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Long Term Monitoring of CFA Energy Pile Schemes in the UK

F.A. Loveridge & W. Powrie
University of Southampton

T. Amis
GI Energy

M. Wischy & J. Kiauk
Siemens

ABSTRACT: Energy pile schemes involve the use of structural foundations as heat exchangers in a ground source heat pump system. Such schemes are attractive, as they reduce energy consumption compared with traditional building heating and cooling systems. As energy prices increase and governments introduce subsidies they are also proving increasingly economically attractive. Additionally, energy piles can contribute to reducing the carbon dioxide emissions associated with a development. However, this approach to heating and cooling building remains relatively novel and the lack of published long term performance data remains a barrier to further implementation. Two issues remain to be addressed by long term monitoring. First, the need for a database of operational energy piles schemes were the energy performance is proven over many years. Secondly, availability of long term datasets of pile thermal behavior that can be used to validate design approaches and tools and hence encourage less conservative design practices. This paper presents the initial results from a study aimed at tackling these issues through long term instrumentation and monitoring of two energy pile schemes in the United Kingdom.

1 INTRODUCTION

Energy pile schemes involve the use of structural foundations as heat exchangers in a ground source heat pump system. Such schemes are attractive, as they reduce energy consumption compared with traditional building heating and cooling systems. As energy prices increase and governments introduce subsidies they are also proving increasingly economically attractive. Additionally, energy piles can contribute to reducing the carbon dioxide emissions associated with a development.

Energy piles have been in operation in Europe since the 1980's (Brandl, 2006). Some notable case studies include Zurich Airport (Pahud & Hubbach, 2007), One New Change in London (Amis & Loveridge, 2014) and Keble College Oxford (Suckling & Smith, 2002, Nicholson et al, 2014). However, despite an increase in constructed cases in recent years, relatively little performance data are available, especially for the long term (Bourne-Webb, 2013). This holds back validation of thermal design approaches, and limits the value of demonstration projects.

Since 2011, the University of Southampton and GI Energy have been working in partnership to develop monitoring sites for energy pile schemes. The project has seen the instrumentation of energy piles beneath two buildings in the United Kingdom. Temperature sensors installed in the foundations are combined with data from building energy management systems to provide the opportunity to assess both the whole system performance and the pile thermal behaviour. The latter is particularly important for understanding modelling and design approaches and their application to energy piles.

This paper provides details of the two monitoring sites and some initial results from the schemes so far. Lessons learnt from both the installation of instrumentation and the resulting data are also considered.

2 THE CRYSTAL, EAST LONDON

The first scheme to be instrumented was Siemens' landmark sustainable building in East London, known as The Crystal (Figure 1). The Crystal is a multi-use development and contains an interactive exhibition of sustainable technologies as well as office space and conference facilities. It has been designed to be an all-electric building and utilises solar thermal and ground source heat pumps to generate all the thermal energy needed by the development. Photovoltaics also generate electricity to reduce reliance on a more carbon intensive national supply.

The source side of the ground source heat pump system comprises 160 pile heat exchangers and a field of 36 deep boreholes. The piles are 600 mm, 750 mm or 1200 mm in diameter and were constructed using contiguous flight auger (CFA) techniques to approximately 21m depth. Each pile incorporates a pair of High Density Polyethylene (HDPE) U-pipes, which were inserted into the centre of the pile 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 continued to the manifold chamber and then on via larger header pipes to the plant room for connection to the heat pumps.

Each borehole is 150m deep and contains a single HDPE U-pipe. Backfill material is gravel through the permeable strata encountered in the lower two thirds of the hole and grout over the upper third (refer to Section 2.1 below for geological information).

The Crystal has been operational since 2012, but it has taken several years for some of the relevant building monitoring data to come on stream. Hence it is only now that initial interpretation of these data can commence.

Figure 1. The Crystal building in East London.

2.1 *Ground Conditions*

The site is underlain by a sequence of London Basin deposits. The piles are founded in the London Clay, but also pass through a significant thickness of superficial and man-made deposits (Table 1). The boreholes continue through the full sequence of strata and are installed for approximately two thirds of their length in the aquifer formed by the Chalk and the overlying Thanet Sands. As the site is located near to the confluence of the Thames and the River Lea in east London, the groundwater table is close to the ground surface, at the base of the Made Ground.

