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Site investigation for energy geostructures

Fleur Loveridge*[1,2], Jasmine Low[3, 4] & William Powrie[1]

1. University of Southampton, Faculty of Engineering and the Environment, Highfield, Southampton, SO17 1BJ

2. University of Leeds, School of Civil Engineering, Woodhouse Lane, Leeds, LS2 9JT

3. Formerly University of Southampton

4. Max Fordham, 42-43 Gloucester Crescent, London, NW1 7PE

* corresponding author: F.A.Loveridge@Leed.ac.uk

Abstract

Energy geostructures are structure or infrastructure foundations used as heat exchangers as part of a ground source heat pump system. While piles remain the most common type of energy geostructure, increasingly infrastructure projects are considering the use of other buried structures such as retaining walls and tunnels for heat exchange. To design and plan for construction of such systems, site investigations must provide appropriate information to derive analysis input parameters. This paper presents a review of what information regarding the ground, and also the structures themselves, would be required for the ground energy system design process. Appropriate site investigation methods for energy gesotructures are reviewed, from desk study stages through in situ testing to laboratory testing of samples recovered. Available methods are described and critically appraised and guidance for practical application is given.

Site investigation for energy geostructures

Energy geostructures are structure or infrastructure foundations used as heat exchangers within a ground source heat pump system. Dual use of the geostructure is achieved by equipping the structural elements with heat transfer pipes during construction and subsequently connecting these pipes, through a series of headers and manifolds, to the ground source heat pump system. In this way the geostructure and the surrounding ground can contribute to the heating and cooling of buildings during the winter and summer months respectively. Providing the system is designed and constructed appropriately there will be long term financial and carbon savings from such schemes, and the energy associated with them is classed as renewable.

Energy geostructures have been successfully constructed using a variety of different types of underground structures including piles, basement slabs, retaining walls and cut and cover tunnels (e.g Brandl, 2006). Successful trials have also been carried out using bored and sprayed concreted tunnel linings and using ground anchors (Adam & Markiewicz, 2009, Franzius & Pralle, 2011). However, piles remain the most commonly constructed type of energy energy geostructure for a number of reasons. First, their relative simplicity of construction. Secondly, piles are commonly constructed to support an overlying building, and use of the heating and cooling energy within that building is straightforward. Thirdly, there are recognised design approaches for piles so that clients may consider the project to be lower risk. By contrast, for other geostructure types, including metro stations and tunnels, projects are always more complicated as the end user for the heat may not be the infrastructure asset owner. Nonetheless, the benefits of ground energy systems mean that they are now more routinely under consideration for major infrastructure schemes (e.g Soga et al, 2014, Nicholson et al, 2015, Barla & Perino, 2015).

As interest in energy geostructures becomes more common, engineering geologists and geotechnical engineers will increasingly be asked to consider these structures when designing and carrying out site investigations for projects. This paper presents a review of the additional information (compared with a traditional ground investigation) regarding the ground, and also the geostructure themselves, required for the ground source heat pump design process. It then considers how such information can be obtained. The paper is arranged to mirror the ground investigation and design process. Section 2 deals with the design objectives and parameters required, Section 3 considers available desk study sources, Section 4 gives guidance on in situ thermal conductivity testing and Section 5 compares in situ and laboratory methods.

1 Design Parameters & Considerations

1.1 Objectives of Design

The recently published Ground Source Heat Pump Association Thermal Pile Standard (GSHPA, 2012) provides a useful review of the relevant parties and their roles in the design and construction process for foundation piles used as heat exchangers. While the document is specific to piles, much of the content could be applicable to energy geostructures more widely. In terms of design, there are two important objectives:

- Determining the energy output of the geostructures within appropriate soil and heat pump temperature limits;
- Ensuring that any additional temperature changes experienced by the geostructure as a result of their dual use do not lead to exceedance of any geotechnical limit states.

The first objective will require information regarding the thermal properties of the soil and concrete that would not normally be considered in routine site investigation. The second objective depends on the geotechnical properties of the system, and whether these are affected by temperature. Additionally, thermal expansion characteristics become relevant. Required design parameters for the two objectives are considered in Section 1.3 below.

1.2 Design Stages

As with any civil engineering scheme, the level of detail and certainty required will depend on the stage of the design. For example, at the planning stage it may be acceptable to make a determination of the likely energy output of a scheme based on "rules of thumb" (see Section 2.1 for further details) to gain an idea of that scheme's feasibility. At conceptual design stage, analysis of the energy output may be carried out based on values of thermal properties determined from the literature (see Section 2.2) before finally using parameters determined from *in situ* site specific testing (see Section 3) during detailed design.

Refinement of the soil and concrete thermal and geotechnical properties must also occur in parallel with the development of the mechanical and electrical design which determines the expected building thermal demand. These thermal loads, while beyond the scope of this paper, are as important as the thermal and geotechnical properties. How a ground energy system behaves thermally, in terms of both energy efficiency and the resultant temperature changes in the ground, will depend significantly on the nature of the thermal demand. In addition, the balance between heat demand and cooling demand will also affect the sensitivity of the ground source heat pump system design to the thermal parameters. For unbalanced systems that are dominated by either heating or cooling, the heat exchange rate is sensitive to the ground and geostructure thermal properties in particular. However, for balanced systems with equal demand for heating and cooling this sensitivity is much reduced (Low, 2015).

1.3 Design Parameters

The key parameters required for the design of an energy geostructure are summarised in Table 1. They can be split into those parameters required for determination of energy output and those required for the geotechnical and structural design of the geostructure. For the former the main focus is on thermal parameters, but groundwater conditions are also very important. In most cases conduction is the dominant heat transfer process within the ground (Farouki, 1986), but flowing groundwater can provide significant additional heat transfer by advection. The impact of this enhanced heat transfer depends on the thermal load requirements. For example, a cooling dominated system exposed to high groundwater flow velocities would experience a more effective transfer of energy to the ground. Conversely, a balanced system designed to provide inter-seasonal storage, would be adversely affected by groundwater flow, which would remove heat and make it unavailable for retrieval when needed. Groundwater flow also leads to thermal pollution over wider areas, which can impact long term sustainability when multiple systems may be in operation within the same locality. Analytical and numerical studies suggest that heat transfer due to groundwater flow may become significant when Darcy velocities reach 1 to 10 m/year (Sutton et al 2003, Claesson & Hellstrom, 2000, Chiasson et al, 2000, Gehlin & Hellstrom, 2003, Banks, 2014).

Undisturbed soil temperature is also an important parameter, because it determines the initial position of a system within the required operational temperature limits. Of particular importance is the lower operational temperature limit, designed to prevent ground freezing. A lower initial ground temperature will therefore offer a lower range within which the system can operate before reaching this limit.

