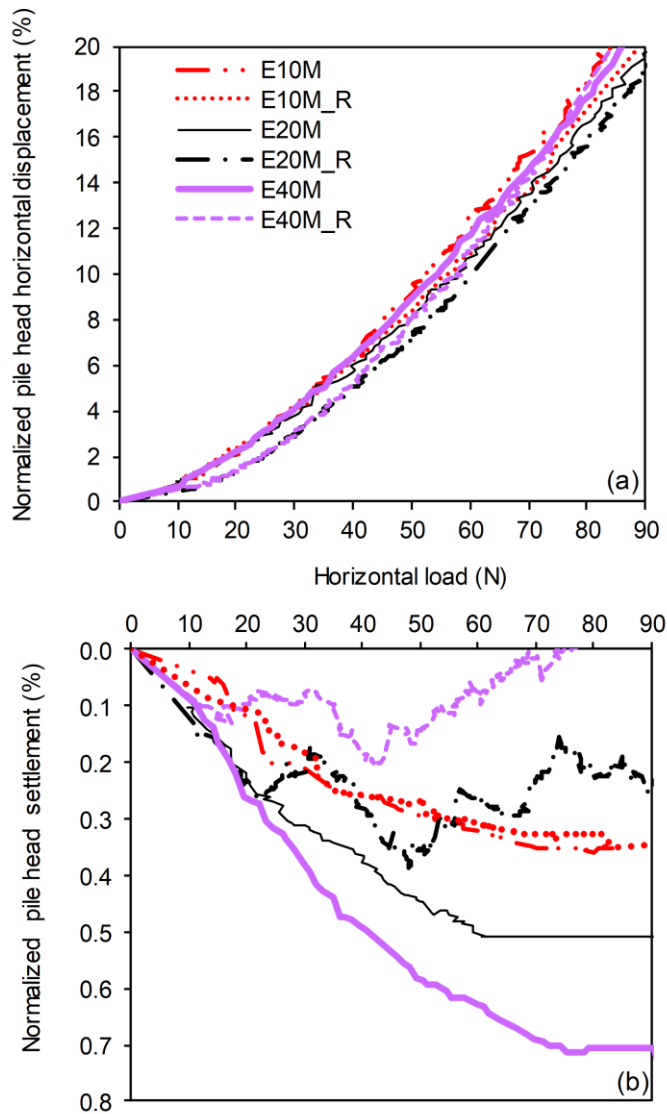


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Fig. 2. Pile head settlement versus axial load measured in mechanical tests without horizontal loading.

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Fig. 3(a) presents the normalized pile head horizontal displacement (i.e. divided by the pile diameter) versus the horizontal load while the axial load is maintained constant for all tests. The similarity of the horizontal load-horizontal displacement curves obtained from replicate tests indicates the high repeatability of the experimental procedure. All the results show an increase of pile head horizontal displacement while the horizontal load is increased. The ultimate horizontal load (corresponding to a normalized pile head horizontal displacement of 20% D) is equal to 86 - 90 N. An increasing pre-applied axial load from 10% to 20% Q_v causes a negligible reduction in pile head horizontal displacement, which agrees with the findings of previous studies using similar soil conditions and experimental set-up [11-14]. On the contrary, with an increase of pre-applied axial load to 40% Q_v , pile head horizontal displacement increases rather than decreases further so that the horizontal load-horizontal displacement curve is almost the same as the case of the pre-applied axial load of 10% Q_v . Overall, where axial load varies between 10% and 40% Q_v , the horizontal behavior of the pile is almost independent of the axial load. It is likely that small pre-applied axial loads ($F_v \leq 40\% Q_v$) have negligible influence on the horizontal soil resistance.



239

240 **Fig. 3.** Variation of (a) pile head horizontal displacement; (b) pile head settlement with horizontal load measured
 241 under constant axial load.
 242

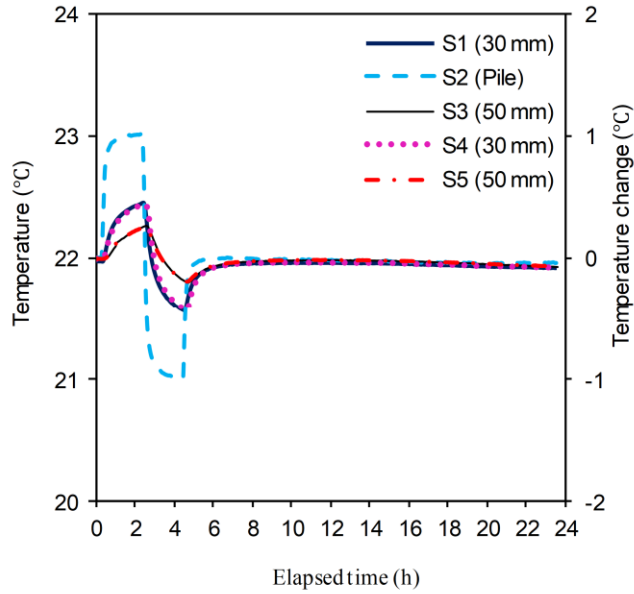
243 Fig. 3(b) indicates the relationship between the horizontal load and normalized pile head settlement of the same
 244 tests. It can be observed that the settlement of experiments E20M and E40M are significantly different to those of
 245 their replicates. As mentioned earlier, in experiments E20M and E40M, pile head settlement was measured by
 246 displacement sensors V1 and V2, while in their replicates (i.e. E20M_R and E40M_R), it was measured by
 247 displacement sensors V3 and V4. Therefore, it is worthy to note that as the model pile starts bending from the top in
 248 response to the horizontal load, the settlement measured by displacements sensors V3 and V4 does not accurately
 249 represent the settlement at the pile head. If the experiments using displacement sensors V3 and V4 (i.e. E20M_R and

