ASSESSING THE APPLICABILITY OF THERMAL RESPONSE TESTING TO ENERGY PILES

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Abstract Deep foundations are increasingly being used, not just to carry structural loads, but also to act as heat exchangers as part of a ground source heat pump system. Such foundations, often called energy piles, have the potential to make significant contributions towards meeting the heating and cooling demands of buildings, thus reducing the overall energy consumption and carbon dioxide emissions during their lifespan. To ensure that the available energy from these systems is maximized, it is important to determine the thermal conductivity of the surrounding soils, a key design input parameter. In situ thermal response tests are commonly used to carry out this task for small diameter borehole heat exchangers. However, there has been debate over the applicability of these tests to energy piles due to their larger diameter and the consequent increased influence of the pile thermal properties on the test outcome. This paper examines the results of three thermal response tests carried out on piles of different diameters and thermal properties installed at the same site in Texas. Transient analysis of the test results, combined with comparisons to laboratory testing of soil samples from the site, is used to given an indication of the applicability of the thermal response test over different timescales for the different piles. It is concluded that the test is most suited to smaller diameter piles constructed with lower thermal diffusivity materials. Recommendations are given for the conduction of pile thermal response tests and interpretation of test data.

INTRODUCTION

As issues of energy security and scarcity become more important, the use of ground source heat pumps to provide renewable and sustainable heating and cooling to buildings is set to increase. Traditionally such systems use special purpose ground heat exchangers to extract and/or inject heat from/into the ground. The heat exchangers comprise a series of plastic pipes cast into the ground and then connected to the heat pump via a series of header pipes. In the case of building space heating, the heat pump then steps up the temperature difference to deliver the extracted heat at a useable level. However, financial and carbon savings can result by utilizing the building foundations as heat exchangers as well as to carry the building structural loads.

Piles, often termed "energy piles", are the most common type of foundation heat exchanger, and their construction has been increasing in recent years (Amis et al, 2009). However, while energy piles have the potential to make significant contributions towards meeting building heating and cooling demands, there remains scope for improving their thermal efficiency through improved analysis approaches (e.g. Loveridge & Powrie, 2013). In fact the greater diameter of many energy piles means they have the potential to deliver increased short term thermal energy storage compared to more commonly installed borehole heat exchangers.

Appropriate selection of thermal parameters is also important in the design of heat pump systems. One parameter which is important for maximizing the thermal output of energy piles is the choice of the design value of soil thermal conductivity. As with other geotechnical parameters, thermal conductivity can be determined in the laboratory. However, there are advantages of field testing, including the ability to test a larger volume of soil, the presence of the correct in situ stresses and groundwater conditions and the avoidance of disturbance during sampling (Graham, 2006).

Field testing for thermal conductivity is most commonly carried out by in situ thermal response testing (Sanner et al, 2005; IGSHPA, 2007). In this method, developed for use with small diameter borehole heat exchangers, heat is injected into the ground at a constant rate via fluid circulated within the heat exchanger pipes. Measurement of the inlet and outlet temperatures to and from the heat exchanger with time is then used for derivation of the thermal conductivity of the surrounding soil. By its very nature the test considers a large volume of soil and returns a single lumped value of thermal conductivity for the full depth of the heat exchanger.

However, simple and commonly applied interpretation methods for thermal response tests rely on the heat exchanger reaching a thermal steady state rapidly so that the test can be completed within 2 or 3 days. This is appropriate for small diameter boreholes. Pile heat exchangers, on the other hand, have a larger diameter, and may take several days to reach a thermal steady state (Loveridge & Powrie, 2014). For this reason international standards suggest that tests should only be carried out on heat exchangers of 152mm (6 inches) diameter or less (IGSHPA, 2007). Despite this, the prospect of extending the applicability of thermal response testing to energy piles is attractive and research is being carried out in a number of institutions to develop test and interpretation methods (e.g. Loveridge, 2012; Bouazza et al, 2013; Hemmingway & Long, 2013). However, the only guidance currently available suggests that application of thermal response tests to energy piles should be limited to those of 300mm diameter or less (GSHPA, 2012).

