Performance of Piled Foundations Used as Heat Exchangers

Performance des fondations sur pieux utilisées comme échangeurs thermiques

Loveridge F., Powrie W.
Faculty of Engineering and the Environment, University of Southampton, Southampton, UK

ABSTRACT: In closed loop ground energy systems, used to provide renewable heat energy to buildings, heat is transferred between a heat pump and the ground via ground heat exchangers. Fluid is circulated through pipes within the heat exchanger. Including these pipes within the concrete of piled foundations can give economies of excavation and materials. However, there remain few validated design approaches for determining the heating and cooling capacity of pile heat exchangers. There have also been concerns that inappropriate operation may cause extreme temperatures to develop in the ground, leading to loss of geotechnical performance. As a result most current design is conservative and does not fully utilise the thermal capacity of the pile-ground system. To permit validation of new design methods, instrumentation has been installed within a pile heat exchanger at a site in London. Initial results are showing the pile concrete to be making a substantial contribution to the short term storage of thermal energy. This is significant, as most design methods assume that the pile concrete merely acts to transfer heat to the surrounding ground. This heat storage also acts to protect the ground against larger fluctuations in the fluid temperature and is therefore beneficial for geotechnical performance.

RÉSUMÉ : Dans les systèmes de transfert d'énergie du sol en circuit fermé, utilisés pour la fourniture d'énergie thermique durable aux immeubles, les échangeurs thermiques transmettent la chaleur du sol à une pompe à chaleur. On peut obtenir des économies lors de l'installation si les tuyaux de l'échangeur thermique se trouvent dans le béton des fondations sur pieux. Il n'existe cependant guère d'approches conceptuelles validées pour la détermination des capacités thermiques des pieux à échangeurs thermiques et des préoccupations existent sur leur utilisation inappropriée ; la plupart des conceptions actuelles est donc conservative. Pour la validation de nouvelles méthodes de conception, on a installé de l'instrumentation dans un pieu à échangeur thermique sur un chantier à Londres. Les premiers résultats démontrent que le béton du pieu offre une contribution substantielle sur l'accumulation à courte durée de l'énergie thermique. Ceci est important pour l'amélioration de la performance géotechnique.

KEYWORDS: ground energy systems, piling, renewable energy, temperature effects

1 INTRODUCTION

It is becoming increasingly common for ground energy systems to utilise building piled foundations as the heat exchanger part of the system, facilitating heat transfer to the ground. In this arrangement, small diameter (<30mm) plastic pipes are cast into the piles, before being connected via larger header pipes to a heat pump. This forms the "source" side of the ground energy system. On the "delivery" side of the system, the heat pump is connected to heating and air conditioning units, which should be a low temperature system to maximise efficiency.

Design of pile heat exchangers is split into two main aspects. First the calculation of the thermal capacity of the pile heat exchanger, ie what heating and cooling power can be achieved from the pile or pile group. Secondly, it is important that additional checks are performed with respect to the geotechnical design so that any additional concrete stresses or displacements resulting from temperature changes induced in the piles can be taken into account in the structural design. These two design aspects do not, however, exist in isolation. The range of temperatures at which the heat pump system operates will directly influence both the available thermal capacity and the geotechnical design. It is therefore important that appropriate temperature limits are agreed between all parties. From a geotechnical perspective it is essential that the pile-ground interface does not reach freezing temperatures, while extreme higher temperatures may affect the efficiency of the heat pump.

While procedures for geotechnical design of pile heat exchangers are developing rapidly (GSHPA 2012; Amatya et al. 2012; Ouyang et al. 2011; Knellwolf et al. 2011), there remain few datasets available with which to permit validation of design methods for the heating and cooling capacity of piles (Loveridge & Powrie 2012). To address this important knowledge gap, the University of Southampton has commenced a programme of in situ monitoring of pile heat exchangers. This paper will present details of an instrumented pile heat exchanger in East London, along with initial data from the first few months of operation of the energy system.

2 SITE DESCRIPTION

The instrumented pile is part of the foundations for "The Crystal", Siemens' new landmark building adjacent to Royal Victoria Dock in East London. The Crystal is a multi-use development and contains an interactive exhibition on sustainable technologies as well as office space. It has been designed to be an all electric building, utilising solar power and ground source heat pumps to generate all the energy for the development.