For geotechnical design, many of the relevant parameters will be the same as for a standard geostructure. This will include the strength, stiffness and *in situ* stress and pore water conditions. No detail is given here on the determination of these parameters, in view of the many suitable texts already available (e.g Gaba et al, 2003, Clayton, 2011). However, the coefficient of thermal expansion may now be important, to estimate the relative expansion potentials of the soil and the geostructure concrete (Bourne-Webb et al, 2015). Furthermore, there is also a need to understand whether and in what way traditional soil mechanical parameters may be influenced by the additional temperature changes controlled by the operation of the ground energy system. A brief discussion of these aspects is given below (Section 1.3.1), but the majority of this paper will focus on determining the thermal parameters which are not normally considered during routine investigations.

1.3.1 Non-isothermal Soil Behaviour and impact on Geotechnical Parameters

The expected temperature changes around energy geostructures are actually relatively modest, being unlikely to exceed ±20°C. For example, Figure 1 shows measured changes within a pile heat exchanger subjected to real and fluctuating thermal loads. While the temperature of the fluid in the heat transfer pipes shows rapid variation in response to the demand (Figure 1a), the pile temperature changes are damped, especially near the edge of the pile (Figure 1b). It follows that any temperature change in the ground will be of relatively small amplitude and long (seasonal) wavelength. In contrast, most thermo-mechanical investigations of soil behaviour have been conducted with reference to applications such as nuclear waste disposal, where much greater temperature changes would be expected. Nonetheless the frameworks developed for use in these areas remain relevant for energy geostructures.

Practically, temperature generally does not have a significant effect on the engineering properties of most soils; generally, the critical state parameter M is independent of temperature (McCartney et al, 2013a). However, the expansion of water in soils during heating will cause excess porewater pressures to develop, which will result in a decrease in the effective stress. In coarse grained soils, any excess porewater pressure will dissipate rapidly. In clay soils there is the potential for excess porewater pressures to persist. No field measurements exist of this phenomenon, although some attempts to investigate it using numerical analysis have been made (Dupray et al, 2014, Di Donna & Laloui, 2015, Fuentes et al, 2015). While results from such analysis are highly model and parameter dependent, these studies suggest that a very low permeability is required to generate any significant porewater pressures. Furthermore, these preliminary analyses use simplified boundary conditions that are unrealistic of routine operation.

Perhaps most relevant for energy geostructures is the impact of temperature-induced volume change in soils. For dense granular soils or heavily over-consolidated clays, temperature induced volume change should be limited to elastic expansion (Cekerevac & Laloui, 2004).

However, for soft normally or lightly over-consolidated clay soils temperature induced mechanical changes in soil structure may occur leading to contraction and consolidation, resulting in large settlements (Boudali et al, 1994). These at first sight contradictory behaviours may be explained by a decrease in the apparent pre-consolidation pressure (at constant specific volume) as temperatures increase during undrained heating (Hueckel & Baldi, 1990). To illustrate this, Figure 2 presents a theoretical framework based on the data of Graham et al (2001). As the temperature increases, so the position of the critical state line in the specific volume – mean effective stress projection translates. Also shown are the corresponding volume changes under drained heating for soils of different OCR (vertical stress paths in Figure 2). For soft normally consolidated soil large plastic volume changes may occur upon heating, making energy geostructures in such soils much more challenging. However, it should also be noted that during any thermal consolidation the soil will work harden and so that further cycles of temperature change within the same temperature range will be elastic.

The thermal consolidation of soft normally consolidated clays causes their undrained shear strength and stiffness to increase (e.g. Abuel-Naga et al, 2007). Conversely, in over-consolidated clays, small reductions in undrained shear strength could result from small thermally driven expansion.

2 Desk Study Approach & Sources

The general approach to gathering desk study data at the project planning and outline design stages should be as described in BS5930 and Euro Code 7 (BSI, 1999, 2004) with additional sources consulted to determine the key design parameters and conditions which would not be required for a standard geostructure. Specific sources are discussed in the following sections and in Busby et al (2009).

During compilation of the desk study, initial consideration should be given to the general geotechnical conditions as these may affect the suitability of the site for an energy geostructure scheme. The most critical factor in this respect is the potential for volume change of the soil due to heating, as discussed in Section 1.3.1 above. Normally consolidated clays may be unsuitable for energy geostructure projects owing to the potential for large settlements. However, if a structure could accommodate such movements initially, later cycles of temperature change would be expected to be thermo-elastic and further movements small.

Other aspects of the ground conditions should not be such that they rule out the use of energy geostructures, although the thermal parameters and ground water conditions will clearly have the potential to influence the energy efficiency of the scheme. However, the designer should always additionally take account of whether construction of a ground energy system could have adverse impacts on other such systems in the vicinity, or on the natural environment more generally. These potential impacts should all be assessed during compilation and review of desk study sources.

2.1 Rules of Thumb

Rules of thumb for the outline design or feasibility assessment for ground source heat pump systems are commonplace for most of the routine types of ground heat exchanger (e.g. MIS, 2011) and are usually expressed as power per metre of heat exchanger length. For piles, initial guidance is given by the SIA (2005) and Brandl (2006). The former suggest heat extraction rates from 25 W/m to 50 W/m depending on the ground and groundwater conditions, with higher conductivity soils and sites with Darcy velocities greater than 1m/year representing the upper end of the range. For heat injection (building cooling), it is suggested that heat exchange rates be limited to 30 W/m. This is due to the reduced efficiency inherent in cooling as the electricity supplied to the heat pump becomes waste heat to be disposed of. Heat exchange rates suggested by Brandl (2006) are 40 W/m to 60 W/m for piles less than 500m in diameter. For large diameter piles Brandl (2006) prefers a surface area approach and suggests 35 W/m^2.These values are of a similar order to the SIA recommendations, albeit slightly larger.

A review of published values of measured energy outputs from thermal response tests and longer term trials of energy geostructures was carried out by Bourne-Webb (2013) and is summarised in Table 2. The longer term data are broadly in keeping with the rules of thumb suggested above. However, the shorter tests show much greater variation, reflecting the influence of the test method and duration on the output. As has already been observed in Figure 1, the actual heat exchange values will also varying throughout the year during operation. For other types of energy geostructure there are no published rules of thumb. Table 2 gives results from two individual wall and slab case studies, but this is a very small database on which to make outline design decisions.

2.2 Thermal Properties

2.2.1 Soil

Published tables of soil thermal properties give indicative values of thermal conductivity and specific heat capacity for different soil types, rock lithologies, or specific stratigraphic units. These databases typically draw on a variety of laboratory testing data, for example see Banks (2008) and Busby et al (2009). In addition Banks et al (2013) have recently published the results of in situ thermal conductivity testing at 61 sites across the UK, with results largely in line with published databases (Figure 3).

