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Static load tests on energy piles: Effects of thermal cycles

Essais de chargement statiques sur des pieux énergétiques: Effets des cycles thermiques

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ABSTRACT: Although energy geostructures, and among them thermoactive piles, have been in use for almost 50 years, design offices and decision makers are still reluctant to routinely integrate this technique in the final design solutions, as some unresolved technical issues appear to remain, as well as comprehensive guidelines based on in situ tests and projects feedback. Indeed, one of the remaining issues is the potential effect of temperature and more importantly of the accumulation of heating-cooling cycles on the soil-pile interface and therefore on the long-term behaviour of a pile, as well as on its bearing capacity. With the ever increasing cost of fossil energy, and the need to propose green solutions limiting global warming and its consequences, it is of the upmost importance to address these issues. To do so, five thermoactive continuous flight auger piles were thus constructed on two different sites (one mostly sandy and the other mostly made of clay and marls). They were mechanically loaded at different levels ranging from the quasi-permanent Serviceability Limit State (SLS) to the characteristic SLS, and submitted to multiple thermal cycles. They were then loaded to the failure, to assess the impact of these cycles on the bearing capacity. The embedded instrumentation (fiber optic, strain gauges, etc.) allowed estimating the distribution of the load along the shafts, and the possible effect of the repeated thermal loadings on the shaft and base resistances. This paper shows that the bearing capacity of piles executed in fine soils does not seem to be affected by temperature cycles, while that of piles executed in sandy soils shows a noticeable increase.

RÉSUMÉ: Bien que les géostructures énergétiques, et notamment les pieux géothermiques, soient utilisés depuis près de 50 ans, les bureaux d'études et les décideurs hésitent encore à intégrer systématiquement cette technique dans les solutions de conception finales, car certaines questions techniques non résolues semblent subsister ; de même, les recommandations basées sur des essais in situ et le retour d'expérience des projets sont encore assez peu nombreux. Notamment, l'une des questions en suspens est l'impact potentiel de la température et, plus important encore, de l'accumulation des cycles de chauffage et de refroidissement sur l'interface sol-pieu et, par conséquent, sur le comportement à long terme d'un pieu, ainsi que sur sa capacité portante. Avec l'augmentation constante du coût des énergies fossiles et la nécessité de proposer des solutions vertes pour limiter le réchauffement climatique et ses conséquences, il est de la plus haute importance d'aborder ces questions. Pour ce faire, cinq pieux réalisés à la tarière creuse et géothermiques ont été réalisés sur deux sites différents (l'un principalement sableux et l'autre principalement constitué d'argile et de marnes). Ils ont été chargés mécaniquement à différents niveaux allant de l'état limite de service quasi-permanent à l'état limite de service caractéristique, et soumis à de multiples cycles thermiques. Ils ont ensuite été chargés jusqu'à la rupture, afin d'évaluer l'impact de ces cycles sur la capacité portante. L'instrumentation embarquée (fibre optique, jauges de contrainte, etc.) a permis d'estimer la distribution de la charge le long des futs, et l'impact possible des chargements thermiques répétés sur les résistances par frottement et de pointe. Cette communication montre que la portance des pieux réalisés dans des sols fins ne semblent pas impactés par les cycles de température, au contraire de celle de pieux réalisé dans des sols sableux, qui a montré une augmentation notable.

Keywords: Deep foundations; energy geostructures; static load tests.

1 INTRODUCTION

The thermo-active pile technique involves integrating heat exchanger elements into deep foundations. This offers the advantage of reducing the drilling cost when compared to vertical geothermal probes. In addition, this technology is considered eco-friendly since it minimizes the consumption of fossil energy sources and the energy bill.

The technique has been used successfully for over 50 years in various countries with more and more reported cases in the past several years (Abdelaziz et al., 2016, Bourne-Webb et al., 2009, Di Donna et al., 2017, to name a few). However, with the exception of a few guidline documents (Rotta-Loria et al. 2020) there is no established design method yet for justifying the geotechnical resistance of the thermo-active piles. Therefore, contractors have been constructing buildings with these piles based on empirical knowledge or conservative designs (Boënnec, 2009 and Knellwolf et al., 2011).

A few tests have been carried out to investigate the thermomechanical behaviour of the soil and of the soil-pile interface, but experimental data remains scarcely available and not generally applicable.

In France, due to insufficient information available regarding the effect of temperature and heating-cooling cycles on the mechanical characteristics of the soil, this technology is still viewed with some skepticism.

Nevertheless, this technology must now be considered as a viable option, with the new regulations and the ever increasing price of energy. Therefore, five continuous flight auger (CFA) piles, fully instrumented, were built and then subjected to combined mechanical and thermal loadings. This communication presents the tests carried out and the obtained initial results.

