FLOATING THERMAL PILES IN SOFT SENSITIVE CLAYS

Anders Bergström Chalmers/NCC teknik, Saqib Javed, Chalmers, Jelke Dijkstra Chalmers

Sammanfattning

Energipålar är pålar som utöver att utgöra konstruktionselement för grundläggningen även utnyttjas för att värmeväxla energi till jordvolymen där de installerats. I denna artikel presenteras kortfattat ett fältförsök med energipålar som utförs i lös sensitiv lera i Göteborg. Syftet med fältförsöket är att följa och få representativa mätdata om hur en energipåle och omgivande lera påverkas då pålen värms och kyls, t.ex. krypning vid cyklisk belastning. Lerans geotekniska egenskaper har bestämts med traditionella undersökningar och provtagningar, kompletterade med ny blockprovtagning. Mätutrustning för registrering av portrycks, temperatur och sättningar har installerats i jorden på olika nivåer och olika avstånd från provpålarna. För att förse pålen med reglerbar önskad effekt vid värmning och kylning har en unik mobil värme-/kylmaskin konstruerats. Första värmecykeln påbörjades i December 2016.

Summary

Thermal piles are building foundation piles which, in addition to transferring the load of the building to the ground, are also used as heat exchangers to provide thermal exchange with the ground. This article shortly presents field testing of thermal piles installed in soft sensitive clay in Gothenburg. The aim of the field tests is to study the thermo-mechanical response of the heating and cooling cycles on the pile/clay system, and to gather representative data for further analysis. The soil properties have been determined from traditional sampling, complemented with a new block sampling method. Instrumentation for measuring pore pressures, temperatures and settlements has been installed at different levels in the soil and at different distances from the test piles. A state-of-the-art thermal response test rig has been developed to perform response testing in both heating and cooling modes. The first heating cycle started in December 2016.

1 Introduction

Energy security and climate change are among the greatest challenges confronting modern society today. The economic and environmental issues related to these challenges are placing greater emphasis on the use of technologies and resources that are energy-efficient and renewable. Thermal piles is one of the technologies that meets this goal, using only low-grade geothermal energy as its source to provide space heating and cooling in buildings. Thermal piles use the potential of the ground for extracting or storage of energy.

Thermal piles as a concept was developed already in the early 1970's (Brandl 2006). By installing collector pipes inside a pile, a heat carrier fluid could be circulated and the pile could also be used as a heat exchanger, in addition to being a construction element in the ground. Currently, this technology is used in many countries internationally including Belgium, China, Japan, Switzerland, the Netherlands, United Kingdom, and United States, among others.

An extensive amount of literature is available on thermal piles. Most recently, Bourne-Webb et al. (2016) have presented a comprehensive review of analysis and design methods for thermal piles. Numerous researchers including Campanella and Mitchell (1968); Leroueil and Marques (1996); Cecerevac and Laloui (2004), among others, have studied the thermal soil behavior, though not necessarily for clays structured such as those in Gothenburg. Cooling of clay below 0 °C has also been investigated. It has been shown that thawing causes a total collapse of the soil structure (Gabrielsson et al., 1990). Field tests on fully instrumented piles have been carried out, for example, by Bourne-Webb et al. (2009); Sutman (2015); Singh (2015); Laloui (2006); McCartney (2012). Based on the field tests on the stiff London clay, a principle model has been developed to analyse the pile response to various combinations of thermal and mechanical loading (Bourne-Webb et al., 2012, 2009; Amatya et al., 2012). On the other hand, there is still a lack of knowledge and understanding regarding the behaviour of soft clays. Consolidation and creep processes complicate the pile/soil behaviour in soft clays. In addition to soft clays, the floating pile foundations have also not been studied in detail.

In the late 1970's, a research group called Jordvärmegruppen (Earth heat pump group) was formed at Chalmers to meet the clearly expressed ambition of limiting the use of energy and the national dependency on oil. The group, financed by the Government (Byggforskningsrådet), was very productive, and resulted in several publications on ground heat exchangers and ground thermal response. The group also yielded a number of publications on large scale installation of collectors in the ground as well as laboratory testing of soil behaviour (e.g. Adolfsson and Sällfors, 1987, 1990, Tidfors 1987). Tidfors (1987) showed that heating of a clay sample performed in the laboratory decreased the apparent pre-consolidation stress of the clay.