250 E40M_R) are ignored, it could be observed that normalized pile head settlement increases at a reducing rate with
251 increasing horizontal load, and tends to stabilize at 0.35%, 0.50%, and 0.70% at high horizontal load under constant
252 axial load of 10% Q_v (E10M, E10M_R), 20% Q_v (E20M), and 40% Q_v (E40M), respectively. This behavior is
253 similar to that obtained in the experimental study of Lu & Zhang [14]. This can be explained by the fact that when
254 the pile has not moved sufficiently in the horizontal direction, the mobilization of passive earth pressure in front of
255 the pile does not compensate for the loss of active earth pressure behind the pile. Thereby, the resulting shaft
256 resistance loss and interface slip lead to the transfer of axial compressive load from the shaft to the pile toe and
257 causes the increase in the pile toe settlement and resistance.

258

259 *3.2. Influence of cyclic thermal loading on the behavior of the model pile subjected in advance to inclined* 260 *mechanical loading*

261 Fig. 4 illustrates the histories of measured temperature of model pile and surrounding soil at various distances from
262 the pile axis for the first thermal cycle of Test T40TM_30. As shown in Fig. 4, when the pile temperature rises up
263 from 22 °C to 23 °C during the heating phase and decreases to 21 °C during the subsequent cooling phase, the
264 variation of soil temperature recorded at 30 mm (*S1* and *S4*) and 50 mm (*S3* and *S5*) from the pile axis have a
265 smaller amplitude, ± 0.5 °C and ± 0.2 °C, respectively. The same phenomenon was also observed by Ng *et al* [40] and
266 Nguyen *et al* [29]. It is important to note that for all thermal cycles in the thermo-mechanical tests, the measured
267 temperatures in the model pile and surrounding soil follow the same trend as observed for the first thermal cycle of
268 Test T40TM_30. Additionally, during the recovery phase, the temperatures of the model pile and the surrounding
269 soil return gradually to the ambient temperature.

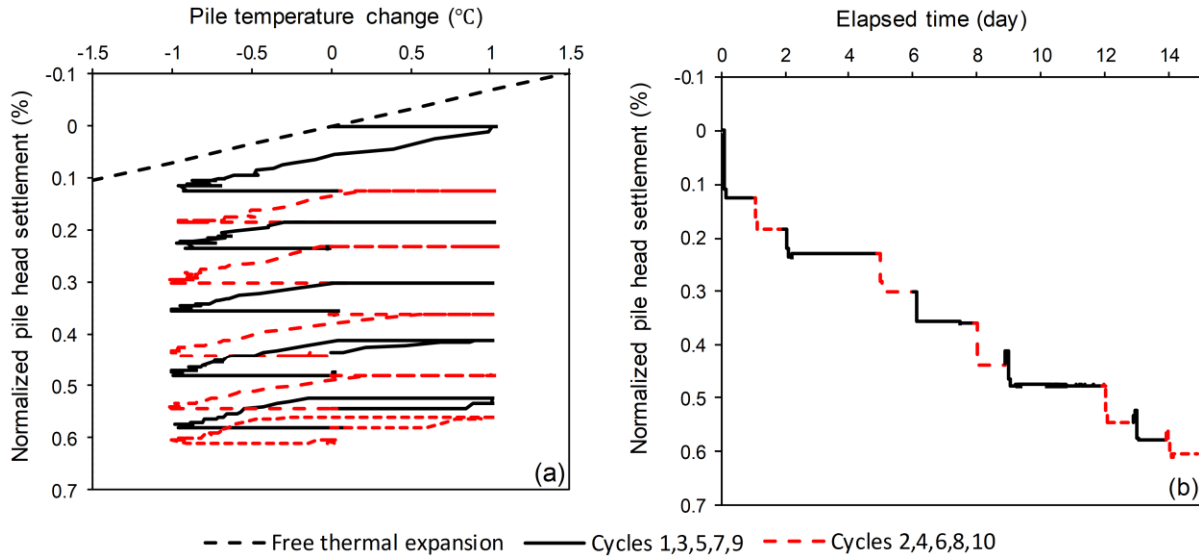


270
271 **Fig. 4.** Soil and pile temperature versus the elapsed time during the first thermal cycle of Test T40TM_30.
272

