Group thermal response testing for energy piles

Les essais réponse thermique de groupe pour les pieux énergétiques

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ABSTRACT Thermal response testing is an in situ technique for characterising the thermal conductivity of the ground around a borehole heat exchanger. The test has seen renewed interest in recent years as an increasing number of ground heat exchangers are being constructed to provide renewable heating and cooling energy as part of ground source heat pump systems. The thermal response test involves applying a constant heating power to the ground via a circulating heat transfer fluid. Most test rigs are set up to cater for deep boreholes, with available heat transfer lengths typically more than 100m, and therefore have electrical heater capacities of a corresponding size. Pile heat exchangers are generally much shorter and the heat exchange length can be a little as 10m. This means that many standard thermal response test rigs cannot provide a low enough heating power and there is a risk of excessive temperature changes developing, especially during longer duration tests which can be recommended for larger diameter piles. One solution is to carry out the thermal response test on a group of piles, thereby increasing the effective heated length. This has the added advantage of testing a larger volume of soil. This paper examines the principles behind group thermal response testing for energy piles and considers the advantages and limitations of the approach with reference to a case study.

RÉSUMÉ Les essais réponse thermique sont une technique de chantier pour la caractérisation de la conductivité du sol autour d'un échangeur de chaleur dans un trou de forage. Depuis quelques années il y a de plus en plus d'intérêt autour de cet essai en raison du fait que l'on construit de plus en plus d'échangeurs de chaleur souterrains pour le chauffage et climatisation à énergie renouvelable comme partie des systèmes de pompe géothermique. Pour faire l'essai réponse thermique l'on expose de la puissance de chauffage constante au sol par moyen de la circulation d'un fluide caloporteur. La plupart des bancs d'essai sont conçus afin que l'on puisse les utiliser avec des trous de forage profonds, ayant typiquement plus de 100m de longueur de transfert de chaleur disponible, et ont donc des capacités de chauffage électrique de dimension adaptée. Les pieux géothermiques sont typiquement beaucoup plus courts et la longueur d'échange de chaleur peut n'être que de 10m. Par conséquent beaucoup de bancs d'essai réponse thermique ne peuvent pas fournir de la puissance de chaleur qui est suffisamment basse et il y a un risque de changements de température excessifs, en particulier pendant les essais d'une durée plus longue qui peut être recommandés pour les pieux de grand diamètre. Une solution est de faire l'essai réponse thermique sur un groupe de pieux, de cette façon on augmente la longueur chauffée effective. Ceci a l'avantage en plus de faire l'essai sur une plus grande volume de terre. Ce rapport examine les principes qui sous-tendent les essais réponse thermique de groupe pour les pieux énergétiques et aborde les avantages et limitations de l'approche en référant à une étude de cas.

1 INTRODUCTION

Thermal response testing (TRT) is an in situ technique to determine the thermal conductivity of the soils surrounding a ground heat exchanger. The technique was originally proposed in the 1980's by Mogensen (1983) and then developed for routine application with borehole heat exchangers in the 1990's (Austin, 1998, Gehlin, 1998). The test involves applying a constant heating power to the ground via a heated circulating fluid and measuring the resulting temperature changes in that fluid. The constant power input, combined with the assumption of a long and slender heat exchanger makes the test results suitable for interpretation using simple techniques such as the line source method, which is mathematically analogous to the Cooper-Jacob approximation used to interpret groundwater pumping tests.

As ground source heat pump (GSHP) schemes becomes more common and novel types of heat exchanger are developed, there has been a desire to test the applicability of the TRT beyond borehole heat exchangers. Energy piles, where the piled foundations of a building perform the heat exchanger role in a GSHP system, are an obvious candidate for thermal response testing, given their superficial similarity to boreholes arising from their axisymmetric geometry. Recent research is showing that at least for small diameter piles (up to 450mm diameter) the TRT can be applied to energy piles, subject to careful consideration of the test length and interpretation methods (Loveridge et al., 2014a, b). However, the greater volume of concrete in larger diameter piles potentially causes problems for short term tests (e.g. as seen in Bouazza et al., 2013), as the temperature response depends on the properties of both the concrete and the ground and a certain time period is required to overcome the thermal capacity of the concrete mass.

