

1 **Effects of cyclic temperature variations on the thermal response**
2 **of an energy pile under a residential building**

3

4 **by**

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32 **Abstract**

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34 The effects of daily cyclic temperature variations on the thermal response
35 of an energy pile built under a six-level residential building are examined.
36 The axial and radial thermal strains along the length of the pile followed
37 stable, linear reversible paths during daily active heating and cooling
38 cycles corresponding to a pile temperature range of 10 to 23°C (ΔT of -8°C
39 to 5°C) around a baseline temperature of 18°C. The stable responses of
40 the thermal strains indicate that plastic deformations did not occur in the
41 pile during the daily cyclic temperature changes coupled with the
42 mechanical load in the pile corresponding to 52% of its estimated ultimate
43 capacity. A complex distribution of axial thermal stresses with depth was
44 observed in the pile with higher stress magnitudes near the pile ends
45 particularly at the end of cooling due to larger temperature changes in the
46 cooling cycle. The magnitudes of radial thermal stresses were
47 considerably smaller than the axial thermal stresses along the length of
48 the pile and are not anticipated to play a significant role in the
49 development of thermo-mechanical loads in the pile. The temperatures
50 over the cross-section of the pile were uniformly distributed at the end of
51 cooling and heating at all depths while the axial thermal stresses had a
52 non-uniform distribution but with magnitudes less than the calculated
53 ultimate capacity of the pile.

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55**Keywords:** *Energy pile; field tests; thermal responses; building loads;*
56*cyclic temperatures.*

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63**Introduction**

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65Energy piles can be subjected to cyclic changes in temperature associated
66with long-term seasonal ground-source heat pump (GSHP) operation
67([Brandl, 2006](#); Murphy and McCartney, 2015; McCartney and Murphy,
682017) and daily intermittent operations of the GSHP (Faizal et al., 2016;
692018). The ground temperatures during daily intermittent operations of
70the GSHP may recover naturally during non-operating times or could be
71recharged forcefully using optimized hybrid systems that utilize cooling
72towers or solar collectors for maintaining a balance of ground
73temperatures and improving geothermal energy utilization (Yi et al., 2008;
74Wood et al., 2010). In such hybrid systems, energy piles may encounter
75frequent cyclic temperature changes that could intensify thermally
76induced deformations at the pile-soil interface compared to application of
77monotonic seasonal changes in pile temperature, depending on the
78magnitude of the axial mechanical load applied at the pile head

79(Suryatriyastuti et al., 2013; Olgun et al., 2014; Pasten and Santamarina,
802014). Effects of this cyclic mechanism on the responses of energy piles
81under building loads are still to be evaluated.

82

83Most of the investigations conducted on field energy piles have focussed
84on their axial thermal responses when subjected to monotonic heating or
85cooling (Laloui et al., 2006; Bourne-Webb et al., 2009; Akrouch et al.,
862014; Mimouni, 2014; Mimouni and Laloui, 2015; Wang et al., 2015;
87Murphy et al., 2015; You et al., 2016; Sutman et al., 2017) or under actual
88heat pump operation (Brandl, 1998, 2006; McCartney and Murphy, 2012;
89Murphy and McCartney, 2015; McCartney and Murphy, 2017). Of these
90studies, only a few were conducted on energy piles installed under
91building loads (Brandl, 2006; Laloui et al., 2006; McCartney and Murphy,
922012; Mimouni and Laloui, 2015; Murphy et al., 2015; Murphy and
93McCartney 2015; McCartney and Murphy, 2017). Also, the evaluation of
94the long-term impacts of daily cyclic temperature changes on the thermal
95response of energy piles in hybrid systems are minimal (Faizal et al.,
962016; 2018). The frequent reversals in pile temperatures in hybrid
97systems compared to normal systems would maintain the pile and ground
98temperatures closer to undisturbed initial temperatures since the pile and
99ground temperature changes will always be recovered when the heating
100and cooling cycles are switched (Yi et al., 2008; Wood et al., 2010).
101However, it is likely that frequent daily cyclic temperature changes in
102hybrid systems may lead to much higher cyclic changes in temperature of
103the pile compared to the surrounding soil due to the relatively low thermal

104conductivity of most soils. The higher cyclic temperature changes of the
105pile could lead to a higher expansion and contraction of the pile compared
106to the surrounding soil, resulting in greater mobilization of side shear
107stresses due to the possible differential movement of the pile and the soil.
108Slower changes in temperatures during seasonal operation may, however,
109lead to volume changes of both the pile and the soil.

110

111Evaluation of radial thermal reactions of energy piles at field scale is
112scarce (Laloui et al., 2006; Amis et al., 2008; Mimouni, 2014; Mimouni and
113Laloui, 2015; Wang et al., 2015; Wang, 2017; Faizal et al., 2018), often
114with conflicting conclusions. For example, the field studies reported by
115Wang et al. (2015) and Faizal et al. (2018) indicated that radial thermal
116responses were not significant in comparison to axial thermal responses
117of the pile, while Mimouni and Laloui (2015) studies suggested that radial
118thermal responses might be significant. The differences in conclusions
119from these studies might be due to differences in soil properties
120encountered on site, and variations in pile construction techniques and
121pile geometries. Numerical analyses have generally reported that the
122radial thermal stresses of energy piles are insignificant compared to axial
123thermal stresses along the length of the pile (Knellwolf et al., 2011;
124Ozudogru et al., 2015; Gawecka et al., 2017; Chen and McCartney, 2016).
125Additional investigation is essential to evaluate the impact of daily cyclic
126temperature changes on the axial and radial thermal responses of energy
127piles under building loads.

128

129 Small-scale physical model studies with thermal cycles on energy piles
130 (Kalantidou et al., 2012; Stewart and McCartney, 2014; Yavari et al., 2014,
131 2016a; Wang et al., 2017; Nguyen et al., 2017) have indicated that the
132 thermally induced axial settlement of the pile is reversible for pile head
133 loads corresponding to as low as 20% of the ultimate pile capacity, but
134 becomes irreversible for higher pile head loads closer to the ultimate pile
135 capacity. The field tests conducted by Faizal et al. (2018) indicated that
136 the axial and radial thermal responses of an unrestrained energy pile
137 embedded in dense sand followed linear reversible paths for heating and
138 cooling cycles, suggesting that both the pile and the soil did not undergo
139 significant thermally induced deformations. As highlighted in the small-
140 scale physical model studies reported by several investigators (Kalantidou
141 et al., 2012; Stewart and McCartney, 2014; Yavari et al., 2014, 2016a;
142 Wang et al., 2017; Nguyen et al., 2017), it is conceivable that building
143 loads could lead to irreversible axial and radial thermal responses along
144 with associated deformations of the pile and the surrounding soil during
145 cyclic temperature changes. Therefore, further investigations are deemed
146 necessary to evaluate the reversibility of the axial and radial thermal
147 responses of energy piles under building loads when subjected to daily
148 cyclic temperature changes.

149

150 Numerical studies reported by Abdelaziz and Ozodugru (2016a, 2016b)
151 and Caulk et al., (2016) have indicated that the presence of non-uniform
152 temperature and axial thermal stress distributions tend to develop over
153 the cross-sectional area of the pile. There are no studies yet on the

154characterization of the complex distribution of temperatures and axial
155thermal stresses across the cross-section of energy piles under building
156loads when subjected to daily cyclic temperature changes.

157

158Based on the gaps in the knowledge noted above, the main aim of this
159paper is to assess the effects of daily cyclic temperature changes on the
160axial and radial thermal responses of an energy pile installed under a
161building. Specifically, the temperature in the energy pile is controlled in a
162way to simulate the expected changes in temperature that may occur in a
163hybrid system with forced thermal recharging of the ground temperature.
164The specific aims of this paper are to assess the reversibility of the axial
165and radial thermal strains versus the variations in pile temperatures and
166to evaluate the temperature and axial thermal stress distributions over
167the cross-section of the energy pile at different depths. For these
168purposes, an energy pile installed under a 6-story student residential
169building was subjected to 16 hours of cooling followed by 8 hours of
170heating, daily, simulating a daily cooling intermittent operation of the pile
171(i.e. building heating) with scheduled forced ground thermal recovery for a
172solar-hybrid system. The 8 hours of heating simulates forced thermal
173recharging of the ground temperature (which would be from a renewable
174source in an actual hybrid system), which in turn improves the geothermal
175energy utilization in the following cooling cycle by increasing the
176temperature gradient between the working fluid and the ground.

177

178**Ground Conditions**

179

180The soil formation at the site consists of shallow surface sands and silt
181underlain by very stiff clays, and medium dense to dense clayey and silty
182sands with increasing depth. The lithology is documented in Table 1,
183further description of the site is also provided in Barry-Macaulay et al.
184(2013, 2014). No groundwater was encountered within the depth of the
185pile during drilling, and the soil was unsaturated.