BERKEL TEST SITE

Berkel & Company have developed an energy pile test site at the location of their regional offices in Richmond, Texas (Brettmann et al 2010; 2011). Three energy piles were installed using auger pressure grouted (or continuous flight auger) techniques to a depth of 18.3m (60 foot). Two polyethylene U-tubes were installed in each pile by attaching them to the outside of a series of 127mm (5 inch) diameter spacers installed on a 25mm (1 inch) diameter steel bar (Figure 1). Two of the piles were 305mm (12 inch) diameter and one was 457mm (18 inch) diameter. They were arranged in a triangular pattern and a soil boring was constructed in the center (Figure 2) to confirm the ground conditions and allow sampling for material properties. Two of the piles were constructed using standard cementitious grout (3.1:1:1.1 cement : fly ash : sand by weight, with a water cement ratio of 0.45), and one using bentonite/silica sand grout (i.e. a "thermal grout") that would more typically be used for borehole heat exchanger applications. A non-shrink additive was also included in the mix designs for both types of grout.

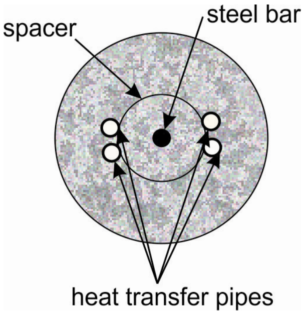

Figure 1. Heat Exchanger Pipe Arrangements (shown for 305mm diameter pile)

Ground conditions at the site comprised 9.8m (32 foot) of silty and sandy clay, overlying 7.6m (25 foot) of dense to very dense sand, with the pile toe in an underlying thin layer of stiff clay. The groundwater level was at 3.3m (11 foot) below the ground surface (Figure 3). Tube samples of the upper clay and split spoon samples of the sand and lower clay were taken for laboratory testing (Table 1). As well as soil characterization, thermal conductivity testing was carried out by the needle probe method (ASTM, 2005). This test is in many respects analogous to a thermal response test but occurs at a much smaller scale, with the radius of soil tested being less than 20mm. However, as noted above, this laboratory test lacks the in situ confining pressure which can potentially affect the sample void ratio and result in a thermal conductivity value different to that obtained in the field.

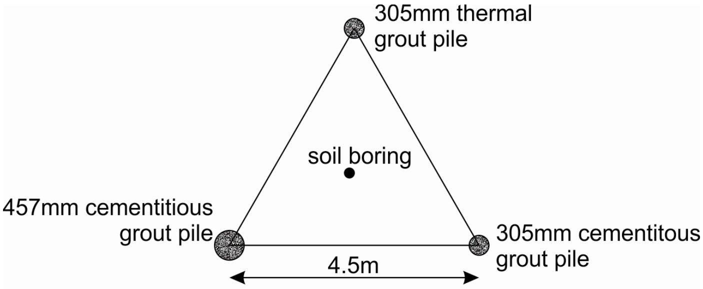

Figure 2. Site Layout

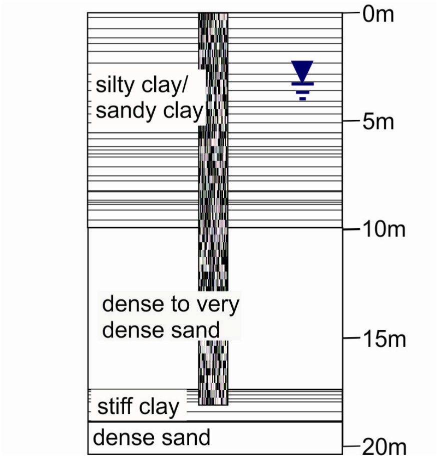

Figure 3. Ground Conditions

Table 1 Soil Laboratory Test Results

Sample	Moisture Content	Density	Thermal Conductivity
Clay (6.1m)	21.1 %	1.73 Mg/m^3	2.22 W/mK
Sand (13.7m)	14.0 %	1.73 Mg/m^3	4.05 W/mK
Clay (18.3m)	28.0 %	1.54 Mg/m^3	2.09 W/mK

