Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Thermal and Thermo-Mechanical Response of a Geothermal Energy Pile

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Keywords: Thermal pile, energy foundation, Osterberg load cell, thermal response, load capacity, heat exchanging loops

ABSTRACT

Geothermal energy pile is an innovative way of reducing carbon footprint of any new building constructed on pile foundations. This technology utilises the pile foundation system for the installation of heat exchanging loops so that heat can be extracted or stored in the ground depending upon the building operation. This paper presents an overview of an investigation conducted on a geothermal energy pile with particular focus on heat performance and side shear resistance. A 0.6 m diameter bored pile, 16 m long, containing three heat exchanging loops was installed in sandy material. Two load cells were installed at two levels within the pile for the purpose of performing the mechanical test. The pile was heated and cooled for various time intervals and tested for static side shear capacity. It was found that the pile consistently provided constant heat exchange rate despite a rise in ground temperature. Side shear capacity of the energy pile was not affected by heating and cooling cycles.

1. INTRODUCTION

Geothermal energy piles also known as thermal piles or energy foundations or energy piles are a direct adoption of vertical borehole closed loop ground source heat pump (GSHP) technology into pile foundations where closed heat exchanging loops are installed within the pile. Thermal piles have great potential of improving energy efficiency of a new building resting on pile foundation by using ground as heat source/sink to provide space heating/cooling to built structures. Recently, the use of thermal piles especially in European countries such as Austria, Switzerland, Germany and UK, has increased significantly as European Union is committed to reduce greenhouse gas emission to 20% below 1990 levels by 2020 as set out in the Kyoto Protocol. In Austria alone 5511 thermal piles were installed in 2004 (Brandl, 2006) while in the UK total 3681 thermal piles were installed by 2008 (Amis, 2009). However, while construction of thermal piles is increasing limited investigation of their thermodynamic and geotechnical aspect is available to date (DeMoel et al., 2010; Bouazza et al., 2011; Wang et al., 2013).

Brandl (1998, 2006) reported the effects of temperature change within a thermal pile on its bearing capacity, especially on its shaft resistance during hydration and subsequent energy extraction. The thermal pile fitted with measuring devices such as pressure cells, fissurometers and thermo-elements, forming part of 143 thermal piles fitted with GSHP, was installed during construction of the rehabilitation centre in Bad Schallerbach, Austria. The test thermal pile was subjected to increasing dead load at different construction stages and was subjected to thermal loads applied via normal operation of the GSHP system. It was found that the shaft resistance of energy piles was not affected by the heat absorption process. The study suggested that the exposure to the surface of pile shaft to sub zero temperature should be avoided

Laloui et al. (1999, 2003, 2006) tested an instrumented pile installed as part of a new building structure while it was under construction at Swiss Federal Institute of Technology in Lausanne. The pile was subjected to two types of load viz. mechanical and thermal. The mechanical load was caused by the dead weight of the building under construction while the thermal load was induced by a heating device controlling the water temperature in closed loops installed in the pile. The two types of load were applied separately and alternately in order to decouple the thermal and mechanical effects. The pile was instrumented with 58 gauges to measure load, strain and temperature within the pile. Strains observed in the test pile were of thermo-elastic in nature. It was concluded that shaft friction resistance was not affected by temperature.

Bourne-Webb et al. (2009, 2013) carried out thermo-mechanical testing on a well instrumented pile located within the grounds of the Clapham Centre of Lambeth College in South London. In addition to the test pile fully instrumented four anchor piles, one heat sink pile and borehole were also installed. All the pile and borehole were instrumented with optical fibre sensors, and vibrating wire strain gauges. The mechanical load was applied using reaction beam and anchor pile system while the thermal load was provided by a heat pump. The borehole was installed at 0.5 m distance from the test pile to measure near-field ground temperature. The study concluded that it was unclear whether the ultimate resistance of the pile was affected by thermal resistance. It was suggested that future investigation is required to understand the variation in mobilised skin friction of the energy pile over the long term.