The source side of the ground energy system comprises 160 pile heat exchangers and a field of 46 150m deep boreholes. The piles are 600mm, 750mm or 1200mm diameter and were constructed using contiguous flight auger techniques. Each pile was installed with a pair of plastic U-pipes, which were inserted into the centre of the pile (Figure 1) after the pile cage had been plunged into the concrete. The U-pipes were then connected together in series and usually joined into a single circuit with a neighbouring pile, before the pipework is continued to the header chamber and then on via larger pipes to the plant room for connection to the heat pumps.

Figure 1. Typical pile heat exchanger at the site (after breaking down to pile cut off level).

2.1 *Ground Conditions*

The site is underlain by a sequence of London Basin deposits. The piles are founded in the London Clay at 21m depth, but also pass through a significant thickness of superficial and man-made deposits (Table 1). As the site is located close to the confluence of the Thames and the River Lea in east London, the groundwater table is close to the ground surface, near to the base of the Made Ground.

Table 1. Table Ground Conditions.

Strata	Description	Depth (m)
Made Ground	Fine to coarse brick and concrete gravel; soft to firm black sandy gravelly clay.	3.3
Alluvium	Very soft clayey silt, sandy clay and peat.	6.3
River Terrace Deposits	Medium dense silty fine to coarse sand and fine to coarse gravel (mainly flint)	11.2
London Clay	Stiff thinly laminated fissured silty clay with silt partings	23.5

2.2 *Instrumentation*

One 1200mm diameter pile near the north east corner of the building was selected for monitoring. The pile was equipped with five thermistor strings. One of these was attached to the central bundle of plastic pipes, themselves inserted into the pile attached to a 40mm steel bar for stiffness (Figure 2). The U-pipes, the steel bar and the thermistor strings were installed to a depth of 20m within the pile. The other four thermistor strings were attached at equal spacings around the circumference of the steel reinforcing cage (Table 2). As the pile cage only extends to 8.5m below the pile cut off level it was not possible to extend the outer thermistor strings over the full 21m pile depth.

3 BACKGROUND DATA

Following construction of the pile, selected thermistors were monitored for approximately one month to provide an indication of the heat of hydration. During this period the groundworks beneath the building footprint were completed and all the pipe circuits were constructed as far as the header chambers. At this point it became possible to data log all the monitoring points to obtain information on the background soil temperatures at different depths.

These initial data are presented in Figure 3. It can be seen that during curing the pile reaches temperatures of almost 35^{o}C at its centre, but that this reduces to approximately 30^{o}C closer to the pile edge. In the main part of the pile, it takes over two months for the heat of hydration to dissipate fully and temperatures to return to between 13^{o}C and 15^{o}C. The near surface monitoring points (thermistor level 1, Figure 3) are influenced by the ambient air conditions. Within one month (when monitoring of these points first commenced) the thermistors at level 1 are already showing daily and longer term seasonal fluctuations reflecting the local air temperature.

Figure 2. Base of the central thermistor string prior to installation of the U-tubes and steel bar.

Table 2. Depths of thermistors installed with the pile.

Thermistor Level	Depth Below Pile Cut Off Level (m)	
	Central String	Outer Strings
1	0.7	0.75
2	3.6	3.25
3	7.1	6.6
4	11.1	-
5	15.1	-
6	19.1	-

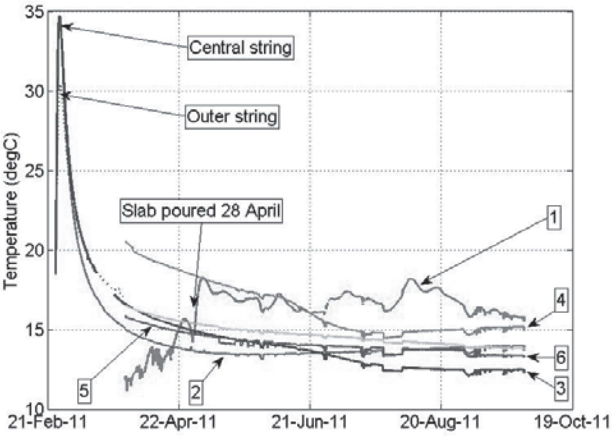

Figure 3. Initial pile temperatures during and after concrete curing (numbers refer to thermistor string levels).