On a site specific basis estimations of thermal conductivity and specific heat can be made based on the relative proportions of the soil phases. A critical review of models for determining soil thermal conductivity in this way is presented by Dong et al (2015). While the accuracy of such models is questionable, at the early stage of a project these can still offer useful upper and lower bounds of thermal conductivity. The simplest are the so called Weiner bounds whereby the soil is assumed to be arranged with the three phases in separate blocks. This means that the upper and lower bounds of thermal conductivity will relate to parallel (weighted mean) and series (weighted harmonic mean) assessments of the phases respectively (eg Woodside & Messmer, 1961):

$$\boldsymbol{\lambda_{eff(max)} = (1-n)\lambda_s + nS_r\lambda_w + (1-S_r)n\lambda_a} \qquad \textit{\textbf{Equation} 1}$$

$$\frac{1}{\lambda_{eff(min)}} = \frac{(1-n)}{\lambda_s} + \frac{nS_r}{\lambda_w} + \frac{(1-S_r)n}{\lambda_a}$$ ***Equation** 2*

where n is the porosity, S_r is the degree of saturation and λ the thermal conductivity of each phase, with the subscripts s, w and a represent soil, water and air respectively. Volumetric heat capacity, S_{vc} (in J/m^{3}K) in soils can be expressed similarly so that:

$$S_{cv} = (1-n)S_{cv-s} + nS_rS_{cv-w} + (1-S_r)nS_{cv-a}$$ ***Equation** 3*

In this case x is the proportion of each different phase by weight. A drawback to these approaches is the need to determine the thermal conductivity and specific heat capacity of the individual phases. While this may be straightforward for air and water, for soil minerals a range of values exists. Quartz has a thermal conductivity of up to 8 W/mK, while other minerals tend to be less conductive with ranges between 1 W/mK and 5 W/mK. Ren et al (2003) quote specific heat capacities for soil solids in the range 650 J/kgK to 950 J/kgK.

National data on ground temperatures have recently been compiled by the British Geological Survey and are interrogated at a national scale in Busby et al (2011). Median values at 100m depth are approximately 12.5 °C. However, ground temperature does vary due to natural geological conditions. For example, consistently higher ground temperatures are observed in the north east of England and the East Midlands. Large cities also see elevated ground temperatures owing to urban heat island effects (e.g. Ferguson & Woodbury, 2004). Buildings, especially those with basements (Menberg et al, 2012), and other infrastructure give rise to an accumulation of heat over long periods of time and can even result in a reversal of the geothermal gradient (Banks et al, 2009). As well as changing the boundary conditions for analysis, this can lead to an increase in stored heat available for exploitation by energy geostructures (Zhu et al, 2010).

2.2.2 Concrete

The thermal conductivity of concrete covers a similar range of values to that of soil, from approximately 1 W/mK to over 4 W/mK, depending on the mix design (Neville, 1995; Tatro, 2006). Concrete thermal conductivity depends mainly on the aggregate lithology, aggregate volume ratio and water content; some typical values are given in Table 3. Additionally, some admixtures can reduce the thermal conductivity of concrete (GSHPA, 2012). The specific heat capacity of concrete is important for storage of heat within the geostructure. It is typically in the range 840 – 1170 J/kgK and would be expected to increase with water content and temperature (Neville, 1995).

An additional parameter not normally considered in foundation analysis is the linear thermal expansion of the concrete itself. This parameter will determine any additional stresses that may occur within the geostructure concrete and will depend on the constituents of the concrete. The coefficient of linear expansion depends on the concrete mix, both in terms of cement aggregate ratio and the aggregate type. Age and water content will also affect the overall coefficient, but it would typically be in the range $7x10^{-6}$ to $13x10^{-6}$, with $10x10^{-6}$ $^{o}C^{-1}$ often used as a general value (Tatro, 2006).

2.3 Thermal Resistance

The thermal resistance of a geostructure is a lumped parameter that accounts for both its thermal conductivity and geometry. Generally, the thermal resistance, R_b, is given by:

$$R_b = \Delta T / q \qquad \textbf{Equation } 4$$

where ΔT is the difference between the average temperature of the fluid within the pipes of the heat exchanger and the average temperature at the edge of the geostructure. q is the applied heat transfer rate in W/m. The parameter is normally determined at a thermal steady state so that the temperature change and hence the resistance is a constant.

Pile thermal resistance can be determined by in situ testing, although this has a number of disadvantages (refer to Section 3). At desk study stage some general values can be taken from SIA (2005) or Pahud (2007), as summarised in Table 4. Table 4 shows that the number of pipes has a significant impact on R_b. However, thermal resistance is also strongly dependent on concrete conductivity (λ_c), a value not considered in Table 4. More specific calculations can be made using either the multipole method (Bennet et al, 1987) or a simplified model as presented by Loveridge & Powrie (2014).The latter includes use of a dimensionless shape factor, S_c, such that:

$$R_b = \frac{1}{\lambda_c S_c} + R_p \qquad \textbf{Equation 5}$$

where λ_c is the concrete thermal conductivity (W/mK) and R_p is the pipe resistance. R_p can be calculated using simple analytical solutions (for example see Loveridge & Powrie, 2014) and is typically between 0.01 and 0.05 mK/W assuming turbulent flow in the pipes. Lower values in the range are appropriate for larger numbers of heat transfer pipes. An indication of the shape factor can be taken from Figure 4.

The resistance approach is not yet well developed for types of energy geostructure other than piles. A resistance model has been proposed for diaphragm walls by Kurten et al (2014), but its use so far has been limited to a small number of numerical applications and no database of values for use in analytical design approaches is available.

Caution must also be exercised when using thermal resistance values for large diameter piles as these are unlikely to be at a thermal steady state during routine operation (e.g. Figure 1). While outline design using steady state resistances may be safe in terms of energy output assessment, it could be overly conservative for detailed design and lead to under-prediction of available energy output (Loveridge & Powrie, 2013).

3 In Situ Thermal Testing

3.1 Traditional Thermal Response Testing

Thermal response testing (TRT) is an *in situ* technique to determine the thermal conductivity of the ground and the thermal resistance of the heat exchanger. Heat is typically injected into the ground at a constant and known rate via a borehole heat exchanger. The temperature change of the fluid circulating in the borehole is monitored and the results used to determine the thermal properties. There are several international and national guidelines for the test to encourage high quality testing and interpretation (Sanner et al, 2005; IGSHPA, 2007; GSHPA, 2011).

3.2 Interpretation Approaches

Thermal response tests have traditionally been interpreted using the simple line source method. This is based on the assumption that the borehole behaves like an infinitely long and infinitesimally thin heat source of constant power. The approach also assumes an infinite and homogeneous 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 circulating fluid 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 change in inlet and outlet temperature to the borehole during the test are plotted against the natural logarithm of time (for example, see Figure 5):

$$\boldsymbol{\lambda = \frac{q}{4\pi k}} \qquad \textbf{\textit{Equation 6}}$$

where λ is the soil thermal conductivity (W/mK), q is the total applied thermal power (W/m), and k is the gradient of the graph. Owing to the mathematical simplifications involved in the line source model, it is important to include a minimum time criterion after which those simplifications are valid. It is normally recommended that the results prior to a non-dimensional time *Fo=5* are neglected. Fo is the Fourier number, with $Fo = \alpha t / r_b^2$ in this application. In this expression α is the soil thermal diffusivity (m^2/s), t is the elapsed time (s) and r_b is the borehole radius (m).

