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Cyclically thermally-activated pile under combined axial/horizontal loads in saturated clay

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1 **Abstract**

2 In the present study, the influence of cyclic thermal loading on the mechanical response of an energy pile installed in
3 saturated clay subjected to sustained combined axial/horizontal mechanical loading was investigated using physical
4 modelling. After completion of the soil saturation process and prior to starting the thermo-mechanical loading, the
5 pile fixation was released inducing pile head heave. When the rate of pile head heave became small, the model pile
6 was subjected to compression axial loading of 100 N (i.e. 20% of the estimated ultimate axial load) followed by
7 horizontal loading of 35, 71, and 109 N (corresponding to accumulative pile head horizontal displacements of 4%,
8 7%, and 12% of pile diameter) before subsequent 15 heating/cooling cycles. The results indicated that imposing
9 heating/cooling cycles to the pile resulted in irreversible horizontal displacement, accumulating at a reducing rate as
10 the number of thermal cycles increased. By the end of the 15th cycle, the accumulated irreversible horizontal
11 displacement was estimated at 0.57%, 1.15%, and 1.84% of pile diameter under the horizontal loads of 35, 71, and
12 109 N, respectively. Reversely, thermally induced pile head axial displacement at the end of the 15th cycle is
13 practically insignificant (smaller than 0.1% of pile diameter).

14 **Keywords**

15 Repeated loading; Soil/structure interaction; Temperature effects

16 **List of notations**

w_L	Liquid limit, %
w_P	Plastic limit, %
S_r	Degree of saturation, %
e	Void ratio
ρ_s	Particle density, Mg/m ³
d_o	Outer diameter of model pile, mm
d_i	Inner diameter of model pile, mm
L	Embedment length of model pile, mm
D_i	Inner diameter of soil tank, mm
h	Soil tank depth, mm
D_{50}	Median grain-size, μm
$(d_h)_p$	Projected pile head horizontal displacement, mm

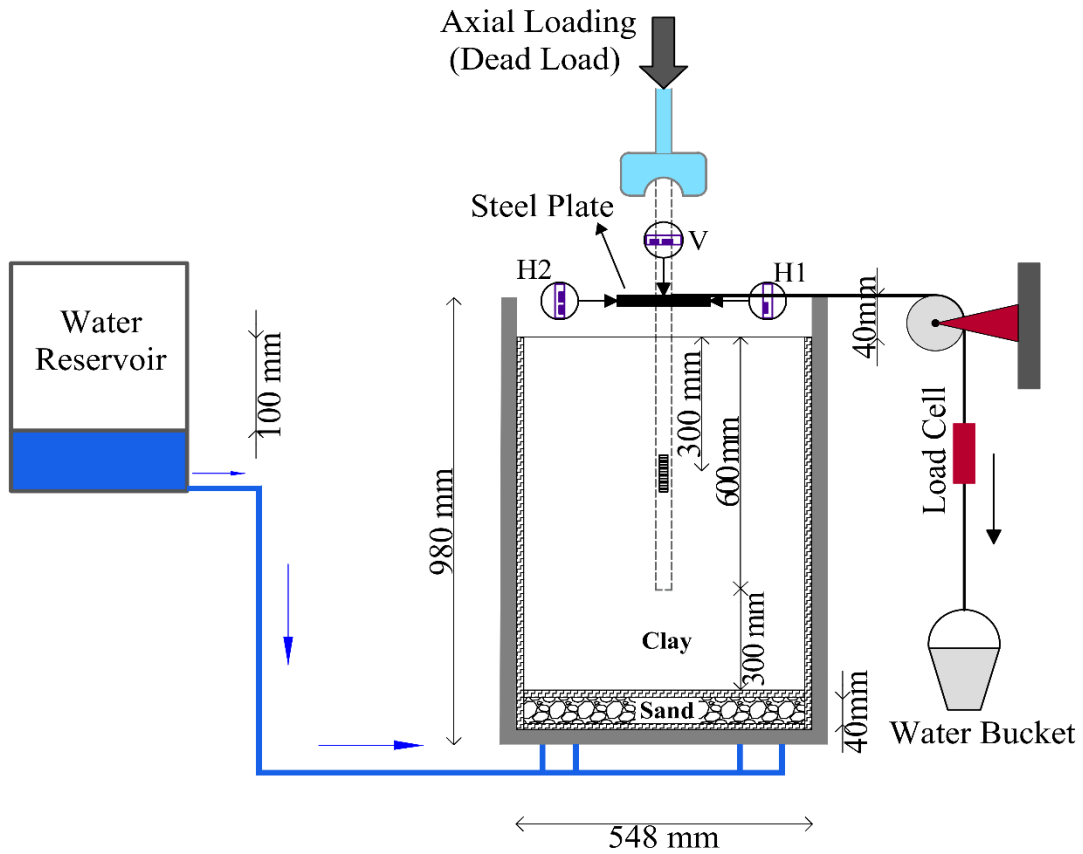
$(d_a)_p$	Projected pile head axial displacement, mm
$(d_h)_m$	Measured pile head horizontal displacement, mm
$(d_a)_m$	Measured pile head axial displacement, mm
t	Elapsed time, day
Q_v	Ultimate axial load (estimated by Nguyen et al. 2020), N