The level 1 thermistors also show a distinct increase in temperature at the end of April 2011, coincident with the date at which the floor slab for the building was cast. This temperature increase will represent the additional heat of hydration from the concrete slab. Following this time, daily variations of temperature are also reduced due to the additional insulation. It is also interesting to note these level 1 temperatures appear to remain elevated for some time after the slab is cast; although it is difficult to separate this effect from that of the surface air temperature which would also be increasing at this time of year.

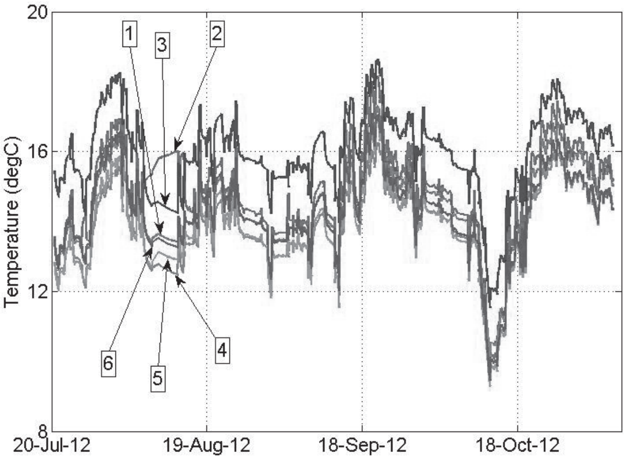

Figure 4. Operational temperatures from the central thermistor string (numbers refer to thermistor string levels).

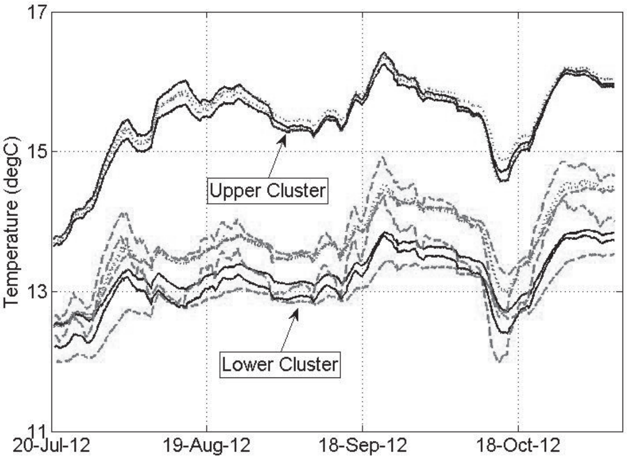

Figure 5. Operational temperatures from the outer thermistor string (dashed = thermistor level 1; solid = level 2; dotted = level 3).

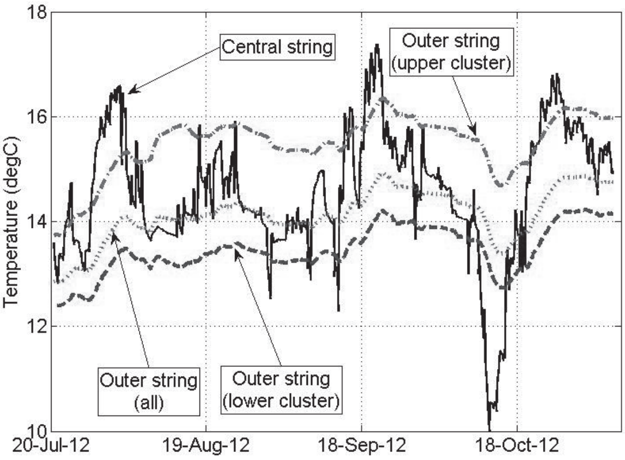

Figure 6. Mean thermistor string temperatures.

4 INITIAL RESULTS

Following collection of the background data it was necessary, due to construction constraints, to disconnect the datalogger until shortly after the Crystal was first occupied. Since collection of data recommenced we now have almost four months of temperature information for the pile under operational conditions.

Figure 4 and 5 present the temperature data from the central thermistor string and the outer thermister strings respectively. The central thermistor string records a greater range of temperatures than the outer strings, with ±4^{o}C and ±1^{o}C variation from the initial ground temperatures respectively. The central string also shows greater short term variation compared with the outer strings. This is because the temperature change of the central thermistors will closely follow that of the heat transfer fluid circulating within the U-tubes. However, by the time heat flow from the fluid reaches the outer thermistor strings any very short term variations will have smoothed out.