Additionally the borehole thermal resistance can be determined from the straight line intercept:

$$I = q\left[R_b + \frac{1}{4\pi\lambda}\left(\ln\left(\frac{4\alpha}{r_b^2}\right) - \gamma\right)\right] \qquad \textbf{\textit{Equation 7}}$$

where α is the soil thermal diffusivity, r_b is the borehole radius and γ is Euler's constant. The advantage of this approach is its simplicity. However, the tendency for the ground not to be homogeneous and isotropic can lead to errors. These have been quantified and are generally within 10% providing the test is well conducted (Witte, 2013, Signorelli et al, 2006, Spitler & Gehlin, 2015).

Various other interpretation methods have also been suggested. Instead of assuming that the borehole acts as a line heat source, it is possible to interpret the results assuming it acts as a cylindrical heat source. This approach tends to give values of thermal conductivity and thermal resistance that are higher by around 10% (Gehlin, 2002). It is also more complicated to apply as the two variables cannot be obtained separately and parameter estimation techniques must be used. Therefore it does not offer much advantage over the line source assumption.

Further disadvantages of both the line and cylindrical source approaches are the assumptions that the borehole resistance is constant (and equal to the steady state value) and that the heat flux applied is constant. The latter can be challenging to achieve in the field when test times of several days are required. These disadvantages can be overcome by using more sophisticated models to interpret the test results. The most accessible is the Geothermal Properties Measurement (GPM) tool, developed by Oak Ridge National Laboratory and freely available. The tool uses numerical solutions to the one dimensional diffusion equation in radial coordinates to determine the best fit thermal resistance and ground thermal conductivity for TRT data (Shonder & Beck, 2000). Other analytical and numerical methods are available (e.g. Javed & Claesson, 2011, Austin et al 2000), but are not yet readily accessible on a routine basis.

3.3 Undisturbed Ground Temperature

Thermal response testing also provides an opportunity to investigate the undisturbed ground temperature. This can be done in several ways. One approach is to lower a sensor down the heat exchange pipes and record the output every few metres. However, care must be taken to prevent mixing of the fluid between different depths (IEA, 2013). An alternative approach, which does not require any additional equipment, is to use data from the fluid temperatures prior to heating. If the fluid is circulated round the ground loop prior to the heaters being turned on for the heat injection part of the test, then temperatures during this period can provide full details of the ground thermal profile, providing the measurement interval is short enough. Full details of the approach are given in Gehlin & Nordell (2003).

3.4 Applicability to Piles

The minimum time criterion requirement of $Fo>5$ for interpretation of thermal response tests by the line source approach has major implications for the application of the test to piles used as ground heat exchangers (Table 5). As the pile size increases the theoretical minimum time also increases. This means that the time required to carry out a test rapidly escalates beyond that which is both economical and practicable. As well as dealing with the mathematical simplifications in the model, the minimum time criterion also allows time for the pile to reach a thermal steady state so that the thermal resistance is constant. Tests that do not allow this will see the influence from the concrete thermal conductivity in the derived soil thermal conductivity results (e.g. Loveridge et al, 2014a, Franco et al, 2016). Research to date suggests that to keep test times within 100 hours, thermal response testing should not be applied to piles greater than 300mm or possibly 450mm in diameter (Loveridge et al, 2014a, b).

Consequently, alternative approaches to test larger piles in practical timescales need to be developed and verified. One challenge is the co-linearity of λ and R_b. When using a line source approach the two parameters can be determined independently. When using other non-linear solutions, parameter estimation must be used. It is always possible to find the best fit thermal conductivity and thermal resistance from the test data, but there will always be a range of pairs of parameters that give similar fits. An example is shown in Figure 6.

An alternative approach is to carry out a thermal response test on a borehole at the site investigation stage of a project. This approach has many advantages, not least cost (owing to the shorter test duration) and programme (owing to the removal of the need to wait for the heat of hydration in a curing pile to subside). However, by conducting the test at an earlier stage in the project the likely depth of the future foundations may not have been finalised. It is also not possible to make any inferences about the pile thermal resistance.

3.5 Group Thermal Response Testing

Another potential problem of applying thermal response tests to pile is the short length of the heat exchanger compared with more typical borehole installations. Many commercial TRT test rigs are set up to deliver the power levels needed for heat exchangers in excess of 100m deep. Therefore the electric heaters used are typically in the range 2 kW to 6 kW, delivering the recommended 30 W/m to 80 W/m (Sanner et al., 2005) to the ground. Delivering the same total power to a 10m or 20m long pile can rapidly lead to overheating and curtailment of the test (for example see Hemingway & Long, 2013). One solution to this problem is to test a group of 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. However this approach does introduce the potential for additional heat losses from the lengths of pipe between the piles. This is illustrated by the pile tests results of Murphy et al (2014), in which horizontal pipe run out lengths were inversely correlated to apparent thermal conductivity, suggesting reduced heat transfer to the ground for tests with extensive surface or near surface pipe lengths. It will also be necessary to consider whether the piles within the group will interact thermally within the timescale of the test (Loveridge et al, 2015).

4 Laboratory Testing for Thermal Properties

Laboratory testing holds a number of attractions over field testing in geotechnics, the most obvious being speed and cost. Both of these are applicable in the case of energy geostructures. However, small scale testing also brings drawbacks which will be discussed further below, following a review of the common methods.

Testing for soil thermal properties usually follows one of two approaches. The first involves development of a thermal steady state within a soil specimen such that Fourier’s Law can be applied directly. The second uses measurement of transient temperature changes over time and compares the results to an appropriate solution to the diffusion equation. Both approaches have advantages and disadvantages which are discussed below.

4.1 Steady State Methods

While there are standard methods for steady state thermal conductivity testing, none are explicitly for use with soils. The guarded hot plate method (or its variants) has been standardised (BSI, 2001a,b, ASTM, 2012) and applied to soils (Farouki, 1986, Mitchell & Kao, 1978), although it is more commonly used for building materials. A heating unit is sandwiched between two thin, flat specimens, which are then subjected to vertical heat flow while the power to the heater is measured. The "guards" are present to prevent lateral heat loss and ensure one dimensional flow. The thermal conductivity can be calculated directly from the temperature gradient across the specimen. A similar approach is used to test rock core and rock fragments using the divided bar method (Birch, 1950, Sass et al, 1971) which has also been applied to stiff soils. In both cases testing takes a long time since a steady state must first be obtained within the specimen. If the specimen is unsaturated, this may result in substantial moisture migration which will affect the accuracy of the result, typically giving lower values of thermal conductivity compared with transient methods. Farouki (1986) also reports differences in results for the upper and lower specimens due to the direction of heat flow (up or down). The guarded hot plate apparatus is also rather large with a minimum specimen diameter of 300mm. This can make it rather impractical for use with routine site investigation samples.