17 **Introduction**

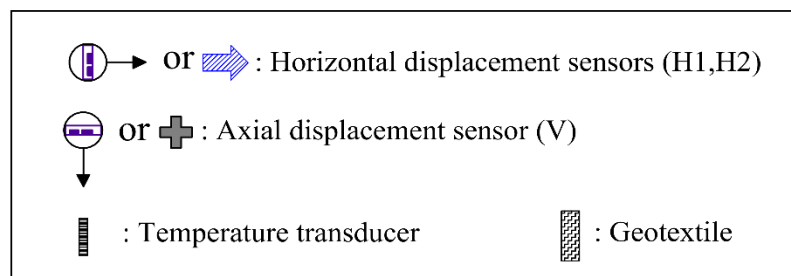
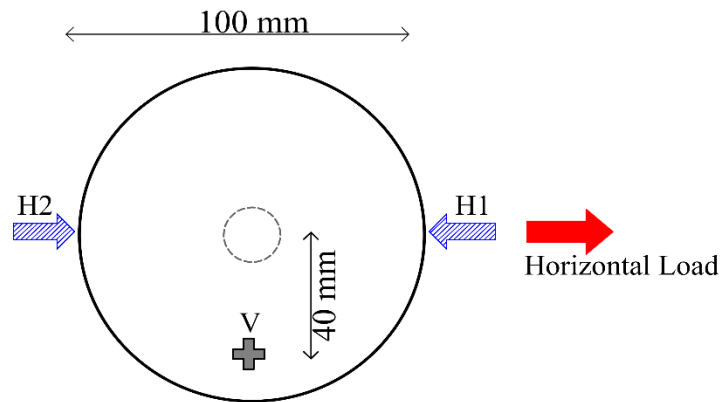
18 The dual functionality of energy piles for supporting the structural loads and meeting the heating/cooling needs of
19 the building imposes additional stresses/strains on the soil-pile system, which could affect the mechanical behaviour
20 of the energy piles. Previous studies revealed that cyclic thermally-induced volume changes are much more
21 predominant in clayey soils compared to sandy soils. Nevertheless, only a limited number of studies focused on the
22 influence of thermal loading on the mechanical response of axially-loaded energy piles embedded in clayey soils by
23 performing full-scale tests (Laloui *et al.* 2006; Bourne-Webb *et al.* 2009; Akrouch *et al.* 2014), centrifuge model
24 tests (Stewart & McCartney 2014; Ng *et al.* 2014, 2021a, b) and 1-g small-scale physical model tests (Yavari *et al.*
25 2016; Wu *et al.* 2020; Yazdani *et al.* 2019; Nguyen *et al.* 2020; Tang *et al.*, 2021). To the authors knowledge, the
26 works of Vitali *et al.* (2022) and Zhao *et al.* (2022) are the only available studies using centrifuge model tests to
27 investigate the influence of monotonic heating and heating-cooling cycles, respectively, on the flexural behaviour of
28 horizontally-loaded energy piles in sands. These studies indicate that (1) the heating operation reduces pile bending
29 moment while causing no additional flexural stress, (2) imposing heating/cooling cycles results in accumulating
30 irreversible horizontal displacement. Although such ratcheting has already been observed in axially loaded energy
31 piles, its occurrence for energy piles subjected to inclined load has not yet been observed. This study thus aims to
32 explore the influence mechanism of cyclic thermal loading on the mechanical response of a single model energy pile
33 installed in saturated clay subjected to sustained combined axial/horizontal mechanical loading through physical
34 modelling under normal gravity.

35 **2. Experimental set-up**

36 In order to use the results obtained from 1-g small-scale model tests to assess the thermo-mechanical response of
37 full-scale energy piles, the test program was designed by considering the geometry difference between the small-
38 scale pile and the full-scale pile. The experimental setup consists of a cylindrical steel soil tank (with $D_i =$
39 548 mm ($D_i \approx 27 d_o$), and $h = 980$ mm), whose internal surface was covered with a two-layer geotextile filter,
40 wrapped in an expanded polystyrene sheet (Fig. 1).



Top view of the pile head



41

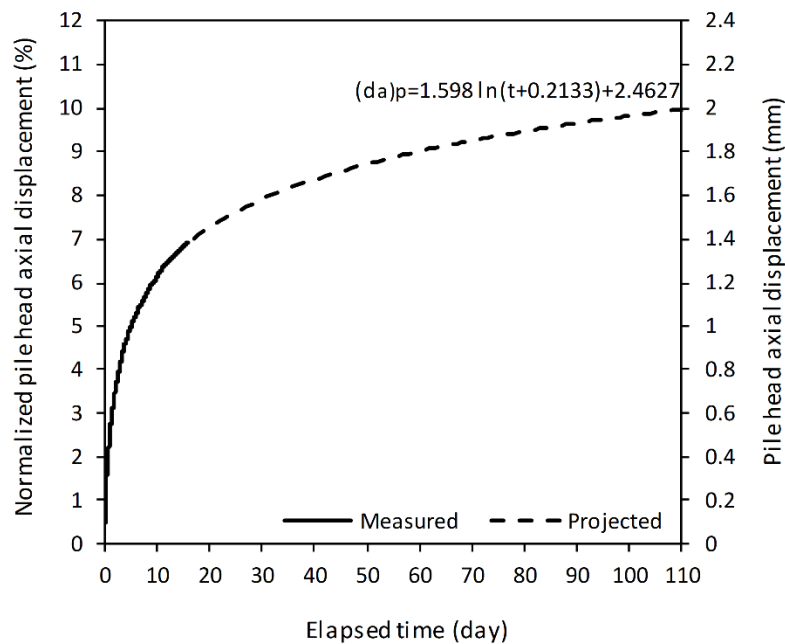
42 Fig. 1. Schematic view of the experimental setup.