THERMAL RESPONSE TESTS

Berkel & Company have conducted a series of thermal response tests on the three energy piles at the test site, both individually and as a group (Brettman et al, 2010; 2011). The tests involved input of a constant heating power to the system fluid which was circulated through the pipes within the energy piles. The tests were run for up to approximately 100 hours, with heat inputs between 1.4 kW and 2.3 kW for the individual pile tests (see also Figure 4). As well as recording the inlet and outlet temperatures to the energy piles, temperature sensors had been installed on the central steel bar within the piles at depths of 6.1m (20 foot), 13.7m (40 foot) and 18.3m (60 foot).

In this paper we will focus on three tests carried out on the individual piles, each connected to the test rig using both U-tubes. All the tests were carried out according to recommended best practice (AHSRAE, 2001).

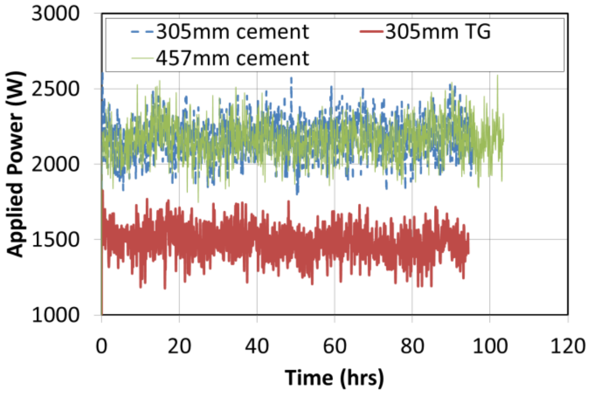

Figure 4 Power Fluctuations during the Thermal Response Tests

Data Interpretation

The tests have been interpreted using the simple line source method. This is based on the assumption that the energy pile behaves like an infinitely long line heat source of constant power, installed within an infinite soil medium with a uniform initial temperature field. When the heat diffusion equation is solved for this case, the evolution of the temperature of the heat exchanger becomes a linear function of the natural logarithm of time, provided that sufficient time has elapsed. Therefore if the gradient of the average of the inlet and outlet temperature to the energy pile during the test are plotted against the natural logarithm of time then:

$$\lambda = \frac{Q}{4\pi Hk} \qquad (1)$$

where λ is the soil thermal conductivity (W/mK), Q is the total applied thermal power (W), H is the length of the pile (m) and k is the gradient of the graph. Due to the mathematical simplifications involved in the line source model it is normally recommended that the results prior to $Fo=5$, where $Fo = \alpha t/r_b^2$, are neglected. In this expression for dimensionless time α is the soil thermal diffusivity (m^2/s), t is the elapsed time (s) and r_b is the pile radius (m).

As well as the mathematical simplification mentioned above, the line source method also assumes that the heat exchanger itself is at a thermal steady state. This means that the temperature difference between the fluid in the pipes and the edge of the pile is constant. When this is true, the thermal properties of the heat exchanger concrete or grout do not influence the gradient k. With energy piles there is concern that the pile does not develop a thermal steady state until several days after the tests has started. This means that the pile thermal conductivity and diffusivity may influence the calculated thermal conductivity of the ground. In the following sections we investigate this possibility by examining the results of the thermal response tests in both a static and a transient manner.