As part of the then Department for Trade and Industry Partners in Innovation Programme, Clarke et al (2008) developed an alternative steady state thermal cell apparatus based on readily available triaxial apparatus to take routine 100mm diameter soil samples. However, subsequent work by Low (2015) comparing the thermal cell and transient methods confirmed the importance of minimising heat losses from any steady state tests. Failure to account for heat losses in steady state testing can lead to an overestimate of the applied power and hence of the thermal conductivity. This is also highlighted by Alrtimi et al (2014), who went on to develop the Clarke et al (2008) thermal cell into a dual specimen arrangement to eliminate losses from the base of the apparatus. Alrtimi et al (2014) also reduced radial losses by the use of a thermal jacket to better control the side boundary condition of the apparatus. This approach appears more reliable.

4.2 Transient Methods

The alternative to steady state thermal conductivity testing is to use transient methods like the needle probe (sometimes called the hot wire method) or the dual needle probe. The needle probe acts as a miniature thermal response test and has been standardised by the IEEE (1996) and ASTM (2014). A needle containing both a wire heating element and temperature sensors is inserted into a specimen. The heater is switched on and the resulting temperature change is measured and then interpreted using a line source approach (see also 4.2). The test is rapid and only results in temperature changes of a few degrees at the most. Hence it minimises moisture migration effects that may be problematic in steady state tests. However a key disadvantage is that a much smaller volume of soil is tested.

The dual needle probe (Campbell et al, 1991) is similar, but contains a second temperature monitoring point in a second needle located a few millimetres from the first. A short heat pulse is released from the heater and the temperature change at both needles monitored. The main advantage of the dual needle probe is that by including two monitoring points the thermal diffusivity and the specific heat capacity can both be calculated. However, the results are very sensitive to the separation of the two needles, which can diverge when inserted into the soil.

4.3 Differences between Steady State and Transient Results

It is often reported (e.g. Alrtimi et al, 2014) that steady state methods are more accurate than transient approaches. However, this is not necessarily the case, and reasonable results from steady state tests can only be achieved if the heat losses can be truly controlled (see 4.1 above and Low et al, 2015). Nonetheless there are other commonly reported discrepancies between steady state and transient test methods and the reasons for these differences are not always clear. For example, Midtomme & Roaldset (1999) review a range of studies comparing the divided bar method with the needle probe. Some studies provide comparable results but often the needle probe values are higher than those of steady state tests by 10% to 20%. Midtomme & Roaldset (1999) variously attributed these discrepancies to different factors including drying of soil samples during long steady state testing and the vertical versus radial heat flow paths in the two tests. They also highlighted the potential for soil anisotropy to affect results; in standard samples cored perpendicular to the stratigraphy, needle probes are more likely to measure horizontal and steady state tests vertical thermal conductivity. However, this can be easily accounted for in site investigation through an appropriate sampling strategy.

4.4 Sampling Issues

Testing of soil specimens to determine their physical properties must always be undertaken with a knowledge of sample scale and quality (Rowe, 1972, Graham, 2006) and thermal properties are no different. It is important to understand that thermal properties depend on the moisture content, density and structure of samples, all of which may change during sampling. Like soil water retention properties, thermal conductivity is a hysteretic property which will vary depending on whether a soil is being wetted or dried (e.g. Tang et al, 2008, Rubio et al, 2011). Thermal conductivity is also dependent on particle contacts (e.g Choo et al, 2013) which may be reduced by stress release on sampling. All these factors mean that additional care must be taken with laboratory testing to ensure samples are either truly undisturbed or reconstituted to appropriate field conditions.

Stress induced changes in porosity leading to thermal conductivity changes have been examined by Abuel-Naga et al (2009) and McCartney et al (2013b), using needle probes installed within modified Rowe Cells and triaxial cells respectively. Both found largely linear relationships between porosity and thermal conductivity, with the latter showing a full recovery in thermal conductivity on unloading even though the soil exhibits a stiffer response.

4.5 Scale in Thermal Conductivity Testing

Few studies compare laboratory tests for thermal conductivity with larger scale tests such as borehole thermal response tests. A number of small scale comparisons have been made as part of other studies, which appear to show good comparability between the needle probe and TRT scale testing (e.g. Witte et al, 2002, Breier et al, 2011) where due care is applied during both tests. In addition, there are a number of recent comparisons using pile heat exchangers. With the exception of Loveridge et al (2014a), these all determined higher values of thermal conductivity from larger scale tests (Table 6, Figure 7). Some of this discrepancy may be attributable to using the line source method with piles, while sample quality could also play a role. It should also be noted that in some of these cases the numbers of laboratory tests was relatively small. In such cases the small volume of soil tested in the laboratory will always be a concern when dealing with inherently heterogeneous natural materials. For example, King et al (2013) have applied the needle probe test to field sites, using the equipment to take multiple measurements in trial pits. Their study showed that at least fifteen separate determinations of thermal conductivity were required for the average value to be representative of the bulk thermal conductivity at the site. Any laboratory to field scale comparison based on only a small number of samples therefore has the potential to be misleading.

A further larger scale study was carried out using boreholes in the Oslo region in Norway, where Leibel et al (2010) compared the results of 1398 thermal conductivity tests on rock core with 67 thermal response tests. The laboratory tests were carried out using a transient method with one dimensional heat flow proposed by Middleton (1993). The thermal conductivity values from the in situ testing were on average approximately 20% greater than the laboratory tests, depending on the rock lithology (Figure 7). The authors attributed some of the differences to the effect of groundwater movements in the field. However, it is also possible to overestimate the heat transfer to the ground in thermal response tests if heat losses from the equipment are not effectively controlled. In such cases the thermal conductivity from TRTs would be an overestimate. Witte et al (2002) advise placing the fluid temperature sensors as close to the ground as possible to minimise this effect. This effect could also have an impact on the pile tests results.

Given the potential difficulties associated with both laboratory and field testing for thermal conductivity, care is required in both test approaches to achieve suitable quality results.

5 Summary

Energy geostructures offer the opportunity to access heat storage volumes beneath and around our buried infrastructure, including building deep foundations, retaining walls and metro tunnels. Inclusion of energy geostructures in projects means that site investigations must expand their scope to consider additional ground parameters which may be required in the design of the energy system.

This paper reviews the thermal parameters required for analysis of ground energy systems, and how they may be estimated or measured in desk studies and laboratory and in situ testing. As with conventional geotechnical properties, particular attention must be paid to understanding the effects of soil sampling and how changes in scale may affect thermal properties. While laboratory testing may be quicker and cheaper than multi-day in situ testing, it requires high quality samples and numerous careful tests to arrive at reliable results.

Consideration is also given to the potential impact of temperature changes on geotechnical properties of soils. The potential for induced porewater pressure and volumetric changes are discussed. The latter may be particularly problematic for normally consolidated soils which will consolidate upon heating. Consequently these soils will require much more careful consideration when proposed as a possible host geology for energy geostructures.

