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Title: Energy Piles: Site Investigation and Analysis

Authors: 1. Phil Hemmingway BE, PhD, MIEI 2. Mike Long BE, MEngSc, PhD, CEng, MIEI, MICE

Affiliation: 1. School of Biosystems Engineering (formerly School of Civil, Structural & Environmental Engineering), University College Dublin, Ireland.

2. School of Civil, Structural & Environmental Engineering, University College Dublin, Ireland.

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Abstract

Despite an increasing use world-wide of geothermal energy foundations there is a lack of published guidelines and results from thermal response testing of such installations. In this paper the results from thermal response, thermal recovery and laboratory thermal testing performed at two sites in Ireland are presented. Some practical issues concerned with use of thermal response testing rigs, designed for use with deep boreholes, on relatively short piles are discussed and addressed. Given the relatively short geothermally active depth of the energy foundations tested and due to the fact that the UCD thermal response testing rig has been designed primarily for testing on medium and deep geothermal boreholes, shorter thermal response test durations than are normally used for deep boreholes were performed. The techniques used to analyse the various test results are outlined and the resulting values of thermal conductivity obtained are within the range of those expected for the prevailing geology of the sites.

Keywords: Energy, foundations, site investigation, geotechnical engineering, field testing & monitoring, thermal effects.

Notation:

cfa	continuous flight auger
BHE	borehole heat exchanger
H	depth of the borehole heat exchanger (m)
h	groundwater head (m)
k	hydraulic conductivity (m/s)
L	length of borehole heat exchanger piping (m)
OD	outer pipe diameter (m)
P	length of above-surface piping (m)
Q	injected heat power (W)
Q_r	radial heat loss (W)

r_1	outer radius of the piping insulation (m)
r_2	inner radius of the piping insulation (m)
r_b	borehole radius (m)
s	groundwater storage capacity (L^{-1})
t	time (s)
T_d	maximal temperature difference between the circulating fluid and ambient air ($^{\circ}C$)
z	groundwater flow (m^3/s)
UCD	University College Dublin
α	thermal diffusivity (m^2/s)
λ	thermal conductivity (W/mK)
λ_p	thermal conductivity of piping insulation (W/mK)

1. Introduction

Piping can be installed into practically any sub-surface engineering structure which provides a large interface area with the ground in order to harness ground thermal energy. Typical examples are bored or pre-fabricated piles, retaining walls, diaphragm walls, tunnel walls, basement slabs, basement walls and soil anchors (Brandl, 2006, Adam and Markiewicz, 2009, Franzius and Pralle, 2011). Although energy foundations are considered to be new relative to other forms of renewable energy technologies such as wind, solar or biomass (Abdelaziz et al., 2011, Peron et al., 2011) they have now been installed in a number of engineering structures throughout the world (Boennec, 2008, Gao et al., 2008, Laloui, 2011). This is in contrast to the Republic of Ireland where it is believed that no such systems exist (Hemmingway and Long, 2011a). In spite of growing interest in the area, there is a distinct lack of documented thermal response tests on energy foundations (Amis et al., 2010, de Moel et al., 2010). A thermal response test (TRT) is a controlled insitu test during which a known quantity of heat energy is injected into (or extracted from) a closed loop borehole heat exchanger via a circulating heat carrier fluid, while the change of the fluid temperature is monitored.

Aside from the thermal response testing operations outlined in the following paragraphs (only one of which was performed on energy piles), very little peer reviewed literature in this specific area is available. Brettmann and Amis (2011) carried out thermal response tests on three continuous flight auger (cfa) piles of varying diameter (300mm and 450mm) and construction and found that the measured values of thermal conductivity in each case was close to what was expected. The International Ground Source Heat Pump Association (2008) recently published design and installation standards for closed loop/geothermal heat pump systems which suggest that the test bore should not exceed 6 inches (152.4mm) in order to carry out a thermal response test. However, the thermal response testing regime performed by Brettmann and Amis (2011) indicates that the test methodology remains valid for larger diameter heat exchangers. Franzius and Pralle (2011) carried out a thermal response test on the 'Katzenbergtunnel' high-speed rail tunnel wall in Germany prior to its opening. Although neither the calculation method used to determine the thermal conductivity results nor the actual value of calculated thermal conductivity are described in detail by Franzius and Pralle (2011), the resulting calculated heat flux from the test was used in the design of a demonstrator project in Jenbach, Austria which is described in detail in Frodl et al. (2010). Schneider et al. (2011) briefly describe the performance of thermal response and laboratory testing carried out on another tunnel in Germany equipped with heat exchanger pipes. Although in-depth detail is not provided, the testing resulted in measured values in the range 2.0W/mK to 2.8W/mK for the clay marl/limestone segment of the formation. The lower value of 2.0W/mK observed by Schneider et al. (2011) is in close

agreement to the value of 1.9W/mK obtained by the UCD TRT Rig for the testing described in Hemmingway and Long (2012c) which was performed on a borehole heat exchanger installed in a similar geological formation. Amis et al. (2010) performed a thermal response test on an 800mm wide, 36m deep diaphragm wall in England. The thermal response test was carried out in two stages, one prior to excavation and one following excavation so that the thermal effect of removing 24m of the 36m of soil from the non-loop side of the diaphragm wall could be analysed. Results from the tests indicate that the thermal resistance increased by 20% and the thermal conductivity decreased by 13% (Amis, 2011) following excavation.

