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Full-scale field observations of the thermo-mechanical behavior of different type of energy pile

Observations in situes des comportements thermomécaniques du pieu d'énergie des types différents

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ABSTRACT: As an insight into the thermo-mechanical behavior of energy piles under multiple mechanical load, this study presents full-scale load tests on three types of energy pile including driven pile, bored pile and long pile with length-diameter ratio reaching 66.7 in the framework of a manufacture plant construction project in a soft clay site in Kunshan, Yangtze river delta. Both heating-recovery cycles and cooling-recovery cycles have been carried out on the energy piles at different levels of mechanical loads. By recording the distributions of temperature, lateral resistance and displacement along the piles in both construction and operation phases, variations of these variables were analyzed and comparisons were made between the three types of energy pile and the obtained results indicated that (1) higher mechanical loads were more likely to cause elastic-plastic response in both heating and cooling cycles while the cooling-induced pile displacement tended to decrease as the mechanical load increased; (2) driven pile underwent smaller displacement than bored pile during heating but larger displacement during cooling at the same level of mechanical load and remarkable cumulative deformations resulted from heating and cooling cycles were observed; and (3) obvious augmentations of the axial force and more complicated profiles of lateral resistance were observed on the long bored pile in comparison to the pile of normal length. The reasons for the results of the field tests and their potential implications to the design of energy piles are discussed.

RÉSUMÉ : Pour mieux comprendre les comportements thermomécaniques des pieux énergétiques sous charge mécanique de plusieurs niveaux, cette étude présente des essais experimentaux in situs sur trois types de pieux énergétiques, notamment le pieu battu, le pieu foré et le pieu long avec un rapport longueur-diamètre atteignant 66,7 dans le cadre d'un projet de construction d'une usine sur un site d'argile molle à Kunshan, dans le delta du fleuve Yangtze. Des cycles de chauffage-récupération et des cycles de refroidissement-récupération ont été effectués sur les piles d'énergie à différents niveaux de charges mécaniques. En enregistrant les distributions de température, de résistance latérale et de déplacement le long des pieux dans les phases de construction et d'exploitation, les variations de ces variables ont été analysées et des comparaisons ont été faites entre les trois types de pieux énergétiques et les résultats obtenus ont indiqué que (1) des charges mécaniques plus élevées étaient plus susceptibles de provoquer une réponse élasto-plastique dans les cycles de chauffage et de refroidissement, tandis que le déplacement du pieu induit par le refroidissement avait tendance à diminuer à mesure que la charge mécanique augmentait ; (2) le pieu battu a subi un déplacement plus faible que le pieu foré pendant le chauffage, mais un déplacement plus important pendant le refroidissement au même niveau de charge mécanique et des déformations cumulatives remarquables résultant des cycles de chauffage et de refroidissement ont été observées ; (3) des augmentations évidentes de la force axiale et des profils plus compliqués de résistance latérale ont été observés sur le pieu fore d'une grande longueur par rapport au pieu de longueur normale. Les raisons des résultats des essais in situs et leurs implications potentielles pour la conception des pieux énergétiques sont discutées.

KEYWORDS: Driven energy pile; Bored energy pile; Full-scale load test; Pile settlement; Thermo-mechanical behavior.

1 INTRODUCTION.

Energy piles, which incorporate shallow geothermal energy system (SGES) into traditional pile foundation, can provide foundation supports to superstructures and renewable energy resources at the same time. With a stable ground temperature, regardless of the ambient air temperature fluctuation with seasons, energy piles can use the ground as a heat source in winter and a heat sink in summer for buildings, representing a 30 – 70% saving on fossil fuels (Brandl, 2006; McCartney and Murphy, 2012). With the same principle, geothermal energy piles are also used for bridge and roadway de-icing in Northern Europe, Japan and the U.S. to improve the driving safety (Xiao et al., 2013). In the context of environment-friendly development, energy piles are gaining popularity around the world as an effective and economic solution to battle again global warming.