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Table 1 Key design parameters

Design Parameter	***Required For***	***Comments***
Soil thermal conductivity	Energy output	An average value is used in most design approaches, although real conditions are likely to be anisotropic and heterogeneous.
Soil specific heat capacity	Energy output	
Undisturbed soil temperature	Energy output	Average value, or preferably a profile with depth
Groundwater flow rate (Darcy velocity)	Energy output	As a minimum, an indication is required of whether significant groundwater flow is to be expected at the site.
Soil strength	Geotechnical design	In total or effective stress terms as appropriate; should include an estimate of whether likely to be significantly temperature dependent
Soil stiffness	Geotechnical design	For serviceability considerations
In situ stresses (K_0) and pore water regime	Geotechnical design	"Apparent" pre-consolidation pressure can be affected by temperature
Stress history	Geotechnical design	
Over Consolidation Ratio (OCR)	Geotechnical design	Determines the nature of the thermo-elastic (or thermo-plastic) response
Concrete thermal conductivity	Energy output	Often included within the thermal resistance parameter
Concrete specific heat	Energy output	For storage of heat within the concrete
Thermal resistance of heat exchanger	Energy output	A lumped parameter that includes for the thermal properties and geometry of the heat exchanger
Concrete coefficient of thermal expansion	Geotechnical design	To determine the potential expansion of the geostructure
Soil coefficient of thermal expansion	Geotechnical design	Expansion of soil relative to concrete may be important for soil structure interactions
Concrete limiting stress	Structural design	Additional stresses may develop due to restraint of the geostructure as it tries to expand on heating

Table 2 Energy exchange rates for different energy geostructures (data from Bourne-Webb, 2013)

	Short term test	**Study >1 year**
Concrete piles	25 – 210 W/m	15 – 45 W/m
Steel piles (fluid infilled)	15 – 140 W/m	
Steel piles (sand/water infilled)	25 – 55 W/m	
Steel piles (concrete infilled)		15 – 20 W/m
Diaphragm wall	30 – 100 W/m	
Slabs		5 W/m^2

Table 3 Typical values of concrete thermal conductivity by aggregate lithology (after Bamforth, 2007)

Aggregate Lithology	**Concrete Thermal Conductivity (W/mK)**	
	Sand and aggregate from same rock type	**Aggregate from defined rock type with siliceous sand**
Quartzite and siliceous gravels with high quartz content	2.9	2.9
Granite, gabbros, hornfels	1.4	2.0
Dolerite, basalt	1.3	1.9
Limestone, sandstone, chert	1.0	1.8

Table 4 Typical values of thermal resistance (R_b) for concrete piles of 0.3m to 1.5m in diameter (after Pahud, 2007)

Double U-pipe placed on reinforcing cage	0.1 to 0.11 mK/W
Triple U-pipe placed on reinforcing cage	0.07 to 0.08 mK/W
Quadruple U-pipe placed on reinforcing cage	0.06 mK/W

Table 5 Minimum elapsed time for interpretation of thermal response tests using a line source approach when Fo > 5

Pile Diameter	**t_{min} (α=0.5x10^{-6}m^2/s)**	**t_{min} (α=1.5x10^{-6}m^2/s)**
200mm	28 hours	9 hours
300mm	63 hours	21 hours
450mm	141 hours	47 hours
600mm	250 hours	83 hours
900mm	563 hours	188 hours
1200mm	1000 hours	333 hours

Table 6 Summary of comparisons between thermal conductivity from laboratory needle probe tests and field scale thermal response testing (line source interpretation unless otherwise indicated)

Reference	No. of laboratory measurements	Average laboratory thermal conductivity W/mK	TRT thermal conductivity W/mK	Comments
Beier et al 2011	4 locations	2.8 ± 0.1	2.9	TRT is laboratory sand box, not full scale
Witte et al 2002	13 locations; 18 determinations	2.1 ± 0.1	2.1 ± 0.2	Borehole TRT
Loveridge et al 2014a	3 locations	3.0	2.7	TRT on pile, 300mm diameter
Low et al 2015	6 locations; 30 determinations	1.3*	2.5	TRT on pile, 300mm diameter
Park et al, 2013	5 determinations (at different moisture contents)	2.0	2.2	TRT on pile, 400mm diameter, interpretation by numerical simulation
Bouazza et al, 2013	28 determiantions (at different moisture contents)	2 - 3	4.3	TRT on pile, 600mm diameter, average of three tests
Murphy et al, 2014	3 locations	1.2	2.0	TRT on piles, 610mm diameter, results corrected for horizontal pipe length

* long time period between sampling and testing suggests some sample drying may have contributed to size of discrepancy with field test

Figure 1 Energy exchanged with and resulting temperature variations within a 1200mm pile with heat transfer pipes installed in the centre (see inset). a) Measured variations in total applied thermal load (absolute value); b) Reduced temperature variations near the edge the pile compared with the central pipe position; c) Plant room air temperature. All data from twelve months of monitoring of a real pile heat exchanger scheme under operational conditions.

