Geothermal energy pile subjected to thermo-mechanical loading

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ABSTRACT

Shallow geothermal energy techniques integrated in structural pile foundation has the capability of being an efficient and cost effective solution to cater 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. The thermal-mechanical coupled load condition highlights the need to have a clearer understanding of temperature effects on the pile and soil interaction mechanism. This paper relates to an ongoing study using laboratory and field pile tests on the impact of coupled thermo-mechanical loads on geothermal energy piles. The full-scale in situ geothermal energy pile equipped with ground loops for heating/cooling and multi-level Osterberg cells for static load testing were installed at Monash University. The multi-level Osterberg cell load tests were performed to obtain accurate site information on side shear capacity of the energy pile before and after coupled with thermal loading. 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 that the temperature is an important factor which influences the pile load capacity.

Keywords: Geothermal energy pile, thermo-mechanical loading, pile load capacity

1 INTRODUCTION

Heat exchangers integrated in structural pile foundations have the capability of being an efficient and cost effective solution to cater for the energy base load demand needed for heating and cooling of a building. The use of heat exchanger piles has rapidly increased in the past two decades (Brandl, 2006). It is currently considered as an efficient energy source that can decrease the use of fossil fuels thus resulting in the reduction of greenhouse gas emissions. However, limited information is available on the effects of temperature on the heat exchanger pile load capacity. The thermal-mechanical coupled load condition highlights the need to have a clear understanding of temperature effects between the soil and the energy pile interaction mechanism.

Energy piles utilize shallow solar energy flux, found within 10 m - 60 m of the ground surface, to transfer heat between the building foundations and the structure. The heat is transferred into or from the ground via a ground source heat pump using high-density polyethylene pipes fixed to the reinforcement cages of individual piles. Brandl (2006) has reported extensively on energy pile applications throughout Europe as well as other ground source heat exchangers such as tunnels, cut-off walls and roadways. More recently two detailed studies have been carried out by Bourne-Webb et al., (2009) and Laloui and Nuth (2006) to examine the effects of a pile subjected to coupled thermal and mechanical loads. The two studies centered their investigation program on field pile tests. Whilst Bourne-Webb et al., (2009) used anchored piles as part of a static testing system, Laloui and Nuth (2006) utilized a pile which was part of a foundation system of a building where pile loading was provided by the building in stages during construction. The two studies suggested that the response of the energy test pile is 'thermo-elastic' due to temperature changes, that is the pile expands and contracts elastically during thermal loading cycles. Bourne-Webb et al., (2009) test results suggest that the peak skin friction mobilised in a thermal cycle was slightly lower than expected design values, a reduction of approximately 17% was observed in their investigation. This highlights the importance of better understanding required for coupled loading conditions and temperature effects on the soil structure interaction mechanism.

This paper presents preliminary results from a study on the impact of coupled thermo-mechanical loads on the load capacity of energy piles currently taking place at Monash University, Victoria, Australia. The initial program includes a field pile test to evaluate the performance of a full scale energy pile embedded in typical soils encountered in South-East Melbourne. This paper discusses the methodology and testing setup of the full scale in-situ energy pile load test and the initial results.

2 HEAT EXCHANGER PILE FIELD TEST

2.1 Background

A heat exchanger pile can be defined as a dual-purpose structural element. It utilises the required ground-concrete contact element to transfer the construction loads to the ground as well as acting as a heat exchanger unit. The energy pile is similar to vertical bore ground-source heat pump (GSHP) systems. The difference is the pile foundation serves as an integral support to the super-structure in addition to heating and cooling the built structure. This in turn saves the cost of installing vertical bores as well as the space required to drill the boreholes. This approach takes advantage of the thermal storage capacity of the ground. Ground-source heat pump technology is very well established but its use via geostructures such as pile foundations is relatively a new concept.

The current 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.

2.2 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 relatively constant ground 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 located at the Clayton Campus, Monash University. The site consists of 3 m thick clay 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 ºC) and are unaffected by seasonal temperatures changes making them suitable for heat exchanger pile systems.