2.2 *Pile and Borehole 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 four pipes (two U-tubes), themselves inserted into the pile attached to a 40 mm steel bar for stiffness. The U-pipes, the steel bar and the thermistor strings were installed to a depth of 20 m 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 8.5 m below the pile cut off level it was not possible to extend the outer thermistor strings over the full 21 m pile depth.

Thermistor strings were also installed in one of the borehole heat exchangers and two additional monitoring boreholes (Loveridge et al, 2013). However, damage occurred to buried cabling during construction which unfortunately meant that data access to these instruments was lost and could not be re-established.

All instrumentation was wired into a datalogging system located in the energy centre building adjacent to The Crystal. The logger can be accessed remotely to allow monitoring of the system from offsite. Temperature data have been collected since the summer of 2012.

Table 1. Ground conditions at the Crystal

Strata	Description	Depth
Made Ground	Fine to coarse brick and concrete gravel; soft to firm black sandy gravelly clay.	3.3m
Alluvium	Very soft clayey silt, sandy clay and peat.	6.3m
River Terrace Deposits	Medium dense silty fine to coarse sand and fine to coarse gravel (mainly flint)	11.2m
London Clay	Stiff thinly laminated fissured silty clay with silt partings	23.5m
Lambeth Group	Silty fine sand and fissured silty clay	43.3m
Thanet Sands	Very dense, slightly silty fine sand	56.1m
Chalk	Medium density (Grade B3) chalk	>150m

Table 2. Depths of thermistors installed within the instrumented pile at The Crystal.

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	-

2.3 *Building Monitoring*

The Crystal is equipped with a comprehensive building energy management system (BEMS). Three heat meters record the heating and cooling energy delivered to the building. Two more heat meters record the amount of heat exchanged with the ground, one for the pile ground loop circuit and one for the borehole ground loop circuit. These data have been available since the spring of 2013, except the heat meter for the borehole ground loop which was not communicating correctly with the BEMS until 2015. Additionally, the ground loop heat meters require further adjustment to differentiate between the direction of heat transfer to (or from) the ground.

A further heat meter was installed by the University of Southampton on the pipe circuit for the instrumented energy pile during construction. However, this meter has also had substantial communication difficulties with the logging equipment and no data are available from this meter at the present time.

2.4 *Results*

Initial results from the pile monitoring during and immediately following construction are included in Loveridge & Powrie (2013a). These data, along with further measurements from a thermal response test carried out in an instrumented borehole at the site (Loveridge et al, 2013), show that the undisturbed ground temperature is approximately 12.8°C over the depth range relevant to the energy piles (refer to Figure 2).

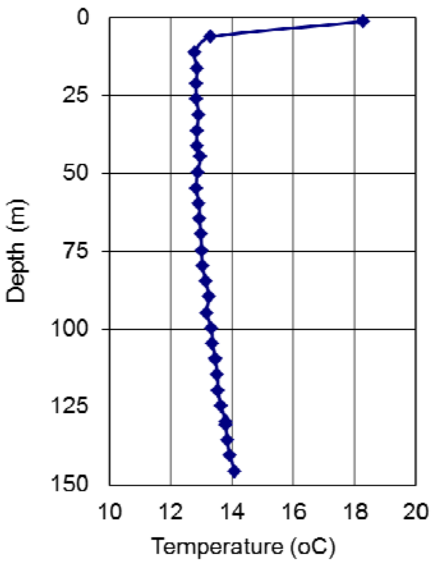

Figure 2.Undisturbed ground temperatures at The Crystal site.

For the purposes of initial analysis of performance, pile temperatures can be taken as approximately constant with depth. Consequently, average operational pile temperatures for the string attached to the pipes and those installed on the reinforcing cage are presented in Figure 3. Using averages removes local variations due to any asymmetric installation of the pile cage and central pipes and allows the overall trends to be identified. However, it does obscure axial effects, which are potentially important, but are outside the scope of this paper.