Extra stress and strain can be observed within energy piles due to temperature variations and the soil-pile interactions and, as a result, pile load capacity can be impacted. In recent years, great research efforts have been dedicated to the energy piles for analyzing their thermal and thermo-mechanical behavior, which encompasses full-scale tests (Bourne-Webb et al., 2009; Brandl, 2006; Faizal et al., 2018; Faizal et al., 2019; McCartney and Murphy, 2012; Mimouni and Laloui, 2015; Murphy et al., 2015; Sutman et al., 2019; Wang et al., 2015), model pile tests (Goode Iii and McCartney, 2015; Liu et al., 2019; Ng et al., 2015; Stewart and McCartney, 2014; Yazdani et al., 2019) and numerical simulations (Chen, 2016; Gawecka et al., 2017; Knellwolf et al., 2011; Laloui et al., 2006; Loria et al., 2015; Rui and Yin, 2018). Although full-scale tests are in general costly, time-consuming and involves uncertainty, they generally reflect the reality, which can be used for calibrating the numerical models. Small-scale tests or model tests are more cost-effective and manageable for qualitative analyses but the scaling and boundary problems need to be addressed appropriately. Numerical modeling, as an important supplement of these two approaches, provides the least expensive alternative and can be used for parametric analyses for a wide range of conditions but is heavily dependent on the appropriate use of constitutive relationships and reliable input parameters. In general, the full-scale tests are considered to give more reliable results. Among the existing full-scale tests, nearly all of them are conducted on bored piles and the piles are of normal length. There is a lack of full-scale examination of the other types of energy pile, for example, driven piles and screwed piles. Most of the studies are focused on the responses of energy piles under monotonic thermal loading that represents single-season ground-source heat pump (GSHP) operation (Faizal et al., 2019) and the effects of cyclic thermal loading are less investigated. The very few studies involving cyclic temperature fluctuations (Faizal et al., 2018; Faizal et al., 2019; Sutman, 2016; Sutman et al., 2020) are carried out on bored energy piles with one fixed mechanical load and the effects of different mechanical load levels are rarely investigated. This study reports full-scale tests on the thermo-mechanical behaviors of three types of energy piles with cyclic temperature variations under multiple mechanical load levels with the objectives of: (a) evaluating the behavior of energy pile of different type (including driven, bored and long bored ones) and (b) investigating the effects of cyclic temperature changes in the energy piles under multiple mechanical loads.

2 FULL-SCALE LOAD TEST PROGRAM.

2.1 *Description of the project*

The project included constructing a three-story office building and a 2947-m^2 manufacture plant, supported by 94 bored piles and 43 driven piles, respectively. The subsurface soil exploration included cone penetration tests (CPTs), standard penetration tests (SPTs), and then retrieved soil samples were tested in the lab. A summary of in-situ and lab testing results are given in Table1 and the profile of CPT tip resistance (q_c) is shown in Figure 1. Within the boring depth of 25 m, the subsurface soil was comprised of fill, silty clay, silt with sand, silty sand, and silt. It can be seen in Table 1 that the soil strength (e.g., CPT tip resistance) generally increased with depth. The weakest soil layer was silty clay with CPT tip resistance of 0.48 MPa. The groundwater was located at depths between 0.78 and 1.19 m below the ground surface with an averaged depth of 1.0 m. The field tests were carried out on three types of energy pile including driven energy pile, bored energy pile (these two were of normal length) and long bored energy pile.

The test driven pile was installed outside the workshop footprint for pure test purpose and was not to support any structure. The driven pile was closed-ended hollow PHC pile with 15 m length, 0.4 m outside diameter and 0.21 m inside diameter, which were driven into the ground in two segments until the head was 0.6 m below the ground surface. The heat exchange tube of single U-shape made of polyethylene (PE) pipes with 25 mm outside diameter and 2.3 mm thickness was embedded into the pile center hole that was then filled with a mixture of saturated sand and in-situ soil. In contrast, the test bored piles were located within the footprint of the structure. The one of normal length was 17 m long with 0.6 m outside diameter and the long one was 40 m long with the same outside diameter. The same type of PE pipes as those in the driven pile were used for the heat exchange tubes in the bored piles with the double spiral-shape for the one of normal length and the double U-shape for the long energy pile.