It is also noted that the outer thermistor readings are grouped into two distinct clusters. The upper cluster is approximately 2^{o}C warmer than the lower cluster, but follows a similar, although not identical trend. If both the U-tubes and steel cage were installed exactly centrally within the pile bore then, ignoring pile end effects and any variation in ground and concrete thermal properties, all the outer thermistors should read the same value. However, since an exactly central installation is not possible, it should be expected that there will be some variation in these values. However, what is surprising is that the upper cluster contains level 2 and level 3 thermistors from opposite sides of the pile, which should only have close to equal values if the cage and the pipes have been installed centrally. This could suggest that the readings in the upper cluster are erroneous.

This view is supported by looking at the average temperatures for the central and outer strings (Figure 6). Temperatures are generally rising with time as heat is rejected to the ground via the pile. Therefore the temperatures closer to the pile edge would be expected to be lower than those in the centre next to the pipes. In this context the upper cluster appears to be erroneously high, while the lower cluster shows temperatures in a more realistic range.

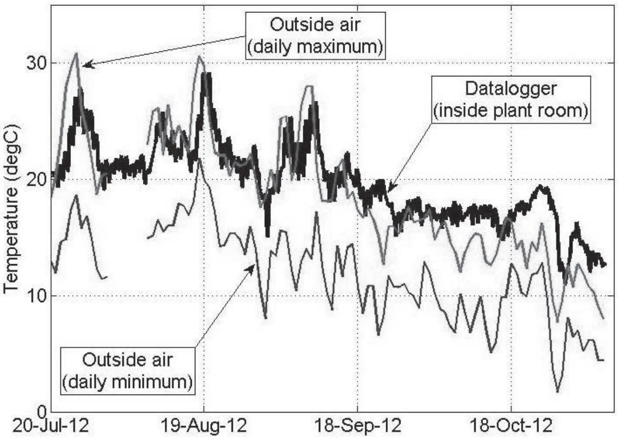

Figure 7. London air temperatures.

The general trend of increasing temperatures, despite the advent of cooler air temperatures as the autumn progressed (Figure 7) is a reflection of the complexity of both modern buildings and the heating-ventilation-air conditioning (HVAC) system in this building in particular. For a system where pile heat exchangers are either providing all of buildings heating and cooling demands, or covering only partial demand in combination with a traditional HVAC system, then the pile temperature would be expected to reflect the outside air temperatures and decrease throughout the winter months. However, in this case the energy needs of the building are being met by a combination of the pile heat exchangers, the borehole heat exchangers and a solar system. These means that the three components will be operated together to achieve the building heating and cooling demands and, for example, on some occasions excess solar thermal energy can be stored in the ground.

There is, however, one clear example of heat extraction visible in mid-October (Figure 6). Here the central thermistor readings dip markedly to around 10°C on average. The corresponding change in the mean outer thermistor readings is much smaller, indicating that much of the heat energy required has actually been extracted from that temporarily stored in the pile concrete, rather than from the surrounding ground.

5 DISCUSSION

An important aspect of pile heat exchanger behavior is illustrated by the data presented in Section 4. As has been shown theoretically by Loveridge, 2012, large diameter piles can take many days to reach a thermal steady state. Therefore, for a heating/cooling demand which is varying on an hourly (or less) timescale the pile concrete will rarely be at thermal steady state. This is illustrated in Figure 6, which shows that the temperature change near to the pile edge is significantly damped compared to that close to the U-tubes and some subsidiary peaks/troughs are not reflected at all. If the pile was at steady state, as is assumed by all traditional design methods, then the temperatures near the pile edge would reflect all the temperature changes at the pipes.

This transient thermal behavior shown by the pile concrete is important for a number of reasons. First, if the pile is assumed to be at a thermal steady state then any ability of the pile concrete to store energy (rather than just transfer it to the ground) is being neglected. As a consequence steady state design will either 1) overestimate the temperature change predicted at the pile-soil boundary for a given heat flux, or 2) underestimate the available thermal energy capacity for a given temperature change. While this provides a safe conservative design it will significantly under-predict the thermal efficiency of the pile heat exchanger.