The data show large fluctuations in temperature at the centre of the pile, from approximately 7°C to 26°C. However, the temperature range at the steel cage, nearer the edge of pile, is much less, approximately 10°C to 18°C. It can also be seen that there is an overall rise in the temperature of the pile over the three years of monitoring. In the summer of 2015 the average temperature of the thermistors installed on the pile cage was approximately two degrees warmer than at the start of monitoring in summer 2012, when it was close to the undisturbed condition (Figure 2).

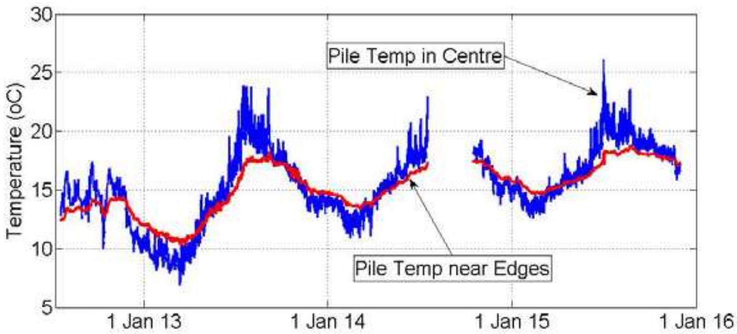

Figure 3. Average operational pile temperatures since 2012 (data gap in the autumn of 2015 due to data logger malfunction).

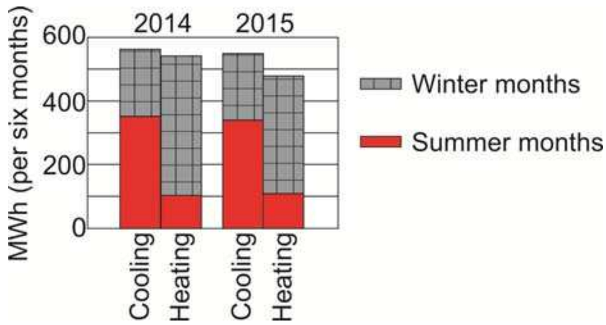

Figure 4. Energy demand of The Crystal during 2014 and 2015. Winter months taken as January to April and November to December; summer months taken as May to October.

The rise in pile temperature is likely to represent a net transfer of heat from the building to the ground during the first three years of operation. However, when the overall thermal energy demand of The Crystal is analysed, the heating and cooling profile is close to balanced (Figure 4), with annual demand approximately 550 MWh per year each for both heating and cooling. On the other hand, the instantaneous rate of energy demand does differ between heating and cooling (Figure 5). The maximum power demand in heating is 399 kW, while in cooling it is 572 kW. This may be the cause of the net heat injection to the ground. Another factor that cannot be assessed yet is the relative contribution of the piles and boreholes to the heating and cooling demand. For example, the piles could be taking a different heating/cooling ratio compared to the borehole field. Finally, the weather during the period of assessment must be considered to place any trends in context. Table 3 shows that during the last four years temperatures in the UK have been warmer that the long term average by several degrees. This may also have affected the rise in temperature seen within the instrumented pile during this period by triggering a higher than normal cooling demand.

Global coefficient of performance (COP) data for the ground source heat pump system at The Crystal can be taken as an initial indicator of the energy efficieny of the system. Current data suggest COPs between 2.5 and 3.0 depending on the time of year. However, the operational control system is still being optimized, hence these values are expected to increase in the future.

