

Field investigation of a geothermal energy pile: Initial Observations

Essai sur site d'un pieu géothermique : observations initiales

Wang B., Bouazza A., Singh R.M., Barry-Macaulay D.

Monash University, Melbourne, Australia

Haberfield C., Chapman G.

Golder Associates Pty Ltd, Melbourne, Australia

Baycan S.

Vibropile Pty Ltd, Melbourne, Australia

ABSTRACT: Shallow geothermal energy techniques integrated in structural pile foundation have the capability of being an efficient and cost effective solution to cater for the energy demand for heating and cooling of a building. However, limited information is available on the effects of temperature on the geothermal energy pile load capacity. This paper discusses a field pile test aimed at assessing the impact of coupled thermo-mechanical loads on the capacity of a geothermal energy pile. The full-scale in situ geothermal energy pile equipped with ground loops for heating/cooling and multi-level Osterberg cells for static load testing was installed at Monash University in a sandy profile. Strain gauges, thermistors and displacement transducer were also installed to study the behaviour of the energy pile during the thermal and mechanical loading periods. Thermal behaviour of the surrounding soils was also examined during the heating and cooling cycles of the energy pile. It has been found the pile shaft capacity increased when the pile was heated and returned to the initial capacity (i.e initial conditions) when the pile was cooled. Thus indicating that no loss in pile shaft capacity was observed after heating and cooling cycles.

RÉSUMÉ : Les pieux géothermiques ont la capacité d'offrir une solution efficace et rentable capable de réduire la demande d'énergie nécessaire pour le chauffage et le refroidissement des bâtiments. Cependant, peu d'informations sont disponibles sur les effets de la température sur la capacité de charge de ce type de pieux. Cet article présente les résultats d'essais in-situ de chargement visant à évaluer l'impact du couplage des charges thermomécaniques sur la capacité d'un pieu géothermique. Un pieu géothermique, équipé de tubes en polyéthylène pour la circulation du liquide nécessaire pour le chauffage/refroidissement du pieu ainsi que des cellules Osterberg multi-niveaux, a été installé dans du sable sur une profondeur de 16 m. En outre, ce pieu a été équipé de jauges de contrainte, thermistances et de capteurs de déplacement pour étudier son comportement pendant les périodes de chargement thermiques et mécaniques. Le comportement thermique des sols environnants a également été examiné lors des cycles de chauffage et de refroidissement du pieu. Ces essais ont montré que le frottement latéral du pieu augmente après qu'il ait été chauffé et retourne à la capacité initiale (c.-à-conditions initiales) après qu'il ait été refroidi. Ceci indique qu'aucune perte de la capacité n'a été observée après des cycles de chauffage et de refroidissement.

KEYWORDS: Energy piles, shaft resistance, Osterberg cells, thermal properties, in-situ pile load test, sustainable development

1 INTRODUCTION

Energy foundations widely known as energy piles can be defined as dual-purpose structural elements. They utilise the required ground-concrete contact element and the shallow solar energy flux, found within 100 m of the ground surface, to transfer the building loads to the ground as well as acting as heat exchanger units. Energy piles may be driven, bored or augered. Reinforced concrete piles have been found to be advantageous due to the material's high thermal storage capacity and enhanced heat transfer capabilities (Brandl, 1998).

Geothermal energy piles bring another dimension to pile design. The principle of energy piles is that energy is extracted from or sunk into the ground by a fluid, circulating via a Ground-Source Heat Pump (GSHP) similar to vertical borehole GSHP systems. The difference is where the energy pile foundation serves as an integral support to the superstructure in addition to heating and cooling the built structure (Bouazza et al., 2011). The advantages of energy piles are the cost saving over installing additional vertical boreholes and additional land areas generally required outside the perimeter of the built structure to accommodate other shallow vertical and horizontal GSHP systems.

Physical testing of pile foundations have been well documented on assessing the pile shaft and base capacity installed in various ground conditions with or without the influence of groundwater. However, the relatively new concept

of energy pile foundations has introduced new parameters to be considered into pile design, to accurately predict the pile behaviour and reliability in modern structures.