Later, Sweden Geotechnical Institute continued this line of research, and performed laboratory and field tests at raised temperatures (e.g. Gabrielsson et al. 1997; Moritz, 1995; Sundberg, 1991). The tests looked primarily at heating soft clays to high temperatures, up to 70 °C. These temperatures are, however, not relevant for thermal piles. Also, the long-term response of the clay was not explicitly studied.

Today, at Chalmers the research on thermal piles focuses on heating and cooling cycles in soft sensitive clays, at a temperature interval of 4-30 °C. The research work comprises of laboratory and field tests, and numerical modelling. This article will focus on the setup of the field tests. The aim of the field tests is to study the thermal and mechanical response of the pile/clay system under cyclic heating and cooling, and to gather representative data for further analysis.

2 FIELD TEST

Figure 1. Gothenburg map. Utby test site (long array) and Chalmers Johanneberg Campus test pile (short array).

The test field with four thermal piles is located in Utby in the east part of Gothenburg, see Figure 1. A thermal test pile for initial tests has also been installed at Chalmers University.

2.1 Utby test site

The natural stratigraphy at the test site in Utby is mostly homogenous soft clay. The top layer has developed into a crust, approximately 1 m in thickness. At bottom of the stratigraphy, there is a 1-3 m thick till deposit. The density of the clay at 5-10 m depth is 1.55-1.6 ton/m^3. Natural water content w_N at the same depth is close to 70-80 %, and the liquid limit w_L is about 55-60 %. Ground water level in the area is 0.5 m below ground level with hydrostatic pore pressure distribution, but with a slight artesian pressure in the bottom till layer.

The properties of the soft clay at Utby have been determined from laboratory tests on collected soil samples, using two different sampling methods (Karlsson et al., 2016). The standard STII 50 mm diameter piston sampler has been compared to the mini-block sampler developed at the Norwegian University of Science and Technology, NTNU. The NTNU mini-block sampler brings samples in the diameter of 165 mm and height of approximately 300 mm. CPT-tests and shear vane tests have been performed to complement the dataset with in-situ tests.

2.2 Chalmers test site and setup

A test pile was installed at Chalmers (Johanneberg Campus) in December 2015. The installation was primarily aimed to investigate various aspects of thermal response testing performed on driven thermal piles. The installed pile was an 18-m-deep floating steel SSAB/Ruukki pile with 115 mm diameter and 6.3 mm wall thickness.

Soil properties at the Chalmers test pile site are characterised as 1 m of gravel on top of 5 m peat and 12 m of soft silty clay. At bottom of the stratigraphy there is a thin layer of till. Ground water level is 0.1-0.2 m below the ground surface. The density of the clay at 10 m depth is 1.5 tons/m^3. Natural water content w_N is about 80 %.

2.3 Utby test site and setup

At the Utby test site, four floating test piles were installed. Two piles were made of steel and the other two were made of concrete. The steel piles were SSAB/Ruukki 115 mm x 6.3 mm with a total length of 28.8 m. The precast concrete piles were 270 mm x 270 mm, with a hollow pipe in centre for the installation of collector pipes. The length of the concrete piles was 28.0 m each. Between the test piles, additional piles were driven to bedrock to serve as vertical reference level, and for bearing of the loading rig used for static loading of the test piles.

Inside the piles a U-tube heat exchanger, made of high density polyethylene (HDPE) pipe, with 25 mm outer diameter was installed for exchanging heat with the ground see Figure 2. The remaining volume inside the pile was filled with water contained in a thin plastic capsule.

Figure 2. Pile head of the steel thermal pile at Utby with U-tube heat exchanger, fibre optics for distributed temperature sensing, and cables, before final insulation. The pipe with a red cap is the head of a bellow hose used for settlement measurment. Below the bucket to the left is a station of 4 pore pressure and temperature sensors (BAT). A pressure cell for measuring data on static load is placed between the pile head and the steel beam on top.