Following completion of a thermal response test a ‘thermal recovery test’ may be performed. A thermal recovery test is carried out immediately following a thermal response test – the heating power of the TRT rig is turned off and the circulating fluid is allowed to continue circulation. The shape of the average borehole heat exchanger (BHE) circulating fluid temperature versus time plot for a recovery test is effectively the inverse of that plotted for the preceding thermal response test and therefore it has been reported that the results can be analysed in exactly the same way (Banks, 2008). Thermal recovery tests are rarely carried out in practice due to time and cost constraints, and very little published information relating to the performance or evaluation of these tests is available.

Gehlin (2002) refers to thermal recovery testing being carried out in the United Kingdom and states that the line source approach may be used in order to evaluate test results. Witte and Gelder (2006) make reference to a number of multi-power step thermal response tests on a borehole heat exchanger with cycles of heat addition followed by heat extraction. Raymond et al. (2011) carried out a number of analytical and numerical simulations of thermal response and recovery tests. They suggest that: (a) the temperature of the circulating fluid inside the BHE homogenises rapidly after heat injection is stopped and therefore performance and analysis of thermal recovery tests reduces the uncertainty of the thermal conductivity results calculated using a conventional thermal response test where placement of the temperature probes may affect the results and (b) the temperature evolution of a thermal recovery test agrees with the line source model. Gehlin and Spitler (2002) state that care should be taken to either make temperature measurements at the borehole inlet and outlet or, if the heat transfer rate is measured elsewhere, to minimise any unmeasured heat loss or gains. Zervantonakis and Reuss (2006) recommend placement of sensors directly in the fluid line. The temperature sensors on the UCD thermal response testing rig are installed in the fluid line at the point of fluid exit and fluid entry from the trailer unit. Readers may refer to Hemmingway and Long (2012a) for further details of the design and construction of the UCD thermal response testing rig. Regardless of where temperature sensors are placed within a thermal

response test rig, it is vital that elements through which heat energy could be lost or gained (for example, all above surface piping) are heavily insulated in order to minimise heat loss or gain which would adversely affect test results.

2. Energy Pile Installations

The primary author organised and supervised the installation of a number of energy piles at two research sites in Co. Cork, Ireland and later carried out thermal response, thermal recovery and laboratory thermal tests. The sites are located at the Cork Docklands (1km east of Cork City Centre) and Carraigtwohill (approximately 15km east of Cork City).

2.1 Cork Docklands Site

Hemmingway and Long (2011b) provide a detailed description of the ground conditions at an adjacent site to the site referred to as the ‘Cork Docklands Site’ in this paper. The distance between the Cork Docklands Site and the adjacent site is less than 150m and therefore similar ground conditions are assumed. This was confirmed by observation of the spoil resulting from the drilling operations at the Cork Docklands Site. The ground conditions consist of a thin layer of alluvium (approximately 1 to 2m in depth) underlain by saturated sand and gravel to bedrock at approximately 42.2m depth, with a layer of very stiff grey silty clay from 15m to 25m below ground level. A graphical representation of the soil strata at the Cork Docklands site is shown in Figure 3. The energy piles are installed to a depth of 14.5m and therefore the bedrock (thought to be at a depth of between 42.2m and 60m (Allen et al., 2003, Hemmingway and Long, 2011b, Long and Roberts, 2008, Milenic and Allen, 2005) is not reached.

Four 14.5m deep energy piles were installed in order to provide media for the completion of thermal response tests, but also in order to understand the practical issues associated with the installation of energy piles. Single-u and double-u shaped piping configurations were installed to a depth of 14.2m into concrete piles of diameter 250mm and 350mm respectively. The dominant geological formation along the length of the installed energy piles is saturated sand with gravel which has an expected thermal conductivity in the range 1.5W/mK to 5.02W/mK (Bristow et al., 2001, Clarke et al., 2008, EED, 2010, Goodrich, 1986, Midttomme and Rolandset, 1998). The database provided in the ground source energy heat exchanger design tool Energy Earth Designer (EED, 2010) quotes a recommended value of thermal conductivity value of 2.4W/mK for saturated sand,

1.8W/mK for alluvium (or saturated silt) and 1.6W/mK for saturated clay. Assuming that the soil profile along the depth of the 14.2m energy pile installation consists of 1.5m of alluvium, 0.5m of clay and 12.2m of saturated sand/gravel, the depth weighted average ‘expected’ thermal conductivity of the formation is 2.31W/mK.