This study presents the results of an investigation conducted on a full scale geothermal energy pile with focus on its response to thermal loading (i.e. heating/cooling test) and mechanical loading (i.e. static pile load test).

2. THERMAL PILE DESCRIPTION

A fully instrumented bored energy pile and two boreholes were installed to investigate the ground response to heating. The pile of diameter 600 mm and 16.1 m long was instrumented with strain cum thermal gauges at various depths within the pile as shown in Figure 1. The steel reinforcement cage consisted of 6 vertical steel bars of 20 mm diameter held by spiral bars of 10 mm diameter

and 250 mm spacing. The concrete mix used for the pile construction was a commercially energy efficient concrete which achieved a 40 MPa compressive strength after 56 days curing. Three heat exchanging U-loops consisting of 6 high density polyethylene (HDPE) pipes of 25 mm diameter and 14.2 m long were attached to inner side of the steel reinforcement cage. It is to be noted that the loops were not extended to the full length of the pile as radial and axial heat transfer can be distinguished. The heat exchanging U-loop was created by connecting two absorber pipes at the end by U-shape electro fusion fitting. The pile has various strain cum temperature gauges installed at various locations. Pair of embedment strain cum temperature gauges were installed at 5.4 m, 6.4 m, 11.6 m, 12.5 m and 13.3 m while pair of sister bars were located at 8.2 m, 11.7 m and 13.2 m. Two load cells known as Osterberg cells (O-cells) were installed within the pile at 10.1 m and 14.4 m from the ground surface, respectively, to allow static shear load testing. Most of the strain cum temperature gauges were installed between the two load cells as this part of the pile was considered to be critical for the static load testing.

The two boreholes (BH1 & BH2) of 100 mm diameter were bored to depths of 18.6 m and 16.1 m respectively, at a distance of 0.8 m and 2.3 m, respectively, from the centre of the thermal pile. The boreholes were filled with cement slurry made with 40 kg cement and 1000 litres water and then thermocouples attached to a hollow plastic pipe were placed at the centre of each borehole. The first thermocouple was installed at 2 m from the ground surface and subsequent thermocouples were placed at every 2 m distance from each other as shown in Figure 1.