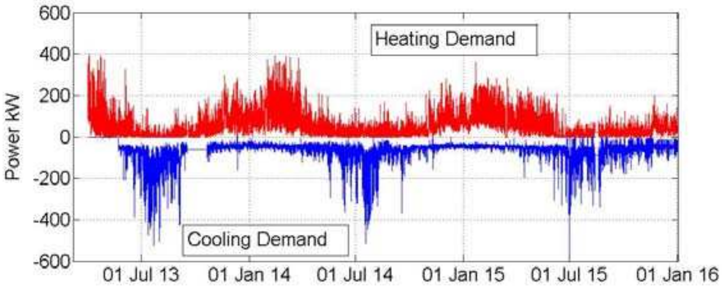

Figure 5. Heating and cooling power required at The Crystal since summer 2013

Table 3. UK mean annual temperature anomalies compared with 1961 to 1990 long term average

Year	Temperature Anomaly (°C)
2015	+0.9
2014	+1.6
2013	+0.5
2012	+0.4

3 22 STATION ROAD, CAMBRIDGE

22 Station Road (Figure 6) is the new building for Mott MacDonald and Birketts in Cambridge. It forms part of the extensive redevelopment of the zone around Cambridge Station known as CB1. The building comprises a basement carpark and a further six floors of office space.

The building is founded on 81 CFA piles of 450 mm diameter and 68 CFA piles of 600 mm diameter. Pile lengths are between 20 m and 25 m. Each pile is equipped with a single polyethylene pipe U-loop. As at The Crystal, the pipes were plunged into the centre of the pile following insertion of the steel reinforcing cage. In this case the pipes were attached to a 32 mm diameter steel bar for weight and stiffness.

The U-loop pipes from individual energy piles were connected together to form a series circuit with the pipes from adjacent piles. Each circuit contains between four and six piles and is connected to the header pipes at the manifold located in the building basement. The header pipes then run to the upper floor of the building, where the heat pumps and other plant are located.

3.1 *Ground Conditions*

The ground conditions at the site are Made Ground, overlying River Terrace Deposits and Gault Clay. Owing to the construction of a new basement and the lowering of the original ground level, the piles were constructed over their full length through the Gault Clay. Boreholes from the site describe the Gault as initially a firm to stiff slightly sandy slightly silty calcareous CLAY to approximately 6.5m below pile cut off level. Beneath this the Gault becomes a stiff to very stiff laminated and fissured calcareous CLAY.

The groundwater table at the site is relatively high, with water strikes during borehole drilling rising to approximately 2m below pile cut-off level.

3.2 *Instrumentation*

A balanced circuit of up to six piles of 600 mm diameter energy piles, each 20 m long, was instrumented using thermistor strings. Each of the six piles was equipped with two four-thermistor strings attached to the U-loop pipes and four two-thermistor strings attached to four of the six main bars on the reinforcement cage (Figures 7 & 8). Table 4 gives a summary of the thermistor levels. As at The Crystal the steel reinforcing cage did not extend the full depth of the pile. Therefore fewer thermistor levels were installed on the steel cage compared with the central pipes.

Figure 6. Artist's impression of the completed building at 22 Station Road (source: http://www.cb1cambridge.eu/22-station-road)

Heat meters were installed by GI Energy on the six-pile circuit where it reached the manifold in the basement, to enable further monitoring of the performance of the ground energy system as a whole and to record:

- Thermal Energy Power (kW)
- Cumulative Thermal Energy delivered (kWh)
- Flow Rate (L/sec)
- Flow Temperature (ºC)
- Return Temperature (ºC)

All the GI Energy monitoring points and the University of Southampton thermistor strings were connected via remote panels to the same monitoring system to allow web-based desktop reading of the data from any location.

Figure 7. Detail of thermistor strings installed on the steel cage at 22 Station Road.

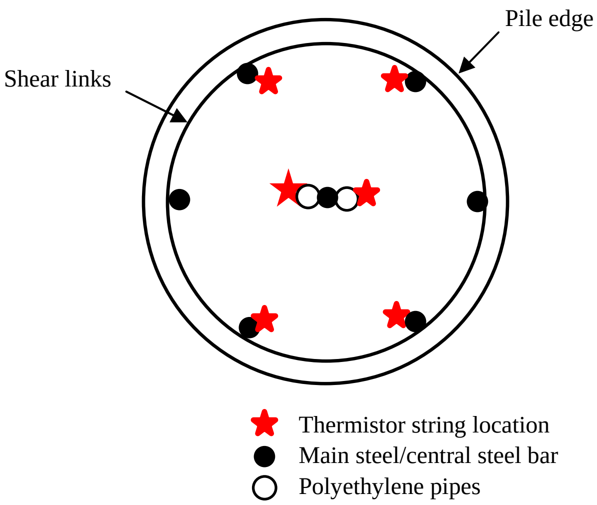

Figure 8. Schematic arrangement of thermistor strings within the instrumented piles at 22 Station Road.