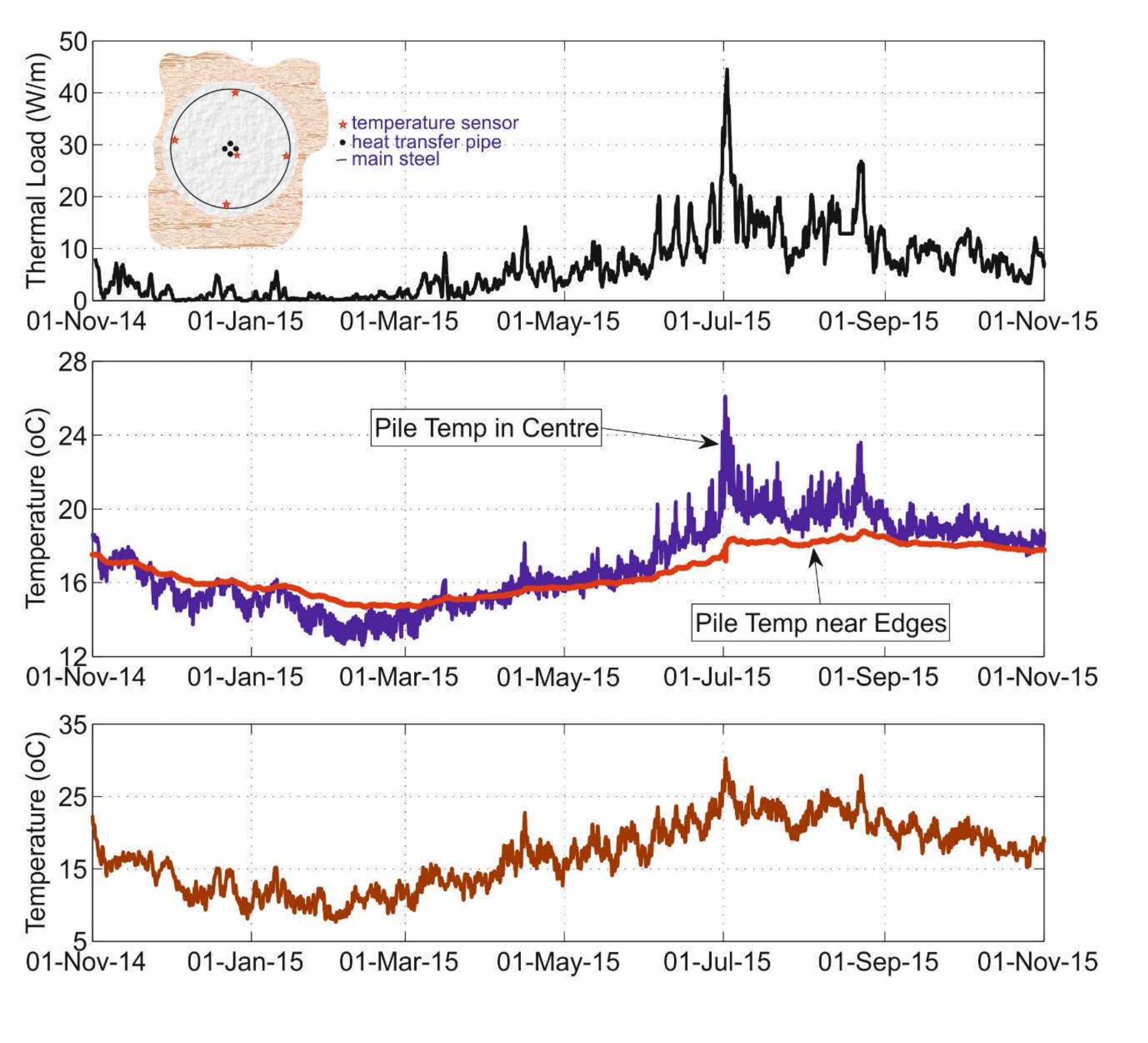

Figure 2 A theoretical framework for understanding non-isothermal volume changes in realtion to mean effective stress (after Graham et al, 2001). Vertical stress paths shows volume change (drained conditions) and horizontal stress paths shows change in apparent pre-consolidation pressure (undrained conditions), both with increase in temperature from T_0 to T_1. NC=normally consolidated; LC=lightly consolidated; OC=over-consolidated.

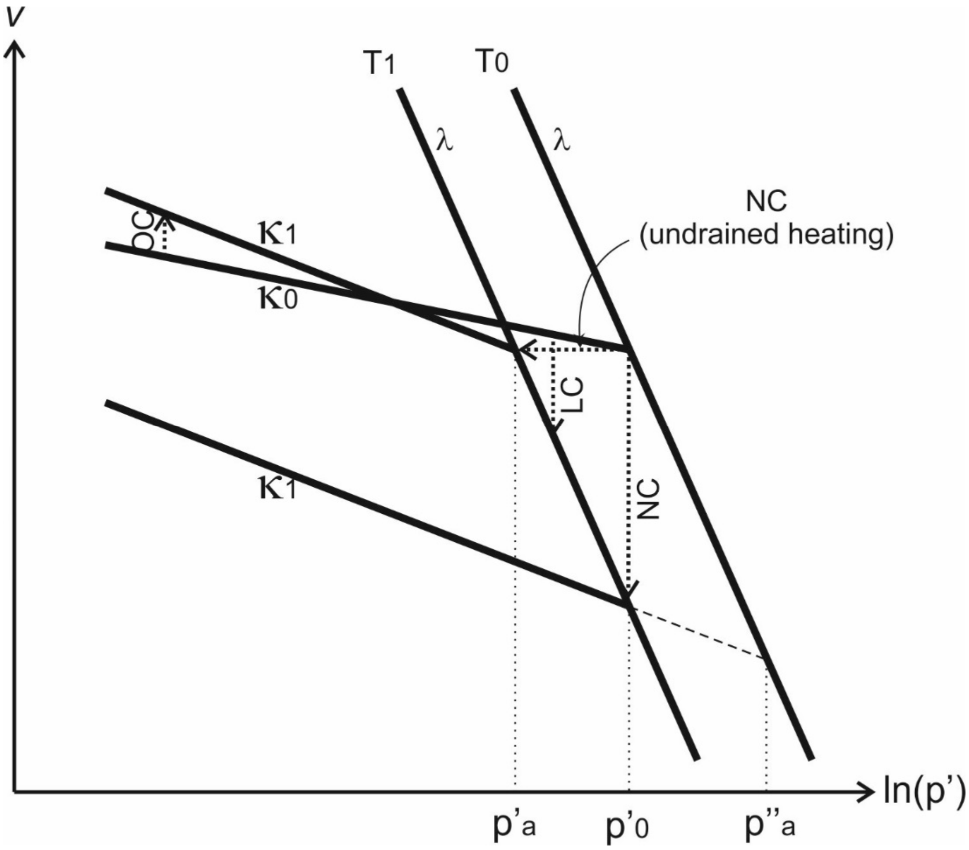

Figure 3 Range of thermal conductivity values for selected UK strata (from data compiled by Banks et al, 2013).

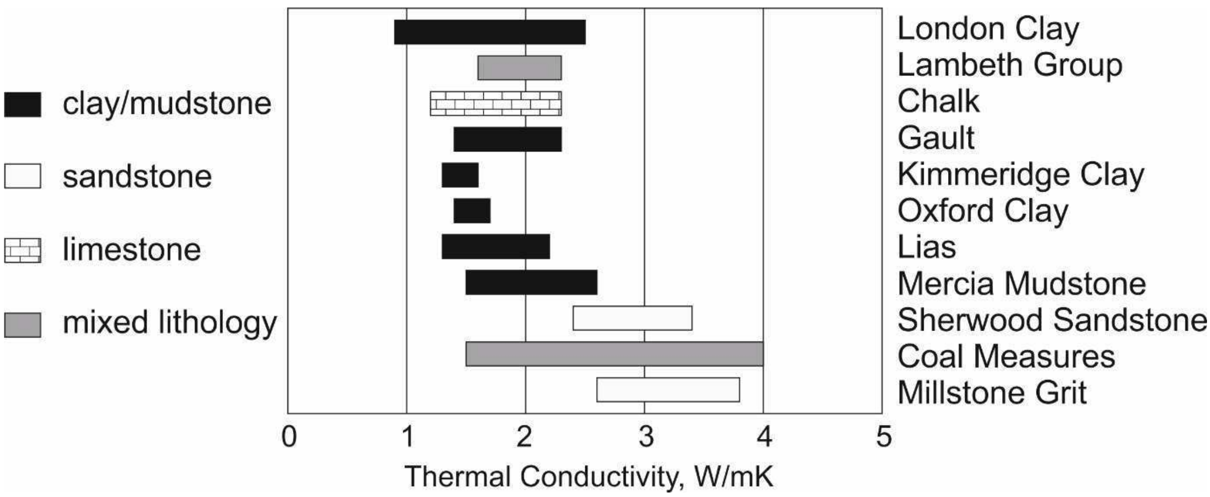

Figure 4 Typical values of the shape factor (S_c) for pile concrete resistance for a) piles with pipes installed on the reinforcing cage (typical for rotary bored piles); and b) piles with pipes installed centrally (typical for contiguous flight auger piles). Based on the results of Loveridge & Powrie (2014)