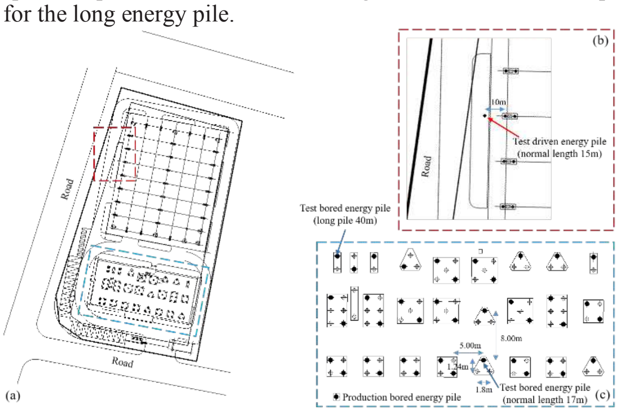


Figure 1. Locations of the energy piles (a) the construction site (b) location of the test driven energy pile (c) location of the test bored energy piles (the long pile and the normal length one)

Table 1. Soil profile.

Soil layer	Average thickness (m)	Unit weight (kN/m^3)	Moisture content (%)	Cohesion (kPa)	Friction angle (°)	CPT tip resistance (MPa)	SPT N
Fill	4.4	18.0	34.6	/	11.6	0.79	/
Silty clay 1	1.1	18.3	32.4	20.5	12.8	0.77	/
Silty clay 2	1.4	17.7	39.8	12.0	10.0	0.48	/
Silty clay 3	4.3	19.4	25.6	40.5	15.0	2.38	/
Silt with sand	5.3	18.4	29.1	7.5	25.1	5.11	14
Silty sand	5.4	18.6	27.4	5.9	27.1	7.73	26
Silt 1	2.0	18.1	30.2	8.3	22.1	4.88	21
Silt 2	› 4.9	18.4	28.9	7.1	25.2	13.65	33

2.2 *Test setup and instrumentation*

Since this study was mainly focused on the effect of interactions between thermal and mechanical loads on the performance of different energy piles (driven, bored and long bored), the test program consisted of three scenarios: mechanical load test alone, heating-recovery cycles at different mechanical loads, and cooling-recovery cycles at different mechanical loads. The pile-head settlement was monitored during these tests using four dial gauges mounted on the pile heads. The positive sign of the settlement denotes the downward movement of pile head while the negative sign indicates the upward movement (i.e., uplift).

The mechanical loads were applied to the energy piles using a hydraulic jack and measured by a load cell. The temperature sensors (i.e., thermocouples) and the strain gauges were embedded at different positions in all the test piles. As PHC piles are made through steel rebar pre-tensioning, pile spinning, and steam curing, this special fabrication process impedes the direct installation of strain gauges and thermocouples in the PHC pile since the pile spinning and the steam curing with high temperature and pressure would easily damage the sensors and connecting cables. Therefore, it is worth noting for the driven energy pile that the strain gauges and thermocouples were not installed in the concrete but attached to the PE tube that was inserted into in the hole of the PHC pile before being backfilled with in-situ soils. Structure information of the energy pile tested are listed in Table 2. Locations of the thermocouples and the strain gauges are summarized in Table 3.