2 TEST SITES AND TEST PILES SPECIFICATIONS

2.1 Location and geological/geotechnical context

The loading tests were carried out on two sites: the first one Coudekerque-Branche (CDK), and the second one in Champs-sur-Marne (CSM), in France. Geotechnical investigations were carried out at the test sites, using core sampling and pressuremeter tests.. The pressuremeter tests carried out at the two sites are shown in Figure 1.

At Coudekerque-Branche, the piles were anchored in the quaternary sands of the Middle Flandrian, which are fine, homometric and shelly (carbonated). These sands were encountered at 3m deep, with the overtopping layer being silts.

At Champs sur Marne, fills were encountered throughout the first 0.7m, then came silty clay until 2m deep, then Green clay from Romainville (Early Oligocene, late Eocene), and then the Marls of Pantin, from the late Eocene, in which the bases of the piles were embedded.

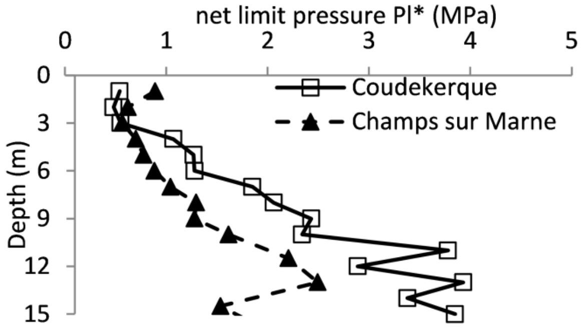

Figure 1. Evolution of net limit pressure as a function of depth at the two sites.

2.2 Test Piles

The five piles tested on the two sites are continuous flight auger piles corresponding, according to standard NF P 94-262 (AFNOR, 2012), to category 6 piles (CFA). This technique was chosen as it is the most common type of piles used in Northern France. It offers a number of advantages: high production rates and expected axial strengths, and the means required for their execution are limited compared with other techniques.

Table 1 details the characteristics of the piles at both the Coudekerque and Champs-sur-Marne sites.

Table 1. Geometric characteristics, types and strengths of piles tested in accordance with French design method.

	Coudekerque	Champs-sur-Marne
	P1/P2/P3	P1/P2
Length (m)	12	12
Diameter (m)	0.52	0.42
Type	CFA	CFA
Instrumented	yes	yes
Test	compression	
R_c (kN)	3297	1856
R_s (kN)	2088	1357
R_b (kN)	1209	499

All the piles were instrumented with various sensors, ranging from LCPC removable extensometers to fiber optics and strain gauges, from which efforts at different depths were derived. As demonstrated by (Szymkiewicz et al., 2021), the instrumentation technology used does not impact the results.

The piles were all tested in compression, and loading tests were carried out until the piles reached geotechnical failure.

3 THERMAL LOADING

Piles CDK P2 and P3 and piles CSM P1 and P2 were subjected to a thermal loading for several months.

More specifically, CDK P2 underwent both thermal and mechanical loading for a duration of five months. During this period, the mechanical load applied at the top of the pile was equivalent to 30% of the bearing capacity determined during the static load test carried out on CDK P1. As for CDK P3, it was loaded only thermally, for a period of five months. No mechanical load was applied on its head during this period.

The thermal cycles applied during these five months were the same for both piles CDK P2 and P3. The duration of normal heating-cooling cycles was around 14 days, with 7 days allotted to heating and an additional 7 days to cooling. However, during the tests, the duration of these cycles had to be adjusted as necessary. The heat pump was programmed to provide fluid at a temperature of 30 C during the heating phase of the cycle and 2 C during the cooling phase.

At Champ-sur-Marne, the pile CSM P1 was first mechanically loaded to 30% of its estimated bearing capacity. Three series of heating-cooling cycles (called H and C on Figure 2, respectively) were then applied over the duration of seven weeks. For each cycle, the temperature of the refrigerated and heated circulating fluid was increased to 30 C and kept constant for one week and then decreased to 0°C and kept constant for another week. The thermal loading test was stopped during the fourth cycle due to a thermal loading system malfunction. After three weeks of thermal recovery, during which the ground cooled back to its initial temperature, the pile was unloaded. Figure 2 shows the evolution of its head settlement as temperature varies during the thermal cycles.

The pile CSM P2 was in turn mechanically loaded to 50% of its estimated bearing capacity. Five series of heating-cooling cycles were then applied over the duration of ten weeks. For each cycle, the temperature of the refrigerated and heated circulating fluid was increased to 30°C and kept constant for one week and then decreased to 5°C and kept constant for another week.