43 In order to minimize the heat dissipation rate, and maximize the roughness of the model pile surface, the outside
44 surface of a closed-end aluminium tube (with $d_o = 20$ mm, $d_i = 18$ mm, and $L = 600$ mm) was coated with
45 Fontainebleau sand. Given that the soil tank dimensions satisfy the following conditions: $D_i \geq 10d_o$, and soil
46 cushion below the pile toe $\geq (3\sim 4)d_o$, boundary effects could be considered negligible (Boominathan &
47 Ayothiraman, 2007; LeBlanc *et al.*, 2010). Kaolin clay powder (with $w_L = 57\%$, $w_P = 33\%$, and $\rho_s = 2.6$ Mg/m³)
48 was mixed with de-aired water to achieve an optimum water content of 29% (Murillo *et al.* 2013). The grain-size
49 scaling effect could be considered negligible in this study since the d_o/D_{50} ratio is much larger than the proposed
50 limit by Fioravante (2002). The model pile was first fixed to the centre of the tank and the soil was compacted by 50
51 mm thick layers around the pile to achieve a maximum dry density of 1.45 Mg/m³ (corresponding to $s_r = 95\%$ and
52 $e = 0.79$). The compacted clay is expected to show a double porosity structure with micropores (0.2 - 2 μ m) and
53 macropores (5 - 20 μ m) (Thom *et al.* 2007). Although this installation method differs from a full-scale bored pile, it
54 would still provide good soil-pile contact. However, a softer displacement response could be expected in the model
55 pile due to some lesser degree of compaction of soil close to the pile. Finally, the soil mass was saturated for two
56 months by slowly injecting de-aired water from the bottom of the soil tank. Using similar procedure, Nguyen *et al.*
57 (2020) showed that two months was long enough a period for the soil mass to be fully saturated. During this
58 saturation, the soil mass globally swelled, thus generating uplift forces on both pile shaft and toe. Afterwards, the
59 pile fixation system was removed and a pile head heave was observed. When the rate of pile head heave became
60 small (after 15 days), a 100 N dead-weight (i.e. 20% Q_v) was placed on the pile head within seconds and was
61 maintained for two hours to reach equilibrium without waiting for the soil to consolidate. Afterwards, horizontal load
62 was applied in three steps by allowing water flow in the plastic bucket linked to the pile head through a piece of rope
63 over a pulley. In the first, second, and third load steps, horizontal load was increased within 10 minutes from zero to
64 35 N, 35 to 71 N, and 71 to 109 N, respectively, corresponding to accumulative horizontal displacements of 4, 7,
65 and 12%D, and maintained for more than 10 days at each loading level to reach equilibrium and to consolidate the
66 soil prior to the cyclic thermal loading. At the end of each load step, 15 heating-cooling cycles with temperature
67 variation of ± 5 °C around an ambient temperature of 20 °C (consisting of a 3-hour heating phase followed by a 3-hour
68 cooling phase and eventually, an 18-hour recovery phase) were imposed to the pile by circulating water in fitted
69 aluminium U-shaped tube linked to a temperature-controlled water bath and a peristaltic pump. The heating and
70 cooling phases of each cycle in the model pile simulate 6 months of temperature changes of ± 10 °C in a full-scale

71 concrete pile of 0.8 m in diameter. This temperature variation is within the range of 3-37 °C of field-scale energy
 72 piles (Jiang et al. 2021). It should be noted that the model test could recreate the thermal and mechanical strains
 73 similar to field ones.