Table 2. Structure details about the three types of energy pile.

	driven pile	**bored pile**	**long bored pile**
Length(m)	15	17	40
Diameter(mm)	400 (thickness 95)	650	600
L/D	37.5	26.2	66.7
Pipe type	U-shape	Spiral-shape	Double U-shape

Table 3. Locations of the thermocouples and the strain gauges for the three types of test energy pile.

	driven pile (15m)		**bored pile (17m)**		**long bored pile (40m)**	
	thermocouples	strain gauges	thermocouples	strain gauges	thermocouples	strain gauges
1	2.0	/	3.0	0.5	3.0	0.5
2	5.0	/	10.0	3.7	10.0	3.4
3	9.0	/	16.0	9.0	13.0	9.0
4	12.0	/	/	11.1	20.0	13.5
5	/	/	/	13.9	/	18.6
6	/	/	/	16.5	/	23.3
7	/	/	/	/	/	27.6
8	/	/	/	/	/	36.4
9	/	/	/	/	/	39.5

*the values are in meter and counted downwards from the pile head;
**no strain gauges in the driven energy pile because of installation difficulty (explained in the text).

2.3 *Test procedures*

2.3.1 *Pile load test*

The pile load test followed the procedure according to Chinese industry standard (2014) JGJ 106-2014. The unit side resistance and end resistance were calculated to be approximately 57 kPa and 2250 kPa for the driven pile, 48 kPa and 800 kPa for the bored pile and 80 kPa and 4600 kPa for the long pile. As the piles penetrated different soil layers, the unit side resistance was calculated based weighted average over the whole length.

2.3.2 *Heating and recovery under different levels of mechanical loading*

In the heating-recovery test, the water was used as the circulating fluid. A thermal response test (TRT) unit (model YTTRT2.0) was used to circulate the water through the PE tube while supplying a constant amount of heat (2.5 kW) to the water. The heating in this work refers to the increasing temperature of the pile with the refrigeration of the supported building.

As the tests of different type of energy pile were carried out in sequence following the progress of the construction project and the embedment depth of piles varied, the ambient temperature and the averaged subsurface temperature during the heating-recovery cycles for the test piles were slightly different. One typical full heating-recovery cycle included 24 hours of heating with the TRT unit and the shut-down and wait of another 24 hours until the outflow returned to the ambient temperature. At a given mechanical load, only one heating-recovery cycle was applied. The increase in fluid temperature caused the expansion of the pile and thus impacted pile settlement. When the pile-head settlement became steady, the next increment of mechanical load was applied.

For mechanical loadings on the test piles, five loading levels [i.e., 0%, 50%, 100%, 150% and 200% of the working load (P_w)] were applied on the driven energy pile while three loading levels [i.e., 0%, 25% and 50% P_w] on the 17 m bored pile and one loading level approximately 20% P_u (with P_u as the ultimate load capacity) on the long bored pile of 40m (as the P_u was estimated for the long bored pile as about 5400 kN according to Chinese Technical Code for Building Pile Foundations JGJ94-2008). For each loading level, only one thermal cycle was applied, which was followed by one recovery to allow the temperature to resume to equilibrium. For the precautionary measure, the temperature was gradually increased during the heating of the pile to prevent any damage to the pile and instruments from possible overheating at the first loading level and then increased straight up in the subsequent cycles since no damage occurred in the first cycle.

2.3.3 *Cooling and recovery at different levels of mechanical loading*

Cooling-recovery cycle tests for each test energy pile were carried out after waiting long enough for the recovery of the subsurface temperature following the completion of the heating-recovery tests (more than one month for each test energy pile). The cooling test in this work means a reduction of the pile temperature in extracting energy from the soil and providing heat for the supported building. For the realization of the cooling conditions, the heat exchange loop (or PE tube) was connected to a cooling box filled with ice water. It was planned that one cooling-recovery cycle was implement per each increment of mechanical load. However, during the whole cooling test for each test pile (approximately 3-5 days), the cooling box only worked in the daytime as the ice was not added in the nights. Therefore, there were additional 3 to 5 sub- cycles of cooling-recovery within each mechanical loading level.

For the tests on the driven energy pile, the cooling-recovery tests were conducted at several loading levels, the same with the heating-recovery tests. For the test bored piles, the cooling-recovery tests were performed only under one mechanical loading level (i.e. 50% P_w for the 17 m one and approximately 20% P_u for the long one of 40 m). During the cooling-recovery cycles, pile settlement and duration of each thermal cycle were measured. Details of the test programs for both the heating-recovery and cooling-recovery are shown in Table 4.