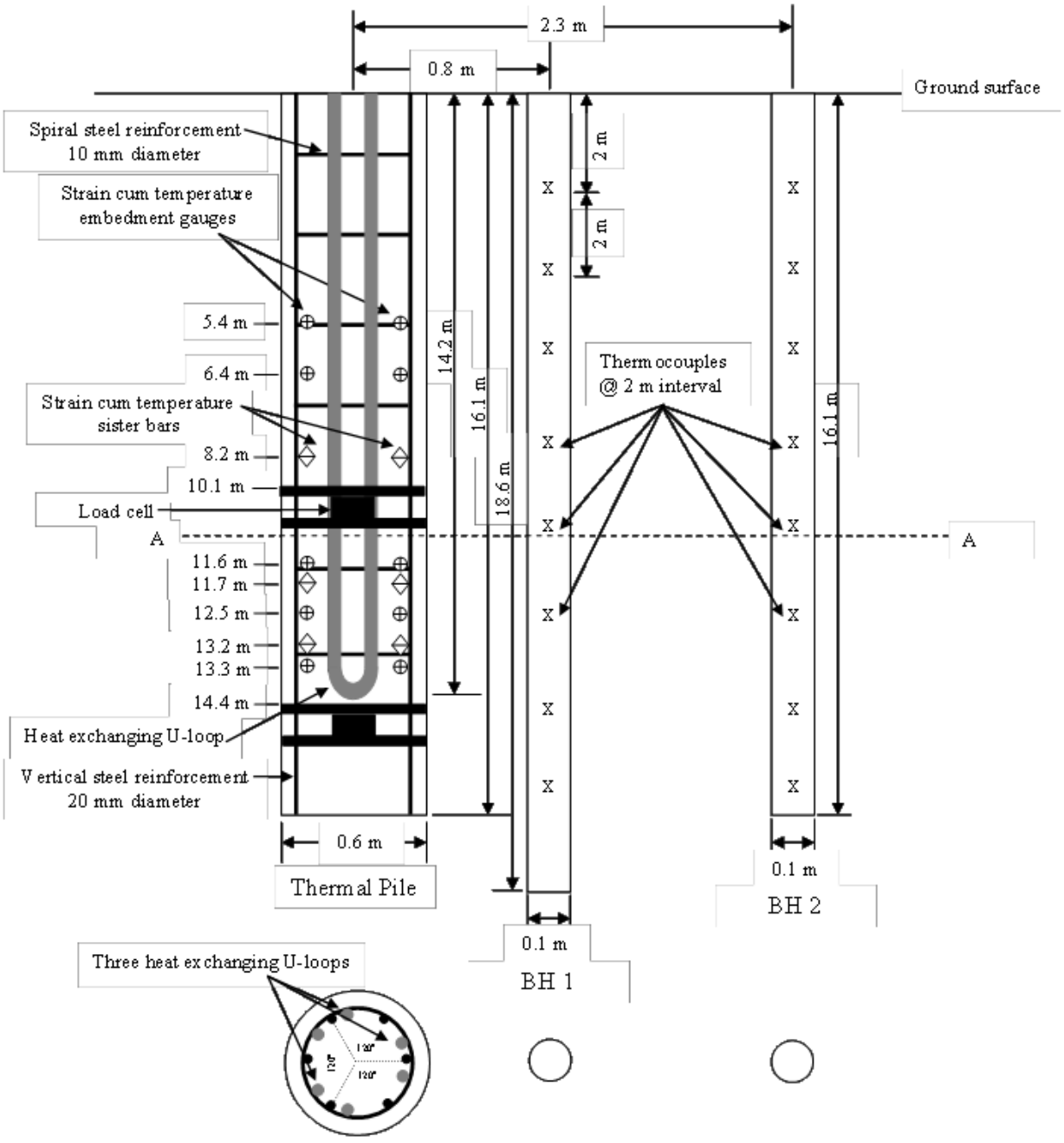

Figure 1 Schematic of energy pile and bore holes

3. SITE INVESTIGATION

The borehole (BH1) at 0.8 m distance was initially bored before the thermal pile construction for site investigation. Solid auger was used for drilling the borehole to a depth of 4.5 m and wash-boring drilling method was employed for the remainder of the borehole depth of 18.6 m. It was found that tertiary aged Brighton group of sediments underlie a fill material of 1.5 m thick. Chandler (1992) reported the area surrounding the site has Brighton group sediments and consists of two formations red bluff sands and black rock sandstone. The red bluff sand is generally found at subsurface and has clay, sandy clay, clayey sand, sand, and occasionally silt. Standard Penetration Testings (SPT) was undertaken at 1.5 m depth intervals in clayey sand and sand found after 2.5 m depth. Pocket Penetrometer (PP) test was used to assess the in-situ soil strength of sandy clay located between 1.5 and 2.5 m depth. The PP test was carried out on soil samples recovered by U63 tube sampler during the solid auger drilling. Soil recovered during the thermal pile drilling was used to determine the water content as the wash-boring technique employed during the site investigation had altered the original in-situ water content. Table 1 presents the findings of site investigation which include soil type, formation, results of SPT and PP, and water content range.

Table 1 Site investigation

Depth (m)	Soil Type	Formation	Insitu test values	Water content range (%)	Remarks
0.0 – 1.5	Fill Material	-	-	19.3 - 28.2	Organic
1.5 – 2.5	Sandy clay	Brighton group (Red bluff sand)	PP > 400 kPa	12.1 - 19.3	Hard
2.5 – 10.0	Clayey sand	Brighton group (Red bluff sand)	N = 26 @ 3m N = HB* >3m	4.9 - 12.1	Very Dense
10.0 – 18.6	Sand	Brighton group (Red bluff sand)	N = HB*	2.2 - 4.9	Very Dense

*HB encountered during SPT is referred to as Hammer Bounce when number of blows N>50

4. EXPERIMENTAL PROTOCOL

The pile ground response to heating was investigated by circulating hot water through the heat exchanging loops. The water was heated by a 2.5 kW electric heating-coil and was circulated by a pump into the heat exchanging loops with a flow rate of 10 litres per minute. Transient temperature at inflow and outflow points of the heat exchanging loops was measured by thermocouples. It is to be noted that during heating tests the 3 loops were connected in series at top end as shown in Figure 2. Table 2 presents the details of the heating tests carried out with recovery time allowed for the ground to reach its normal temperature.