Polyethylene piping with an outer diameter of 40mm and wall thickness of 3.7mm was used for the installations. The piping was tied to either side of a central ‘plunge bar’ prior to insertion into the energy piles following installation of the piles using the cfa piling process. Figure 1(a) shows heat exchanger piping being installed into one of the cfa piles at the Cork Docklands site. Figure 2 shows a sketch of the energy pile installation geometry for the Cork Docklands and Carraigtwohill sites. In both the single-u and double-u piping configurations, u-shaped pipes are tied onto a central steel plunge bar.

Figure 1 (a) Piping installation at the Cork Docklands & (b) Carraigtwohill Energy Pile Layout

Figure 2 Sketch of Energy Pile Installation Geometry

2.2 Carraigtwohill Site

According to the GSI Quaternary and bedrock geology maps (Geological Survey of Ireland, 2011a, Geological Survey of Ireland, 2011b) the site is underlain by undifferentiated till which in turn is underlain by a limestone bedrock formation. These findings are consistent with nearby borehole site investigations carried out for the Bray to Cork Gas Pipeline (Geological Survey of Ireland, 1976) which runs from West to East at a distance approximately 2km south of the Carraigtwohill site. These site investigation records indicate that the soil in the area is primarily made up of sandy/gravelly clay (i.e. typical boulder clay) and that bedrock is located at depths ranging from 3m to 10m. A graphical representation of the soil strata at the Carraigtwohill site is shown in Figure 3. Energy piles of 300mm diameter and 6m depth were installed at the site (see Figure 1(b)). The underlying bedrock was not penetrated during the drilling operations and therefore each of the piles were installed into a geological formation consisting of saturated sandy/gravelly clay. The expected thermal conductivity of moist clay and saturated sand falls in the range of 0.9W/mK to 2.22W/mK and 1.5W/mK to 5.02W/mK respectively (EED, 2010). Therefore the expected thermal conductivity of the material present at the Carraigtwohill site may be estimated in the region of 2.2W/mK or above.

Figure 3 Ground Conditions at (a) Cork Docklands and (b) Carraigtwohill Sites

3. Thermal Test Analysis

3.1 Thermal Response Test Analysis – Line Source Method

The most widely used theory for the evaluation of thermal response test results is the analytical line source method which is developed from Kelvin's line source theory such that Equation 1 may be written.

$$\lambda = Q/4\pi kH \quad (1)$$

Where λ is thermal conductivity, Q is injected heat power (W), H is the depth of the borehole heat exchanger (m), k is the slope of the line on a plot of average temperature versus $\ln(\text{time})$. Data can be evaluated to an accuracy of within 10% if the lower time criterion shown in Equation 2 is satisfied (Florides and Kalogirou, 2008).

$$t > 5r_b^2/\alpha \quad (2)$$

where r_b is the borehole radius (m), t is time (s) and α is thermal diffusivity (m^2/s). For a detailed overview of the theory underlying the development of the analytical line source method, readers may refer to Ingersoll and Plass (1948), Eskilson (1987), Gehlin (2002), Signorelli et al. (2007) or Hwang et al. (2010).

3.2 Thermal Response Test Analysis – Geothermal Properties Measurement Model

A second, more advanced method which may be used to evaluate the results of thermal response tests is called the 'Geothermal Properties Measurement (GPM) Model' developed by Shonder and Beck (2000). The GPM method was developed in order to analyse thermal properties from short duration thermal response tests using a parameter estimation technique. The technique is referred to by several authors (Florides and Kalogirou, 2007, Hu et al., 2012, Rey-Ronco et al., 2012, Schiavi, 2009) but it does not seem to be widely applied in either academia or industry where, in both cases, application of the analytical line source method appears to be the norm due to its simplicity of application (Saljnikov et al., 2007). Shonder and Beck (2000) present an analysis of thermal response test data from three 50 hour field tests carried out at two sites and compare these results against those derived from yearlong operating data at each respective site. The GPM calculated thermal conductivity values were found to agree within 2% and 4% respectively. Rey-Ronco et al. (2012) state that the GPM method is one of the main methods for determining ground thermal conductivity from a thermal response test and analyse a set of test results using the analytical line source method, the GPM method and a two-variable parameter fitting methods. Thermal conductivity values ranging from 1.75 W/mK to 2.35 W/mK were

calculated using the three methods. Previous research suggests that the GPM method is suitable for analysis of standard, best practice conventional thermal response test data. However, further investigation of the applicability of the method in the case of short duration tests or tests performed on energy piles is merited. The GPM model operates by obtaining the finite-difference solution of the Fourier equation (Equation 3; where r is the distance from the centre of the heat exchanger, z is the depth of the heat exchanger, and ∇ is the Laplace operator) in the geological domain. The borehole backfill material (e.g. grout or concrete) and the geometric arrangement of the pipes are modelled as a single pipe of an effective radius. Using this approach, the model solves the Fourier equation by assuming the temperature field along the vertical axis of the borehole heat exchanger is constant and also that the heat exchanger is of a constant radius about the vertical axis (Rainieri et al., 2011).

$$\nabla^2 = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial}{\partial r} \right) + \frac{1}{r^2} \left(\frac{\partial^2}{\partial \theta^2} \right) + \frac{\partial^2}{\partial z^2} \quad (3)$$

Readers may refer to Shonder and Beck (2000) for a detailed description of the theory underlying the development and operation of the GPM model.