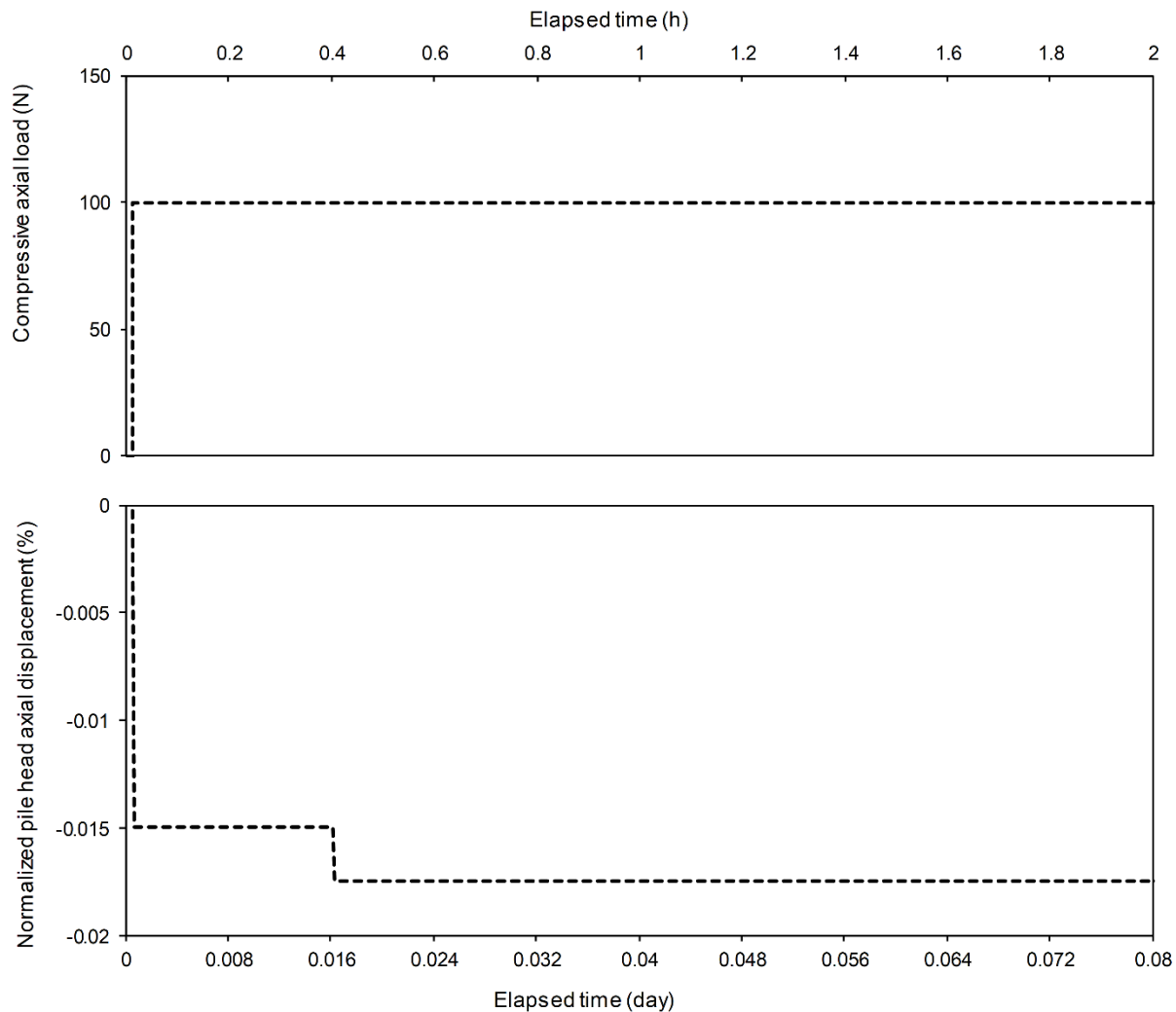
74 3. Results

75 In Fig. 2, the continuous line represents the measured pile head heave immediately after removing the fixation
 76 system for the first 15-days before starting thermo-mechanical testing, while the dashed line shows the pile head
 77 heave extrapolated for the subsequent 90 days during thermo-mechanical testing. The measurements indicate that
 78 the pile head heaves rapidly with time in the first days and continues to heave at a reducing rate reaching 6.8% D
 79 after 15 days. The reason for this heave could be the pre-mobilized uplift forces on both pile shaft and toe, arising
 80 from the saturation-induced soil swelling in the vicinity of the fixed-headed pile (Lalicata *et al.* 2019; Yunlong &
 81 Vanapalli 2021).



82
 83 **Fig. 2 Time dependent heave of the pile head after removing the fixation system, measured and extrapolated**
 84 **curves**
 85

86 As illustrated in Fig. 3, prior to the application of horizontal mechanical and cyclic thermal loads, the pile head
 87 moves axially by about -0.015%D due to the compressive axial loading of 100 N. This negligible pile head
 88 settlement could be attributed to the counteracting effect of the swelling-induced uplift forces.

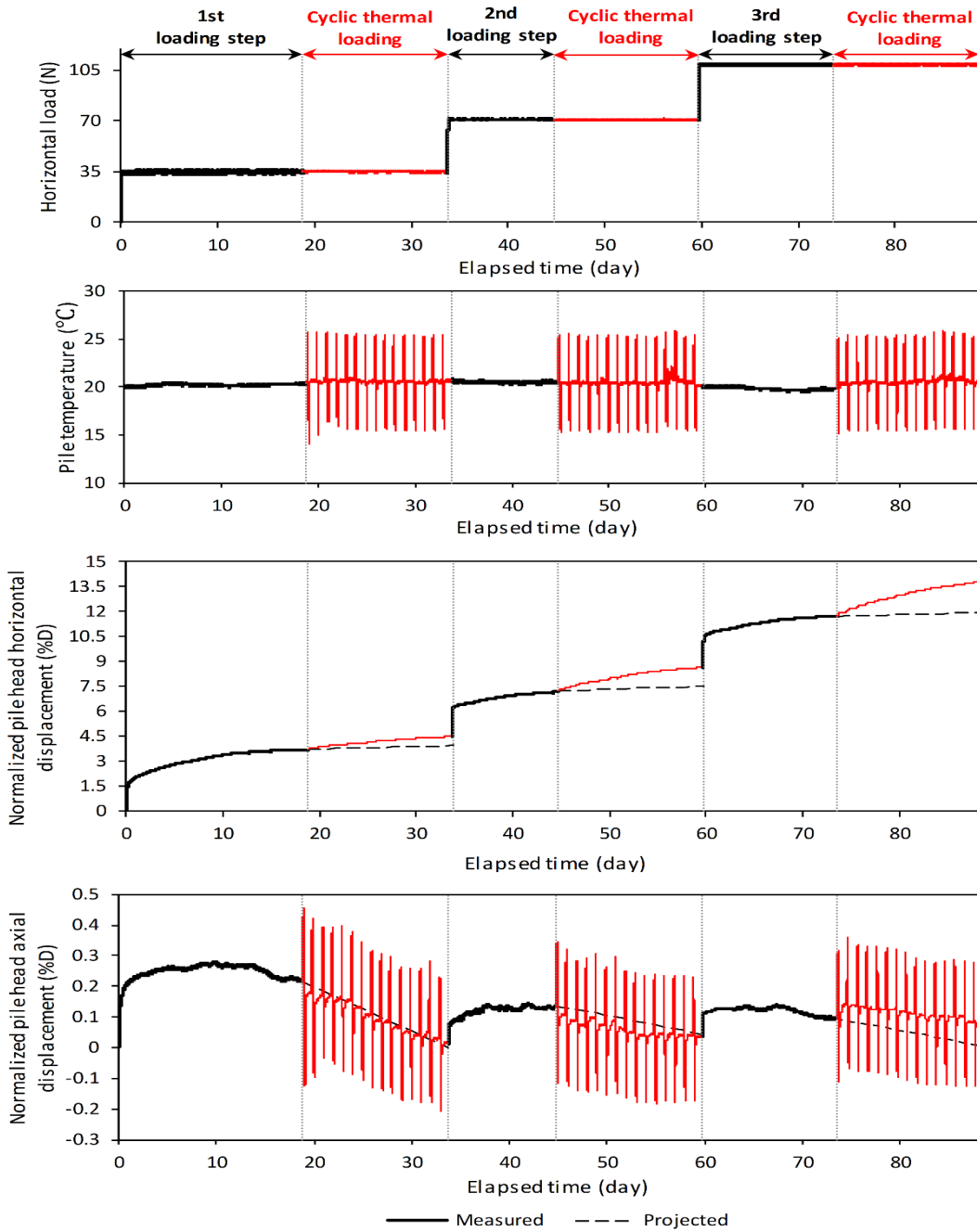


90

91 **Fig. 3 Changes in pile head axial displacement with time during the compressive axial loading period**