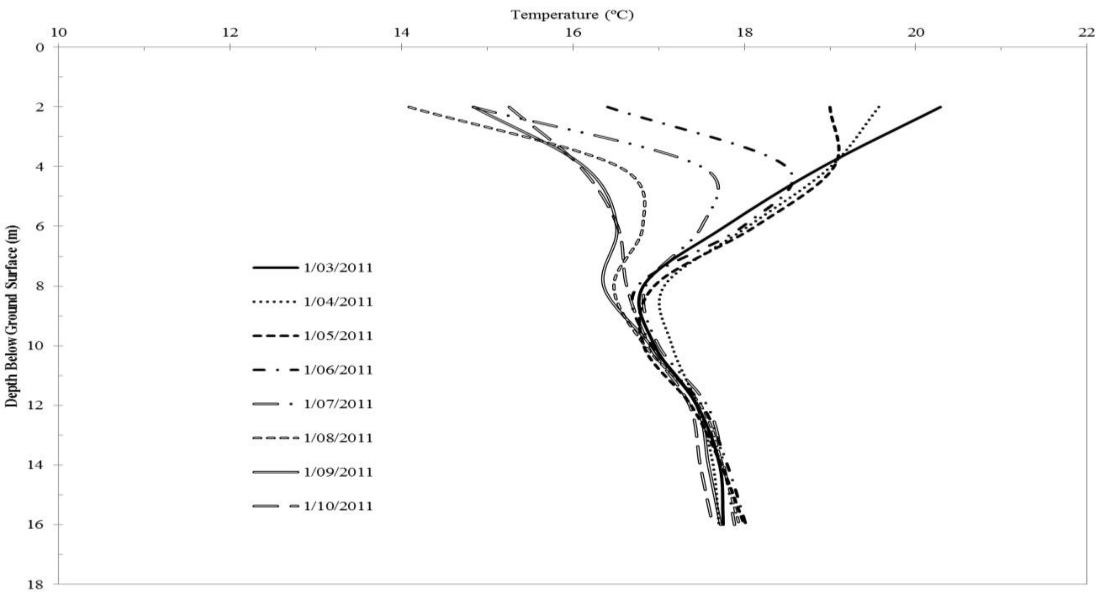

Figure 1. Typical temperature variation with depth recorded at Clayton

2.3 Heat Exchanger Pile Test 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 diameter) attached to the pile cage to transfer the heating fluid in and out.
- 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 movement.
- All vibrating wire instrumentations were fitted with a thermistor, and temperature of the concrete monitored at various levels.

Two boreholes were also 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. The first test was conducted in late July 2011 and results will be reported at a later stage.