3.3 Thermal Recovery Test Analysis

A direct mathematical analogy between the analysis of groundwater flow and subsurface heat flow exists (Banks, 2009). The key analogy is that between Fourier's Law which describes heat transfer by conduction and Darcy's Law which describes ground water flow. Both equations are shown in Table 1 which is edited after Banks (2009). By comparing the variables in each of the equations, it is easy to see that groundwater flow (Z) is analogous to heat flow (Q), hydraulic conductivity or permeability (k) to thermal conductivity (λ) and groundwater head (h) to temperature (T). Similarly, the concept of a 'hydraulic skin' which accounts for head losses in the vicinity of a pumped well (Kruseman and de Ridder, 2000) may be considered to the thermal phenomenon referred to as 'borehole thermal resistance', which refers to the resistance to transportation of heat from the borehole wall into the fluid inside the pipes and is controlled *inter alia* by the type of grouting, the pipe material and the borehole and pipe geometry (Sanner et al., 2011). Although not specifically analysed in the presented work, borehole thermal resistance has shown to be an important consideration in the design of energy piles due the transient nature of energy loads on energy piles and the possible large diameter of some piles.

Readers may refer to work of researchers such as Loveridge and Powrie (2012) and Pahud (2007) for more information relating to borehole thermal resistance and energy piles.

Table 1 Analogy between Water Flow and Heat Flow

	Groundwater flow	Subsurface heat flow
Key Physical Law	Darcy's Law $z = -KA dh/dx$	Fourier's Law $Q = -\lambda A dT/dx$
Flow	z = groundwater flow (m^3/s)	Q = heat flow (J/s or W)
Property of Conduction	k = hydraulic conductivity (m/s)	λ = thermal conductivity (W/mK)
Measure of Potential Energy	h = groundwater head (m)	T = temperature ($^{\circ}C$ or K)
Measure of storage	s = groundwater storage	Svc = specific heat capacity (J/ m^3K or J/kgK)
Measure of bore efficiency	Well loss / hydraulic skin	Borehole thermal resistance

The hydrological characteristics of an aquifer may be determined by carrying out a pumping test. In order to carry out a pumping test, water is pumped from one well and the resulting fall in groundwater level at nearby observation well(s)/piezometer(s) is monitored (Powrie, 2004). Following completion of a pumping test the pump is shut down and the water levels in the observation wells gradually rise until they reach their initial levels. This is known as a pumping recovery test. Data from a pumping recovery test can provide an independent check on the results of the preceding pumping test. It has been stated that the data collected from a pumping recovery test are more reliable than those collected from a pumping test because water level recovery occurs at a constant rate, whereas a constant discharge during pumping can be difficult to achieve in the field (Kruseman and de Ridder, 2000). Figure 4 shows a plot of typical test data from a pumping test and pumping recovery test (Osborne, 1993). A pre-pumping measurement period precedes the tests so that any regional effects on groundwater level (e.g. caused by tidal variation) can be recorded. Following the pre-pumping measurement, the pump is switched on, resulting in a period of rapid drawdown, followed by a gradual reduction in the slope of the rate of change of the drawdown until a steady state is reached where the level of drawdown is controlled by the hydraulic conductivity of the aquifer. The length of pumping test required may vary depending on the objectives of the test, the type of aquifer, location of suspected boundaries and the degree of accuracy required (Osborne, 1993). In general the length of test is determined when the test operator is satisfied that the quantity of data collected is adequate for the purposes of that particular test. At the end of the

pumping test the pump is switched off and recovery of water levels in the observation wells/piezometers commences. The equation of a trend line imposed on the latter portion of pumping test data may then be used to extend the pumping test data to show the trend which would have eventuated were the pumping to continue (this is shown as the lower dashed line in Figure 4). The difference between the collected pumping recovery test data and the extended pumping test data for each respective data point is termed the ‘recovery’.

Figure 4 Typical Pumping Test and Pumping Recovery Test (Osborne, 1993)

The correlation between pumping/pumping recovery tests and thermal response/thermal recovery tests may immediately be seen by comparing Figure 4 (pumping test followed by pumping recovery test) with Figure 5 (thermal response test followed by thermal recovery test). Commencement of the heating period (or the thermal ‘response’ test) corresponds to a steep initial increase in the temperature of the water circulating around the BHE piping, following which a steady state rate of temperature increase develops where the rate of temperature increase is controlled by the thermal conductivity of the geological formation surrounding the BHE. At the end of the thermal response test the heaters are turned off and the circulating fluid continues circulation. The fluid temperature then begins to return to a temperature near (but slightly above) its initial standing temperature. The reason that the temperature of the circulating fluid will not fully return to its initial standing temperature is that after the heaters have been turned off the circulating pump continues impart a small amount of heat energy. This supplementary energy addition can be easily quantified and factored into the thermal response and thermal recovery test analyses as shown in the following section.