92 As can be seen in Fig. 4, during the application of horizontal loading at each load step, the pile head horizontal
 93 displacement increases rapidly with the increase of horizontal load, then keeps on increasing at a reducing rate under
 94 the constant horizontal load and reaching 4%D, 7%D, and 12%D at the end of the first, second and third load steps,
 95 respectively. Meanwhile, the pile head heaves immediately after increasing the horizontal load, which might be due
 96 to further mobilization of the uplift force on the pile shaft due to the tendency of soil located in front of the pile close
 97 to the surface to heave. Afterwards, under the constant horizontal loads of 35 and 109 N, the pile head heave initially
 98 fluctuates around a steady value of 0.27%D and 0.12%D for about ten days, then begins to decrease gradually and
 99 reaches 0.22%D and 0.09%D at the end of the 19-day and 14-day period, respectively. However, under the constant
 100 horizontal load of 71 N, pile head heave fluctuates around a steady value of 0.12%D within a period of 11 days. The

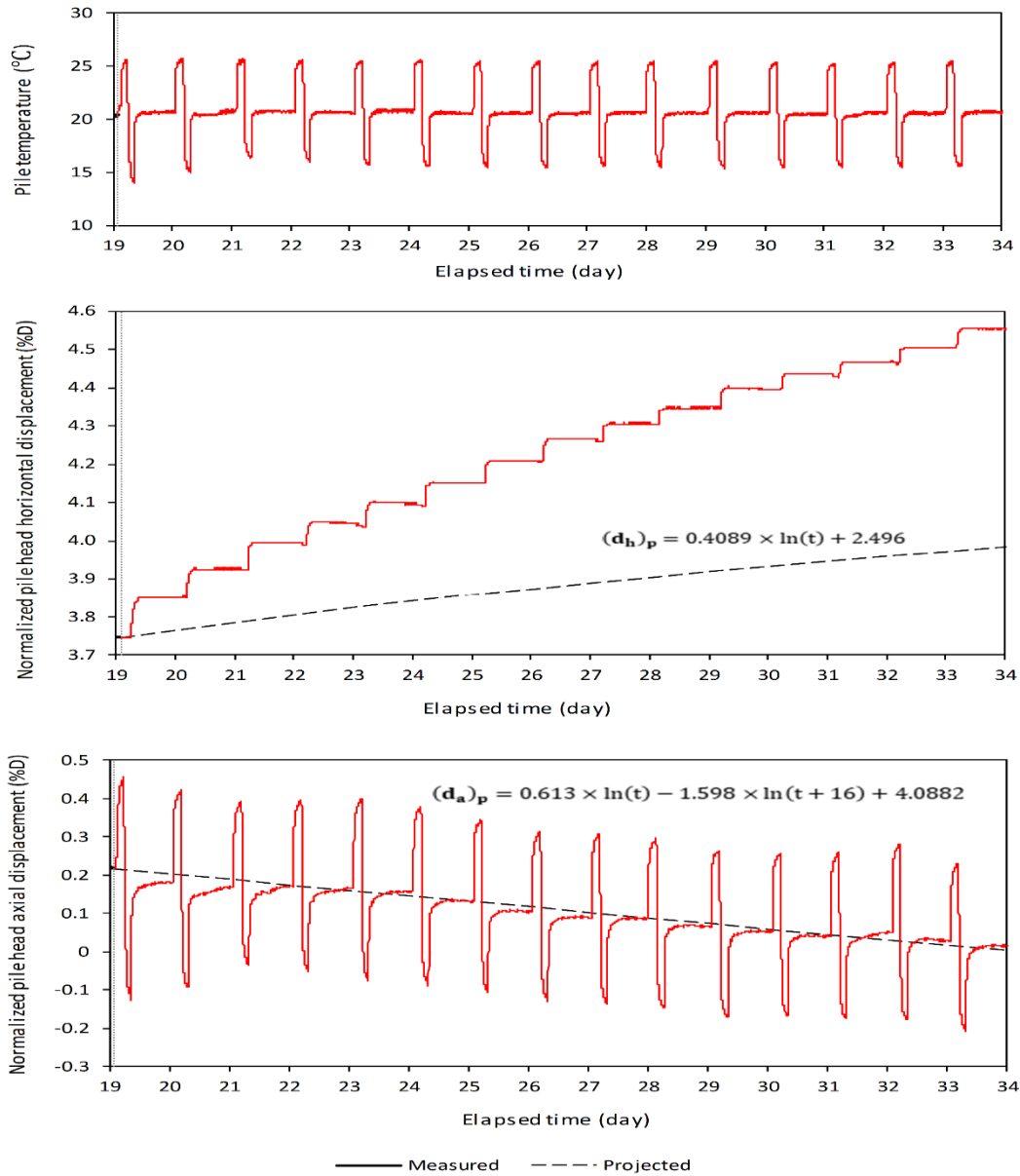
101 gradual reduction of pile head heave could be attributed to the pile being pulled downwards by the mechanically-
 102 induced consolidation and creep of the surrounding clay (Fellenius, 2006).