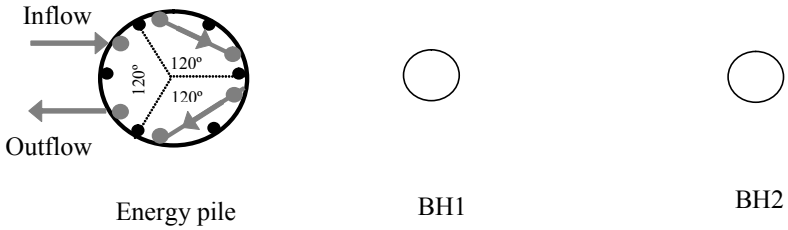

Figure 2 Three loops connected in series for heating test

Table 2: Schedule of thermal and thermo-mechanical tests

Heating test name	Starting of heating test	Ending of heating test	Duration of heating test	Static load test	Recovery time after heating test
Three loops short term (3-Loop ST)	3:10 pm 18 Oct 2011	11:50 am 27 Oct 2011	9 days	27 Oct 2011	47 days

5. RESULTS

This paper presents thermo-mechanical results heating test and static load test which was carried out immediately after the heating test.

5.1 Thermal results

Transient temperature of circulating water in the heat exchanging loops and heat exchange rate of the energy pile during the heating test is shown in Figure 3. The loop length of 85.2 m was used in the 3-loop test. The maximum temperature of water entering and leaving the loops reached 41°C and 36°C, respectively, at the end of the heating test. During the test, water temperature kept increasing as constant heat energy was provided to the water. At the start of the test there is no temperature difference between the water entering and leaving the loop as the heat takes some time to overcome the resistance of the absorber pipe walls and heat capacity of the pile concrete material. The temperature difference between water entering and leaving the loops is 5°C and remained the same throughout the test. The temperature difference remained constant during the test because constant fluid flow rate of 10 litres/minute was kept constant throughout the test.

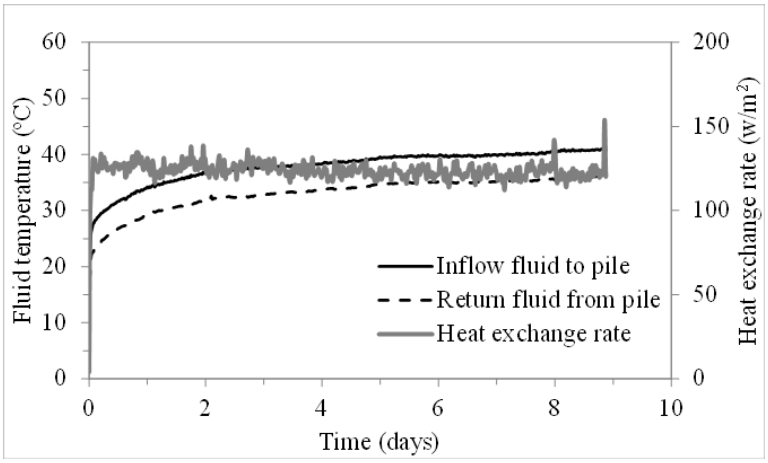

Figure 3. Heat transfer fluid temperature during heating test

Heat exchange rate of the energy pile was calculated using the following relationship:

$$Q = \frac{ms\Delta\theta}{A} \quad (1)$$

where Q (W/m2) is the heat exchange rate, m is the flow rate (10 litres/minute), s is the volumetric heat capacity of water (4.18 MJ/m3K), Δθ is the fluid temperature difference and A is the surface area of the energy pile (26.76 m2). It is to be noted that surface area of the energy pile was calculated using the pile length of 14.2 m that was equal to loop length. The heat exchange rate of the energy pile is also shown in Figure 3.The average heat exchange rate of the energy pile was 122 W/m2 and remained constant as the temperature difference and fluid flow rate remained constant. It is to be noted that constant heat exchange rate was achieved despite continuous increase in pile temperature and ground temperature.