Figure 5 Typical Thermal Response and Thermal Recovery Test Data

The solid line on Figure 5 shows the trend which would have eventuated were the thermal response test (i.e. heating period) to continue, and is calculated in exactly the same way as for the pumping test which is described earlier in this Section. The difference between the collected thermal recovery test data and the extended thermal response test data (the solid line in Figure 5) for each respective data point is termed the ‘recovery’ and results from the drop in power due to switching off the heaters. The calculated recovery may be plotted on a graph of temperature recovery versus the natural logarithm of time and then evaluated using the line source method in exactly the same manner as the thermal response results.

3.4 Heat Addition & Loss

The heating power supplied by the resistance heaters in each of the tests presented is 3kW (this is the minimum in heat injection rate of the UCD TRT rig: the heat injection rate (W/m) for the two tests referred to are therefore somewhat above the level of heat injection/extraction which would be realised when operating a ground source energy system – this may or may not have an impact on the thermal diffusive properties of the ground). A small amount of heat is also added to the heat transfer fluid by the circulating pump. The circulating pump on the UCD TRT rig is rated at 185W. The heat added to the circulating fluid by the pump during the thermal response test may be estimated as 150W by assuming reasonable electrical motor and mechanical efficiencies of 80%. Therefore the total heat added to the circulating fluid in all tests presented is 3,150W.

In the case of the Carraigtwohill thermal response and thermal recovery tests, there is a significant quantity of above-surface heat exchanger piping through which the heat exchanger fluid must circulate (i.e. the piping joining Pile A to Pile B (see Figure 1(b))). Although this piping was insulated with high-density pipe lagging to

minimise heat loss, it is important to estimate the level of heat loss during the tests so that it can be factored into subsequent calculations. The radial heat loss equation for a multi-layered cylinder given as Equation 4 by Cengel (2006) is used in order to calculate the instantaneous loss of heat due the above-surface insulated piping at the worst case scenario, i.e. when the differential between the temperature within the piping and the ambient air are at a maximum.

$$Q_r = T_d / \frac{\ln(\frac{r_1}{r_2})}{2\pi P \lambda_p} \quad (4)$$

Taking the total length of above-surface piping (P) to be 10m, the maximal temperature difference between the circulating fluid and ambient air (T_d) to be 20°C, the outer radius of the insulation surrounding the piping (r_1) to be 31mm, the inner radius of the insulation (r_2) to be 20mm and the thermal conductivity of the selected insulation (λ_p) to be 0.03 W/mK; the total heat loss is calculated as 70W. The injected heat power used in the calculations for the Carraigtwohill thermal response test is therefore 3,080W.

4. Thermal Test Results

The thermal response and recovery tests were performed using the thermal response testing rig and operating fundamentals described in (Hemmingway and Long, 2012a) approximately 12 months after pile construction. Temperature distribution along the length (in depth) of a test energy pile and in other elements at varying distances from a test pile presented in the research carried out by Bourne-Webb et al. (2009) suggest that the key assumption required for analysis using the analytical line source method (i.e. the assumption that the pile behaves as an infinitely long line source) is reasonable in the case of an energy pile. The applicability of the analytical line source method to thermal response test data gathered from tests carried out on energy piles is further confirmed by Brettmann and Amis (2011) who successfully evaluated results from thermal response tests carried out on energy piles of 300mm and 450mm diameters using the analytical line source method.

4.1 Cork Docklands Response Test

Prior to commencement of thermal response and thermal recovery tests, the undisturbed ground temperature (T_0) along the length of the borehole/pile should be established. A temperature probe was lowered down the length

of the Cork Docklands energy pile, resulting in a measured average undisturbed ground temperature of 12.8°C (denoted ‘Before TRT’ in Figure 6(a), where the left-most vertical line represents the average temperature).

Figure 6 Cork Docklands (a) Pre and Post TRT Temperature Measurement; (b) CPTU Corrected Cone Resistance & (c) CPTU Friction Ratio

A temperature with depth measurement was also taken 5.5 hours after completion of the thermal recovery test and is denoted ‘5.5 hrs. after Recovery’ in Figure 6(a). This measurement confirms the findings of Hemmingway and Long (2011b) where the results of a number of geotechnical site investigations suggest the presence of soft clay layers at approximately 6m depth. The temperature with depth measurements presented in Figure 6(a) show a slower rate of return to natural soil temperature conditions at depth 6m relative to the rate of return to natural ground temperature below this point. This indicates that a thin formation of low conductivity material (such as clay/alluvium) may be present at this point. The rate of return to natural temperature conditions below 6m is likely higher because the material (i.e. saturated sand and gravel) is of higher relative thermal conductivity and therefore the heat generated by the thermal response test is able to dissipate at a faster rate and also due to the presence of a complicated tidal groundwater flow regime in the area Hemmingway (2012). This finding is confirmed by inspection of site investigation data presented by Hemmingway (2012) which are shown in Figure 6(b) and (c). It is clear from the plots of CPTU cone resistance and CPTU friction ratio with depth that a soft (e.g. clay/alluvium) layer exists at approximately 6m depth below ground level.