3 RESULTS AND DISCUSSIONS

3.1 *Axial force distributions with the temperature changes*

The temperatures measured in the bored energy pile of normal length (17 m) and longer length (40 m) during the heating recovery cycle under a mechanical load of 840kN are presented in Figure 2 and 3 (a) and (b). In the course of heating for the normal-length pile, the temperature at the outlet was found to increase less than that that of the inlet (with a maximum of 13.6℃) and was close to the temperature difference at a depth of 3 m. The temperature difference between the ingress and the egress was maintained near 10℃ during the whole heating process and found to be even larger during the recovery process. During the cooling-recovery process, the maximum temperature difference reached -10.9℃. For the long bored pile, the temperature difference between the ingress and egress was between 3℃ and 5℃ in heating and the maximum temperature difference (5℃) was reached when the fluid was heated to 57℃ at the inlet of the incorporated tube. On average, the temperature of the pile has increased by 12.9℃. During the cooling process, the average temperature of the pile decreased approximately 4.2℃ and the temperature difference between the ingress and egress reached 6~8℃.

Table 4. Details of the test programs for the three types of energy pile.

	Heating-recovery cycle				Cooling-recovery cycle			
	Applied mechanical load		Duration (hours)		Applied mechanical load		Duration (hours)	
	%P_w*	**kN**	**Heating**	**Recovery**	**%P_w***	**kN**	**Cooling**	**Recovery**
driven pile (15m)	0	0	26	22	0	0	96**	
	50	315	17	10	50	315	60	40
	100	630	24	25	100	630	72	48
	150	945	16	30	150	945	96	24
	200	1260	22	24	200	1260	100	20
	%P_w	**kN**	**Heating**	**Recovery**	**%P_w**	**kN**	**Cooling**	**Recovery**
bored pile (17m)	0	0	22	28	/	/	/	/
	25	420	35	30	/	/	/	/
	50	840	45	30	50	840	25	28
long pile	**%P_u*****	**kN**	**Heating**	**Recovery**	**%P_u**	**kN**	**Cooling**	**Recovery**
(40m)	20	840	144	>200	20	840	96	>200

*P_w is working load; **only the total hours used for cooling and recovery were recorded; *** P_u is the ultimate load capacity

The distributions of axial force under a mechanical load of 840 kN are presented in Figure 2(c) and (d) and Figure 3(c) and (d) for both piles. The depth is normalized by the pile length for the convenience of comparisons between the two piles. In heating, augmentations of the axial force were generally observed in the middle part of the piles. For the normal bored pile of 17 m, although the maximum axial force occurred at the top of the pile in most of the time, the augmentation amplitude due to the temperature variation reached the same order of magnitude with the axial force generated by pure mechanical loads. In cooling, with the contraction of the pile, axial force along the pile was found to decrease and even down to negative values in the part deeper than the middle point of the pile with relatively large temperature variations (for $\Delta T = -7℃$ and $-10.9℃$). This transition from compression state to tension state is of concern in engineering practice. With the extraordinary length, the long bored pile of 40 m experienced larger axial forces in the middle part than the pile top when it was heated up to higher than 20℃ with ΔT larger than 3.6℃. Without significant temperature decrease in the long bored pile, there was a reduction of the axial force along the pile but the compression state was generally maintained in most part of the long bored pile. Small negative values were found very close to the pile tip with the temperature decrease overpassing -1.6℃.