273 For the sake of brevity, only the results of test T40TM_30 are discussed here in detail. Pile head displacement
274 measurements of the eight other thermo-mechanical tests show a trend similar to that of test T40TM_30. In order to
275 provide detailed insight into the transient response of model pile during heating, cooling and recovery phases,
276 thermally-induced axial and horizontal displacements of pile head are plotted versus the elapsed time along with
277 temperature changes during 10 thermal cycles of test T40TM_30 in Figs. 5 and 6, respectively. It is worth
278 mentioning that the positive and negative values of the axial displacement measurements represent the downward
279 (i.e. settlement) and upward movement (i.e. heave) of the pile head, respectively. In addition, in Figs. 5-8, the
280 displacements are solely thermally-induced; i.e., displacement readings at the pile head are zeroed before the
281 beginning of the thermal loading.

282
283 As can be seen from Fig. 5, during the first thermal cycle, the heating phase did not lead to axial displacement at the
284 pile head, while the cooling phase causes a continuous pile head settlement of up to 0.13%D. With increasing the
285 number of thermal cycles, the pile head tends to move slightly upward with increasing temperature to 23°C in the
286 heating phase. Meanwhile, during cooling the pile temperature to the ambient temperature (i.e. 22 °C), the pile head
287 does not move axially but with a further decrease in pile temperature to 21 °C, the pile head begins to move
288 downward with a settlement of approximately 0.06%D. Eventually, during the recovery phase of all thermal cycles,

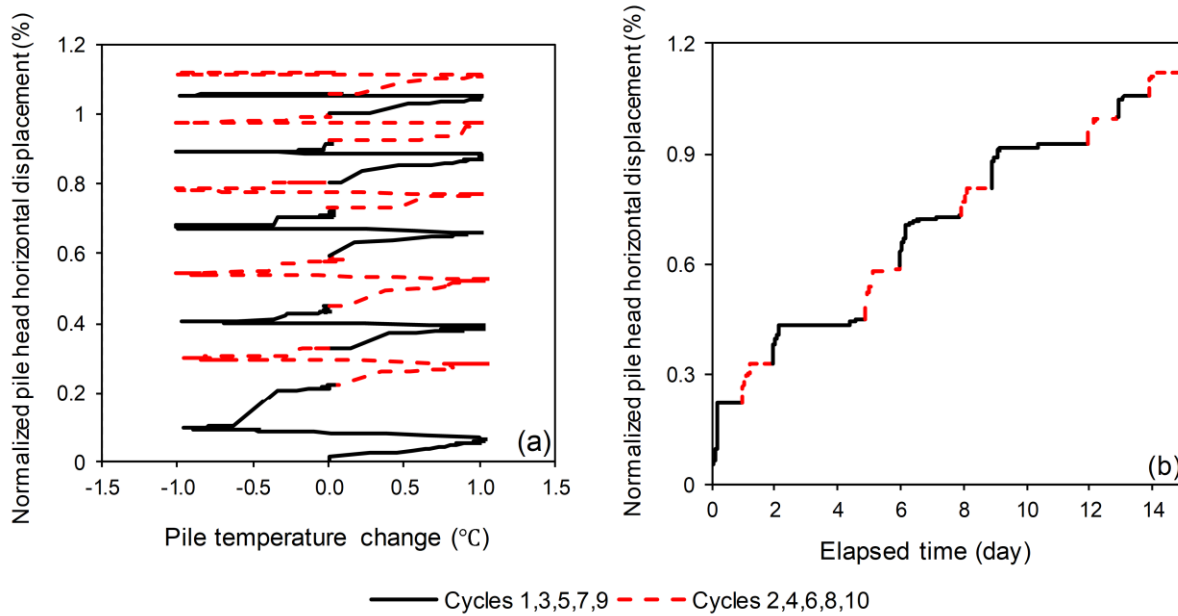
289 there is no axial movement of the pile head. In the cooling phase of each thermal cycle, the settlement/temperature
 290 slope is similar to that of the free thermal expansion/contraction curve (i.e. equal to α_m), which corresponds to the
 291 thermally-induced axial displacement of a fully toe-restrained pile being free to move in other directions. This trend
 292 is consistent with those obtained from previous experimental studies on dry sand [26,27,29].