186

187**Energy pile details and experimental procedure**

188

189Two cast-in-place bored foundation piles with a diameter of 0.6 m and
190length of 10 m, from a set of 114 foundation piles for a residential building
191located at Monash University (Melbourne, Australia), were constructed as
192energy piles below a ground beam of 800 mm depth and 1200 mm width.
193One of the two energy piles was instrumented with vibrating wire strain
194gauges (VWSGs) and thermocouples as shown in the schematic in
195Figure 1 and was subjected to thermal cycles in this study. Faizal et al
196(2018b) described in details the instrumentation and installation of these
197energy piles. In summary, the instrumented energy pile contained 30
198VWSGs (model Geokon 4200) installed at five depths of the pile to monitor
199both axial and radial strains. All the VWSGs were mounted on 30 mm high
200Styrofoam blocks using cable ties fastened away from the end blocks of
201the gauges (Figure 2b). The outer axial VWSGs were attached to the
202reinforcement bars, the central axial VWSGs were attached to the outer
203side of the tremie guides that housed removable tremies used to pour

204concrete, and the radial VWSGs were attached to steel bars welded across
205the diameter of the pile. Further details about the sensors,
206instrumentation and installation process are documented elsewhere
207(Faizal 2018; Faizal et al. 2018b). The concrete temperatures were
208recorded from day two of casting and were observed to reduce with curing
209time to the magnitudes of the surrounding undisturbed soil temperatures
210(Bouazza et al. 2015; Singh et al., 2015, Faizal 2018) and were evenly
211distributed with depth, indicating that the shaft geometry remained
212uniform with depth without any defects in the concrete.

213

214Faizal et al (2018b) indicated that the four high-density polyethylene U-
215loops pipes were attached to the inside of the reinforcing cage of the pile,
216as illustrated in Figure 2a. The nominal concrete cover to the edge of the
217pipes is 95 mm. The horizontal spacing between the pipes in a given U-
218loop is about 200 mm. The concrete mix consisted of 7 mm aggregated
219cement, slag, and fly ash with water to cement ratio of 0.42. The
220compressive strengths of unreinforced concrete samples were 40 MPa and
22162 MPa at 7 and 33 days of installation, respectively, with a modulus of
222elasticity of 34 GPa at 133 days of installation (Faizal et al., 2018b).

223

224A commercial 2-5 kW Envision geothermal/water source heat pump was
225used for the experiment. The inlet and outlet of all the U-loops were
226connected to the inlet and outlet of the heat pump through a plumbing
227manifold. Type T thermocouples, supplied by ECEFast (Melbourne,
228Australia), recorded the fluid temperatures at the inlet and outlet of each

229U-loop. The fluid flow rates were recorded using TM series digital water
230flowmeters installed at the inlet and outlet of the plumbing manifold. Data
231from the thermocouples and the VWSGs were logged using Pico
232Technology's USB-TC08 data loggers and Campbell Scientific CR1000 data
233loggers, respectively (Faizal et al., 2018b).

234

235The cyclic cooling and heating experiment was conducted for 17 days at a
236fluid flow rate of approximately 16 litres per minute. The fluid returning
237from the piles exited into a buffer tank installed at the inlet of the heat
238pump. A Fernox Alphi-11 antifreeze protector was added to the water (at
239approximately 25% of the total volume of water in the system) to ensure
240that water did not freeze and block the pipelines during the cooling cycles.
241All the four U-loops in the pile were thermally active giving an even heat
242exchanger layout in the pile. The four U-loops in the pile were connected
243in series where the fluid flowed successively in each loop from the inlet of
244the first loop to the outlet of the fourth loop. The pile was cooled for
24516 hours followed by heating for 8 hours, daily. There were some
246performance issues of the heat pump in the first cooling cycle which
247disrupted cooling temperatures for up to 10 hours. Once this was
248resolved, the cooling cycle was restarted for 16 hours. Hence, the total
249time for the first cooling cycle is 26 hours, while the other cooling cycles
250were 16 hours followed by 8 hours heating. No other issues were
251encountered for the duration of the experiment. The fluid inlet and outlet
252temperatures recorded at the pile head consistently cycled between
253approximately 8 to 30°C, as shown in Figure 3a. The range of

254temperatures for energy piles during operation has been reported to be
255approximately between 10 to 35°C depending on the usage requirement
256(Brandl, 2006; McCartney and Murphy, 2012; Murphy and McCartney,
2572015; McCartney and Murphy, 2017). The change in fluid temperatures
258were approximately -2.5°C at the end of cooling and 3°C at the end of
259heating, as shown in Figure 3b.

260

261**Results and discussions**

262

263**Time series of temperatures and thermal strains**

264

265The thermal strains, ε_T , were calculated using the calibration factors of the
266VWSGs and by correcting for temperature changes, as follows (Faizal et
267al., 2018b):

268

$$269 \varepsilon_T = (\varepsilon_i - \varepsilon_o) B + (T_i - T_o) \alpha_s \quad (1)$$

270

271where ε_i is strain at time i , ε_o is the reference strain and is selected at the
272beginning of the thermal cycles, and hence the calculated thermal strains
273neglects the effects of building loads, B is the batch calibration factor of
274the strain gauges with a magnitude of 0.975, T_i is the temperature of the
275strain gauges at time i , T_o is the reference temperature of the strain
276gauges, α_s is the coefficient of linear thermal expansion of steel wire in

277the strain gauges ($12.2 \mu\epsilon/^\circ\text{C}$). The strains ϵ_i and ϵ_o were calculated as
278follows:

279

$$280\epsilon = G(f^2 \times 10^{-3}) \quad (2)$$

281

282where f is the resonant frequency of the strain gauges at the reference or
283at time i , and G is the gauge factor with a magnitude of 3.304.

284

285The time series of the pile temperatures and change in pile temperatures
286recorded from the axial and radial VWSGs are presented in Figure 4.
287Average magnitudes of pile temperatures and thermal strains from the
288axial VWSGs are considered for ease of comparison with pile temperatures
289and thermal strains from radial VWSGs. The temperatures plotted in
290Figure 4 are for depths below 3 m to compare between the axial and
291radial thermal responses, as the radial VWSG at a depth of 1.36 m was
292damaged and did not provide any data on the radial thermal strains. One
293of the axial VWSGs at 1 m depth was also damaged and did not provide
294any data on the variation of axial thermal strains. The axial thermal
295responses against depth are presented later in the paper. The pile
296temperatures (including change in pile temperatures) recorded from the
297axial and radial VWSGs (Figure 4) showed similar magnitudes with slight
298differences at the end of heating/cooling cycles between consecutive
299days. The pile temperatures at the end of heating and cooling are above
300and below the initial undisturbed pile temperatures of approximately 18°C
301recorded prior to the experiments, respectively; hence the ΔT magnitudes

302cycled between positive and negative magnitudes. The pile temperatures
303cycled approximately between 10°C and 23°C and the change in pile
304temperatures, ΔT , cycled approximately between -8°C and 5°C.

305

306The time series of axial and radial thermal strains below a depth of 3 m is
307shown in Figure 5. Similar to the ΔT magnitudes, the thermal strains also
308cycled between positive and negative magnitudes. The ranges of
309magnitudes of radial thermal strains are generally larger than the range of
310magnitudes of axial thermal strains at all depths, indicating an overall
311higher restriction to thermal expansion/contraction of the pile in the axial
312direction.

313

314The largest difference in the magnitudes between the axial and radial
315thermal strains at the end of heating and cooling is at an approximate
316depth of 3 m (axial and radial strains at depths of 3.05 m and 3.3 m,
317respectively) (Figure 5a), which is possibly the location of the null point as
318the range of magnitudes of the axial thermal strains are also the lowest at
319this depth. The axial thermal strains are lower than the radial thermal
320strains at the end of cooling and heating at this depth, indicating that the
321energy pile is more restrained to axial thermal expansion and contraction.
322The null point or the neutral plane is the location in the pile where ideally
323the thermally induced axial displacement is zero and the axial thermal
324stress is the maximum. The thermally induced axial displacements and
325mobilised side shear stresses act in opposite vertical directions from this
326point to ensure vertical equilibrium (Bourne-Webb et al. 2009; Amatya et

327al. 2012; Bourne-Webb et al. 2013). The axial and radial thermal strains at
328depths of 5 m and 5.3 m, respectively, show similar magnitudes (hence,
329same restriction) at the end of cooling, while the axial thermal strains are
330more restrained at the end of heating (Figure 5b). The axial thermal
331strains at a depth of 7.28 m (Figure 5c) is more restricted than radial
332thermal strains at a depth of 7.46 m at the end of heating, while the radial
333thermal strains are more restricted than axial thermal strains at the end of
334cooling. The axial thermal strains at a depth of 9.5 m are more restricted
335than the radial thermal strains at a depth of 9.25 m at the end of cooling
336but show similar magnitudes at the end of heating.