Table 4. Depths of thermistors installed within the piles at 22 Station Road.

Thermistor Level	Height Above Pile Toe (m)	
	Central Strings	Outer Strings
1	17.5 – 18.0	17.5 – 18.0
2	13.5 – 14.0	13.5 – 14.0
3	7.5 – 8.0	7.5 – 8.0
4	1.5 – 2.0	1.5 – 2.0

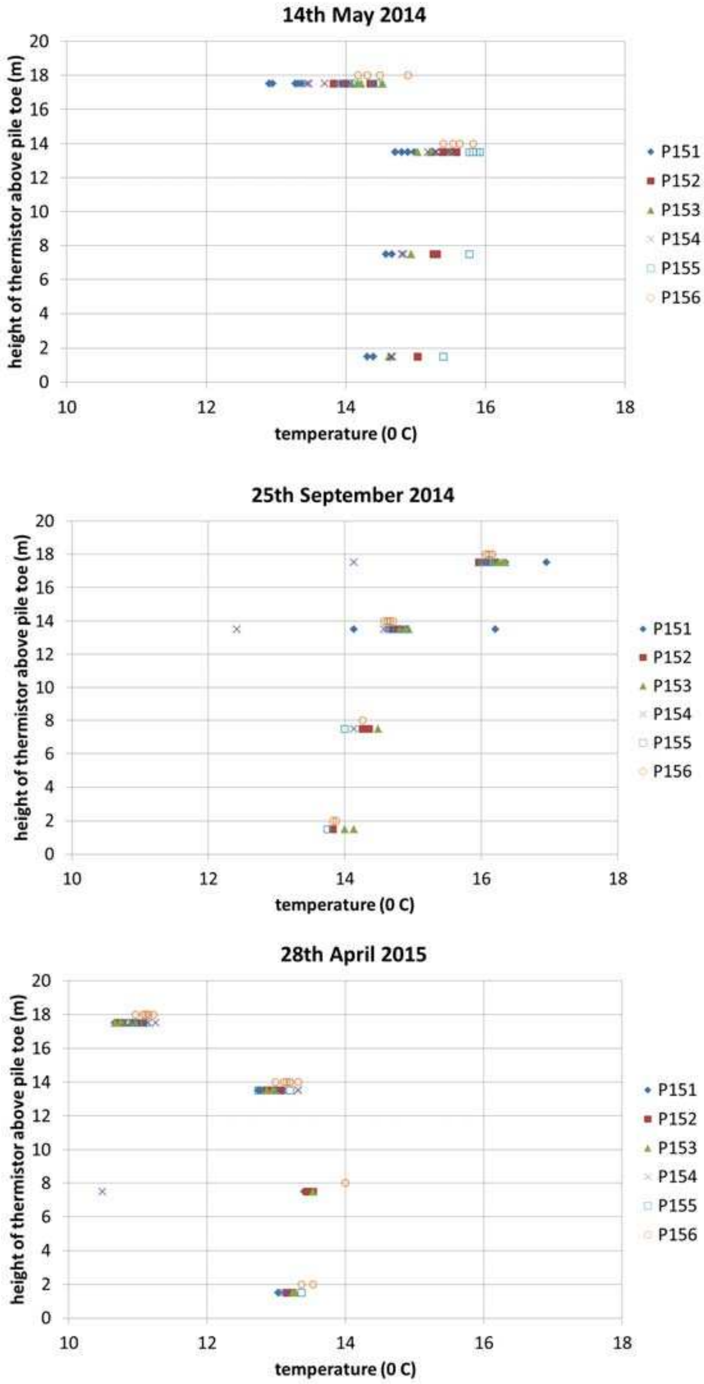

Figure 9. Temperatures within the six instrumented piles at 22 Station Road at three dates during construction.