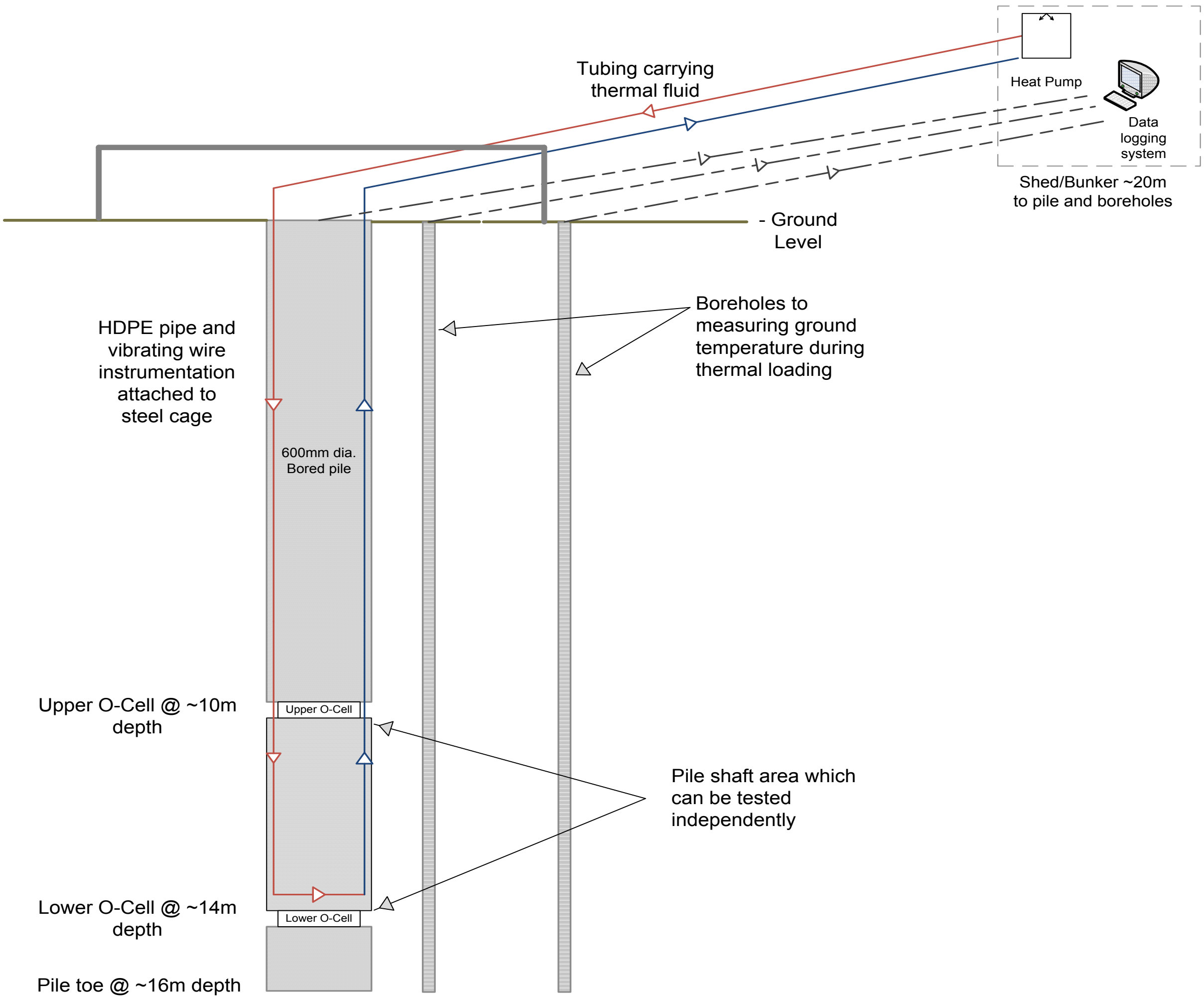

Figure 2. Field Energy Pile Testing Setup

The purpose of the Monash field pile test is to explore the relationship between the pile behaviour and surrounding soil properties under thermo-mechanical conditions. Although energy pile have been used extensively in Europe for a number of years, there is very limited information on how coupled thermo-mechanical loading affects the soil-pile interaction mechanism of an energy pile under full scaled conditions. The O-Cells 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. Installation of only one level of O-Cell means that only the base or shaft resistance can be determined. This problem can be overcome by installing two levels of O-Cells as has been done for this project. The top and bottom O-Cells can loaded open and closed and a resulting shaft resistance obtained, whilst closing the upper O-Cell and loading the lower O-Cell will result in the base resistance being determined.

2.4 Thermal Loading of Heat Exchanger Pile

Water was used as the thermal transfer medium during thermal loading of the energy pile. The 3 loops of HDPE pipe within the pile was connected in a series to the water pump, heating element and data logging system above ground. Exposed HDPE pipe above ground was insulated to minimise the daily fluctuation influence of ambient air temperature. Aluminium foil was also wrapped around on the outside of the insulation to reflect solar radiation rays. Figure 3 below shows the temperature of the heating fluid during the initial heating period of the energy pile. The initial heating period of the energy pile was 9 days, the peak inflow (into the ground) temperature reached up to 40ºC and the return (out of the ground) fluid temperature reached up to 36ºC at the end of the heating period. Throughout this period the temperature or the energy transferred into the ground is about 4ºC.