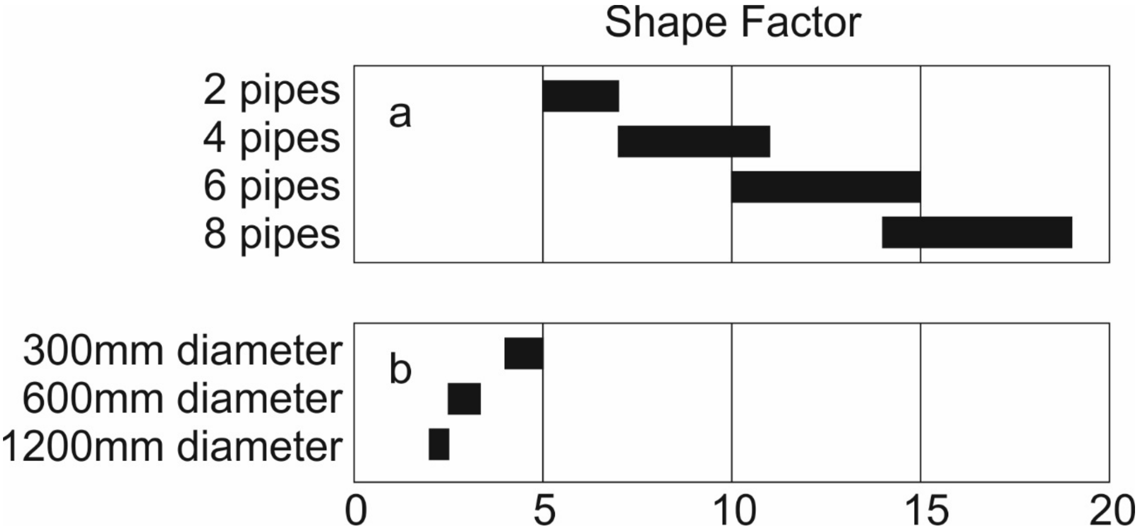

Figure 5 Example thermal response test data from a 150m deep borehole in the London Basin (Loveridge et al, 2013), showing traditional line source interpretation. Applied power is 8kW.

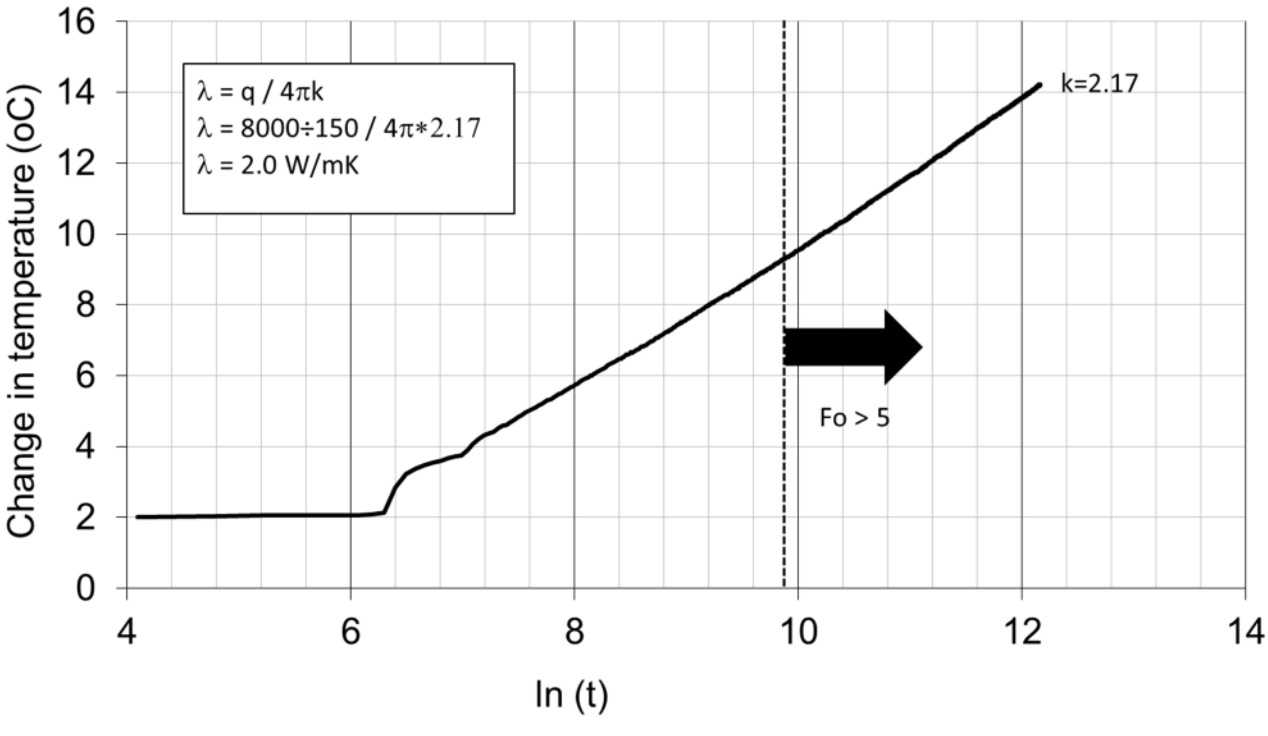

Figure 6 Results of numerical simulation of two borehole thermal response tests after Wagner et al, 2012. Dark grey shading shows range of results achieved by parameter estimation with root mean square error (RMSE) less than 0.14ºC. Range of ± 10% on simulated thermal conductivity and thermal resistance also highlighted.

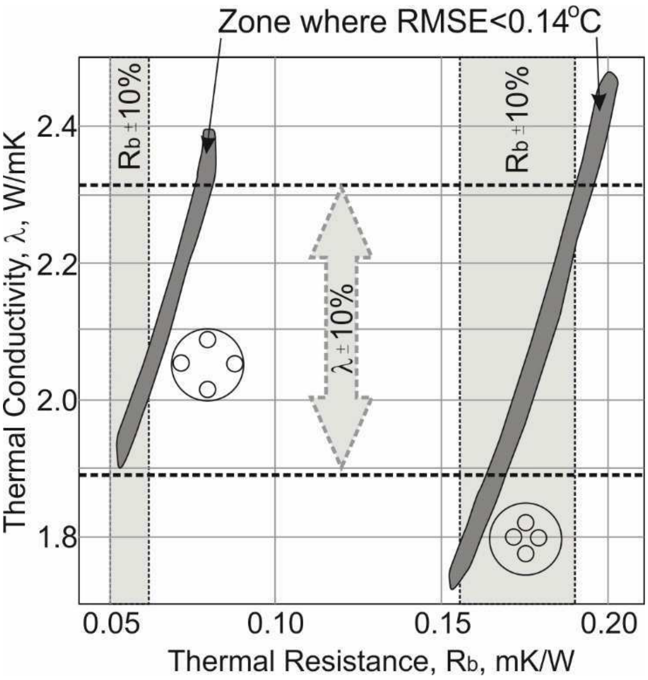

Figure 7 Difference between laboratory and full scale testing for thermal conductivity. Multiple values for Liebel et al represent different rock lithologies.