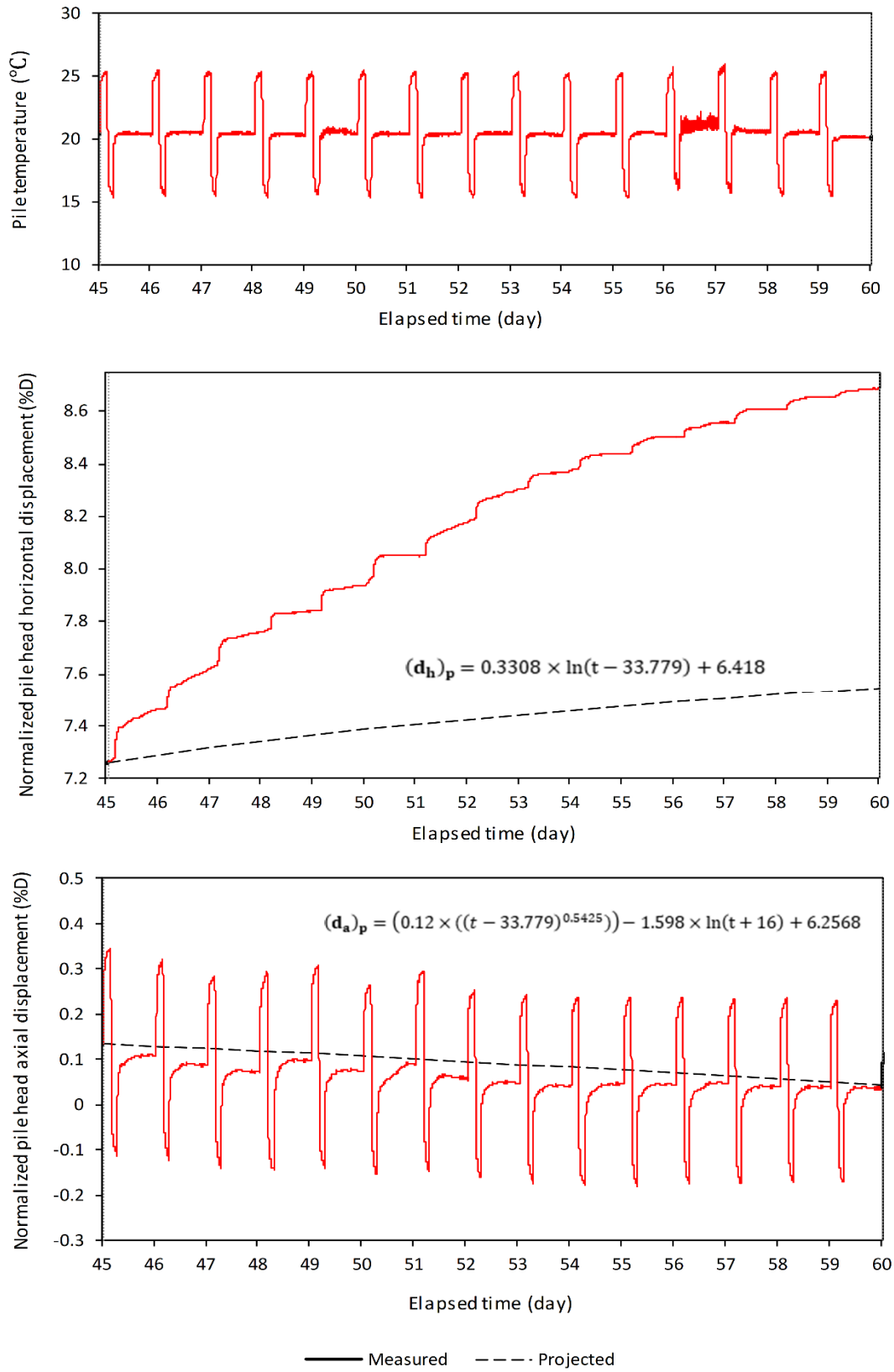
1st loading step: $(d_h)_p = 0.613 \times \ln(t) - 1.598 \times \ln(t + 16) + 4.0882$; $(d_h)_p = 0.4089 \times \ln(t) + 2.496$
 2nd loading step: $(d_h)_p = (0.12 \times ((t - 33.779)^{0.5425})) - 1.598 \times \ln(t + 16) + 6.2568$; $(d_h)_p = 0.3308 \times \ln(t - 33.779) + 6.418$
 3rd loading step: $(d_h)_p = (0.08 \times ((t - 59.724)^{0.534})) - 1.598 \times \ln(t + 16) + 6.9513$; $(d_h)_p = 0.2946 \times \ln(t - 59.724) + 10.937$

103
 104 **Fig. 4** Changes in horizontal load, pile temperature, and pile head axial and horizontal displacements with
 105 time during thermo-mechanical loading stage (Displacement readings at the pile head are zeroed before
 106 starting thermo-mechanical testing. The swelling-induced pile head heave has been subtracted from the
 107 measured total pile head heave. The dashed line demonstrates displacements extrapolated for the subsequent
 108 15 days at the end of each loading step).

109 As shown in Fig. 5 (a)-(c), at any level of horizontal loading, the pile head heaves during the heating phase then
 110 settles quickly during the subsequent cooling phase, and heaves again during the recovery phase. Meanwhile, it also
 111 moves horizontally throughout the entire thermal cycle, except when the horizontal load equals 35 N, the recovery
 112 phase could not lead to the pile head horizontal displacement. By the end of each thermal cycle, the model pile
 113 keeps accumulating axial and horizontal movements instead of returning to its initial position before the thermal
 114 cycle, which means that irreversible displacements occur in both horizontal and axial directions.