Figure 4 presents the pile transient temperature in response to the heat test. The temperature was found to increase at all locations within the pile during the heating test and decrease steadily after the test was stopped. No time lag was observed, as the temperatures reached their peak values exactly at the same time when the test was completed. This is because the heat had already overcome the pipe resistance during the one loop test. The thermal pile is heated uniformly during the heat test. The highest temperature (35°C) was recorded at locations where the temperature gauges were closest to the loops while the lowest temperatures (31°C) were observed away from the loops. The sister bar gauges show lower temperature compared to the embedment gauges because they are longer and capture the temperature range for a larger portion of the pile. The temperature decreases rapidly and uniformly 5 days after the heating test is completed. There is a lesser temperature fall after 10 and 20 days from the test stoppage compared to 5 days cooling period. There is a full thermal recovery after 20 days as the temperature reaches the initial values observed before the heating test. The pile takes twice the amount of time used for the heating test to have full thermal recovery. After 47 days cooling the pile returned fully to the temperature levels recorded before any heating test took place on the site (i.e. temperature profile similar to ground temperature profile).

Transient ground temperature variation of BH1 during the heating test is presented in Figure 5. The maximum temperature of 26ºC was observed at 12 m depth at the end of the heating test. Furthermore, temperature reached maximum values at all locations at the end of heating test and therefore no time lag was observed. The temperatures started to decrease as soon as the heating test was stopped. This shows the immediate ground thermal response during and after the heating test. The shape of thermal profiles remained the same at all the selected time periods. This indicates uniform ground thermal response to the heat test at all depths. The heat test has raised the ground temperature in BH1 by 5°C to 7°C at every location except 14 m and 16 m. As noted earlier the loop was extended to 14.2 m and the ground temperature has increased up to 14 m depth. One can conclude from this observation that the heat moved predominantly in a radial direction. The highest temperature increase at the end of the heating test happened at 12 m depth which could be due to existence of highly conductive soil layer at that location. Lower temperature increase at 2 m and 4 m depths is due to lower air temperature during the test duration. The ground temperature is affected to large extent by ambient air temperature to the depth of 6 m (Bouazza et al., 2011). Lower temperature increase at 6 m, 8 m and 10 m depths is due to the

properties of the soil material at these depths and discontinuity in the energy pile caused by the presence of the load cell located at 10m depth. The temperature drop is higher 5 days after cooling compared to 10 days cooling. Heat dissipated faster in the beginning after the heating is stopped. The ground temperature returned to its initial value after 20 days cooling. Therefore the ground recovery took twice the time of the heating test duration as observed earlier within the pile. Full thermal recovery based on natural heat dissipation (i.e. return to original ground temperatures prior to any heating tests) took 47 days to complete. It is to be noted that the ground temperature decreases after 47 days at every location apart from 2 to 4 m depth. This is due to the effect of solar radiation as the pile was exposed to sun.