Figure 7 shows the results from the thermal response test performed on the 250mm diameter single-u pipe energy pile installation at the Cork Docklands site. The solid black line on the graph represents the energy pile injected fluid temperature (denoted $T(\text{Down})$), the dashed line represents the return fluid temperature (denoted $T(\text{Up})$) and the grey line represents the flow rate, which remained turbulent throughout the testing period. Heat input rates of between 30W/m (for low conductivity formations) and 80W/m (for high conductivity formations) are suggested by ASHRAE (2002) and Sanner et al. (2005). The net result of using a heat input rate of 3kW (the minimal injectable heating power of the UCD TRT rig) for evaluation of the thermal properties of the ground surrounding the 14.2m deep energy pile is that the thermal response heating period was curtailed in order to protect against damage to the system due to overheating. The temperature profile for the injected and return fluid temperatures ($T(\text{Down})$ and $T(\text{Up})$, respectively) shown in Figures 7 and 10a appear to be quite smooth. However, there are a small number of ‘dips’ in the temperature where the resistance heaters switch off for a number of seconds and then switched back on again. Examination of the test data shown and those presented by Hemmingway and Long (2012a) indicates that this occurred only approximately once per hour during the thermal response testing and appears to have a negligible effect on the results of the test due to the smooth profile of the circulating fluid temperature development over the duration of the tests. A reduction in flow during progression of the thermal response test is evident in Figure 7. It is believed that this reduction in flow may be due to either thermal expansion of the borehole heat exchanger piping as the test progressed, resulting in a gradual reduction in system pressure, or due to a small leak in the closed loop system resulting in increasing pumping difficulty as the test progressed. No fluid leakage was observed on site. Examination of the relationship between commencement of heat energy injection and reduction in circulation fluid flow associated with the UCD thermal response testing rig is currently under examination. Readers may refer to (Hemmingway and Long, 2012a) and Hemmingway (2012) for details of how these issues were resolved for subsequent tests.

Figure 7 Cork Docklands Thermal Response Measurements

Figure 8(a–d) shows evaluation of differing portions of the results from the thermal response test using the analytical line source method. Separate evaluation of data from (a) the final eight hours, (b) the final six hours, (c) the final four hours and (d) the final two hours of test data was performed in order to investigate whether or not steady state conditions had been reached. The slope (k) of the selected portion of data was determined for each of the graphs and entered into Equation 1, with the injected heat flux (Q) set to 3,150W and depth of bore (H) set to 14.2m. This analysis resulted in calculated thermal conductivity values of 5.33W/mk, 5.40W/mK, 5.03 W/mK and 3.23W/mK for the evaluation periods included in Figure 8(a-d) respectively. The continual reduction in calculated thermal conductivity in each subsequent evaluation indicates that steady-state conditions had not been fully achieved. The lower time criterion for use of the analytical line source method described by Equation 2 is 22.5 hours. The ground thermal diffusivity (α) was calculated by dividing the calculated thermal conductivity from the test results by the volumetric heat capacity for the soil taken from a database such as that provided in EED (2010) (note: this value is known not to vary greatly in saturated strata (Sanner et al., 2011)). This suggests that 22 hours of data is required in order to evaluate test data using the analytical line source method to an accuracy of within 10%.

Figure 8 LSM Analysis of Cork Docklands Single-u TRT (a) last 8 hours, (b) last 6 hours, (c) last 4 hours & (d) last 2 hours

The best estimate of thermal conductivity available from the thermal response test data as calculated using the analytical line source method is 3.23W/mK as analysed in Figure 8(d). This is the only one of the analyses which fully complies with the (ASHRAE, 2002) recommendation to disregard the first five to ten hours of test data prior to evaluation. The coefficient of determination (R^2 value) for the portion of data from which this slope is measured is 0.68 (as shown in Figure 8(d)) and therefore due to this relatively low value, further validation of the calculated thermal conductivity value would increase confidence in the evaluation accuracy. Analysis of the Cork Docklands data using the GPM method referred to in Section 3.2 results in a calculated thermal conductivity value of 5.82 W/mK. Due to the divergence between the values obtained by the line source method

and GPM method analyses, further investigation is attempted by performance of a thermal recovery test and laboratory thermal conductivity tests.