293
 294 **Fig. 5.** Thermally-induced pile head settlement versus (a) temperature changes and (b) elapsed time during ten
 295 heating-cooling cycles of test T40TM_30.
 296

297 In Fig. 6, generally, it can be observed that the pile head horizontal displacement increases continuously throughout
 298 each heating-cooling cycle. However, the rate of increase of the pile head horizontal displacement due to the cooling
 299 phase is negligible and could be ignored compared to that due to the heating phase. When the number of thermal
 300 cycles increases, the model pile tends to move less in the horizontal direction during the recovery phase, so that for
 301 the last few thermal cycles, the horizontal displacement could be neglected when compared to the one taking place
 302 during the heating phase. As can be seen from Fig. 6, for the first thermal cycle, the pile head initially moves
 303 horizontally by about 0.063%D during the heating phase, and then it continues to move horizontally for another
 304 0.007%D during the subsequent cooling phase. Afterward, during the recovery phase, the pile head horizontal
 305 displacement continues to increase, reaching a peak value of 0.22%D. Correspondingly, for the tenth thermal cycle,
 306 pile head moves horizontally to 0.053%D during the heating phase while it moves marginally during the subsequent
 307 cooling phase. Afterward, during the recovery phase, the pile head exhibits no horizontal displacement and stabilizes
 308 at 0.06%. This kind of phenomenon is similarly observed in available centrifuge observations for horizontally-

309 loaded energy pile [19], where the pile head movement in the horizontal direction increases clearly during the
 310 heating cycle and it remains approximately unchanged during the subsequent cooling phase.



311 — Cycles 1,3,5,7,9 - - Cycles 2,4,6,8,10
 312 **Fig. 6.** Thermally-induced pile head horizontal displacement versus (a) temperature changes and (b) elapsed time
 313 during ten heating-cooling cycles of test T40TM_30.
 314

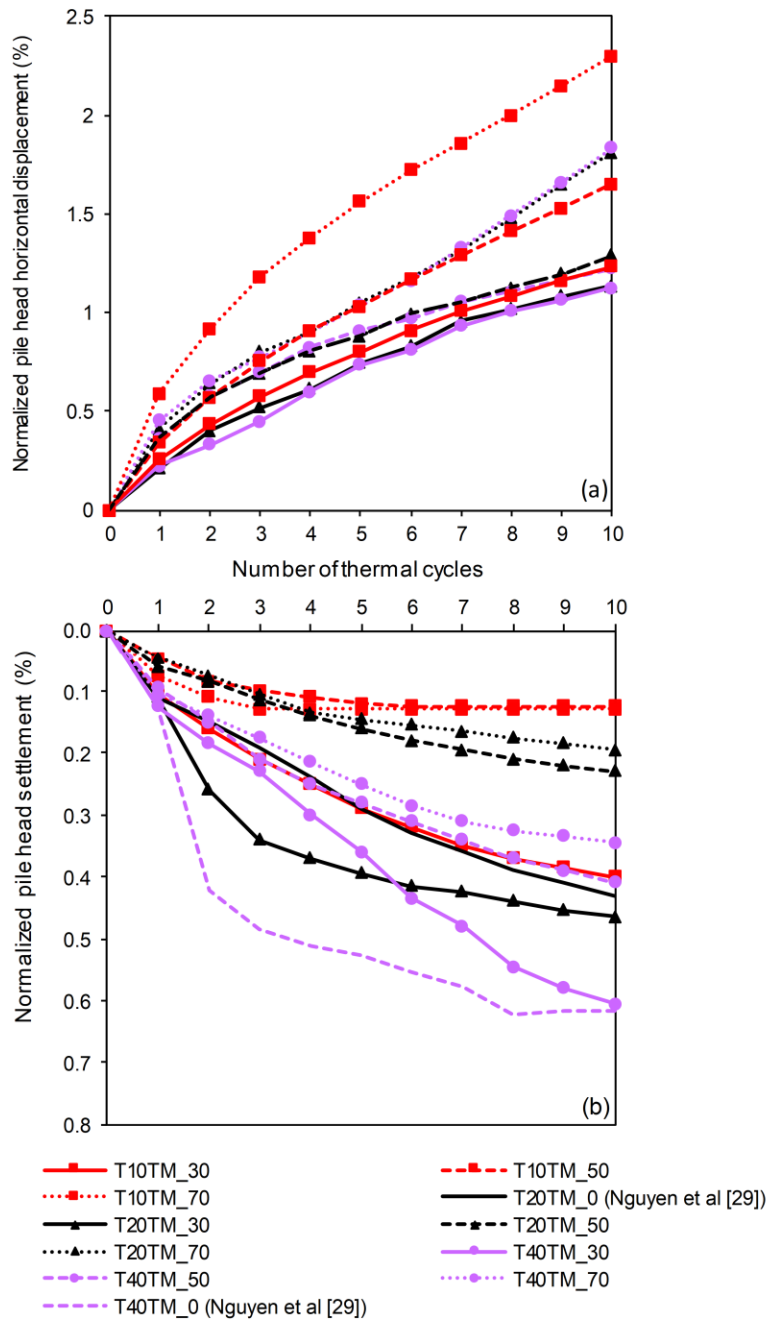
315 It can be also noticed from Figs. 5 and 6 that although the pile has been subjected to some constant temperature for a
 316 long time in some thermal cycles due to continuing tests during weekends, its settlement and horizontal
 317 displacement are nearly stabilized. By the end of each thermal cycle, the model pile keeps settling and accumulating
 318 horizontal movement instead of returning to its initial position. This irreversible phenomenon may occur as a result
 319 of the cooling-induced radial contraction and constrained heating-induced downward expansion of the model pile
 320 accompanied by the thermally-induced volumetric contraction of surrounding sandy soil. When the surrounding soil
 321 experiences a volumetric contraction under the heating/cooling cycle (evidence of this phenomenon is available in
 322 previous works [36,39]) or when the model pile contracts radially under decreasing temperature, the lateral pressure
 323 acting on the pile shaft decreases, resulting in a reduction of the passive soil resistance as well as the shaft
 324 resistance. Since the surrounding soil is less resistant against the inclined mechanical loads, the amount of pile head
 325 horizontal displacement and pile toe settlement would increase to further mobilize the passive soil resistance in front
 326 of the pile and the base resistance at the pile toe.