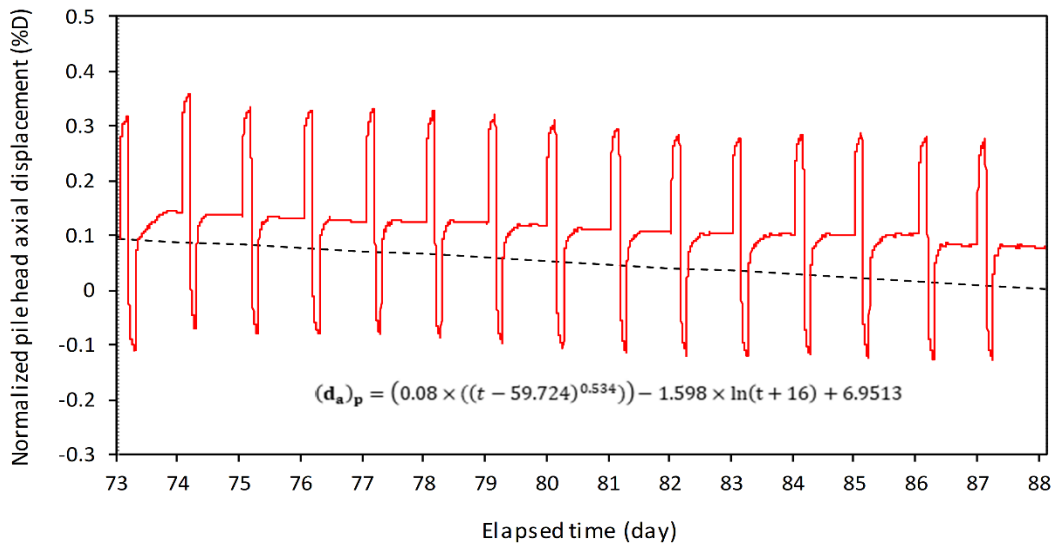
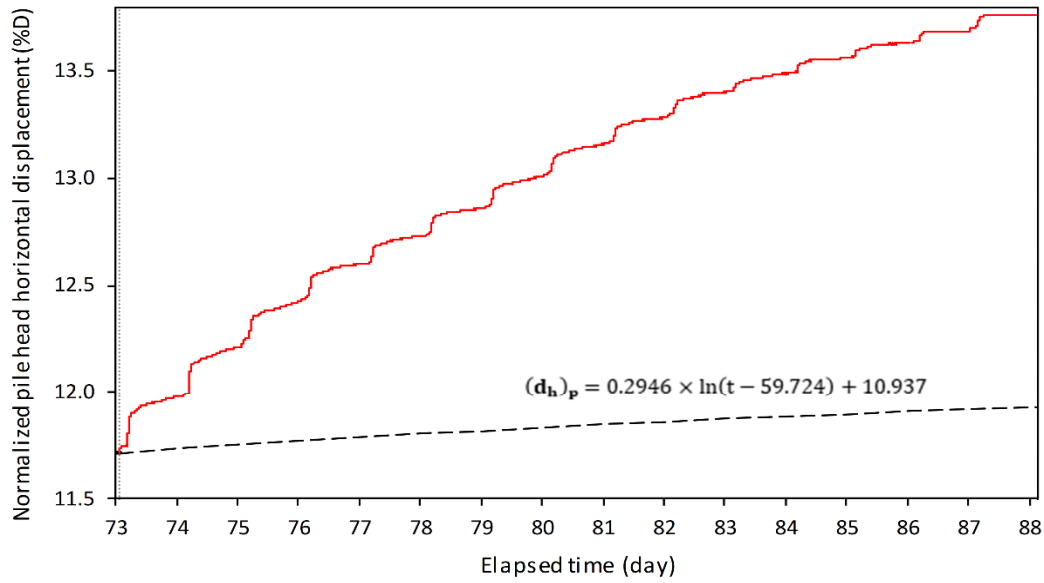
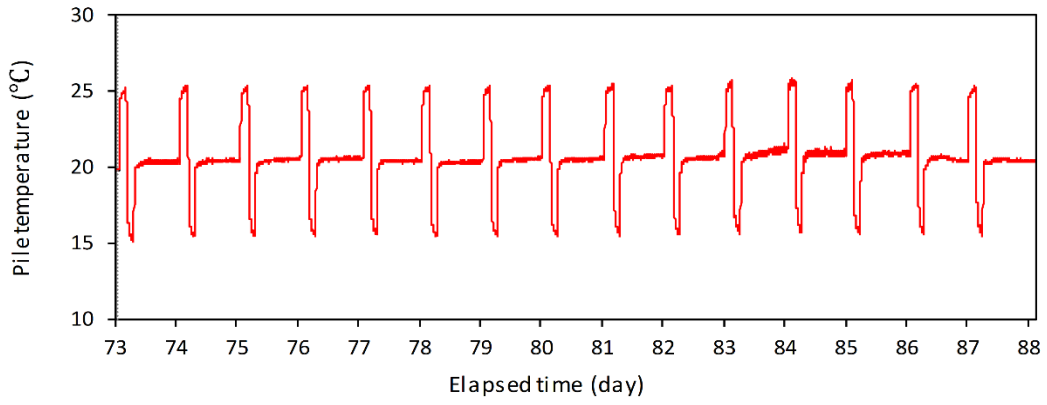
115
 116 **Fig. 5 Magnified view of the thermal-loading period at the end of (a) the first load step, (b) the second load**
 117 **step, and (c) the third load step.**
 118