2 BACKGROUND

Austria, Switzerland and Germany can be regarded as the pioneering countries that have investigated this technology for decades. Extensive use of energy geostructures have been featured in Austria. Brandl (2006) reported that more than 25,000 energy foundations (piles, etc.) were in use in Austria with installations dating as early as the 1980's.

Over the past five years, the installation of thermo active pile foundations has grown exponentially in the UK (Amis et al. 2008). There were approximately ten times more thermo-active foundations installed in 2008 than in 2005. The reason for this rise in production is mainly driven by the code for sustainable buildings that requires the construction of zero-carbon buildings by 2019 (Bourne-Webb et al. 2009). The implementation of the thermo active pile technology in the USA is very limited by comparison to Europe. Traditionally, reliance was on the use of ground source heat pumps (GSHPs) to reduce building energy consumption for heating and cooling (McCartney et al., 2010). Recently, the USA is experiencing a renewed interest in the use of energy piles as they have been identified as being a more cost effective solution compared to the use of other GSHPs systems

(McCartney et al., 2010). Countries such as China, Ireland and Japan are also experiencing an increased interest in the use of thermo-active piles (Hamada et al., 2007, Gao et al., 2008, Hemmingway and Long, 2011, Jalaluddin et al., 2011).

3 ENERGY PILE FIELD TEST

3.1 Background

The study conducted at Monash University is part of an international research effort aimed at obtaining a much better understanding of the thermo-mechanical effect on piles with the view of reducing the conservative approach taken so far in the design of energy piles. The study involves evaluation of the thermo-mechanical behaviour of soils, the thermal capacity of the pile, the built structure heat balance, soil thermal properties and influence of heat transfer on pile load capacity and shaft resistance. This paper reports on the pile field test undertaken at the Clayton campus of Monash University, Victoria, Australia.

3.2 Site temperature profile

To efficiently operate a heat exchanger pile system, the ground temperature needs to be warmer than the air temperature in winter and cooler than the air temperature during summer. This requires a ground with relatively constant temperature and knowledge of the magnitude of ground temperature changes for this system to operate efficiently. In-situ temperature profiling was conducted at the pile field test site. The site consists of 3 m thick clayey fill overlying Brighton Group materials from 3 m onward. The Brighton group consists mostly of fine to coarse very dense clayey sands and sands. Monitoring of ground temperature variation (Figure 1) indicates that the temperature of the surface zone (approximately 2 m below ground surface) and, to a lesser extent, that of the shallow zone (2 to 6 m) are influenced by short term ambient temperature changes. These variations begin to diminish upon reaching a depth greater than that of the shallow zone. Beyond 8 m (deep zone) temperatures are relatively constant (17-18 °C) and are unaffected by seasonal temperatures changes making them suitable for heat exchanger pile systems.

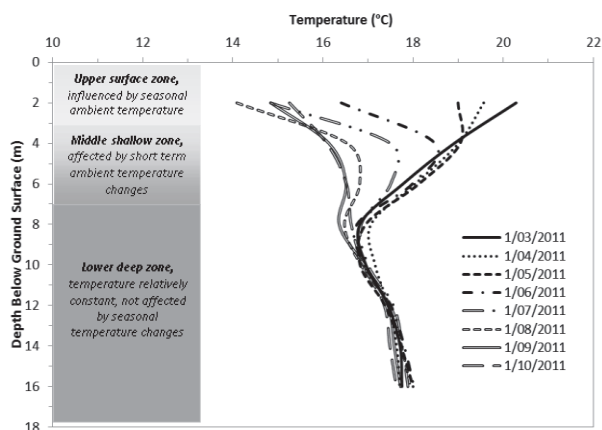


Figure 1. Typical ground temperature variation with depth, recorded at Clayton, Australia.