An additional problem with the application of TRT to energy piles relates to their much shorter length. Many commercial test rigs are set up to deliver the power levels needed for more common borehole testing where the heat exchanger length is generally in excess of 100m. Therefore the electric heaters powering the tests are typically in the range 2 kW to 6 kW, delivering the recommended 30 W/m to 80 W/m (ASHRAE, 2002, Sanner et al., 2005) to the ground. Delivering the same total power to a 10m or 20m long energy pile can rapidly lead to overheating and curtailment of the test (for example see Hemingway & Long, 2013). This means there are difficulties in carrying out tests for long enough to overcome the thermal capacity of the concrete and thus truly measure the ground thermal conductivity. One possible solution to this latter problem is to test a group of energy piles in a single circuit, thereby increasing the total heat exchange length and reducing the power applied per drilled metre. This also has the advantage of testing a larger volume of soil, although it does introduce the potential for additional heat losses relating to the lengths of pipe between the piles.

2 TRT INTERPRETATION METHODS

Traditionally TRTs are interpreted using the line source method. This assumes that the heat exchanger being tested is an infinitely long and thin heat source and hence simple analytical solutions to the diffusion equation can be applied to the data. In its simplest form the line source method applies a mathematical approximation analogous to the Cooper-Jacob approximation in groundwater engineering to reduce the expected temperature change of the circulating fluid to a log-linear relationship. In this case the soil thermal conductivity, λ (W/mK), can be calculated from the applied thermal power, Q (W), the heat exchanger length, H (m) and the gradient (k) of a graph of the temperature change against the natural logarithm of time:

$$\lambda = \frac{Q}{4\pi H k} \tag{1}$$

This mathematical approximation is not valid at small values of time, and the minimum time for its application is usually taken as $t_{min} > 5r_b^2/\alpha$, where r_b is the radius of the pile and α is the soil thermal diffusivity. It is good practice to apply the method dynamically, gradually including more time series data after the t_{min} to check the sensitivity of the output.

When applying the line source method, it is also important to understand that it implicitly assumes that the heat exchanger itself has overcome the concrete thermal capacity to reach a thermal steady state. Thus any further changes in the circulating fluid temperature are a reflection of the ground thermal properties only. This condition will take longer to be fulfilled for larger diameter piles.

Other methods of interpretation are available (e.g. Gehlin, 2002, Javed et al., 2012, Loveridge et al., 2014b), but the line source is used most routinely owing to its simplicity. In this paper we will adopt the line source approach for the group test interpretation because previous work on the individual piles involved in this study showed less than 10 % variation in thermal conductivity values calculated using different methods (Loveridge et al., 2014b).

3 THE BERKEL TEST SITE

3.1 *Site Layout and Ground Conditions*

Berkel & Company constructed an energy pile field test setup at Richmond in Texas (Brettmann et al., 2010, Brettmann and Amis, 2011) to allow testing of TRT methods applied to piles. Three piles were constructed using continuous flight auger (CFA) techniques to a depth of 18.3m. Each pile contains two polyethylene pipes forming U-loops, which are attached to the outside of a series of spacers to keep the pipes approximately 127mm apart along the centre of the pile. Two piles were constructed at 305mm diameter and one pile at 457mm diameter. One of the 305mm piles was backfilled with low density thermal grout (material more typically used for borehole heat exchangers), and the other two piles were constructed using cementitious grout. The piles were arranged in a triangular pattern at 4.5m spacing (centre to centre).

Ground conditions at the site were a mixture of silts, sands and clays (Brettmann et al., 2010). Groundwater was approximately 3m below ground level, so most of the soils are saturated. Soil samples from a borehole located at the centre of the site were tested for thermal conductivity using a needle probe (ASTM, 2008). The results give an average thermal conductivity, weighted for the proportions of different materials, of 3.0 W/mK.

3.2 *Individual Thermal Response Tests*

Four-day duration individual thermal response tests were carried out on the three piles at the site. The results and interpretation of these tests are described in detail by Brettmann et al. (2010) and Loveridge et al (2014a, b). The values of thermal conductivity calculated for the three piles are given in Table 1 and are within 10% of laboratory value for the cementitious piles. The smaller pile gave the value closest to the laboratory results, which would be expected because:

- The smaller diameter means the pile moves closer to steady state within the test time
- The larger diameter results in a smaller dataset for analysis (because the neglected initial period is longer), hence results are more susceptible to uncertainty from power fluctuations.

Table 1. Results of the individual thermal response tests (Loveridge et al., 2014b).

Pile Diameter (mm)	Material	Ground Thermal Conductivity (W/mK)
305	thermal grout	2.5
305	cementitious grout	2.9
457	cementitious grout	3.3
Laboratory testing		3.0

The thermal grout pile shows a slightly larger discrepancy compared with the laboratory data and other piles, which is explained by the fact that the thermal grout actually has worse thermal properties than the cementitious grout (Table 2) and therefore takes also longer to reach steady state conditions.

Table 2. Grout thermal conductivity determined by back analysis of TRT results, refer to Loveridge et al., 2014b.