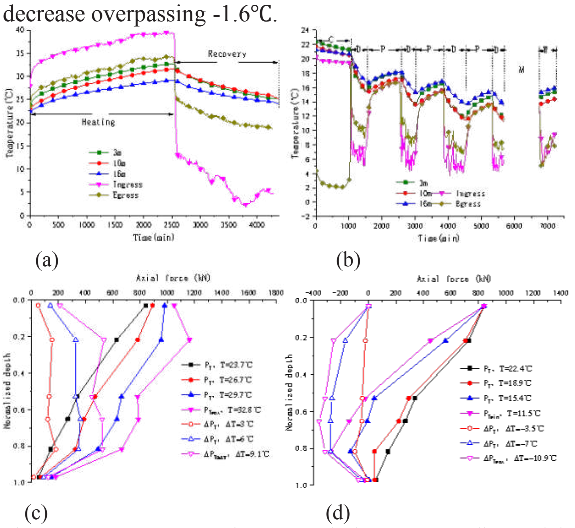


Figure 2. Temperature changes and the corresponding axial force distributions of the bored pile of normal length with (a) the temperature variations during heating-recovery with 50% P_u; (b) the temperature variations during cooling-recovery with 50% P_u; (c) the axial force distributions during heating-recovery with 50% P_u; (d) the axial force distributions during cooling-recovery with 50% P_u.

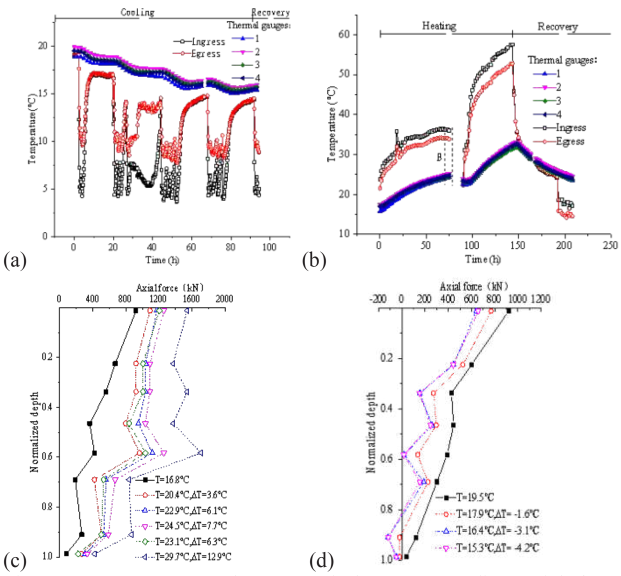
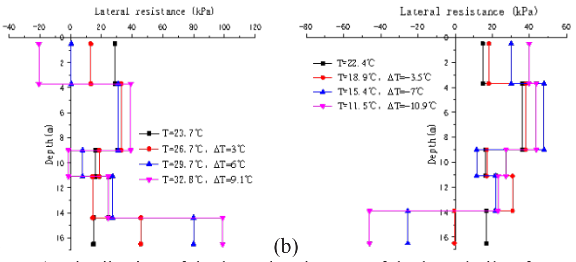


Figure 3. Temperature changes and the corresponding axial force distributions of the long bored pile with (a) the temperature variations during heating-recovery with 20% P_u; (b) the temperature variations during cooling-recovery with 20% P_u; (c) the axial force distributions during heating-recovery with 20% P_u; (d) the axial force distributions during cooling-recovery with 20% P_u.

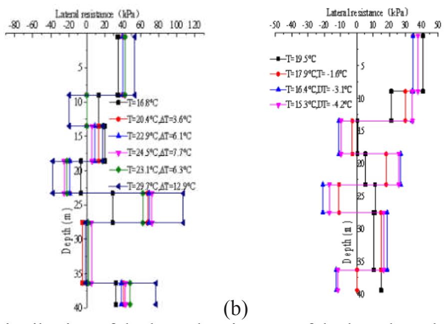
3.2 *Distributions of the lateral resistance*