4.2 Cork Docklands Thermal Recovery Test

Following completion of the thermal response test, the heater power was switched off and the heat carrier fluid circulated for a period of six hours. The resulting data measurements, alongside the calculation of the ‘extended’ thermal response testing data trend which would have eventuated had the heaters been left on are shown in Figure 9(a). The results from the recovery test are analysed using the analytical line source method, resulting in a calculated thermal conductivity value of 3.53W/mK for the formation. As was the case for the evaluation of the data from the thermal response test, the calculated value is above the depth weighted estimated value of 2.31W/mK. The values obtained by the thermal response test (3.23W/mK) and the thermal recovery test (3.53W/mK) while not exactly the same, are in reasonably good agreement. The difference between the two may be due to the thermal response test not fully reaching steady state conditions, illustrated by the evaluation of data from varying time ranges as shown in Figure 8 or due to the existence of a tidal groundwater flow which is thought to be present at the site following site investigations presented in Hemmingway (2012).

Figure 9 Cork Docklands (a) Calculation of ‘Extended’ Thermal Response Test Data & (b) Line Source Analysis of Thermal Recovery Data

4.3 Laboratory Thermal Measurement of Cork Docklands Soil

A laboratory thermal conductivity measurement was performed on a soil sample from the Cork Docklands site. The sample was extracted at a depth of 12m below ground level during the site investigations described in Hemmingway and Long (2011b). A full description of the thermal probe used to perform the laboratory thermal conductivity measurement alongside the evaluation theory is provided in Hemmingway and Long (2012b). The excavated sample was re-compacted back to conditions which are representative of those present at the site (bulk density of 2Mg/m^3 at 15% water content). The laboratory test resulted in a measured thermal conductivity value of 3.15W/mK . The measured thermal conductivity values from the thermal response, thermal recovery and laboratory tests are therefore 3.23W/mK , 3.53W/mK and 3.15W/mK respectively. Each of these values are greater than the calculated depth weighted average ‘expected’ thermal conductivity of the tested formation (2.31W/mK). This illustrates the importance of direct site or laboratory thermal conductivity measurements during the design of ground source energy systems so that inherently conservative or ambitious values are not used.

4.4 Carraigtwohill Thermal Response Test

A group thermal response test was performed at the Carraigtwohill site by connecting two piles in series as shown in Figure 1(b), thereby increasing the available ‘geothermally active depth’ of heat exchanger to be tested. Figure 10(a) shows the results from the group thermal response test. Visual inspection of the Figure indicates that the profile of the response test is in-line with that which would be expected, with a sharp increase in the average circulating fluid temperature in the early stages of the thermal response test when the backfill material is heating up, followed by a stabilisation of the rate of temperature increase with time (suggesting achievement of steady state conditions). The thermal response test lasted for 10 hours, at which time the electrical resistance heater was turned off.

Figure 10 Carraigtwohill (a) Group Response Test Data & (b) Pre-TRT Temperature Measurement

Figure 11 shows a plot of the average circulating fluid temperature versus the natural logarithm of time for the thermal response test data. The data is analysed in the same manner as the data collected during the Cork Docklands thermal response test and the resulting best estimate of thermal conductivity of 2.87W/mK is calculated using the analytical line source analysis method. In the case the measured thermal conductivity value is higher than the calculated depth weighted expected thermal conductivity of the ground formation. Analysis of the Carraigtwohill thermal response data using the GPM method referred to in Section 3.2 results in a calculated thermal conductivity value of 2.94 W/mK which is in excellent agreement with the value calculated using the analytical line source method.

Figure 11 LSM Analysis of Carraigtwohill Group TRT (a) last 8 hours, (b) last 6 hours, (c) last 4 hours & (d) last 2 hours

4.5 Carraigtwohill Thermal Recovery Test

Figure 12(a) shows the data measurements from the thermal response and recovery tests at the Carraigtwohill site alongside the calculation of the ‘extended’ thermal response testing data trend which would have eventuated had the heaters been left on. The results of the thermal recovery test (shown in Figure 12(b)) are analysed in the same fashion as for the Cork Docklands thermal recovery data, resulting in a calculated thermal conductivity value of 2.60W/mK. The measured values of thermal conductivity are therefore 2.87W/mK from the thermal response test and 2.60W/mK from the thermal recovery test. Although the results are very similar, the small difference is thought to be due to the shortened test duration, necessitated by the combination of the shallow

geothermally active depth of the energy piles (12m) and the minimum heating power of the UCD TRT rig (3kW).