337

338The results of the daily cyclic pile temperature changes presented by
339Faizal et al. (2018) at a single depth for an unrestrained field-scale energy
340pile installed in dense sand and subjected to a temperature change of
341-10°C to 22.5°C indicated that the axial thermal strains were more
342restricted to thermal expansion/contraction than the radial thermal
343strains. The results of Figure 5, however, indicate that depending on the
344location in the energy pile under building loads, the radial thermal strains
345may not always show lower restrictions to thermal expansion or
346contraction at the end of heating or cooling when the pile is subjected to
347daily cyclic temperature changes. The range of temperature changes of
348the energy pile in the present study compared to the study of Faizal et al.
349(2018a, b) is, however, relatively low (i.e. approximately - 8°C to 5°C in
350the present study). This could have prevented the radial thermal strains
351from fully developing in the pile.

352

353 **Thermal responses to change in pile temperatures**

354

355 The variations of the axial and radial thermal strains versus the change in
356 pile temperatures, ΔT , at four-day intervals are shown in Figure 6. The
357 observed linear trends confirm that the range of magnitudes of the axial
358 thermal strains is lower than the range of magnitudes of the radial
359 thermal strains for a similar range of pile temperature changes (i.e.
360 approximately -8°C to 5°C). The axial thermal strains follow almost linear
361 reversible paths against the variation in cyclic pile temperatures for daily
362 heating and cooling cycles, at all depths. There is, however, an initial
363 ratcheting behaviour observed mostly in the radial thermal strains
364 between 3.3 m to 7.46 m, the highest being at 7.46 m (Figure 6b, 6d, and
365 6f). This initial ratcheting **behavior**, which reduced with operating time as
366 thermal strains stabilized towards the end of the experiment, possibly
367 occurred due to high initial heat dissipation into the surrounding sand
368 resulting from high initial thermal gradient between the inlet fluid and the
369 ground. Although plastic deformations is unlikely to have occurred, the
370 **behavior** of radial thermal responses at a depth of 7.46 m shown in Figure
371 6f would require further long-term simulations to fully evaluate if any
372 plastic deformations occurred at the pile-soil interface at that location.
373 However, as discussed later in the paper, the magnitudes of radial
374 thermal stresses developed in the energy pile are negligible compared to
375 axial thermal stresses, hence radial thermal effects on the pile-soil
376 interface would also be very low compared to axial thermal effects.

377

378The results shown in Figure 6 indicate that the load of the building does
379not have any significant impact on the reversibility of the axial thermal
380strains for frequent cyclic temperature changes of the pile. The calculated
381ultimate capacities of compressive and tension mechanical loads are
3822701 kN (9.6 MPa) and 2157 kN (7.6 MPa), respectively (Faizal et al.,
3832018b). The design compressive and tension axial working mechanical
384loads of the 10 m long, 0.6 m diameter energy pile with a factor of safety
385of 1.9 are 1404 kN (4.96 MPa) and 1122 kN (3.97 MPa), respectively
386(Faizal et al., 2018b). The design pile head load is thus approximately 52%
387of the calculated ultimate pile head load and the results shown in Figure 6
388indicate that the thermal strains are reversible for frequent cyclic
389temperature changes at this working load ratio of the energy pile for the
390duration of the experiment. The current results are different from the
391findings reported for small-scale model studies due to differences in soil
392types and preparation techniques and differences in boundary conditions
393since field installations represent actual effects of the surrounding soil and
394pile installation effects compared to idealized installations in small-scale
395studies.

396

397The thermal strains are reversible for daily cyclic temperature changes of
398the pile likely due to its adequate design factor of safety which considers
399the mechanical loads imposed by the building as well as the thermal loads
400induced in the pile for the range of temperatures studied. The type of soil
401also plays an essential role in the thermal response of the energy pile. It is

402likely that the dense sand at this site has also contributed to the
403reversible axial and radial thermal responses of the energy pile by
404providing a higher resistance to thermal expansion and contraction. As
405has also been shown in numerical studies, the settlement of energy piles
406is much lower in dense sand than in loose sand due to differences in the
407shaft friction (Saggu and Chakraborty, 2015). The linear reversible paths
408of the thermal strains at all depths indicate that any temperature induced
409relative settlements between the pile and the soil was reversible.

410

411**Evaluation of thermal responses against depth**

412

413The profiles of temperatures, variation in temperatures, and axial and
414radial thermal strains plotted against depth at four-day intervals are
415shown in Figure 7. The pile temperatures and variation in pile
416temperatures shown in Figure 7a to Figure 7d indicate that the sixteen-
417hour cooling cycle imposed larger pile temperature variations (ΔT up to
418-9°C) than the eight-hour heating cycle (ΔT up to 5°C). The temperatures
419return to similar magnitudes at the end of heating and cooling (apart for
420Day 4 where the heat pump imposed higher temperatures during
421heating).

422

423The axial thermal strains at the end of cooling in Figure 7e show larger
424variations with depth compared to the end of heating, likely due to larger
425changes in pile temperatures during the cooling cycle. The most
426significant restriction to axial thermal strains at the end of cooling is at a

427depth of 3.05 m, possibly the location of the null point where ideally the
428axial thermal stresses are the maximum. The pile toe also appears to
429provide resistance to axial thermal strains at the end of cooling, leading to
430a complex distribution of axial thermal strains with depth. The restraints
431provided by the building on the pile head and by the dense sand on the
432toe could have provided differing stiffness at each end of the pile which
433could have affected the axial thermal load distribution in the pile during
434temperature cycles (Bourne-Webb et al., 2013). Locations of high
435restrictions in axial thermal strains are not evident with depth at the end
436of heating likely due to the lower pile temperature changes imposed in the
437heating cycle.

438

439The cyclic pile temperature changes also affected the distribution of the
440radial thermal strains with depth, particularly at a depth of 7.46 m. The
441radial thermal strains at 7.46 m are unexpectedly lower than the axial
442thermal strains at a depth of 7.28 m at the end of cooling. This was,
443however, not observed at the end of heating. The magnitudes of radial
444thermal strains at other depths shown in Figure 7f are either similar or
445larger than the magnitudes of axial thermal strains at the end of cooling
446or heating, confirming that radial thermal strains may not always show
447lower restrictions than axial thermal strains for an energy pile under
448building loads subjected to the range of daily cyclic temperatures reported
449in this paper.

450

451The thermal and thermo-mechanical stresses developed in the pile are
452shown in Figure 8. The tensile stresses developed during cooling and
453compressive stresses developed during heating are deemed to be positive
454and negative, respectively. The thermal stresses, which develop when the
455free thermal expansion/contraction of the energy pile is restricted by the
456soil-structure interaction, are a function of the modulus of the pile and can
457be estimated as follows (Amatya et al., 2012; Murphy et al., 2015; Caulk
458et al., 2016):

459

$$460 \sigma_T = E_p (\varepsilon_T - \varepsilon_{free}) \quad (3)$$

461

462where E_p is the Young's modulus of the concrete, ε_T is the actual thermal
463strains measured in the pile calculated using equation 1, and ε_{free} is the
464free thermal expansion of the pile estimated by multiplying the change in
465pile temperature, ΔT , and the coefficient of thermal expansion of the
466concrete, α_c .

467

468Upon calculation of the free thermal strains using an average value of α_c
469= $13 \mu\text{e}/^\circ\text{C}$ and the ΔT magnitudes shown in Figure 7c and Figure 7d, it
470was found that the actual radial thermal strains measured in the pile
471exceeded the free radial thermal strains, particularly at the end of
472heating. This could be credited to the transient effects of temperature
473reversals between positive and negative magnitudes which has been
474previously identified to cause issues in estimating thermal stresses

475(Murphy and McCartney, 2015; Faizal et al., 2018). Another reason could
476be the temperature recorded by the gauge that is used to estimate the
477thermal stresses is different from the average temperature of the pile
478(Murphy and McCartney, 2015). For the sake of simplicity in the analysis,
479the axial thermal stresses were estimated using Equation 3 whereas a
480cavity expansion analysis (Equation 4) was used to estimate the radial
481thermal stresses in the pile since the mobilized radial pile-soil contact
482stresses, σ_n , are equal to the radial thermal stresses developed in the pile
483for radial stress equilibrium (Faizal et al., 2018):

484

$$485 \sigma_n = \frac{E_s}{1 + \nu_s} \frac{\Delta r}{r}$$

486(4)

487

488Where r is the radius of the pile, Δr is the thermally induced radial
489displacement of the pile, $\Delta r/r$ is assumed to be equal to the radial thermal
490strain for a given change in temperature, and E_s and ν_s are the Young's
491modulus and Poisson's ratio of the surrounding dense sand, respectively
492(assumed to be 60 MPa and 0.3, respectively, based on typical values for
493dense sand, Faizal et al , 2018b). This simple model with a constant
494stiffness is used to estimate the mobilized radial pile-soil contact stresses
495(and hence the radial thermal stresses developed in the pile) since the
496thermally induced radial pile displacement, Δr , is relatively small
497compared to the initial pile radius and the shear strength of sand is not

498 expected to be affected by temperature variations (Barry-Macaulay, 2013;
499 Donna et al., 2015; Yavari et al., 2016b).