The lateral resistance profiles were obtained at 50% P_W for the bored pile of normal length and at 20% P_u for the long bored pile in the heating-recovery process which are presented in Figure 4 and 5 (a) and in the cooling-recovery process shown in Figure 4 and 5 (b). Expansion of the bored energy pile due to the increasing temperature also compressed the lateral soil leading to an increase of the lateral resistance. Negative lateral resistances were observed for the normal length bored pile for all the mechanical levels when the pile expanded due to the heating. While the absolute values of the lateral resistance increased with higher level of mechanical loads, negative resistance parts of the pile were found to lessen when the mechanical loads increased. For the cooling-recovery process, the lateral resistance along the pile length was also found to increase with larger temperature variation in comparison with that under pure mechanical load (50% P_u). Important negative resistance values were measured in the vicinity of the pile tip with a decrease of the pile temperature about 7 ℃ and greater, which was consistent with the insignificant axial force shown in Figure 2 leading to a nearly complete floating characteristic of the pile when subjected to strong cooling conditions.

More complex profiles of the lateral resistance were found for the long bored pile in the heating and cooling processes with the resistance fluctuating between positive and negative values along the total length of the pile. Although the lateral resistances are both positive at the top of the long bored pile in heating and cooling conditions originated from the same mechanical load applied there, the variations along the pile were observed to be opposite to each other. Similar to the bored energy pile of normal length, a negative value was also measured for the long bored pile at the pile tip where the axial force also trivial.



(a) (b)
Figure 4. Distribution of the lateral resistance of the bored pile of normal length with (a) under 50% P_w during heating and (b) under 50% P_w during cooling.



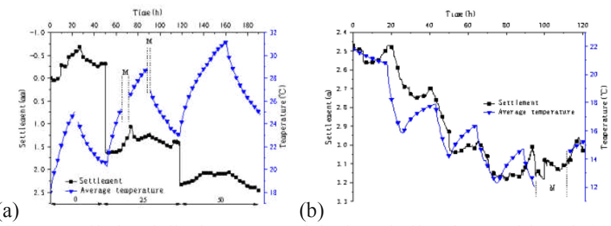
(a) (b)
Figure 5. Distribution of the lateral resistance of the long bored pile under 20% P_u during (a) heating and (b) cooling.

3.3 *Displacements of the pile head*

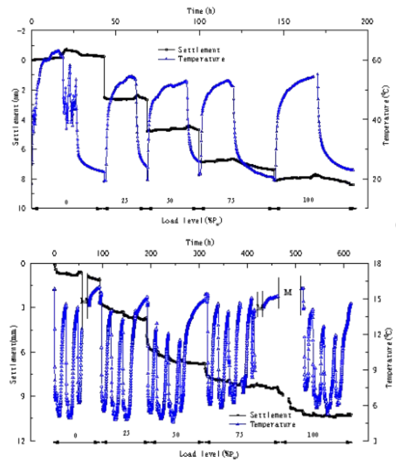
The displacements of top of the bored energy pile of normal length under different level of mechanical load during the heating-recovery processes are presented in Figure 6(a). The increasing temperature led in general to slight rises of the pile top, which largely vanished in the recovery periods for all the mechanical load levels. Different from the heating-recovery processes, non-recoverable downward displacements were measured for the bored energy pile in cooling which reached 22.6% of the original displacement induced by the mechanical load (at 50% P_u) (shown in Figure 6(b)). This indicates that the accumulation of the additional displacements with the cooling effects is worthy of attention since the bored energy pile may be subjected to cooling-recoveries recurrently during its whole operation period. The displacements of the top of the driven energy pile are shown in Figure 7 with the heating-recovery cycles and the cooling-recovery cycles under multiple mechanical load levels. Similar to those of the bored pile of normal length, uplifting behavior of the pile top was observed for every mechanical load level during the heating process with nearly total restoration during the recovery process for relatively low mechanical load levels (<50% P_u) and a less than 10% additional settlement for relatively high mechanical load levels (>50% P_u). For the cooling-recovery processes, obvious residual settlements were also measured after each cooling-recovery cycle for the driven energy pile. Although the additional displacements induced by the cooling effects were found to be nearly 80% those of pure mechanical loads <50% P_u, a reduction of them was observed with the increasing mechanical loads higher than 50% P_u. A rough comparison between the bored energy pile and the driven energy pile of almost the length and diameter in Table 5 within 50% P_u mechanical load level shows that the bored pile was more sensitive to the heating processes whereas the driven one was more sensitive to the cooling processes. For the long bored pile shown in Figure 8, as the mechanical load of 840 kN was estimated as far less than its total load capacity, very small displacements of the pile top were measured (with 3.57 mm before the heating process and 1.0 mm before the cooling process). However, the important additional settlements were observed with temperature variations. The maximum displacement variation was measured up to 41.5% for the heating process while the cooling process induced a maximum variation value even reaching 104% that of the displacement of pure mechanical loads, which is worthy of concern in engineering practice.