Figure 12 Carraigtwohill Group Test (a) Calculation of ‘Extended’ Thermal Response Test Data & (b) Line Source Analysis of Thermal Recovery Data

5. Discussion

The installation of a number of research energy piles at two sites is described in this paper. A description of each site is provided alongside a depth-weighted average estimated thermal conductivity value for the ground formation along the depth of the installed energy foundations. Shorter thermal response test durations than are normally used for deep boreholes were necessary in the case of the tests performed at both sites due to the fact that the minimum heat injection rate of the UCD thermal response testing rig is 3kW. This necessitated completion of the thermal response tests when the temperature of the circulating fluid reached the upper limit allowable for protection of the rig components (ca. 40 °C). It is important to note that the authors do not suggest that thermal response test durations should necessarily be shortened to those presented in this paper. This paper simply presents an analysis of the best available thermal response test results from Cork Docklands and Carraigtwohill sites. Thermal recovery and laboratory thermal tests were performed in order to provide additional confidence to the results obtained from the preceding thermal response tests. The resulting values of thermal conductivity are within the range expected for the prevailing geology of the sites but are higher than the calculated depth weighted expected thermal conductivity values at each respective site. This illustrates the issue

associated with relying on average values from generalised databases of thermal conductivity. It is recommended that thermal conductivity values are only taken from databases when (a) the database has been produced to take account of regional and local geological conditions and (b) the database has been developed using scientifically rigorous methods such as proven correlations between thermal parameters and, for example, common engineering parameters. Insitu measurement of thermal properties is recommended for the design of medium to large scale ground source energy systems. Laboratory measurements may be suitable in cases where the designer is very familiar with the geology at a particular site and is fully satisfied that laboratory tests will appropriately represent the insitu conditions (e.g. issues such as ground thermal parameter heterogeneity, groundwater flow and borehole construction require in-depth consideration).

The results of the thermal response tests at the Carraigtwohill and Cork Docklands sites are analysed using both the analytical line source method and the geothermal properties measurement (GPM) method. The analytical line source method is the most widely used method in industry for the analysis of thermal response test results. The duration of the Cork Docklands and Carraigtwohill thermal response tests was 13 and 10 hours respectively, necessitated by the minimum injectable heating power of the UCD thermal response testing rig coupled with the shallow depth of the installed energy piles. Analysis of thermal response test data to an accuracy of within 10% using the analytical line source method requires a thermal response test of duration greater than that described by Equation 2. Following this theory, in the case of the thermal response tests presented in this paper therefore, 22 hours of test data in order to evaluate using the analytical line source method to an accuracy of 10%. The presented thermal response tests are of course shorter than this, and therefore additional testing and analyses are completed in order to provide further confidence in the results calculated by the analytical line source method. Additional analyses are performed by examining the thermal response test data from both sites using a method known as the 'Geothermal Properties Measurement' (GPM) method. The GPM method was developed in order to analyse thermal properties from short duration thermal response tests using a parameter estimation technique.

The results obtained from the analytical line source method and GPM analyses of the thermal response test data obtained at the Cork Docklands and Carraigtwohill sites are shown in Table 2. In the case of the Carraigtwohill site, the values resulting from both the analytical line source and GPM methods are in excellent agreement. However in the case of the Cork Docklands site, there is a divergence in results. It is believed that this analysis is complicated by the complex groundwater flow regime operating on the Cork Docklands as described by (Hemmingway, 2012). However, further analysis will be required in order to confirm whether this divergence is due solely to the complex groundwater flow regime at the site or also due to the reliability of the GPM method.

In addition to the analysis of the thermal response test data using the analytical line source and GPM methods, thermal recovery tests and lab thermal test were performed, the results of which are also shown in Table 2. The thermal conductivity values calculated from the thermal recovery tests at both sites are close to those calculated from the analytical line source analyses, while the results of laboratory thermal conductivity testing on material extracted from beneath the Cork Docklands also reveals a result close to that calculated using the analytical line source method.

Table 2 Thermal Test Results

Test / Analysis Type	Thermal Conductivity (W/mK) Carraigtwohill Site	Thermal Conductivity (W/mK) Cork Docklands Site
Thermal Response Test / Analytical Line Source Analysis	2.87	3.23
Thermal Response Test / GPM Analysis	2.94	5.82
Thermal Recovery Test	2.60	3.53
Lab Thermal Conductivity Test	-	3.15

6. Conclusions and Recommendations

The purpose of the work presented is to the analyses of a number of thermal tests performed on energy pile foundations at two sites in Carraigtwohill and on the Cork Docklands, both of which are located in Co. Cork, Ireland. Unfortunately the minimum injectable heating power of the UCD thermal response testing rig, coupled with the shallow depth of the energy piles (when compared to conventional closed loop borehole heat exchanger installations) meant that the length of the thermal response tests presented had to be curtailed to shorter lengths than those typically used in industry. In order to provide further confidence in the thermal conductivity values calculated by the industry standard ‘analytical line source’ technique, additional interpretation methods (thermal recovery testing and analysis of the thermal response test data using the GPM method) were undertaken. These analysis techniques were supplemented by laboratory testing on soils samples extracted from beneath the Cork Docklands site. All results were in general agreement, except in the case of the Cork Docklands where some anomalies exist. The case of the Cork Docklands is complicated by the complex groundwater flow regime operating on the Cork Docklands and further research is required in order to define the extent, characteristics and effect that this groundwater flow has on these analyses. The most widely used theory for the evaluation of thermal response test results in industry is the analytical line source method; it is recommended that use of the GPM method be further explored.

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