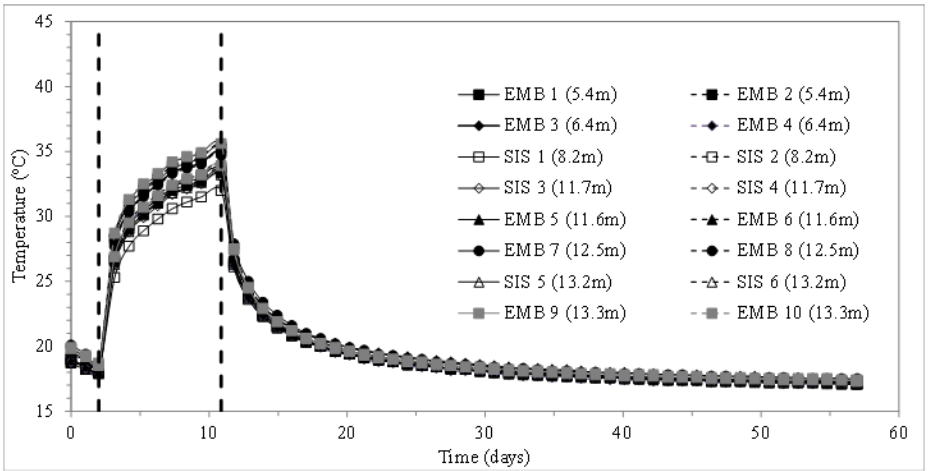

Figure 4. Energy pile temperature response to heating test

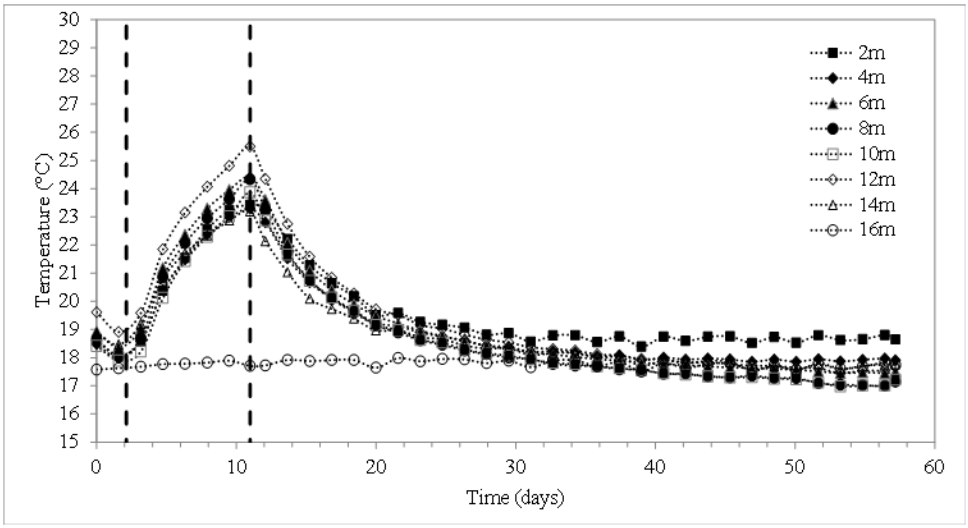

Figure 5. Ground temperature response of BH1

The ground temperature response in BH2 is shown in Figure 6. The temperature does not increase immediately following the start of the heating test. Changes in temperatures started to be observed 5 days after the heating tests was completed as the heat wave reached BH2. The peak temperature of 19°C was recorded at 12 m depth. There is little increase in ground temperature during the heating test but as discussed earlier the maximum increase in temperature occurred 5 days after the completion of the heating test. The ground temperature increased by 1°C to 2°C at every depth apart from 16 m. As explained earlier heat moves in radial direction predominantly and the loop length was 14.2 m which resulted in no temperature change at 16 m depth. The ground temperature started to decrease 10 days after the heating test was stopped. The ground thermal recovery in BH2 is slow as temperatures returned to their original values at deeper locations only after 47 days of cooling. The ground temperature near the surface at 2 m and 4 m is affected by solar radiation as the test was performed in summer and the pile was exposed to sun.

5.2 Mechanical results

The energy pile was tested for its side shear load capacity after the heating test. The test was carried out by opening the first load cell and closing the bottom cell (see Wang et al. 2014, for further details). The pile load capacity against cumulative displacement is shown in Figure 7. The pile was loaded, unloaded and reloaded to assess its load capacity. The pile load capacity of about 1650 kN was achieved before the heating test. The pile load capacity increased to 1860 kN after the heating test. The increase in pile side shear load capacity can be attributed to increase in frictional resistance due to pile expansion and possibly increase in frictional resistance due to drying.