RESULTS

Static Interpretation

Initially the soil thermal conductivity (Table 2) was calculated from the graph of the fluid temperatures vs. natural logarithm of time as described above. The calculations were done for the case where $Fo \geq 5$, assuming $\alpha=1\text{x}10^{-6} m^2/s$, a typical midrange value for soils. This equates to around 32 hours for the 305mm diameter piles and 73 hours for the 457mm pile. It should be noted that the results are not identical to those presented by Brettmann et al (2010) as only ten hours of the initial data were discarded in that case (as is common practice for small diameter heat exchangers). If the calculated thermal conductivity converges during transient interpretation (see below), then the difference in analysis start times should not have a large influence on the results. However, in some cases this condition is not met and the reasons for and consequences of this will be discussed below.

The thermal response test results presented in Table 2 are all within 0.16 W/mK of each other. Theoretically the results should be the same in each case, but to be within 6% is reasonable, given the test is generally only accepted to be accurate to within 10% (Javed & Fahlen, 2011; Witte, 2013). Table 2 also presents the average soil thermal conductivity calculated from the laboratory tests. This is higher than the in situ test results by around 12%.

Table 2 Results of Thermal Response Tests (Static Interpretation, $Fo \geq 5$)

Case	Thermal Conductivity	Mean Applied Power
305mm cementitious pile	2.73 W/mK	2171 W
305mm thermal grout pile	2.58 W/mK	1484 W
457mm cementitious pile	2.72 W/mK	2161 W
Weighted average of soil testing over pile depth	2.98 W/mK	N/A

Transient Interpretation

The conditions for the line source model are not met perfectly by the tests. This is due to factors including the pile finite length and diameter (which means that the pile is a long way from an ideal infinitely long and zero thickness heat source), the expected non-uniform initial temperature field and the potential for power fluctuations during the test (Figure 4). Consequently, the precise portion of the test datasets which are used in the interpretation will determine the final calculated thermal conductivity. To investigate the validity of the results presented in Table 2, and of the test method itself, a transient approach has been adopted to the interpretation of the test data. The portion of the datasets used in calculation of the slope gradient k, and thus the thermal conductivity λ, has been systematically varied.

Any fluctuations in the power supply (Figure 4), either directly due to instability in supply, or indirectly due to the influence of the ambient air temperature (i.e uncontrolled external effects due to exchange of heat with the surrounding air) also affect the results. These effects cause more significant errors in the resulting thermal conductivity as the test progresses and smaller portions of the test results are used in the interpretation. To minimize this effect, the transient analysis has been carried out using data from the temperature sensors embedded within the piles, rather than the fluid temperature measurements. This will cause damping of any short term power variation effects. In all three cases the 6.1m and 13.7m temperature sensors were averaged; the 18.3m temperature sensor was not used as this could potentially be influenced by any end effects at the base of the pile.

For each thermal response test five different analysis start times have been used: $Fo=1, 2, 3, 4$ & 5, with the analysis end time then being varied from immediately after the start time until the end of the test. The results are presented in Figures 5, 6 & 7 for the three energy piles. The first important observation is the cyclic nature of the results. The peaks and troughs have an approximate 24 hour wave length, indicating that these fluctuations relate to imperfect insulation of the surface pipework leading to influence of the ambient air conditions on the results. The effect of ambient air conditions on these tests has been separately investigated using 3D numerical modeling and was posed as a possible cause of the measured temperature fluctuations (Olgun et al., 2014). This effect is greatest when the start time of the analysis is closest to the end of the test, i.e. the sub-set of the dataset under consideration is small. This is most obvious in Figure 7, for the larger pile, where $Fo=5$ is equivalent to a longer time period, approximately 73 hours, and is therefore close to the end of the test.

Only the 305mm diameter cementitious pile shows any convergence of the calculated thermal conductivity as the test progresses (Figure 5), with λ=2.75 W/mK being a common value once the test time has exceeded approximately 70 hours. There is still some small increase in thermal conductivity with time after this, but it is small.