3.3 Energy pile setup

The Monash field heat exchanger or energy pile was installed in December 2010. It is a 600 mm diameter bored pile drilled to a depth of 16.1 m in Brighton Group materials. Groundwater was not observed during the installation process. Two levels of Osterberg cells (O-cells) were installed at 10 m and 14.5 m depth. By using two O-Cell levels, an accurate independent measurement can be taken for the material within the

intermediate sections of the pile by observing the reaction of the relevant strain and displacement gauges with or without thermal loading. The use of O-cell also eliminates health and safety and other constraints associated with conventional static testing systems such as kentledge or anchor piles. The testing and monitoring equipment installed within the pile consisted of the following:

- Three loops of HDPE pipe (25 mm OD) attached to the pile cage, to 14.2 m, to circulate the heating transfer fluid.
- 10 vibrating wire strain gauges installed between the two O-cells levels and 6 vibrating wire strain gauges installed above the upper O-cell level.
- 12 vibrating wire displacement transducers installed within the pile to measure O-cell and pile movements.
- All vibrating wire instrumentations were fitted with a thermistor, and temperature of the concrete monitored at various levels.

Two boreholes were installed at a distance of 0.5 m and 2.0 m to the energy test pile, thermocouples were installed at 2 m intervals in each borehole to profile the temperature changes with depth and measure ground temperature during thermal loading.

4 FIELD PILE TEST RESULTS

4.1 Thermal properties

The ground thermal properties are paramount for an accurate design of a geothermal energy installation especially when it comes to sizing and costing the system. In this respect, in-situ ground thermal conductivity, pile thermal resistance and undisturbed ground temperature are key parameters for a successful design. The most important parameter required to optimise the design of energy piles or boreholes ground heat exchangers is the thermal conductivity of the ground (heat exchanger system and the surrounding soils). For the preliminary design of complex energy foundations or the detailed design of standard geothermal systems, sufficient accuracy of ground thermal properties can be obtained from field thermal response or laboratory testing. The thermal conductivity of the ground, which is directly relevant to the temperature-depth relationship, is sensitive to the local on-site geology and affected by its mineralogical composition, density, pore fluid and degree of saturation (Abuel-Naga et al., 2008, 2009). As a result, there is no constant depth at which all geothermal energy systems should be installed. Rather, factors such as local geology, climate and even surface cover must be considered in order to help determine a depth at which the ground temperature is relatively unaffected by seasonal temperature changes and to specify the required length of heat exchangers needed for the pile foundation.

Some of the thermal property parameters can be determined in laboratory tests but inclusion of site specific conditions such as groundwater flow and in-situ stresses are difficult to implement. Currently there is no testing standard available to conduct in-situ thermal conductivity of energy piles and assess their thermal resistance. However, the American Society of Heating, Refrigeration and Air Conditioning (ASHRAE) published a set of recommended procedures for undertaking thermal conductivity tests for geothermal applications (ASHRAE 1118-TRP). This procedure is popular with the borehole ground loop systems. However, the diameter of a borehole compared to a pile is a lot smaller and the number of piping loops is also lower.

Three Thermal Response Tests (TRTs) were carried out during the heating periods of the field testing program. The TRTs were carried out utilising a TRT unit consisting of a computerised logging system, control box, water pump, heating elements and a water reservoir. There is one outlet and one inlet on the TRT Unit. One TRT was carried out by circulating

the heat transfer fluid through one loop of absorber pipes closest to the boreholes equipped with thermocouples. Two TRTs were carried out by transporting the fluid through all three loops of absorber pipes in a continuous series within the energy pile. Inflow and outflow temperature of the heat transfer fluid, ground temperature at every 2 m to 16 m depth within the two boreholes located at 0.5 m and 2.0 m from the edge of the test pile as well as the pile concrete temperature were recorded continuously during the heating periods. The test pile and the ground were cooled naturally by letting the induced heat dissipate into the surrounding environment following each TRT. The subsequent TRT did not start until the temperature readings within the pile and the boreholes were returned, as close as possible, to their initial undisturbed temperatures. The duration of each TRT are summarised in Table 1.