3.3 *Initial Data*

The remote monitoring system is not yet available as final commissioning of the system is ongoing. However, spot readings from the thermistors were taken at various points during construction (Figure 9). The piles were cast during April 2014, with the slab construction proceeding the following month. By September 2014 the instrument cables and polyethylene pipes were all routed to the manifold located in the basement and the building was being constructed around this. Subsequent readings were taken in the autumn of 2015 as the cables were wired into the remote panels. By this time the structure was largely complete, although fit-out and commissioning work continued throughout the remainder of the year.

Spot readings from the thermistor strings at three points during construction of the building are shown in Figure 9. Shortly after construction of the piles (May 2014) there was an elevated temperature of 14°C to 16°C in the lower part of the piles, probably reflecting the residual heat of hydration of the concrete. At the top of the piles the temperature readings were reduced, reflecting the time of year (late spring to early summer) when summer air temperatures had not yet had a chance to be reflected in the near surface layers. By September 2014 the upper part of the piles have increased in temperature as the average air temperature also increased over the summer, but the values recorded in the lower part of the pile have reduced as the heat of hydration in the pile dissipates. The following spring, in April 2015, when it can be assumed that the heat of hydration has fully dissipated, the temperature near the base of the piles was around 13°C. This can be taken as representative of undisturbed conditions. Lower temperatures were recorded near the ground surface, reflecting the cooler air temperatures in the preceding winter period.

4 DISCUSSION

4.1 *Lessons learnt from installations*

The Crystal instrumentation was arranged very close to construction which left few options for optimising the thermistor arrangements within the framework of the thermal design of the system. By contrast, involvement with the development of the new building at 22 Station Road commenced much earlier in the project cycle. This allowed greater planning time and as a result the entire six pile circuit was instrumented rather than just one of the piles within a circuit as at the Crystal. This additional planning also allowed integration of the pile and building monitoring systems into a single remote access arrangement.

Both case studies illustrate the need to allow sufficient redundancy within any instrumentation scheme implemented within the framework of a live construction project. In only instrumenting one pile at the Crystal, it was fortunate that most of the thermistors have remained fully functional for over three years. However, unfortunately, access to the borehole heat exchanger instrumentation was lost due to cable breaks, caused by construction which were subsequently buried before they could be located and rectified. Having six piles instrumented at Station Road has meant the significance of some instrument losses during pile breakout has been reduced. A further lesson regarding redundancy learnt from the Crystal and applied to Station Road was the inclusion of two strings attached to the central pipes installed within each pile.

One advantage of the building arrangement at the Station Road site is that the manifold is located within the basement of the building, making it potentially much more accessible in the future. The corresponding manifold at The Crystal is contained within a deep manhole in the grounds of the building. While this is accessible, additional health and safety considerations of the deep manhole make maintaining instrumentation in this area (the heat meter and a logger remote panel) more challenging.

At both sites it would have been beneficial to have included in-ground instrumentation to provide additional temperature data beyond those measured within the piles. Despite the additional planning time available at Station Road, it just would not have been possible within a tight construction programme on a very constricted site to bring in additional plant to achieve this goal. Consequently this additional information remains recommended for future monitoring sites where possible.

4.2 *Key observations from operation*

The building at 22 Station Road has yet to experience an operational period. However, operational data are now available for a number of years at The Crystal, although not all of the building monitoring equipment has been online for the entire duration. Nonetheless some interesting observations can be drawn out.

As shown in Section 2.4 above, despite a nominally balanced energy requirement it is possible for the peak power requirements to be uneven. This may be responsible for the gradual increase in the pile temperatures over the last three years, however, other factors may also be relevant and additional data are required to analyse these. Nonetheless, the observation still demonstrates an important point with regard to the design of ground source heat pump systems. The data show how lumped demand can be misleading when real demand varies over short timescales. This is illustrated in Figure 10, which shows some detail from Figure 5 during two days in July 2015. Consequently, design of complex ground source heat pump systems should be carried out using hourly energy demand data (kWh per hour) – effectively instantaneous power.