500

501 The axial thermal stresses developed in the pile at the end of cooling and
502 heating are plotted together with the mechanical stresses imposed by the
503 load of the building in Figure 8a. The mechanical stresses are the vertical
504 stress distribution of the building load along the length of the pile, and are
505 estimated from the variations in strains during building construction times
506 the modulus of elasticity of the pile. The magnitudes reduce with depth as
507 the building load is taken up by the shaft friction, with minimal effects at
508 the pile toe. There is a change in soil profile at a depth of 3.5 m which
509 could have affected the mechanical stress distribution at that location.
510 The sign convention in the present paper is that compressive and tensile
511 stresses are considered as negative and positive, respectively. The
512 magnitudes of tensile axial thermal stresses at the end of cooling are
513 larger than the compressive axial thermal stresses at the end of heating,
514 due to differences in ΔT magnitudes shown in Figure 7c. Also, the axial
515 thermal stresses at the end of cooling show larger variations with depth
516 due to larger changes in the axial thermal strains with depth at the end of
517 cooling, shown in Figure 7e. The radial thermal stresses presented in
518 Figure 8b are significantly lower (up to 0.004 MPa) than the axial thermal
519 stresses (up to 2.5 MPa) developed in the pile and are not expected to
520 modify the radial mechanical loads imposed by the building. This low
521 magnitude of radial thermal stresses indicates that the radial thermal
522 effects do not contribute significantly to the development of axial thermal

523 strains and stresses in the pile. Radial thermal stresses in energy piles
524 have also been reported to have significantly low magnitudes in numerical
525 studies (Olgun et al., 2014; Ozudogru et al., 2015; Gawecka et al., 2017)
526 and field studies (Faizal et al., 2018). The study on an unrestrained energy
527 pile installed in dense sand conducted by Faizal et al. (2018) reported
528 axial and radial thermal stresses up to 3 MPa and 0.012 MPa, respectively.
529 Gawecka et al. (2017) numerically back analyzed the Lambeth College
530 field energy pile installed in London clay with a 1200 kN head load
531 (studied by Bourne-Webb et al., 2009) and reported axial and radial
532 thermal stresses ranging from approximately 5 - 0.5 MPa and 0.01 -
533 0.03 MPa from the head to the toe of the pile, respectively. Ozudogru et
534 al. (2015) conducted a numerical study on an energy pile embedded in
535 cohesive soil and without head loads and also reported that the radial
536 stresses were small in magnitude (≈ 0.005 MPa) compared to the axial
537 thermal stresses (≈ 0.55 MPa). The radial thermal stresses for a plane-
538 stress (floating) and plane-strain (fixed at the top and bottom) energy pile
539 in a numerical analysis performed by Olgun et al. (2014) was reported to
540 be lower than 15 kPa and was concluded to be insignificant in causing
541 thermally induced changes at the pile-soil interface.

542

543 The axial thermo-mechanical stresses, which are the total of the axial
544 mechanical stresses imposed by the load of the building and the axial
545 thermal stresses developed in the pile, are shown in Figure 8c. The largest
546 axial thermo-mechanical stresses at the end of heating are -4.3 MPa at
547 the pile head and -0.3 MPa near the toe. The largest thermo-mechanical

548 stresses at the end of cooling are - 3.2 MPa at the pile head and 1.2 MPa
549 near the toe. The magnitudes of these stresses are lower than the
550 ultimate compressive, and tensile capacities of the pile, hence the range
551 of frequent cyclic pile temperature changes reported in this paper are not
552 expected to lead to any temperature-induced change in the capacity of
553 the pile.

554

555 **Cross-sectional distribution of temperatures and axial thermal** 556 **stresses**

557

558 The variation of pile temperatures and axial thermal stresses over the
559 cross-sectional area of the pile at all depths, obtained from the individual
560 axial VWSGs, are presented in Figure 9 and Figure 10, respectively. The
561 locations of the axial VWSGs are non-dimensionalized with respect to the
562 radius of the pile. The axial VWSGs at locations V1 and V2, displayed in
563 Figure 1, correspond to the non-dimensionalized radius of -0.47, V5
564 corresponds to the centre of the pile, and V3 and V4 correspond to the
565 non-dimensionalized radius of 0.47. The results are presented at end of
566 heating and cooling for Day 4 and Day 8. Similar trends were observed for
567 other days.

568

569 The pile temperature variations shown in Figure 9 are highest near the
570 pile toe at a depth of 9.5 m (Figure 9e) with a variation of up to 3.3°C at
571 the end of heating, probably due to the cluster of U-bends causing
572 turbulence in the pipes. The pile temperatures at other depths shown in

573 Figure 9a to Figure 9d are within a low range of magnitudes of 0.2°C to
574 1.1°C, indicating that uniform temperature distributions across the cross-
575 section of the energy pile with even heat exchanger layout could be
576 considered for design purposes for the range of cyclic temperatures
577 studied in this paper.

578

579 The frequent temperature reversals develop non-uniform axial thermal
580 stress distributions over the planar cross-section of the energy pile at all
581 depths, as indicated in Figure 10. The axial thermal stresses at one of the
582 locations at a depth of 1 m is not calculated as the VWSG (EV3) at this
583 location was damaged and did not provide any data on the axial thermal
584 strains (Figure 10a). The largest variations in axial thermal stresses over
585 the cross-section of the pile are observed near the pile ends, particularly
586 near the pile toe at a depth of 9.5 m (Figure 10e) where the range of
587 magnitudes of axial thermal stresses is approximately 2.5 MPa at the end
588 of cooling. The results indicate that pile end restraint leads to higher non-
589 uniformities in axial thermal stress distributions for cyclic temperature
590 changes. The range of magnitudes of axial thermal stresses at other
591 depths shown in Figure 10a to Figure 10d are within a low range of
592 ± 1.7 MPa. The magnitudes of the axial thermal stresses at any location of
593 the cross-section at the end of cooling or heating are however within the
594 ultimate capacities of the pile, and thus the non-uniform stress
595 distribution is not expected to cause any temperature-induced changes in
596 the capacity of the pile. Further simulation studies are warranted to verify
597 and extrapolate thermal stress contours over the cross-section of the

598energy pile and better identify regions of high-stress concentration,
599especially near the HDPE pipes where the concrete temperatures will be
600highest or lowest. Further investigations are also required to gauge the
601likelihood of concrete micro-cracking from frequent temperature reversals
602of the energy pile, even though it is not expected to occur in reinforced
603concrete.

604

605**Conclusions**

606

607This paper assessed the impact of daily cyclic temperature variations on
608the axial and radial thermal responses of an energy pile installed under a
609six-story building. For a pile design to ultimate head load ratio of 52% and
610for pile temperature changes of -8°C to 5°C , the axial thermal strains
611followed linear reversible paths along the length of the pile for daily
612thermal cycles, indicating that frequent cyclic temperature variations
613coupled with the load of the built structure did not result into thermally
614induced plastic deformations for the cast-in-place energy pile installed in
615dense sand studied in this paper. Some initial rateching behaviour was
616observed in the radial thermal strains which stablized towards the end of
617the experiment. The magnitudes of radial thermal stresses were found to
618be insignificant in comparison to axial thermal stresses developed in the
619pile at all depths indicating that radial thermal expansion/contraction of
620the pile does not have major impact on the skin friction of the pile. The
621temperature distribution over the cross-section of the pile at the end of
622cooling and heating indicated that a low range of variations was achieved

623at all depths and can be considered to be uniformly distributed for design
624purposes for energy piles with even heat exchanger layouts installed in
625dense sand. The axial thermal stresses were non-uniformly distributed
626across the cross-section of the pile at the end of cooling and heating for
627all depths, but the magnitudes were within the ultimate capacities of the
628pile. The results presented in this paper are for a single energy pile.
629Further studies are required to evaluate the effects of cyclic temperature
630changes on multiple energy piles installed under built structures that
631better represent real operating conditions.