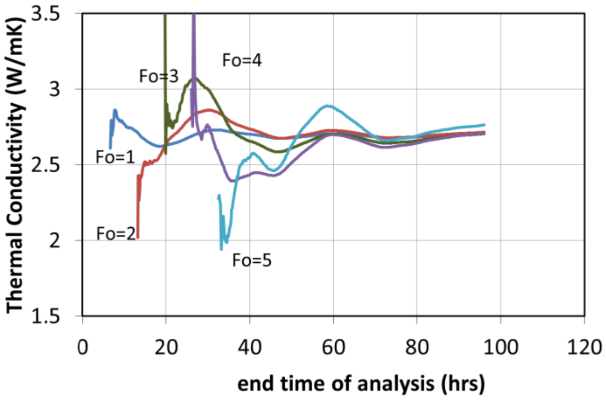

Figure 5 Transient Thermal Conductivity for 305mm Cementitious Pile

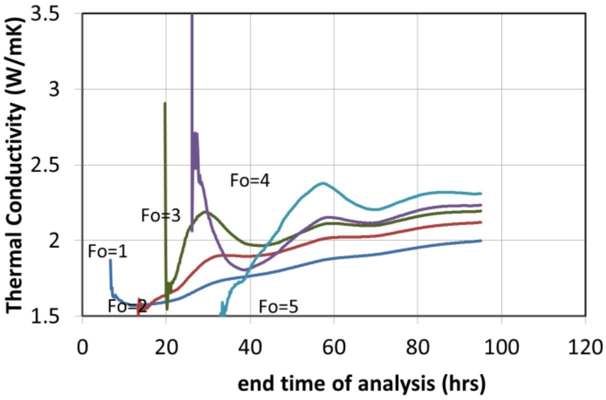

Figure 6 Transient Thermal Conductivity for 305mm Thermal Grout Pile

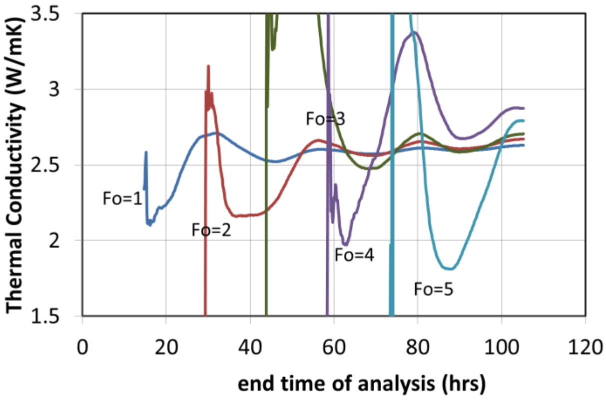

Figure 7 Transient Thermal Conductivity for 457mm Cementitious Pile

By contrast the 305mm diameter pile with the thermal grout shows a distinct increase in the calculated thermal conductivity throughout the test, with no convergence between values calculated with different start times (Figure 6). The 457mm diameter pile on the other hand gives highly variable results (Figure 7). The effect of the ambient temperature is far greater for this pile. Without these fluctuations it may be possible to suggest some convergence of the results, but given the variations act to mask possible trends, the results are much less reliable. The reason for the greater variability relates to the larger diameter. Although the test is of similar length in real terms, in terms of non-dimensional time, *Fo*, the test duration is shorter with respect to the pile diameter.

It is also instructive to consider the calculated thermal conductivity for each test when the end time of the analysis is kept constant. This is shown in Figure 8 for a common 95 hour test duration. This way of presenting the results strengthens the observations made above. First, the 305mm diameter cementitious pile shows the most consistent and stable calculation of thermal conductivity. The exception to this is when the analysis commences at higher values of *Fo*, close to the end of the test. For *Fo* > 8 there is a sharp increase in thermal conductivity. This could be explained by two phenomena. Either it is a reflection of the increased sensitivity to variability towards the end of all the tests when the sub set of data being considered is small. Alternatively, it may be a reflection of end effects. The latter is less likely as only the temperature sensors within the central portion of the pile were used. However, it is recognized that end effects for energy piles do start to become significant by the time *Fo=10* (Loveridge & Powrie, 2013).