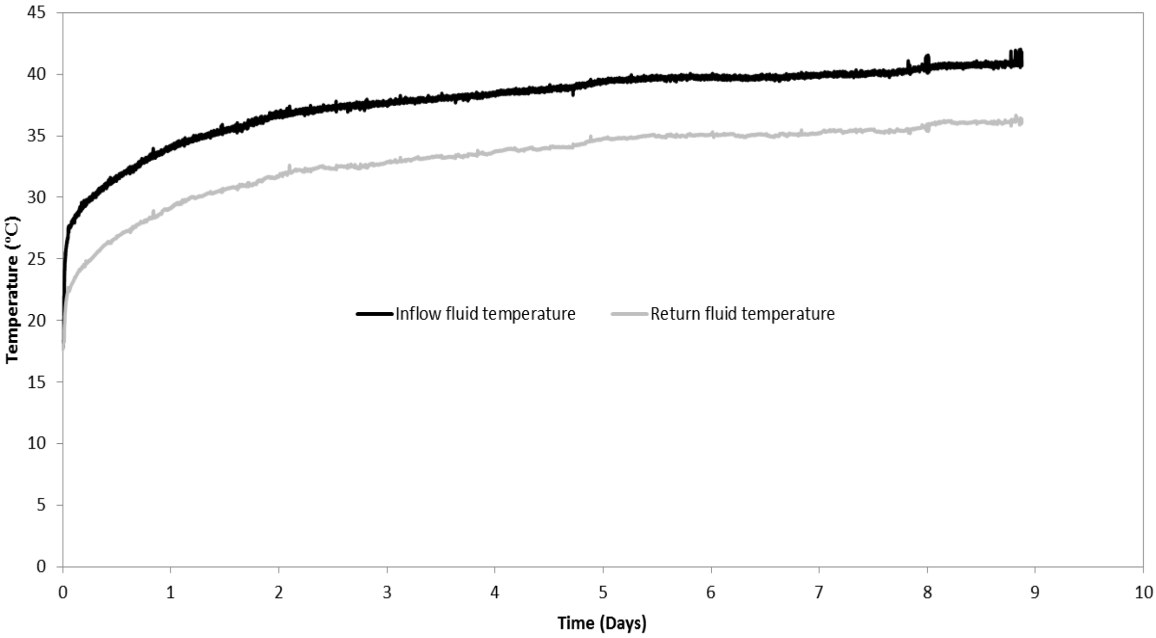

Figure 3. Thermal loading of the energy pile

2.5 Thermo-Mechanical Loading of Heat Exchanger Pile

The energy pile was subjected to three separate mechanical load tests on its pile shaft, the first was performed prior to any thermal loading was introduced to the ground, the second was performed immediately following the completion of thermal loading (at the end of the 9 day heating period), the third and final test was carried out six weeks after of thermal loading was completed, thus following "cooling" of the ground.

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 three mechanical pile tests shown in Figure 4. 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.

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, this was done by pressurising the UOC until a constant pile shaft load was reached, the pressure is then released and re-pressurised to achieve the constant mechanical load.

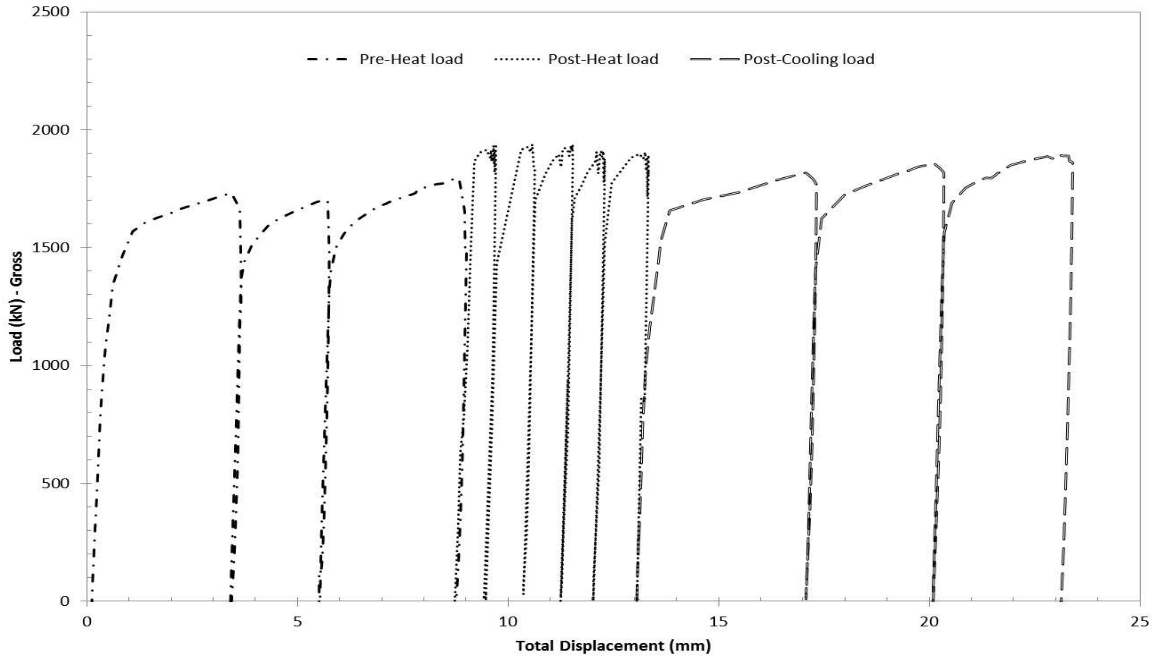

Figure 4. Ultimate pile shaft load before and after thermal loading

The field pile testing show a peak shaft load of the upper 10.1 m of approximately 1750kN was achieve in normal ground conditions with no thermal loading. Following a thermal load of approximately 40°C was applied to the energy pile for a period of 9 days the peak shaft load for the same upper section of pile was approximately 1900 kN. Following a cooling period of six weeks, the peak shaft load of the upper section of pile was approximately 1850 kN.

The loading results show for an energy pile founded within a very dense, fine to coarse sand with no presence of groundwater the thermal loading does not reduce the peak ultimate shaft resistance of the pile. However, further investigation of the thermo-mechanical behaviour of the pile shaft will be carried out with alternative thermal loads.

3 CONCLUSION

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 is not effects by thermal loading where the pile is founded in unsaturated, very dense sand. However, further work is needed to shed more light on the mechanisms controlling piles behaviour when subjected to cycling heating and cooling in different ground conditions. In particular there is a need to have a better understanding of the thermo-mechanical effects on the deformations and capacity of the piles. The ongoing project reported in this paper is a step in this direction.

4 ACKNOWLEDGEMENTS

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