Differences in predicted system capacities when using longer duration rather than hourly demand data has recently been highlighted by Zhang (2016), who used hourly, monthly and yearly demand data for a Westminster wide district heating study and compared the results. In this case the use of monthly or yearly demand data was found to be non-conservative in terms of estimating the proportion of the city that could be included within the district heating scheme. The difference in predicted capacity between using monthly or yearly data and using hourly data was between 10% and 15%.

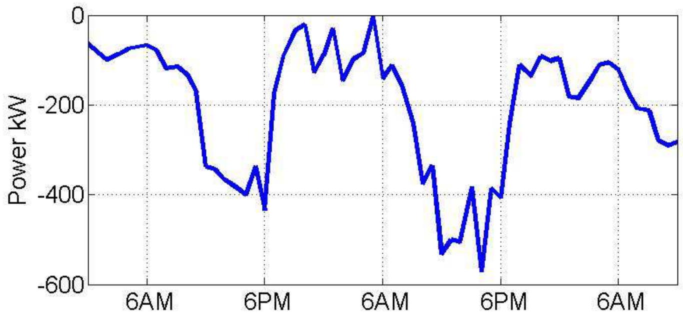

Figure 10. Hourly cooling demand at the Crystal during two days in July 2015

The second important observation from The Crystal data is the extent of the temperature gradient across the instrumented pile. This varies throughout the year (Figure 11) and reaches a peak value of approximately 8 degrees. Peak values typically occur at times of peak demand. The additional superimposed variability is a reflection of two factors, first the variable thermal load (Figure 5 & Figure 10) and secondly the fact that the pile is not at a thermal steady state as assumed by many design approaches.

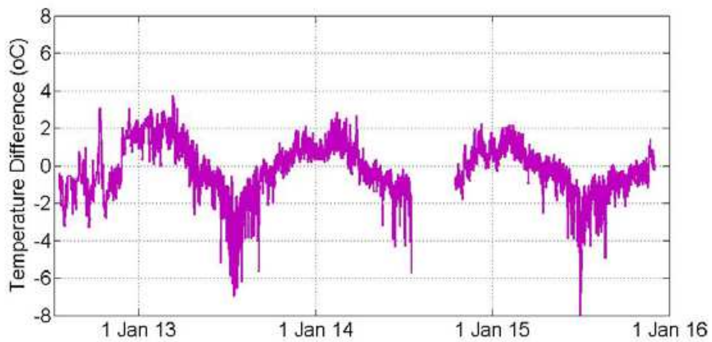

Figure 11. Temperature difference between the thermistor strings installed on the pile cage and those on the central U-pipes. Positive difference indicates a cooler pile centre and hence heat extraction from the pile and ground.

The thermal load and pile temperature data can be used to quantify the degree of steady state within the pile. For clarity, considering only the same two days in July (Figure 10), Figure 12 shows corresponding changes in apparent thermal resistance. Thermal resistance is the ratio of the thermal power applied to the pile and the temperature difference across the pile. In this instance it has been calculated using the pile temperature sensors and hence is not the full pile resistance, just the resistance between the outside of the pipes and the pile cage. In this case the term "apparent" thermal resistance has been used since strictly speaking resistance is a steady state concept and within this large diameter pile a steady state will not be present. Nonetheless, consideration of the changes in values of apparent resistance allows some interesting observations to be made.

The results show that the calculated apparent resistance in the pile concrete is far from constant (as would be the case if there was a thermal steady state). When there is a sustained period of heat injection (Figure 10) the apparent resistance stabilises at approximately to 0.1 mK/W, and this could be close to a steady state value. Certainly it is not an unreasonable value for a pile of this size and type (e.g. SIA, 2005).

However, sometimes the apparent resistance value is smaller than this and often the value is larger. The larger values reflect periods when the thermal load is reducing so that the temperature close to the pipes is falling more quickly than at the pile edge. In these cases as the power drops, the temperature difference also drops but not as rapidly. This causes the apparent increase in resistance.