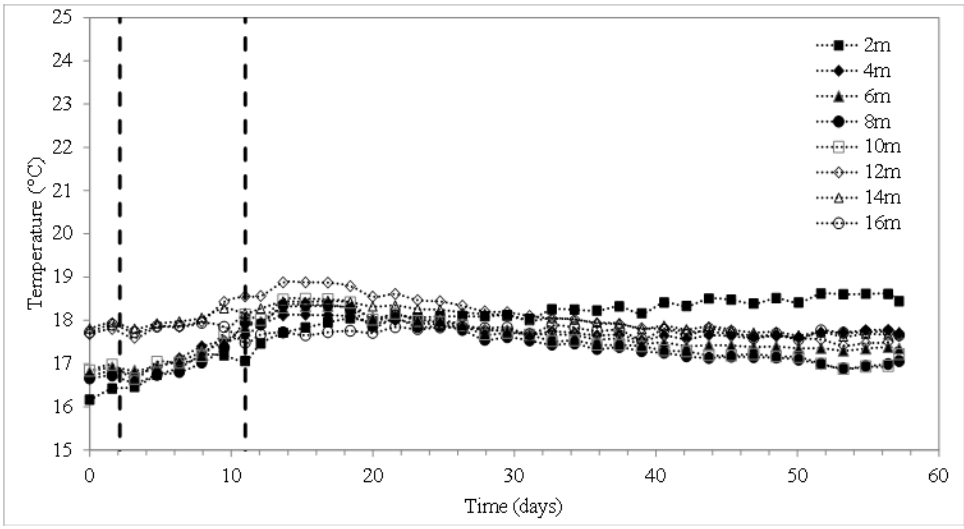

Figure 6. Ground temperature response of BH2

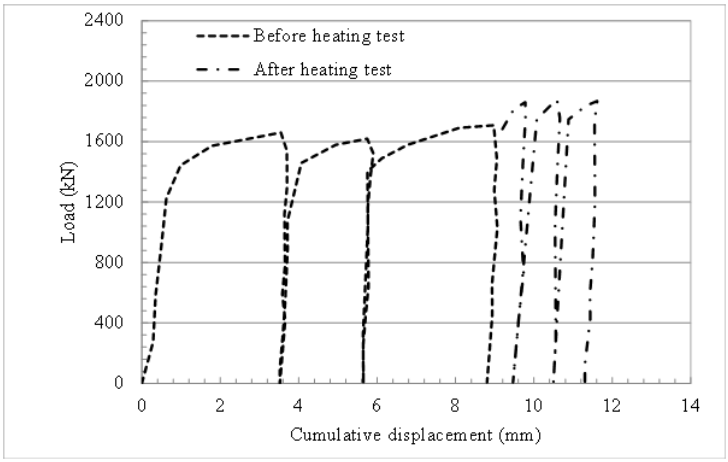

Figure 7. Pile frictional load capacity before and after heating test

6. CONCLUSIONS

This paper presents the thermal and thermo-mechanical response of a field scale bored geothermal energy pile installed in sandy soil with two observation boreholes. The pile was subjected to a heating test and was allowed to recover through natural heat dissipation. It was found that heat predominantly moved in radial direction and there was a time lag in heat wave reaching to boreholes. The ground needed about twice the time of heating test to recover fully to achieve temperatures existed before heating test. The constant heat exchange rate of 122 W/m^2 was achieved despite increase in ground temperature and pile temperature with time. The heat exchange rate directly depends on fluid flow rate and slower flow rate renders lower heat exchange rate. The pile was subjected to static mechanical load test after the heating test. The pile load capacity increased after the heating test suggests that the pile foundation can be used as energy pile to harness ground energy which is available in abundance under our feet at shallow depth.

ACKNOWLEDGEMENT

This project was funded by the Australian Research Council, Golder Associates Pty. Ltd., Vibropile Pty. Ltd. and Geoexchange Australia Pty. Ltd. Their support is gratefully acknowledged.

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