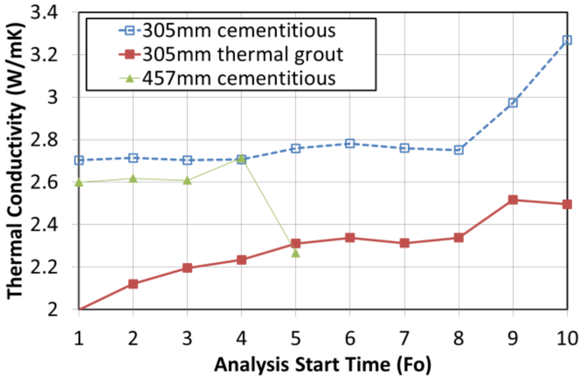

Figure 8 Transient Thermal Conductivity for all Piles with Constant Analysis End Times (95 hours)

Figure 8 again shows that the 305mm diameter pile with thermal grout gives consistently increasing thermal conductivity throughout the test. The results come to a brief plateau around *6 < Fo < 8*, before a step increase in the latter part of the test, which could be related to the reasons discussed above. The 457mm diameter pile only shows the thermal conductivity calculated until *Fo=5* due to the larger pile diameter. The values are briefly consistent, but soon the effect of ambient conditions near the end of the test comes to dominate.

In terms of the actual values of thermal conductivity calculated by the analysis, the two cementitious piles show similar results, with λ between 2.6 W/mK and 2.8 W/mK. The pile with the thermal grout shows initially much lower values of thermal conductivity, only coming to approach 2.5 W/mK at the very end of the test duration. These values are broadly consistent with the static analyses presented in Table 2. However, the advantage of performing the transient analyses is that it provides a better understanding of the level of uncertainty associated with the static values. It should also be noted that the Table 2 and Figures 5 to 8 results should not be exactly equal in any case. This is because the static analysis makes use of the fluid temperatures while the transient analysis applies the temperature from the sensors embedded within the piles.

DISCUSSION

Influences on Test Results

While the thermal conductivity of the ground measured by a thermal response test should be independent of the pile properties, it is clear from the results presented that both the pile diameter and pile material are affecting the results of the test. There is some increased uncertainty with respect to the results for the larger diameter pile and a clear lack of convergence for the pile constructed using a thermal grout.

Both the thermal grout and the cementitious grout were tested in the laboratory and shown to have similar values of thermal conductivity, at around 1.35 W/mK (Brettmann et al, 2010). The fact that these results are lower than the laboratory test results for the soil thermal conductivity (Table 2) is consistent with the observed increase in calculated thermal conductivity during the thermal responses tests. If piles had been of higher conductivity grout compared to the surrounding soils then the calculated value of soil conductivity would be expected to reduce with time (Loveridge, 2012). These observations reflect the influence the grout thermal properties are having early in the tests. Given that the thermal response tests of the pile with the thermal grout always obtains a lower calculated value of thermal conductivity, then this also suggests that the rate of heat transfer through the thermal grout is slower than through the cementitious grout. This would suggest the thermal grout is of lower thermal diffusivity. While initially surprising, this result is consistent with laboratory measured densities for the two grouts: the thermal grout being approximately half the density of the cementitous grout. This means that the thermal grout diffusivity could be as much as half that of the cementitious grout.

The importance of the pile diameter in the test results is perhaps more obvious. The size of the pile is an input to the dimensionless time, Fo, and therefore for the thermal response test to be valid at $Fo=5$, a longer period of time is required to have elapsed for larger diameter piles. Larger diameter piles also take longer to reach a thermal steady state (Loveridge & Powrie, 2014) and during the transient initial period any results obtained will include some influence from the pile thermal properties as well as the surrounding ground.