Table 1. Duration of Thermal Response Tests

TRT Name	Test Duration (Heating)	Rest After Test (Cooling)
1 loop (3 days)	3 days	5 days
3 loop ST (9 days)	9 days	47 days
3 loop LT (52 days)	52 days	78 days

Field research of in-situ measurement of the soil thermal conductivity was undertaken across Europe and USA on borehole ground heat exchangers for a number of years. Published literature (Gehlin, 2002; Austin, 1998) showed that during a TRT, based on the line source method, a defined energy was applied to the heat exchanger whilst the power input and the inflow and out flow temperature of the heat transfer medium was recorded. This measures the entire length of the ground heat exchanger, providing an effective thermal conductivity value whilst considering the borehole backfilling (or pile properties), variable ground and groundwater conditions. The effective thermal conductivity measured from a field TRT can be calculated by Equation 1:

$$\lambda_{eff} = \frac{Q}{4\pi k L_b} \quad (1)$$

Where:

- Q = constant heat power (W)
- L_b = length of heat exchanger (m)
- k = logarithmic relationship (slope of curve) between test duration (in log time), and the mean temperature of the heat transfer fluid

In-situ field estimation of the ground system's effective thermal conductivity consists of incorporating the energy pile ground heat exchanger and the surrounding soils as a whole system. This study presents an estimate of the effective thermal conductivity utilising the three TRTs. k is found by plotting the regression line derived from the time temperature series of a TRT, during the steady increase period of the fluid temperature. The average heat transfer fluid temperatures, with an applied Q of 2.4 kW, were plotted against time for each of the tests and the regression lines are shown in Figure 2.

The effective thermal conductivity calculated from Equation 1 was based on the heat exchanger and its immediate vicinity attaining steady-state conditions (Eskilson, 1987). This requires a minimum time criterion, as shown in Equation 2, to be satisfied.

$$t \geq \frac{5r_b^2}{a} \quad (2)$$

Where:

- t = "minimum-time" criterion for test duration (s)
- r_b = borehole or pile radius (m)
- a = thermal diffusivity ($J/m^3 K$)

The test data prior to this initial period, $t = 100$ hours for 3 loop TRTs, needs to be ignored to reduce errors as during this initial heating stage, the thermal front gradually reaches further beyond the heat exchanger wall. The average heating fluid temperature rises rapidly during this initial period, then as the thermal front travels further into the surrounding ground, the increase in average fluid temperature becomes steady. However, for the 1 loop TRT, the test was terminated after 3 days. Therefore, the first 48 hours of test data was ignored for comparison between the three TRTs.

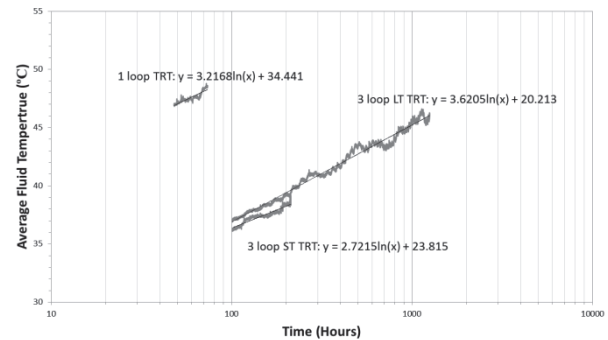


Figure 2. Estimation of effective thermal conductivity – slope of average fluid temperature vs. logarithmic of time

The results of effective thermal conductivity carried out in the three TRTs were not consistent. The 3 loop ST TRT achieved the highest value of 4.99 W/mK whilst the 3 loop LT TRT achieved the lowest value of 3.75 W/mK and the 1 loop TRT achieved an effective thermal conductivity of 4.19 W/mK for the energy pile system.

Austin (1998) showed that the line source model utilised by TRTs to estimate thermal conductivity were very sensitive to the temperature fluctuations. Figure 2 shows that there were fluctuations of the heat transfer fluid temperature during the heating periods of each TRT. The HDPE absorber pipes were insulated between the top of the energy pile to the testing unit with a combination of insulation foam, aluminium foil and soil. However, the top of the energy pile was exposed to the summer environment and direct solar energy. The fluctuation of average fluid temperature shown in Figure 2 was likely to be caused by solar radiation. The direct sunlight would heat up the concrete of the energy pile's upper surface section whilst increasing the average fluid temperature within the absorber pipes. Subsequently, during cooler nights where solar radiation was not present, the pile concrete cooled down significantly and decreased the average fluid temperature.