Taking a transient view of the pile concrete behaviour also shows there to be a reduced risk of extreme temperatures developing in the ground. Current practice (eg NHBC 2010; SIA 2005) tends to recommend that the lower limit on the heat transfer fluid temperature in pile heat exchangers should be kept above freezing with a 2°C margin of error. However, given that the largest dips in the central thermistor temperatures shown in Figure 6 are not reflected to the same degree in the temperature changes of the outer thermistors, this approach clearly would be conservative in this case. This real behaviour is similar in nature to recent theoretical studies (Loveridge et al. 2012) which show that, for large diameter piles at least, temperatures lower than 0°C can be sustained within the heat transfer fluid for short periods and have no detrimental effects on the ground. Similar conclusions were reached by Brandl in his Rankine Lecture (Brandl 2006), but do not seem to have been acted upon in general practice.

5.1 Further Work

The data presented in this paper is the beginning of a long term monitoring programme. The temperature data in the pile will subsequently be supplemented by energy data, both with respect to the heat transferred to the instrumented pile and for the balance of thermal energy between the different renewable energy systems in the building. This is essential for fuller interpretation of the pile data and will allow linking of the energy demand and pile temperature changes. This will provide a valuable dataset for validation of pile heat exchanger thermal design methods.

6 CONCLUSIONS

Temperature sensors have been installed within a working foundation pile which is also used as a heat exchanger within a ground energy system. Initial data from the pile is now available and demonstrates the transient nature of the heat transfer within the pile. This is significant, as most existing design methods for the thermal capacity of piles assume that the pile is at a steady state. For large diameter piles such as the one instrumented in this scheme, this is clearly not the case. Instead the largest fluctuations in temperature at the centre of the pile close to the pipe U-tubes are not reflected closer to the edge of the pile. This is due to the thermal buffering provided by the pile concrete, which acts as a short term energy store during short duration peaks in thermal demand.

The consequence of neglecting this short term concrete thermal storage is that design becomes over conservative and underestimates the thermal capacity of the pile. It also leads to an over estimation of the risk of ground freezing for large diameter piles.

7 ACKNOWLEDGEMENTS

The authors would like to thank Joel Smethurst and Harvey Skinner for assistance with installing the thermistors and datalogger respectively. The work would not have been possible without initial introductions and enthusiasm from Arup and Balfour Beatty Ground Engineering and subsequent support and commitment from Siemens Plc. We are also indebted to site support from ISG, Foundation Developments Ltd and Geothermal International Ltd. This work forms part of a larger project funded by EPSRC (ref EP/H0490101/1) and supported by Mott MacDonald, Cementation Skanska, WJ Groundwater and Golder Associates.

8 REFERENCES

Amatya B.L., Soga K., Bourne-Webb P.J. and Laloui L. 2012: Thermo-mechanical performance of energy piles. *Geotechnique* 62 (6), 503 -519.

Brandl H. 2006. Energy foundations and other thermo active ground structures. *Geotechnique* 56 (2), 81 – 122.

GSHPA 2012. *Thermal pile design, installation and materials standard.* Ground Source Heat Pump Association, Milton Keynes, October 2012.

Knellwolf C., Peron H. & Laloui L. 2011. Geotechnical analysis of heat exchanger piles. *Journal of Geotechnical and Geoenvironmental Engineering 1*37 (10), 890 - 902.

Loveridge F. 2012. *The Thermal Performance of Foundation Piles used as Heat Exchangers in Ground Energy System*s. Doctoral Thesis, University of Southampton.

Loveridge F. & Powrie W. 2012. Pile heat exchangers: thermal behaviour and interactions. *Proceedings of the Institution of Civil Engineers Geotechnical Engineering.* Available ahead of print at http://dx.doi.org/10.1680/geng.11.00042.

Loveridge F., Amis T. and Powrie W. 2012. Energy Pile Performance and Preventing Ground Freezing. *Proceedings of the 2012 International Conference on Geomechanics and Engineering (ICGE'12)*, Seoul, August, 2012.

NHBC 2010. *Efficient design of piled foundations for low rise housing, design guide.* BC Foundation.

Ouyang Y., Soga K. & Leung Y. F. 2011. Numerical back analysis of energy pile test at Lambeth College, London. *Proc ASCE GeoFrontiers 2011 Conference*, Dallas, Texas, http://dx.doi.org/10.1061/41165(397)46.

SIA 2005. *Utilisation de la chaleur du sol par des ouvrages de fondation et de soutènement en béton, Guide pour la conception, la réalisation et al maintenance.* Swiss Society of Engineers and Architects, Documentation D 0190.