632

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634

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641

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832 **Table 1.** Summary of ground conditions at the test site.

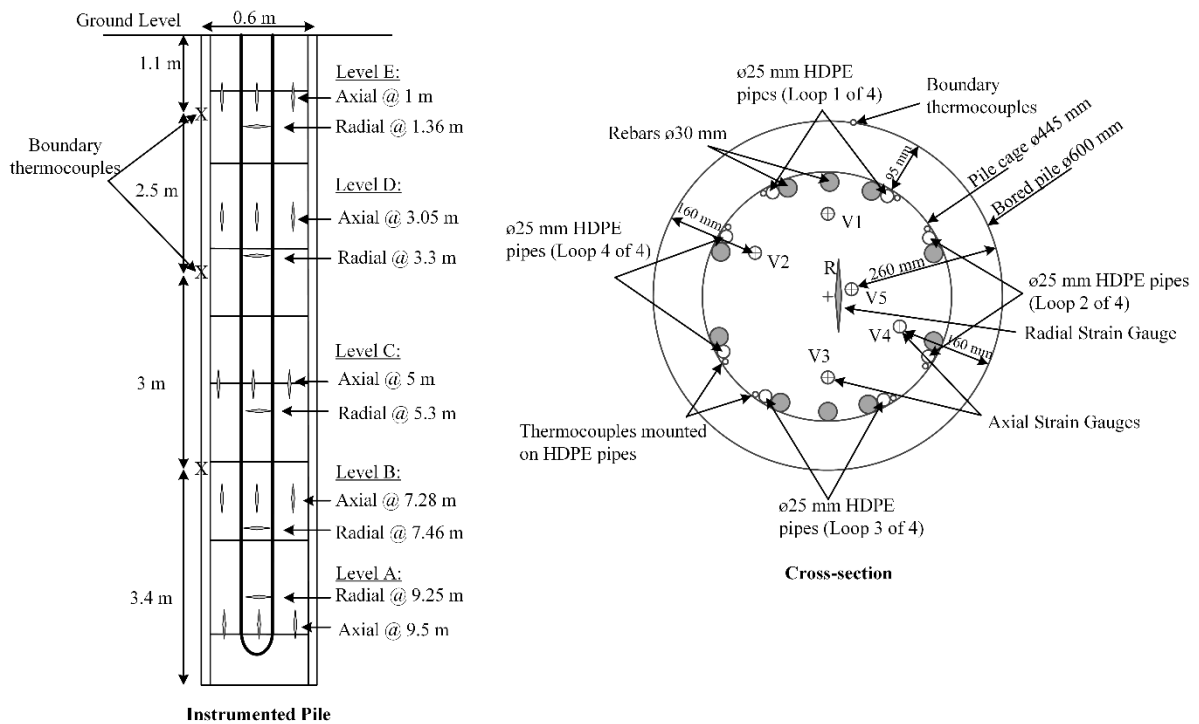
Depth (m)	Soil type	Soil description	In-situ values	test	Gravimetric water content (%)
0 - 0.4	Fill material	Crushed rock silt, sand, moist, medium dense	-	-	-
0.4 - 3.5	Sandy clay	Silt, sand (sand lenses) moist, stiff - very stiff	S: 90 - 140 kPa SPT N: 12 - 27		13 - 24
3.5 - 12.5	Sand	Sand, clay	SPT N: 25 - 30		5 - 13

lenses, silt,
cemented
lenses, moist,
dense

833S: Vane shear strength.

834SPT N: Standard penetration test blow count.

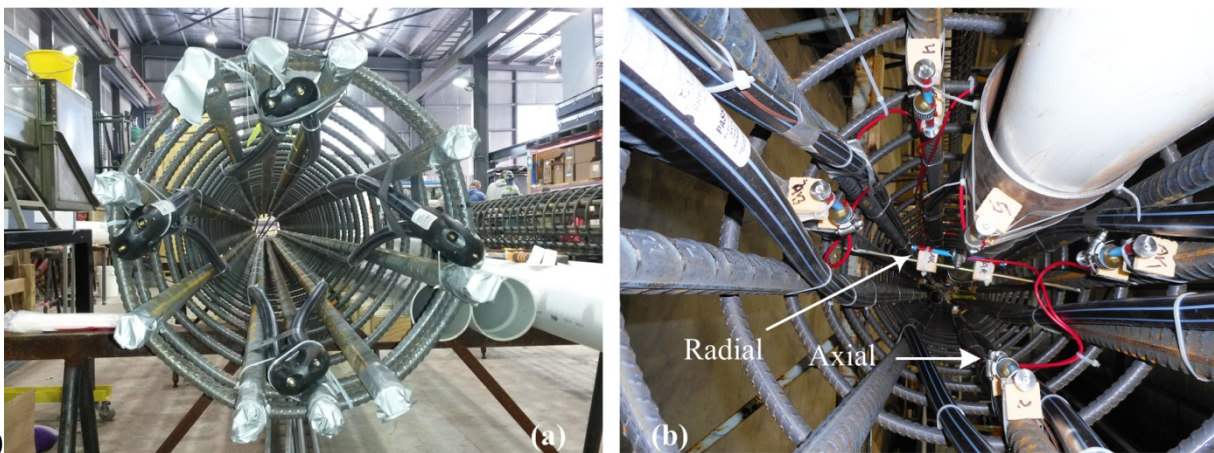
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837 **Figure 1.** Schematic of the instrumented energy pile and a typical cross
 838 section showing the location of sensors at each depth.

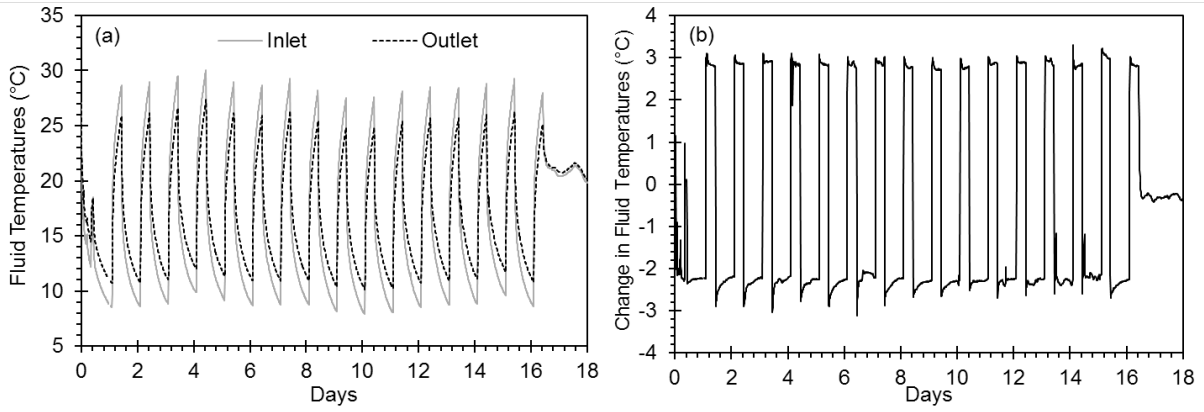
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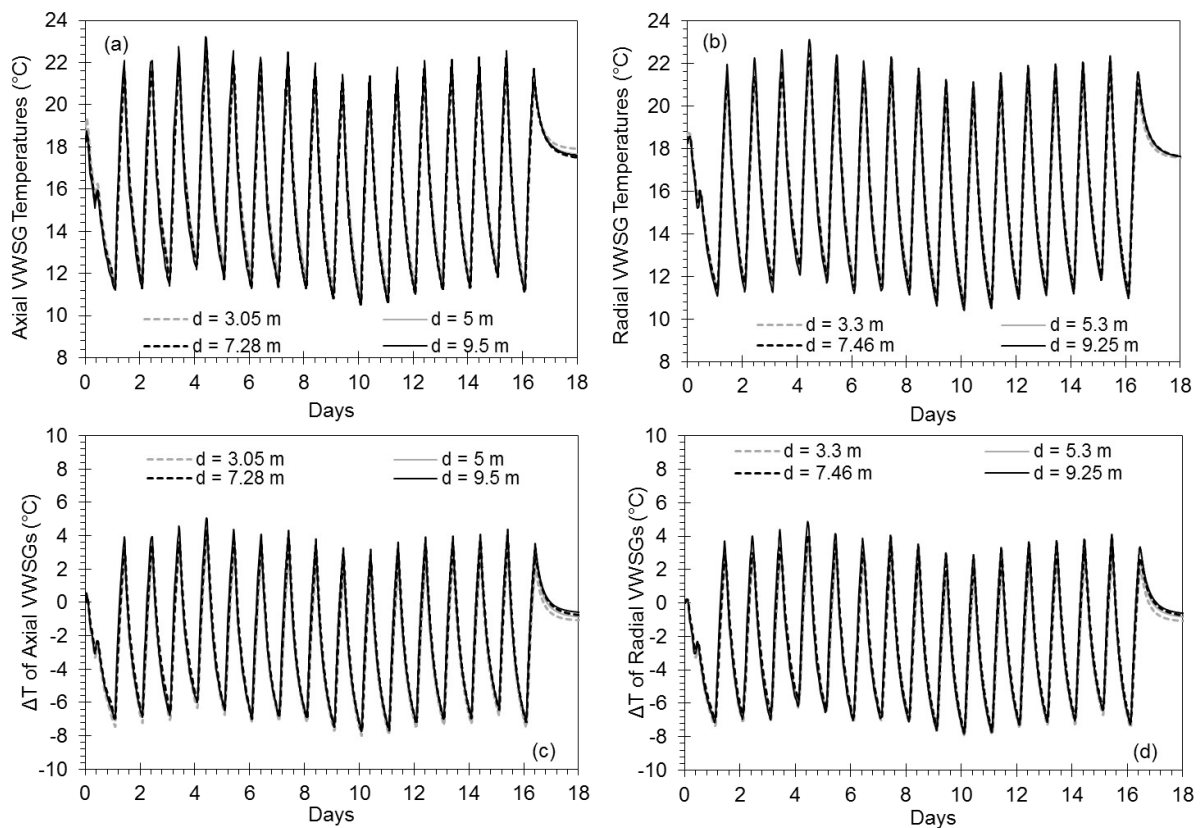
841 **Figure 2.** Images of the experimental setup: a) U-loops inside the energy
 842 pile cage b) axial and radial VWGs inside the energy pile cage near the
 843 pile toe.