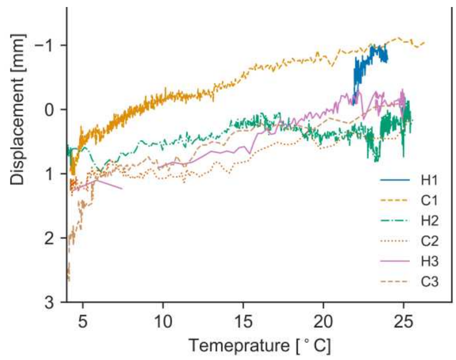

Figure 2. Displacement –Temperature relationship for CSM P1.

4 RESISTANCE OF THE PILES

After the thermal cycles were finished, CDK P2 and P3 and CSM P1 and P2 were loaded to the failure. CDK P1 was loaded without having been previously subjected to any thermal loading.

The loading tests were carried out in compliance with the requirements of the test standards in force at the time and the base resistances (R_b) and shaft resistances (R_s) were derived from the strain measurements along the shaft of the piles, using the estimated deformation modulus of the pile. It is to note that strain recordings encountered some problems for CSM P2, and therefore base and shaft resistances for this pile are not presented.

Table 2 summarizes the results achieved during these tests. From these results, it is clear that multiple thermal cycles performed on CSM P1 and P2 did not affect the resistance, as it is very close to the expected theoretical value (Figure3). However, the distribution of the load at failure between the base and the shaft is not as expected. It is something somewhat usual, as the French design method is calibrated on global resistance and not on local values, which can vary greatly for a number of reasons (heterogeneity of the soil, slight variation of stiffness of the shaft, etc.).

For CDK P2 and P3, it can be seen that they exhibit a higher resistance than the one achieved on CDK P1. Furthermore, these values are quite similar to the theoretical one, while the resistance of CDK P1 is much lower. This was explained by the nature of the sand encountered and by the installation methods (Szymkiewicz et al., 2024), for which the French standard seems over-optimistic.

For the tests at Coudekerque, it is clear that the base resistance is not impacted by the thermal cycles, but that the shaft resistance is strongly impacted, on the other end. However, this impact is on the positive side, as the shaft resistance increases by 40%, thus increasing naturally the bearing capacity by 30%, in this configuration.

Table 2. Measured (m) limit (R_c), shaft (R_s) and base (R_b) resistances, and ratios to calculated (cal) values.

Pile	$R_{s;\,m}$ (kN)	$R_{s;\,m}$ / $R_{s;\,cal}$	$R_{b;\,m}$ (kN)	$R_{b;\,m}$ / $R_{b;\,cal}$	$R_{c\,m}$ (kN)	$R_{c;\,m}$ / $R_{c;\,cal}$
CDK P1	1751	0.84	699	0.58	2450	0.74
CDK P2	2450	1.17	726	0.60	3176	0.96
CDK P3	2450	1.17	752	0.62	3202	0.96
CSM P1	1100	0.81	700	1.40	1800	0.97
CSM P2					1800	0.97

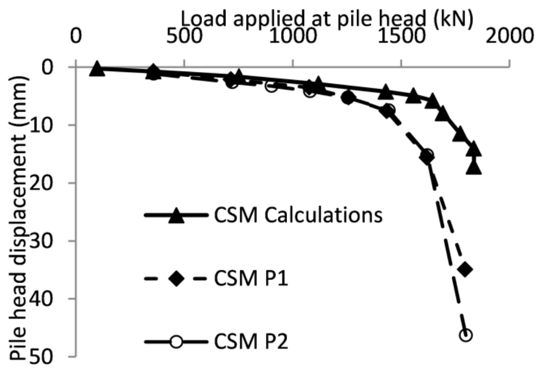

Figure 3. Calculated and experimental load-displacement curves for piles CSM1 and CSM 2.

5 CONCLUSIONS

Five CFA geothermal piles, two installed in fine-grained soils and two in sands, were loaded to the failure, after having been subjected to several thermal cycles.

The results show that the bearing capacity of the piles installed in fine-grained soils was not affected by the thermal loading, while that of the piles installed in sands was clearly affected by the thermal cycles. In particular, it was exclusively the shaft resistance that was impacted. However, this impact appeared to be positive, as the bearing capacity increased by 30% after the thermal cycles.

More tests should be carried out in the near future to validate these results: in particular, other tests should be carried out in another type of sand.

Furthermore, a test on a pile without any thermal history should be carried out on the Champs-sur-Marne site, so as to assess the experimental bearing capacity. This will be done, among other tests, during the research project "COOP", funded by a grant from the French National Research Agency (ANR-22-CE22-0007) and involving Université de Lille, Université Gustave Eiffel, Ecole des Ponts ParisTech and Pinto.

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