119

120 Fig. 5 Continued (the second load step)

121

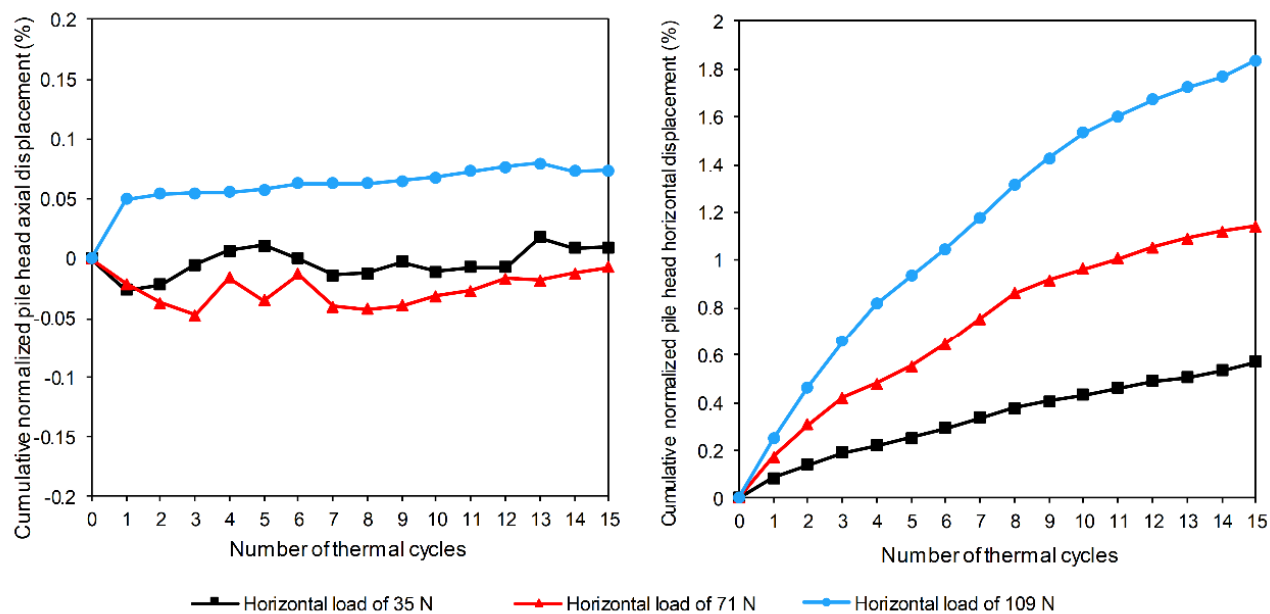


— Measured - - - Projected

122

123 Fig. 5 Continued (the third load step)

124 As illustrated in Fig. 6, under the horizontal loads of 35, 71, and 109 N, the irreversible horizontal displacement
 125 rapidly increases to 0.09%D, 0.17%D, and 0.25%D during the first thermal cycle, then continues to increase at a
 126 decreasing rate with the increasing number of cycles, reaching 0.57%D, 1.15%D, 1.84%D at the end of the 15th
 127 cycle, respectively. Thermally-induced irreversible horizontal displacements could be explained by the combined
 128 effect of both soil and pile contraction and build-up of excess pore water pressure, contributing to the reduction of
 129 horizontal effective stress acting on the pile shaft and subsequently, the reduction of passive soil resistance.
 130 Additionally, thermally-induced soil consolidation and creep could contribute in turn to a time-dependent increase in
 131 horizontal displacement during the recovery phase. Evidence of these phenomena are available in previous works
 132 (Akrouch *et al.* 2014; Wu *et al.* 2020; Ng *et al.* 2014, 2021a, b). The gradual accumulation of thermally-induced
 133 irreversible horizontal displacements during thermal cycles could be caused by thermally-induced passive soil
 134 resistance mobilization. This kind of ratcheting response was similarly observed for axially-loaded energy piles
 135 embedded in clay reported by Nguyen *et al.* (2020), Wu *et al.* (2020) and Ng *et al.* (2014, 2021a, b), and for
 136 horizontally-loaded energy pile embedded in dry sand reported by Zhao *et al.* (2022).



137
 138 **Fig. 6 Pile head irreversible axial and horizontal displacements versus the number of heating-cooling cycles**
 139 **(mechanically-induced pile head axial and horizontal displacements due to consolidation and creep of the**
 140 **surrounding clay have been subtracted from the measured total displacements during the thermal-loading**
 141 **period of each respective load step).**
 142

143 It is also inferred from Fig. 6 that under the horizontal loads of 35 and 71 N, the first cycles induce irreversible axial
144 displacement up to $-0.03\%D$ and $-0.05\%D$, respectively. This negligible settlement is fully compensated by the pile
145 head heave during subsequent cycles. However, under the horizontal load of 109 N, the first cycle induces
146 irreversible heave up to $0.05\%D$, which almost remains constant during subsequent cycles and gains an increment of
147 only $0.02\%D$. This reverse trend could be attributed to the uplift force on the pile shaft effectively mobilized in
148 previous loading steps. It is further worth noting that the accumulated thermally-induced irreversible axial and
149 horizontal displacements under the horizontal load of 71 and 109 N might be influenced by the accumulated
150 irreversible displacements induced by previous loading steps. Overall, with increase in horizontal load, thermal
151 cycles tend to cause a higher irreversible horizontal displacement, resulting in a negligible irreversible heave at the
152 pile head.

153 **Conclusions**

154 The main conclusion of this study is that under the combined axial/horizontal mechanical loading, imposing heating-
155 cooling cycles to the pile results in irreversible horizontal displacement at the pile head, accumulating at a reducing
156 rate as the number of thermal cycles increases. After 15 heating-cooling cycles, the amount of accumulated
157 thermally-induced irreversible horizontal displacement is estimated at $0.57\%D$, $1.15\%D$, and $1.84\%D$ under the
158 horizontal loads of 35, 71, and 109 N, respectively. Reversely, thermally-induced pile head axial displacement at the
159 end of the 15th cycle is practically insignificant (smaller than $0.1\%D$). At higher horizontal loads, thermal cycles
160 induce a higher irreversible horizontal displacement, resulting in a negligible irreversible heave. It is recommended
161 that thermo-mechanical tests are performed with a more significant number of heating/cooling cycles to determine a
162 stabilization threshold of the thermally-induced irreversible pile head horizontal displacement. This study is subject
163 to some limitations, including (1) the absence of pore-water pressure measurement, (2) partial rotational restraint at
164 the pile head, (3) uncertainty about the consolidation degree of the soil mass, (4) the existence of swelling-induced
165 heave, (5) mismatch of the thermal properties of aluminium and concrete, (6) inability in simultaneous scaling of
166 both strength and stiffness of the prototype pile, and (7) inability to reproduce the soil stiffness, stress level and
167 excess pore water pressure within the soil mass at the prototype scale. However, the obtained qualitative results
168 could provide insight into the thermally-induced ratcheting behaviour of mechanically-loaded piles.

169

170

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172

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