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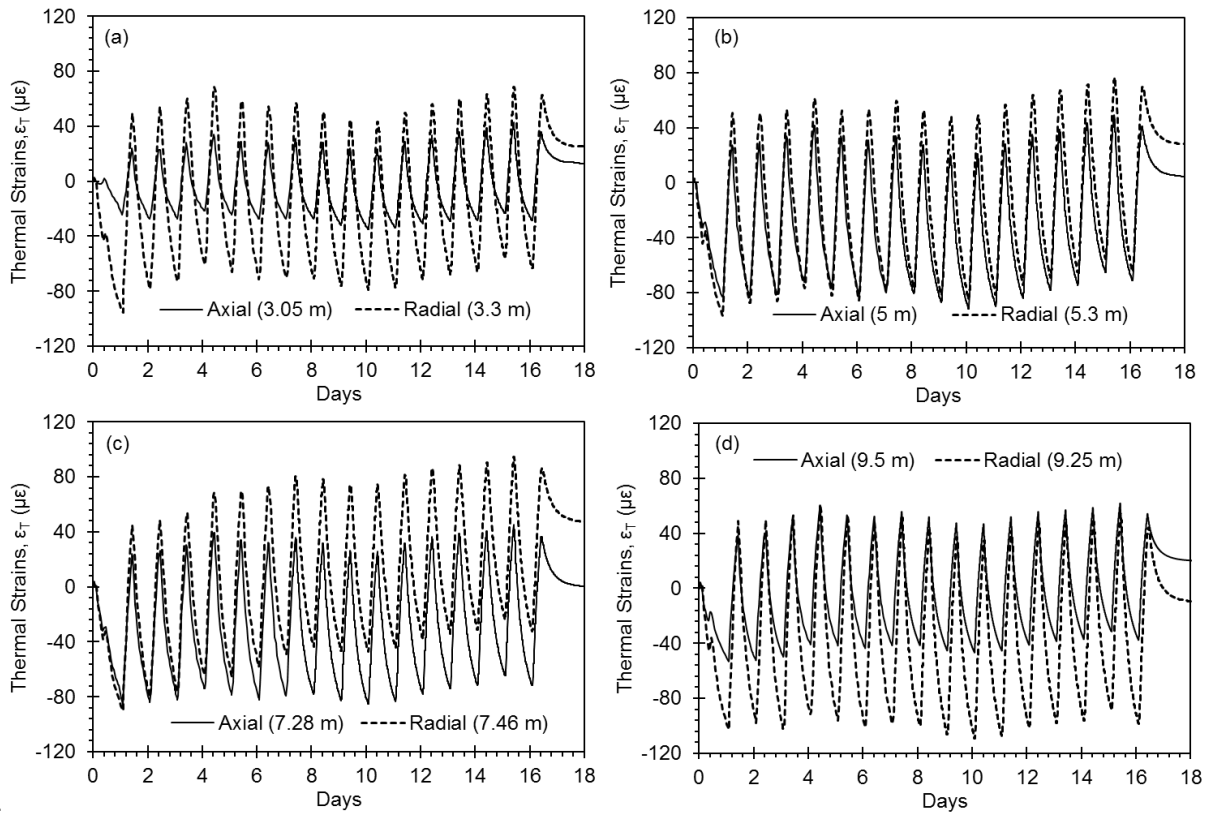
846 **Figure 3.** Fluid temperatures: a) at the inlet and outlet b) change in fluid
847 temperatures.



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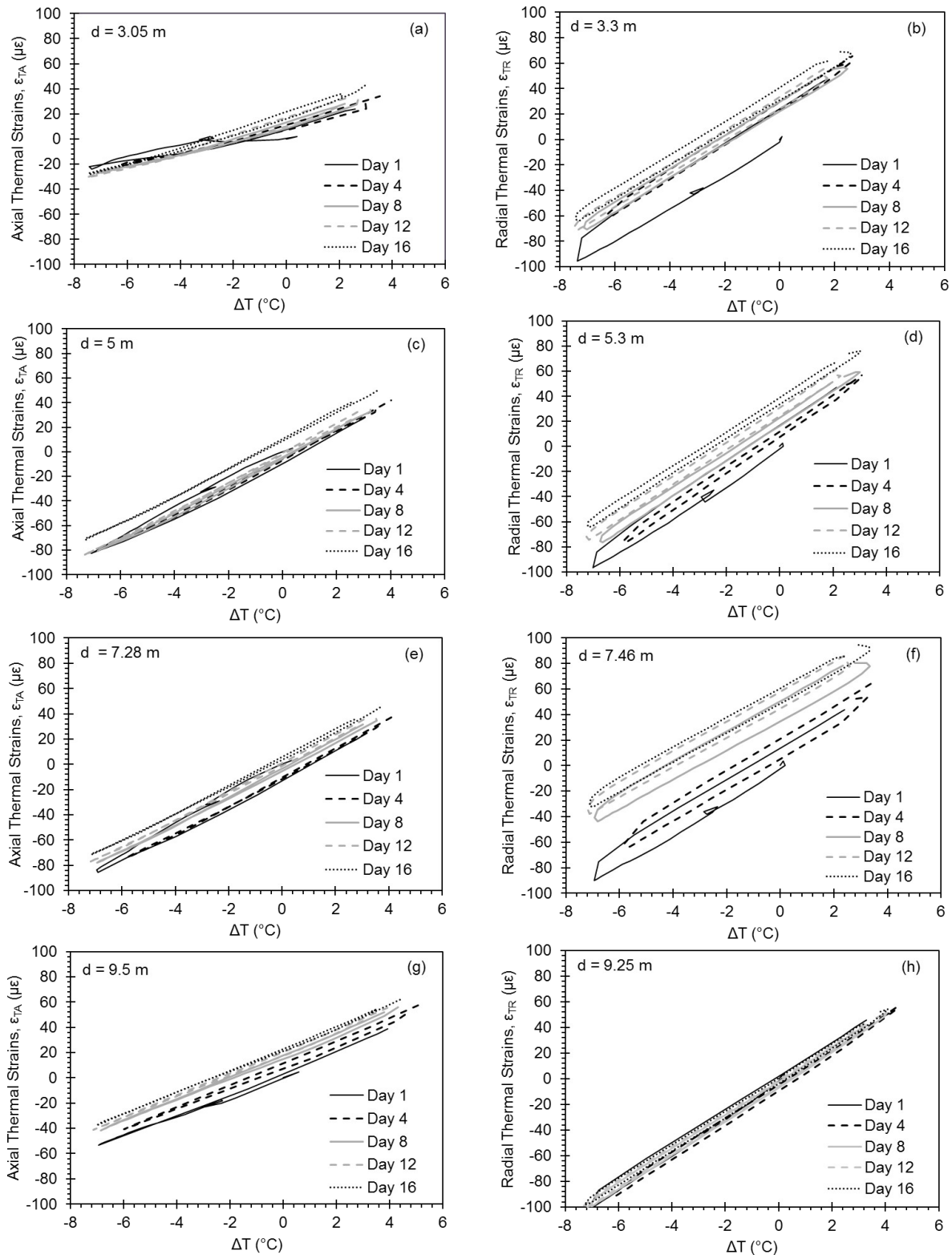
849 **Figure 4.** Time series of pile temperatures: a) pile temperatures from
850 axial VWSGs b) pile temperatures from radial VWSGs c) change in pile
851 temperatures, ΔT , from axial VWSGs d) change in pile temperatures, ΔT ,
852 from radial VWSGs.