For static loading of the floating test piles a steel dead weight loading rig was placed on top of the piles. Concrete elements provided the weight required to load the pile up to serviceability load levels. A load cell is used to measure data on the applied load.

Further instrumentation, including distributed temperature sensing, and pore pressure and temperature sensors, was incorporated to capture pile and soil response due to thermal and mechanical loading.

Pore pressure sensors (BAT) were used for logging of temperature and pore pressures in the soil. They are installed at different depths and distances from the thermal pile (Figure 3). The sensors comprise of plastic pipes to avoid thermal distortion, which could have been caused by using ordinary and more thermally conductive steel pipes.

A number of optical fibres were installed in and outside the pile to measure the vertical temperature distribution. The fibre optics were also complemented with PT100 sensors at different positions in the pile section.

Figure 3. Utby test site. Position of sensors (BAT) in the ground for logging of temperature and pore pressure in the soil.

Furthermore, custom full-bridge strain gauges were glued at 4 levels in the pile section to have a better indication on the stress distribution in the pile.

Finally, six bellow hoses were installed, from the ground surface down to the bottom till layer, to monitor the distributed settlements along the pile depth. The bellow hoses have a metal ring at 1-m intervals for taking measurements. The loading rig is instrumented with levelling points and also inclinometers on the cross-members for automatic logging of any pile head displacement in time.

All sensors are connected to a data acquisition system controlled by a bespoke Labview programme running on a laptop that is connected to the internet using a GPRS modem. The BAT-probes, for pore pressure and temperature measurements, are logged with the proprietary hardware solution, though the data is synchronised with other sensors. Logging of the BAT-probes started in December 2015. Installation of the test piles was performed during spring 2016 and the thermal tests started in winter 2016.

2.4 Test plan

The heating and cooling is provided by a specially designed mobile thermal response testing rig. The heating/cooling cycles were started in December 2016, with a 3-week long heating cycle followed by a corresponding cooling cycle. The heating effect was approximately 50 W/m. As the hydro-mechanical soil response has a different time-course than the thermal response, the relatively long first cycle is used to investigate the development of excess pore pressures and temperature changes in the clay around the pile. After completion of the first relatively-long heating and cooling cycle, several short heating and cooling cycles of 4-5 days have been performed.

3 PRELIMINARY RESULTS

3.1 Utby test site, soil sampling

The soil sampling from the Utby test site has been quite extensive. As shown by Karlsson et al. (2016), the sampling method and effects of sample disturbance are of great importance when evaluating the soil properties. Comparison of 1D compression data from the block samples to ST50 piston samples, has indicated consistently larger values of OCR (>20 %), constrained modulus M (>50 %) as well as more pronounced peak strength, and faster decay of creep rate. Also, differences in unloading-reloading stiffness have been observed. Relevant values of these parameters are also of great importance for analysing effects of heating and cooling cycles of an operational thermal pile. Additional thermal properties (e.g. heat conductivity and specific heat) as well as the soil response to temperature change are further tested in a parallel project at Chalmers.

3.2 Chalmers, test pile

The Chalmers test site has been mainly used for thermal response testing of thermal piles. Thermal response tests are generally performed on borehole heat exchangers to estimate ground thermal conductivity and thermal resistance of the ground heat exchanger, but are also recommended for thermal piles (GSHPA, 2012). In a thermal response test, a constant amount of power is injected to or extracted from the ground by means of the heat carrier fluid. The thermal properties are estimated by analyzing the steady-state heat transfer between the heat carrier fluid and the ground. At the Chalmers test site, the thermal response testing was carried out for several days. It has been noticed that the thermal response of a pile in the soil is much slower than a borehole in the bedrock. Furthermore, it has also been observed that the hydro-mechanical response (i.e. ongoing creep) of the soil does not necessarily has the same time scale as the heating response.

3.2.1 Utby, test piles

Preparing for a field test with full-scale piles and instrumentation has been a challenge of endurance. Finding a test site, designing the mechanical setup, developing the thermal testing rig, installing and calibrating the instrumentation, and finally making everything work together in the field needed a lot of time. For the Utby test site, the preparation period was nearly 2 years. Nevertheless, the full-scale field testing finally started in December 2016.