Pile Material	Thermal Conductivity (W/mK)
thermal grout	1.3 – 1.6
cementitious grout	2.0

3.3 *Group Thermal Response Test*

The pipes within all three of the piles described above were connected in series, first the 457mm cementitious pile, then the 305mm cementitious pile and finally the 305mm thermal grout pile. The system was then subjected to a thermal response test of 8 days duration. This time period is substantially longer than a “standard” borehole tests and was prudent given the diameter of the piles. The power applied during the tests was nominally constant with an average value of 4.1kW. However, power fluctuations did occur with a standard deviation up to 3% of the mean. Strictly, this is outside ASHRAE (2007) recommendations, and as a consequence there are some fluctuations in the results shown in Section 4.

The average temperature change of the circulating fluid (calculated as the mean of the inlet and outlet temperatures) as a result of the applied thermal power is presented in Figure 1 and is close to a log-linear relationship. The three piles were equipped with additional temperature sensors at their centre. The average temperature change at the two sensors placed at 6m and 14m depth in each pile is shown in Figure 2. As would be expected, the temperature change in the centre of the piles is generally less than the fluid. The first pile in the system experiences approximately the same temperature change as the average of the fluid temperature with the other two piles exhibiting smaller changes. This would be expected as the amount of heat transfer will reduce around the pipe circuit. If the piles had equal thermal properties, the thermal grout pile (last in the sequence) would have experienced less temperature change, but its lower thermal conductivity means that its temperature increased more than the preceding 305mm diameter cementitious grout pile. The pile temperature change is also delayed relative to the fluid temperature change in each case as it takes longer for the thermal pulse to reach the centre of the piles.

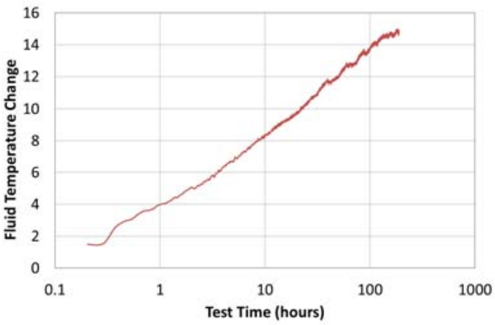

Figure 1. Average fluid temperature change for the pile group thermal response test.

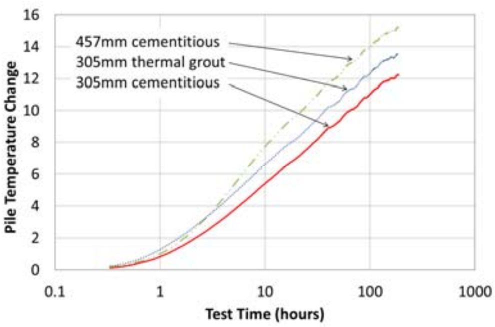

Figure 2. Average temperature change at the centre of each pile during the pile group thermal response test.

3.4 *Analysis Approach*

Before the group thermal response test data can be analysed using the line source method it must first be checked to see whether there has been any thermal interaction between the three piles owing to their proximity. This can be done both theoretically and in this case practically, as the borehole at the centre of the three piles also contained temperature sensors.

Theoretically the potential for interactions can be assessed according to the approach set out in Loveridge & Powrie (2014). This involves considering the spacing of the piles and the elapsed time. Calculations following this approach suggest that the test would need to be run for approximately 24 days for the adjacent piles to affect each other. This is borne out by the central borehole temperature measurements which showed negligible change during the test period.

The absence of thermal interactions allowed the line source method to be applied directly to the fluid data assuming that the total heat exchanger length (H) was three times the pile length. The average thermal conductivity of the ground surrounding the pile was then determined dynamically by gradually including more data from the tests, starting from t_{min}=45 hours (assuming an average r_b of 0.178m).

It has been shown (Bozis et al., 2011) that the centre of a pile will increase in temperature at the same rate as the fluid temperature. Hence the gradient of temperature change within the pile (Figure 2) can be used to calculate the surrounding thermal conductivity in exactly the same way as the average fluid temperature. The only difference is that the pile length and applied power values input to the calculation need to be appropriate for each individual pile. In this case the total power applied has been divided by three for these calculations, assuming equal delivery to each pile. However, as mentioned above, in reality the power delivered will reduce around the length of the pipe circuit.