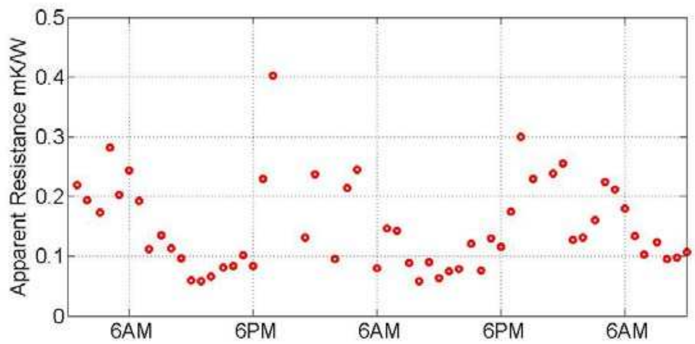

Figure 12. Apparent thermal resistance of the pile between the pipes and the steel cage, calculated for two days in July 2015.

The implications of the absence of a thermal steady state within the pile are described by Loveridge & Powrie (2013b). Assuming a steady state where none is present can lead to the overestimation of the temperature changes that will occur within the pile and the ground. This means that the true capacity of the associated ground source heat pump system will be underestimated during design.

5 SUMMARY

This paper presents initial results from two energy pile monitoring schemes in the UK. Such schemes are essential to allow better understanding of the long term benefits of using energy piles with ground source heat pump schemes and also to allow verification of appropriate and rigorous design approaches.

Initial data from the first scheme are showing the importance of understanding the nature of the applied thermal loads for such systems. This is in terms of both the overall seasonal energy balance and the short term variation in demand.

The short term variation in demand also contributes to the variable temperature observed within the pile. This causes fluctuation in the temperature difference across the pile and hence also the dynamic thermal resistance. Such transient behavior must be accounted for in design to prevent under-estimation of the ground source heat pump system capacity.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

Amis, T. & Loveridge, F. (2014) Energy piles and other thermal foundations for GSHP – Developments in UK practice and research, *The REHVA European HVAC Journal*, January, 2014, 32 – 35.

Bourne-Webb, P. (2013) Observed response of energy geostructures, In: Laloui & Di Donna (Eds), *Energy Geostructures*, Wiley, London. p 45 – 77.

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

Loveridge, F. & Powrie, W. (2013a) Performance of Piled Foundations Used as Heat Exchangers, In: *Proceedings of the 18th International Conference for Soil Mechanics and Geotechnical Engineering*, Paris, France, September 2-5, 2013.

Loveridge, F. & Powrie, W. (2013b) Temperature response functions (G-functions) for single pile heat exchangers, *Energy*, 57, 554 – 564.

Loveridge, F., Holmes, G., Powrie, W. & Roberts, T. (2013) Thermal response testing through the Chalk aquifer, *Proceedings of the Institution of Civil Engineers Geotechnical Engineering*, 166 (2), 197 – 210.

Met Office (2016) Climate summaries [online http://www.metoffice.gov.uk/climate/uk/summaries; accessed 21st January 2016].

Nicholson, D., Smith, P., Bowers, G. A., Cuceoglu, F., Olgun, C. G., McCartney, J. S., Henry, K., Meyer, L. L. & Loveridge, F. A. (2014a) Environmental impact calculations, life cycle cost analysis, *DFI Journal*, 8 (2), 130-146.

Pahud, D. & Hubbach, M. (2007) Measured Thermal Performances of the Energy Pile System of the Dock Midfield at Zürich Airport, *Proceedings European Geothermal Congress 2007*, Unterhaching, Germany, 30 May-1 June 2007.

SIA (2005) *Utilisation de la chaleur du sol par des ouvrages de fondation et de soutenement en beton, Guide pour la conception, la realisation et la maintenance,* Swiss Society of Engineers and Architects, Documentation D 0190. (In French).

Suckling, T. P. & Smith, P. E. H. (2002) Environmentally Friendly Geothermal Piles At Keble College, Oxford, UK. *In: Proceedings of the Ninth International Conference on Piling and Deep Foundations*, 2002, Nice, France. Deep Foundations Institute, New Jersey, USA.

Zhang, Y. (2016) *Application Potential of Shallow Geothermal Energy at City Scale*. PhD Thesis, Department of Engineering, University of Cambridge