Most instrumentation survived the harsh installation process in the field. The installation of BAT-sensor in plastic pipes needed a special arrangement in order to press the sensors to the required depths. Inside the steel piles, the strain gages survived the installation, but later stopped working probably because of short circuiting due to cable damage and water ingress.

Despite the loss of some sensors, the main response caused by the cyclic heating and cooling of the test thermal pile is still adequately captured. The response can be seen as a temperature change in the clay surrounding the pile during heating, and also as the resulting excess pore pressure caused by the heating cycles. An example of the thermal response is plotted in Figure 4.

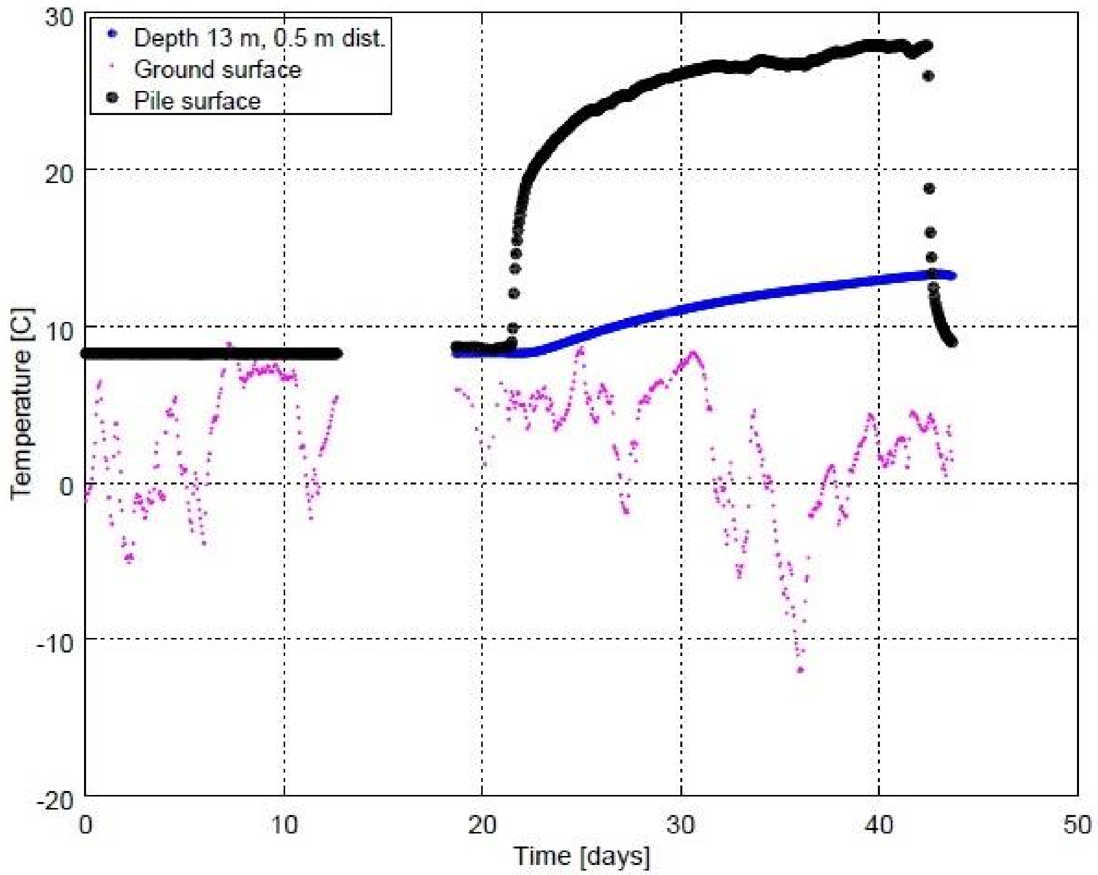

Figure 4. Utby test site. Temperature measurements taken at the ground level, and on the pile surface (at 13-m depth) and at 0.5-m radial distance from the pile (at 13-m depth). Heating starts at day 22.

4 CONCLUSIONS

In order to determine most relevant soil properties, different soil sampling methods were used. Compared to piston samples, consistently large values of OCR and constrained modulus M were found for the block samples. The block samples also showed more pronounced creep rates. These results are of great importance in the future evaluation of thermal effects from heating and cooling cycles on the soil properties.