327

328 The accumulated irreversible settlement and horizontal displacement of pile head are plotted against the number of
329 thermal cycles in Fig. 7. In Fig. 7(a), the results show a general trend with a quick increase of normalized horizontal
330 displacement during the first cycles and a continued increase at a smaller rate during the remaining cycles, which
331 reaches 1.1-1.25%, 1.2-1.65% and 1.8-2.3% after ten cycles for the cases with $F_h=30\% Q_h$, $50\% Q_h$ and $70\% Q_h$,
332 respectively. In Fig. 7(b), the results of Nguyen *et al* [29], using identical pile and soil, under axial load only ($F_h =$
333 0) are also shown for comparison purposes. The results show that, for the cases with $F_v = 10\% Q_v$, irreversible
334 normalized pile head settlement increases continuously and reaches 0.4% after ten cycles for $F_h = 30\% Q_h$
335 (T10TM_30); for $F_h = 50\% Q_h$ (T10TM_50) and $F_h = 70\% Q_h$ (T10TM_70), it increases during the first three cycles
336 and stabilizes at 0.13%. For the cases with $F_v = 20\% Q_v$, irreversible normalized pile head settlement increases
337 continuously and reaches 0.43%, 0.23% and 0.2% after ten cycles for $F_h = 0$ (i.e. T20TM_0 [29]), $F_h=50\% Q_h$
338 (T20TM_50) and $F_h = 70\% Q_h$ (T20TM_70), respectively, while for $F_h = 30\% Q_h$ (T20TM_30), it rapidly increases
339 during the first three cycles and tends to stabilize at 0.47%. Finally, for the cases with $F_v = 40\% Q_v$, irreversible
340 normalized pile head settlement increases continuously and reaches 0.61%, 0.41% and 0.35% after ten cycles for F_h
341 $= 30\% Q_h$ (T40TM_30), $F_h = 50\% Q_h$ (T40TM_50) and $F_h = 70\% Q_h$ (T40TM_70), respectively. For the pure axial
342 loading case with $F_v = 40\% Q_v$ (i.e. T40TM_0 [29]), the accumulation rate of the irreversible settlement during the
343 first two cycles is much higher than that in the cases of inclined loading; however, it decreases significantly during
344 subsequent cycles and the accumulated irreversible normalized settlement stabilizes at 0.62% after ten cycles.