853



854

855 **Figure 5.** Time series of axial and radial thermal strains at different
 856 depths, d : a) $d \approx 3$ m b) $d \approx 5$ m c) $d \approx 7$ m d) $d \approx 9$ m.

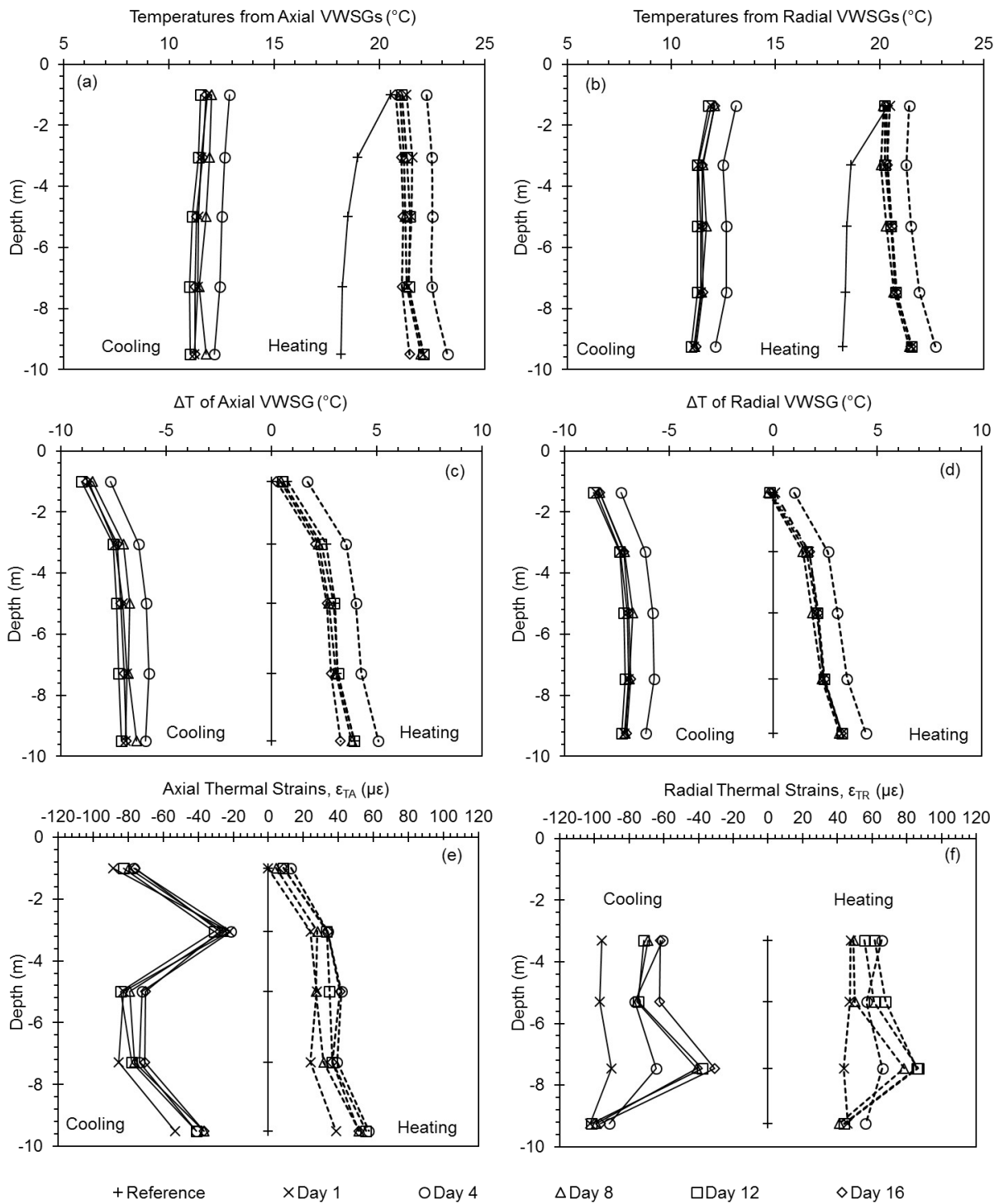


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858 **Figure 6.** Axial (ϵ_{TA}) and radial (ϵ_{TR}) thermal strains plotted against, ΔT , at

859 different depths, d : a) ϵ_{TA} at $d = 3.05$ m b) ϵ_{TR} at $d = 3.3$ m c) ϵ_{TA} at $d = 5$

860m d) ϵ_{TR} at d = 5.3 m e) ϵ_{TA} at d = 7.28 m f) ϵ_{TR} at d = 7.46 m g) ϵ_{TA} at d = 8619.5 m h) ϵ_{TR} at d = 9.25 m.

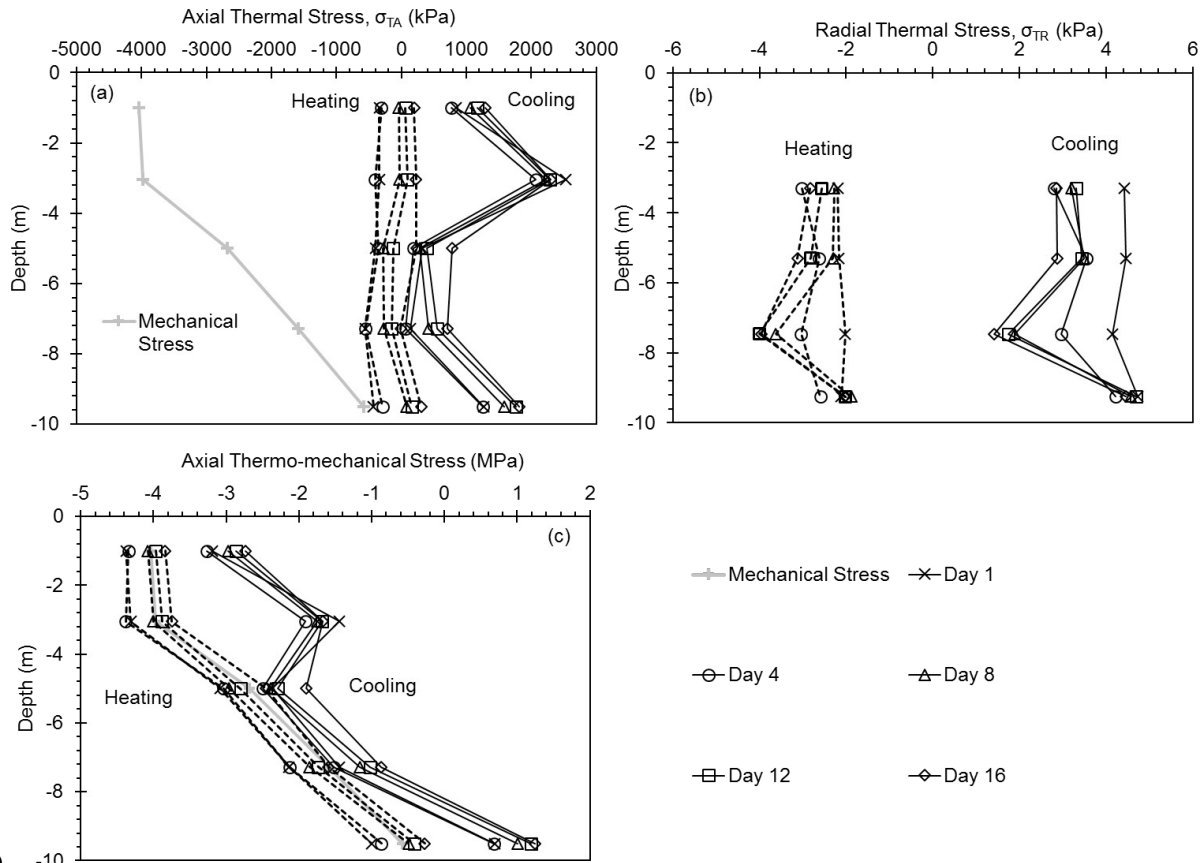


862

863 **Figure 7.** Pile temperatures and thermal strains plotted against depth
 864 (dashed line - end of heating; solid line - end of cooling): pile

865temperatures from axial VWSGs b) pile temperatures from radial VWSGs
 866c) change in pile temperatures, ΔT , from axial VWSGs d) change in pile
 867temperatures ΔT , from radial VWSGs e) axial thermal strains f) radial
 868thermal strains.