Test Length and Interpretation

The tests presented in this paper were approximately 100 hours in length. For the 305mm diameter cementitious piles this appears to be long enough to obtain consistent results using the line source method. However, for the larger diameter pile and especially the pile constructed using a thermal grout, there remain uncertainties over the results when tested in this timescale. These uncertainties could be reduced by testing for extended periods. However, as end effects are expected to play a role beyond $Fo=10$, tests lengths beyond 100 hours for a 300mm diameter piles or 150 hours for a 450mm pile are not recommended in combination with a line source interpretation. In addition, ambient air temperature effects will increase in significance for longer tests. These factors suggest that a longer test duration may be appropriate for higher thermal diffusivity concretes or grouts (e.g. cementitous ones), but may not be reliable for lower thermal diffusivity pile materials.

A more thorough and rigorous approach would be to use an interpretation method which better reflects the real conditions within the pile and the ground. There are few bespoke analysis methods applicable for energy piles and hence numerical methods may be the most appropriate for this task. Ongoing work by the authors seeks to develop reliable routine interpretation methods applicable to short tests on large diameter piles.

Comments on Laboratory Results

The weighted average of the soil laboratory test results for thermal conductivity (Table 2) is higher than the values calculated from the thermal response tests. On the one hand this is surprising as some recent work is suggesting that in situ or large scale thermal conductivity can be significantly greater than laboratory scale thermal conductivity (Low et al 2014). This is backed up by numerical studies where parameter estimation techniques applied to thermal response tests suggested actual in situ thermal conductivity could be 30-50% higher than laboratory measurements (Olgun et al. 2014). This phenomenon potentially arises from changes in moisture content and loss of confining stress during sampling. The latter would lead to a change in void ratio of the sample and potential reduction in thermal conductivity as the void filling materials (water and air) are always less conductive than the soil grains (for example, see McCartney et al, 2013).

On the other hand, lower values of thermal conductivity calculated from the thermal response tests could suggest that even for the 305mm diameter cementitious piles, where the test results appear stable; there is still some influence of the lower conductivity pile grout. Finally, given the smaller scale of the needle probe laboratory tests, the potential for natural variability to influence these results must not be discounted. King et al. (2013) demonstrated that at least 12 to 16 separate measurements with a needle probe were needed until the geometric mean of those results was stable. Given the smaller number of tests conducted from the Berkel Test Site, some degree of uncertainty must also be attributed to the laboratory results.

Given these various factors, and considering all the results presented, it may be expected that both the laboratory and the thermal response tests remain an underestimate of the “true” thermal conductivity. The 12% discrepancy between the laboratory and in situ tests must therefore be regarded as a minimum error bar for the results overall.

CONCLUSIONS

The thermal response test is a useful in situ test for determining the thermal conductivity of the ground around a heat exchanger. Its application to piles requires some additional care and caution due to the potential for the pile properties to influence the result. Consequently greater errors are expected when applied thermal response test techniques to piles rather than boreholes.

When using the line source method, tests of 70 to 100 hours carried out on 300mm diameter piles (or smaller) which are constructed using cementitious material are expected to be reliable within acceptable tolerances. Larger diameter piles, or those where the pile is expected to transfer heat slowly (i.e. of low thermal diffusivity), will lead to greater uncertainties in results when subjected to short term tests. Longer duration tests can be appropriate in these cases, but the potential for the influence of end effects needs to be considered.

Consequently, the use of the simple line source methods are not recommended for piles when either 1) the test lengths extends significantly beyond Fo=10 or 2) the pile material is likely to be of low thermal diffusivity (e.g. a low density thermal grout). Care must be taken when carrying out longer duration tests on larger diameter piles (e.g. 450mm) as the ambient air temperature will have greater impact on the results. For all piles, the influence of this and the pile material should always be checked by applying the line source method in a transient manner so that any uncertainties with respect to the results can be understood. Further work is ongoing to develop alternative TRT interpretation methods for energy piles which will reduce these uncertainties and hence increase the robustness of future energy pile designs.

In the meantime, however, it remains important that appropriate error bars are considered with both in situ and laboratory thermal conductivity test data, and that the significance of these uncertainties are recognized in the design of ground sourced heat pump systems.

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