4 RESULTS AND DISCUSSION

The thermal conductivity values calculated from the average fluid temperature data are shown in Figure 3. At the end of the test the thermal conductivity value is approximately 2.8 W/mK, which is within 20% of the laboratory test results. However this result is not stable (Figure 3) and is continuing to increase with time throughout the latter part of the test. A similar phenomenon was seen with the individual tests, with only the smaller diameter (305mm) cementitious pile results stabilising over the test timescale as the other two piles had not fully reached steady state. As all three piles are being tested together in the group test, there is clearly a sufficient influence from the two larger and lower thermal conductivity piles to mean that the group as a whole has not reached a steady state, even within the extended eight-day test period. Whether solely due to this, or whether there are additional heat losses from the connecting pipes, the result is a loss of accuracy in the group test compared with the 305mm individual test.

The results from the fluid data are compared with the results from the temperature sensors in the individual piles in Figure 4. A similar trend is seen, but some additional inferences can be made. Firstly it is apparent that some variability is superimposed on the trend and this is likely related to power supply variations and additional variations in power delivered to the ground due to heat losses to the air.

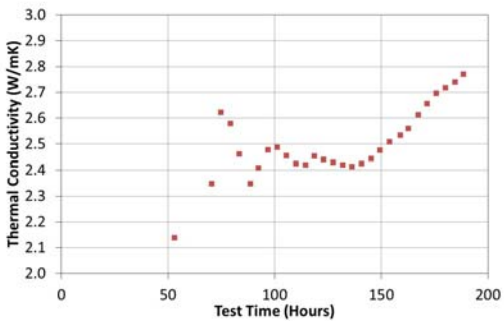

Figure 3. Thermal conductivity calculated from changes in fluid temperature.

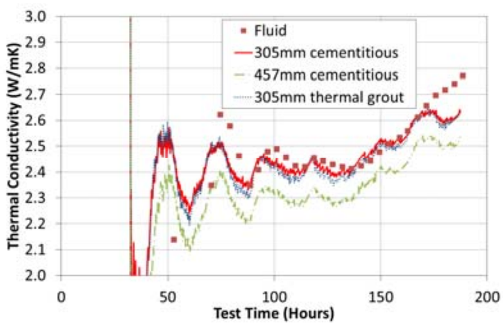

Figure 4. Thermal conductivity calculated from changes pile temperature.

Second, the three individual piles do not all give the same values of thermal conductivity as the fluid analysis. This is explained by a combination of factors. As has been indicated, the rate of heat transfer to the piles is expected to reduce around the pipe circuit. However this is not quantified and hence the calculations assume each pile receives the same thermal load. The temperature at the centre of the pile is governed only by the injection diameter (Bozis et al., 2011), which is the same for all three piles in this case, and the thermal properties. Only the two cementitious piles have equal thermal properties and in this case the 457mm pile gives a lower thermal conductivity in Figure 4. Given this is the first pile in the circuit the results are consistent with the heat transferred having been underestimated in this case, i.e. this pile actually receiving more than a third of the total thermal power. Conversely, the last pile in the sequence, the 305mm thermal grout pile would be expected to receive less than one third of the total thermal power. The results in Figure 4 for this pile are therefore an overestimate. This is consistent with the lower thermal conductivity grout in the pile being a long way from steady state and hence giving the impression of a lower soil thermal conductivity.

5 CONSIDERATIONS FOR PILE GROUP TRTS

The results presented show that group pile tests need to be subject to the same considerations as single pile tests. These include making sure the test length is appropriate and heat losses are minimised. Figures 3 and 4 illustrate that tests of insufficient length will lead to uncertainty in the calculated values of thermal conductivity.

However, group tests do offer the opportunity to inject a greater amount of total heat into the ground which can be beneficial when using test rigs designed for longer ground heat exchangers. The total pile length and desired heating power to be applied should be checked before planning a test.

The next consideration is whether the piles will interact over the timescale of the test. Placing piles closer together will minimise heat losses from connecting pipework, but potentially reduce the time before interactions occur. While tests can be run with interacting piles, their interpretation would be more complicated and require the application of non-linear models.

Whether the piles in the group are of the same size, length and construction is also an important consideration. Theoretically this should not matter for thermal conductivity determination if all piles in the system reach steady state within the test time. However, larger piles or piles of lower thermal conductivity can have an undue influence on the results as in the case study in this paper.

Thermal response tests can also be used to calculate the thermal resistance of piles (not covered in this paper), which would become impossible on a group test with different sized piles as each would have a different resistance.

6 CONCLUSIONS

Conducting thermal response tests on a group of piles rather than a single pile to determine the ground thermal conductivity is a potential solution to problems caused by oversized heaters on TRT rigs. Providing the normal considerations for pile TRTs are respected, interpretation of group tests should be straightforward. However it is important that consideration is given to whether the piles within the pile group will interact thermally within the timescale of the test and any adverse impacts that may occur if the piles are of different sizes or constructed from different materials. It should also be recognised that there may be a loss of accuracy compared with a single pile test owing to additional heat losses.

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