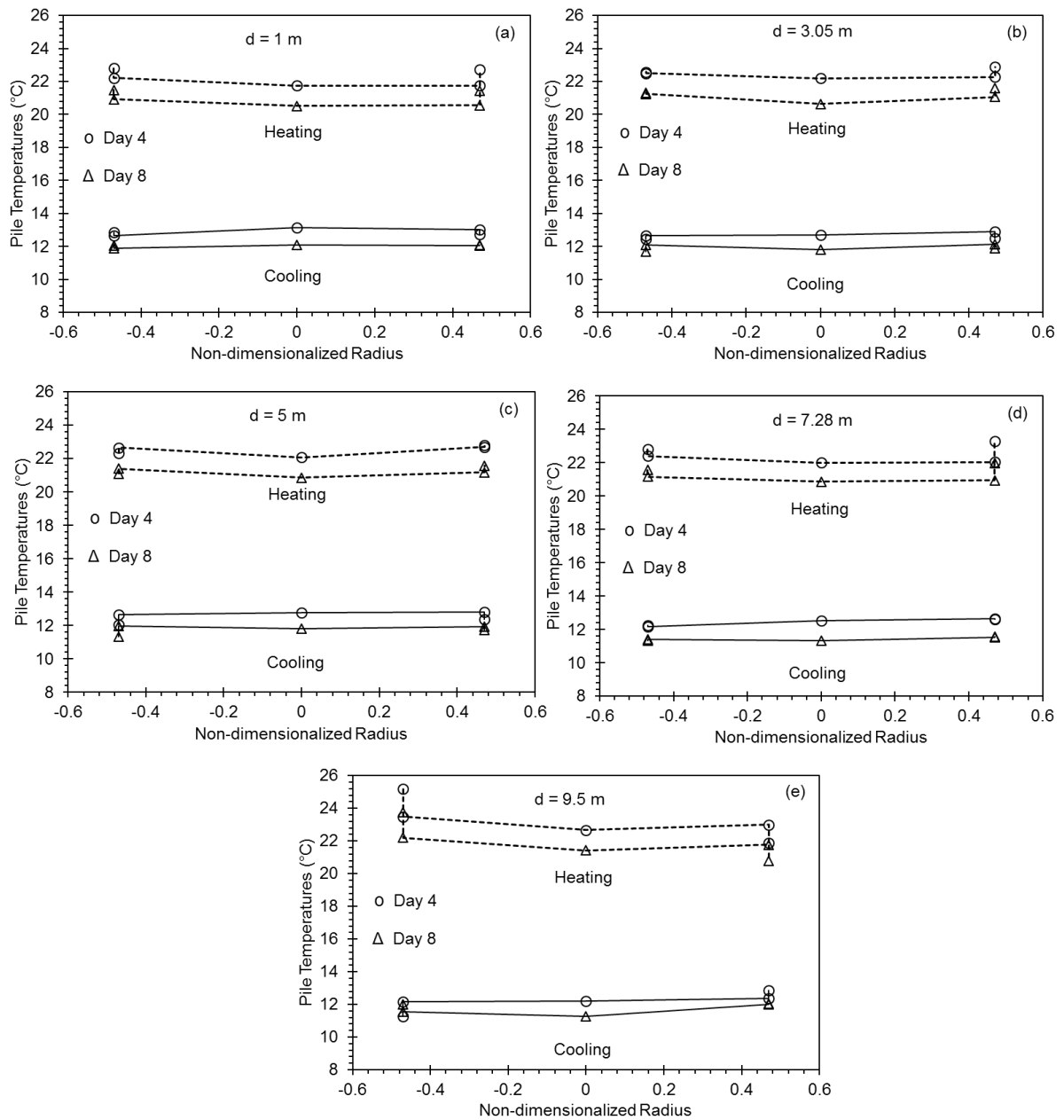
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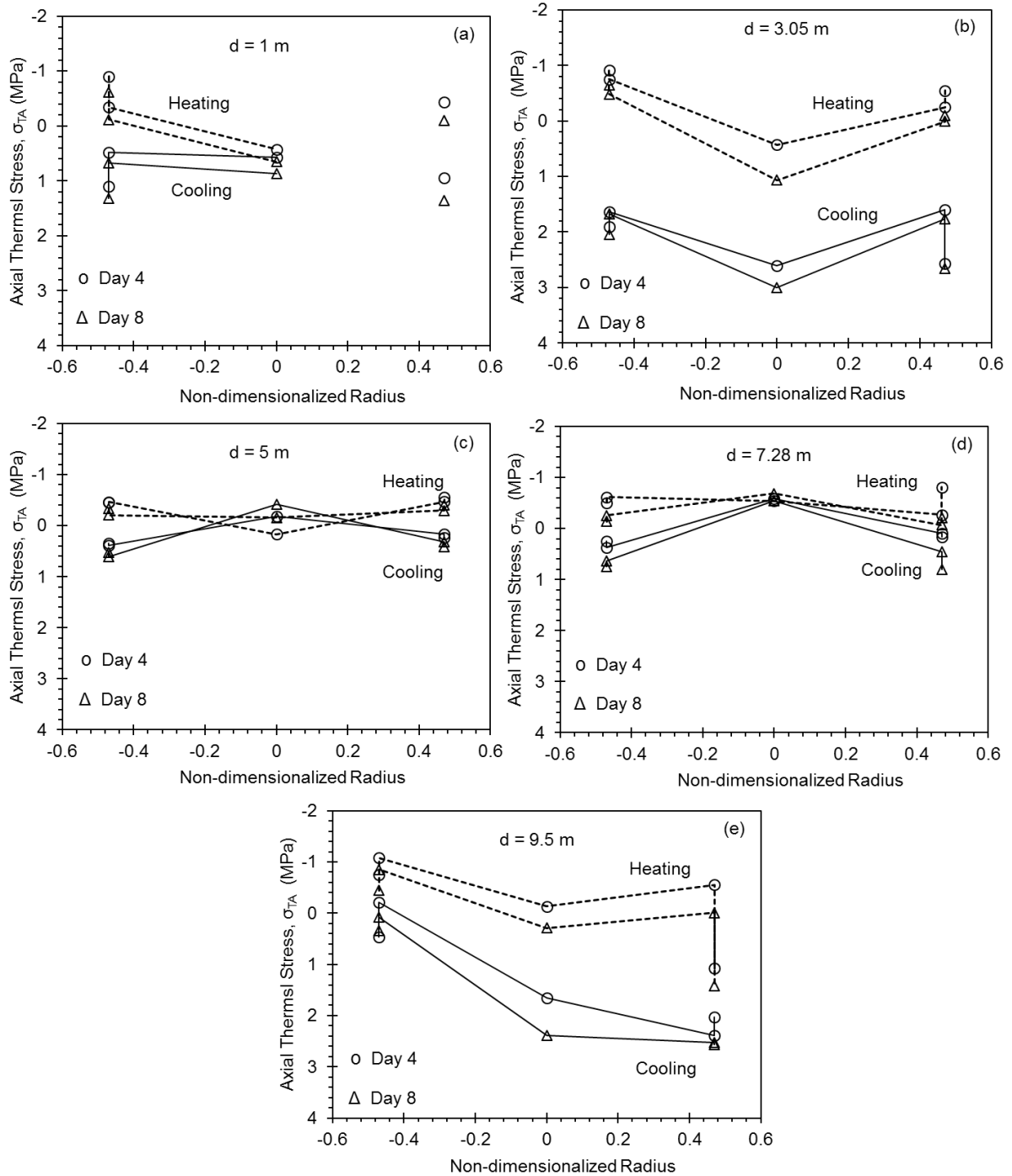
872**Figure 8.** Thermal and thermo-mechanical loads (dashed line - end of
 873heating; solid line - end of cooling): a) axial thermal stresses b) radial
 874thermal stresses c) axial thermo-mechanical stresses.



875

876 **Figure 9.** Temperature distribution over the planar cross-section of the
 877 energy pile at different depths, d (dashed line - end of heating; solid line -
 878 end of cooling): a) $d = 1$ m b) $d = 3.05$ m c) $d = 5$ m d) $d = 7.28$ m e)
 879 $d = 9.5$ m.

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881

882 **Figure 10.** Axial thermal stress distribution over the planar cross-section
 883 of the energy pile at different depths, d (dashed line - end of heating;
 884 solid line - end of cooling): a) $d = 1$ m b) $d = 3.05$ m c) $d = 5$ m d)
 885 $d = 7.28$ m e) $d = 9.5$ m.

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887