The estimated effective thermal conductivity found in this study is comparable to other published literature utilising energy piles as the ground heat exchanger. Published data (Brandl et al., 2006; Gao et al., 2008; Brettmann and Amis, 2011) shows that whilst utilising energy piles of at least 0.6 m in diameter during TRTs, effective thermal conductivity of the ground systems reached between 4 W/mK to nearly 7 W/mK in sandy and clayey soils. However, within smaller diameter piles the effective thermal conductivity was found to be between 2 W/mK and 3 W/mK. The long term TRT (3 loop LT) carried out over 52 days shown in this study is not a practical test to carry out due to the length of the testing period.

4.2 Shaft resistance subject to thermo-mechanical loads

The O-cell is a static form of testing although its application is inherently different to other existing pile load tests (i.e. Statnamic, anchored loading system, etc.). The O-cell is a bi-directional, hydraulic driven, sacrificial loading jack installed within the test pile. It is capable of creating pressures which subsequently are applied to the pile shaft and base. The cell is capable of opening or expanding to 150 mm and is usually attached to the reinforcing cage that is cast within the pile. Where the O-cell is placed determines the testing schedule of the pile. The energy pile was subjected to mechanical load tests on its pile shaft, the first was performed prior to any thermal loading was introduced to the ground. At the end of each 3 loop ST and 3 loop LT heating and cooling periods the pile shaft was mechanically loaded and compared to the initial load test result.

Peak Upper O-Cell (UOC) load before and after thermal loading was carried out on the energy pile, the upper section of the pile shaft (10.1 m) was displaced in a upwards direction with the average displacement of the upper pile shaft for the mechanical pile tests shown in Figure 3. During loading (pressurising) of UOC the Lower O-Cell (LOC) was “closed” where the middle and lower section of the pile act as one whole section. This allowed the UOC to use the base resistance and the lower 6 m of the pile shaft resistance to react against the upper 10.1 m of the pile shaft resistance. The maximum applicable load on the 10.1 m pile upper section was approximately 1885 kN.

During mechanical loading of the energy pile, the shaft resistance can be variable. To evaluate the mechanical behaviour due to temperature change, consistent mechanical behaviour of the pile shaft is required before and after thermal loading to determine if there is any change in the shaft resistance. Load/unload cycles were applied until the loading behaviour was constant, thus, pile shaft reaching its ultimate residual resistance.

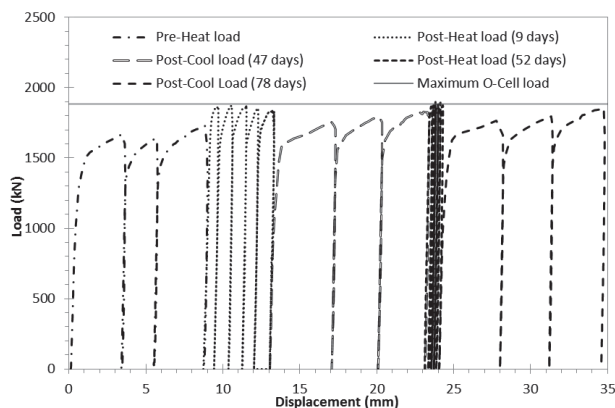


Figure 3. Load vs. pile upper-section average shaft displacement – initial, after heating and after cooling.

Figure 3 presents the pile loading tests carried out during the initial conditions, following the short-term and long-term thermal heating and cooling periods. The test results indicate that whilst the pile shaft of an energy pile undergoes thermal heating, the pile concrete slowly expands and the ultimate shaft resistance increases. However, as the energy pile was cooled following the heating period, the pile concrete slowly contracted back to its initial conditions, the ultimate shaft resistance decreased and returned closely to its initial conditions. Figure 3 also shows that the shaft resistance gained during the heating period was lost during the cooling period. However, ultimate shaft resistance did not decrease following the heating or cooling periods compared to its initial conditions.