Table 5. Comparisons between the driven pile and the bored pile of normal length.

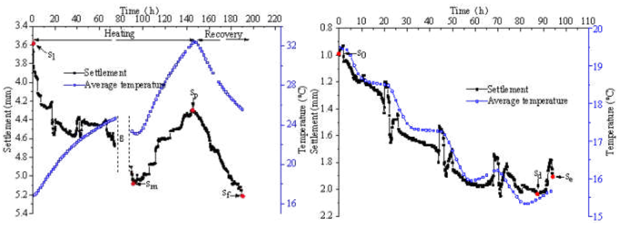
Load level % P_u		Driven pile		Bored pile of normal length	
		ΔT(℃)	Settlement variation (%)	ΔT(℃)	Settlement variation (%)
Heating	25%	34	5.5%	11	8.75%
	50%	32	2%	14	6%
Cooling	50%	-14.4	85%	-10	22.67%



(a) (b)
Figure 6. Pile head displacements of the bored pile of normal length (a) under 0%, 25% and 50% P_w during heating and (b) under 50% P_w during cooling presented with the temperature changes.



(a)
(b)
Figure 7. Pile head displacements of the driven energy pile under multiple mechanical load levels during cyclic heating and cooling tests presented with the temperature changes with (a) for the cyclic heating-recovery and (b) for the cyclic cooling-recovery.



(a) (b)

Figure 8. Pile head displacements of the long bored pile under 20% P_u during (a) heating and (b) cooling presented with the temperature changes.

4 CONCLUSIONS

Full-scale field tests on three different types of energy piles with both heating-recovery and cooling-recovery cycles under different mechanical load levels are reported in this paper. Performance of the three types of energy piles including a driven pile, a bored pile of normal length and a long bored pile in soft clay was evaluated in the framework of a construction project of a manufacture plant in Kunshan, Yangze River delta. Temperature variations and the changes of the axial force and lateral resistance were mainly analyzed for the two bored piles of different length whereas the settlement variations were studies for all these three types of energy piles. For both the bored pile of normal length and the long bored pile, the switch from the compression state to tension state of the middle-lower part of the piles is worthy of engineering concern when the piles experience relatively large temperature changes. The negative lateral resistances were observed to be in consistency with the tension state of the piles. With a comparison between the driven energy pile and the bored one, different sensitivity was found for them to heating cooling. With an extraordinary pile length, the energy pile shows more complex behavior in terms of both the axial force and the lateral resistance although under very limited mechanical load.

For the displacements of the energy piles under mechanical loads of multiple levels combined with thermal effects, additional settlements can be observed. With relatively small mechanical load levels, the upheaving of the pile top during heating may recover during the recovery of the temperature and the heating effects on the pile settlements can to some extent be neglected. In contrast, obvious additional settlements were induced by the cooling. With larger mechanical loads, additional settlements were found to be more important for both heating-recoveries and cooling recoveries. Although the heating and cooling were observed to have limited effects on the settlements of energy piles in the field tests of this work, influence of the accumulations of the additional settlements upon the performance of the energy pile during the long-term use is still unclear and requires further investigations. In general, for the determination of the bearing capacity of energy pile under combined thermo-mechanical loads with Q-S method, the additional settlements due to the operation of the ground-source heat pump system incorporated with the energy pile should be included in consideration.

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