345

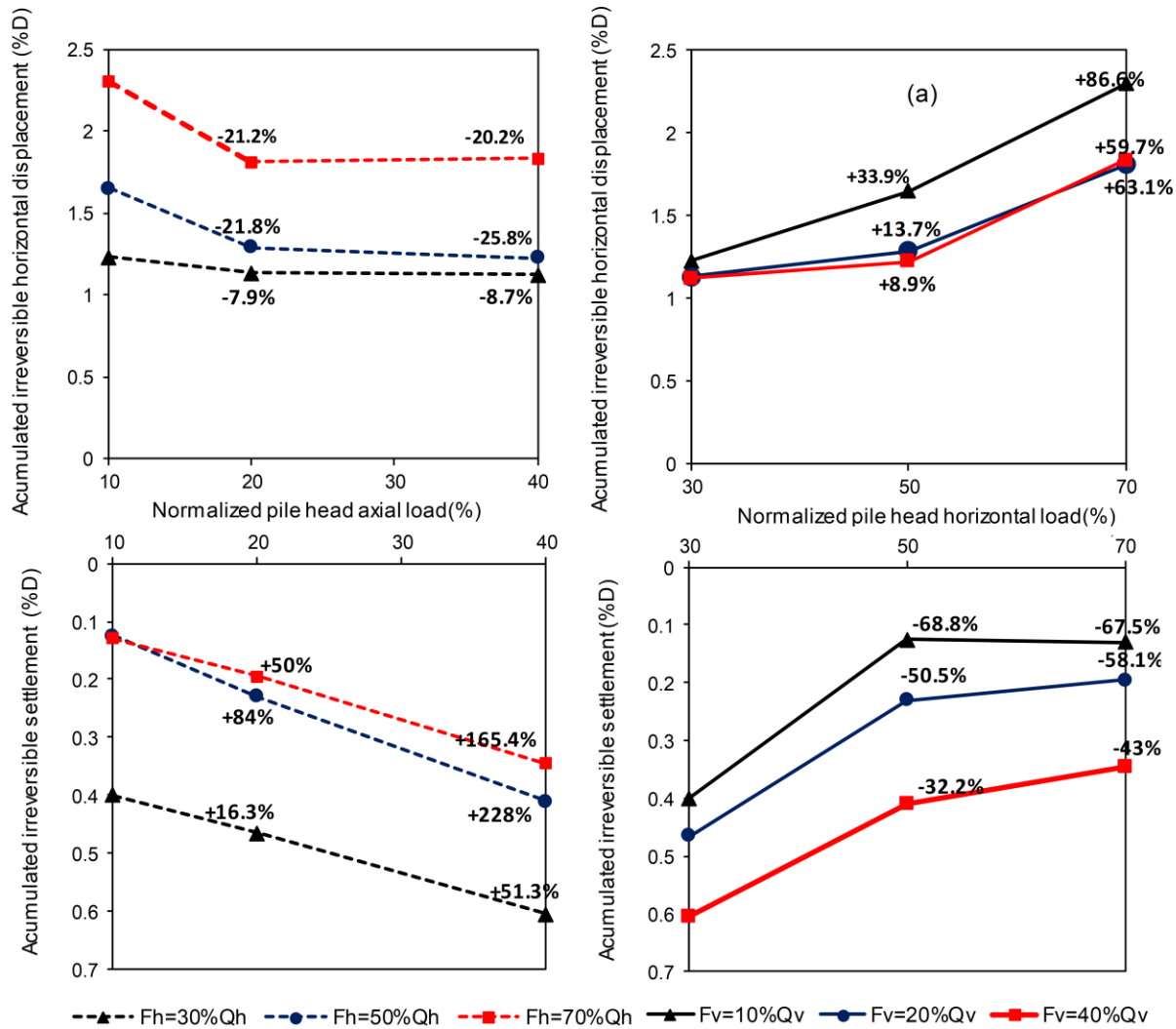
346 What should be noted from Fig. 7 is that for all the nine thermo-mechanical tests, regardless of the magnitude of the
347 applied mechanical loads, the observed ratcheting pattern for axial and horizontal displacements is characterized by
348 two features: first, the largest increment of irreversible settlement and horizontal displacement are induced by the
349 first thermal cycle; second, after a fast accumulation of irreversible displacement in the first thermal cycle, the
350 accumulation rate initially decreases slightly, and then almost remains constant when increasing the number of
351 thermal cycles. The tendency for a model pile to exhibit less settlement and horizontal displacement with an increase
352 in the number of thermal cycles is commonly explained by the strengthening of surrounding soil due to the
353 thermally-induced gradual densification (which is a phenomenon observed in previous works [55]). This kind of
354 ratcheting response was similarly observed for axially-loaded energy piles reported by Nguyen *et al* [29], Yavari *et*
355 *al* [27] and Ng *et al* [39-41], and for horizontally-loaded energy pile reported by Zhao *et al* [19].



356
 357 **Fig. 7.** (a) Irreversible horizontal displacements; (b) irreversible settlement of pile head versus the number of
 358 heating-cooling cycles.
 359

360 **3.3. Coupling effects on the thermally-induced mechanical response of model pile**

361 Fig. 8 demonstrates the coupling effects on the irreversible settlement and horizontal displacements accumulated
 362 over ten heating/cooling cycles at the pile head.