At the test site, instrumentation and sensors have been installed to measure temperatures, pore pressures, mechanical loads and settlements. A mobile rig for thermal response testing has been developed and is being used for testing of thermal piles under controlled heating and cooling cycles. Temperature developments in the clay surrounding the thermal pile have been studied together with excess pore pressure.

ACKNOWLEDGEMENTS

The authors would like to thank NCC Recycling Sweden for providing an excellent location for the installation of thermal piles. We also acknowledge Hercules and SSAB/Ruukki for providing and installing the test piles. Research funding from FORMAS, Chalmers, SBUF, Energimyndigheten (Swedish Energy Agency) and NCC Sweden AB is also gratefully acknowledged.

REFERENCES

Adolfsson K., Sällfors. G., 1987. *Energilagring i lera: värmeströmning, värmeväxlarutformning och påverkan av lerans geotekniska egenskaper.* Statens råd för byggnadsforskning.

Adolfsson K., Sällfors. G., 1990. *Energilagring i lera med sanddränering.* Statens råd för byggnadsforskning.

Amatya B. L., Soga. K., Bourne-Webb P.J., Amis T., Laloui L., 2012. *Thermo-Mechanical behaviour of energy piles.* Geotechnique, ss. 503-519.

Bourne-Webb P.J., Burlon S., Javed S., Kürten S., Loveridge F., 2016. *Analysis and design methods for energy geostructures.* Renewable and Sustainable Energy reviews, ss. 402-419.

Bourne-Webb P.J., Amatya K., Soga K., Amis T., Davidson C., Payne P., 2009. *Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles.* Geotechnique, ss. 237-248.

Bourne-Webb, P. J., Amatya B., and K. Soga (2012). *A framework for understanding energy pile behaviour*. Proceedings of the ICE-geotechnical Engineering 166.2, pp. 170–177.

Brandl H. 2006. *Energy foundations and other thermo-active ground structures.* Geotechnique.

Campanella R.G., Mitchell J.K. 1968. *Influence of temperature variation on the soil behaviour.* Journal of Soil Mechanics & Foundation Div.

Cekerevac C., Laloui L., 2004. *Experimental study of thermal effects on the mechanical behavior of a clay.* International Journal for numerical and analytical methods in geomechanics 28.3, pp 209-228.

Gabrielsson A., Lehtmets M., Moritz L., Bergdahl U., 1997. *Heat storage in soft clay Field tests with heating (70 °C) and freezing of the soil.* SGI Report 53.

Ground Source Heat Pump (GSHP) Association, 2012. *Thermal Pile, Design, Installation & Material standards, 2012.*

Karlsson M., Emdal A., Dijkstra J., 2016. *Consequences of sample disturbance when predicting long-term settlements in soft clay.* Canadian Geotechnical Journal.

Laloui L., Nuth M., Vulliet L., 2006. *Experimental and numerical investigations of the behaviour of heat exchanger pile.* International Journal for Numerical and Analytical Methods in Geomechanics, 763-781.

Leroueil S., Marques M. E. S., 1996. *Importance of strain rate and temperature effects in geotechnical engineering*. SOA Report.

McCartney J. S., Murphy K.D., 2012. *Strain Distributions in Full-Scale Energy Foundations.* DFY Journal, 26-38.

Moritz L., 1995. *Geotechnical Properties of Clay at Elevated Temperatures*. SGI Technical report No 47.

Singh R. M., Boazza A., Wang B., Haberfield C.H., Baycan S., Carden Y., 2015. *Thermal and Thermo-Mechanical Response of a Geothermal Energy Pile.* Proceedings World Geothermal Congress 2015. Melbourne, Australia.

Sundberg J., 1991. *Termiska egenskaper i jord och berg*. SGI Information 12.

Sutman M., Olgun C. G., Brettman T., 2015. *Full-Scale Field Testing of Energy Piles.* IFCEE 2015, (ss. 1638-1643).

Tidfors M., 1987. *Temperaturens påverkan på leras deformationsegenskaper – en laboratoriestudie*. CTH Licentiate thesis.