5 CONCLUSIONS

Heat exchanger or energy piles have the potential to reduce energy demand in built structures and tackle the ever challenging climate debate. Energy piles are increasingly used in various parts of the world today, and the benefits, experiences and opportunities gained from these experiences can be adapted and applied to the local conditions. The energy pile testing works carried out at Monash University shows pile shaft resistance gained during thermal heating loads where the pile is founded in unsaturated, very dense sand. However, further research is required to understand the pile shaft behaviour in different soil conditions as well as assessing thermal properties of the energy pile ground heat exchanger and the surrounding soils in field conditions.

6 ACKNOWLEDGEMENTS

This study was part of a larger research program on geothermal energy piles funded by the Victorian Government Sustainability Fund, Vibropile Pty. Ltd., Golder Associates Pty. Ltd., GenesisNow, MIRVAC and GeoExchange Australia Pty. Ltd. Their support is gratefully acknowledged.

7 REFERENCES

- Abuel-Naga, H.M., Bergado, D.T. and Bouazza, A., (2008). Thermal conductivity evolution of saturated clay under consolidation process. *International Journal of Geomechanics*, Vol.8, No2, pp. 114-122.
- Abuel-Naga, H. M., Bergado, D. T., Bouazza, A. and Pender, M. J. (2009). Thermal conductivity of soft Bangkok clay from laboratory and field measurements. *Engineering Geology*, Vol. 105, pp. 211-219.
- Amis, T., Bourne-Webb, P., Davidson, C., Amatya, B. and Soga, K. (2008). An investigation into the effects of heating and cooling energy piles whilst under working load at Lambeth College, Clapham Common, U.K. *Proceedings 11th Int. Conf. Deep Foundations*, Deep Foundation Institute, CD Rom.
- ASHRAE 1118-TRP. Methods for determining soil and rock formation thermal properties from field tests.
- Austin, W. A. (1998). Development of an insitu system for measuring ground thermal properties. Thesis, Oklahoma State University.
- Bourne-Webb, P. J., Amatya, B., Soga, K., Amis, T., Davidson, C. and Payne, P. (2009). Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles. *Géotechnique*, Vol. 59, No. 3, pp. 237-248.
- Brandl, H. (2006) Energy foundations and other thermo-active ground structures. *Géotechnique*, 56, No2, pp.81-122.
- Brettman, T. and Amis, T. (2011). Thermal conductivity evaluation of a pile group using geothermal energy piles. *Proceedings Geo-Frontiers 2011, Dallas, USA*, pp. 499-508.
- Bouazza, A., Singh, M., Wang, B., Barry-Macaulay, D., Haberfield, C., Chapman, G., Baycan, S., Carden, Y. (2011). Harnessing onsite renewable energy through pile foundations. *Australian Geomechanics*, 46, No 4.
- Gao, J., Zhang, X., Liu, J., Li, K.S. and Yang, J. (2008). Thermal performance and ground temperature of vertical pile-foundation heat exchangers: A case study. *Applied Thermal Engineering*, 28, 2295-2304.
- Gehlin, S. (2002). Thermal response test, method development and evaluation. Thesis, Lulea University of Technology.
- Hamada, Y., Saitoh, H., Nakamura, M., Kubota, H. and Ochifuji, K. (2007). Field performance of an energy pile system for space heating. *Energy and Building*, Vol. 39, pp. 517-54.
- Hemmingway, P. and Long, M. (2011). Energy foundations-potential for Ireland. *Proceedings Geo-Frontiers 2011, Dallas, USA*, pp. 460469.
- Jalaluddin, Miyara, A., Tsubaki, K., Inoue, S. and Yoshida, K. (2011). Experimental study of several types of ground heat exchanger using a steel pile foundation. *Renewable Energy*, vol. 36, pp.764-771
- McCartney, J., Rosenberg, J. and Sultanova, A. (2010). Engineering performance of thermo-active foundations. *Proceedings GeoTrends 2010, West Palm Beach, Florida, USA*, pp.27-42.