363

364 **Fig. 8.** Coupling effects on the irreversible settlement and horizontal displacement accumulated over ten
 365 heating/cooling cycles at the pile head.
 366

367 As shown in Fig. 8, for the same horizontal load, imposing ten thermal cycles at an axial load higher than 10% Q_v ,
 368 induces a higher accumulated irreversible settlement of up to 228% but a lower accumulated irreversible horizontal
 369 displacement of up to 25.8%. For the same axial load, imposing ten thermal cycles at a horizontal load higher than
 370 30% Q_h induces a lower accumulated irreversible settlement of up to 68.8% but a higher accumulated irreversible
 371 horizontal displacement of up to 86.6%. This possibly occurs because of the influence of mechanical loading
 372 condition on the soil-pile stiffness before the application of thermal loading. In general, it could be stated that at a
 373 specific axial load, the axial stiffness of the soil-pile system increases with an increase in horizontal load due to the
 374 increase in mobilized skin friction stresses, which result from increasing horizontal stresses and upward-directed

375 movement of passive earth pressure wedge in front of the pile. Moreover, at a specific horizontal load, the horizontal
376 stiffness of the soil-pile system increases with the increasing axial load. This could be explained by the increase in
377 mobilized passive earth pressure, which arises from increasing level of confinement provided by the surrounding
378 soil due to the axial load-induced settlement of pile.

379

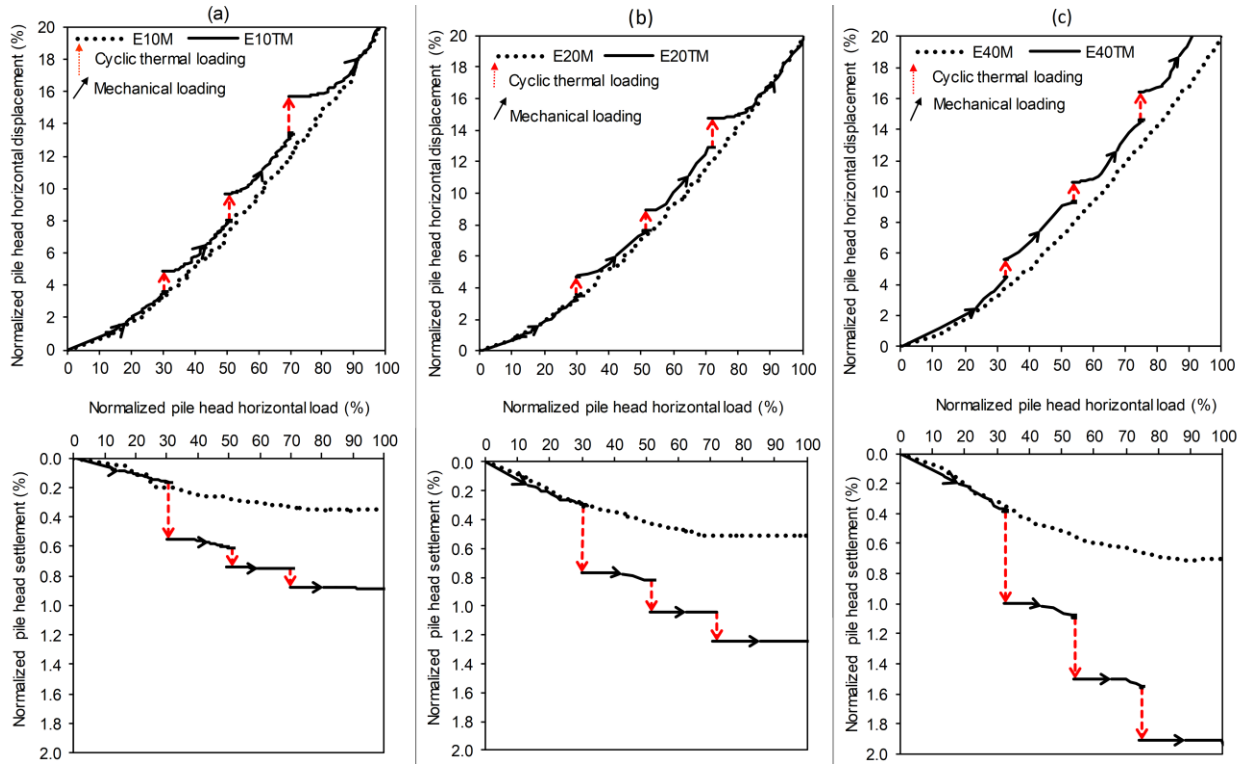
380 These results agree with those obtained for purely mechanical loading, in which the increase of axial load at the
381 same horizontal load leads to a reduction in horizontal displacement, but an increase in the settlement; Moreover, the
382 increase of horizontal load at the same axial load leads to an increase in horizontal displacement. Only the reduction
383 of the accumulated irreversible settlement with the increase of horizontal load at the same axial load is contrary to
384 that observed for purely mechanical loading. Since for the same axial load, the horizontal load increases in three
385 steps, and ten thermal cycles are imposed to the pile at the end of each step (as described in section 2.2), the
386 accumulated thermally-induced irreversible settlement under the horizontal loads of 50% and 70% Q_h might be
387 influenced by the accumulated thermally-induced irreversible settlement induced by the horizontal loads of 30% and
388 50% Q_h .

389

390 ***3.4. Load-displacement response of model pile subjected to thermo-mechanical load***

391 In order to investigate the influence of thermal loading on the pile response, the results obtained from the
392 mechanical and thermo-mechanical experiments are presented in terms of normalized pile head horizontal
393 displacement and settlement versus normalized horizontal load (i.e. divided by pile's ultimate horizontal load for the
394 mechanical tests) in Fig. 9. As shown in Fig. 9, during the initial increase of F_h to 30% Q_h prior to the application of
395 thermal loading, the settlement and horizontal displacement of pile head in thermo-mechanical tests are similar to
396 those in mechanical ones. In the subsequent increments of the horizontal load to 50%, 70%, and 100% Q_h after the
397 application of thermal loading, pile head horizontal displacement remains unchanged for a while and then increases
398 again with increment rates equal to those in mechanical tests. Meanwhile, pile head settlement almost does not
399 change with horizontal load increments after having been thermally loaded. When comparing the horizontal load-
400 displacement response of the pile in mechanical experiments to those in thermo-mechanical ones, it must be pointed
401 out that the thermal loading does not affect the horizontal response of the soil-pile system. The reason for this is that
402 the large extent of reduction in the horizontal stress and mobilized skin friction is recovered by the subsequent

403 reloading phase. Therefore, it could be concluded that the total axial and lateral resistance of the pile is affected only
 404 slightly by the thermal loading. By comparing the horizontal load at a pile head horizontal displacement of 4 mm
 405 (i.e. 20% pile diameter), the ultimate horizontal bearing capacity of pile may remain unchanged after ten heating-
 406 cooling cycles. However, due to the gradual accumulation of the irreversible pile head horizontal displacement over
 407 thermal cycles, it is recommended that the long-term performance of the energy pile is controlled by horizontal
 408 displacement rather than ultimate horizontal bearing capacity.



409
 410 **Fig. 9.** Temperature-induced change in pile head response to horizontal load under a constant axial load of (a) 10%
 411 (b) 20% and (c) 40% of the axial pile resistance.
 412

413 4. Conclusions

414 The thermo-mechanical behavior of a model energy pile subjected to inclined mechanical loads and temperature
 415 variations was experimentally investigated in dry sand. Ten heating-cooling cycles were applied to the pile under
 416 various combination of axial and horizontal mechanical loading (axial loads equal to 10, 20, and 40% of the ultimate
 417 axial load; horizontal loads equal to 30, 50, and 70% of the ultimate horizontal load). The main conclusions that can
 418 be drawn from this study are the following:

- 419 • For $F_v \leq 40\% Q_v$, effect of F_v on the horizontal response of the pile under horizontal loading could be
420 considered negligible. Moreover, additional settlement occurs at pile head due to the horizontal
421 loading.
- 422 • The application of temperature variations along with inclined mechanical loads results in irreversible
423 settlement and horizontal displacement at the pile head, whose largest increment takes place during the
424 first thermal cycle. After a fast accumulation of irreversible displacement in the first thermal cycle, the
425 increments of irreversible settlement and horizontal displacement, accumulating after each thermal
426 cycle, initially decrease slightly and then almost remain constant with an increase in the number of
427 heating-cooling cycles. By the end of the tenth thermal cycle, the amount of accumulated irreversible
428 settlement and horizontal displacement are generally in the range of 0.1-0.6%D and 1.1-2.3%D,
429 respectively.
- 430 • Under the same horizontal load, thermal cycles at a higher axial load induce a higher irreversible
431 settlement but a lower horizontal displacement at the pile head.
- 432 • Under the same axial load, thermal cycles at a higher horizontal load induce a lower settlement but a
433 higher horizontal displacement at the pile head.
- 434 • Thermal loading did not affect the subsequent horizontal load-displacement response of the pile.
435 Likewise, by comparing the horizontal load at a pile head horizontal displacement of 4 mm (i.e.
436 20%D), the ultimate horizontal bearing capacity of the pile remained barely unchanged after ten
437 heating-cooling cycles. However, due to the accumulation of irreversible horizontal displacement
438 during the cyclic thermal loading, it is vital to ensure that the long-term cyclic thermal loading does not
439 degrade the safety and durability of the energy piles for the service life of the building. Therefore, it is
440 highly recommended that the long-term performance of the energy pile is controlled by horizontal
441 displacement rather than ultimate horizontal bearing capacity.

442 The results of 1-g model tests carried out in this study could be helpful to gain insights into the qualitative influence
443 of inclined mechanical loading on the thermally-induced displacements in both axial and horizontal directions;
444 however, in order to provide quantitative confirmation of these initial findings, further studies are required to be
445 conducted using centrifuge and field-scale tests.

446

447

448

449

450 **Declarations**

451

452 **Data availability and materials**

453 The data that support the findings of this study are available from the corresponding author on reasonable request.

454

455 **Conflict of Interest**

456 The authors declare that they have no known competing for financial interests or personal relationships that could

457 have appeared to influence the work reported in this paper.

458

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